SUMMETH

SUMMETH – Sustainable Marine Methanol

Deliverable D5.1

Expected benefits, strategies, and implementation of methanol as a marine fuel for the smaller vessel fleet

Date: 2018-04-10

Authors: Joanne Ellis, Martin Svanberg (SSPA)

Document Status: Final Report

Document Number: D5.1

PROJECT PARTNERS

TRAFIKVERKET SWEDISH TRANSPORT ADMINISTRATION · LUND UNIVERSITY · MARINE BENCHMARK · SCANIA · VTT · SSPA · ScandiNAOS AB

CO-FUNDED BY

SWEDISH MARITIME ADMINISTRATION · REGION VÄSTRA GÖTALAND · METHANOL INSTITUTE · Oiltanking

Supported by the MARTEC II Network

ABSTRACT

This report describes an assessment of environmental, economic, safety, and supply and distribution considerations regarding the use of methanol as a sustainable fuel for small commercial vessels. Methanol produced from both conventional and renewable feedstocks was compared to the conventional diesel fuel currently used by vessels with propulsion engines in the size range 250 kW to 1200 kW. There were no barriers identified from a safety perspective. Methanol produced from fossil feedstock is widely available and distribution systems currently in place would be suitable for provision of methanol to smaller vessels, as many are currently bunkered by truck. The cost of production of sustainable methanol is currently higher than the price of conventional fuels and is a barrier to uptake. Measures requiring reduction of greenhouse gas emissions from ships could favour the uptake of renewable methanol and reduce the economic barrier, as other measures to reduce GHGs would also entail costs. There is good potential for production of renewable methanol within Sweden, with some technologies that have been tested at pilot scale now considered ready for scale up to industrial level. The environmental assessment showed that there are many benefits to be realised from using methanol as a marine fuel, including significantly lower emissions from combustion, and large reductions in greenhouse gas emissions if sustainable methanol is used.

SUMMETH PROJECT SUMMARY

SUMMETH, the **Su**stainable **M**arine **Meth**anol project, is focussed on developing clean methanol engine and fuel solutions for smaller ships. The project is advancing the development of methanol engines, fuel system installations, and distribution systems to facilitate the uptake of sustainable methanol as a fuel for coastal and inland waterway vessels through:

- developing, testing and evaluating different methanol combustion concepts for the smaller engine segment
- identifying the total greenhouse gas and emissions reduction potential of sustainable methanol through market investigations
- producing a case design for converting a road ferry to methanol operation
- assessing the requirements for transport and distribution of sustainable methanol.

The SUMMETH project consortium consists of SSPA Sweden, ScandiNAOS, Lund University, VTT Technical Research Centre of Finland, Scania AB, Marine Benchmark, Swedish Transport Administration Road Ferries, and the Swedish Maritime Technology Forum.

ACKNOWLEDGEMENTS

The SUMMETH project is supported by the MARTEC II network and co-funded by the Swedish Maritime Administration, Region Västra Götaland, the Methanol Institute and Oiltanking Finland Oy.

Document Data

Document Title:	D5.1 Expected benefits, strategies, and implementation of methanol as a marine fuel for the smaller vessel fleet
WP and/or Task:	WP5
Responsible Author	Joanne Ellis
Co-authors	Martin Svanberg
Date and Version:	20180410, partner and funding agency logos added to the cover; executive summary added;
Previous Versions:	20180115, abstract revised, chapter numbers in the introduction paragraphs corrected, minor editorial corrections throughout 20171221 Draft

EXECUTIVE SUMMARY

The Sustainable Marine Methanol (SUMMETH) project was carried out to investigate and develop methanol engine and fuel solutions for smaller ships and to assess the environmental benefits and feasibility of transporting and supplying sustainable methanol as ship fuel. Improved environmental performance through reduction of emissions of SOx, NOx, and particulates was previously demonstrated for dual-fuel methanol engines for larger vessels and the SUMMETH project had the goal of estimating the benefits that could be achieved for smaller engine concepts. Reduction of greenhouse gas (GHG) emissions is becoming increasingly important for shipping. Operators of smaller vessels such as state-owned road ferries, pilot boats, and work boats are already setting targets for reductions. Methanol produced from renewable feedstock can result in much lower GHG emissions, and this SUMMETH study also investigated the feasibility of supplying and using it as fuel for smaller vessels.

Methanol produced from both conventional and renewable feedstocks was compared to the conventional diesel fuel currently used in marine propulsion engines in the size range 250 kW to 1200 kW. A fuel life cycle comparison showed that methanol produced from renewable feedstock such as wood residuals and pulp mill black liquor can result in greenhouse gas emissions reductions of 75 to 90%. Methanol produced from fossil feedstock results in slightly higher GHG emissions than conventional petroleum fuels. Methanol fuels resulted in significantly lower particulate emissions, and NO_x emissions were less than half of those for diesel fuel. These values were for combustion without aftertreatment.

Safety was investigated for smaller vessels and not considered to be a barrier for adoption of methanol fuel. A hazard identification and assessment carried out for a road ferry case study design for the SUMMETH project found the hazards identified to be within the “low risk” or “as low as reasonable practicable” zones.

An assessment of renewable methanol production and feedstock possibilities within Sweden found that technologies for production from wood biomass, including gasification of wood residual and gasification of pulp mill black liquor, have been investigated extensively and tested in pilot plants. The technology is considered mature enough to start larger scale production. Production of methanol from CO_2 is also being tested and planned in Sweden. An investigation into marine fuel supply in Sweden found that smaller vessels are typically bunkered by tanker truck, and thus there are no barriers anticipated if methanol is used instead of conventional fuel, as methanol is routinely transported by tanker truck.

Regarding costs of renewable methanol, estimates from other recent studies showed production costs of renewable methanol to be on average higher than prices of MGO and methanol from fossil feedstock, but the low range of the estimates show production costs that are almost competitive. A possibility for reducing costs could be to use methanol of a lower purity than the 99.85% specified for the chemical industry. Although production of a lower purity “fuel grade” methanol may be impractical for producers with primarily chemical industry customers, it may be a good opportunity for smaller plants producing renewable methanol to reduce their costs, if they have local fuel customers.

Although the cost of methanol is currently higher than that of diesel fuel, it has much better environmental performance. Measures such as stricter emissions regulations regarding particulate emissions, or requirements for reduction of GHG from shipping could favour the uptake of methanol, as other measures to meet these goals would also entail higher costs.

TABLE OF CONTENTS

LIST OF ACRONYMS AND ABBREVIATIONS

ADR	International Carriage of Dangerous Goods by Road
AIS	Automatic Identification System
BLG	Black Liquor Gasification
CO_2e	Carbon dioxide equivalent
ECA	Emission Control Area
GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection
GHG	Greenhouse gas
GWP	Gobal Warming Potential
IBC Code	International Code for the Construction and Equipment of Ships carrying Dangerous Chemicals in Bulk
IGF Code	Draft international code of safety for ships using gases or other low flash point fuels
IMO	International Maritime Organization
IMPCA	International Methanol Consumers and Producers Association
IOELVs	Indicative Occupational Exposure Limit Values
LNG	Liquefied Natural Gas
MGO	Marine Gas Oil
MK 1	Swedish environment class 1 diesel fuel
NOx	Nitrogen Oxides
OELs	Occupational Exposure Limits
PM	Particulate Matter
SECA	Sulphur Emission Control Areas
SOLAS	Safety of Life at Sea convention
SO_x	Sulphur oxides
STCW	Standards of Training, Certification and Watchkeeping for Seafarers
TFCA	Total Fuel Cycle Analysis

1 INTRODUCTION

Interest in methanol as a marine fuel developed after the International Maritime Organization (IMO) decided to implement sulphur fuel limits in Sulphur Emission Control Areas (SECAs). These limits came into effect in the Baltic Sea area in 2015. Methanol, a clean-burning alcohol that does not contain sulphur, was less expensive than low sulphur marine gas oil (MGO) for a period between 2011 and mid-2013, and was thus considered a very good fuel to investigate from both economic and emissions perspectives. Studies and tests were focussed on larger vessels, and in 2015 the *Stena Germanica* ro-pax ferry was retrofitted for methanol / diesel dual fuel operation. Seven new build chemical tankers with dual fuel methanol engines entered service in 2017.

Methanol fuel was considered a very good option compared to the other main solutions for large vessels to meet SECA emission requirements. Methanol compared favourably because investment costs for vessel conversion were lower than those for converting to LNG fuel use, and about equivalent to scrubber investment costs, and fuel costs were lower than MGO. The lower conversion costs and emissions benefits of methanol fuel as experienced for the larger vessels could also be benefits for smaller vessels, although the solutions used may need to be adapted.

Methanol is also a good fuel for improving the environmental performance of shipping by reducing emissions of particles and NOx, and of greenhouse gases (GHG) when it is produced from renewable feedstocks. Tests on the Wärtsilä methanol dual-fuel engines used in the *Stena Germanica* showed substantially lower NOx and particulate emissions as compared to emissions from diesel oil operation (Stojcevski, 2016). Greenhouse gas emissions are increasingly becoming a concern for shipping, with reduction targets being set at international, national, and individual company levels. The IMO recently announced a climate change strategy for shipping, with the target to reduce GHG emissions from shipping by at least 50% by 2050 (IMO, 2018). On the national level, Norway's National Transport Plan 2018-2029 states that the government should ensure that new ferries connected to the national public road system use zero or low emission technology (Norwegian Ministry of Transport and Communications, 2016). The Swedish Government directed the Swedish Transport Administration to carry out an analysis of how operation of state-owned vessels, including road ferries and pilot boats, could be fossil-free. The analysis should use 2030 and 2045 as alternative years for achieving this goal (Regeringskansliet, 2018). Methanol has good potential as a fossil-free fuel because it can be produced from many different feedstocks, included CO_2 and renewable electricity.

There are many factors to consider when evaluating the feasibility of a new marine fuel. These include market considerations such as fuel supply and availability, technical/operational factors, and environmental factors, as shown in Figure 1.

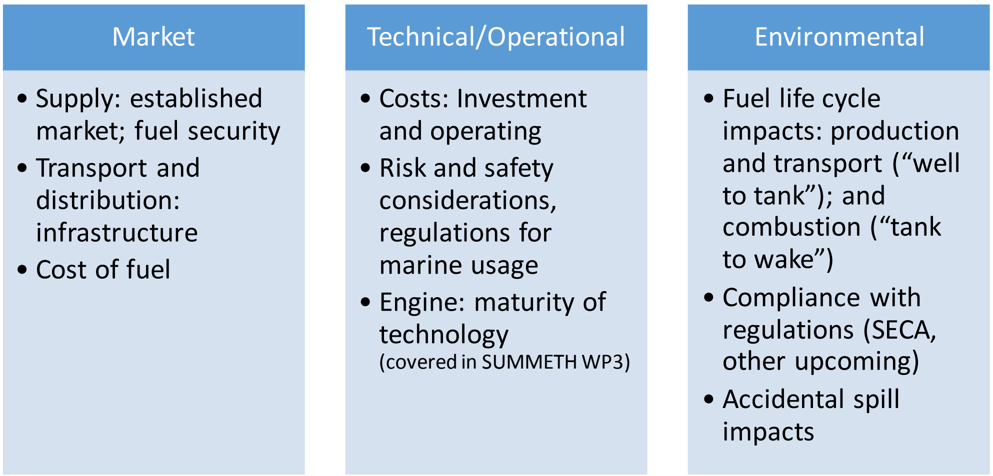

Figure 1 Considerations for assessing the feasibility of a new fuel

The SUMMETH project evaluated these factors as applicable to smaller vessels with engines in the size range 250 kW to 1200 kW. Market considerations including the supply and distribution of methanol, with a particular focus on renewable methanol production potential in Sweden, are covered in Chapter 5. Costs are discussed in Chapter 3, while risk and safety considerations and regulations applicable to smaller marine vessels are discussed in Chapter 4. The technical issues regarding engine development and technology maturity are described in the SUMMETH report "Engine Technology, Research, and Development for Methanol in Internal Combustion Engines" (Tunér et al., 2017). The environmental assessment described in Chapter 2 compares vessel operation using methanol produced from both fossil and renewable feedstocks to operation using the conventional fuels (MGO and diesel) currently used by smaller vessels. The environmental benefits were evaluated from a fuel life cycle perspective, considering fuel supply chains that are feasible within Sweden.

2 ENVIRONMENTAL PERFORMANCE IMPROVEMENT

2.1 INTRODUCTION

This chapter describes the environmental assessment work carried out within the SUMMETH project, where a fuel switch to methanol for vessels using propulsion engines in the size range 250 kW to 1200 kW was assessed. The baseline comparison fuels are two currently used conventional distillate fuel oils used for smaller vessels: MGO, which is used by the majority of vessels in this segment, and MK 1 (Environment Class 1) diesel fuel, which is used by road ferries and commuter ferries. The assessment takes a fuel life cycle approach and includes the fuel life cycle components “well to tank” and “tank to propeller” for methanol (with a focus on that produced from renewable feedstock) and conventional fuel. The focus was on smaller vessels operating in the North West Europe area. The specific case of a Swedish road ferry was also assessed.

2.2 OBJECTIVE

The objective of the task was to estimate the potential emission and GHG reductions for vessels using propulsion engines in the size range 250 kW to 1200 kW, if methanol was used instead of conventional fuel oil. The comparison considers both fuel production and use, and sustainable methanol as well as conventional methanol, with feasible fuel supply pathways for smaller vessels assessed. The case study of a road ferry operating within Sweden was also to be assessed.

2.3 BACKGROUND TO FUEL LIFE CYCLE ASSESSMENT APPROACH

A Life Cycle Assessment (LCA) study investigates and evaluates the environmental impact of a specific product or activity “from the cradle to the grave”. These studies can be very detailed and assess the whole life cycle of a process or product, from the environmental impacts of raw material extraction to the final disposal. An LCA may also take a streamlined approach, with limits set on the extent of the study, the detail of the information collected, or the types of environmental impacts to be addressed (Environmental Resource Management, 2002). For the SUMMETH project, the intent was to compare the environment performance of smaller vessels operating on methanol fuel with those operating on conventional fuel oil. Thus a more focussed approach was taken for the study, concentrating primarily on fuel production and use for propulsion on board a ship.

Total Fuel Cycle Analysis (TFCA), which is considered a sub-set of LCA, is a type of assessment that developed as alternative fuels were being investigated and their emissions assessed and compared. In recent years the TFCA methodology has been applied to shipping in several studies. Examples include a study by Corbett et al. (2014) that evaluated extraction, processing, distribution, and use of fuels in three case study vessels, and a comparison of alternative and conventional marine fuels by Brynolf (2014).

The International Organization for Standardization (ISA) Life Cycle Assessment standard, 1SO 14040 (ISO 14040:2006), sets out a framework for an LCA that includes the following four phases:

- Goal and scope definition
- Inventory analysis (inputs and outputs)
- Impact assessment
- Interpretation of results

The interactions between these phases are shown in Figure 2.

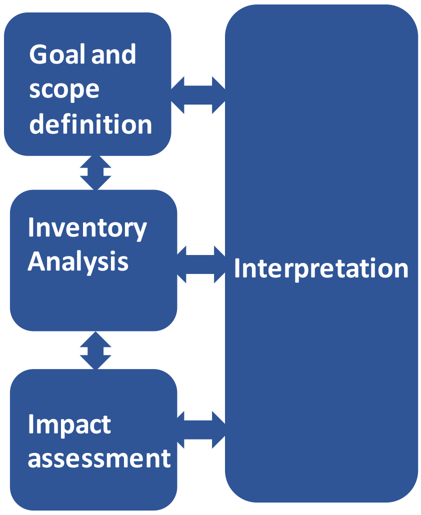

Figure 2. Main components of an LCA study [ISO 14040] 1997

An LCA is typically an iterative process and adaptations and modifications may need to occur as the study proceeds, to accommodate changes in available information and resources. The scope, inventory analysis, and impact assessment work carried out for the SUMMETH project are described in the following sub-sections.

2.4 METHOD

The life cycle of a marine fuel includes both fuel production and use. Fuel production and distribution to the vessel is referred to as the "well to propeller" phase and fuel use is referred to as the "tank to propeller" phase, as shown in Figure 3.

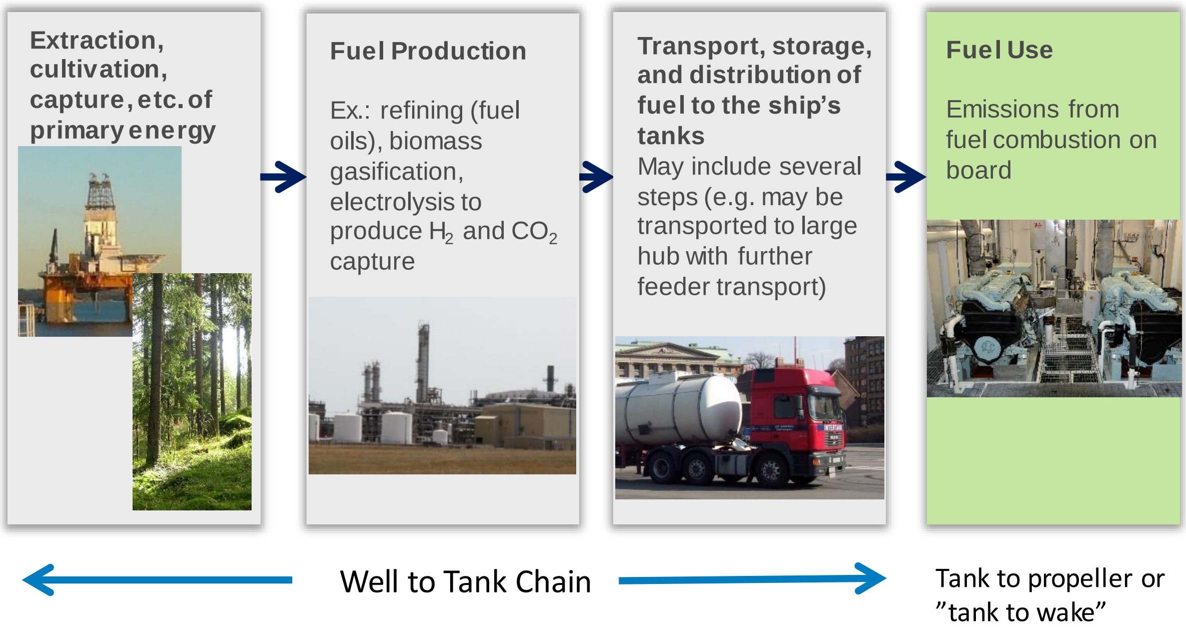

Figure 3 Marine Fuel LCA Chain

For the well to tank data, existing life cycle inventory data was used and adjusted as appropriate for final transport steps for distribution to the vessel. Data specific to the Northern European area and for marine fuels was sought out and used where available. For conventional fuels and methanol produced from natural gas, the environmental flows for well to tank (raw material acquisition, fuel production, and distribution) reported in "Fuels in the Baltic Sea after SECA" (Trafikanalys report by Andersson et al., 2016) were used. For methanol produced from biomass, data was sourced from LCAs conducted at Chalmers University Department of Shipping and Marine Technology (Brynolf, 2014; Brynolf et al., 2014) and from the well to tank data presented in the "JEC Well-to-wheels analysis" (Edwards et al., 2014). As the JEC study was for automotive fuels in the European context, the data were adjusted for use in the marine context. This involved adjustments to the final transport and distribution steps. For methanol produced from renewable electricity and CO_2, a literature search was carried out to find studies and data to serve as input for estimations of life cycle data for production of a similar fuel in Sweden. The production pathways and data adjustments made for the specific fuels in the study are described in the results section.

For tank to propeller emissions data, sources were as follows:

- Marine Gas Oil fuels for Northern European area: Emissions factors for ships for marine distillate fuel in a high speed diesel engine as reported in Cooper and Gustafsson (2004) were used.
- MK 1 Fuel: Measurement data from the Swedish road ferry Göta, as reported in Winnes and Peterson (2012); Measurement data from an STT Emtec Test report, carried out in a laboratory setting.
- Methanol: Measurement data from the methanol concepts tested in SUMMETH were used. The concepts and testing are described in SUMMETH Deliverable report D3.1 (Tunér et al., 2017). In addition, on board measurements carried out on board a pilot boat converted to methanol operation were included. The pilot boat conversion was carried out as part of the GreenPilot project.

For vessel fuel use, data for vessels using propulsion engines in the size range 250 kW to 1200 kW and operating in the North West Europe area was obtained from the SUMMETH WP2 report "Market Report" (Rydbergh and Berneblad, 2017). This study used AIS (Automatic Identification System) data to estimate vessel operating times, distances, and speeds to estimate fuel use. Engine size data and type were identified either through use of the vessel's IMO (International Maritime Organization) number where available or estimated using a modelling approach.

Fuel use for the case study road ferry was obtained from the ship operator (the Swedish Transport Administration Ferry Operations). Emissions data for ferries operating on MK 1 diesel fuel was also from this source.

2.5 SCOPE AND SYSTEM DESCRIPTION

2.5.1 North West Europe fleet of vessels with main engines in the 250 – 1200 kW range

The scope and boundaries for the comparative assessment of the operation of smaller vessels on methanol fuel as compared to MGO were set as follows:

System Boundary: The fuel chain for vessel propulsion was assessed, and this included raw material extraction, production, transportation, storage, bunkering, and combustion of the fuel for operation of the vessels with main engines in the 250 – 1300 kW range operating over a one-year period in the North West Europe area in 2016. The geographical area included is shown in Figure 4.

Figure 4 Geographical area considered in the SUMMETH study

Functional Unit: The functional unit was set to a year of vessel operation. Annual fuel consumption was estimated using AIS data from a six month period in 2016. Operating distances, speeds, and operating times from the AIS data were used to estimate fuel use (see Rydbergh and Berneblad, 2017). For the purposes of the comparison it was assumed that all vessels were operating on MGO with 0.1% sulphur. The fuel consumption was converted to an energy requirement, and the amount of methanol required to provide the energy for one year's worth of operation was estimated.

2.5.2 Swedish Road Ferry Jupiter Case Study

System Boundary: The fuel supply and use by the vessel over a one-year period was assessed. For fuel production and supply raw material extraction, production, transportation, storage, and bunkering were included. Fuel used included combustion of the fuel for operation of the vessel.

Functional Unit: The functional unit was set to be the fuel use during a year of vessel operation for the Swedish Transport Administration road ferry *M/S Jupiter,* shown in Figure 5. This ferry transports passengers and road vehicles, operating on a route between Östano and Ljusterö in Stockholm's archipelago. Fuel consumption figures were provided by the SwedishTransport Administration Ferry Operations. The ferry uses MK 1 diesel fuel (Swedish environment class 1 diesel). This is a distillate fuel with less than 10 ppm sulphur (0.001), which is also used for road vehicles. The fuel consumption was converted to an energy requirement, and the amount of methanol required to provide the energy for one year's worth of operation was estimated. For both the case of MK 1 fuel and the case of methanol fuel, the transport work was assumed to be the same. Thus total impacts per year of operation were compared.

Figure 5 The M/S Jupiter (Photo by Andreas Lundqvist)

Vessel particulars and operational profile: The Swedish Transport Administration road ferry *M/S Jupiter* is a free sailing road ferry that was built in 2007 at the Työvene shipyard in Finland. It operates on a 1100 metre long route between Östano and Ljusterö in Stockholm's archipelago, with a crossing time of approximately seven minutes (Trafikverket, 2016). The vessel operates year round. The vessel particulars of the *M/S Jupiter* are shown in the Table 1.

Table 1 M/S Jupiter Vessel Particulars and Machinery and Fuel Capacity

M/S Jupiter Vessel Particulars	
Main Dimensions	
Length Overall (LOA)	86 m
Breadth	14 m
Depth	3.45 m
Ramp Length	11 m
GT	737 tonnes
Design speed	11.6 knots
Cargo	
Passengers	397
Passenger cars	60
Loading capacity	340 tonnes
Main Engine	4 x Volvo Penta D12D-C, 331 kW, total installed power is 1324 kW
Fuel Tank	2 x 28 m^3 (diesel) (total capacity 56 m^3)

Ref: Data on M/S Jupiter from Trafikverket: https://www.trafikverket.se/farjerederiet/om-farjerederiet/vara-farjor/Vara-farjor/Jupiter/"

2.6 Environmental Impacts Assessed

The main environmental impact category used for the comparison of fuels in the SUMMETH project is global warming potential (GWP), calculated as greenhouse gas (GHG) equivalents. Emissions of greenhouse gases from fuel production and use have a direct impact on climate, and are very important to consider when comparing the environmental impact of alternative fuels. Although greenhouse gas emissions from ships are not directly regulated, they have been the subject of major studies carried out for the International Maritime Organization (e.g. the 3rd IMO GHG Study (Smith et al., 2014)). The IMO study reports that for the period 2007 to 2012, shipping was responsible for approximately 3.1% of annual global CO_2 and approximately 2.8% of annual GHGs on a carbon dioxide equivalent (CO_2e) basis.

Some vessel operators, such as national road and maritime administrations, and regional commuter ferry operators, have set their own targets for reducing GHG emissions, even though there are no international regulations in place. The Swedish Road Ferries, for example, is investigating the feasibility of reducing CO_2 emissions from their ferries by 15% by 2020 and 30% by 2030, compared to the emissions level in 2015 (Borgh, 2015). The Norwegian National Transport Plan 2018-2029 has stated that the government should ensure that new ferries connected to the national public road system use zero or low emission technology (Norwegian Ministry of Transport and Communications, 2016). There is also a goal for 40% of all ships operating on local shipping routes to use bio-fuels or be powered by low or zero-emission vessels by 2030 (Norwegian Ministry of Transport and Communications, 2016).

In life cycle inventories, greenhouse gas (GHG) emissions are usually estimated and presented as carbon dioxide equivalency (CO_2e), which describes the amount of CO_2 that would have the same global warming potential (GWP) as other emitted substances such as methane (CH_4) and nitrous oxide (N_2O) when measured over a specified time period. For the SUMMETH study, emissions of CO_2, CH_4, and N_2O from fuel production and use were estimated and combined to estimate the GWP expressed as GHG equivalents (CO_2e). One gram of CH_4 was taken to be equivalent to 28 g CO_2 and one gram of N_2O was taken to be equivalent to 265 g CO_2 (IPCC 2013).

Other emissions of concern from shipping included in the SUMMETH assessment are nitrous oxides (NO_x), particulate matter, and SO_X. NOx contributes to ozone formation and reacts to form particles and nitrate aerosols that cause health problems, as well as contributing to GHG emissions. NO_x emission standards have been established in emission control areas (ECAs) in North America and the Caribbean and will come into effect for the Baltic and North Sea ECAs for new ships built after 2021.
Particulate emissions result in health impacts and are linked to premature deaths. The European Environment Agency 2016 air quality report (EEA, 2016) states that estimates of health impacts from air pollution have attributed $PM_{2.5}$ emissions to 467,000 premature deaths in Europe from long term exposure. The European Federation for Transport and Environment states that air pollution from international shipping is responsible for 50,000 premature deaths per year in Europe (Transport & Environment, 2017). A recent study of lightning data has hypothesized that ship exhaust particles are responsible for increased storm electrification, after data analysis showed that lightning was enhanced by a factor of two over two of the busiest shipping lanes in the Indian Ocean and South China Sea (Thornton et al., 2017).

2.7 FUEL CYCLE ENVIRONMENTAL ANALYSIS

The fuel cycle "well to propeller" chain includes both a "well to tank" portion, covering the extraction of raw materials, fuel production, and provision of the fuel to the vessel, and a "tank to propeller" portion that includes the impacts related to combustion of the fuel on board the vessel. Details of the "well to tank" and "tank to propeller" parts of the fuel life cycle used for the SUMMETH project are described in the following sub-sections.

2.7.1 Well to tank

The fuel production and transport process consumes energy and results in air emissions. The conventional fuels used for the base case included MGO (0.1% S) and MK 1 diesel. Both methanol produced from natural gas and renewable methanol were included in the comparison. Production pathways for renewable methanol selected for the study include those relevant for the Swedish case. These were selected based on a review of existing and planned renewable methanol production facilities, including pilot facilities, as well as studies on feedstock availability and the feasibility of renewable methanol production. In addition it was necessary to select those production pathways where there was sufficient data available to estimate life cycle environmental flows. The fuel production and transport pathways and data sources for emissions used in the SUMMETH study are described in the following sub-sections.

2.7.1.1 MGO and MK 1 Diesel

The environmental flows for well to tank (raw material acquisition, fuel production, and distribution) for MGO (0.1% S) reported in "Fuels in the Baltic Sea after SECA" (Trafikanalys report by Andersson et al., 2016) were used. The fuel data from MGO was stated to be from Brynolf (2014), where data for fuel production was from the ELCD core database. The feedstock for production of MGO is crude oil, which is extracted from an underground reservoir (on land or off shore). The crude is then conditioned or stabilized as required for shipping and transported to a refinery. It may be transported by pipeline or by ship. The crude oil is then processed at a refinery. The finished fuel is transported to the user. For the general fleet assessment, transport by truck would occur from a nearby depot, on average a distance of 10 km. For the road ferry case study, a longer distance of 50 km was assumed. This is the distance from an oil depot in Loudden or Bergs oil harbor to Östano. Oil is transferred to the depot by ship from a refinery in Göteborg or Lysekil. MK1 was assumed to have the same production flows as MGO.

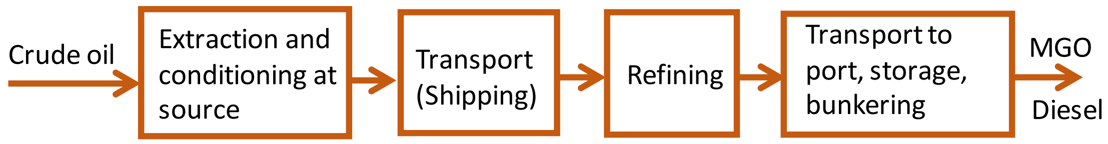

Figure 6 MGO Simplified Pathway for Production and Transport

2.7.1.2 Methanol produced from natural gas

Steam reformation of fossil natural gas is the most common and lowest cost production method of fossil methanol that is available in Europe. The environmental flows for production of methanol were from Brynolf (2014), which assumed production of methanol in Norway from Norwegian natural gas, and transport of the methanol by chemical tanker a distance of 350 nautical miles (NM) (from the facility to Göteborg). For the SUMMETH study, the same production environmental flows were used but sea transport was increased to an average distance of 500 NM, to cover small vessel users further away from production facilities, and a road transport leg of 20 km was added for transport of the methanol by tanker truck to be bunkered on the vessels. For the specific road ferry case study, a road transport distance of 90 km was assumed to cover road transport from methanol storage in Södertalje to Östano.

Figure 7 Simplified pathway for production of methanol from natural gas

2.7.1.3 Methanol Produced from forest residues

Environmental flows for methanol from forest residues was as described in Brynolf (2014), with production data from Börjesson. For the SUMMETH analysis, a transport distance of 400 km by road tanker was chosen to represent transport from the production facility to ports bunkered by truck at nearby harbours, as shown in figure 8.

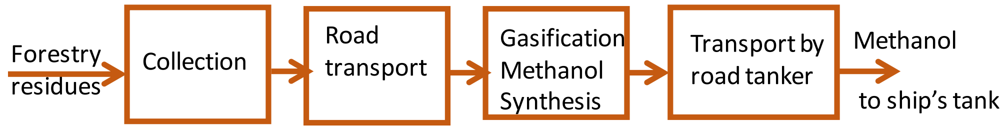

Figure 8 Simplified pathway for production of methanol from forest residues

2.7.1.4 Methanol produced from black liquor (via waste wood)

Methanol from waste wood can be produced via black liquor, which is a by-product of the process at mills to turn wood into pulp for making paper. A main ingredient in black liquor is lignin, which contains much of the energy content of wood. Extensive work on producing methanol from black liquor has been carried out in Sweden, and a pilot plant in Piteå that produces methanol and DME via this method has successfully operated for about 11,000 hours (Landälv, 2017). "Well to tank" data for methanol produced from black liquor was obtained from the JEC - Joint Research Centre-EUCAR-CONCAWE collaboration study "Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context" (Edwards, 2014). Ahlgren and Eriksson's 2013 review of fuel LCA data sources stated that this reference is appropriate for use when comparing fossil fuels with biofuels. Edwards (2014) used data from the Swedish technical study by Ekbom (2003) which describes the same process tested at pilot scale at Piteå. The simplified pathway for productions as adapted from Edwards is shown in Figure 9.

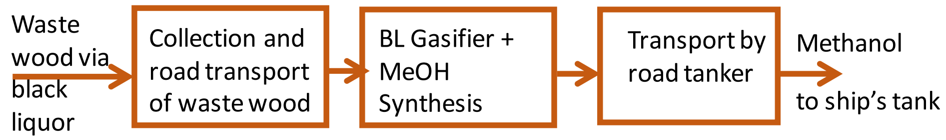

Figure 9 Simplified pathway for production of methanol from forest residues

2.7.1.5 Methanol from CO_2 and renewable energy

Methanol produced from carbon dioxide, which is captured from flue gas or other waste streams, and hydrogen produced by electrolysis using renewable energy, is considered to have great potential for being produced with very low or even negative greenhouse gas emissions. Fuels such as this which are produced by converting the energy from renewable electricity are referred to as electrofuels, and although more energy is required to produce them than conventional fuels, they are considered the only way to achieve large reductions of GHGs while still using a conventional fuel form (liquid or gas) for propulsion. There is only one commercial example where methanol is produced from captured carbon dioxide – the Carbon Recycling International plant on Iceland. This plant produces renewable methanol using renewable energy and carbon dioxide from flue gas from a geothermal power plant.

Life cycle inventory data is not available for this plant, but the fuel has been certified by the International Sustainability and Carbon Certification system (ISCC) as an ultra-low carbon advanced renewable transport fuel. It is claimed that the methanol has 75% lower GHG emissions than standard fuel.

Production of methanol in Western Sweden on a small to medium scale using wind energy and CO_2 of primarily biogen origin is being investigated by the Liquid Wind project (Liquid Wind Team, 2017). Sources of carbon dioxide being considered include a waste to energy plant and a sewage treatment plant (Liquid Wind Team, 2017). As there are no existing plants for producing methanol from waste-generated CO_2 and wind energy, and the plant design is still in a conceptual phase, and only approximate estimates of GHG emissions can be estimated. The Liquid Wind team estimated that a pilot plant with a production capacity of 1500 tonnes of methanol would reduce CO_2 emissions by 2000000 kg annually (assuming the CO_2 that is used in the process would otherwise be released to the atmosphere). A life cycle assessment was recently conducted by Matzen and Demirel (2016) of a process designed to produce methanol using hydrogen produced using wind energy and biogenic CO_2 produced from biomass fermentation in an ethanol production facility. The cradle to gate LCA, using data produced from simulations or obtained from the GREET LCI database, calculated the GHG from methanol production to be -1128.5 kg CO_2 equivalent/tonne methanol produced (converts to -56 g/MJ). The negative value is obtained because biogenic CO_2 is captured in the methanol produced. Although different conditions would apply for a process using CO_2 from other waste forms, this give an approximate indication of the reduction potential that can be achieved with methanol produced from non-fossil CO_2 and wind power.

2.7.1.6 Methanol from municipal solid waste

A small commercial plant in Canada produces methanol from a feedstock of non-recyclable non-compostable municipal solid waste (Verhout, 2016). This is gasified using a fluidized bed technology to produce syngas, which is then used to produce methanol. In 2017 a process step to produce ethanol from methanol was added, and the carbon intensity value (GHG as CO_2e) was certified by the Government of British Columbia under the renewable and low carbon fuel regulation. The ethanol, produced by Enerkem, received the lowest carbon intensity value ever issued by the British Columbia Ministry of Energy and Mines Renewable and Low Carbon Fuel Requirements Regulation (Sapp, 2017). The carbon intensity value obtained, -55 gCO_2e/MJ, is significantly lower than the carbon intensity of gasoline of +88 gCO_2e/MJ (Sapp, 2017). The municipal waste used as feedstock for the ethanol would otherwise be destined for a landfill, which has associated greenhouse gas emissions. It is also counted as a biogenic source of CO_2 (Verhout, 2016). The BC Ministry of Energy and Mines defines the carbon intensity as the measure of greenhouse gas (GHG) emissions associated with producing and consuming a transportation fuel, measured in grams of carbon dioxide equivalent per megajoule of energy (gCO2e/MJ) (BC Ministry of Energy and Mines, 2010).

2.7.1.7 Summary of Well to Tank Emissions

A summary of the well to tank emissions of GHG, SO_2, NO_x, and particulates for methanol produced from natural gas, forest residues, and black liquor is shown in Table 2. MGO is also shown as the comparison fuel.

Fuels	CO_2 g/MJ	CH_4 g/MJ	N_2O g/MJ	GHGs g CO_2e/MJ	NOx g/MJ	SOx g/MJ	PM10 g/MJ
MGO, 0.1% S[1]	7,1	0,078	0,00017	9,3	0,023	0,041	0,00110
Methanol from natural gas[1]	20,5	0,011	0,00031	20,9	0,051	0,003	0,00063
Methanol, from forest residues[1]	17,0	0,043	0,00021	18,3	0,047	0,046	0,01080
Methanol black liquor[2]	3,1	0,011	0,00835	5,7	-	-	-

Table 2 Well to tank (WTT) (raw materials aquisition, fuel production, and transport to vessel) emissions for MJ of fuel produced.
[1] Data for production from Brynolf (2014) Environmental assessment of present and future marine fuels. Doctoral Dissertation. Chalmers University of Technology, with transport emissions estimated for supply to smaller vessels; [2] Production data from Edwards, R., Larivé, J.-F., Rickeard, D., and W. Weindorf. 2014. Well-to-wheels analysis of future automotive fuels and powertrains in the European Context, Well-To-Tank (WTT) report, Version 4a, transport emissions estimated for supply to smaller vessels; with estimated emissions for fuel transport to supply smaller vessels. Emissions from transport of the fuel by truck to the vessel were estimated using NTM Calc. 4.0 baseline data.

2.7.2 "Tank to propeller" emissions

Tank to propeller emissions from combustion of methanol were obtained from measurements taken by SUMMETH project partners. For the reference fuels that are currently used, values from Cooper and Gustafsson (2004) and measured values from a road ferry vessel (Winnes and Peterson, 2012) were used. A summary table showing emissions factors for combustion of MGO, MK 1, and methanol in high speed engine concepts is shown in Table 3.

Fuel and Engine Concept	CO_2 g/MJ	CH_4 g/MJ	N_2O g/MJ	GHGs g CO_2e/MJ	NOx g/MJ	SOx g/MJ	PM10* g/MJ
MGO, 0.1% S, High Speed Diesel[1]	74,5	0,00046	0,004	75,4	1,371	0,047	0,011
MK 1 (Diesel), with particle filter, measurements on Göta (Scania)[2]	71,5			71,5	0,781	0,000046	0,00048
MK 1 (Diesel), no particle filter, measurements on Göta (Scania)[2]	72,3			72,3	0,820	0,000046	0,00947
MK 1 (Diesel), with particle filter, lab measurements (by EMTEC, Penta engine)[3]	74,3			74,3	0,635		0,00056
MK 1 (Diesel), no particle filter, lab measuremenets (Penta engine)[3]	74,2			74,2	0,639		0,0054
Methanol, spark ignited, port fuel injection, no particle filter, 64% MCR[4]	70,0			70,0	0,285		1,9E-06
Methanol, PPC, lab measurements (Lund)[5]	*69,1*			*69,1*	*0,039*		*5,2E-07*
Methanol, DI-SI, 3 way catalyst, ab measurements (Lund)[6]	*69,1*			*69,1*	*0,012*		*< 0,0001*

*Table 3 Emissions per MJ fuel combusted for MGO, MK 1, and methanol. [1] from Cooper and Gustafsson (2004) and Brynolf (2014); [2] Winnes and Peterson, 2012; [3] STT Emtec Presentation; [4] Molander, 2017; [5] scaled from Shamun et al. 2016; [6] Björnestrand, 2017. *For the methanol spark ignited port fuel injection concept total particulate matter was measured.*

Emissions of both particulates and NOx from combustion of methanol are significantly lower than the MK1 diesel and MGO, without after treatment.

2.7.3 Well to propeller impact

The total life cycle GHG emissions for the reference fuels and methanol produced from three different feedstocks are shown in Figure 10.

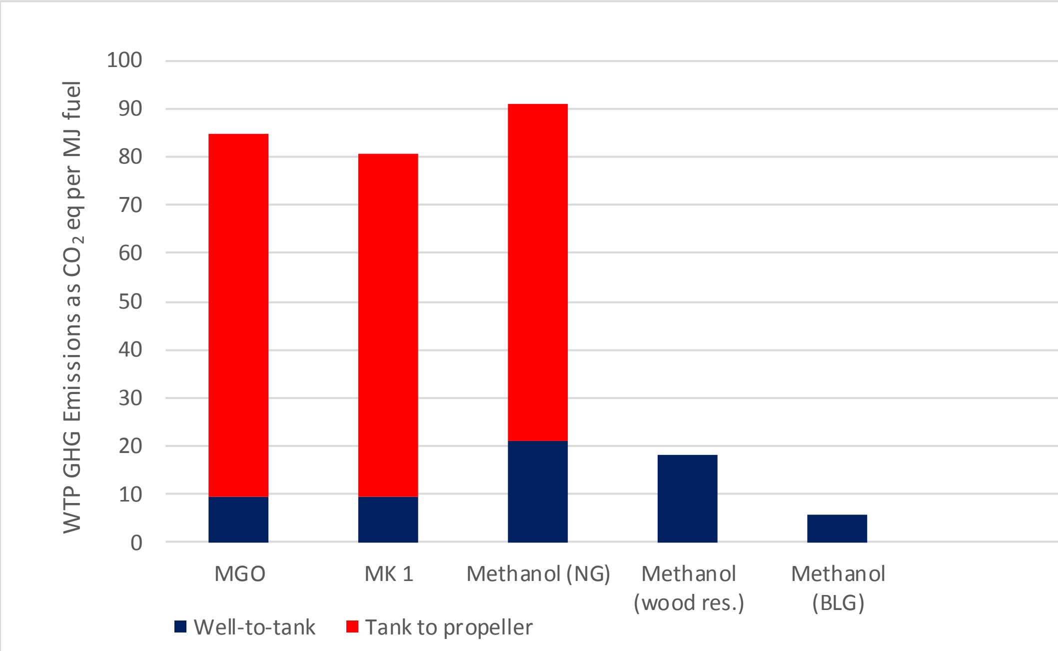

Figure 10 GHG emissions per MJ fuel for methanol from natural gas (NG), wood residues, and black liquor gasification (BLG) as compared to marine gasoil and MK 1 diesel.

The emissions from fuel oil and methanol produced from natural gas (fossil feedstock) are quite similar, with the methanol having slightly lower emissions during combustion but higher during production of the fuel.

Emissions of carbon dioxide from combustion of methanol produced from renewable feedstock (wood residue and black liquor gasification) are taken to be zero. This is consistent with the EU Renewable Energy Directive (2009/28/EC) rules for calculating the greenhouse gas impact of biofuels. The amount of CO_2 released during combustion is the same as that captured by the plant during growth (Brynolf, 2014). There are some emissions attributed to production because fossil fuels may be combusted for some parts of the process, such as for transporting feedstock to the gasification facility.

Particles emitted over the life cycle of the fuels are show in Figure 11.

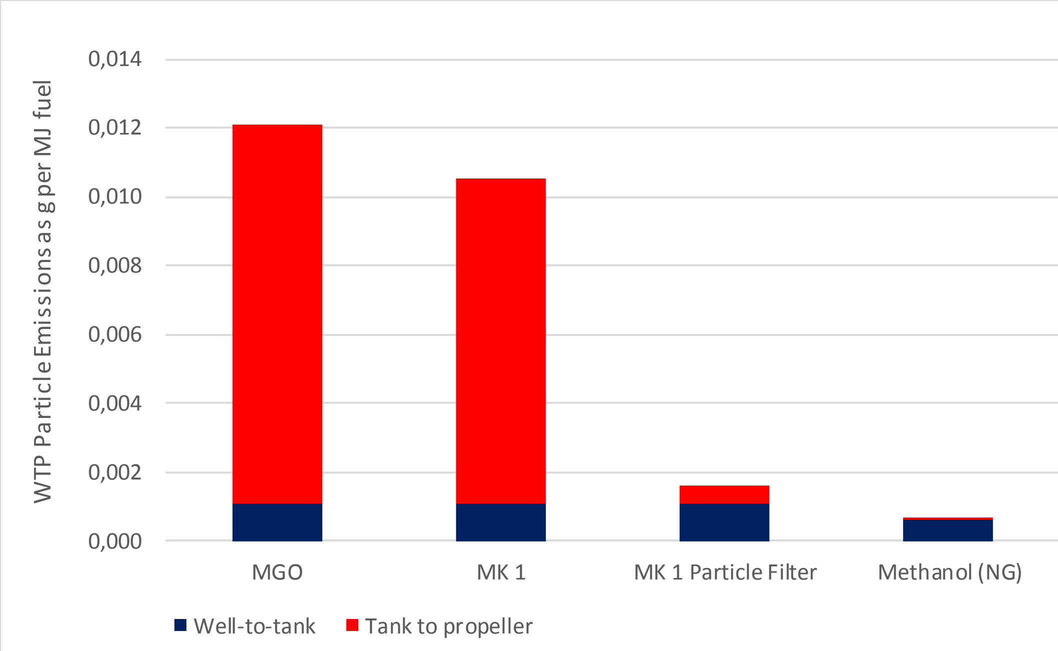

Figure 11 Particle emissions as g/MJ fuel for marine gas oil, MK1 diesel with and without a particle filter, and methanol produced from natural gas (spark ignited port fuel injection engine with no exhaust gas after treatment).

NOx emissions for the life cycle of the fuels are show in Figure 12.

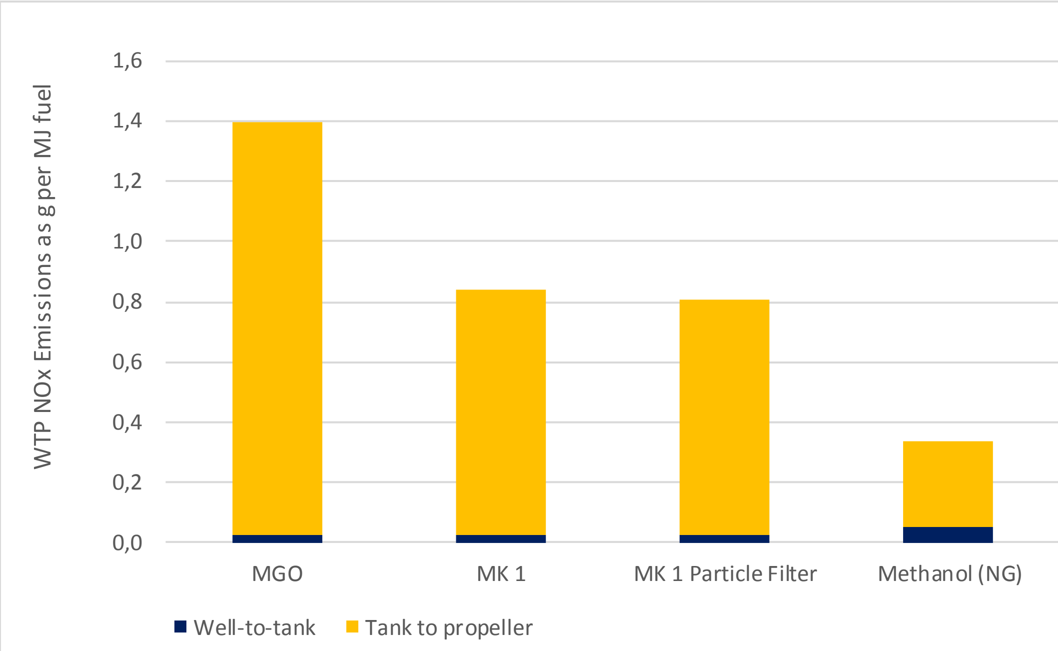

Figure 12 NOx emissions as g/MJ fuel for marine gas oil, MK1 diesel with and without a particle filter, and methanol produced from natural gas (spark ignited port fuel injection engine with no exhaust gas after treatment).

For NOx, the majority of the emissions are associated with combustion of the fuel, rather than combustion. This is also the case for particle emissions from the diesel fuels without after treatment. For MK1 fuel combustion in an engine fitted with a particle filter, and for methanol, the particle emissions are higher during fuel production than for the fuel combustion phase.

2.7.4 Case Study M/S Jupiter Road Ferry

Emissions values for fuel production and use, as used in the case study estimate, are as shown in Table 2. For fuel use, the emissions values used are shown in Table 4. The M/S Jupiter has 4 Volvo Penta engines installed on board.

Fuel and Engine Concept	CO_2 g/MJ	CH_4 g/MJ	N_2O g/MJ	GHGs g CO_2e/MJ	NOx g/MJ	SOx g/MJ	PM10* g/MJ
MK 1 (Diesel), with particle filter, lab measurements (by EMTEC, Penta engine)[1]	74,3			74,3	0,635		0,00056
MK 1 (Diesel), no particle filter, lab measuremenets (Penta engine)[1]	74,2			74,2	0,639		0,0054
Methanol, spark ignited, port fuel injection, no particle filter, 64% MCR[3]	70,0			70,0	0,285		1,9E-06

*Table 4. Emissions per MJ fuel combusted for MK 1 and methanol. [1] STT Emtec Presentation; [2] Molander, 2017; *For the methanol spark ignited port fuel injection total particulate matter was measured.*

The *M/S Jupiter* uses approximately one tonne of MK1 diesel fuel per day. Assuming a fuel consumption of 365 tonnes of MK1 diesel fuel per year, the energy requirement was calculated to be 15800 gigajoules. Emissions were calculated for each of the fuels to provide the energy required – noting that methanol has a lower energy content than diesel fuel so more fuel must be combusted to provide the same energy. The total estimated annual emissions in terms of GHG are shown in Figure 13.

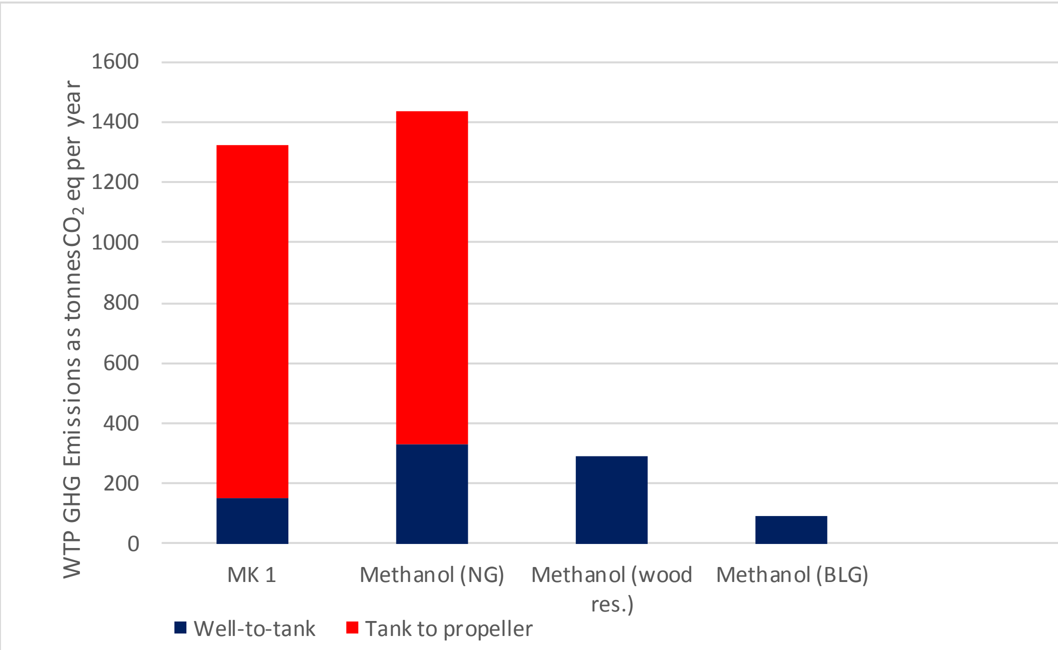

Figure 13 Annual emissions of GHG for case study vessel with MK1 diesel and methanol from fossil and bio feedstocks

Annual emissions of particles and NOx for the case study vessel were also estimated on an annual basis, and are shown in Figures 14 and 15.

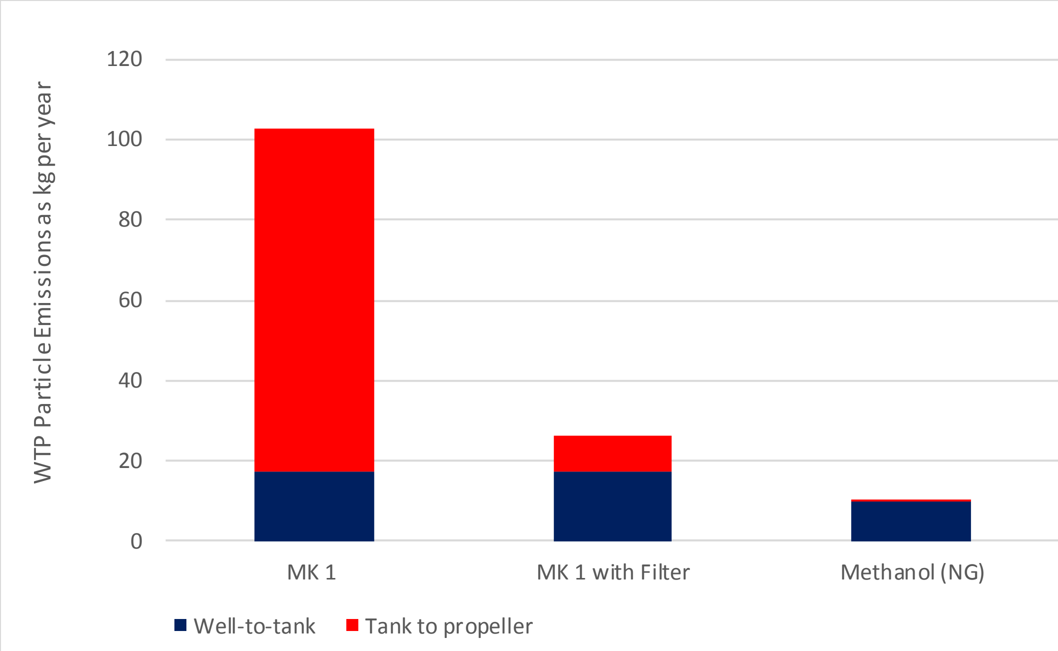

Figure 14 Annual emissions of particles for the case study vessel for MK 1 diesel, with and without the use of a particle filter, and methanol

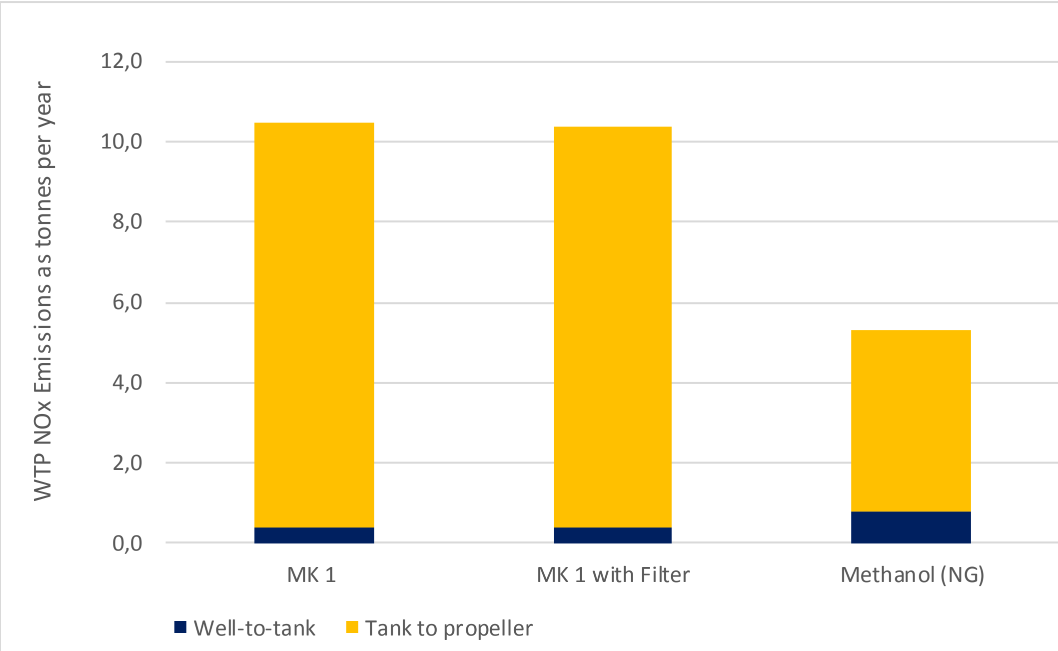

Figure 15 Annual emissions of NOx for the case study vessel for MK 1 diesel, with and without the use of a particle filter, and methanol

2.8 Environmental effects due to accidental spills

The environmental impact of a fuel when accidentally spilled to a waterbody is also important to consider when evaluating a new alternative fuel. Fuel oils can have significant consequences and require spill response. The Bonn Agreement Counter Pollution Manual contains a behavior classification system that classifies gaseous, liquid, and solid chemicals according to their physical behaviour when spilled to the sea (GESAMP, 2013). The main categories are evaporators, floaters, dissolvers, and sinkers. Methanol is completely soluble in water and is classified as a "dissolver evaporator" by the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP). Although methanol is toxic to humans it is not rated as toxic to aquatic organisms using the GESAMP rating system. The Baltic Sea Risk (BRISK) study did not consider methanol to be hazardous to the marine environment of the Baltic Sea in the event of a spill, due to its solubility and low toxicity to aquatic organisms (COWI, 2011).

2.9 Discussion and Conclusion

A comparison of diesel and methanol fuel for vessels using propulsion engines in the size range 250 kW to 1200 kW was carried out with respect to the emissions improvements that could be achieved. From a fuel life cycle perspective, diesel fuels and methanol produced from natural gas had similar emissions of greenhouse gases. Methanol produced from the renewable feedstocks wood residuals and pulp mill black liquor can result in GHG emissions reductions of 75 to 90%. For fuels from fossil feedstock, the fuel combustion phase of the life cycle accounts for about 80-90% of the emissions. For methanol produced from renewable feedstock, combustion emissions are not counted towards the GHG totals, as the CO_2 from the feedstock was of biological origin. Thus it is only production emissions of GHGs that are considered, and these vary depending on the feedstock collection and fuel production methods.

For particle emissions, the "use" phase of the fuel was dominant for emissions for diesel oil fuels. For methanol, the particle emissions during use were 99% lower than those from diesel fuel when no particle filter is used. Use of a particle filter reduces particulates by more than 90%, but still does not result in values as low as those measured for methanol combustion. NOx emissions were also reduced for methanol combustion as compared to combustion of diesel fuels. Emissions from methanol were less than half of those for diesel fuel. These values were for combustion without after treatment.

Regarding effects of a fuel spill on the marine environment, methanol would have a far lower impact than diesel fuel as it is completely soluble and is not rated as toxic to aquatic organisms by the GESAMP (the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) rating system.

3 COST ASSESSMENT

Introduction of methanol as a fuel requires an investment by the vessel operator for fuel system conversion. It will also result in a change in operational costs related to the price differential between methanol and conventional fuels. An analysis of all life cycle costs of vessel operation generally includes investment costs (design, construction), operating costs, and end of life costs including scrapping and recycling. Costs expected to result from a fuel switch to methanol are those in the investment and operating cost categories, as shown in Figure 16. Life termination costs were excluded from the analysis.

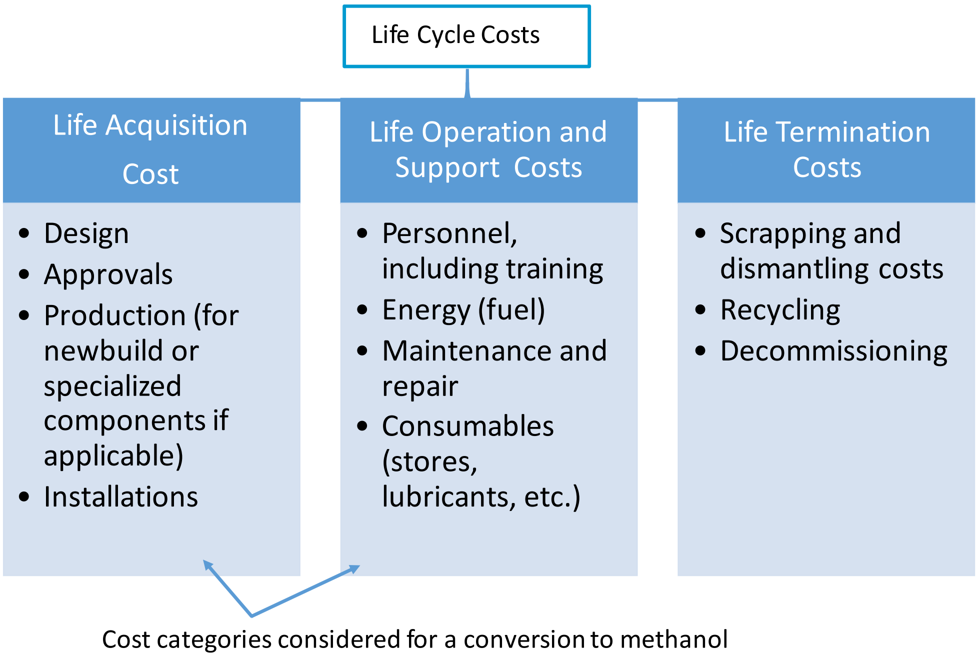

Figure 16 Life cycle cost categories to consider for analysis of a switch to methanol fuel

Investment and operational costs considered within the SUMMETH project are described in the following sections.

3.1 INVESTMENT COSTS

Typical investment cost categories for conversion of a small vessel to methanol operation include the following:

- Engine: purchase of a methanol engine (or in some cases conversion may be possible). There are currently no commercial marine engines available in the smaller engine segment for a cost comparison, but within the GreenPilot project a methanol engine conversion for a WeiChai engine using a kit developed by the FiTech company was carried out successfully at reasonable cost.
- Tank retrofit (new coating compatible with methanol) or new tank
- Double walled piping for fuel system
- Supply system for inert gas: establishing a storage location for nitrogen bottles, or installing a nitrogen gas generator, and provision of piping to the fuel storage tank
- Purchase and installation of methanol detectors

- Fuel pumps specific to methanol
- Upgrades to firefighting system as applicable for methanol (for example if the system is CO_2 then capacity for 50% more will be required).

Further description of these systems are provided in SUMMETH report 4.1 (Bomanson et al., 2017). Particle filters would not be required for a vessel running on methanol so there would savings in this cost category for vessels currently using this equipment.

3.2 Operational Costs

3.2.1 Fuel Costs

Fuel costs account for the majority of ship operating costs. Future fuel costs are difficult to predict accurately yet have a large impact on an analysis of payback times for investments. Historical fuel prices can give an indication of the price differential between different fuels. For the case of renewable fuels, however, there is little information available as most experience has been with pilot plants or “first of a kind” facilities. Landälv and Waldheim (2017) state in their report “Cost of Biofuel” that the advanced biofuels industry is only beginning the path to commercialization and thus there is no data based on the experience of years of operation and construction of several plants. They therefore provide a range of production costs for biofuels produced in Europe, based on different feedstock costs prices and estimates of production costs.

Historical prices of marine gas oil (MGO) and methanol from fossil fuels for the eight-year period from 2009 to 2017 are shown in Figure 16. MGO prices are the Bunker Index MGO price, which is an average global bunker price. Methanol has only been used as a marine fuel in a few cases so there is no historical price information as supply of a bunker fuel, but it is a widely traded chemical commodity. Methanex, the world’s largest producer and supplier of methanol to international markets, posts 3-month regional contract prices for Europe, North America, and Asia, and these prices as compared to the MGO prices can give an indication of the price differential. Large producers such as Methanex usually offer their customers discounts from the list price: Stenhede (2013) stated that in 2010 the “average” discount on contracted prices was 15%. Historical prices for MGO and methanol as EUR/MWh are shown on Figure 17. Some cost production ranges from recent reports and publications on production of methanol from renewable feedstock and from CO_2 and renewable electricity are also shown.

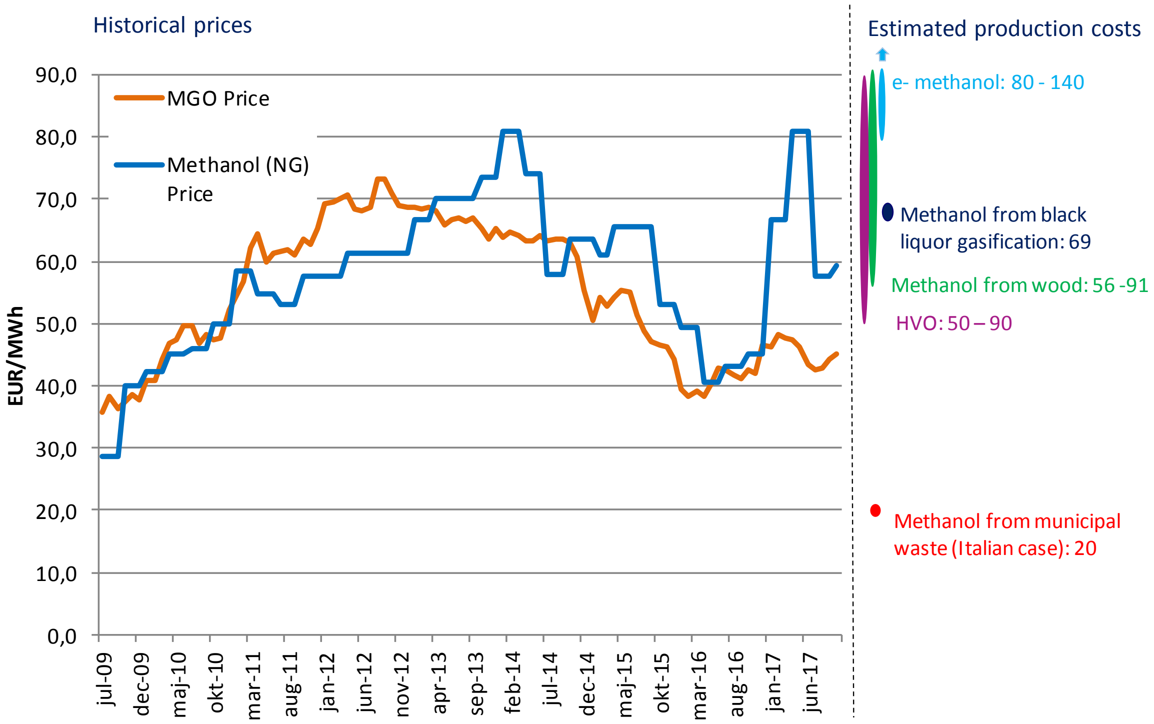

Figure 17 Historical prices for MGO and methanol produced from natural gas; estimated production costs for renewable methanol. Data sources: Bunker Index for MGO; Methanex for Methanol NG (European contract price); Landälv (2017) methanol BLG; Landälv and Waldheim (2017) HVO and methanol from wood; Ianquaniello et al. (2017) for methanol from municipal waste; Taljegård et al. 2015 for e-methanol

From late 2009 until early 2013, methanol prices were comparable to or lower than MGO prices on an energy basis. Estimated costs for production of renewable methanol are on average higher than MGO and methanol from fossil feedstock, but the low range of the estimates are almost competitive. Cost for production of methanol from municipal waste is considerably lower than the fossil feedstock fuels. This estimate, by Iaquaniello et al. (2017), is based on a high temperature gasification production process and assumes that income (tipping fee) is received from acceptance of the refuse that is used for feedstock. The estimated cost of methanol from wood is from Landälv and Waldheim (2017), where the production cost of methanol produced from wood is estimated to range from 16 to 25 EUR per GJ (56-91 EUR MWh), with the range partly depending on the feedstock price. A cost range of 56 to 75 EUR MWh was given for feedstock price in the range of 10 to 15 EUR/MWh, while production costs of 71 to 91 EUR/MWh were estimated for feedstock prices in the range of 20 EUR/MWh.

For production of methanol as an e-fuel from CO_2 and renewable electricity, Talegård et al. (2015) provide an estimated range of costs of 80 to 140 EUR/MWh, based on Nordic electricity prices. They found that the price of electricity was the dominant part of production cost. The Liquid Wind Team is investigating production of methanol from CO2 and wind energy in West Sweden, and estimates production costs ranging from about 70 to 160 EUR / MWh (Liquid Wind, 2017).

The possibility of using fuel methanol with a lower degree of purity than that produced for the chemical market has been raised and could potentially be possible for smaller producers of renewable methanol, and result in lower production costs. Currently industrial grade methanol used in the chemical industry is provided 99.85% pure on a weight basis according to the International Methanol Consumers and Producers Association (IMPCA) methanol standard (Ellis and Tanneberger, 2015). For use in a combustion engine the methanol can be less pure, as low as 90%, as shown in tests by Ryan et al. (1994). Stenhede (2013) also reported good results in diesel engine tests using a “crude” methanol (10% water by weight).

3.2.2 Other operating costs

Other operating costs associated with a switch from diesel fuel to methanol fuel are as follows:

- Cost for supply of nitrogen as inert gas blanket in the methanol tank. Nitrogen bottles will need to be exchanged regularly.
- Crew training: basic training regarding the hazards of methanol should be provided to crew members responsible for safety duties. Advanced training on operation of the methanol engine and fuel system should be provided to crew members responsible for the engine room and fuel supply. The IGF code (International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels) that came into effect for LNG in 2017 has added aspects to STCW for IGF training requirements. As an example, companies such as Exmar offer a 2-day IGF code basic training and a 3-day IGF advanced training course (Exmar, 2017). ABS (2015) suggests that training for crew handling LNG would typically be 3 to 5 days. The part of the IGF code covering methanol is still under development, but the working version specifies that training is an area that needs to be regulated. Stena provides its own training program for crew on the *Stena Germanica*. The chemical tankers operating on methanol carry it as a cargo so in addition have experience and training related to carriage of methanol.

Maintenance: With no long term data for marine methanol engine operation, it is difficult to assess whether there would be a significant difference in costs as compared to conventional diesel fuel operation. A long term demonstration of methanol-fuelled engines in two heavy duty trucks (operating 5310 hours and 4404 hours respectively) carried out in the 1980s concluded after a post-test inspection that major component life was equal to or better than the diesel-fuelled engine (Richards, 1990). Components such as glow plugs, fuel injection nozzles, and valves were stated to require additional development at that time. They had not been optimized as part of the demonstration.

<u>Cost savings</u>:

Reduction in annual operating costs with methanol as compared to diesel fuel are expected as follows:

- Particle filters: This equipment is not required for a methanol engine as emissions levels are already very low.
- Cleaning of tanks and fuel lines: Bacterial growth will not occur in methanol tanks and lines. Although some bacteria can use low concentrations of methanol as a food source, higher concentrations such as the almost pure methanol used for fuel will kill or inactivate bacteria. For diesel fuels, cleaning of tanks and lines is required due to biological contamination in the fuel and growth of micro-organisms, which can cause filter blockage and associated loss of power.

4 SAFETY CONSIDERATIONS

Methanol is a low flashpoint fuel that has been used in only a few marine commercial applications to date, with the first being on the RoPax ferry *Stena Germanica*. This ferry has been operating with methanol as a fuel for at least one of four engines since 2015. As of late 2017 all four main engines had been converted to dual fuel methanol operation. Seven chemical tanker new builds, which entered service in 2016, also use methanol as fuel. These ships have large methanol / diesel dual fuel engines and systems that were developed specifically for the vessels. There are not yet any smaller commercial vessels such as road ferries and inland waterway vessels that have used methanol as a fuel.

This chapter describes safety considerations for using methanol as a fuel for smaller vessel applications as investigated within the SUMMETH project.

4.1 METHANOL PROPERTIES

Selected properties of methanol as compared to conventional marine gas oil fuel and ethanol are shown in Table 5.

Table 5 Selected chemical and physical properties of methanol as compared to MGO and ethanol (data from Ellis and Tanneberger, 2015)

Properties	MGO	Ethanol	Methanol
Physical State	liquid	liquid	liquid
Boiling Temperature at 1 bar [°C]	175-650	78	65
Density at 15°C [kg/m^3]	Max. 900	792	796
Dynamic Viscosity [cSt]	(at 40°C) 3.5	(at 40°C) 1.1	(at 25°C) 0.6
Lower Heating Value [MJ/kg]	43	28	20
Lubricity WSD [µm]	280-400	1057	1100
Vapour Density air=1	>5	1.6	1.1
Flash Point (TCC) [°C]	>60	17	12
Auto Ignition Temperature [°C]	250 - 500	363	464
Flammability Limits [by % Vol of Mixture]	0.3 -10	3.3 – 1.9	6 – 36

In addition to the lower flashpoint, some of the properties of methanol that differ from conventional MGO and that should be considered when selecting and locating safety equipment such as detectors include its vapour density (only a bit heavier than air as compared to MGO vapours which are much heavier and will flow downwards), and the wider flammability limits. Because methanol's vapour density is close to that of air, its vapours can follow air movements (Methanol Institute, 2017). However, if the methanol is warmer than air the vapours may rise and if colder the vapours may sink (Methanol Institute, 2017). This should be considered when selecting locations for methanol vapour detectors. Portable methanol vapour detectors have a resolution of 0.5 ppm (Dräger).

Other characteristics for methanol that are relevant from a safety perspective include:

- It burns with a clear flame, which is difficult to see in daylight. Thus smoke detectors are not effective for giving early warning of a methanol fire because no soot is released and smoke will not be produced until adjacent materials become involved in the fire (Methanol Institute, 2017). Infrared (IR) flame detectors have been shown to be effective in detecting methanol fires in recent tests carried out by SP in Sweden (Evegren, 2017).

- It burns with a lower heat release rate than conventional marine fuels: about 1/3 as compared to diesel (Evegren, 2017).
- It is corrosive, so care should be taken with material selection (stainless steel is a recommended material for use with methanol (Methanol Institute, 2013). Methanol is compatible with only some plastics and rubbers (Methanol Institute, 2017), so the materials used in seals, o-rings, gaskets, etc., should be checked for compatibility with methanol.
- It is toxic to humans by ingestion, inhalation, or contact.
- It is completely soluble in water, and water/methanol solutions are non-flammable when methanol concentration is less than 25% in water. This means if water is used to control fires the volume should be at least four times the volume of methanol (Methanol Institute, 2017).

The Methanol Safe Handling Manual (Methanol Institute, 2017) provides guidance on working safely with methanol.

4.2 Health and Safety Aspects

Methanol is toxic by inhalation, ingestion, and absorption through the skin, so precautions need to be taken to avoid harmful exposure. The minimum lethal dose of methanol in the absence of medical treatment is between 0.3 and 1 g/kg (World Health Organization, 1997). The lethal dose by volume by oral ingestion is 10 – 30 ml for an adult (Methanol Institute, 2017). As comparison to the existing fuels used for small vessels, it should be noted that petroleum fuels are also rated as toxic. Bromberg and Cheng (2010), in a comparison of exposure routes, state that the toxicity (mortality) of methanol is comparable to or better than gasoline. Although methanol is toxic at higher levels to humans, it "occurs naturally in humans, animals and plants", with natural sources of methanol including fresh fruits and vegetables, fruit juices (average 140 mg/L, range 12 to 640 mg/L), and fermented beverages (up to 1.5 g/L) (World Health Organisation, 1997). Other commonly encountered substances which contain methanol are exhausts from both gasoline and diesel engines and tobacco smoke (World Health Organization, 1997).

Recommended or mandatory occupational exposure limits (OELs) have been developed in many countries for airborne exposure to chemicals (International Labour Organization, 2011). On a European-wide basis, Indicative Occupational Exposure Limit Values (IOELVs) are set in Commission Directives. Table 6 shows the indicative occupational exposure limit value for methanol in Sweden. The Swedish Work Environment Authority provides maximum acceptable total concentration of hydrocarbons in air for selected petroleum fuels. They stated that limit values were not defined for petroleum fuels because these fuels are mixtures of a large number of substances where concentrations are often not known in detail, and which can vary from one batch of fuel to another. The maximum acceptable total concentration of hydrocarbons in air, given as a time-weighted average for a working day, for diesel and heating oil (approximately equivalent to MGO) are shown in Table 6.

Table 6 Swedish Occupational Exposure Limit Values for methanol and two types of diesel / fuel oil: diesel values are specified as maximum total hydrocarbons in air

Swedish Occupational Exposure Limit	Methanol	Diesel
Level Limit Value (LVL) – value for exposure for one working day (8 hours)	200 ppm 250 mg/m^3	Diesel MK1: 350 mg/m^3 Heating oil: 250 mg/m^3
Short Term Value (STV) – time weighted average for a 15 minute reference period	250 ppm 350 mg/m^3	

Reference: Swedish Work Environment Authority, 2005.

Despite the toxicity hazards, methanol is quite commonly used in many different applications, and the usage demonstrates that it can be safely handled with appropriate precautions. Methanol was tested as an automotive fuel in California in a program that ran from 1980 to 1990, with more than 200 million miles of driving, with no cases of accidental methanol poisoning (Bromberg and Cheng, 2010).

In Finland, 100% methanol fuel is used in three speedway motorcycle classes, three drag racing classes, and five tractor pulling classes (Finnish Institute of Occupational Health, 2009). Hobbyists in Finland also use methanol blend fuels for miniature cars (60-80% methanol) and model airplanes (70-75% methanol) (Finnish Institute of Occupational Health, 2009). A study by the Finnish Institute of Occupational Health assessed consumer exposure for these uses of methanol fuel through measuring air concentrations in the breathing zone atmosphere. The highest exposure was found to be drag racing, where the largest volume of fuel (40 litres) is used during the racing period of four hours. Concentrations assessed for the whole day were 6 mg/m^3 (Finnish Institute of Occupational Health, 2009). This is considerably lower than the occupational exposure limit values shown in Table 6. The study noted that dermal exposure was a possibility and recommended that protective gloves be used when filling fuel tanks. The Finnish study also assessed workplace exposure for uses including manufacture of windshield wiper fluid containing methanol, for loading and unloading of methanol for transport, in wastewater treatment plants, pharmaceutical, and laboratory work. Workplace exposure values were exceeded for some of these cases, and it was recommended that personal protective equipment be used. In the case of windshield wiper fluid manufacture it was recommended that work place ventilation be provided as some of the facilities tested did not use local exhaust ventilation and workers did not use respiratory protection.

4.3 REGULATIONS APPLICABLE TO MARINE TRANSPORT

International regulations for use of methanol as a ship fuel are under development by the International Maritime Organization's Sub-Committee on Carriage of Cargoes and Containers. The regulations for methanol will be covered in Part A-2 of the International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels (IGF CODE). Sweden is coordinating the correspondence group that is developing the code further. The most recent meeting of the correspondence group was in September 2017, where an updated version of the "Draft Technical Provisions for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel" was developed and discussed.

Until the specific regulations for methanol are finalised and approved, those ship operators wishing to use it as a fuel must obtain approval from the flag state for "alternative design" through carrying out analysis and risk assessment. This is as specified in the Safety of Life at Sea convention (SOLAS), which requires that fuels shall have a flashpoint of 60°C or higher (with some exceptions), and if arrangements deviate from this then "… engineering analysis, evaluation and approval of the alternative design and arrangements shall be carried out in accordance with this regulation." (IMO, 1974). This was the path used to obtain approval for the *Stena Germanica* ferry methanol conversion and for the seven newbuild methanol tankers, with analyses and risk assessments concluding that the vessels had safety levels that were at least equivalent to vessels using conventional fuels (Ellis and Tanneberger, 2015). The seven methanol tankers were reported to have operated safely and reliably during their first year of service (Lampert, 2017).

Methanol has been carried as a cargo for many years and its carriage in bulk at sea is regulated by the International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk (IBC Code) (IMO, 2012). The IBC code defines design requirements for specific cargoes based on its properties, which are assessed by GESAMP (Joint Group of Experts on the Scientific Aspects of Marine Environment Protection), Working Group 1 on the Evaluation of the Hazards of Harmful Substances Carried by Ships. The IBC code ship type listed for methanol is type 3, which has no distance requirements for the tank location from the outer hull. This same approach is taken by the IGF code and the class society regulations under development for methanol fuel tank locations, which currently state that the methanol fuel tank may be placed next to the bottom shell plating (unlike petroleum fuel tanks which need double bottom).

Ship classification societies have also developed rules for methanol fuelled ships. Lloyd's Register released their "Provisional Rules for Methanol Fuelled Ships" in 2015, and DNV GL developed "Tentative Rules for Low Flashpoint Liquid Fuelled Ship Installations" in 2013.

Although the above international regulations are not necessarily applicable to all small vessels – many of these vessels may be classified under national regulations – they provide guidance and indication of good practice for handling methanol as a marine fuel and of the hazards that need to be addressed. National regulations in any case often refer to the international regulations and class rules, although may grant exceptions for vessels operating only in national waters and with service restrictions on distances travelled by the vessel. For the SUMMETH project, a hazard identification and assessment was carried out for a road ferry case study design, with the hazards identified being ranked within the "low risk" or "as low as reasonable practicable" zones. Results are reported in SUMMETH Deliverable report 4.1b (Ellis and Bomanson, 2017).

5 SUPPLY AND DISTRIBUTION OF METHANOL

Supply and availability are important considerations for ship operators considering switching to an alternative fuel. The production capacity and the systems for transporting and distributing the fuel to ships are important when considering feasibility of their use. For the SUMMETH project, sustainable methanol is a particular focus and production and supply of this fuel was considered for the case of Sweden. A simplified supply chain approach was taken, considering production and feedstock possibilities, transport, and bunkering of methanol to ships.

5.1 METHANOL FEEDSTOCKS AND POTENTIAL SUPPLY VOLUMES

Methanol can be produced from many feedstocks, and some examples of feedstocks and production pathways are given in Chapter 2 of this report. An overview of potential feedstocks is shown in Figure 18.

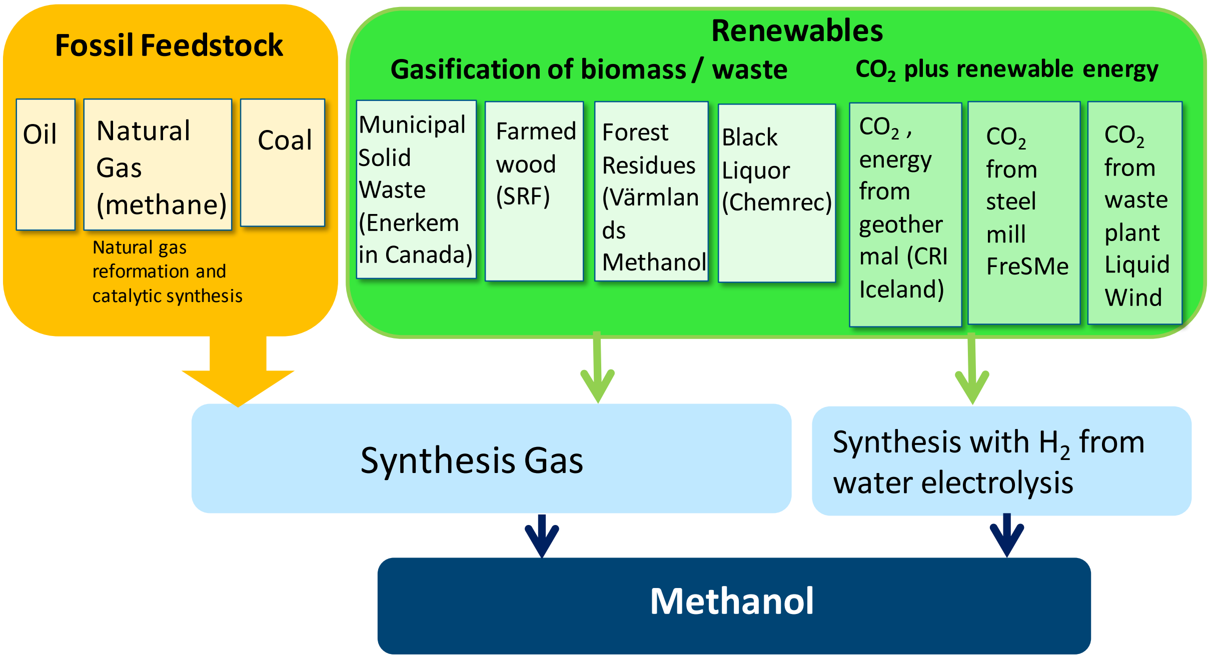

Figure 18 Overview and examples of feedstocks used to produce methanol

Natural gas is the most common feedstock used to produce methanol, but in China, most methanol is produced from coal (Methanol Institute, 2017). Although there are many potential renewable feedstocks, only a very small volume of methanol is produced from these sources.

5.1.1 Methanol from fossil feedstock

The main methanol depots in Sweden are located in Malmö and Södertalje (Forsman, 2017). The methanol, which is produced from natural gas, is regularly imported by ship and stored at these terminals, before being further transported to customers by road or rail. The transport system is well established as there are long-term customers such as Perstorp Specialty Chemicals, which use methanol to produce their products. In Malmö, methanol is stored in two tanks in the harbor, one holding 20 000 m^3 and the other 15 000 m^3 (Forsman, 2017). In Södertalje, the methanol storage company is Inter Terminals AB. The worldwide supply of methanol in 2016 was estimated to be about 86 million metric tonnes (Methanol Institute, 2017).

Methanol is a Class 3 flammable liquids (UN dangerous goods classification), which is the same class as many other liquid fuels such as gasoline, petroleum distillates, and ethanol. Storage and distribution procedures are similar for these types of liquids. The Swedish Civil Contingencies Agency (MSB) has regulatory responsibility for ensuring land-based handling and storage of inflammable liquids meet applicable standards. Accredited inspection bodies verify that storage tanks meet the requirements regarding wall thickness and spill containment construction.

5.1.2 Methanol from wood biomass

Production routes of methanol from wood biomass that have been investigated in Sweden include gasification of wood residuals and gasification of pulp mill black liquor. Co-gasification of black liquor and pyrolysis oil has also been investigated (Andersson, 2016).

The potential for production of methanol from wood biomass in Sweden was estimated in a recent report by Landälv (2017). This report provided a description of some biomass estimates that have been made to illustrate the variability and uncertainty that exists. Landälv indicated a range of possible methanol production quantities based on the biomass feedstock estimates together with three different estimates of energy conversion efficiency, as shown in Figure 19. Energy conversion efficiencies were an average for gasification using biomass, black liquor from pulp mills, and pyrolysis oil mixed with black liquor.

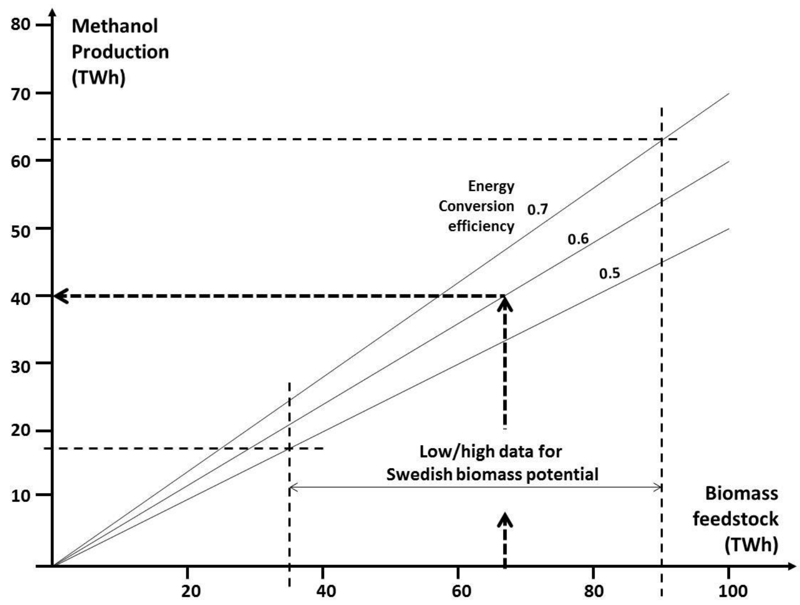

Figure 19 Annual methanol production as a function of biomass potential for different conversion efficiencies (from Landälv, 2017)

The middle estimated value for methanol production, 40 TWh of methanol per year, is equivalent to 7.2 million metric tonnes production. This can be compared to the amount of fuel used annually in the North West Europe area for vessels in the target engine range of 250 kW to 1200 kW, which was estimated to be 262 458 tonnes of MGO in the SUMMETH marketing study (Rydbergh and Berneblad, 2017). As methanol has about half of the energy content of MGO, about 524 916 tonnes of methanol would be required to meet the demands of this fleet segment. Biomass potential in Sweden as estimated in Landälv (2017) could easily meet this demand.

Another route for production of biomass that has been extensively investigated and tested in Sweden is black liquor gasification (BLG). Black liquor is a by-product of the pulp mill process. Andersson et al. (2016) have estimated that there are about 10 pulp mills in Sweden that would be suitable for production of methanol from black liquor, based on an analysis of current pulp production, recovery boiler capacity, and age structure. They estimate that 12 TWh of methanol could be produced from the black liquor from these 10 plants. Additional forest residues would be needed to be collected to meet the pulp mill steam demands (which otherwise would have been covered by the black liquor). An annual production of 12 TWh is equivalent to 2.2 million tonnes of methanol.

Methanol production plants using biomass as a feedstock base that are under development, have been run as a pilot facility, or have reached a detailed planning level in Sweden include:

- A facility at Södra Cell AB's pulp mill in Mönsterås that will produce 5000 tonnes of methanol per year from raw methanol that is a by-product of pulp production. This facility is expected to be completed in 2019 (Jacobsson, 2017).
- The LTU Green Fuels pilot plant in Piteå has operated for over 11000 hours, successfully producing gas from black liquor for further conversion to methanol or DME (Landälv, 2017). Earlier work in this area investigating the technical and commercial feasibility of producing methanol from pulp mill black liquor for the automotive sector was carried out in 2001-2003 partly under the framework of the EU Altener programme (Ekbom et al., 2003). Methanol produced at the LTU plant was tested in a pilot boat as part of the GreenPilot project. The plant is currently not producing methanol but is being maintained in a state of readiness waiting for additional funding or projects to be secured.
- An industrial scale plant using the Chemrec technology for producing methanol from black liquor was planned for the Domsjö Fabriker, a biorefinery complex in Örnsköldsvik, Sweden. This received funding from the Swedish government in 2009 and the state aid was approved by the European Commision in 2011 (EC, 2011). The plant was projected to produce 140,000 tonnes of bio-methanol per year but the project was cancelled.
- Värmlandsmetanol has planned a plant to produce methanol from domestic forest residues. A technical and economic pre-study was done in 2010, including basic engineering, and an environmental impact assessment and risk study was completed for the plant in 2014 (Hintze, 2015). The plant was designed to produce 315 tonnes of methanol per day (115,000 tonnes per year). The plant could be ready to be in operation 36 months after financing is secured (Hintze, 2015).

5.1.3 e-methanol

Although there are currently no plants producing methanol from CO_2 and renewable electricity in Sweden, there is a pilot project underway to produce methanol from steel mill flue gases, and a feasibility study was completed in 2017 for a small to medium scale plant to produce methanol from wind energy and CO_2 of primarily biogen origin. The FReSMe project, funded by the EU Horizon 2020 program, began in 2016, and will use CO2 from steel mill blast furnace gasses to produce methanol. The demonstration plant will be located at SSAB in Luleå, and the *Stena Germanica* will be the end user for the methanol. The pilot plant is projected to be in operation in 2019 (FReSMe, 2017).

The Liquid Wind project has investigated the feasibility of producing renewable methanol in western Sweden using wind energy and carbon dioxide. Sources being considered for the carbon dioxide supply include a waste to energy plant and a sewage treatment plant (Liquid Wind Team, 2017). A 5 MW plant producing 4000 tonnes per methanol per year and a 50 MW plant producing 40 000 tonnes per year were considered (Liquid Wind team, 2017). The study concluded that the plant was feasible if a certain set of conditions are met and recommended that the project advance to the next level where site location will be selected, detailed engineering work done, and financing preparations continued.

Regarding total production of e-fuels that would be possible in Sweden, a study by Taljegård et al. (2015) estimated that supply of CO_2 from point sources such as industries and combined heat and power plants was not a limiting factor in creating enough e-methanol to supply all domestic and international ships currently bunkering in Sweden. The electricity supply, however, was judged to have to increase significantly to produce this amount of electrofuels.

5.2 METHANOL STORAGE AND PRODUCTION SITES

Locations of the methanol storage sites and the planned (or pilot) production sites described in Section 5.1 are shown in Figure 20.

Figure 20 Location of imported methanol storage depots (red pins); pilot and planned black liquor gasification plants (purple pins); planned plants for methanol production from forest residues (yellow pins); and methanol production from electricity and CO_2.

Imported methanol is stored at two large ports that are located close to major methanol consumers within Sweden. Major methanol production facilities around the world are usually located close to natural gas sources, which are a significant distance from the majority of methanol users, and as much as 80% of the methanol produced is transported by ship (Methanol Institute, 2017).

Methanol produced from renewable feedstock typically must be much smaller in scale than plants producing methanol from natural gas, due to the need to transport feedstock longer distances from areas surrounding the plant. Economies of scale of production need to be considered against the diseconomies of scale of acquiring larger volumes due to longer distances and higher transport costs (Svanberg et al, 2013). Natarajan et al. (2012), in their study of optimal locations of methanol and combined heat and power plants, looked at how production costs could be minimized by optimizing the plant locations with respect to factors including "biomass supply, biomass and biofuel transportation, biomass conversion, energy distribution, and emissions." They found that spatial distribution of biomass supply was one of the dominant factors in determining the optimal location of plants. Figure 21 show on an overview level the steps that may be involved in production and supply of methanol produced from fossil feedstock as compared to renewable feedstock.

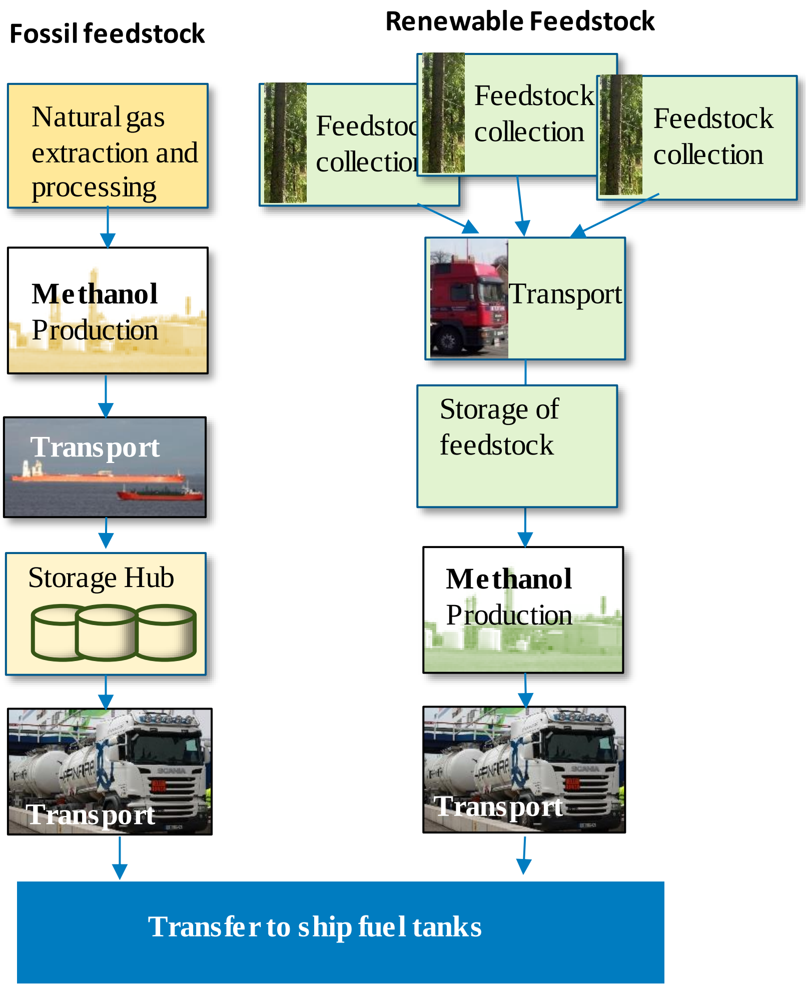

Figure 21 Simplified examples of production and supply chain for methanol produced from fossil feedstock and renewable biomass based feedstock

For production of methanol from CO_2 and electricity, plant location will be influenced by availability of a CO_2 source, until CO_2 capture from ambient air becomes economically viable. Taljeård et al. (2015) state that the main source of biogenic CO_2 in Sweden is the pulp and paper industry. Production of biofuels (through fermentation, for example) produces a relatively pure source of CO_2 but there is limited availability. The Liquid Wind project feasibility study considered options where CO_2 was transported by trailer and by pipeline (Liquid Wind Team, 2017).

5.3 Transport of methanol

Transport of methanol from a storage depot or producer to consumers is by road or rail. Methanol is a class 3 flammable liquid and must be transported according to dangerous goods transport regulations. ADR is the European regulations for road transport and RID is the regulation for rail. ADR-S is the Swedish national variation of the ADR regulations. If transported by sea, the IMDG (International Maritime Dangerous Goods) code applies for container transport and the IBC Code (International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk) applies to bulk transport in chemical tankers. Inland waterways transport is according to ADN (European Agreement for Inland Waterways). There is considerable experience with transporting methanol by road and rail as it is a widely used commodity.

5.4 Bunkering

There are three main methods of providing bunker fuel to ships, as follows:

- Ship to ship bunkering (delivery by bunker vessel)
- Truck to ship bunkering using a road tanker
- Land storage tank to ship bunkering, using a pipe connection.

Within Swedish waters, ship to ship bunkering is generally only carried out for the larger vessels. This is done on the west coast of Sweden in the Göteborg-Skagen area, and there are about five large bunker companies that provide the majority of the fuel (Jivén et al., 2016). Other harbours such as Helsingborg and Malmö have some possibilities for fuel delivery from bunker vessels but the majority is by road tanker truck, as the volumes are smaller. About 20% of bunkering takes place on the east coast of Sweden, and delivery is almost exclusively by tanker truck (Jivén et al., 2016). Direct delivery by pipe from land storage is only possible on the west coast in Brofjorden (Jivén et al., 2016). On the east coast, the Swedish icebreaker fleet receives bunker fuel from a tank (14,000 m^3 capacity) located in Piteå (Forsman, 2017).

For recreational vessels and some of the smaller commercial vessels, it is also possible to purchase fuel from fuel pumps at harbours and marinas. These facilities are similar to fuel stations on land. In Sweden, these fuel stations sell fuel types that are suitable for recreational boat engines, including gasoline and diesel. The bunker types used by the larger vessels are not available, nor are the facilities suitable for larger vessels.

Most smaller vessels of the size range targeted by the SUMMETH project would currently be bunkered by tanker truck. The case study vessel, the road ferry *M/S Jupiter*, is bunkered by tanker truck that drives on to the deck. Other Swedish road ferries are also bunkered by tanker truck.

Vessels that have been bunkered with methanol by truck include the following:

- Wallenius car carrier *MV Undine*, which bunkered methanol from a tanker truck located on the quay to a tank located on deck. Methanol was used in a test of a solid oxide fuel cell during 2010 (Fort, 2011).
- *Stena Scanrail*, a ropax ferry which bunkered methanol from a tanker truck located on the deck of the vehicle to a tank located on deck, as shown in Figure 22. This was carried out as part of the SPIRETH project (Ellis et al., 2014) during 2013-2014. Methanol was converted on board to a DME fuel mixture.

- *Stena Germanica,* which has been bunkering methanol since 2015 for use in its dual-fuel main engines. Bunkering is carried out from the quayside using a specially built pump station, which is required due to the large volumes to be bunkered. Road tanker trucks provide methanol, which is pumped on board using the pumps on the quay. A Manntek "drip free" coupling is used for the connection to the ship.

Figure 22 Bunkering methanol from a tanker truck on the Stena Scanrail for the SPIRETH project

As many smaller vessels are already bunkered by tanker truck for conventional fuels, there would be little change needed if they were to switch to methanol fuel. Additional infrastructure would be minimal. Bunkering procedures should be reviewed and adapted for methanol, following procedures as required by ADR-S for transport, and with review of the procedures used for previous vessels bunkering methanol.

6 SUMMARY AND DISCUSSION

The potential of methanol as a fuel for smaller vessels, with main engines in the size range 250 kW to 1200 kW, was assessed through analysis of the following main areas:

- Environmental impacts including production and supply of methanol (fossil and renewable), combustion emissions, and impacts resulting from accidental spills to the marine environment
- Costs
- Safety and regulations applicable to smaller vessels
- Production, availability, and distribution of fossil and renewable methanol.

Both benefits and potential barriers were identified and comparisons made with the conventional fuels currently used for this vessel segment. Technical issues regarding engine development and technology maturity are only briefly mentioned here - a detailed discussion is included in the SUMMETH report "Engine Technology, Research, and Development for Methanol in Internal Combustion Engines" (Tunér et al., 2017).

Environmental performance

Use of methanol as a fuel in smaller vessels results in fewer environmental impacts overall as compared to the marine gas oil and diesel fuels currently used. A fuel life cycle comparison of methanol and conventional fuels showed that methanol produced from renewable feedstock such as wood residuals and pulp mill black liquor can result in greenhouse gas emissions reductions of 75 to 90%. Methanol produced from fossil feedstock results in a slightly higher GHG emission than conventional petroleum fuels. Methanol fuels resulted in significantly lower particulate emissions, even as compared to conventional fuels combusted in an engine using a particle filter. NO_x emissions were also reduced for methanol combustion as compared to combustion of diesel fuels. Emissions from methanol were less than half of those for diesel fuel. These values were for combustion without after treatment. Impacts of accidental spills of methanol would be less than those of an equivalent fuel oil spill. Thus there are clear environmental benefits for smaller vessels switching to operation on methanol fuels.

Costs

The cost of methanol produced from fossil feedstock has been higher than MGO for most of the period between 2013 and 2017. There is no historical price information for renewable methanol and plants currently in operation are pilot scale or "first of a kind". Estimates from recent studies show production costs of renewable methanol to be on average higher than prices of MGO and methanol from fossil feedstock, but the low range of the estimates show production costs that are almost competitive. Estimates show cost of production of methanol from municipal waste could be considerably lower than that of fossil feedstock fuels when a tipping fee is paid for accepting the waste (meaning the plant receives revenues from accepting the feedstock).

At this time costs of methanol are a barrier to their uptake as a marine fuel. Measures such as stricter emissions regulations regarding particulate emissions, or requirements for reduction of GHG from shipping could favour the uptake of methanol, as other measures to meet these goals would also entail higher costs. Another possibility for reducing costs could be using methanol of a lower purity than the 99.85% specified for the chemical industry. Combustion engines have been shown to operate well with purities as low as 90% (Ryan et al. 1994; Stenhede, 2013). Although production of a lower purity "fuel grade" methanol has been considered to be impractical for larger suppliers that are producing for chemical industry customers, it could be a good opportunity for smaller plants producing renewable methanol to reduce their costs, if they have a local fuel market.

Safety

Safety is not considered to be a barrier for adoption of methanol fuel by smaller vessels. The few large ships using methanol in dual-fuel engines, the *Stena Germanica* and the Waterfront shipping vessels, have undergone safety assessments prior to approval and to date have been operating safely. International regulations for use of methanol as a ship fuel are under development at the IMO and classification societies have developed tentative or provisions rules. Although these international regulations are not necessarily applicable to smaller vessels classified under national regulations they provide guidance and indication of good practice for handling methanol as a marine fuel. For the SUMMETH project, a hazard identification and assessment was carried out for a road ferry case study vessel, with the hazards identified being ranked within the “low risk” or “as low as reasonable practicable” zones.

Production, availability, and distribution of fossil and renewable methanol

Methanol produced from natural gas is imported by ship to Sweden and distributed routinely by road and rail. There are no barriers regarding availability and supply of this methanol to smaller vessels. Sustainable methanol is a particular focus for the SUMMETH project and production and feedstock possibilities within Sweden were assessed. Production of methanol from wood biomass, including gasification of wood residual and gasification of pulp mill black liquor, has been investigated and tested in Sweden. A pilot plant producing methanol from pulp mill black liquor in Piteå has operated successfully, and detailed plans were developed for an industrial scale facility. This has not been built due to uncertainties regarding regulations and taxes for bio-fuels for automotive use. A plant using domestic forest residues as feedstock, Värmlandsmetanol, has been planned and designed, but has not been constructed for the same reason. Work has started on a small plant producing methanol from pulp production by-products at Södra’s pulp mill in Mönsterås (Jacobsson, 2017). These developments indicate that technology is mature enough for production of methanol from biomass in Sweden, with the only barriers being uncertainty about a market for the fuel. Estimates of biomass production potential indicate that there is sufficient feedstock to produce enough methanol to more than meet the needs of the smaller vessel segment.

Production of methanol from CO_2 is also being tested and planned in Sweden. A pilot project to produce methanol from steel mill flue gases was started in 2017. A feasibility study was completed in 2017 for a small to medium scale plant to produce methanol from wind energy and CO_2 of primarily biogen origin (Liquid Wind, 2017).

Regarding distribution of methanol from renewable production plants to smaller vessels, there are no barriers anticipated as many smaller vessels are already bunkered by tanker truck for conventional fuels. There would be minimal changes if they were to switch to methanol fuel, as methanol is routinely transported by tanker truck to customers.

In summary the few barriers identified for use of sustainable methanol are related to the production costs as compared to conventional fuel, and the lack of certainty for producers for an end user market. Technology for a port fuel injected spark ignition engine is a dependable and affordable concept (Tunér et al., 2017) but there are no commercial production solutions yet and this is also a potential barrier for users. On the environmental side, there are many benefits to be realized from using methanol as fuel, including significantly lower emissions during combustion, and large reductions in GHG emissions if sustainable methanol is used.

7 REFERENCES

ABS. 2015. LNG Bunkering: Technical and Operational Advisory. Available: http://ww2.eagle.org/content/dam/eagle/publications/2015/LNG_Bunkering%20Advisory.pdf

Anderson, K., Brynolf, S., and M. Izzo. 2016. Fuels in the Baltic Sea after SECA. Trafikanalys PM 2016:12. Stockholm: Trafikanalys Available: http://www.trafa.se/globalassets/pm/pm-2016_12-fuels-in-the-baltic-sea-after-seca.pdf

Andersson, J., Furusjö, E., Wetterlund, E., Lundgren, J., and I. Landälv. 2016. Co-gasification of black liquor and pyrolysis oil: Evaluation of blend ratios and methanol production capacities. Energy Conversion and Management 110:240- 248.

Bengtsson, S., Andersson, K. and E. Fridell. 2011. Life Cycle Assessment of Marine Fuels – A comparative study of four fossil fuels for marine propulsion. Report prepared for the Department of Shipping and Marine Technology. Available: https://pdfs.semanticscholar.org/a11e/c74b9d71866e9cf7a25655a393bd30372744.pdf

Bomanson, J., and B. Ramne. 2017. General Arrangement, Class Documentation. SUMMETH Report 4.1.

Borgh, M.E. 2015. Konsekvensbeskrivning för klimat- och energikrav på färjeverksamhet – del B. SSPA Rapport Nr: RE20157370-01-01-A- Report prepared for Färjerederiet. Available: http://www.sspa.se/sites/www.sspa.se/files/field_page_files/sspa_re20157370-01-00-a.pdf

British Columbia Ministry of Energy and Mines. 2010 (revised 2017). Carbon Intensity Records under the Renewable and Low Carbon Fuel Requirements Regulation. Information Bulletin RLCF-006. Available: https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/electricity-alternative-energy/transportation/renewable-low-carbon-fuels/rlcf006_-_determination_of_carbon_intensity.pdf

Broberg, M. and M. Nilsson. 2012. Environmental review of the Swedish Transport Administration Road Ferries with suggestions for measures and objectives. (In Swedish: Miljöutredning för Trafikverket Färjerederiet samt förslag på åtgärder och målsättningar). Master's Thesis report. Department of Geosciences, Air, Water and Landscape Sciences, Uppsala University.

Bromberg, L. and W.K. Cheng. 2010. Methanol as an alternative transportation fuel in the US: Options for sustainable and/or energy-secure transportation. Cambridge, MA: Sloan Automotive Laboratory, Massachusetts Institute of Technology

Brynolf, S. 2014. Environmental assessment of present and future marine fuels. Doctoral Dissertation. Gothenburg: Department of Shipping and Marine Technology, Chalmers University of Technology.

Brynolf, S., Fridell, E. and K. Andersson. 2014. Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. Journal of Cleaner Production, 74, 86-95.

Börjesson, P., Lundgren, J., Ahlgren, S., and I. Nyström. 2013. Dagens och framtidens hållbara biodrivemedel. Underlagsrapport från f3 till utredningen om FossilFri Fordonstrafik. Report f3 2013:13.

Cooper, D. and T. Gustafsson, 2004. "Methodology for calculating emissions from ships: 1, Update of emission factors", Report series SMED and SMED&SLU Nr 4 2004 (http://www.smed.se/).

Corbett, J.J., Thomson, H., and J.J. Winebrake. 2014. Natural Gas for Waterborne Freight Transport: A Life Cycle Emissions Assessment with Case Studies. Report prepared for US Department of Transportation, Maritime Administration.

COWI. 2011. #14 BRISK Sub-Regional Risk of Spill of Oil and Hazardous Substances in the Baltic Sea. Summary Report.

Edwards, R., Larivé, J.-F., Rickeard, D., and W. Weindorf. 2014. Well-to-wheels analysis of future automotive fuels and powertrains in the European Context, Well-To-Tank (WTT) report, Version 4a, April 2014. JRC Technical report of study carried out jointly by JRC, EUCAR, and CONCAWE. Luxembourg: Publications Office of the European Union.

Ekbom, T., Lindblom, M., Berglin, N., and P. Ahlvik. 2003. Technical and Commercial Feasibility Study of Black Liquor Gasification with Methanol/DME Production as Motor Fuels for Automotive Uses – BLGMF. Nykomb Synergetic AB: Stockholm.

Ellis, J. and J. Bomanson. 2017. Hazard Identification Study for the M/S Jupiter Methanol Conversion Design. SUMMETH Report D4.1b.

Environmental Resources Management. 2002. Streamlined Life Cycle Assessment of Two Marks & Spencer plc Apparel Products. Draft Final Report. Report prepared for Marks & Spencer plc. Oxford, U.K. Available: http://www2.marksandspencer.com/thecompany/ourcommitmenttosociety/environment/pdfs/Final_LCA_report.pdf

Eriksson, M., and Ahlgren, S. 2013. LCAs of petrol and diesel – a literature review. Report 2013:058. Uppsala: SLU Swedish University of Agricultural Science, Department of Energy and Technology.

European Commission. 2011. State aid: Commission approves Swedish €55 million aid for «Domsjö» R&D project. Available: http://europa.eu/rapid/press-release_IP-11-67_en.htm?locale=en

European Environment Agency. 2016. Air Quality in Europe – 2016. EEA Report No. 28/2016. Copenhagen: European Environment Agency.

European Federation for Transport and Environment. 2017. Air Pollution from Ships. Available: https://www.transportenvironment.org/what-we-do/shipping/air-pollution-ships.

Evegren, F. 2017. proFLASH: Methanol fire detection and extinguishment. Borås: RISE Research Institutes of Sweden.

Exmar, 2017. IGF Training. http://www.exmaracademy.com/our-courses/igf-training/

Finnish Institute of Occupational Health. 2008 (translation 2009). Development of initial REACH exposure scenarios for methanol. Funded by the Finnish Work Environment Fund.

Forsman, N. 2017. IB2020 DP5: Val av bränsle: utredning av alternativa bränslen. Report prepared by SSPA for the Swedish Maritime Administration.

Fort, E. 2011. Sustainable Marine Power – the METHAPU Project. Lloyds Register Technology Days 2011. Paper 15. Available: http://vk.od.ua/ufiles/MethapuProject.pdf

FReSMe. 2017. From residual steel gases to methanol - methanol from CO_2 blast furnace gasses to be used as ship transportation fuel. Available: http://www.fresme.eu/ Accessed 20171009.

GESAMP. 2013. Revised GESAMP Hazard Evaluation Procedure for Chemical Substances Carried by Ships (IMO/FAO/UNESCO-IOC/WMO/ IAEA/UN/UNEP/UNIDO/UNDP) Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection, Rep. Stud. GESAMP No. 64.

Hallberg, L., Tomas Rydberg, T., Bolin, L., Dahllöf, L., Mikaelsson, H., Iverfeldt, E., and J. Tivander. 2013. WELL-TO-WHEEL LCI DATA FOR FOSSIL AND RENEWABLE FUELS ON THE SWEDISH MARKET. f3 Report 2013:29. F3 the Swedish Knowledge Centre for Renewable Transportation Fuels.

Hintze, W. 2015. Värmlandsmetanol AB – Ett biomassebaserat fordonsbränsleföretag. Presentation given at "(Bio-)metanol som drivmedel" Workshop, 11 September 2015.

Iaquaniello, G., Centi, G., Salladini, A., Palo, E., Perathoner, S., and L. Spadaccini. 2017. Waste-to-methanol: Process and economics assessment. Bioresource Technology, Volume 243, pages 611-619.

IMO. 1974. SOLAS - International Convention for the Safety of Life at Sea, as amended.

IMO. 2012. IBC Code - International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk, Amended by Resolution MEPC.225 (64). London: IMO.

IMO. 2018. UN Body Adopts Climate Change Strategy for Shipping. Briefing 20180413. London: IMO. Available at: http://www.imo.org/en/MediaCentre/PressBriefings/Pages/06GHGinitialstrategy.aspx

IMPCA. 2008. IMPCA Methanol Reference Specifications. Brussels: International Methanol Producers and Consumers Association. Available: http://www.methanol.org/Technical-Information/Resources/Technical-Information/Methanol-Specifications-(IMPCA).aspx [Accessed 20130226].

International Labour Organization, 2011. Chemical Exposure Limits. Available: http://www.ilo.org/safework/info/publications/WCMS_151534/lang--en/index.htm#P158_12821 [accessed: 20150811].

IPCC. 2013. Climate Change 2013: The Physical Science Basis.

Jacobsson, M. 2017. Södra mångmiljonsatsar på biodrivmedel. Skog Supply. Available: https://www.skog-supply.se/article/view/552636/sodra_mangmiljonsatsar_pa_biodrivmedel

Jivén, A., Renhammar, T., Sköld, S., and L. Styhre. 2016. Sjöfartens energianvändning – Hinder och möjligheter för omställning till fossilfrihet. Report prepared for the Swedish Energy Agency.

Lampert, E. 2017. Methanol-fuelled tankers one year on. Tanker Shipping and Trade. Available: http://www.tankershipping.com/news/view,methanolfuelled-tankers-one-year-on_47529.htm. Accessed 20170922.

Landälv, I., and L. Waldheim, L. 2017. Building up the future - cost of biofuel. Report prepared for the Sub Group on Advanced Biofuels, European Commission, Sustainable Transport Forum.

Landälv, I. 2017. Methanol as a renewable fuel – a knowledge synthesis. Report No 2015:08, f3 The Swedish Knowledge Centre for Renewable Transportation Fuels, Sweden. Available at: www.f3centre.se.

Liquid Wind Team. 2017. Liquid Wind - Storing Energy by Making Fuel. Final Report. Available: https://www.innovatum.se/wp-content/uploads/2017/05/final-final-liquid-wind-report-may-2017.pdf

Matzen, M.J. and Y. Demeril. 2016. Methanol and dimethyl ether from renewable hydrogen and carbon dioxide: Alternative fuels production and life cycle assessment. Journal of Cleaner Production. Volume 139, p. 1068-1077.

Methanol Institute. 2017. Methanol Safe Handling Manual. Available: http://www.methanol.org/wp-content/uploads/2017/03/Safe-Handling-Manual.pdf

Molander, P. 2017. Field Test 2 – Environmental Performance Methanol Engine. GreenPilot Report 7.2.

Natarajan, K., Leduc, S., Pelkonen, P., Tomppo, E., and E. Dotzauer. 2012. Optimal locations for methanol and CHP production in Eastern Finland. Bioenergy Research, Vol. 5, No. 2, pp. 412-423.

Norwegian Ministry of Transport and Communications. 2016. National Transport Plan 2018-2029. Meld. St. 33 (2016-2017) Report to the Storting (white paper). Available: https://www.regjeringen.no/no/dokumenter/meld.-st.-33-20162017/id2546287/ [Accessed: 20170815].

Regeringskansliet. 2018. Regeringen ger uppdrag att analysera fossilfrihet för statligt ägda fartyg. Published 20180223. Available: http://www.regeringen.se/pressmeddelanden/2018/02/regeringen-ger-uppdrag-att-analysera-fossilfrihet-for-statligt-agda-fartyg/. Accessed 20180228.

Richards, B.G. 1990. Methanol-Fueled Caterpillar 3406 Engine Experience in On-Highway Trucks. SAE Technical Paper 902160, doi:10.4271/902160.

Ryan, T., Maymar, M., Ott, D., Laviolette, R., and R. Macdowall. 1994. Combustion and Emissions Characteristics of Minimally Processed Methanol in a Diesel Engine Without Ignition Assist. SAE Technical Paper 940326.

Rydbergh, T., and B. Berneblad. 2017. Market Report. Deliverable D2.1. SUMMETH – Sustainable Marine Methanol.

Sapp, M. 2017. Enerkem gets lowest ever carbon intensity value from BC for 2G ethanol. Biofuels digest. Available: http://www.biofuelsdigest.com/bdigest/2017/04/19/enerkem-gets-lowest-ever-carbon-intensity-value-from-bc-for-2g-ethanol/

Smith, T. W. P.; Jalkanen, J. P.; Anderson, B. A.; Corbett, J. J.; Faber, J.; Hanayama, S.; O'Keefe, E.; Parker, S.; Johansson, L.; Aldous, L.; Raucci, C.; Traut, M.; Ettinger, S.; Nelissen, D.; Lee, D. S.; Ng, S.; Agrawal, A.; Winebrake, J.J.; Hoen, M.; Chesworth, S.; Pandey, A. 2014. Third IMO GHG Study 2014. International Maritime Organization (IMO) London, UK, June 2014.

Stenhede, T. 2013. EffShip WP2 Present and Future Maritime Fuels Report. Gothenburg: SSPA.

Stojecvski, T., Jay, D., and L. Vicenzi. 2016. Operation experience of world's first methanol engine in a ferry installation. Paper Number 2016/099. Paper presented at CIMAC Congerss, Helsinki. June 6-10, 2016.

Svanberg, M., Olofsson, I., Flodén, J., and A. Nordin. 2013. Analysing biomass torrefaction supply chain costs. *Bioresource technology*, *142*, 287-296.

Swedish Work Environment Authority. 2005. Occupational Exposure Limit Values and Measures Against Air Contaminants. Provisions of the Swedish Work Environment Authority on Occupational Exposure Limit Values and Measures against Air Contaminants, together with General Recommendations on the implementation of the Provisions. AFS 2005:17. Available: http://www.av.se/dokument/inenglish/legislations/eng0517.pdf

Taljegård, M., Brynolf, S., Hanson, J., Hackl, R., Grahn, M., and K. Andersson. 2015. Electrofuels – A possiblity for shipping in a low carbon future? Proceedings of International Conference on Shipping in Changing Climates, Glasgow, Nov 2015 Vol. 2 (2015), p. 405-418.

Thornton, J.A., Virst, K.S., Holzworth, R.H., and T.P. Mitchell. 2017. Lightning enhancement over major oceanic shipping lanes. Geophysical Research Letters. Research Letter 10.1002/2017GL074982.

Trafikverket, 2016. Tidtabell Vägfärja Ljusteröleden. Trafikverket Beställningsnr. 100153.

Tunér, M., Aakko-Saksa, P., and P. Molander. 2017. Engine Technology, Research, and Development for Methanol in Internal Combustion Engines. SUMMETH Report D3.1.

Verhout, R. 2016. Enerkem biorefineries: setting a new global standard in biofuels, chemicals and waste management. Presentation to European Biofuels Technology Platform Meeting – Brussels, 21 June 2016. Available: http://www.etipbioenergy.eu/images/160621_ENERKEM_Brussels_EBTP_final.pdf Accessed 20171127.

Winnes, H., and E. Fridell. 2009. Particle Emissions from Ships: Dependence on Fuel Type. Journal of the Air & Waste Management Association. Volume 59:1391-1398.

World Health Organization. 1997. Environmental Health Criteria 196, Methanol. International Programme on Chemical Safety (IPCS), Published under the joint sponsorship of the United Nations Environment Programme, the International Labour Organisation, and the World Health Organization, and produced within the framework of the Inter-Organization Programme for the Sound Management of Chemicals. Geneva. Available: http://www.inchem.org/documents/ehc/ehc/ehc196.htm