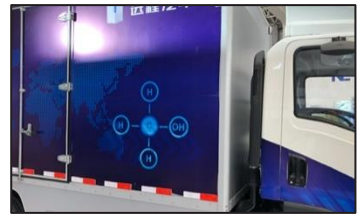
Annex 56

A Report from the
Advanced Motor Fuels Technology Collaboration

Technology Collaboration Programme on Advanced Motor Fuels



Methanol as Motor Fuel Summary Report

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ADVANCED MOTOR FUELS
IEA-AMF
Technology Collaboration Programme on
Advanced Motor Fuels

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Executive Summary

Global warming is a major threat for continuation of humankind as we know it today, and concerted actions are needed in all economic sectors to reduce GHG emissions. Improving energy efficiency of engines is not enough, and thus fossil-free fuels are required to alleviate climate burden especially of the transport sector. The most effective fuels are those with minimum GHG emissions and minimum pollutants along the well-to-wheel (WTW) chain, while compatible with common internal combustion engines and fuel infrastructure. There are many alternative fuel options (e.g. methane, methanol and other hydrocarbons as well as hydrogen) using different resources – mainly renewables – and conversion technologies. Providing renewable fuels for combustion engines does not renounce the need for adaptation of advanced technologies, such as electric powertrains.

In this Annex 56 various aspects of methanol as fuel for the transport sector are reviewed and evaluated: from its production to its application in engines, including advantages and disadvantages. Barriers and an outlook on the potential and possibilities of methanol as motor fuel are given.

Renewable transport fuels such as methanol could become an important solution to combat global warming and air pollution for sectors and regions where the electrification of the powertrain is challenging, e. g. in the shipping sector. The greenhouse gas saving potential of renewable methanol are quite high and the physical properties of methanol support a clean and efficient combustion. Therefore, the operational production capacities have to be strengthened massively to get a perceptible impact of substituting fossil energy carrier in the future. A wide range of resources could be utilized to produce renewable methanol, from bio- and waste-based streams to renewable hydrogen and circular CO_2. Methanol as motor fuel was demonstrated in large vehicle fleet during the 1980/90s. Despite technical success methanol was not a commercial success. Recently, there is again an increasing interest on methanol as fuel. Prominent examples are China as largest user of methanol as automotive fuel and Europe where methanol is being considered as marine fuel or to be used in fuel cell electric vehicles.

Internal combustion engines using methanol as a fuel could be further developed for high efficiency to gain maximum energy and pollutant savings. However, if methanol will be applied as automotive fuel with higher blending rates or as pure fuel technical adjustments of the fuel existing infrastructure are required (e.g. modifications of some fuel-carrying materials, safety measures).

Key findings from the report are summarized as follows:

- **Methanol is a multipurpose fuel** as it could be used straight or as blending component in fuels, for the production of fuel additives or for fuel cell application.
- **Several concepts for internal combustion engines are available for using methanol** in passenger cars, light-duty and heavy-duty engines as well as in ships.
- **Straight methanol burns with very low particle and NO_X emissions** in refitted engines. A further reduction of pollutants could be expected for future high efficiency combustion engines.
- **Methanol could significantly increase the engine efficiency in dedicated engines.** Therefore additional research and development is needed to realize this potential – also from an OEM perspective.
- The existing fuel infrastructure requires no adjustments for low level methanol blends. **For higher methanol blends and straight methanol, the adjustments of the existing fuel infrastructure are well known.** There are consideration needed regarding material compatibility and safety handling.
- **In order to support GHG mitigation in transport, production capacity of sustainable renewable methanol has to increase** from the current level of less than 1 million tonnes per year to cover a part of the transport sector. Today methanol is mainly produced from fossil resources at the global production capacity of about 125 million tonnes.
- **Production costs and GHG reduction potentials of renewable methanol** produced on an industrial scale **can be competitive** to established renewable fuels, if using suitable resources like waste wood and cultivated wood.
- **Supporting elements on strategic, regulatory, technical and communicative level** are of overarching importance like for any alternative fuel in transport.

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The studies and reports submitted under Annex 56 were carried out and authored by numerous researchers as indicated below.

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Abbreviations

ADR....*European Agreement of the International Carriage of Dangerous Goods by Road*
AMF.............................. *Technology Collaboration Programme on Advanced Motor Fuel*
CI...*Compression ignition*
CNG .... *Compressed natural gas*
CR .... *Compression ratio*
DBFZ.................. *DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH*
DF ....*Dual fuel*
DI...*Direct injection*
DISI .... *Direct injected spark ignition*
DMFC.. *Direct Methanol Fuel Cell*
DOC .... *Diesel oxidation catalyst*
DTC... *Diagnostic trouble code*
DTI .... *Danish Technological Institute*
ECU... *Engine controll unit*
ED95 ....*Ethanol-based fuel with 95 vol% ethanol for CI application*
EGR .... *Exhaust gas recirculation*
EN .... *European standard*
ERG ....*Emergency Response Guidebook*
EU .... *European Union*
FC ....*Fuel cell*
FCEV.. *Fuel cell electric vehicle*
FFV .... *Flex fuel vehicle*
FNR..*Fachagentur Nachwachsende Rohstoffe e.V. (FNR)*
GEM .... *Gasoline-ethanol-methanol fuel*
GHG .... *Greenhouse gas*
HC .... *Hydrocarbons*
HCCI .... *Homogeneous charge compression ignition*
HDV.. *Heavy-duty vehicle*
HEME.. *High efficiency methanol engines*
HEV... *Hybrid electric vehicle*
HFO... *Heavy fuel oil*
HT-PEMFC.............................. *High Temperature Proton Exchange Membrane Fuel Cell*
IEA .... *International Energy Agency*

IMO ....International Maritime Organization
LDV .... *Light-duty vehicle*
LNG.. *Liquefied natural gas*
MD95................................ *Methanol-based fuel with 95 vol% methanol for CI application*
MGO.. *Marine gas oil*
MTA..Methanol-to-aromatics
Mxxx.. *Methanol blend with 0 to 100 vol% methanol content*
NECA .... *Nitrogen emission control area*
NEDC .... *New European Driving Cycle*
NO_X .... *Nitrogen oxide*
PC .... *Passenger car*
PFI.. *Port fuel injection*
PHEV .... *Plug-in hybrid electric vehicle*
PM.. *Particulate matter*
PPC.. *Partially premixed combustion*
RED... *Renewable Energy Directive*
SDGs... *Sustainable development goals*
SECA .... *Sulphur emission control area*
SI... *Spark ignition*
SO_X .... *Sulphur oxide*
STA .... *Swedish Transport Administration*
VGT.. V*ariable geometry turbine*
VTT .... *VTT Technical Research Centre of Finland LTD*
WTT .... *Well-to-Tank*
WTW .... *Well-to-Wheel*

1 Introduction

1.1. Context and participants

This summary report is based on five technical reports completed in five countries participating in Annex 56: Methanol as motor fuel, under the Technology Collaboration Programme (TCP) of Advanced Motor Fuels (AMF) of the International Energy Agency (IEA).

Technion (Israel Institute of Technology), VTT and FNR acted as operating agent for the Annex 56 project.

The technical reports and corresponding organizations in charge of the participating countries are as follows:

Appendix I:	General issues on methanol as motor fuel (Fachagentur Nachwachsende Rohstoffe e.V. (FNR) and DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH, Germany) [1]
Appendix II:	Heavy duty methanol engines (Fachagentur Nachwachsende Rohstoffe e.V. (FNR) and DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH, Germany) [2]
Appendix III:	Marine methanol (VTT Technical Research Centre of Finland LTD, Finland) [3]
Appendix IV:	High efficiency methanol engines – HEME (Lund University, Sweden) [4]
Appendix V:	Methanol as motor fuel – Barriers of commercialization (Danish Technological Institute, Denmark) [5]

The authors would like to acknowledge the Executive Committee of the IEA-AMF for supporting this Annex and the Methanol Institute for co-funding related to the technical report preparation and dissemination.

1.2. Objectives of Annex 56

The purpose of this review is to explore potential of methanol to act as motor fuel and to meet global challenges related to economy, energy security and climate change. Possibilities to produce methanol economically today creates markets for tomorrow's renewable methanol produced using renewable sources. Different transport sectors will be covered including light-duty (passenger cars) and heavy-duty road as well as marine vehicles. In the transport sector, there are ambitious current and anticipated regulations on greenhouse gases and pollutant emissions.

In the following report of Annex 56 results of the above mentioned Appendixes are summarized. The report is structured into three parts focusing on methanol production and supply (Part A), on application of methanol as engine fuel (Part B) as well as on prospects to commercialize methanol as motor fuel for transport (Part C).

1.3. Previous related work of AMF TCP

Methanol as motor fuel has been studied in AMF TCP for many years. The first co-operative project dealt with the topic "Alcohols and alcohol blends as motor fuels" in 1986 and had as objectives

i. Collect, classify, and comment on data obtained by international experience in the generation and use of alcohols and alcohol blends as motor fuels;
ii. Collect guidelines, that could be used in choosing national strategies for replacing motor fuels in whole or in part by alcohols and
iii. Obtain appropriate proposals for relevant developments in this field and to identify the potential need for future evaluation, analysis and development programs.

These objectives are completely up to date and are the main focus of our project. Since then, methanol has been studied in AMF TCP projects as well and which are listed below:

Annex 1:	Alcohols and alcohol blends as motor fuels (1986)
Annex 4:	Production of alcohols and other oxygenates from fossil fuels and renewables (1994)
Annex 26:	Alcohols and Ethers as Oxygenates in Diesel Fuels (2002 – 2005)
Annex 41:	Alternative Fuels for Marine Applications (2011 – 2013)
Annex 44:	Research on Unregulated Pollutants Emissions of Vehicles Fueled with Alcohol Alternative Fuels (2012 – 2014)
Annex 46:	Alcohol Application in CI Engines (2013 – 2015)
Annex 52:	Fuels for Efficiency (2015 – 2017)
Annex 54:	GDI Engines and Alcohol Fuels (2016 – 2019)

2 Part A | Methanol production and supply

Part A provides general information about methanol in general and as motor fuel and summarizes aspects of the methanol supply chain including issues related to greenhouse gas emissions and economic aspects. Other documented aspects are the properties and the handling of methanol as fuel. The summary in Part A is mainly based on Appendix I (General issues on methanol as motor fuel) reported by DBFZ.

While in the past methanol came into focus primarily due to its economic advantages during the oil crises, the use of methanol is now being promoted due to its ecological advantages (mainly reduction of pollutants, greenhouse gas (GHG) reduction potential in case of renewable methanol) and due to the reduction of the oil dependency [6,7].

2.1. Methanol production

The production capacity (125 million tonnes or 2.4 EJ in 2016) as well as the demand (85 million tonnes or 1.7 EJ in 2016) of methanol have risen rapidly in the past years (Fig. 1). Methanol producers are usually located in regions where natural gas or coal is increasingly being mined or an excellent infrastructure of natural gas or coal supply is available. Sixty percent of global methanol demand are used as intermediate in chemical industry (e.g. formaldehyde, acetic acid or methanol-to-olefine). The other forty percent are used as energy carrier in fuel industry (pure methanol, intermediate for methyl tert-butyl ether (MTBE), biodiesel, dimethyl ether or methanol-to-gasoline (MTG)). The expected increases in the coming years are likely to be driven by Chinese demand and the continuously increasing energy demand in transport and power supply. [7–10] Today, the methanol quantities annual available could only substitute a small proportion of the world's final energy consumption in the transport sector (120 EJ in 2020) and this methanol is mainly produced from fossil resources [11]. Assuming for instance that 3 vol% methanol in gasoline (M3) will be implemented across the European Union (approximately 80 million tonnes or 3.5 PJ gasoline in 2018), about 2.5 million tonnes or 0.05 PJ of methanol would be required [12].

Today, there are also a few small-scale pre commercial facilities for renewable methanol production on the market or at the planning stage, e.g. Södra in Sweden, Enerkem in Canada, CRI in Iceland and BioMCN and W2C in The Netherlands. Other renewable methanol plants and projects are documented in Appendix I. [7,10,13–15].

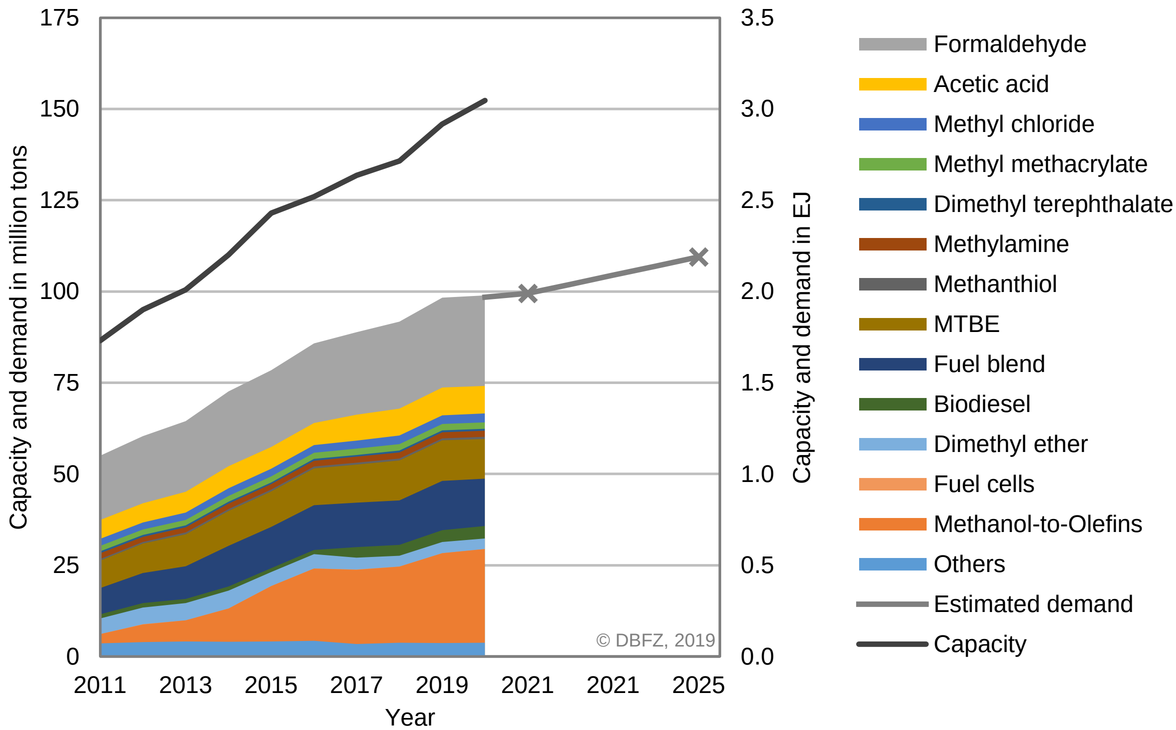

Fig. 1 Capacity and demand of methanol [7–9,16]

2.1.1. Technology aspects

The production of methanol can be subdivided into the steps of (i) synthesis gas production, (ii) methanol synthesis and (iii) product purification (Fig. 2). The synthesis gas (a mixture of hydrogen, carbon monoxide and carbon dioxide) is obtained from a variety of resources such as natural gas, coal and lignite, municipal solid waste, lignocellulose, biogas or using renewable electricity for hydrogen electrolysis. Based on the resource used it can be distinguished between fossil and renewable methanol.

Historically, methanol was produced by pyrolysis of wood. Currently, methanol is mainly produced of natural gas and coal with the synthesis gas processes autothermal reforming and gasification. Other conversion technologies like anaerobic fermentation and electrolysis can be brought into focus, if using renewable resources [7].

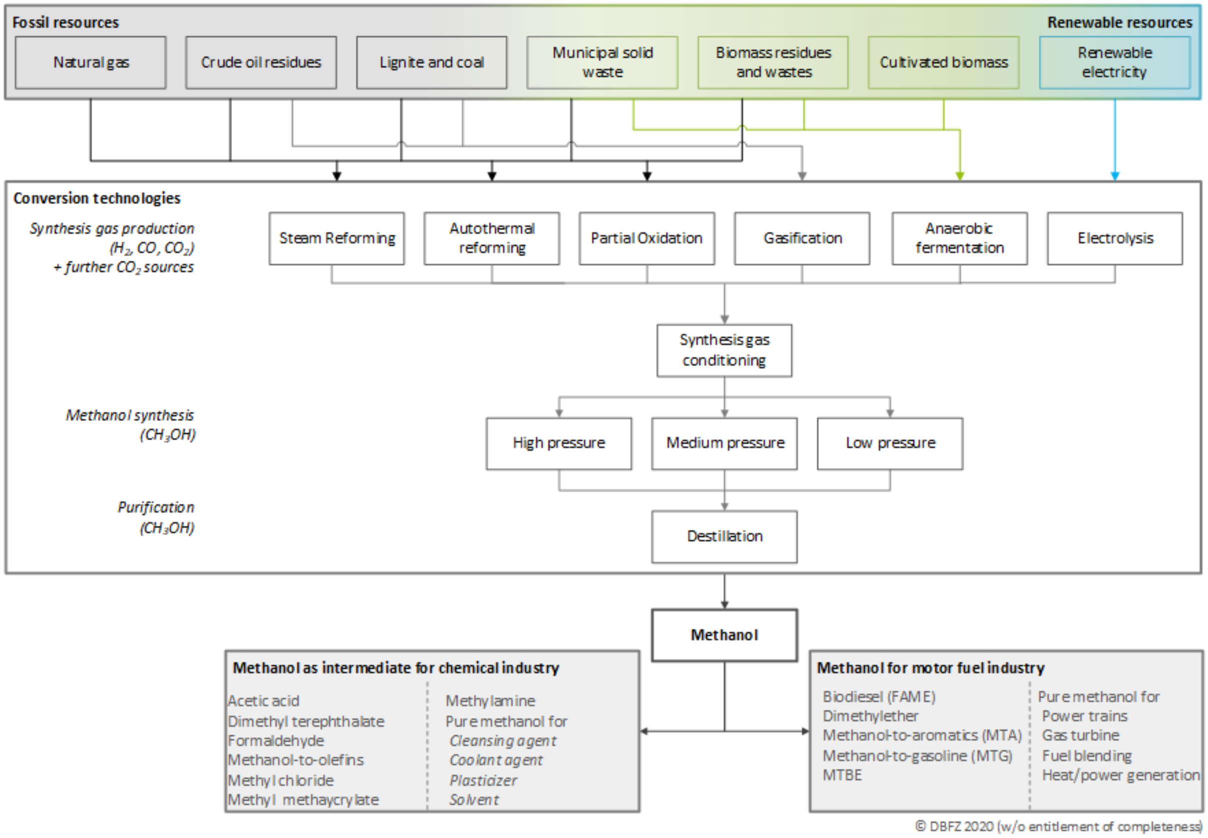

Fig. 2 Simplified scheme on resources, conversion technologies to methanol and further application of methanol [7,17]

The first industrial scale methanol synthesis plant started production in 1923 and was developed by BASF in Leuna (Germany). The developed high-pressure methanol synthesis converted a coal based synthesis gas of hydrogen and carbon monoxide at a specific catalyst and pressures above 300 bar and temperatures of about 300 to 400 °C. The first modern low-pressure methanol synthesis was developed by ICI in the 1960s. This synthesis used natural gas as resource at 30 to 120 bar and 200 to 300 °C. For purification the distillation of crude methanol removes byproducts such as water, ethanol and dimethyl ether. Crude methanol may sufficient for the energy sector [7,18].

Modern methanol plants are comparable to the developments in the 1960s and 1970s with further optimization in the synthesis process as well as in the used catalysts according to investment costs, efficiency, energy requirement and the supply of carbon monoxide and carbon dioxide. Typical capacities of these world scale methanol plants are 5,000 tonnes per day (5,000 MTPD) [7,19]. Further information on resources and conversion technologies for methanol production as described can be found in Appendix I.

2.1.2. GHG emissions of methanol

Mitigation of greenhouse gas emissions is one of the important sustainable development goals (SDGs) [20]. The results presented on GHG aspects are based on Appendix I and are compared to the default values of other renewable fuels defined in the European Renewable Energy Directive RED II.

The potential of GHG reduction with fuels essentially depends on the resource and conversion technology used, following the Well-to-Tank (WTT) perspective. Therefore, aspects such as transport and distribution processes have only a minor impact on the GHG emissions of a fuel. For efficient GHG mitigation, upstream GHG emissions of fuels are crucial, and thus the use of renewable, sustainable, fossil-free resource is needed. For example, the European Union defines that the GHG emission savings from the use of renewable fuels shall be at least 65% (biomass-based) or 70% (power-based), which are produced in plants starting operation from 2021 onwards [21].

As shown in Fig. 3, the GHG reduction potential of renewable methanol is approximately 65% to 95% compared to fossil methanol. The production and use of renewable methanol causes GHG emissions between 3.2 and 69.0 g CO2-eq. MJ^{-1}. Except for power-based methanol, studies assessing the GHG emissions of renewable methanol show very similar results (see Appendix I, Table 6).

In comparing the default values of the European Renewable Energy Directive binding from 2021 onwards (RED II) [21] for methanol to other renewable fuels it becomes clear that methanol potentially causes relatively low GHG emissions (see Appendix I, Table 4). If biogas or biomethane from wet manure alone would to be used to produce methanol, negative GHG emissions could even be achieved.

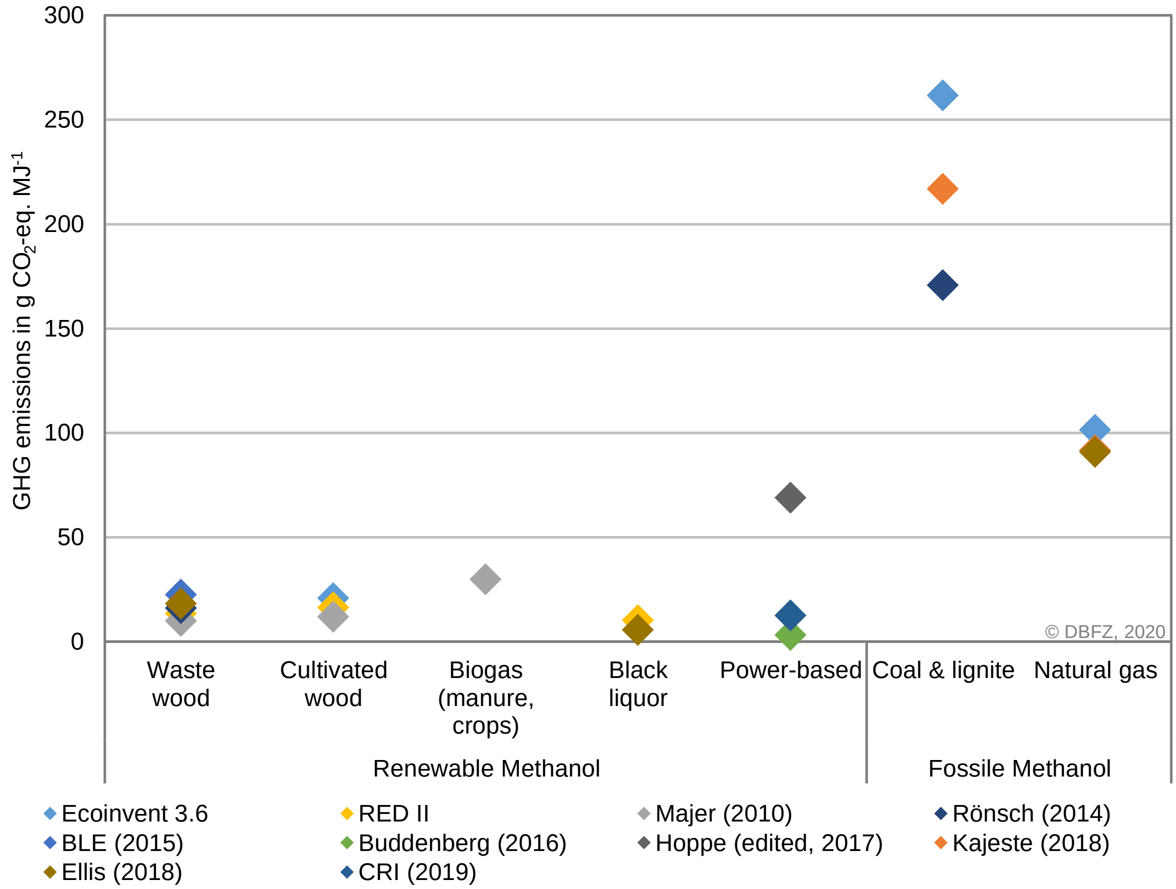

Fig. 3 GHG emissions of methanol from different resources based on [21–31]

2.1.3. Economic aspects

A first overview considering fossil-based methanol prices during the last 35 years are provided in Fig. 4. For comparison, methanol spot market prices in the USA and Europe are shown.

As diagramed, the two methanol spot market prices are over the whole time comparable and have the same peaks, as it is to be expected with a globally traded product. An analysis of the trend shows the influence of the oil price related to the methanol price. Especially in the last 10 years after the commercial crisis from 2008/09, there has been a similar trend between the methanol and the oil price. In contrast, supposed correlation between the methanol and the natural gas price cannot be seen. Since 2010, the price range of fossil methanol (Europe and US) is with the exception of singular peaks between 10 and 20 EUR GJ^{-1}, the price of Brent Oil ranged between 5 and 17 EUR GJ^{-1} and the price of natural gas between 3 and 5 EUR GJ^{-1}.

Like other alternative fuels fossil methanol is less costly compared to established renewable fuels such as biodiesel (FAME) from rapeseed (Europe: 20 – 30 EUR GJ^{-1}) and bioethanol (Europe: 20 – 35 EUR GJ^{-1}; US: 15 – 25 EUR GJ^{-1}). For renewable methanol there are no price listings, but most often it is sold at the quarterly Methanex or ICIS price plus a premium. [17]

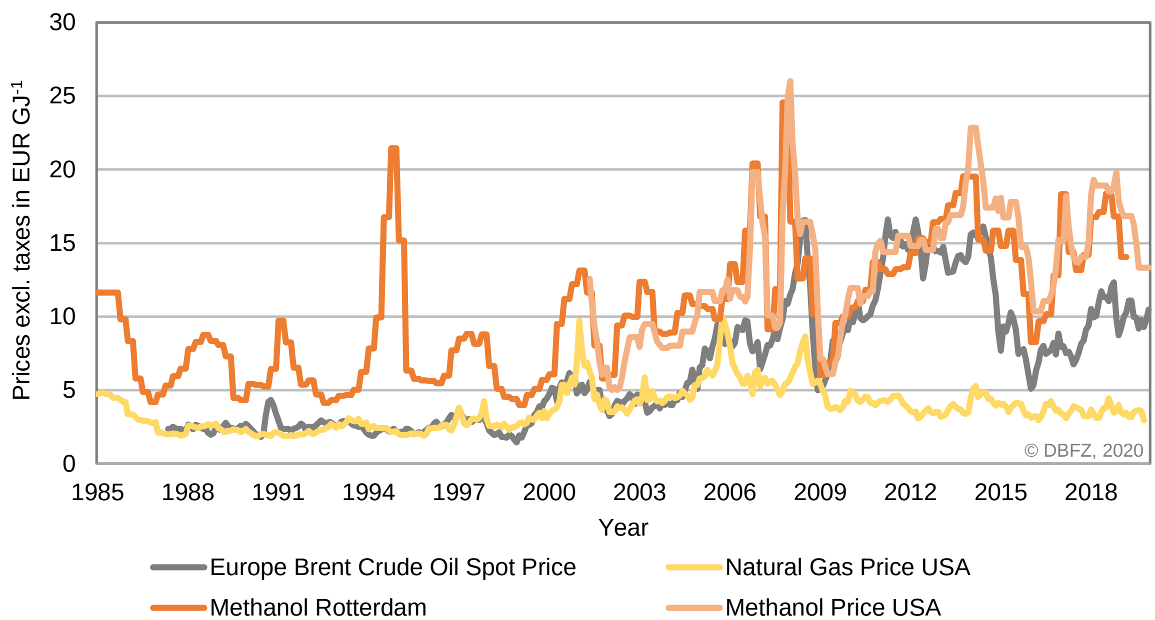

Fig. 4 Price development methanol in relation to oil and gas [32–36]

The analysis of the price structure of fossil-based methanol shows that the most sensitive factor is the resource price of natural gas or coal. In the natural gas producing countries such as Saudi Arabia, Russia and the USA the production price for methanol is lower than in the other considered countries. The second relevant component on the methanol price are the labor costs. Therefore, different renewable options have been discussed in the given references. Based on a review of different studies, Fig. 5 shows that renewable methanol cannot compete against fossil methanol. This aspect is similarly to other renewable fuels as mentioned above.

Other cost analyses of renewable methanol from cellulosic resources and from renewable electricity are presented in the maritime report (Appendix III, Fig. 3) [3]. One of the techno-economic studies on renewable fuels produced from cellulosic resources showed that Biomass-to-Liquid (BTL) fuels could be produced at reasonable costs, and production of methanol and dimethyl ether (DME) was more cost-effective than production of Fischer-Tropsch liquids or synthetic gasoline. However, fuel distribution costs would be lower for drop-in Fischer-Tropsch and MTG fuels. For pressurised fluidised-bed oxygen gasification plant studied, the lower end of the production cost estimates would not require substantial incentives to break even, although for first-of-a-kind BTL plants regulatory actions and significant public support are necessary. [37] Costs of producing power-based fuels depend on costs of renewable hydrogen dominated by the renewable electricity price. Hannula and Reiner [38] estimated that the production costs of power-based methane could be 1.5 to 2.5 times higher than those of hydrogen, while power-based methanol would be only slightly more costly than power-based methane, and power-based Fischer-Tropsch diesel would be approximately 1.4 times more costly than power-based methane. When considering additional storage and distribution costs for maritime sector, differences in costs between liquid and gaseous fuels narrows. [38]

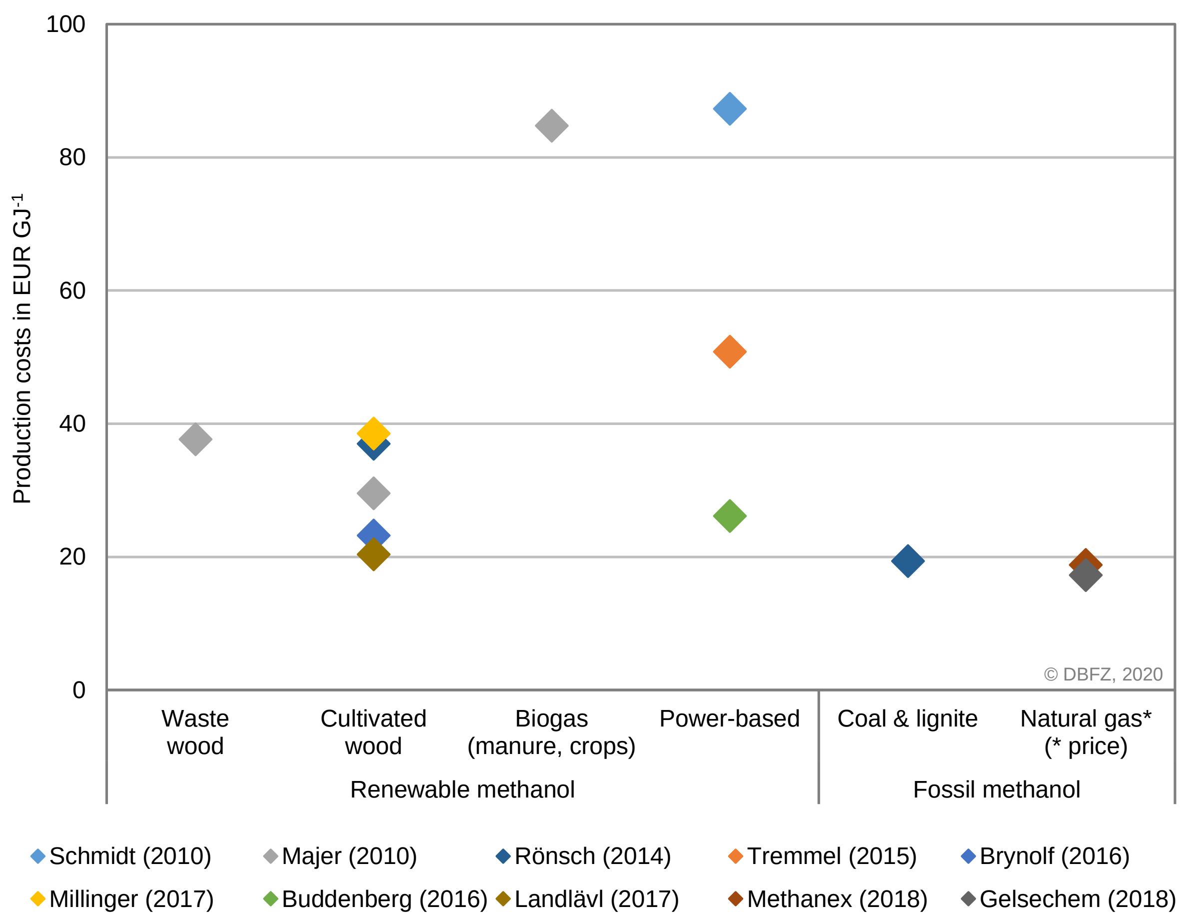

Fig. 5 Cost of methanol from different resources (normalized to 2018) [23,24,32,36,39–44]

In summary renewable methanol is usually more expensive on the market than fossil methanol, similarly as other renewable fuels are more expensive than fossil fuels today. However, when considering production of advanced renewable fuels, methanol is one of the most cost-efficient options. One possibility to reduce costs of methanol is to use a lower purity than 99.85% required for the chemical industry [30]. Combustion engines operate even when purity of methanol is 90% (ref. in [30]) or with higher water content (hydrous ethanol E100 application in Brazil [45]). Both options reduce the technical effort of methanol production, but require a separate infrastructure which is independent of that established for methanol for chemical industry.

2.2. Methanol characteristics

The results presented on methanol characteristics are based on all five Appendixes [1–5].

Methanol is the simplest representative of the group of alcohols. Under ambient conditions, methanol is a clear, colorless, flammable and volatile liquid with an alcoholic odor. It mixes with many organic solvents and in any ratio with water [7,46]. Methanol has positive properties regarding its use as fuel in internal combustion engines [47]:

- High octane number and high knocking resistance;
- No carbon-to-carbon bonds (soot-free combustion);
- High oxygen content (avoidance of fuel rich combustion zones);
- High heat of evaporation and high volumetric efficiency;
- Low lean flammability limit;
- High volatility

Nonetheless, there are also adverse properties according to fuel and material:

- Low volumetric energy content;
- Low vapor pressure and low cold starting performance of engines;
- Tendency to evaporate in fuel lines;
- Corrosive and chemical degradation of materials;
- Low cetane number and adverse self-ignition properties;
- Poor miscibility with diesel;
- Poor lubrication properties and degradation of oil lubrication properties.

Both, positive as well as adverse properties, have been known since first methanol as motor fuel tests in 1970s and have been addressed in methanol engine development.

2.2.1. Fuel properties and material compatibility

The high knocking resistance and high heat of vaporization of methanol allow higher compression ratios and thus also a higher thermodynamic efficiency compared to gasoline-fueled engines. Due to the molecular structure (bounded oxygen and no carbon-carbon bonds), the use of methanol as fuel can additionally reduce soot emissions (depending on methanol content). On the other hand, properties such as low energy content, viscosity, corrosive behavior and seal-swelling properties requires adjustments in the fuel system (larger fuel tank, methanol compatible seals, pumps and injectors with higher flow rates). Considerable adjustments in combustion process are necessary to counteract the low ignition quality and the high evaporation enthalpy. Moreover, incomplete combustion of methanol gives rise to formaldehyde and formic acid as pollutants. Properties such as flash point, flammability limits, corrosive behavior and toxicity cause similar attention when handling with methanol as with gasoline. [1]

A tabular comparison of the methanol properties with other fuels is shown in Appendix I and an overview and description of the properties of methanol as a fuel is presented in the SGS-report Methanol: Properties and Uses [47].

Knocking resistance and heat of vaporization. Methanol has an octane rating around 110 which is significantly higher than for gasoline (81-90). The high octane number is synonymous with a high knock resistance of methanol, which means that the fuel does not tend to autoignite. Due to the high heat of vaporization methanol cools down the intake air and the low air temperature allows the combustion of more fuel. Both properties enable increase the compression ratio of engines. Hence, smaller, more economic high performance engines can be used.

Chemical structure. Due to the molecular structure (i.e. bounded oxygen and no carbon-carbon bonds), the use of methanol as motor fuel can reduce soot emissions (depending on methanol content [30]). Furthermore, this means that well-known internal engine measures such as exhaust gas recirculation (EGR) can additionally reduce NO_X emissions, if using CI engine concepts. On the other hand, incomplete combustion of methanol produces more formaldehyde and formic acid emissions.

Energy content. Straight methanol and methanol blends have a lower heating value than straight gasoline, diesel or ethanol respectively. This will affect, in terms of reduce the driving range of the vehicle, but it can be compensated with more frequent fueling, larger tank or more efficient combustion engines. The engine fuel system needs to be modified due to the lower heating value. [5]

Vapor pressure. The low vapor pressure of methanol is an objection which have to be taken into account. A minimum vapor pressure is required to ensure good cold starting and drivability. A maximum vapor pressure is required to control the evaporative emissions from the vehicle. Therefore, requirements contain both a high and a low threshold. Methanol-gasoline mixtures show azeotropic behavior of vapor pressure. Most of the vapor pressure increase from blending methanol in gasoline occurs with up to 3 vol% methanol content. Higher methanol blends or neat methanol are less affected. [48,49]

Lubricity. Compared to hydrocarbon fuels methanol provides less lubricity. For high-level methanol blends this can result in an increased wear on engine fuel system components lubricity additives have to be used. [5]

Material compatibility. Most materials used for gasoline are also suitable for use with methanol blends. In order to resist phase separation, maintain stability and safety for methanol-gasoline blends corrosion inhibitors, co-solvents, and alcohol compatible materials are needed. [47,48] In contrast to other hydrocarbons, methanol is a polar molecule and thus corrosive to individual metals and alloys as well as elastomers and polymers that are widely used in engine fuel systems. This is also true for distribution, filling and tank equipment in the mineral oil industry. Elastomers and polymers that are not recommended include fluorosilicone (FVMQ), fluororubber (FPM, FKM), hydrogenated nitrile butadiene rubber (HNBR), neoprene (CR), nitrile butadiene rubber (NBR), polyurethane (PUR) and polyvinyl chloride (PVC). Metals that are not compatible with methanol are aluminium, copper, titanium, zinc and some of their alloys. [48,50,51]

2.2.2. Fuel standards

Fuel standards define specifications of fuels and allow refineries, fuel traders, automotive and engine companies to appropriately examine and process these fuel ensure their quality towards safe and efficient use. They binding for a market role out. Most of current methanol standardizations are related to the automotive sector. A range of methanol fuel standards are figured in the world map of Fig. 6. [47]

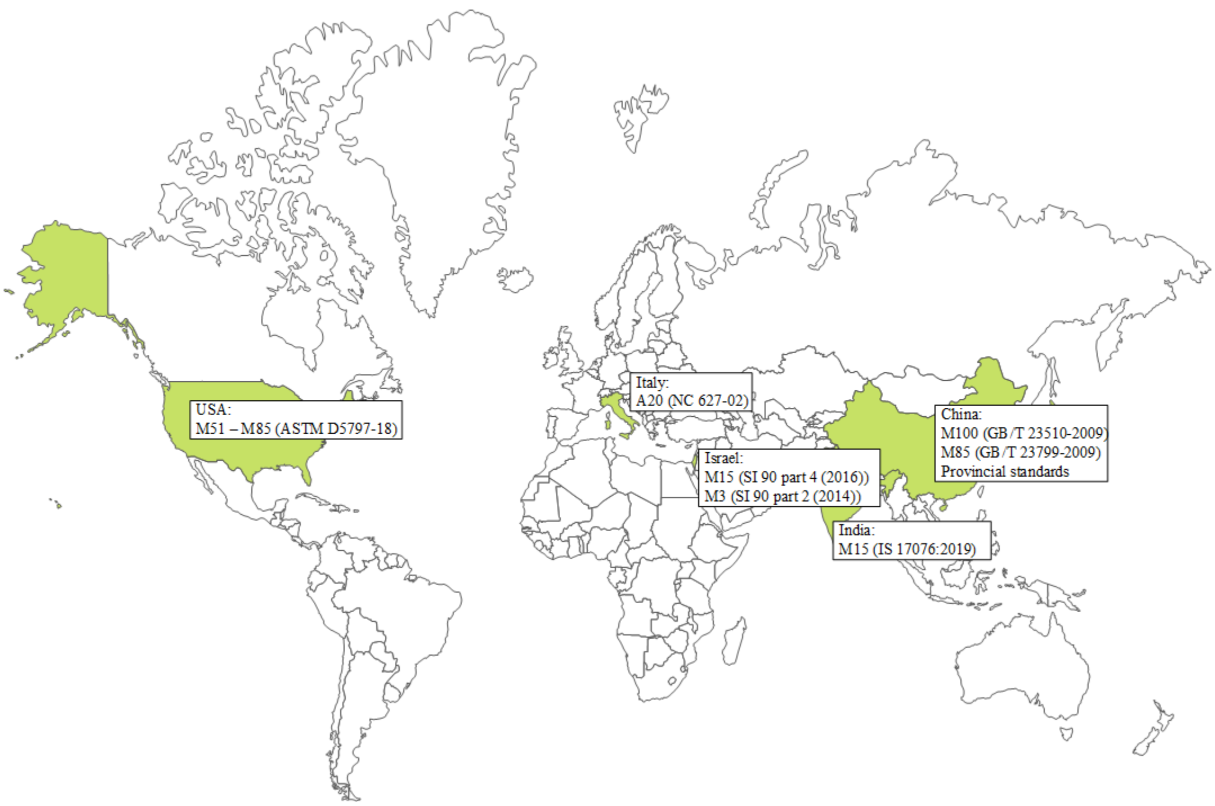

Fig. 6 Public automotive methanol fuel standards [47]

Regardless of this, there is still a need to catch up with the standardization of methanol as motor fuel in many regions worldwide. Current activities are unknown to the authors in this regard.

2.2.3. Health and safety issues

Various health and safety regulations have been established based on the physical and toxicological properties of pure methanol. The safety information regarding the pure components cannot be applied to mixtures, i.e. methanol blends. [1]

Human toxicology. Typical routes of methanol exposure in human body are inhalation, absorption through the skin due to direct contact, eye contact, and ingestion (eating or drinking). The human body absorbs and distributes methanol easily and rapidly (60% to 85% by inhalation exposure). [8] Metabolism and toxicity of methanol are similar to those found with ethylene glycol. Non-metabolized methanol is only of low toxicity. Toxic are essentially its degradation products such as formaldehyde and formic acid. In particular, formic acid leads after a latency period of 6 to 30 hours without symptoms to the formation of the typical poisoning symptoms of methanol. [52,53] The symptoms of methanol poisoning proceed in three phases. Directly after intake, methanol shows a narcotic stage comparably to that of ethanol, but the intoxicating effect is lower. After the latency period, headache, weakness, nausea, vomiting, dizziness and accelerated breathing are associated with metabolic acidosis. Temporary vision disorders arise first by edema at the retina. In the further course, complete degeneration of the optic nerve can lead to complete irreversible blindness. Deadly poisoning occurs due to respiratory paralysis. Doses from 0.1 g of methanol per kg of body weight are dangerous, over 1 g per kg of body weight life threatening. [53,54] Single symptoms can lead to chronic symptoms as well as disorders of the visual and central nervous system and other organ toxicity. In this context, there have been no documented cases of methanol poisoning from its use as a motor fuel in the USA. [8,55,56]

Environmental toxicology. According to the screening information data set (SIDS) of the OECD, methanol is a low-prority chemical whose properties are not considered harmful to the environment under normal circumstances. [8] Methanol is completely miscible with water in all proportions. The methanol-water mixture is very stable. Therefore, it is very difficult to remediate methanol contaminations. In contrast to crude oil (derivatives), methanol quickly dissolves in case of accidents on the high sea, due to its good miscibility and fast diffusion in water. Otherwise, if toxic quantities of methanol are present in water or mineral surfaces, it biodegrades rapidly. [7,8]

Further health and safety information are described and explained in the Methanol Safe Handling Manual of the Methanol Institute [8].

2.3. Infrastructure for handling, transport and storage

The infrastructure for methanol transport is mainly characterized by freight traffic (ship, road and rail) and is well established for chemical application. Transport via pipeline has only become established within chemical parks or ports. Material compatibility aspects have to be taken into account (*section 2.2.1*). The technology and safety precautions are based on long experience from methanol deliveries for other applications [7]. Requirements of handling and storage of methanol are similar to gasoline storage. Methanol is typically stored in floating roof tanks at marine terminals and docks, tank farms at chemical parks and portable containers for final use. Further information for safe storage of methanol are documented in a Technical bulletin for methanol drums and the Methanol Safe Handling Manual of the Methanol Institute [8,48] and an example for Denmark is shown in Info box 1.

Various application specific regulations (e.g. ADR and ERG) define requirements for transportation, handling and storage [57–62]. They are all comparable to the requirements for gasoline or ethanol. The UN number of methanol is 1230 with the transportation hazard class 3 (flammable liquids) and packing group II (substance presenting medium danger).

Marine sector. Intercontinental distribution of methanol is performed by tanker ships and from the hubs by 1,200-tonne barges, rail, or tank trucks. Therefore infrastructure for methanol is widely available for shipping purposes, and only local changes (e.g. integration in port bunker station) are needed. Adjustments are necessary, especially if there is no methanol infrastructure available at the respective port. Similar to other liquid fuels, transportation to water takes place in double-hulled tanks with methanol safety precautions. Bunkering of methanol fueled ships (e.g. ferries) is realized by trucks which deliver the fuel to a bunkering container with pumps on the dock. [3]

Road and rail sector. Transport requirements are comparable to those of other highly flammable liquid fuels such as gasoline and ethanol. Tank wagons should be able to allow pressure relief in order to accommodate thermal expansion and require a grounding against static charge.

To introduce methanol (blends) in road transport, a sufficient infrastructure is necessary. At service stations, the methanol (blend) has to be stored in double-walled, grounded tanks made with safety precautions against the ingress of moisture and flammable methanol vapor. Existing petroleum tanks have to be completely cleaned (petroleum, sediments and water) before storing methanol, the liner may need to be replaced with a methanol resistant liner and seals have to be replaced with methanol resistant seals. Comparable requirements also apply to the fuel pump and dispensing hoses at the service station. [63,64]

Info box 1

Case study Denmark | Blending, storage and handling [5]

Fuel logistics involves large investments in port-, dispensing and blending facilities etc. However, proper storages for methanol already exist in Denmark. Some fuel stations will need a protective coating inside the storage tanks, but this can be done in connection with a planned 5-year inspection (costs less than EUR 3,000 per station). Gasoline blendstock is a liquid hydrocarbon component suitable for use in SI engine fuels such as conventional gasoline blendstock for oxygenated blending (CBOB), and reformulated gasoline blendstock for oxygenate blending (RBOB). Methanol shall comply with the IMPCA (Methanol Reference Specifications) issued by International Methanol Producers & Consumers Association [65]. Comparably to most other fuels, methanol is toxic. Therefore, bitter agents or odorant should be added to M100 fuel methanol as a precaution. However, methanol-gasoline-blends are denatured by gasoline.

Methanol can be used in different blends together with gasoline. The most promising blends are A7, M15, M56, M85 and M100.

Recipe for a 105 octane M85 fuel:

- 85 vol% methanol
- 15 vol% gasoline
- a suitable amount of lubricant additive
- a suitable amount of anti-corrosive additive

For winter driving in Denmark it may be practical to reduce methanol content to 70 vol%. This will ensure a higher vapor pressure, which helps cold starting in general. For a lubricant and anti-corrosion additive there are several options available, e.g. Redline SI-Alcohol. In M85 there is no need for a co-solvent or ignition improver.

3 Part B | Methanol for engine application

Methanol provides several advantageous properties as a fuel, such as high knocking resistance, high flame speed, high latent heat of vaporization, high hydrogen and oxygen versus carbon ratio as well as a lack of carbon-carbon bonds, that offers higher improved overall engine efficiency and reduced emissions of NO_X, soot and CO_2, compared to conventional fuels such as gasoline and diesel. Reduced emissions and high efficiency, but also methanol's ability for high power engine operation motivates the current use in as diverse applications as in shipping, passenger cars and motorsports. However, the beneficial properties have so far not been enough for a global large-scale market penetration of methanol engines, mainly due to the availability of lower cost fossil gasoline and diesel fuels. [4]

Part B starts with a brief history of methanol as motor fuel followed by an introduction on concepts of methanol engines and their application in different transport sectors. At the end of part B, there is a short overview of methanol in fuel cell electric vehicles.

3.1. Brief history of methanol as motor fuel

After use of methanol as motor fuel during the World Wars due to gasoline shortages in Germany and France, methanol as motor fuel received attention again during the oil crises of the 1970s [66]. Small vehicle fleet trials of methanol-blended gasoline were done in Germany in mid-1970s [7]. Larger fleet trials were conducted in Germany, Sweden, New Zealand and China in the late 1970s and early 1980s. The interest on methanol as alternative fuel and also octane booster when lead was banned in gasoline resulted in several programs during 1980 to 1990, mainly in the California (USA). In the 1980s Ford and Volkswagen developed first flexible fuel vehicles (FFV) and in the 1990s participated in the test programme in California as well with about 100 vehicles. A consortia with Volkswagen (Germany), FEV (Germany) and EPA (USA) presented a M100 (pure methanol) engine concept. [67,68] By the mid-1990s, over 21,000 methanol M85 flexible fuel vehicles (FFV) capable of operating on methanol or gasoline were used in the U.S. with approximately 15,000 of these in California, which had over 100 refueling stations [69]. While the methanol FFV program was a technical success, rising methanol pricing in the mid- to late-1990s during a period of slumping gasoline pump prices diminished interest in methanol fuels. Moreover, ethanol as fuel received more relevance on the market. The methanol program in California ended in 2005. Automobile industry (e.g. Ford, Chrysler and

GM, Volkswagen) stopped building methanol FFVs by the late-1990s, switching their attention to ethanol-fueled vehicles. High performance experiences with methanol as automotive fuel has been obtained in racing (e.g. in the U.S. USAC Indy car competition starting in 1965 and CART circuit from 1979 to 2007 as well as in Europe [69]).

Low levels of methanol (M3) were blended in gasoline fuels and were sold in Europe mainly during the 1980s and early-1990s, but also today in Great Britain. Methanol is mainly used as fuel in the shipping sector (e.g. Stena Line, Methanex vessels) and in Chinese road transport (M15, M30, M85 and M100), where research and development of methanol vehicles was started in the 1990s and is rolling out to commercial application right now. [70,71]

3.2. Methanol engines concepts

This section provides insights into the state of the art and research and future perspectives of high efficiency methanol engines (Table 1). It is mainly based on Appendix IV (High efficiency methanol engines – HEME) reported by the Lund University. Much of the material is based on a recent comprehensive review paper by Verhelst et al. [72]; more recent research work are additionally cited in the text below.

Due to the strong demands on improved fuel efficiency and reductions on pollutant and greenhouse gas emissions, there is currently a rapid development of combustion engines in general that also benefits the development of methanol engines. The beneficial properties of methanol fuel are, however, likely to maintain the benefits in terms of efficiency and emissions over other fuels also in future engines, or alternatively offer similar performance at lower cost.

Table 1 Methanol engine concepts

Engine type	Mode	Fuel	Transport sector
Spark ignition (SI)	Port fuel injection (PFI)	M0 to M85, GEM	PC, LDV, HDV
	Direct injection (DI)	M0 to M85, GEM	PC, LDV, HDV
	Direct injection (DI lean)	M0 to M85, GEM	PC, LDV, HDV
Compression ignition (CI)	Dual fuel (DF)	M0 to M50	HDV, Marine
	Direct injection (DI)	M100, MD95	HDV, Marine
	New concepts (HCCI, PPC)	M100	HDV, Marine
Fuel Cell (FC)		M100	PC, LDV, HDV, Marine

3.2.1. Spark ignition engines

Methanol's high research octane number, high heat of vaporization, and high burning velocity, increase the resistance to autoignition. This opens the possibility for increasing engine efficiency compared to the more knock-limited fuel gasoline. The high flame velocity of methanol can also increase efficiency, through shorter combustion duration and thus better combustion phasing or through enabling higher dilution (extended lean burn limit or higher EGR tolerance). Finally, high heat of vaporization lowers temperatures in the combustion chamber, decreasing heat losses (and NO_X emissions).

Assuming a SI engine as base engine without any hardware adaptation (i.e. original compression ratio) the gains are limited. For naturally aspirated engines, efficiency gains depend on the conditions: the effects of lowering heat losses and shorter combustion duration benefit efficiency overall, but the increased knock resistance obviously only benefits those points that are knock limited on gasoline. This also means gains can be expected to be higher for a directly injected (DISI) engine than for a port fuel injected (PFI) SI engine. Published data is however limited to a handful of papers, indicating relative efficiency benefits up to 10% for a PFI-SI engine [73] and up to 15% for a DISI engine and to a decrease in CO_2 emissions of 21% [74]. Boosted engines (e.g. downsized engines) are typically more knock limited, and are hence even more suited for exploiting methanol's beneficial fuel properties. Relative efficiency gains of 25% have been reported [75] on a turbocharged DISI engine, where more optimal spark timing can be maintained on methanol instead of knock-limited spark advance on gasoline. In addition, lean operation for turbocharged DISI engines shows benefits up to 20% in brake thermal efficiency compared between methanol and gasoline [76].

Considering a CI engine as base engine, which has then been converted to SI operation, two features are important: (i) the peak pressure limitation is removed, or at least greatly increased over an SI engine block; (ii) the compression ratio (CR) will typically be higher, making better use of methanol's higher resistance to autoignition. On the other hand, the CR will likely be higher than optimal, possibly imposing a knock limit and leading to higher frictional and heat losses. A higher peak pressure limit can allow a larger improvement of the efficiency since it removes a potential limit for combustion phasing. Peak brake thermal efficiencies up to 42%, higher than the base engine achieved on diesel, are reported [77,78]. If the engine could be optimized for dedicated operation on methanol, it would likely have the following features: (i) the compression ratio could be higher than for gasoline, leading to an efficiency benefit over the entire load range; (ii)with a higher peak pressure capability than for gasoline, peak pressures would not limit combustion phasing; (iii)it would be possible to downsize the engine more than what would be possible on gasoline; in this context, Nguyen et al. reported 10% additional reduction in displacement [75]. Thanks to optimal combustion phasing and cooler combustion overall, exhaust temperatures would be substantially lower on methanol than on gasoline, so that fuel enrichment would not be necessary to protect the turbine and a variable geometry turbine (VGT) would be more easily implemented. This would benefit efficiency over the load range by reducing pumping losses, and at high loads through stoichiometric operation. Due to the wider dilution tolerance of methanol, the degrees of freedom of a variable valve actuation system would increase, which could be used to benefit part load efficiency, reducing pumping losses for instance through internal EGR.

3.2.2. Compression ignition engines

According to the fuel properties of methanol (e.g. extremely low cetane number [79]), it cannot be compared to diesel fuel. Still, given that most commercial applications use CI engines and that CI engines typically obtain higher efficiencies (peak and part load), several research groups have looked into methanol's use in CI engines. An overview is given in Verhelst et al. [72] and cited references therein.

There are several possibilities for burning methanol in CI engines: (i) premixing methanol with the intake air and adding a fuel with high cetane number to aid with ignition; (ii) adding an ignition enhancer to methanol; (iii) increasing the temperature around top dead center by e.g. preheating the intake air; (iv) using glow-plugs to assisting ignition or increasing the compression ratio; or (v) new combustion concepts.

Premixing methanol with the intake air and using a small diesel spray (the so-called 'pilot'), i.e. using dual fuel combustion, is the most common approach for the combustion of methanol in a CI engine. In its basic form, this only requires the addition of a methanol PFI system. So it offers a solution that can be retrofitted. Recent work has shown that the efficiency can be either higher or lower than for base diesel operation [80], with relative increases in efficiency up to 12% for higher loads. Dual fuel approaches can improve the NO_X-soot trade-off of diesel engines, but inherently are a compromise as the approach has limits (combustion stability limits at low loads, knocking limits at high loads).

Analogous to ED95, in which ethanol is directly injected as a blend containing 5% of high cetane number ignition enhancer, MD95 has been proposed. This has recently been shown to work, with reduced emissions compared to ED95 [81].

Glow-plug assisted combustion was used in a study by Caterpillar back in 1989 and 1990 where two diesel engine trucks where modified for CI operation on methanol fuel and driven in commercial use for about 60,000 km year around in snowy to hot weather. The engines used in this study had fuel systems compatible with methanol and glow plugs installed but where otherwise based on the original diesel engine with the same pistons and compression ratio. Energy consumption was similar to the two reference diesel fueled trucks. The methanol engines suffered from frequent replacement of glow plugs and also from occasional need for replacing intake valves.

However, the most attractive concept could be one that uses 100% methanol without ignition enhancer. Measurements and simulations considered with partially premixed combustion (PPC) using methanol as fuel, a form of low temperature combustion, in which all fuel is injected before combustion starts. This allows some time for fuel-air mixing, beneficial for hydrocarbons to lower soot formation (this is not being of concern to methanol, which does not form soot), and for lowering combustion temperatures so that NO_X formation is limited. Preliminary work on an externally charged single cylinder heavy-duty engine has shown a peak gross indicated efficiency of 52.8% [82]. Data resulting from this work validated a simulation model of detecting the efficiency potential of the PPC concept on methanol [83–85]. It was found that, over the investigated load range, the brake efficiency on methanol was on average 5.5% higher relative to gasoline [85]. Further optimization of the compression ratio (from 17.3 to 21.6) led to an average 1.4% higher efficiency. Highest efficiencies were reached with early injection timings, which could be a challenge in practice (crevice losses, controllability) [83]. These results – but with limited experimental data, and the simulation data that remains to be validated – demonstrate the potential of high efficiency with ultralow emissions. However, more research work in this area is needed.

3.2.3. Fuel reforming

Reforming of liquid fuel to a gaseous fuel, typically containing hydrogen, making use of waste exhaust heat, has been investigated for different reasons [86]. One aim is reducing emissions, either through the benefits of having a gaseous fuel instead of a liquid one; or using the hydrogen-rich gas to more easily regenerate after-treatment, or reduce NOx emissions by extending the lean limit. The second aim is increasing the overall system efficiency. As the reforming reactions are typically endothermic, and are driven by waste exhaust heat, the increased heating value of the reforming products are a form of waste heat recovery. Instead of for instance an organic Rankine cycle, the fuel itself is now the waste heat recovery medium. A heat exchanger in the exhaust is still needed, and a catalyst to promote the reforming reactions, but no additional expander is required.

Methanol is attractive for fuel reforming concepts since it is more readily reformed than other liquid fuels [72]. The thermal decomposition of methanol into carbon monoxide and hydrogen theoretically leads up to a 20% increase in the heating value. However, while the heating value of the reformed stream might increase, there are competing effects such as the decrease of the molar expansion ratio (mole ratio of products to reactants, which is much lower for hydrogen and carbon monoxide compared to methanol) [87]. Recently it was found that the effect negates most of the heating value increase so actual efficiency increases are quite modest [88].

3.2.4. Perspectives for future high efficiency methanol engines

Stricter emission regulations and fuel efficiency goals, the rapid development of computers that allows more advanced engine control as well as numerical models for engine development, and not least the competition from and integration with electric powertrains have mainly enhanced a rapid engine development during the last decades, which is an ongoing process.. In accordance, the interest for research on methanol engines has increased the last decade. Although there is still a limited amount of data, already at this stage methanol engines show strong potential for high efficiency and low engine-out emissions compared to equivalent engines fuelled with gasoline or diesel that have been extensively developed and optimized over more than a century. In the future, the advantages in efficiency of methanol engines over their conventional counterparts is expected to diminish as overall efficiency increases.

Considering the currently very small market penetration of advanced motor fuels, research and, especially industry development of combustion engines is primarily directed towards engines running on conventional fuels. These research and development efforts create an improved understanding about combustion engines in general and are valuable for future methanol engines, too. For example, light-duty SI engines on “super-lean” operation (thermal efficiency of 50% and higher) could be even more suitable for methanol combustion with its well-known extended lean limit operation capability [72,89]. Considering the promising research results on compression ignition engines running on methanol, further research and also industrial development is relevant. Much of the research on PPC methanol engines at Lund University has been performed on diesel engines with modifications to the fuelling system to tolerate methanol, cold start support, and modifications on control strategies to optimize the methanol operation. This engine hardware setup runs efficiently on a multitude of liquid fuels, such as diesel fuel, gasoline, ethanol, E85, HVO and biodiesel. What varies is primarily the strategies to control the combustion. This fuel-flexibility ranging from high cetane number fuels (diesel type fuels) to high octane number fuels (gasoline, alcohols) poses an interesting opportunity for commercial fleet operators willing to operate on renewable methanol, but not being certain to always find methanol filling stations and thus needing a conventional fuel as back-up. Similar to spark-ignited engines, there is strong development on compression ignition engines as well. One example is the Department of Energy’s SuperTruck Program in the USA where 55% brake thermal efficiency is targeted and achieved [90,91]. In combination with methanol, this optimized CI engines could achieve even higher brake thermal efficiency [92].

Many of the described methanol applications could be also adopted to hybrid applications (HEV, PHEV), where an electric drive enables a partial (parallel hybrids) or complete electric (range extended electric vehicles) driving. , range extender solutions with more powerful electric drive systems, with small batteries and small but efficient range extender engines on renewable fuels can most likely have a strong potential for heavy duty vehicle fleets, where operating costs are decisive for the choice of drive type.

3.3. Passenger car and light-duty application

This section provides insights into the state of the art and research of high efficiency methanol engines for passenger car (PC) and light-duty application. It is mainly based on previous related work in IEA-AMF (https://www.iea-amf.org/content/fuel_information/methanol) expanded by the

Danish technical report of this annex (Appendix V) and a section on fuel cell electric vehicles using methanol as energy carrier.

From the current 90 million cars and trucks sold annually (thereof two million electric vehicles), most of the increase comes from car sales in countries with developing or newly industrialized economies, where there is a demand for low cost cars [93]. Considering that methanol engines do not require any unusual or rare materials, there is technical little challenging the realism of massive scale production of such engines. The beneficial properties of methanol allow more efficient naturally aspirated low cost engines suitable for low cost vehicles compared to gasoline and diesel fuel. Substantial knowledge is also available to construct such engines in a fuel-flexible manner and allowing operation on methanol, ethanol and gasoline and blends thereof. Ethanol is currently more readily available on several markets and is also an alcohol with quite similar properties to methanol. Gasoline is a less fuel efficient fuel compared to alcohols but its availability guarantees mobility in a transition period towards fossil free transportation. Today, main market of methanol as motor fuel is China.

Most of small engines used in the world for motorcycles, mopeds, as well as for chain-saws, lawn-movers and several other hand-held devices, are also typically based on simple spark-ignition gasoline engine technology. These applications are in several cases suitable for similarly simple spark-ignited methanol or ethanol engines where low overall costs, added efficiency and increased power density are reasonable. However, many of these applications are being replaced by battery electric powertrains, which is especially valuable where exposure to exhausts can be an issue and could lead to negative health effects.

High methanol concentrations, e.g. containing 85 vol% methanol in gasoline (M85), can be used only in special Flexible Fuel Vehicles (FFVs), which were first developed for methanol and later on optimized for ethanol. Today, main market of methanol as motor fuel is China, where 7 – 8 % of China's transportation fuel pool is based on methanol. Methanol fuel used is ranging from 5 vol% methanol in gasoline (M5) to 100 vol% methanol (M100). Methanol-blended fuels are explored also by other countries, such as Israel, Australia, and Iceland. However, for example in Europe and North America, blending of methanol is limited up to a few percentages in gasoline according to EN 228 and ASTM D4814. Infrastructure and cars are not designed for methanol use in these regions. Mid-level alcohol fuel blends (A20-A30) or high-level alcohol fuels can be high octane fuels that would allow automakers to optimize cars with higher engine compression ratios, downsized engines, increased turbocharging, and enhanced direct injection. High engine efficiency could compensate for methanol's low energy density.

In IEA-AMF Annex 54, M56 (and E85) was tested in three different FFV (two GDI, one PFI engine) with the NEDC test. The results show that using oxygenated fuels could decrease substantially the emissions compared to gasoline. While the effect on NO_X was relatively small, all other emissions which include HC, CO, CO_2, and NMHC (with the exception of formaldehyde) decreased. There is no legislation for formaldehyde emissions in the EU but limits are specified in the US and Canada, with the possible carcinogenic effects of formaldehyde being of general concern. Between the two oxygenated fuels M56 caused larger increases in formaldehyde emissions than E85. The pre- and post- particulate results measurements of formaldehyde for all three vehicles show that the TWC was quite effective in reducing these emissions. [94]

In IEA-AMF Annex 44, methanol blends (M15 and M30) were studied in comparison with neat gasoline using two PFI and two GDI vehicles. The tests were conducted at normal (25 °C) and at low ambient temperatures (-7 °C). Many emission components were high during the first acceleration, but reduced to nearly zero as the catalyst lighted off. In both test temperatures, HC, CO and methane emissions decreased slightly as the alcohol proportion of fuel increased, while nitrogen oxides (NO_X) increased slightly. Tailpipe CO_2 did not change substantially. Unburned methanol, formaldehyde and acetaldehyde emissions increased proportionally with the increasing alcohol content, while benzene, toluene, ethylene, propylene, 1,3-butadiene and isobutene decreased slightly. [95]

In earlier work, increasing methanol content of fuel has reduced CO, HC and NO_X when compared to gasoline, while formaldehyde emissions have increased, especially at cold-starts [63,69,96].

In some markets, the focus is set on blends of gasoline, ethanol and methanol (GEM). In this concept, ethanol is serving as a co-solvent for methanol. These tri-component blends obtain a constant air-to-fuel ratio of 9.7:1, which is same ratio as air-to-fuel ratio for E85 fuel. Behavior of virtual and physical alcohol sensors used in the FFVs have been studied with GEM blends, as well as performance of cars at cold temperatures, emissions and costs. The results indicate that GEM blends could be used in FFV cars as a drop-in alternative to E85 fuel [97].

Generally, the special engine technologies discussed for ethanol can also be considered for methanol use.

In China, mass production of methanol vehicles already started, production facilities capable of producing 300,000 to 500,000 M100 engine units per are established [70].

Further examples of light-duty application on methanol are shown in Table 2 and in the Info box 2.

Table 2 Examples of light-duty application [31,70,98,99]

Location	Fuel	Type of implementation	Year
China	M5 – M85 (12 million tonnes a^{-1})	~ 100 million	since 2000
Israel	M15	FFV test trial	2012 – 2015
Italy	A20 (M15 + E5)	FFV test trial	2017 – 2019
Denmark	M100 (FCEV)	Test trial	2015 - 2018
China	M100	~ 10,000	2012 – 2019
Iceland	M100	Test trial	2016 – 2017
USA	M100	Motor sports	
Australia	GEM	FFV test trial	

Info box 2

Case study Denmark | Retrofitting passenger cars [5]

In 2018, the Danish Technological Institute (DTI) tested a small passenger car with different methanol-gasoline blends. The purpose of the vehicle experiments was capability of a standard gasoline car with methanol as fuel and was focused on engine performance, fuel economy, emissions, noise and drivability. This section is mainly based on Appendix V (Methanol as motor fuel) reported by DTI.

Fig. 7 Methanol as motor fuel tested by DTI in a passenger car (2018)

The used vehicle, a Peugeot 107, has a 998 cm^3 3-cylinder SI engine with a nominal output of 50 kW. The used engine has among other things an electronically controlled multi-point port injection system with 3 Injectors, a cable drawn intake air throttle, a variable valve timing system and a knock sensor. Compression ratio is 10.5:1, which is normal for a naturally aspirated gasoline engine. The tests were performed with neat gasoline (E5 according to EN 228), neat methanol (according to IMPCA methanol specifications reference [65]) and several methanol-gasoline-blends (M15, M25, M50, M65, M75 and M85) without and partial with a FFV kit. The fuel injection pulses of the FFV kit, i.e. Flex fuel ethanol conversion kit from Artline International SARL, were prolonged due to the use of methanol instead of ethanol. The tests include chassis dyno tests for engine power and torque measurements and WLTP/RDE tests for emissions and fuel consumption. The M85 of the RDE-test was additionally mixed with 0.1 vol% of an additive for alcohol fuels (Redline SI Alcohol).

The initial work on the test vehicle – without the FFV kit – showed that the engine could run on any blend up to M100, when the tests were conducted in a warm laboratory environment. The power and torque outputs were normal. However, when moving to outdoor tests the engine had difficulties starting up and the Diagnostic Trouble Code (DTC) warning lamp came on after few hours of operation. Even worse, the NO_X emissions increased which is attributed to the fact that the engine was running too lean for the 3-way catalytic converter to operate properly. The 3-way catalytic converter requires almost zero oxygen content in the exhaust gas which prohibits lean operation.

To achieve full engine power and torque with M85 the volumetric fuel delivery must be 74 % larger than with gasoline. The original engine control unit (ECU) will accept a certain increase in fuel flow. However, it can result in the ECU issuing a DTC which will cause a failure at the vehicle inspection.

Upon installation of the FFV kit, the car ran almost perfectly. The maximum power and torque increased about 5% from standard which could be noticed when accelerating.

The engine also ran more quietly due to the absence of combustion noise. Cold starting was acceptable, however not completely perfect.

The results of the methanol tests in Denmark can be summarized as followed:

- Engine performance:
  - Slight problems with cold start during cold weather conditions,
  - Highest engine power and torque was reached with M85 and the Flex Fuel Kit installed, overall an increase of 5% in engine power and 7% in torque compared to E5,
  - Slight troubles with variable valve timing and performing below 3,500 rpm with M65, M75 and M100 and without FFV kit.
- Consumption:
  - 7% lower caloric consumption for WLTP tests with M85 compared to E5 (Fig. 8),
  - Comparable caloric consumption for RDE tests with E5 and M85 (Fig. 8),
  - 68% higher volumetric consumption for RDE tests with M85 due to the lower heating value of methanol.
- Emissions:
  - Increase of NOX emissions for tests without FFV kit, slight increase for tests with FFV kit,
  - Decrease of CO emissions,
  - Decrease of particle emissions without FFV kit, comparable emissions with FFV kit.

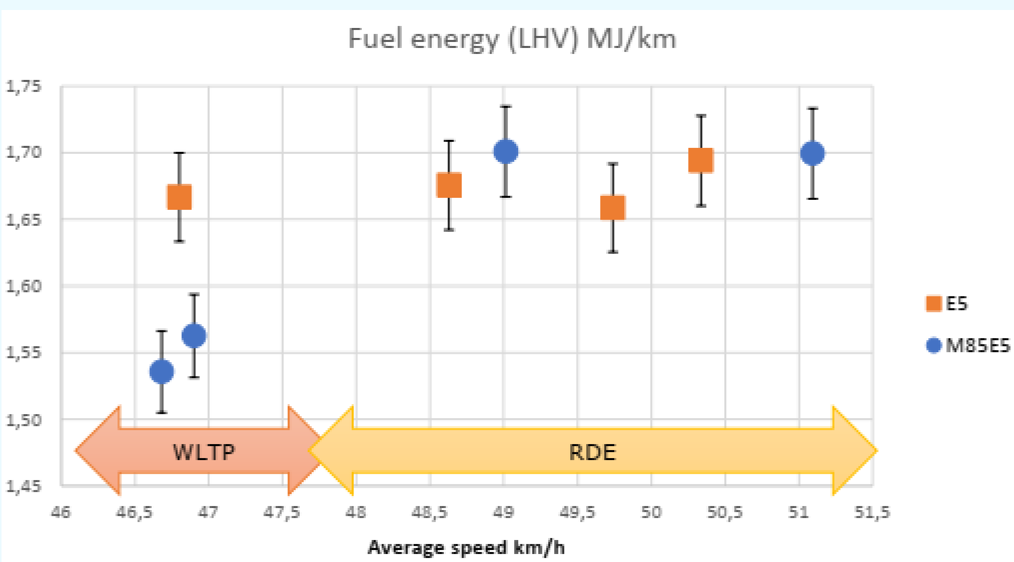

Fig. 8 Caloric consumption of M85 fueled PC

3.4. Heavy-duty application

This section provides insights into the state of the art and research of high efficiency methanol engines for heavy-duty application. It is mainly based on Appendix II (Heavy duty methanol engine) reported by the DBFZ [2]. A comparison of various methanol engine concepts according to engine performance and exhaust emissions is provided in *section 3.5* (cf. also Appendix III [3]).

Heavy-duty vehicles (trucks, coaches, agricultural and off-road machines) are currently driven by diesel engines (CI-engine) as a result of the higher fuel efficiency and the lower final torque compared to spark ignition engines (SI-engine), which leads to better operating characteristics and cost-saving application. The comparatively higher engine-out emissions of CI-engines – especially NO_X and PM pollutants – due to the heterogeneous combustion are disadvantageous. These pollutants have to be reduced through complex and cost-intensive exhaust gas after-treatment. In the future, with increasing demands on pollutant avoidance and fleet consumption, economical alternative fuels with cleaner combustion properties can play a much more significant role as an energy carrier for HDV powertrains than today. Mainly discussed alternatives for HDV application are liquid natural gas (LNG), paraffinic hydrocarbons (such as HVO, Fischer-Tropsch fuels), fatty acid methyl ester (FAME), alcohols (methanol, ethanol), ethers (dimethyl ether, poly(oxymethylene) dimethyl ether) and hydrogen. All of these alternatives need modification in the engine system and even partially in the infrastructure [17,100–102].

Current research activities in the HDV sector are focused in reducing the costs of operation (higher engine efficiency, lower pollution and waste energy level) as well as in electrification or hybridization of the vehicle. In combination with alternative motor fuels, a number of new low temperature SI and CI combustion systems were developed in the last years. In this context, many ways of using methanol in diesel engines have been researched including use in blends, emulsions, fumigation, with the addition of ignition improvers, in dual injection engines, and in engines modified to achieve direct compression ignition of methanol. [63,81,100,103] The MD95 concept, shown in Aakko-Saksa et al. [81], uses neat methanol with 5 vol% ignition improver. This methanol application is comparable to the Swedish ED95 concept and has benefits in performance and exhaust emissions compared to conventional diesel engines. Another common used CI-concept for heavy-duty application is the dual fuel engine with port fuel injection of methanol. This fuel fumigation is an alternative method for retrofitting diesel engine. The ignition occurs by diesel fuel injection. This method requires a secondary fuel system and a complex controlling for the maximum possible methanol amount, which depends on the engine load and it has the potential for reducing NO_X (especially NO) and particulates emissions in the whole range of engine operation, but it could lead to a significant increase in HC, CO emissions and NO_2 emission [63,104–106]. Alternatively, the use of conventional SI-engines driven by methanol (M85) is also a possibility especially for light and medium duty vehicles. However, this means a change in the combustion method from compression ignition to spark ignition and therefore a supposed lower thermal efficiency [107]. Furthermore, modern direct injection, spark ignition combustion concepts (DISI) with high compression ratio and a highly turbocharged, downsized engine can achieve low NO_X and PM emissions as well as a high efficiency, if using pure methanol (M100). This positive effect is caused due to the high octane number of methanol [108–110].

Methanol heavy-duty application are currently mainly tested in China. Other current HDV test trails are unknown to the authors. In the early 1990s, a number of heavy duty (fleet) tests with methanol engines (PFI-SI engines with M85 and M100) have been performed in the USA; a selection of trials is shown in Table 3.

Table 3 Examples of heavy-duty application [64,70,111–113]

Application	Engine	Location	Manufacture	Mode	Year
More than 300 Buses	PFI-SI	USA and Canada	Detroit Diesel Corporation	fleet test	1990 - 1995
Heavy-duty truck	DISI	China	Yuan Cheng (Geely)	commercial	2019
96 buses	DF	China (Changzhi, Shanxi)	Zhengzhou Yutong Bus	fleet test	2019
5 self-dumping trucks	DF	China (Yulin, Shannxi)	Shaanxi Heavy Auto Enterprise	fleet test	2019
15 multi purpose vehicles	DF	China (Baoji, Shannxi)	Shaanxi Tongjia Automobile Co.	fleet test	2019
Heavy-duty truck	DF	China (Tianjin)	Tianjin University	demonstration vehicle	ongoing
Trucks in coal mines	DF	China	FAW	fleet test	ongoing

Most of available data for cost of operation is related to the Chinese heavy-duty vehicle market, due to the long-term experience with methanol as motor fuel. For more than 40 years methanol has been supported in China and has reached a tiny market share today. Around 50 service station are operating with methanol mainly for PC and LDV application [114]. Geely Auto Group rolled out the first modern methanol powered heavy-duty truck in China in 2019 [115]. The truck is promoted for less than 50,000 EUR [116,117]. Before entering the whole market with M100 heavy-duty trucks, it is also possible to convert already existing diesel trucks into methanol and diesel compatible vehicles (dual fuel engine concept). This conversion would cost around 3,000 EUR [114,117]. The China Internal Combustion Engine Industry Association suggest that this investment charge off after around 100,000 kilometers [114].

The amortization is possible through the lower methanol fuel cost per kilometer, compared to diesel. The saving is specified with over 50% comparing with vehicles with the same displacement [118,119]. The fuel cost saving results from two different reasons: On one hand methanol has a higher efficiency, on the other hand, in China, methanol (resource: coal) is 25% cheaper compared to diesel on energy basis [109].

3.5. Marine application

This section deals with the state of the art and research of methanol as fuel in marine application. It is mainly based on Appendix III (Marine methanol) reported by VTT Technical Research Centre of Finland [3].

The shipping sector is already making in-routes towards operation with methanol engines [120]. The main objective has been to meet the introduction of emission regulations at coastal areas, without the need to introduce expensive emissions after-treatment devices. Other benefits discovered include improved efficiency, cleaner and lower temperature in machine rooms, and reduce risk at spillages. Stena Line for instance has pioneered efforts and has gained substantial experience through the conversion and operation of the four on-board engines of the Stena Germanica ferry from diesel fuel to methanol. As emissions regulations continue to be introduced for global shipping, the ship owners need to comply with these by either implementing advanced emissions aftertreatment or by modifying engines for operation on cleaner fuels, such as LNG or methanol. Modifying engines has the added benefit to provide a solution for future regulation to reduce CO_2 emissions from shipping. [4]

Following the emission regulations of the sulphur emission control areas (SECA), marine fuels with a sulphur content below 0.1% or scrubbers are required. Furthermore, sulphur content of marine fuels has limited to max. 0.5% globally since 2020 [121]. Tier III regulations are challenging in the NO_X emissions control areas (NECA) for new vessels. Additionally, need to control black carbon emissions from shipping is evaluated by the IMO, and HFO-ban in the Arctic region is considered. At the same time, GHG strategy of the IMO is ambitious: cutting CO_2 emissions from shipping by at least 50% by 2050 compared to 2008 [122]. In addition to larger ships, regulations for smaller vessels are also tightening.

Consequently, clean, sustainable and climate-neutral advanced fuels in addition to advanced engine technologies are needed. Methanol is one of the advanced fuel options considered for marine engines. However, technical feasibility and economy aspects need careful consideration before decisions on technologies are taken by industry and politicians. Special feature of shipping industry is that due to large size and high fuel consumption of ships, even ship-specific technology choices have to be taken into account.

For shipping, there are dual-fuel marine methanol engines on market. Wärtsilä has developed a methanol-diesel retrofit concept for four-stroke medium-speed marine engines, called GD methanol-diesel, which has the advantage of using diesel as a back-up fuel (used in the Stena Germanica ferry). In this technology, changes in the cylinder heads, fuel injectors and fuel pumps are needed, as well as a special common rail system and ECU [123,124]. Retrofitting reduces costs, although if the engine is too old it might be more cost effective to replace the complete engine. However, retrofitting has also challenges depending on the generation of the engine to be modified [30]. Another dual-fuel engine concept for methanol developed by MAN for new-build is used in several tankers by Waterfront Shipping [125].

Another CI concept, the MD95 concept, uses additive-enhanced methanol and has been tested based on already commercially available engines designed for additive-enhanced ethanol (ED95 developed by Scania). The modifications to the conventional diesel engines include increased compression ratio (28:1), a special fuel injection system and a catalyst to control aldehyde emissions [126]. This monofuel alcohol engine concept was studied with methanol using the commercial additives of ED95 by Nylund et al. [127,128]. New research on MD95 concept was demonstrated in the SUMMETH project [81] and in the GreenPilot project [129].

Spark-ignited engines, such as PFI-SI or DISI could be used in vessels, with pistons and cylinder heads adapted for spark plugs. These engines are on Chinese market for cars, and some smaller size classes for vessels [129]. Some promising advanced combustion systems are under development as described in *section 3.2*.

The power output from methanol engines are expected to be similar to those of diesel engines, but compression ratio is high for MD95 and PFI-SI engine is vulnerable to knock.

Methanol has low emissions in many respects compared to conventional maritime fuels such as MGO or HFO, Table 4. Its high oxygen content means low carbon based soot emissions in engine combustion. In dual-fuel engines, diesel pilot results in some soot emissions, but still lower than from conventional diesel engines. For MD95, there are no soot emissions, but some unburned additives are seen on particulate filters. Dual-Fuel and MD95 concepts can reduce NO_X emission down to approximately 2 g kWh^{-1} without SCR system, and even lower NO_X can be achieved by the use of lean operation or EGR. For current SECA, low Sulphur oxide (SO_X) emissions with methanol alleviates costs as exhaust after-treatment with scrubbers are not needed. HC, CO and aldehyde emissions measured from methanol engines have been low and to secure low emissions of organic gases, low-cost diesel oxidation catalysts (DOC) can be used. Methanol engines are less noisy than diesel [30,130].

Table 4 Comparison of various methanol engine concepts in comparison with HFO/diesel use in marine diesel engines

Engine type	Robust-ness	Power, efficiency	SO_X	HC, CO	NO_X	PM
CI (HFO/diesel)	0	0	0	0	0	0
CI DF	-	0	+	0	+	+
CI MD95 with DOC	-	-	+	0	+	+
SI (DISI, PFI)	-	0 / +	+	0	+	+

0 = similar performance with methanol compared to HFO/diesel
- = worse performance with methanol compared to HFO/diesel
+ = better performance with methanol compared to HFO/diesel

The large ships using methanol in dual-fuel engines, the Stena Germanica and the Waterfront shipping chemical tankers, 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. These international regulations provide guidance for good practice for handling methanol as a marine fuel also in smaller vessels. For small vessels some requirements applicable for large ships are not suitable, e.g. some automation requirements. However, less special arrangements are necessary for methanol use in smaller vessels than in larger ships. Practically, requirements would be very similar to those for gasoline. Notable is that impacts of accidental spills of methanol would be less than those of a HFO or diesel spill as methanol is biodegradable. Thus there are clear environmental benefits for vessels and ships switching to operation on methanol fuels. [30]

3.6. Methanol in fuel cell electric vehicles (FCEV)

Fuel cell is a technology that uses hydrogen or hydrogen carriers in the production of energy through electrochemical reaction. The cell is mainly composed of two separated sections: one that flows air and another that flows the hydrogen source, both separated by a membrane. Although there are several types of fuel cells, their process converges to the same principle: Hydrogen carrier oxidize in one section of the cell called cathode, which realize electrons in the medium. The membrane allows the oxidized hydrogen pass to the other side section of the cell and reacts with the oxygen contained in the air, producing water. The membrane is selective to electrons and the coupling of an extern electric system enables the accumulated electrons flow and generate energy to the vehicle. [131]

As methanol is the simplest alcohol and has no carbon to carbon bounds, it has a 4:1 hydrogen to carbon ratio, which makes methanol the main candidate for utilization as hydrogen carrier. The fuel cells are divided mainly in two applications: Direct Methanol Fuel Cell (DMFC) and High Temperature Proton Exchange Membrane Fuel Cells (HT-PEMFC). In DMFC, methanol reacts with water in the cathode to form hydrogen and realize electrons. Despite its simplicity, this approach is related to low efficiencies and causes problems regarding to migration of methanol and formaldehyde (product of side reaction) through the membrane, and the presence of both components in the off-gas can raise safety problems. In HT-PEMFC, methanol is first reformed, producing a mixture of hydrogen, carbon dioxide and traces of carbon monoxide besides unreacted water and methanol. The reformate gas can be used directly in the fuel cell without purification, and as the reaction happens before the pass in the cell, the efficiency is reported to be higher than DMFC and the off-gas hazard problems are minimized. The need of coupling a reformer to the cell associates this technology with more complexity. [132]

Due to the high energy density and low space usage of methanol fuel cells, its usage has been investigated for PC or LDV, HDV and marine applications. The integration in PCs follows the same design as for hydrogen fuel cells: The air provided by the cells enters the PC through large inlet grills inside the front bumper; a tank is needed specifically for methanol usage; the fuel cell unit is coupled with a battery, a power unit control is needed to manage the stock of energy in the battery as well as the required energy demand of the powertrain. The advantage of the usage of methanol fuel cell cars instead of internal combustion is the cleaner off-gas (mainly water and carbon dioxide) [72]. In this perspective, the methanol fuel cells can be realized within for example range extenders for electric city buses and auxiliary power for ships. Another possible synergy lies in the residual heat that remains from the fuel cell, which can be used as heat provider for the vehicle. As it is a compact technology, its usage is also investigated for home storage units for houses with solar panels as vehicle-to-grid technology [133].

In 2015, the first methanol fueling station for fuel cells in Europe was opened by the petrol company OK in Denmark [134]. SerEnergy has made prototypes of the usage of methanol fuel cells using a 5 kW methanol fuel cell in a 10 kWh battery Fiat 500, a 24 kWh battery Nissan eNV200 and of a 25 kW methanol fuel in an urban bus, claiming 800 km hybrid range for the cars and 500 km range for the bus prototype [135]. Two example applications were conducted in the marine sector in Europe: A touristic boat in Lake Baldeneysee, Essen, Germany was equipped with a 35 kW methanol fuel cell and a Viking line ferry boat was equipped with 90 kW methanol fuel cell to operate in the route Stockholm-Helsinki. In these examples, the increasing capacity of the cells were done linking modular 5 kW-fuel-cell-units. [135,136] At the Beijing Auto Show in 2018, Gumpert presented a methanol fuel electric supercar with a projected range of 1,200 km and maximum speed of 300 km h^{-1}[137].

The use of methanol in fuel cells concurs with the actual and already deployed hydrogen fuel cells. The main advantage of hydrogen utilization is the simpler and cheaper production process (normally water electrolysis), but as hydrogen is gaseous under ambient conditions, the costs related to the transport, tankage and fueling station adaptations are reported to be much higher than the adaptations required for methanol deployment, exceeding the benefits of production costs. As methanol is a simple molecule of alcohol, it can use the infrastructure of ethanol fuel without major modifications. The liquid state of methanol brings further benefits compared to hydrogen: Higher distance autonomy within the same volume of tankage, faster fueling as well as cheaper and safer logistic und transport. More information reviewing the methanol fuel cells can be found in Simon et al. [132], for marine utilization in Andersson et al. [71].

4 Part C | Prospects of commercialization of methanol as motor fuel

This chapter deals with the various potentials as well as challenges of methanol as a motor fuel. It consists of the corresponding recommendations from the five technical reports (Appendices I-V) and lessons learned studies.

4.1. Potential future engine developments

Methanol provides several advantageous properties as a fuel, such as high flame speed, high latent heat of vaporization, high hydrogen and oxygen versus carbon ratio as well as a lack of carbon-carbon bonds, that offers higher improved overall engine efficiency and reduced emissions of NO_X, soot and CO_2, compared to conventional fuels such as gasoline and diesel. The reduced emissions and high efficiency, but also methanol's ability for high power engine operation motivates the current use in as diverse applications as in shipping, motorsports and miniature model airplane engines. The use of methanol instead of gasoline is reported to reach peak efficiency increases in the order of 25% in spark ignited gasoline engines. Another 5 to 10% improvements seem relatively easy to be achievable with dedicated methanol engines, primarily through increased compression ratio and increased peak pressure capability. Novel combustion strategies using compression ignition of methanol, such as HCCI, PPC and MD95, show promising results with further gains in efficiency and reduction of emissions. [4]

All methanol combustion methods need to be further developed to reduce exhaust emissions and to increase engine efficiency. Especially, further potentials are seen in the optimization of

- Methanol combustion process (e.g. combustion geometry, compression ratio, supercharging),
- Fuel injection system (e.g. high pressure injection, flex fuel injection),
- Engine control (e.g. injection and ignition timing, cold start behaviour), and
- Exhaust gas after-treatment (e.g. catalyst, particulate filter, exhaust gas recirculation).

Blending methanol and ethanol into gasoline is a cost-effective solution and can also be relevant for partially electrified vehicles such as hybrid and range extended electric vehicles. By significantly increasing the mixing ratios permitted in SI-engines and optimizing the engines for such mixing, the higher octane content of alcohols could be fully used. Even if the use of alcohols in SI-engines is very mature, further improvements in efficiency could be achieved by optimizing the entire combustion process. In addition, more attention must be paid to currently unregulated emissions such as formaldehyde. [100]

4.2. Barriers of commercialization methanol as motor fuel

For significant global market shares in the transport sector, methanol has to fulfil different requirements such as functionality, scalability, affordability and sustainability. Covering the aspect of sustainability, which is currently – on one hand – the main motivator to replace fossil fuels, methanol can be produced and used in ways that offer very low environmental impact (*section 2.1.2*). On the other hand, the affordability of a fuel is the main motivator of fuel distributors and this means that methanol is in direct competition to other alternative fuels, some of which are already established. Partly, due to the simplicity of the methanol molecule, it can also be produced efficiently in several ways from a multitude of resources, which offers scalability and affordability (*section 2.1*). And compared to gaseous fuels like hydrogen and natural gas or biomethane (as CNG or LNG), the distribution of methanol can be more cost-efficient where sufficient gas grids are not available.

At present, methanol is primarily produced from natural gas and coal (global capacities about 125 million tonnes per year). Methanol from renewables is increasingly considered, however mostly on pilot and demonstration scale (global capacities below 1 million tonnes per year). In order to have an impact with regard to increasing renewable shares and thus also GHG mitigation in transport a strong increase of renewable methanol capacities is required above the existing examples (*section 2.1*).

Regarding functionality, methanol is an efficient engine fuel and offers strongly reduced particulate and NO_X engine-out emissions. This explains the early market penetration as a fuel for maritime applications, where expensive emissions after-treatment systems can be avoided. Functional barriers for short and medium term market penetration are:

- Fuel standards for neat methanol and various blends of methanol with other fuel components,
- Certification tests for the engine and vehicle manufacturers,
- Optimized and cost-efficient methanol engines and vehicles,
- Retrofit kits for existing vehicles a fuel infrastructure.

Fuel standards are needed to make sure that fuels that are produced and marketed fulfil the criteria agreed upon for use in engines according to defined testing methods. For example in Europe, the commonly used standard for gasoline is the EN 228 while diesel fuel can be marketed according to EN 590. Although EN 228 allows 3% methanol within the total allowed 10% oxygenates, there are no standards specifying neat methanol as fuel (M100) or blends containing higher fractions of methanol in Europe. With a few exceptions (e.g. China, Israel, USA and other regions, where the American ASTM fuel standards are approved), the global situation is comparable to Europe.

The certification tests are used to determine that an engine or vehicle fulfils all legislated requirements, for instance regarding emissions (e.g. in Europe according to Regulation (EU) 2018/858 [138] and Regulation (EU) 2019/631 [139]). Over the years, these tests have become increasingly extensive due to the increased number of factors and operating conditions that are examined and also due to the complexity of measuring the extremely low levels of emissions that modern engines emit. Such tests demand huge monetary resources from the engine manufacturers, and for obvious reasons challenges the opportunity to certify several fuels and powertrains.

From the above mentioned statements, it can be derived that for enabling the highest engine efficiencies on methanol, a dedicated engine design is required. As the initial market (international marine market, and Chinese market) currently is rather small (limited number of engines sold to those markets), it can be difficult for engine manufacturers to justify the investment in such methanol engines. Perhaps synergies and experiences to natural gas engine concepts (can be sought for those manufacturers that are considering the market introduction of natural gas engines (e.g. higher compression ratio) are helpful. The most important engine component that has to be, is the fuel injection equipment. Port fuel injectors are available for light and heavy-duty applications, but durability remains to be proven. For bigger engines (e.g. medium speed ship engines) and for direct injection systems, there are currently no commercially available fuel injectors for methanol. Otherwise, global regulations pushing automakers to improve the energy efficiency of internal combustion engines are encouraging the renewed interest in methanol as a fuel.

For the introduction of cars that supports higher percentage of methanol, the required modifications are similar to the needed by ethanol vehicles. The first matter is related to the vapour pressure, which decreases as the mixing in gasoline increases. A sufficient cold start system is needed for higher mixtures. There are some approaches commercially available and utilized for ethanol, being examples the coupling of a small gasoline tank to supply the initial spark and electric heating during the fuel injection, which can be adjusted to heat the fuel only when it is needed. Some options were studied but not commercially applied, for example the electric heating of the tankage to provide warmer fuel during injection [49,113]. Methanol has a significantly lower heating value (16 MJ l^{-1}) than gasoline (32 MJ l^{-1}) and this characteristic can be overcome either with frequent fuelling or bigger tanks. This barrier interacts different with the mode of utilization, as for long distance transportation frequent fueling is not always possible. Regarding the necessity of higher volume of methanol to reach the same energy input for the vehicle, the fuel system should be adapted. As the compression rate is altered, above M85 methanol mixtures engine modifications are needed. If the objective is to establish flex fuel methanol vehicles, a lambda oxygen sensor needs to be installed to determine the air-fuel ratio for every possible mixture of methanol and gasoline, calibrated by software and the electronic control unit (ECU), which have to be updated to this application [5,45]. It is related concerns about negative effects of the alcohol usage in some vehicle components, and for methanol usage the following modifications should be planned: Motor valves, motor fuel supply system fuel pump and exhaust system built to resist corrosion from gasoline and methanol. As methanol may be also implemented in a water mixture, the exhaust system have to be designed to support higher volumes of water. The catalytic converter has to be adjusted for off-gas from methanol usage and the fuel filter porosity has also to be adjusted for this implementation [45].

From an end user's point of view, the lack of available methanol vehicles and the fuel distribution infrastructure itself are an obstacle to be grappling with. This is already known for other, far more well-established techniques, such as CNG or E85 vehicles.

Info box 3

Case study Denmark | M85 demonstration project and distribution plan [5]

The Danish Technological Institute (DTI) and Danish methanol stakeholder plan a nationwide demonstration project based on the identified technologies and barriers. Inspiration is taken from past successful projects such as Biodiesel Danmark and B5NEXT which have had real impact on the national fuel strategy.

With the well-proven test of a M85 test car, the pilot project needs to plan a fleet trial for the coming year. Also, for M85, the infrastructure is more or less in place. A fleet trial, however, will identify any shortcomings and how to remedy. The trial will show people and not least the government that we have enough renewable energy from wind and biomass to produce methanol for transport – if only the barriers are removed.

At one and the same time a maximum number of car brands are tested, and their numbers are set to minimize measurement uncertainties. These numbers are determined by statistical assessment of previous trials. The scope is narrowed as required by financial resources. A long-term fleet trial is preferably conducted with over 100 cars and for at least one year.

Since the 92-octane gasoline was removed from the market in Denmark, there are extra pumps available which can be used for M85 fuel. In workplaces 330 l portable tanks with 12 V pumps and dispenser can provide additional access for refueling. 50 – 100 l portable trolleys provide convenient loading on construction sites. The mixing and distribution of M85 is left to the refinery as the immediate best solution. Alternatively, mixing can take place in the road tanker serving the filling stations.

The Federation of Danish Motorists and oil companies are supposed to assist identifying interested participants. Applications are also made to municipalities and companies that previously have shown green initiatives. Non-FFVs are fitted with a Flex Fuel Kit, which will be removed after the end of the test. The kit used in the test car was purchased in France. Other kits are tested including a Chinese kit specifically designed for methanol. Car manufacturers are requested to assist in specifying the cars that can use the 105 octane M85 with the least possible changes and which may advantageously install a Flex Fuel Kit. An engine examination is performed before and after testing. One Dyno metering for each car on E5 and M85 is part of the examination. DTI cooperates with workshops with equipment and interest in following and documenting the test. For each participant, insurance against machine damage attributable to the fuel is written.

There are very few Real Driving Emission (RDE) measurements of vehicles and their efficiency - including electric cars. Inspired by the so-called Diesel Gate Scam, a standard test under real-life conditions has been developed. Therefore, an RDE measurement of comparable cars on electricity and M85 is performed - for example a VW UP in electric and M85 version. This will give the government a qualified basis for environmental policy in this area. Results from the trial fleet will contribute further to this decision basis.

The Fleet trial with 100 cars á 25,000 km a year will require 31,800 l of E5 gasoline and 1.2 GWh of biogas for making biomethanol (212,000 l).

DTI and partners have suggested a complete distribution plan for methanol fuel in Denmark. The main resource for the methanol will be Danish Biogas. Danish biogas is produced and purified locally and injected into the European gas grid as biomethane. Certificates are then transferred to a methanol factory, also connected to the European gas grid, and the methanol is returned to Denmark by ship. This part of the process is already in place.

Methanol shipments are currently coming from Tjelbergodden in Norway via Aarhus Port but should in the future be landed directly at the Shell Marine Terminal in

Fredericia, which is connected by pipelines to the refinery. The refinery will then handle the blending and final quality assurance. The eastern part of the country can be serviced through the refinery in Kalundborg. Smaller oil companies do not currently have storage suitable for methanol and should therefore leave this to refineries. Because of the non-corrosive properties of methanol, mixing with gasoline at the refinery is a good option. This may of course change in the very long term, when gasoline is no longer used.

The main product shall be M85, which is adjusted between 70 and 85 vol% methanol to account for seasonal changes in Denmark. A7 may be produced in parallel using ethanol-methanol blended at the refineries or imported ready to use, which may replace conventional E5 gasoline.

For local distribution of methanol or methanol blends there are two possible strategies. The preferred one is to use the existing 92-octane infrastructure so that the refinery simply delivers a methanol blend instead of the previous 92-octane gasoline. The blend is then transported with road tankers as it is done today. The changes would be minimal apart from non-resistant sealing, which will have to be replaced. Another strategy is to introduce blender pumps, which blend the methanol and gasoline in any ratio. This enables both A7, M30, M85 and M100 at the same dispenser. It should be left to the local gas companies to decide whether they want readymade blends or use blender pumps.

4.3. Recommendation and outlook

The recommendations for a long-term introduction of methanol as a motor fuel includes the removing of the barriers mentioned in *section 4.2* and comprise four levels:

- Strategic level (stakeholder and roadmap)
- Regulatory level (legislative, standards and technical instructions)
- Technical level (removing technical barriers, fuel and vehicle availability)
- Communicative level (visibility and demonstration projects)

The introduction of methanol as alternative fuel in the transport sector is clearly expandable compared to others like CNG and LNG. The engine technology itself is available and consumers of individual fields of application (especially fleet operators in shipping and heavy duty segment) show interest. Regarding the urgency to reduce GHG emissions especially in transport, increasing shares on sustainable renewable fuels are essential; renewable methanol could be a part of this. Nevertheless, methanol cannot develop its full potential as motor fuel due to the ongoing challenging obstacles in the different local markets of the fuel industry and the transport sector. It is therefore important to clarify how the stagnation can be overcome and the potential released. Experience with the introduction of other renewable fuels can be helpful. Among other things, IEA AMF Annex 59 deals with this in a lesson learned study [140] and Info box 3 shows an example for Denmark.

First of all, the identification of interested stakeholder is most important. When fuels are introduced, these are usually vehicle and engine manufacturers, fuel producers and suppliers, filling station operators, political decisions-maker and transport mode owners. Former experiences with implementing new fuels had shown that, in the early phases, coordination and information provision from market players were the main barriers. The likelihood of an undesirable development due to a lack of coordination (so called chicken or egg dilemma) is high, if the development in one market (availability of methanol vehicles and engines) depends on developments in another market (methanol fuel market and especially the development on renewable methanol production capacities). Potential methanol filling station investors are reluctant to release funds until fleet operators and shipping companies have invested in methanol-compatible applications. At the same time, fleet operators expect an attractive methanol filling station network for an investment decision.

In order to solve this chicken and egg dilemma, it is crucial to pursue a corresponding strategy and to focus on potential early adopters. With the help of multi-stakeholder platforms, problems that exist for or between stakeholders along the overall value chain can be identified more quickly and the knowledge and data base for companies and political decision-makers is being expanded. Especially in early market phases, which are characterized by weak price signals and long amortization periods, such platforms can reduce the risk of the companies involved by building trust between the stakeholders. A cross-border strategy platform would facilitate the definition of common goals and their implementation in a roadmap and could reduce supply and demand uncertainties along the value chain. Incomplete information on technical or financial developments make suppliers and consumers hesitate. In view of the necessary financial and operational investments, even early adopters prefer a longer-term planning period. Clear political guidelines would be necessary here.

The development of the market for methanol engines is highly dependent on legislation. Usually, current legislative of the transport sector focus on tailpipe CO_2 and pollutant emissions and do not consider the impact of the overall life cycle for powertrains (product's manufacture, distribution and use, recycling and final disposal) or the motor fuel itself. This legislation is reflected in the strategies of the automotive and engine industry that needs to comply with the regulations and business logic, with a high emphasis on developing and marketing electric vehicles and very limited activities on renewable fuels and engines adapted for those. However, the ambitious goals to reach renewable and GHG reduced transportation due to the sustainable development goals (SDGs) of the United Nations within the coming decades [141] calls for a holistic approach and legislation that is based on a Well-to-Wheel (WTW) approach of the different transport modes including the specific powertrains and relevant infrastructure. In addition, the legal framework, standards, certification tests and technical instructions for the use of methanol (blends) in the transport sector must be initiated.

Early large scale use of methanol in transport could be the blend wall of methanol for gasoline standards (e.g. 3 vol% in European gasoline standard EN 228) for use in regular gasoline engines. Considering the similarity between methanol and ethanol (see GEM above) high ratio 56 vol% drop-in of methanol in gasoline could be an attractive way to increase the use of methanol for future vehicles certified for both E85 and M56. M100 (100% methanol) is already used and is likely to grow with captive fleets using dedicated methanol engines, dual-fuel engines or the proposed flex-fuel engines discussed earlier. These are applications within shipping, heavy-duty trucks and non-road machinery, where synergies in the engine design are obviously. As methanol engine technology matures and renewable methanol production picks up there is potential for an increased number of applications using engines running on up to 100 vol% methanol. Many of these will be integrated in hybrid applications running large shares of operation on renewable electricity coproduced with renewable methanol.

In order to launch methanol (blends) on the fuel market, remaining technical barriers have to be removed and benefits of renewable methanol in terms of GHG mitigation have to be well-promoted. For that, capacities of renewable methanol have to be massively increased in the short term in a competitive manner compared to other renewable fuels with significant market shares today (e.g. bioethanol, biodiesel, HVO). In addition, new sales markets for renewable methanol outside of the fuel market, for instance as renewable chemicals, have to be explored in order to further increase demand and attract investors. On the engine side, the further development of methanol engines with increased efficiency in terms of fuel consumption and exhaust gas emissions, as well as the offer of certified retrofitting systems, is expedient.

In all of the above, the interests of the end user must be taken into account in the decision and implementation. The focus is much more on the cost, safety and durability of the vehicles. In order to reduce corresponding concerns, the communication and the supply of information between the marketers and the user is decisive. Here, increasing the visibility of methanol as a motor fuel in demonstration projects and practical workshops can be a useful measure, but also other means such as internet platforms for methanol (e.g. well-known for instance from CNG vehicles) may be also helpful and could be designed based on good practice examples (cf. IEA Bioenergy activities, IEA AMF TCP, ETIP Bioenergy SABS Platform etc.). A continued effort is needed to convince decision makers, vehicle and engine suppliers and the general public that methanol fuel is as safe and practical as gasoline.

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