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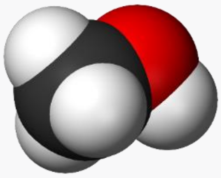

IEA-AMF Annex 56

Methanol as motor fuel

“ – CO_2 emission was reduced to just 40 g/km.

M85 has ideal properties for both summer and winter in Denmark.

Title:
Methanol as motor fuel

Prepared for:
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1. Executive summary

Methanol as motor fuel has regained interest in recent year due to its low price, easy handling and high octane number. Methanol can nowadays be produced from biogas which yields an extremely low Greenhouse Gas emission – easily comparable to those of electric vehicles. According to the latest EU-Renewable Energy Directive, with biogas, it is possible to reach even negative CO_2-eqivalent emissions!

Efforts to establish large methanol factory in Denmark with connection to the Danish gas grid are ongoing. Until that happens methanol can easily be imported from Norway. Certificate trading ensures that the methanol is based on Danish biogas.

Methanol is not yet implemented in the Danish transport sector. The current exchange agreement between the fuel companies only allows ethanol to be added to gasoline. However, this barrier can be removed, and 3% methanol be introduced in a new A7 (A for alcohol with 3% methanol and 4% ethanol). A7 can easily and advantageously replace E5 as the current standard gasoline.

In the long term, however, completely new fuels are required. The Danish participants in the project "IEA-AMF Annex 56 Methanol as Motor Fuel" have therefore tested a 105 Octane M85 fuel consisting of 85% methanol and 15% petrol. The pilot car, a Peugeot 107, got a € 100 flex fuel kit installed and its engine performance on 105 Octane M85 went up by 5-7% with all emissions kept in place.

The report finds that methanol can be introduced into the current gasoline infrastructure with very little investment and with no loss of tax revenues. A complete distribution setup is described in the report.

Technical or legislative barriers that need attention are also described in the report.

2. Introduction

The Shanxi province has since 2008 had local methanol gasoline standards for M5, M15, M85 and M100. In 2014 the consumption in China of methanol blends with gasoline grew to 7 million tons[1].

The strategy of The European Commission Climate Action is among other things to promote the use of advanced biofuels like 2G-biomethanol. Transport represents almost a quarter of Europe's greenhouse gas emissions and is the main cause of air pollution in cities. The transport sector has not seen the same gradual decline in CO_2-emissions as other sectors. Within this sector, road transport is by far the biggest emitter accounting for more than 70 % of all GHG emissions from transport in 2014[2].

Danish Technological Institute and Danish Methanol Association[3] have jointly applied for EUDP support for this preliminary project to pave the way for the use of methanol in the transport sector. July 2, 2018 The Danish Energy Agency announced its support for the project.

The project is part of IEA-Advanced Motor Fuels Annex 56 "Methanol as Motor Fuel" led by the Israeli operating agent, Technion. This report includes the Danish part and focuses on bringing methanol to the short-term market, by overcoming distribution and application barriers.

The report covers the following working packages:

- WP1: Study of barriers to methanol
- WP2: Engine testing with methanol high blends
- WP3: Outline for a National demonstration project
- WP4: Communication and dissemination effort

[1] http://www.methanol.org/wp-content/uploads/2016/06/China-Methanol-Fact-Sheet-1.pdf
[2] https://ec.europa.eu/clima/policies/transport_en
[3] http://danskbiomethanol.dk/profile/home.html

3. Vehicle experiments

The purpose of the vehicle experiments was to see if a standard gasoline car would be able to run on methanol.

Figure 1 Test vehicle equipped with measurement system

3.1. Test setup

The test is focused on engine performance, fuel economy, emissions, noise and drivability.

First the vehicle was tested on standard E5 gasoline. The maximum engine power and torque was measured on a chassis dyno. Then emissions and fuel consumption were measured according to World Light-duty Test Protocol (WLTP) and Real Driving Emission (RDE). Finally, a sample of the engine oil was taken.

The vehicle was then fueled successively with methanol blended gasoline gradually raised in ratio from $15\%_{vol}$ to $100\%_{vol}$ - M15, M25, M50, M65, M75, M85 and M100.

The test vehicle was a Peugeot 107 1.0 68hk from 2008. It has a Toyota/Daihatsu 1KR-FE 998cm^3 3-cylinder spark ignition engine with a nominal output of 50 kW. The engine is known from other vehicles such as Toyota Aygo and Citroën C1.

The engine has a cable drawn intake air throttle, a variable valve timing system, knock sensor, crank angle sensor, manifold air pressure sensor and an oxygen sensor. Compression ratio is 10.5:1 which is normal for a naturally aspirated gasoline engine.

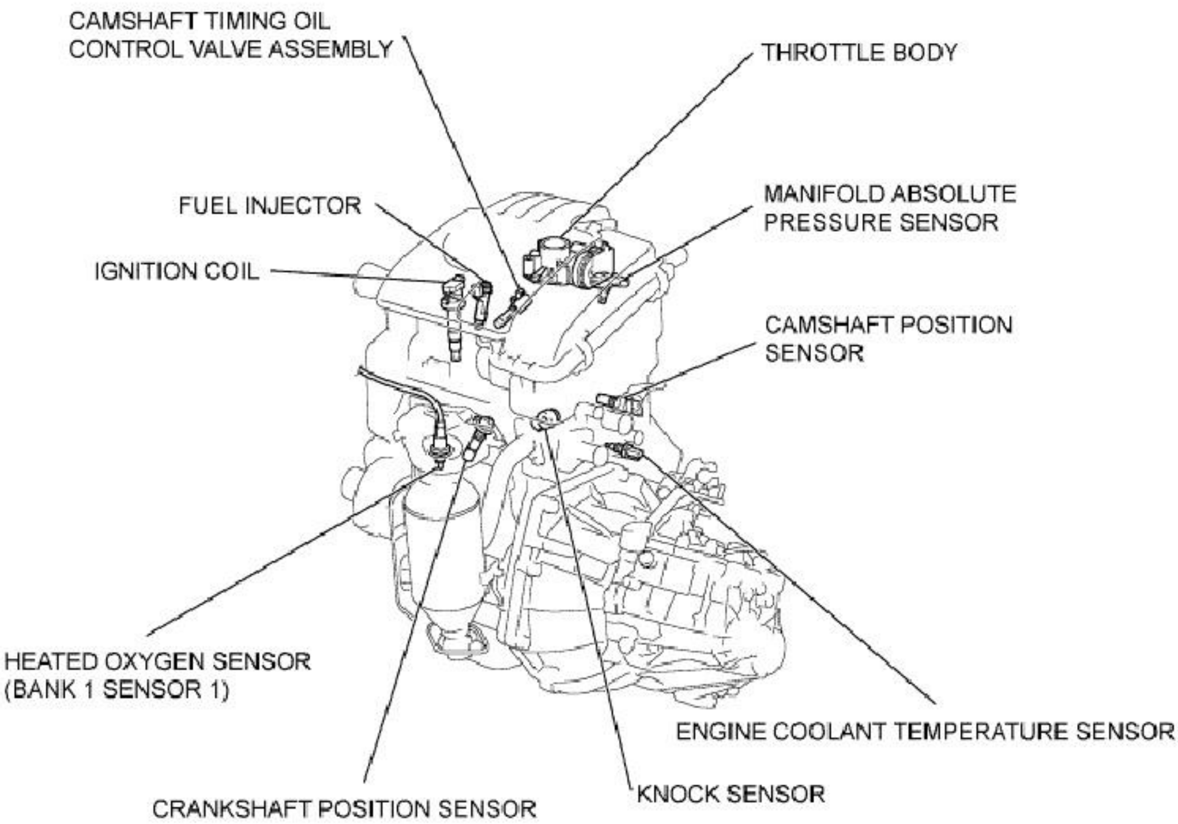

Figure 2 Main fuel related components on the 1KR-FE engine.

For the test run Sunoco Racing Methanol has been used. The product complies with the IMPCA METHANOL REFERENCE SPECIFICATIONS.

For the test run 15 vol% 95-octane E5 gasoline has been used. The product complies with the CEN-standard EN228.

For the test run 1 ‰ Redline SI Alcohol has been used. SI-Alcohol is a new additive for alcohol fuels (E85, ethanol and methanol) designed for daily use for so-called FlexiFuel or BioPower engines as well as for Rally / Racing.

3.2. Engine control unit and fuel system

The fueling system is an electronically controlled multi-point port injection system with 3 injectors.

It is important to use the right type of connector. The connector type for this vehicle is 'New Toyota' (Type F in Figure 3).

Figure 3 Fuel rail with 3 injectors (left) - Different types of connectors (right)

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 Diagnostic Trouble Code (DTC) which will cause a failure at the vehicle inspection. See Figure 4.

Unofficial reports from French motorists talk about more than 20 000 km of driving with E85 on this engine. However, DTC's are observed after 200 km.

Figure 4 Max acceleration uphill can cause error. "P0171 System Too Lean Bank 1" and "P0130 O2 Sensor Circuit Bank 1 Sensor1". The errors turn on "Check Engine" light. The diagnostic trouble codes can be cleared with an OBD2 dongle.

The initial work on the test vehicle in this project 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 DTC warning lamp came on after few hours of operation. Even worse, the NOx 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 overcome these initial difficulties a flex-fuel conversion kit from Artline International SARL in Lyon, France was installed on the car. See Figure 5. The kit, which is designed for E85, works by prolonging the fuel injection pulses thus increasing the amount of fuel delivered.

Upon installation of the 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.

Figure 5 ETHANOL FLEX E85® Ethanol Conversion Kit. Fully Automatic Digital 3-Cylinders E85 Ethanol Conversion Kit with Cold Start Assist. Made in France.

3.3. Results

In general, the car performed well on M85. In cold weather, the engine starts willingly, but should be kept up for 30 seconds before idling.

3.3.1. Engine power

The highest engine power was reached with M85 and the Flex Fuel Kit installed (M85C).

Table 1 Engine power and torque of Peugeot 107 with gasoline and methanol blends

	Max torque [Nm]	at RPM	Max power [kW]	at RPM
Gasoline E5	97.3	3450	50.3	5900
M15	97.9	3650	52.3	5900
M25	97.8	3600	51.5	6000
M50	97.3	3550	50.8	5950
M65	97.1	3700	51.3	6000
M75	96.8	3650	51.8	5950
M85	97.7	3500	51.8	5850
M85C	102.3	3550	53.4	5800
M100	97.7	3650	52.5	5950

The power and torque curves (Figure 6 and Figure 7) revealed a slight problem with the engine's variable valve timing system when running om M100. The system is set to kick in at 3500 RPM and normally this cannot be felt or seen in the curves. However, on M65, M75 and M100, the engine clearly didn't perform right below 3500 RPM and the VVT kick-in was noticeable.

A much smoother power delivery was found on M85. The results turned even better when the Flex Fuel Kit was later installed (M85C).

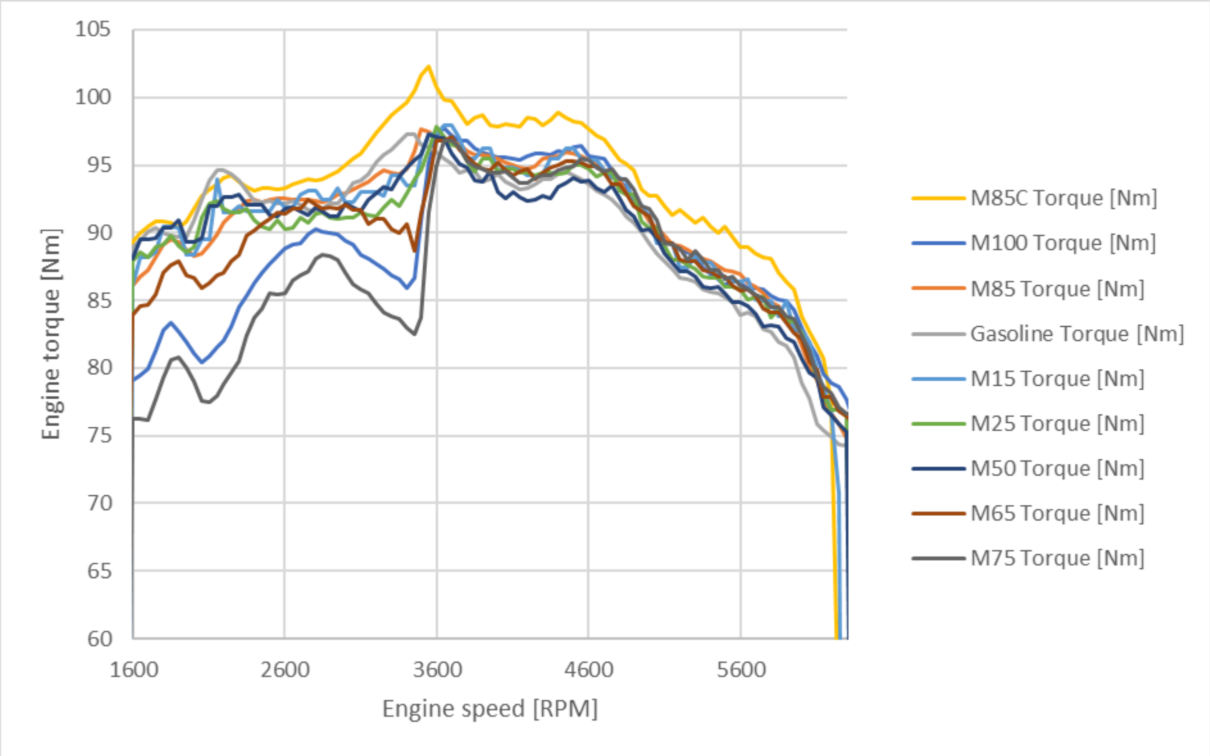

Figure 6 Torque curve showing VVT kick-in on M65, M75 and M100 at 3500 RPM

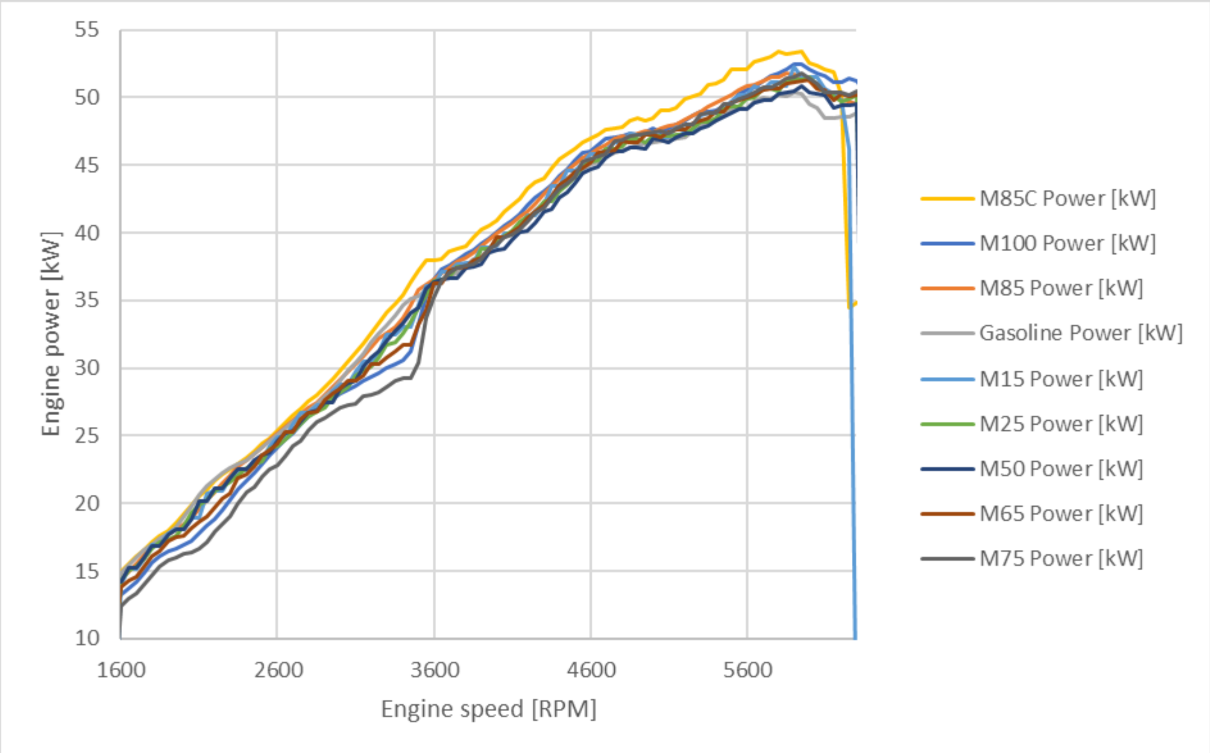

Figure 7 Power curve showing best overall result for M85C (Flex Fuel Kit installed)

Overall, a 5% increase in engine power and 7% increase in engine torque was reached. This is a very satisfying result.

3.3.2. Fuel consumption

Comparison of the fuels were based on energy content. The difference between E5 and M85 is in the range of ±3 % to either side. Due to the lower calorific value of M85 the consumption is off course higher on a km/l basis. In real driving (RDE) we achieved 11.8 km/l on M85 and 19.8 km/l on E5. Measured energy consumption on dynamometer (WLTP) and real driving (RDE) are seen in Figure 8. The benefit of M85 on the dynamometer could not be replicated on the road, possibly due to temperature differences.

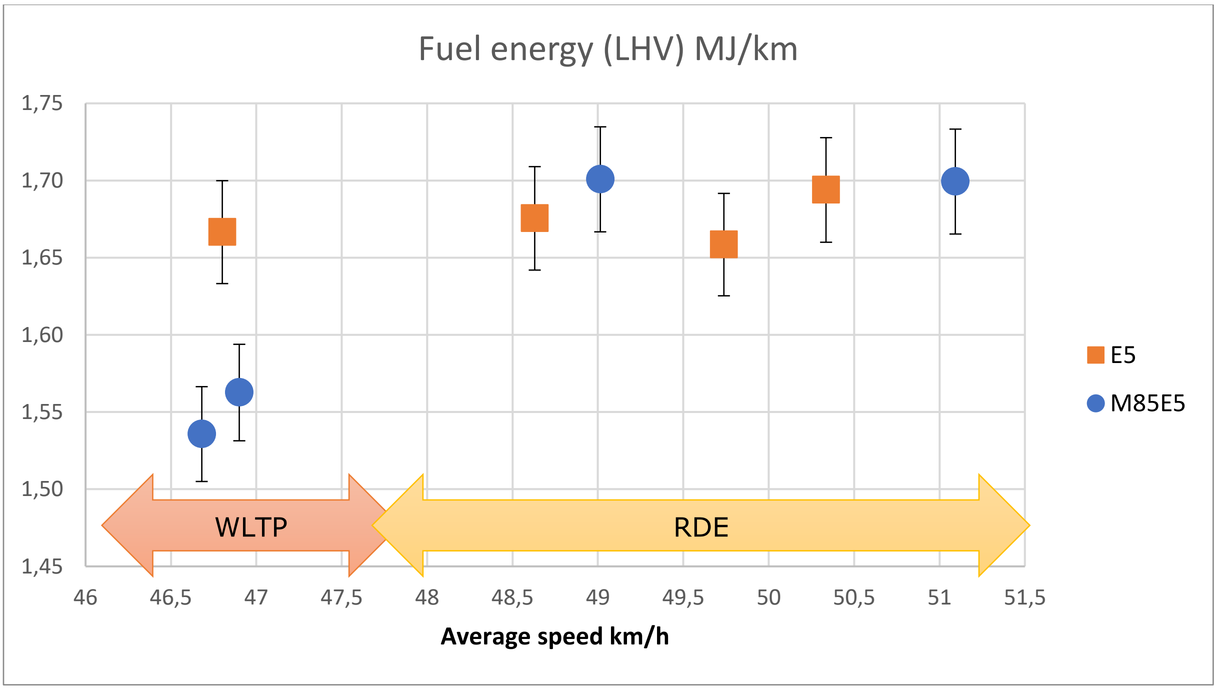

Figure 8 Fuel energy per distance driven is almost the same on E5 and M85

3.3.3. Noise

It was immediately noticed by the test crew that the engine sound seemed smoother on M85. This can be explained by the fact that methanol burns more uniformly than gasoline due to its homogeneity and high octane number.

To investigate this, without scientific equipment available, two identical cars were placed front-to-front with their engines running (Figure 9). The difference between the E5 gasoline-fueled and the M85 car was clearly audible. Gasoline creates much more irregular combustion noise than M85.

Figure 9 Sound test on two identical cars, one with gasoline (left) and one with E85 (right)

A video was captured which demonstrates clearly the difference in engine noise (Motorlyd benzin vs metanol.MOV).

3.3.4. Emissions

While running the car without the Flex Fuel Kit it was noticed that NOx emissions were too high as mentioned in Section 3.2. This shown in the table below.

Table 2 NOx emission is reduced significantly with Flex-fuel kit

Route	Fuel	Motor	Tail pipe CO_2 g/km	c	Hn	km/h	MJ/km	CO g/km	NO_x g/km
RDE Aarhus	M85	Standard.	118,1	0,4428	23,244	51,1	1,69	0,14	2,02
RDE Aarhus	M85	Flex Fuel	118,2	0,4428	23,244	49,0	1,69	0,44	0,63
WLTP Dyno	M85	Flex Fuel	108,6	0,4428	23,244	46,9	1,55	0,32	0,55
WLTP Dyno	M85	Standard	106,7	0,4428	23,244	46,7	1,53	0,12	1,51

The table values correspond to the **blue dots** on the following diagrams (Figure 10, Figure 11 and Figure 12). The **orange dots** are gasoline for comparison.

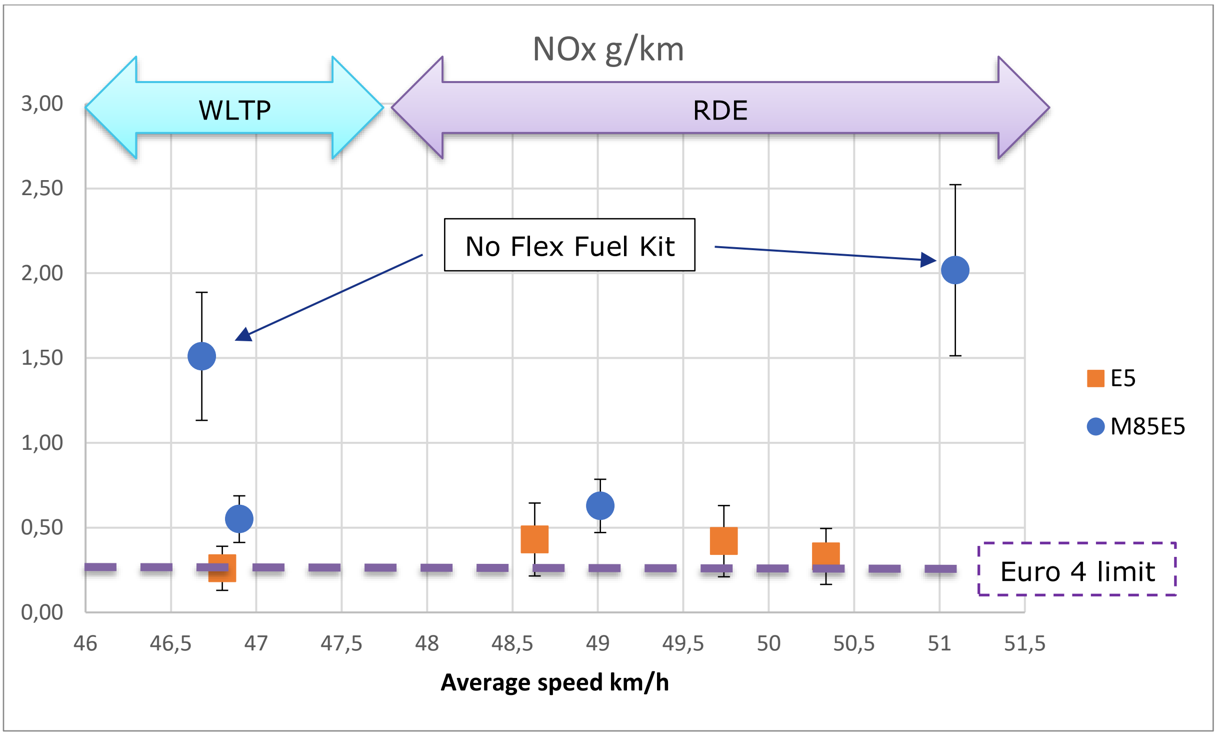

Figure 10 The two highest NOx values are without Flex-fuel Kit

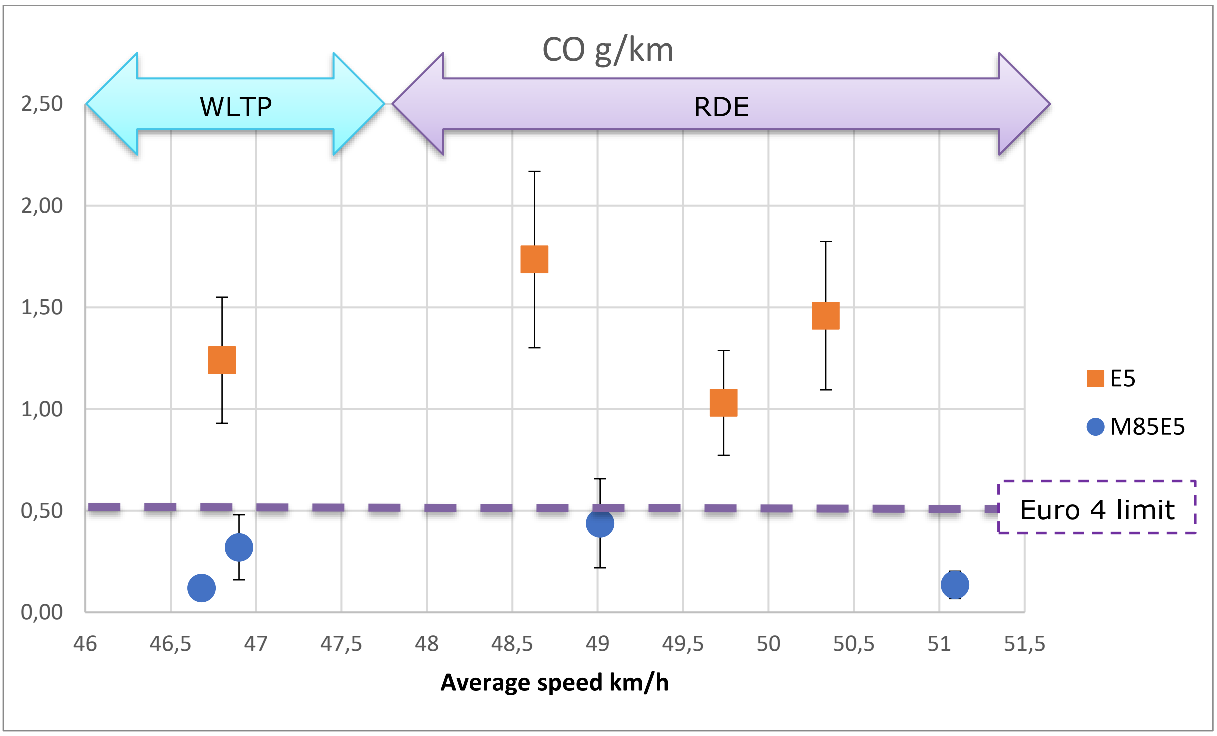

Figure 11 CO emissions are overall much lower with M85

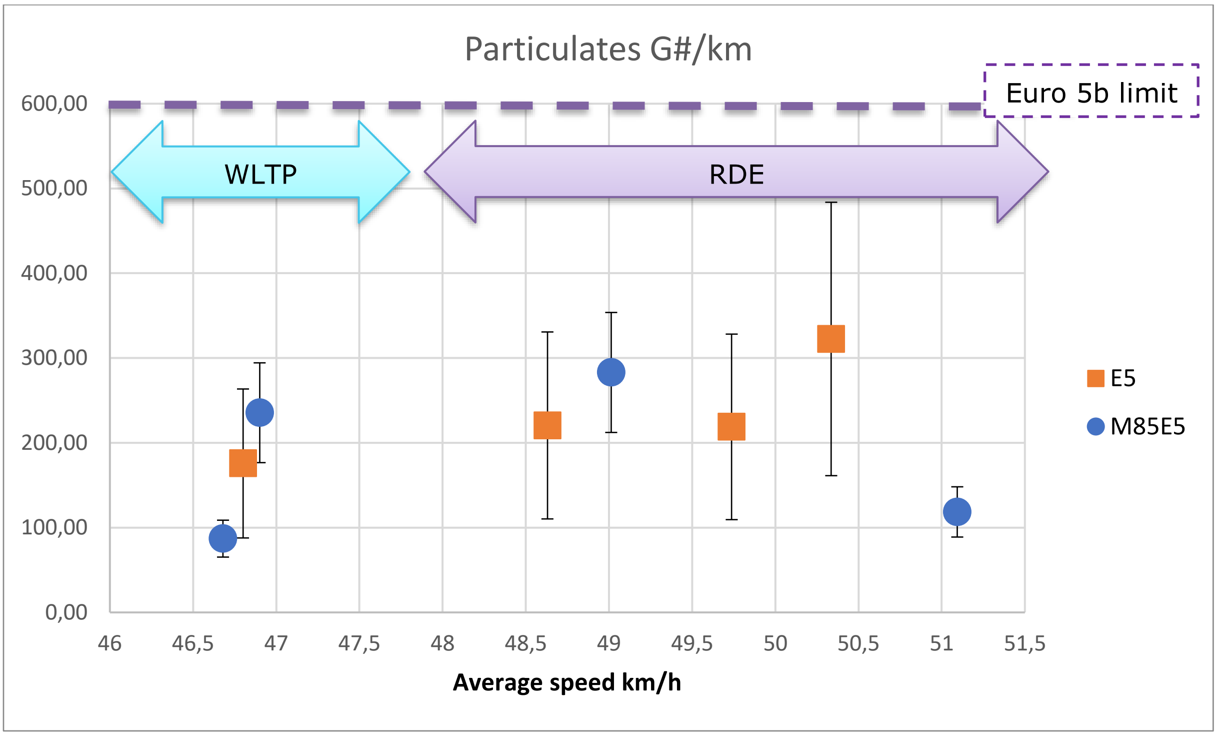

Figure 12 Particle emissions with E5 and M85 are similar

Overall the emissions were quite acceptable after the Flex Fuel Kit was installed. CO decreased a lot compared to gasoline while NOx increased a little bit. The vehicle exceeds some Euro emission limits by a factor 2-3. However, that is perfectly normal for a 10-year-old car and even for new cars.

3.4. Summary of vehicle performance and emissions

Real Driving Emission (RDE) was measured using mobile equipment (PEMS) under realistic conditions. Power and torque are measured on rolling road Dyno:

Table 3 Summary of performance with M85 compared to gasoline on Peugeot 107

Fuel type	95 Octane Petrol	105 Octane M85
Air-Fuel Ratio	14,0:1	7,6:1
Fuel energy MJ/l	32,2	18,2
Performance		
Max. power	68 hk	73 hk
Max. torque	97 Nm	102 Nm
MJ/km	1,63	1,62
km/l	19,8	11,8
Car efficiency	15%	15%
Engine efficiency	25%	25%
Emissions		
CO2, g/km	118	118
CO, g/km	1,4	0,4
NOx, g/km	0,4	0,6
Pn, G#/km	234	259

3.5. Engine oil

The initial engine oil sample showed an elevated gasoline content which is the result of driving too many short trips. After some weeks of testing with M85 the engine oil was in better shape, primarily because the vehicle had been used more frequently and for longer trips.

There were no signs of unusual wear. The vehicle has covered 2400 km in 4 months on M85.

Anbefaling
Olien er klar til fortsat brug.

PRØVESTATUS

NORMALT

Har du spørgsmål til analysen bedes den kontakte OK på 70121201 eller din lokale distrikschef.

Prøve Nummer		1 **	2
Analysedato		10-09-18	16-11-18
Prøven Udtaget Dato		04-09-18	09-11-18
Rapport Reference		OK27013	OK27344
Maskinens Driftstid		51265	52802
Oliens Driftstid		1442	2979
Olie Efterfyldt		-	-
Label Nummer		031042	032003
Fysiske Tilstand			
Viskositet på 40°C	cSt	54 *	58
Viskositet på 100°C	cSt	9.8	10.2
Viskositetsindeks		169	165
Flammepunkt	deg. C	110+	130+
Brændstofindhold	% wt	3.5 **	<2.0
Vand	% wt	<0.05	0.0743

Figure 13 Oil samples from the test vehicle showed improvement after driving on M85

3.6. IEA work

This report is part of IEA-Advanced Motor Fuels Annex 56, which can be found on http://iea-amf.org.

The active contributors to the annex are Denmark, Finland, Germany, Israel, Sweden and India. Also, China and Canada have supplied useful information.

Israel reported a successful long-term trial of M15 with Fiat vehicles. From China, where methanol is widely used, a M85 fuel standard was received. Canada reported tests on M56 with direct injected engines in IEA-AMF Annex 54 "GDI engines and alcohol fuels".

A collated report from AMF will be available by March 2020.

4. Barriers to methanol

Important barriers are illustrated by the following parliamentary question and answer induced by Danish Methanol Association:

Parliamentary question 14 February 2012:

(1) Will the Commission explain why there is a limit of 3 % for methanol in fuels in the Fuel Directive?

(2) Can the Commission also say if it is considering giving it the same treatment as ethanol and raising the 3 % limit for methanol in fuels?

Answer 28 March 2012 given by Ms. Hedegaard on behalf of the Commission:

The methanol content of fuel is set at 3 % by the Fuel Quality Directive 98/70/EC. Its use was addressed in the impact assessment associated with the 2009 revision of the directive.

If added in a higher percentage, methanol could have damaging effects on vehicles engines. It would also therefore have a negative effect on vehicle warranties, drivability and durability, and have implications for the emissions of such vehicles. Furthermore, adding methanol to petrol raises its vapor pressure which could give rise to air quality problems. Finally, the energy content of methanol is about half that of petrol making it a less efficient fuel additive than ethanol which has about two-thirds the energy content of petrol.

The Commission is therefore not considering revising this limit.

The following sections of the report deals with these concerns and other barriers to methanol.

4.1. Corrosion

As mentioned in Commissioner Connie Hedegaard's reply to Parliament, methanol could have damaging effects on vehicles engines. It would also therefore have a negative effect on vehicle warranties, drivability and durability, and have implications for the emissions of such vehicles.

With reference to countries where methanol is widespread as motor fuel, such as China, and to our own investigations, shown in Chapter 3, the Commissioner's concerns seem to be exaggerated. Additives – like E.M.SH Ng-Tech Super Heavy-Duty Anti-Corrosion & Lubricant Additive – will help keep gasoline engines at work on Methanol/Gasoline Blends. Same with Beraid® 3555M from AkzoNobel.

Alcohol is considered very dry without lubricating properties. Therefore, a lubricant is supplied in a quantity recommended by the lubricant manufacturer.

ASTM D5797 – 17 places demand on the used gasoline blendstock and also mentions "*that unprotected aluminum and an unlined nitrile rubber dispensing hose should be avoided in methanol fuel blend distribution and dispensing systems*". GB/T 23799-2009 – Chinese

M85 Specification - mentions more specifically that "*an effective metallic corrosion depressor and motor gasoline detergent meeting the requirements of GB 19592 should be added*".

On 2010 International Conference on Advances in Energy Engineering a test was reported "*Metal corrosion by methanol and methanol-gasoline has become a key problem for methanol as one of substitute fuels. Many kinds of metal samples were dipped in methanol and methanol-gasoline. No obvious corrosion happened with the samples in pure methanol and M85, but the copper sample in M15 was obviously corroded.*"

Corrosion inhibitors (e.g. a combination of cyclohexyldimethylamine, xylene, and ethylbenzene) are widely used in E85.

Innospec Inc. offers as part of their corrosion inhibitors range:

- **DCI-11** for fuel alcohols and a Treat Rate (TR) equivalent to 6-12 mg/l in finished fuels – typical 9 mg/l.
- **DCI-11 Plus** for alcohol fuel blends with TR of 30-86 mg/l blend. Both are registered by EPA as gasoline additives.
- **Biostable E85 G-Plus** – an all in one - containing a lubricant and a TR of 350 mg/l. The product is not registered by EPA, literature is scarce, and the lubricant may be overkill in our Recipe.

Eco-Energy, LLC and Gevo Inc. specify TR min 10 PTB DCi-11 Plus; LINCOLNWAY ENERGY, LLC, NORTH PIPELINE and Magellan Midstream Partners specify min. 6 PTB DCi-11 Plus. 1 PTB (Pounds per thousand Barrels) =2.853 mg/l. A few mention as alternative vendors: Ashland, G E Betz, Midcontinental, Nalco, Petrolite, and US Water Services.

The answer to this problem is that long-term demonstration is needed to convince Europeans that methanol is not harmful to engines. As for warranties this is handled in Chapter 8 of this report.

4.2. Vapor pressure

As mentioned in Commissioner Connie Hedegaard's reply to Parliament, vapor pressure is a serious objection.

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.

The vapor pressure of gasoline shall comply with the European Standard EN228. This standard has several ranges for vapor pressure depending on the climate in which the gasoline is used. The exchange agreement in Denmark specifies the following ranges for blended E5:

- Summer **45-70 kPa**
- Spring/fall **45-95 kPa**
- Winter **65-95 kPa**

For Danish raw gasoline, known as BOB (Blendstock for Oxygenate Blending) without ethanol, the ranges are:

- Summer **40-63 kPa**
- Spring/Fall **40-88 kPa**
- Winter **60-88 kPa**

For Chinese and Israeli standards, see section 9.4.

The raw gasoline, BOB, is designed such that when blended with 5% ethanol the vapor pressure matches the requirements of E5. Thus, ethanol increases the vapor pressure.

Methanol lowers the vapor pressure when added in percentages above 82%. This means that M85 will have a lower vapor pressure than the base gasoline.

Should a higher vapor pressure be required then a blend between 70-82% methanol will ensure that.

At 82% methanol the vapor pressure is equal to the base gasoline. See Figure 14.

Unblended methanol M100 has a vapor pressure of only 32 kPa. This is much too low for use in the winter and even too low for Danish summer. This fuel is therefore not desirable for vehicles with indirect injection (port injection). Vehicles with direct injection are on the market but have not yet been tested in this project.

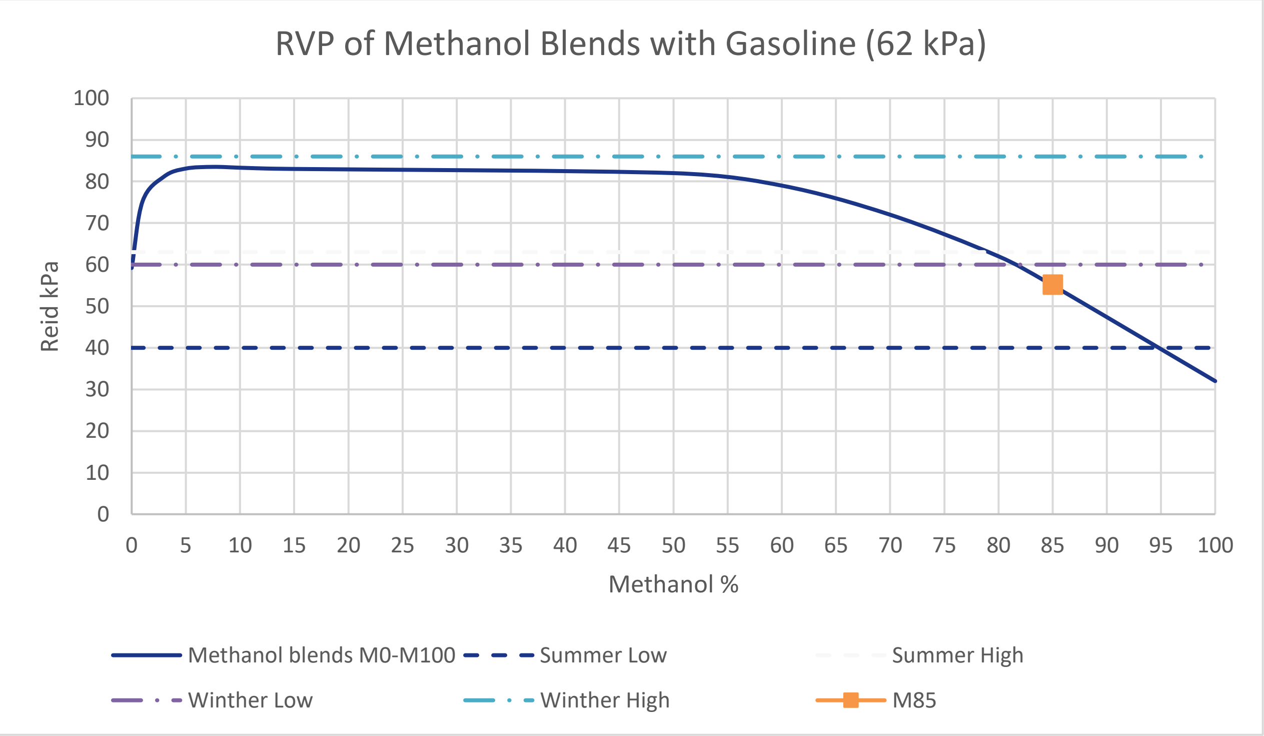

Figure 14. Combined data for vapor pressure of methanol-gasoline blends. Data Source Methanol Institute for M0-M15; ASTM D5797-17 for M51-M85. Interval between M15 and M51 is unknown.

ASTM D5797-17 tells the relationship between vapor pressure in a base gasoline, BOB, and the corresponding M85 blend.

$y = 0{,}4357x + 4{,}0834$, where

- y=Vapor pressure [psi] of M85
- x=Vapor pressure [psi] of BOB.
- 1 kPa = 0.145037738 psi.

This is shown in Figure 15.

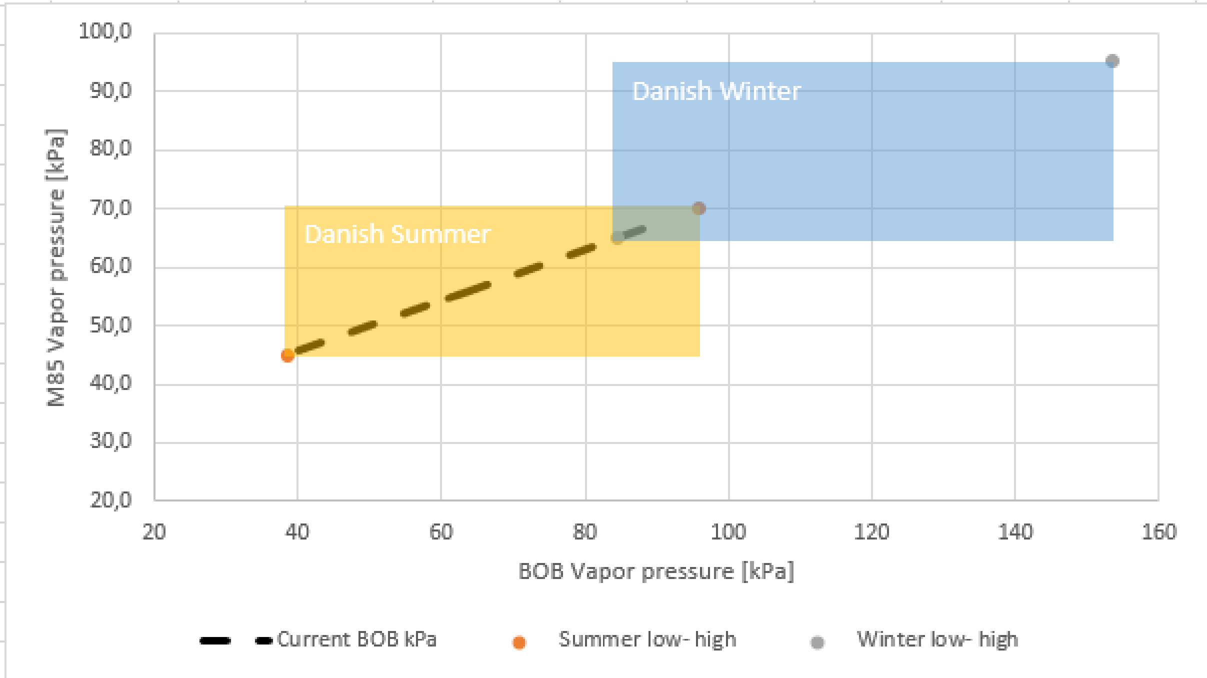

Figure 15 Resulting vapor pressure in M85 as function of the raw gasoline.

The Methanol Institute has produced a bulletin on Methanol Gasoline Blends. Methanol has azeotropic effects with the vapor pressure of gasoline. Methanol itself has a low Reid Vapor Pressure (RVP) but RVP increases in blends – most of the increase, however, takes place in blends of up to 3 vol% volume methanol. Refineries may remove some butane as a compensation. The vapor pressure is lowered when lowering the butane content of the BOB.

In conclusion vapor pressure is **not a problem** for high blends of methanol. For low blends it can easily be handled by adjusting the BOB at the refinery. A blend of 82% methanol M82 will result in a neutral vapor pressure. M85 will be good for summer and M70 will probably be perfect for winter in Denmark.

4.3. Energy content

As mentioned in Commissioner Connie Hedegaard's reply to Parliament, methanol has a low heating value - it is 16 MJ/l versus 21 and 32 for ethanol and gasoline respectively.

This will affect the driving range of the vehicle, but it can be compensated with more frequent fueling or a larger tank. After all, a larger fuel tank is much cheaper than a larger battery. Furthermore, methanol has an octane rating around 110 - so much higher than gasoline that boost, compression and timing advancement can be increased. This will benefit fuel economy. Due to the high heat of vaporization methanol cools down the intake air and the low air temperature produces more horsepower and torque, so that smaller engines can be used. The potential of high-compression methanol engines was documented by Chinese researchers in 2013[4].

30-40% higher mileage calculated on energy content has been reported by the US EPA[5] – when standard and high compression engines (alcohol engine vs. gasoline engine) are compared. By raising compression ratios in methanol engines from 8.8 to 11.4, FORD engineers in 1981 were able to get about two-thirds as much energy per liter from methanol engines as from gasoline engines[6].

American aerospace engineer Robert Zubrin[7] wrote this in 2011:

… First, I ran the car on 100 percent methanol. This required replacing the fuel-pump seal made of Viton, which is not methanol compatible, with one made of Buna-N, which is. The new part cost 41 cents, retail. In order to take proper advantage of methanol's very high-octane rating (about 109), I advanced the timing appropriately. This dramatically improved the motor efficiency and allowed the ordinarily sedate sedan to perform with a significantly sportier spirit. As measured on the dyno, horsepower increased 10 percent. With these modifications complete, I took my Cobalt out for a road test. The result: 24.6 miles per gallon.

When I first made the bet, many commentators thought that I would aim for high-efficiency performance with high-octane fuel by increasing the compression ratio of the engine (which is how race-car drivers using methanol have done it for the past half-century). However, with modern cars using electronic fuel injection, this is unnecessary. Instead, the necessary changes to the engine can be made simply by adjusting the Engine Control Unit software. Thus, except for switching the fuel-pump seal as noted above, no physical changes to the car were required.

The mileage reported by Mr. Zubrin as Miles/gal recalculated to Miles/MJ shows 15% better energy mileage on M60 and **23% better energy mileage on M100.**

[4] https://www.sciencedirect.com/science/article/pii/S0196890413003725
[5] An Alcohol Engine will produce 30-40% greater fuel efficiency than a gasoline engine http://www.americanenergyindependence.com/efficiency.aspx

[6] METHANOL WINS FORD COMPETITION https://trid.trb.org/view/174467

[7] Methanol Wins https://www.nationalreview.com/2011/12/methanol-wins-robert-zubrin/
Incl. Table: http://danskbiomethanol.dk/papers/Methanol%20Wins.pdf

Table 4 Data reported by Robert Zubrin shows great improvement over E10 gasoline

	M100	M60	E10
Miles per gallon as reported	24,6	32,3	36,3
Miles per MJ - recalculated	0,41	0,38	0,33

The present study did however not achieve higher energy mileage on M85. The effect of methanol on fuel economy are further described in Section 3.3.2.

4.4. Vehicle approvals

Vehicle manufacturers in the EU restrict fuel use to a maximum of 3% methanol, although the same car models are sometimes exported to China without such restrictions. Dedicated Flex Fuel Vehicles are no longer offered on the European market.

The Danish Road Safety Agency (Færdselsstyrelsen) does not currently permit the adaptation of cars to methanol. Only factory adapted FFVs are allowed.

To promote the methanol market the Agency should be allowed to authorize workshops to customize regular car for methanol high blends according to ASTM D5797 - 07 Standard Specification for Fuel Methanol (M70-M85) for Automotive Spark-ignition Engines for cars that are adapted to M85 by the car manufacturer as FFV or by an approved workshop.

One EU member country, France, has already approved the use of Flex Fuel Kits. On Friday 15th December 2018, the French Ministry for Environment and Energy published the bylaw (NOR: TRER1734649A) setting forth the terms to approve Superethanol-E85 conversion systems for petrol-powered vehicles to also use Superethanol-E85. Being subject to less taxation because of its environmental edge, Superethanol-E85 is the cheapest fuel on the French market. This has brought plug and play Flex Fuel Kits on the market. They can be installed by laymen in a matter of minutes virtually without the need for tools. For example, ETHANOL FLEX E85® Ethanol Conversion Kit reportedly allows any gasoline vehicle to run either on Ethanol E85 (also known as Bioethanol) or unleaded petrol 95/98 and save up to 40% of your fuel budget on every tank fill in France.

Such kits have been on the US market for some years - for example, Flex Fuel U.S., original manufactured by Chrysler and approved 2006 by EPA for certain cars. In Sweden, BSR Svenska AB has obtained approval of their kit (SAAB only). The same for StepOne Tech Ltd. in Finland. In France, we find the FlexFuel Company with their DriveCleanBox, Ethanol Flex - E85 Ethanol Conversion Kits from Artline International SARL and now quite a few others. The general working principle is shown in Figure 16.

The kit is an electronical device (piggyback device) to plug in between the injector wires and the injectors. It will expand the injector pulse widths by approximately 30% and it will have the possibility of both running on gasoline and M85. It also adds cold start ability.

Advantages:

- Very low cost
- Easy to install and use
- Has the capability of both gasoline, E85 and M85

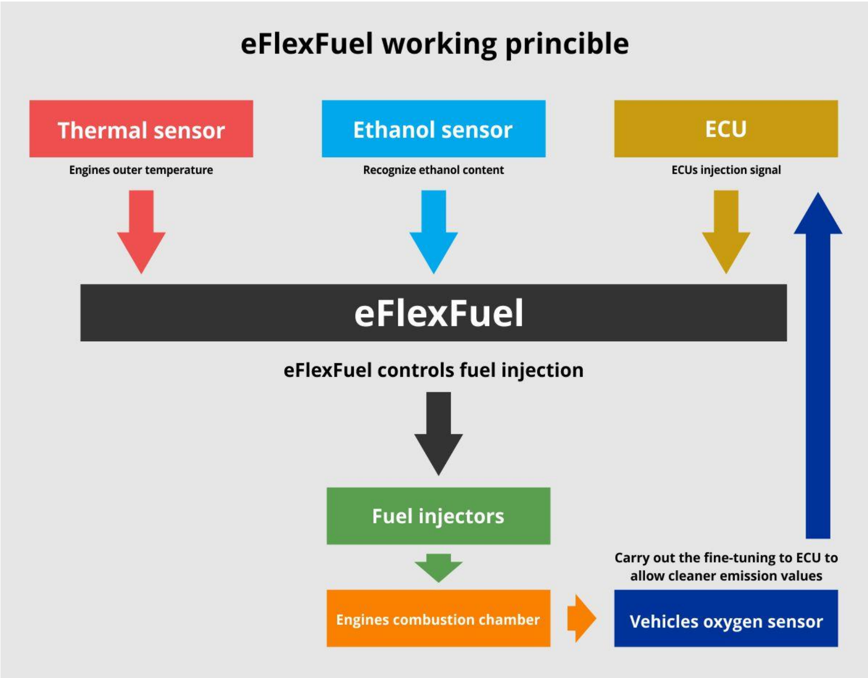

Figure 16 The eFlexFuel working principle illustrates the application of a Flex Fuel Sensor as well as an exterior thermometer. Some kits are simplified by omitting the Flex Fuel Sensor.

These kits vary slightly in simplicity with varying installation from a few minutes to a couple of hours. Bosch offers a supplementary Flexstart, a complete Fuel Rail System with pre-heating to improve cold start in frosty weather. Bosch claims their systems are media-resistant for ethanol and methanol applications.

The simplest Flex fuel kit installs as a plug and play device in the vehicles fuel Injection system, by means of rerouting the signal from the Electronic Control Unit (ECU) to the fuel injectors. Takes less than 25 minutes to install. There are no wires to cut or solder. They offer cold starting assistance technology with built in temperature sensor. After installation vehicle will become a Flex Fuel vehicle able to run high alcohol blends and regular gasoline and any blends.

A Fully Automatic Digital 3-Cylinders E85 Ethanol Conversion Kit with Cold Start Assistance Kit "Ethanol E85 3-Cylinders" at 189 € is installed in our test car (see section 3 Vehicle experiments). The kit from Artline International SARL has an integrated cold-start system with an internal temperature sensor, capable of starting the engine in very low temperatures.

4.5. Biofuel legislation

In Europe the fuel suppliers are obligated to add 5.75% biofuel measured as energy content. If this is to be fulfilled for gasoline alone it must contain approx. 7%vol ethanol or approx. 11%vol methanol. Both options are, however, in excess of the allowed mixing rate according to EN228, so basically, it’s not an option.

European Standards for gasoline (EN 228) and diesel (EN 590) as well as the Fuel Quality Directive (FQD) limits the use of methanol to a maximum of 3 vol%. Gasoline blends with less than 70 vol% gasoline are not covered by the Fuel Quality Directive (FQD) meaning that M30 and higher blends are allowed. Therefore, focus needs to be blends with less than 3% or higher than 30% methanol.

There are currently two certification systems for bioenergy. Energinet.dk issues green certificates. These certificates are not recognized by the EU, which only recognizes certificates (Proof of Sustainability) under the Renewable Energy Directive (RED). It drives the price of bio methanol unreasonably.

To promote the methanol market Energinet.dk should meet EU requirements so that the market is aligned with one certification system only.

Rules for transport in the gas and electricity networks, respectively, are significantly different.

Certified biomethane from waste and residues injected into the grid may be withdrawn as a corresponding amount of natural gas anywhere at no cost and the methanol will be recognized as second generation fuel.

Wind power cannot be “moved” in a similar way and methanol from electricity is not recognized as advanced bio fuel. This is a significant trade barrier preventing use of wind power as “liquid electricity” for transportation.

4.6. Competition from ethanol

Significant research means have been spent on lignocellulosic ethanol in Denmark and for years ethanol was the fuel of choice for researchers in Denmark.

Oxygen bearing liquids (oxygenates) are often added to gasoline to enhance octane rating and for a more complete combustion. Ethanol is the leading oxygenate added to gasoline in most countries. In Denmark, oil companies have agreed to use only ethanol as an oxygenate. This is partly to avoid the use of MTBE, which is harmful to ground water. Furthermore, national exchange agreements on fuels require a uniform product specification.

These agreements are, however, also a barrier for the use of methanol for transportation in Denmark.

The prevalent mixture today is E5, which has a bio content of 3.35% energy. This blend is in line with EN228.

One could increase the bio content by adding bio methanol together with ethanol. The limit for methanol is 3%$_{vol}$ and furthermore, the oxygen content may not exceed 3.7%$_{m}$.

This exact limit is reached with 3%$_{vol}$ methanol and 4%$_{vol}$ ethanol. This blend has a bio content of 5,6% energy. The blend can be obtained by adding 3%$_{vol}$ methanol to the existing E5 gasoline. However, the vapor pressure would probably go too high for summer operation as shown in Figure 14.

An alternate route is to increase ethanol content to 10%$_{vol}$. This gives a bio energy content of 6.8% which is more than the methanol blend. Also, the oxygen content is just below 3.7%$_{m}$. The vapor pressure would not increase.

Due to these regulations it may seem easier for fuel companies to go for added ethanol content rather than adding methanol.

However upcoming regulations might change this. From January 1, 2020, Danish law enforces the EU RED II directive which will change the biofuel obligation to include at least 0.9 energy% advanced biofuel in transport fuel. Since advanced methanol is cheaper than advanced ethanol, this law may bring bio methanol into play.

Ethanol absorbs water and gets corrosive to pipelines and should therefore preferably be mixed at local terminals. Gasoline refilling stations have fiberglass and corrosive-resistant plastics and road tankers are protected likewise. The refineries therefore also offer a Blend stock for Oxygenate Blending (BOB) which does not contain ethanol.

To open the market for low-blend methanol it would be beneficial to have the Danish BOB adjusted so that it, in terms of vapor pressure etc., accommodates low-blends with up to 3 vol% methanol.

4.7. Wind energy subsidies

The wind industry could potentially benefit from the methanol market if methanol is produced as an electro fuel (see section 9.2).

However, the business case for methanization and conversion of the energy and carbon dioxide to methanol is weak because the power is subsidized and thus cannot be acquired profitably. This prevents the use of Danish wind power for use as a methanol feedstock.

To benefit the methanol market RED-Certified wind energy should be supplied to the electric grid and taken out anywhere for any purpose with a certified documentary track, which is used today for biogas. This path is not allowed today.

5. Blending, storage and handling

Fuel logistics involves large investments in port-, dispensing and blending facilities etc. However, proper storages for methanol already exist in Denmark (Figure 17). 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 at an estimated cost between EUR 1,100-2,700 per station.

Figure 17 One of two Methanol tanks – each 2.500 m³ - owned by Nordalim A/S, Port of Aarhus. The tanks are ISCC certified as warehouse for bio methanol traded by New Fuel A/S.

The gasoline blendstock is a liquid hydrocarbon component suitable for use in spark-ignition engine fuels such as conventional gasoline blendstock for oxygenated blending (CBOB), and reformulated gasoline blendstock for oxygenate blending (RBOB).

When gasoline is added the usual $5\%_{vol}$ bioethanol, the blend is sensitive to moisture and must therefore be stored and transported in dry environments. This is the reason why some fuel companies choose to do the blending themselves close to the end user, to avoid moisture problems. The readymade E5 bland can also be taken directly from the refinery, but it will need protection from moist onwards from there.

Methanol blends are much more stable in that sense.

Methanol is toxic like most other fuels. Both bitterant and odorant is therefore added to M100 fuel methanol as a precaution. The M85 blend, however, is denatured by the gasoline so it cannot be ingested by mistake.

The Methanol Institute has created the Methanol Safe Handling Manual[8] to address both common and technical questions related to methanol handling, storage and transport.

[8]http://www.methanol.org/wp-content/uploads/2017/03/Safe-Handling-Manual.pdf

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

5.1. A7 vs E5

Danish gasoline usually contains 5 vol% ethanol. It is not enough to meet the requirement of 5.75% calculated as energy. However, a blend with 3 vol% 2G-biomethanol and 4 vol% 1G-bioethanol satisfies the requirement of 5.75 energy%, because 2G-biomethanol counts twice. The ethanol also acts as cosolvent.

M3E4 or catchier A7 (A for Alcohol) complies with EN 228 for gasoline and no test is required on the vehicle.

Except for a minor adaptation of an existing storage tank to methanol, the infrastructure is completely in place all the way from refinery to our service stations and our gasoline cars.

Commence sales of A7 replacing the current E5 gasoline can begin right away. The methanol may be added at the refinery and the ethanol by the oil company or both can be added by the oil company by using a pre-mixed blend of methanol and ethanol with a ratio of 3:4 vol%.

The refinery would need to adjust vapor pressure by removing butane from the BOB.

5.2. M15

M15, a mixture of 15%$_{vol}$ methanol and 85%$_{vol}$ gasoline, is popular because modern cars can usually run it without engine changes. In China, M15 is the largest utilization of methanol and Israel has recently concluded promising M15 tests.

In long term, long distance trials a modern European gasoline engine ran seamlessly on M15 without any increase in emissions. This was shown on a Fiat 500 MTA FIRE 1.2 8V Euro 6 with stop-start system (shown in Figure 18).

The trials also revealed that the car could run on gasoline with up to 20%$_{vol}$ methanol.

Figure 18 The production ready Fiat 500M15 - November 2016

Sadly, M15 is not allowed in the EU. Only fuels with less than 3 vol% and more than 30 vol% methanol are allowed.

5.3. M56

Flex-fuel vehicles, which have been widely used in Sweden, are designed to run on $85\%_{vol}$ ethanol (E85). E85 in flex fuel vehicles is a well proven solution. For these vehicles a natural starting point would be M56, M85 or M100.

The equivalent methanol blend which gives the same air-to-fuel ratio as E85, is M56. This blend is presently undergoing tests by IEA-AMF Annex 54 ”GDI Engines and Alcohol Fuels”. An earlier study from the university of Luleå showed that current E85-cars run just fine on M56. M56 has a bio energy percentage of 38.4%.

Original flex-fuel vehicles are no longer produced in Europe but can be bought second hand in Germany or Sweden. E.g. 2014 VW Golf VII 1,4 TSI MultiFuel BMT, shown in Figure 19. (more are available on https://bilweb.se/sok/bensin-etanol).

Figure 19 The legacy VW Golf Multifuel – winner of 2016 MAAF Auto Environmental Award

Original fuel injectors adapted to E85/M56 are available for certain car models, e.g. Ford F-150, which however is not usual on the European market.

For M56 the vapor pressure would be rather high. Good for winter but not for summer in Denmark.

5.4. M85

Dedicated M85 vehicles are not available on the market today. Instead, a vision of an M85 car is shown in Figure 20.

Figure 20 Vision of a M85 vehicle

M85 has a bio energy percentage of 73.5%. There is no increase in vapor pressure compared to base gasoline.

High blends require adaptation of the engine and since this adaptation does not cost more at a higher content of methanol, the M85 appears to be an obvious choice. There is an ASTM standard that does not give rise to cold weather problems and which has an excellent driving economy. The ASTM D5797-17, Standard Specification for Methanol Fuel Blends (M51–M85) for Methanol-Capable Automotive Spark-Ignition Engines is adopted as Danish Standard (DS). The standard allows vehicles to achieve cold-start and improve the visibility of methanol flames.

It is a goal to have the ASTM definition further reviewed, tested and recognized in Denmark.

GB/T 23799-2009 Methanol Gasoline (M85) for Motor Vehicles is a national standard of the People´s Republic of China. The Chinese standard is close to the previous ASTM D5797-2007 with few deviations. Among other things, a note is added: "effective metallic corrosion depressor and motor gasoline detergent meeting the requirements of GB 19592 shall be added".

In order to use M85 a gasoline engine must give a 70% higher injected fuel amount per engine revolution. It might therefore be convenient to begin with a E85 compliant vehicle, which has larger injectors as standard. However, ordinary gasoline cars can also be fixed to run on M85.

It is quite probable that many car models can be programmed through the OBD-connector, also known as ECU flashing. Swiss company Flashtec SA offers this kind of services. They did however not respond to our enquiries.

Complete engine control units from VEMS, Megasquirt, AEM, ECU Master etc. can be bought from Danish company QualiTec in Ringkøbing. They can be configured in various ways. QualiTec offered to do the complete conversion at a reasonable fee.

This study points to all legal forms of modification, including authorized ECU flashing, provided the acceptance of Danish road authorities (see section 8).

5.5. M100

It is also possible to run on neat methanol M100, but this can result in cold-starting issues because the vapor pressure is much too low for Danish winter. It may be that cold-starting issues are eliminated on newer vehicles with direct fuel injection but is remains to be verified. A new factory-built methanol car is available from Chinese manufacturer Geely. It’s called Emgrand M100 EC7 1,8 127hp. This model runs now in a trial fleet of six car on Iceland. Geely Emgrand M100 EC7 uses gasoline at cold-start to avoid problems.

Figure 21 Geely Emgrand 7 with and engine for 100% methanol

Due to the cold-starting issues and the need for a denaturant/odorant M100 is not seen as favorable.

5.6. Use of cosolvents

During the 1980s and through much of the 1990s, most gasoline in Western Europe contained a small percent of methanol, usually 2-3%, along with a cosolvent alcohol. Ethanol will work as a cosolvent with an optimal methanol-to-ethanol ratio of 3:4 vol%.

Cosolvent alcohols like ethanol, propanol or butanol are normally added to methanol blends to provide water tolerance or phase stability in colder areas. With water tolerance and corrosion inhibitor protection, methanol gasoline blends have safely been shipped just like gasoline. Cosolvent alcohols also provide reduction in the vapor pressure in methanol blends.

For high methanol content fuels such as M85, phase separation is not a problem because of the large capacity of methanol to absorb water[9]. Thus, M85 does not need a cosolvent.

[9] Use of Methanol as a Transportation Fuel, Methanol Institute, Nov. 2007
http://www.methanol.org/wp-content/uploads/2016/06/Methanol-Use-in-Transportation.pdf

6. Stakeholders

Part of this project is to identify major stakeholders in the Danish region. As stakeholder we define someone with a positive interest in methanol fuels.

The stakeholders can be mapped in the following categories.

6.1. Methanol producers

Worldwide, there are over 90 methanol producers with a combined annual production capacity of about 110 Megatons per year. This methanol is almost entirely fossil based.

For bio-methanol, agriculture is a key player because this is where solar energy is naturally captured. Livestock farming can convert some of this energy into food products. The rest is bound in waste such as straw and manure. This is the part that the EU Commission allows for use in advanced (2nd generation) biofuels.

Biogas producers are the next link in the chain. They are spread throughout the country, thus reducing road transport of biomass. They are represented by "FORENINGEN BIOGASBRANCHEN".

The actual factories that can convert methane to methanol are a necessary link in the chain. For example, New Fuel A/S is ISCC EU approved as a methanol producer and uses Statoil's plant at Tjeldbergodden in Norway for this purpose. This plant has a capacity close to one million tons methanol a year. Methanol is dispatched from the factory at Tjeldbergodden to Warehouse in Port of Aarhus.

A plan for a 1,000 ton per day bio-methanol factory in Aarhus exists and is currently seeking co-investors. The placement of the factory is shown on the map in Figure 22.

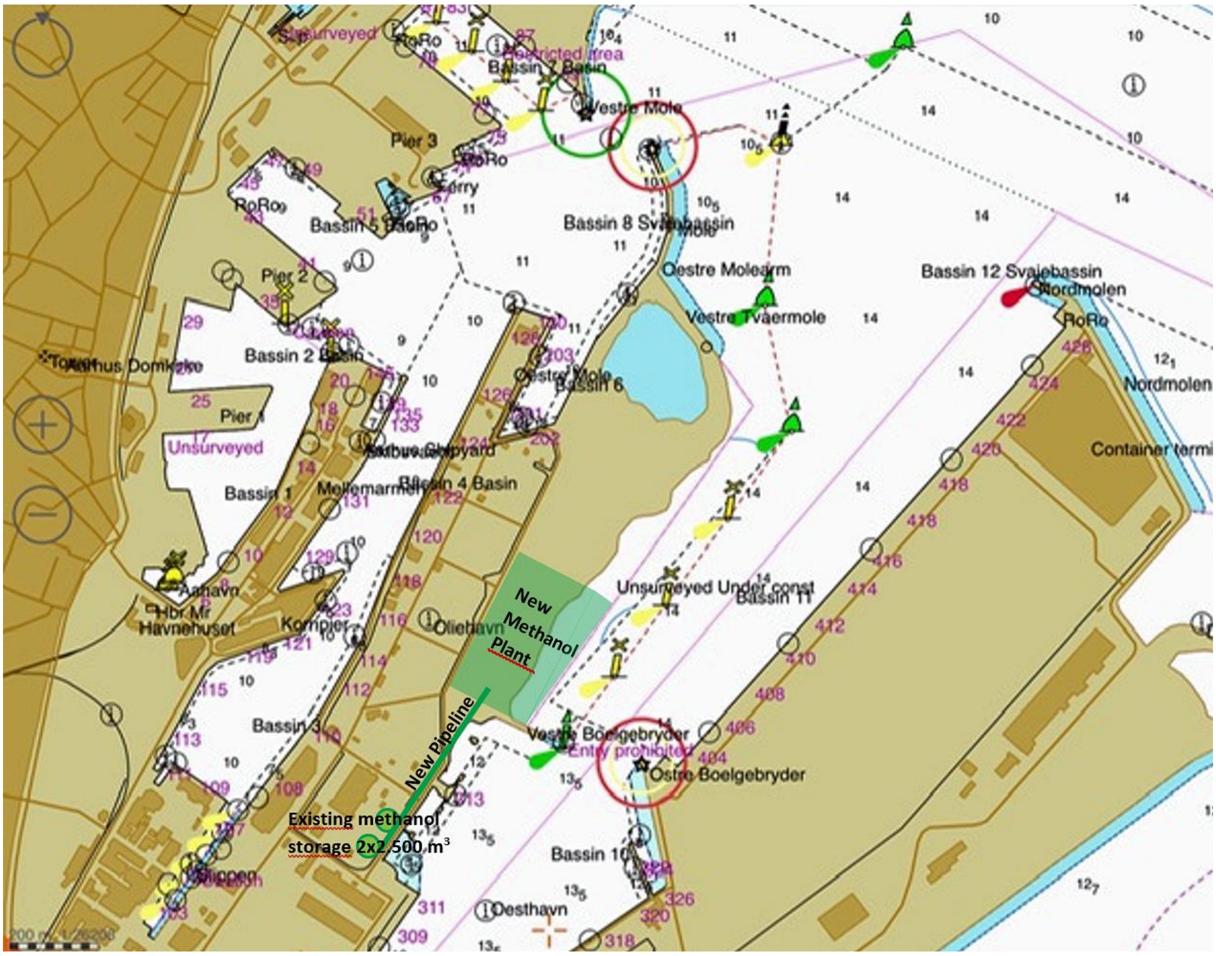

Figure 22 Location for a 1 kton/day methanol plant in Aarhus

6.2. Refineries.

Refineries play an important role because the vapor pressure and other quality parameters of the gasoline blend needs to be controlled. This is done easily by reducing the content of butane in the raw gasoline. However, it can only be done at the refinery. Denmark currently has refineries in Fredericia and Kalundborg located perfectly for in-shipping of methanol.

Danish Fuels Industry Association (Drivkraft Danmark) is an independent business association for the Danish petroleum & gas companies representing a major part of the Danish petroleum & gas retailers as well as the refineries.

6.3. Traders, shippers and retailers

Gas traders are usually also shippers approved for gas transport by energinet.dk. There is a list of Biomethane Certificates Account Holders available at https://energinet.dk/Gas/Biogas/Liste-over-kontoindehavere. Some biogas becomes RED-certified and thus useful to produce RED-certified biomethanol. This amount is increasing.

New Fuel A/S shipped the very first shipload of bio methanol made of Danish biogas on August 23, 2018 (see Figure 23).

Figure 23 Bomar Quest en route from Tjeldbergodden to Port of Aarhus with methanol.

6.4. Car owners

Car owners may be looking for alternatives to electric vehicles due to the cost of purchasing, lack of appropriate charging space or because they need towing capacity for e.g. a caravan. Methanol offers the convenience of a liquid fuel, improved engine torque and less combustion noise compared to gasoline.

The automotive industry seems to have little interest in renewable fuels. Therefore, new flex fuel compliant cars are hard to find. When converting existing vehicles, it would most likely mean that the original warranty is void. Thus, it would be advisable to draw up an insurance policy for the vehicles against technical break down related to the fuel. This approach was used successfully in a former project 'Biodiesel Danmark' and can be done similarly with M85.

7. Nationwide distribution plan

The authors of this report have suggested a complete path for methanol fuel in Denmark (Figure 24). The main feedstock 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.

The complete distribution chain is seen below.

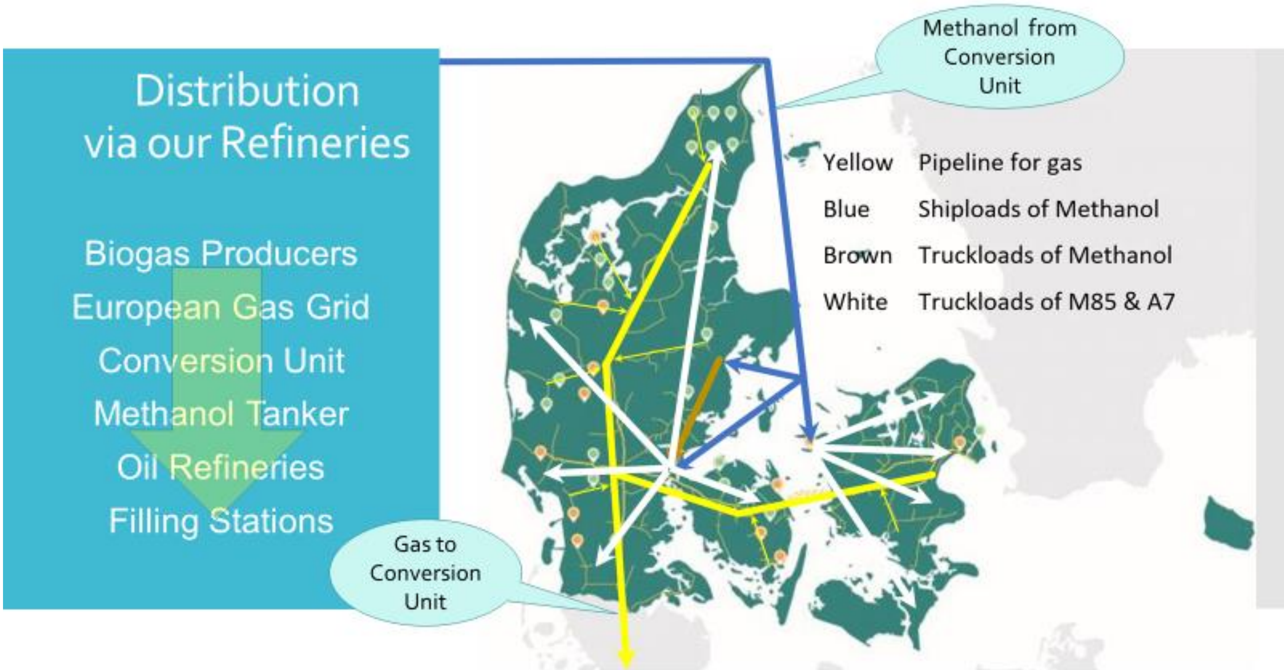

Figure 24 Nationwide distribution plan for M85

Smaller oil companies do not currently have storage suitable for methanol and should therefore leave this to refineries. Unlike ethanol that is too corrosive to mix at the refinery and therefore must be blended with gasoline immediately before being shipped to filling stations, mixing with gasoline at the refinery is a good option for methanol. 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% methanol to account for seasonal changes in Denmark, according Figure 14. The reasons for choosing M85 is covered in section 5.4.

A7 may be produced in parallel using ethanol-methanol blended at the refineries or imported ready to use. Ready to use 4:3 alcohol blends may replace the ethanol used in E5 today.

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 sealings made of flouro-elastomers or polyurethane, 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 (Figure 25). It should be left to the local gas companies to decide whether they want readymade blends or use blender pumps.

Figure 25 Vision of an alternative fuel dispenser

8. Outline for a national demonstration project

Part of this project 2018-2019 was to identify topics for a larger demonstration project in 2019-2022. Based on the identified stakeholders, technologies and barriers, a national demo project is outlined. Inspiration is taken from past successful projects such as Bio-diesel Danmark and B5NEXT which have had real impact on the national fuel strategy.

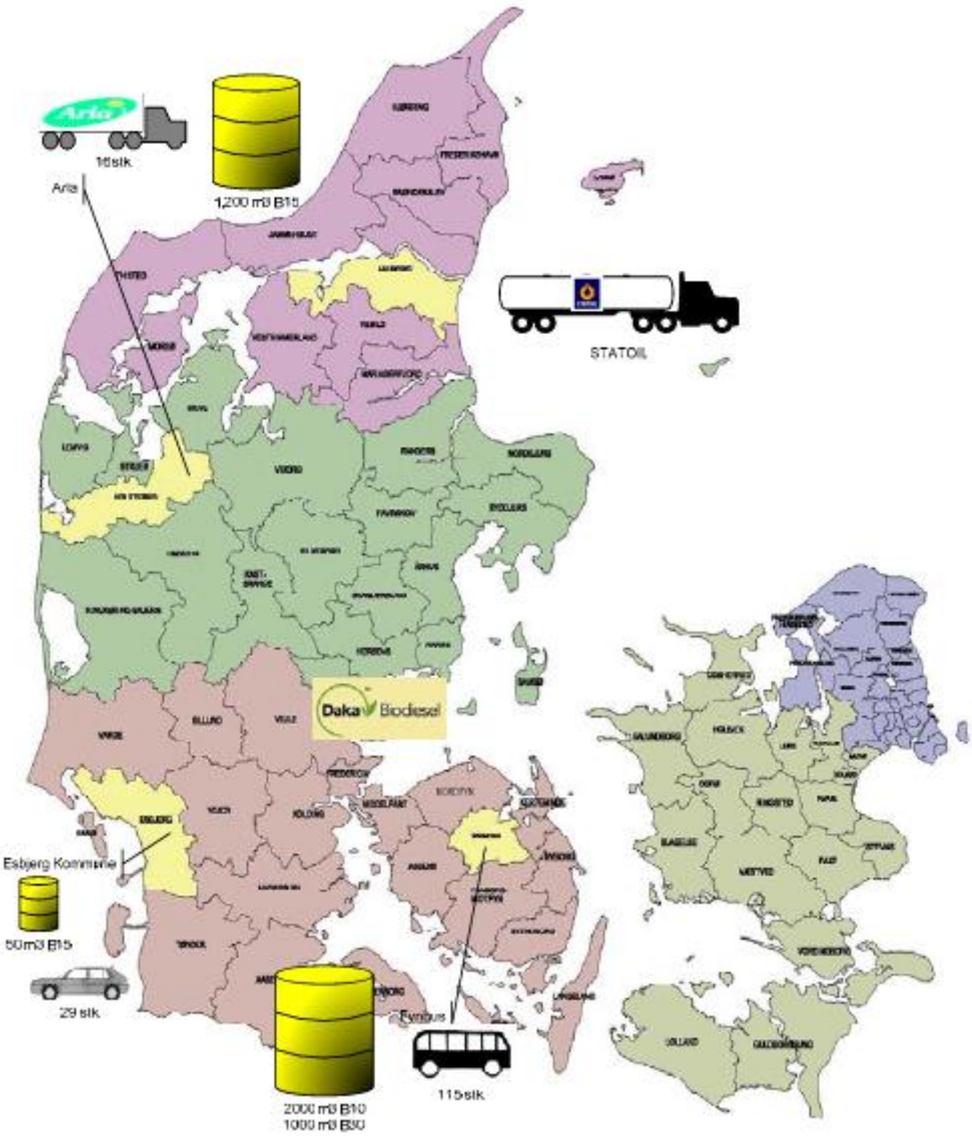

Figure 26: Outline of the 2010 national biodiesel project (SAE 2010-01-0474)

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. A setup as shown in Figure 27 can be used for M85 – possibly using currently vacant 92-octane petrol pumps.

Figure 27 A refueling pump for Propel Fuels alongside traditional gasoline pumps in Citrus Heights, California.

8.1. Organization

FDM 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. Bell Add is offering such service. 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.

Oil companies are requested to provide a smaller number of pumps for M85 – possibly by changing some 92 octane pumps to 105 octane M85. NPS A/S. Nordic Petrol Systems estimates a cost of DKK 20,000 per tank for cleaning and conversion of existing ground tank and pump as well as an approx. DKK 10,000 for reprograming, so it is only can be used by participants.

Malte Fuel & Wash, Sweden offers a mobile tank station with 5 m3 tank, dispenser and a Codab registration system with online registration. The installation cost is approx. 450,000 per piece exclusive VAT.

In workplaces 330 l portable tanks with 12-volt pumps and dispenser can provide additional access for refueling. 50-100 l portable trolleys provide convenient loading on construction sites.

Mixing and distribution is left to the refinery as the immediate best solution. Alternatively, mixing can take place in the road tanker serving the filling stations

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.

8.2. Tentative budget

A Fleet trial with 100 cars a 25.000 km a year ~ 2½ million km will require 31.800 l E5 gasoline and 1.2 GWh biogas for making biomethanol (212.000 l).

Table 5 Indicative budget for at large fleet trial in Denmark (1 kr. = 0.13 EUR)

Fuel on-cost 2 kr. per liter gasoline equivalent	kr. 250,000
Mechanical insurance for 100 vehicles, 30 months	kr. 360,000
Technical examinations and oil probes	kr. 300,000
Vehicle conversions	kr. 350,000
Dyno tests	kr. 150,000
RDE tests	kr. 650,000
Storage & blending facilities at refinery	kr. 500,000
Gasoline pump conversions	kr. 300,000
Hosting an IEA meeting	kr. 80,000
Travel cost	kr. 200,000
Administration and reporting	kr. 1,500,000
Total project expenses	kr. 4,640,000

9. Methanol Handbook

This chapter provides information on production, GHG balances, cost and taxation of methanol fuels. It also contains reference to methanol fuel standards and information on electric cars for comparison.

9.1. Raw material and potential quantities

Methanol is made from a wide range of feedstocks. In Denmark it is practical to produce methanol from biogas and wind energy (Figure 28).

Denmark's biogas potential is substantial due to the large stock of farm animals, about 14 million cattle and hogs.

Figure 28: Two sustainable feedstocks for bio methanol are biogas and wind power

Until 2014, biogas was mainly used in gas engines for electricity and heat. This form of utilization, however, is stagnating and the gas is instead upgraded to biomethane that can be injected into the gas grid. According to the European Biogas Association and the EU Commission, biogas plants that upgrade to biomethane for injection into the grid will grow 15x between 2015-2030. This forecast growth is driven by a new EU directive (RED II), that will require minimum renewable sources in the heating and cooling markets and limit the use of energy crops for production of biofuels and favour the use of waste-derived biofuels in the transport sector. As a result, the next phase of market growth will favour plants using waste as a feedstock, producing biogas direct to grid.

This trend is shown in Figure 29.

Green Gas Denmark has estimated that the Danish Gas grid could be running entirely on green gas by 2038. By then the capacity for biogas should be about 72 PJ/year. Figure 29 illustrates this by the crossing of the line "DK total gas consumption" with the area "Biogas potential".

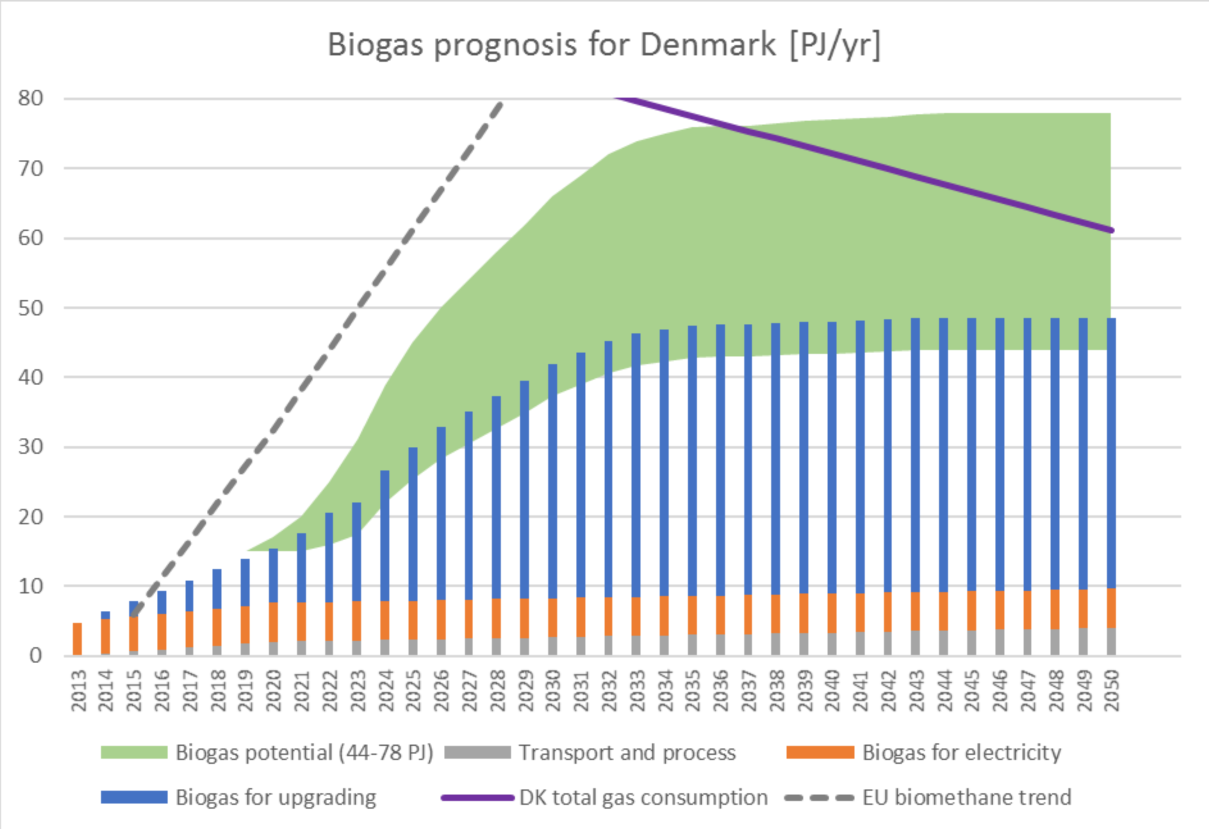

Figure 29 Biogas potential and growth rates based on collated information from Green Gas Denmark, Danish Energy Agency, European Commission.

This estimate agrees with "Biogas in Denmark - Status, Barriers and Perspectives" prepared by the Danish Energy Agency February 2014. It states that the maximum technical biogas potential based on Danish biomass resources can be estimated between 44 and 78 PJ depending on the time perspective and the amount of energy crops. In Figure 29 the interval between high (78 PJ) and low (44 PJ) scenario is marked as the green area.

The Danish Biogas Taskforce has for the analysis of the use of biogas in the future energy system used a slightly more conservative biogas potential of 48.6 PJ. This is within the green area in Figure 29.

For illustration the European biomethane trend is included as a dotted line in Figure 29. It is based on a prediction from European Biogas Association and the European Commission, that EU biomethane production will grow 15 times from 2015 to 2030. Applying this trend to the Danish 2015 production sees an even higher increase than any other estimates. Thus, EU is very optimistic about biogas potential.

Assuming the potential in Denmark is 48.6 PJ and 9.6 PJ is used for other purposes, there is 39 PJ biogas available for methanol production. This yields 30 PJ of methanol plus some useful heat.

On top of this, there is an additional potential of methanized wind energy. Statistics Denmark reported a production of 13,000 GWh wind energy in 2014 ~ 47 PJ wind energy, enough for 28 PJ methanol.

Denmark has about 1.64 million gasoline cars consuming a total of 1.8 million m3 petrol per year, corresponding to 58 PJ.

One car thus consumes approximately 10,000 kWh per year. One PJ fuels about 28 000 cars for one year.

The Danish biogas-methanol potential thus corresponds to 0.8 million cars. Wind power adds potentially another 0.8 million cars. The estimates are summarized in Table 6.

Table 6 Potential number of cars to be fueled by methanol from renewable sources

Estimate	PJ wind	PJ biogas	PJ methanol	MWh methanol	Number of methanol cars
Available bio methane		39.0	30.0	8,336,763	833,676
Available wind	47.0		28.0	7,777,778	777,778
Wind and biogas combined	47.0	39.0	58.0	16,114,540	1,611,454

Table 6 shows that there is enough potential to fuel every gasoline car in Denmark with methanol from wind and biogas in 2035.

9.2. Conversion to methanol

Conversion can be done as Gas-to-Liquid or Power-to-liquid as illustrated in Figure 30.

In the case of Gas-to-liquid, manure and waste biomass from farms is transported by road to biogas digesters. The biogas is then purified to biomethane and trough a short pipeline injected into the gas grid. The European gas network can be regarded as a container capable of receiving gas from many sources and from which gas can be taken in many places for many purposes. When gas is taken by a production facility and converted to methanol, it is transported by ship, road tanker or rail wagon to a Warehouse and distributed to an end-user.

Production facilities for methanol abroad can be used, as the EU Commission recognizes the transport of biogas in the European gas network as illustrated in Figure 33. When the gas is first injected into the gas network, it loses its identity, but an EU-certification system ensures a documentary track.

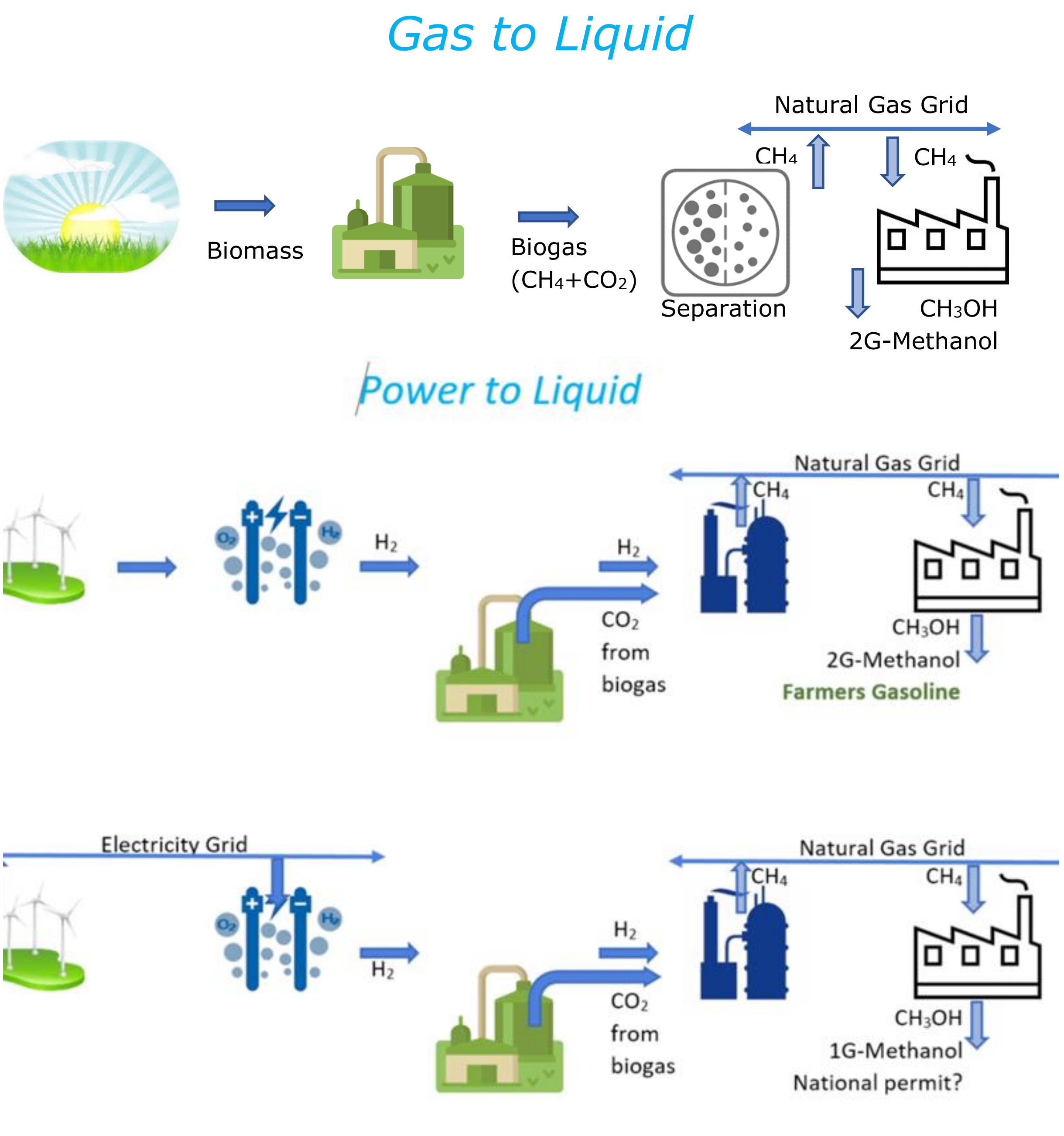

Figure 30 Illustration of gas-to-liquid and power-to-liquid methanol production methods

Energinet.dk owns the overall distribution system for both electricity and gas in Denmark. Permits to use the national gas grid are in place. New permits are needed to use also the national electricity grid, as shown in the bottom example in Figure 30.

Most industrial methanol is manufactured from methane by the ICI Low-Pressure Methanol Synthesis Process. Conversion efficiency of 69,3% is reported by the 2400 ton per day Methanol Plant at Tjeldbergodden, Norway, commissioned in 1997[10].

[10] http://newfuel.dk/ne/CU2%20WMC%201998%20without%20color%20frontpage.pdf

For power-to-liquid, The MeGa-StoRE project reports a yield of 600 m^3 methane (21,5 GJ_{LHV}) from 10 MWh (36 GJ) electricity. The methane may be converted to 748 kg (14,9 GJ_{LHV}) methanol – an overall efficiency of 41.3 $\%_{LHV}$. For motor fuels, only lower heating values LHV are relevant.

Electro fuels (methanol) may also be manufactured by hydrogenating carbon dioxide captured from air, fermentation exhausts or flue gases with unreported efficiencies.

Other examples of conversion efficiencies are:

Example 1: Power to hydrogen

The process is realized by electrolysis, $H_2O \rightarrow H_2 + ½O_2$ (Data from HyProvide A6).

Power consumption for a 250kW stack:	972 MJ/h
Hydrogen Production 60 Nm^3/h or 5.4 kg/h	648 MJ/h (LHV)
Electrolysis Efficiency at LHV and HHV	66.7 $\%_{LHV}$

Example 2: Hydrogen to methane

The process is done by a Sabatier reactor using CO_2 from e.g. biogas, $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ (Data from MeGa-StoRE).

Hydrogen consumption 2400 m^3/h or 8,4 MW_{HHV}:	25.6 GJ_{LHV} /h
Methane production 600 m^3/h or 6,6 MW_{HHV}:	21.4 GJ_{LHV}
Sabatier efficiency	83.6 $\%_{LHV}$

Example 3: Methane to methanol

This process has two steps. Steam reforming, $CH_4 + H_2O \rightarrow CO + 3H_2$ followed by Syngas conversion, $CO + 2H_2 \rightarrow CH_3OH$ (Data from 1998 World Methanol Conference).

Methane consumption 28.74 $GJ_{LHV}/t_{methanol}$	2.977 GJ_{LHV}/h
Methanol production 103.6 t/h	2.062 GJ_{LHV}/h
Methane to methanol efficiency	69.3$\%_{LHV}$

Example 4: Hydrogen to methanol

This process uses hydrogenation of CO_2. (Data from Chemical Engineering Transactions Vol 29, 2012).

Hydrogen consumption 2.3 kt/yr	31.4 GJ_{LHV}/h
Methanol production 1kt/yr	22.7 GJ_{LHV}/h
Hydrogenation efficiency	72.3%

Example 5: Power to methanol

This process also has two steps. Electrolysis followed by CO_2 hydrogenation, $3H_2 + CO_2 \rightarrow CH_3OH + H_2O$ (Data from CRI Iceland).

Hydrogen production by electrolysis 800 t/yr 66.7%$_{LHV}$

CO_2 hydrogenation 5.5 kt/yr 72.3%$_{LHV}$

Power to methanol efficiency 48.2%

A summary of conversion efficiencies are shown in Table 7.

Table 7 Summary of conversion efficiencies

		Input GJ/h LHV			Output GJ/h LHV			
		Electricity	Hydrogen	Methane	Hydrogen	Methane	Methanol	Efficiency
Example 1	Electrolysis	0.972			0.648			66.7%
Example 2	Sabatier		25.8			21.5		83.2%
Example 3	Tjelbergodden 1998			2,977			2,064	69.3%
Example 4	CO2 hydrogenation		31.4				22.7	72.3%
Example 5	George Olah 2015	18.7					9.00	48.2%

Examples 3 and 5 are shown in Figure 31 and Figure 32.

Figure 31 Gas-to-Liquid, Tjelbergodden Plant in Norway, commissioned in 1997. Capacity 1000 mill. liters per year

Figure 32 Power-to-Liquid, George Olah Plant in Svartsengi, near Grindavik, Iceland, 2012. Capacity 5 mio. liters per year.

9.3. Certification

An increasing proportion of Danish biogas (Figure 29) is being RED-certified and hence suitable for green second-generation biofuel in the form of bio methanol.

Biogas used for transportation as "Liquid Gas", must be produced from waste and residues and upgraded to natural gas quality and RED-certified. Otherwise the product is of no interest to the market.

In Denmark two EU accredited inspection and certification companies operate, which have obtained their certification system recognized by EU (see Figure 33). These are ISCC System GmbH and REDcert International Pvt Ltd. Both act through partnerships with designated certification bodies. The third certification company RSB is currently not operating in Denmark.

Figure 33 European RED certification bureaus of which 2 operate in Denmark

The emission savings for certification are found using a tool provided by Biograce [11]. The BioGrace greenhouse gas (GHG) calculation tool has been recognized as a voluntary scheme by the European Commission.

A current example of RED-certified bio methanol, branded as 'Farmers Gasoline' in Denmark, is shown in Figure 34.

[11] http://www.biograce.net/home

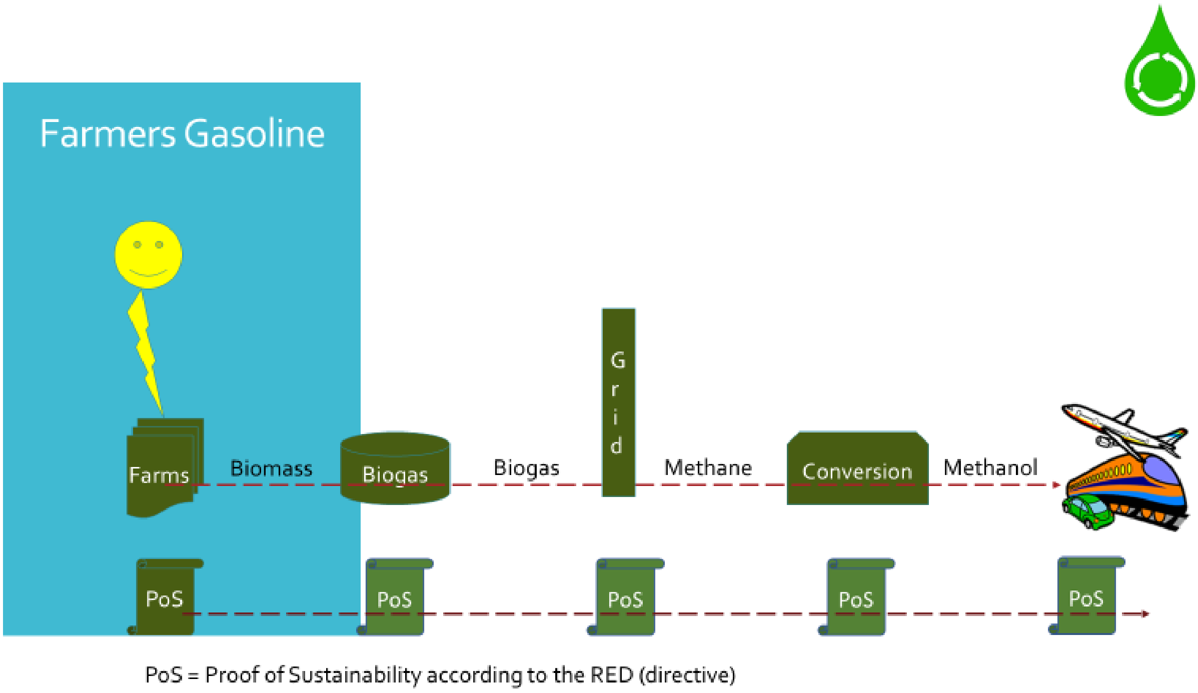

Figure 34 Certification pathway for 'Farmers Gasoline' ISCC EU certified bio methanol

Decentral collection of biomass and conversion to biomethane saves transport. Placement of methanol plant 'Conversion' can be central and given a profitable capacity of a few thousand tons of methanol per day.

Profitability could be increased by concurrent use of wind power for central electrolysis. This would allow the use of both oxygen and hydrogen from the electrolysis - but it requires regulatory changes.

Under ISCC EU and European legislation (FQD) the following power-to-liquid pathways will be possible:

1. CO_2 from biogas processed using electricity from renewable sources
2. CO_2 from fossil sources (non-biological origin) processed using electricity from renewable sources

The direct supply of renewable electricity (without grid connection) will be possible.

For the off-taking of electricity from the grid, national obligations shall probably be considered. As a first step this can be certified under ISCC, if certain requirements will be fulfilled (e.g. double-accounting of the renewable electricity is excluded).

Until more favourable rules for using wind power are introduced, Denmark may continue to use the pathway illustrated in Figure 34.

The crucial RED II-directive is implemented according to the timeline below:

- 13/11/2018: Provisional agreement passed by the EU Parliament
- 03/12/2018: Final approval by the EU Council (Member States)
- 21/12/2018: Publication in the official journal of the EU

- February 2019: Delegated act on EU ruling for high and low iLUC biofuels
- 30/06/2021: Deadline for transposition into national legislation in Member States

9.4. Methanol fuel standards

There are 3 methanol fuel standards of major interest. These are the American ASTM standard for M85, the Chinese counterpart GB/T, also for M85, and finally the Israeli standard for M15. The standards are compared in the table below.

For Denmark, it is recommended to use ASTM International Designation: D5797 – 17; Standard Specification for Methanol Fuel Blends (M51–M85) for Methanol-Capable Automotive Spark-Ignition Engines. This specification is under the jurisdiction of ASTM Committee D02 on Petroleum Products, Liquid Fuels, and Lubricants and is under the direct responsibility of Subcommittee D02.A0.02 on Oxygenated Fuels and Components. The specification is also adopted as Danish Standard.

Table 8 Summary of methanol fuel standards

Property	ASTM 1	ASTM 2	ASTM 3	GB/T 23799	SI 90 M15
Methanol incl. higher alcohols $\%_{vol}$	> 84	> 80	> 70	84..86	10..17
Higher alcohols $\%_{vol}$	< 2	< 2	<2	< 2	< 10
Hydro carbons $\%_{vol}$	14..16	14..20	14..30	14..16	< 54
Vapor pressure kPa	48..62	62..83	83..103	< 78 Winter < 68 Summer	50..80 Winter 45..65 Summer
Lead mg/l	< 2,6	< 2,6	< 3,9	< 2,5	< 5
Sulphur mg/kg	< 160	< 200	< 300	< 80	< 10
Phosphorus mg/l	< 0,2	< 0,3	< 0,4	< 2	
Acid mg/kg	< 50	< 50	< 50	< 50	
Gum washed mg/100ml	< 5	< 5	< 5	< 5	< 5
Gum unwashed mg/100ml	< 20	< 20	< 20	< 20	
Chlorides mg/kg	< 2	< 2	< 2	< 2	
Inorganic chloride mg/kg	< 1	< 1	< 1	< 1	
Water $\%_{wt.}$	< 0,5	< 0,5	< 0,5	< 0,5	< 0,2
Appearance	Bright and clear with no particles visible				
RON					> 95
MON					> 85
Density kg/m^3					720..775
Oxidation, min.					> 360
Oxygen $\%_{wt.}$					< 9
Copper- corrosion					Class 1

9.5. Recipe for M85

105 octane M85 is a mixture of:

- 85 volume percent methanol
- 15 volume percent gasoline
- Q.S. (a suitable amount) lubricant
- Q.S. (a suitable amount) anti-corrosive additive

For winter driving in Denmark it may be practical to reduce methanol content to 70%. This will ensure a higher vapor pressure as indicated in Table 8. A higher vapor pressure helps cold starting in general.

The methanol shall comply with the IMPCA METHANOL REFERENCE SPECIFICATIONS issued by International Methanol Producers & Consumers Association, Avenue de Tervueren 270 Tervurenlaan - 1150 Brussels – Belgium. The specification limits water to max 0,100 % w/w acc. to ASTM E1064-12 and limits purity on dry basis to min 99.85% w/w acc. to IMPCA 001-14.

For a lubricant and anti-corrosion additive there are several options, e.g. Redline SI-Alcohol.

In M85 there is no need for a co-solvent or ignition improver.

9.6. Properties of methanol blends

Table 9 shows the properties of each fuel component. The numbers are based on the RED Directive GHG emission 26 g CO_2 /MJ for 1G-ethanol from wheat (with straw combustion for CHP) and 5 gCO_2 / MJ 2G-methanol from waste wood. As stated in the RED Directive, the greenhouse gas emission varies for biofuels with the raw material and process/pathway used. For 1G ethanol, the default value thus varies between 24 and 70 g CO_{2eq} / MJ. For 2G methanol, the emission varies between 5 and 7 g CO_{2eq} / MJ.

There is no pathway for biogas in the current RED. Biograce standard values can be used instead.

Table 9 Base data for biofuels and gasoline

	Density	LHV energy	Bioenergy	Advanced bio	Oxygen	Carbon	Energy	Range	WtW CO2	WtW CO2
Component	g/l	MJ/l	%LHV	%LHV	%m	%m	MJ/km	km/l	g/l	g/km
Ethanol 1G	0.794	21.3	100%	0%	35%	52.2%	1.68	12.7	553	44
Methanol 2G	0.793	15.8	200%	200%	50%	37.5%	1.68	9.4	79	8
Gasoline	0.745	32.9	0%	0%	0%	85.0%	1.68	19.6	2757	141

Energy consumption per km is obtained from the Real Driving test in Chapter 3. Taxes are Danish rates as of September 2018. Based on the information in Table 9 the blends can be characterized.

Table 10 Properties of typical European E5 gasoline

	Content	LHV energy	Bioenergy	Advanced bio	Oxygen	Carbon	Energy	Range	WtW CO2	WtW CO2
Component	%vol	MJ/l	%LHV	%LHV	%m	%m	MJ/km	km/l	g/l	g/km
Ethanol 1G	4.8%	1.0	100%	0%	1.8%	2.7%	1.68	0.6	27	44
Gasoline	95%	31.3	0%	0%	0%	80.7%	1.68	18.6	2625	141
95 octane E5	100%	32.3	3.16%	0.00%	1.77%	83%	1.68	19.3	2651	138

It is apparent from Table 10 that E5 does not meet present biofuel obligations in the EU. The bio energy content is only 3.16% whereas the obligation is 5.75%. This means that biofuels must be added elsewhere to compensate, e.g. in the diesel sector.

A7 on the other hand, as seen in Table 11, complies with both the present and the 2020 biofuel commitment. It is therefore an excellent successor to E5.

Table 11 Properties of 95 octane A7

	Content	LHV energy	Bioenergy	Advanced bio	Oxygen	Carbon	Energy	Range	WtW CO2	WtW CO2
Component	%vol	MJ/l	%LHV	%LHV	%m	%m	MJ/km	km/l	g/l	g/km
Ethanol 1G	4%	0.9	100%	0%	1.5%	2%	1.68	0.5	22	44
Methanol 2G	3%	0.5	200%	200%	1.6%	1%	1.68	0.3	2	8
Gasoline	93%	30.6	0%	0%	0%	79%	1.68	18.2	2564	141
95 octane A7	100%	31.9	5.63%	2.97%	3.07%	82%	1.68	19.0	2588	136

Table 12 Properties of 105 Octane M85

	Content	LHV energy	Bioenergy	Advanced bio	Oxygen	Carbon	Energy	Range	WtW CO2	WtW CO2
Component	%vol	MJ/l	%LHV	%LHV	%m	%m	MJ/km	km/l	g/l	g/km
Methanol 2G	85%	13.4	200%	200%	43%	32%	1.68	8.0	67	8
Gasoline	15%	4.9	0%	0%	0%	12%	1.68	2.9	414	141
105 octane M85	100%	18.3	146%	146%	42.9%	44%	1.68	10.9	481	44

The M85 based on 2nd generation methanol has a CO_2 emission of only 44 g/km. This corresponds to the emission of an electric car with the Danish electricity mix.

9.7. Cost and taxation

Price fluctuations over time and origin makes it difficult to calculate comparable consumer prices. Figure 35 shows the historical price fluctuations.

The Ethanol price is indirectly affected by oil prices but most directly by US corn prices.

Methanol price is driven up by the Chinese market for transportation fuel. The large gas discoveries in the US and Canada, however, have attracted new methanol mega-plants with the capacities of 5-10 kt per day, which could reverse the price trend. Large quantity buyers typically get 15-20 % off the list price.

For bio-methanol there are no price listings, but most often it is sold at the quarterly Methanex or ICIS price plus a bio-premium. The surcharge is justified because bio methanol is a 2nd generation fuel counting twice in the EU RED national obligations.

The Danish energy tax for petrol in 2019 is 4.339 DKK per litre petrol. Biofuels are taxed relatively to their energy content. In the same period, gasoline attracts a CO_2 tax of DKK 0.421 per litre, while biofuels are exempted from CO_2 tax.

The use of methanol and bio methanol is tax-neutral according to current regulations. I.e. that the state tax revenue is unchanged.

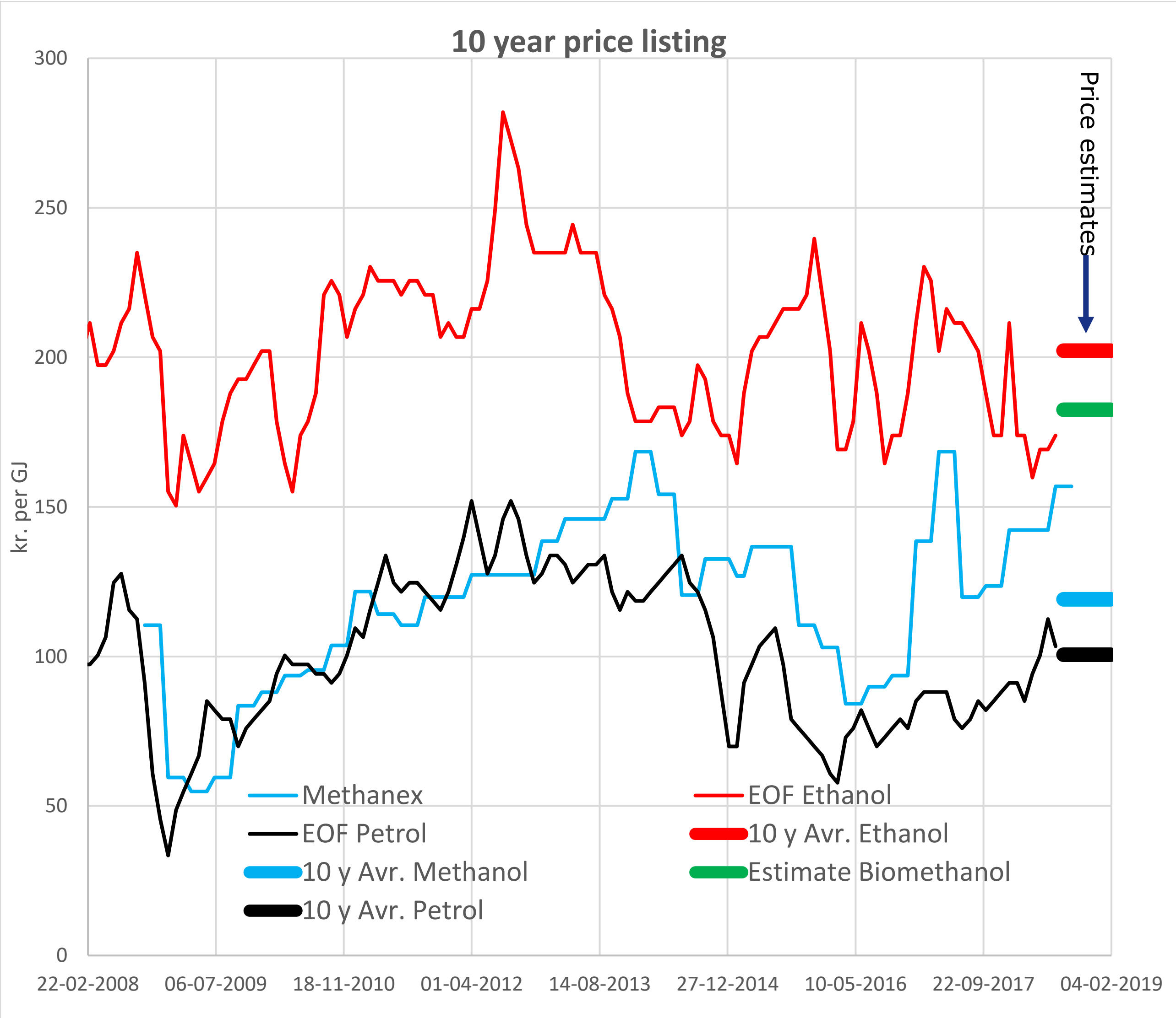

Figure 35 Estimated cost of petrol, ethanol and methanol based on historical price listings (EOF and Methanex). The estimates at the far right will be used for further cost calculations

Based on the fuel prices in Figure 35 and test performance (19.3 km/l) of the city car, the total cost to the consumer including taxation and VAT can be calculated. This is done in Figure 36.

Component	Content %vol	Energy tax kr/l	CO2 tax kr/l	Total tax kr/km	Fuel cost kr/l	Surcharge kr/l	Product cost kr/l	Pump price kr/l	Consumer cost kr/km
Ethanol 1G	100%	2.81	0	0.222	4.30	0.85	7.96	9.95	0.79
Methanol 2G	100%	2.08	0	0.222	2.98	0.63	5.69	7.12	0.76
Gasoline	100%	4.34	0.42	0.243	3.31	1.32	9.39	11.73	0.60

Component	Content %vol	Energy tax kr/l	CO2 tax kr/l	Total tax kr/km	Fuel cost kr/l	Surcharge kr/l	Product cost kr/l	Pump price kr/l	Consumer cost kr/km
Ethanol 1G	4.8%	0.13	0	0.011	0.21	0.04	0.38	0.48	0.04
Gasoline	95%	4.13	0.40	0.231	3.15	1.25	8.94	11.17	0.57
95 octane E5	100%	4.27	0.40	0.24	3.36	1.29	9.32	11.65	0.61

Component	Content %vol	Energy tax kr/l	CO2 tax kr/l	Total tax kr/km	Fuel cost kr/l	Surcharge kr/l	Product cost kr/l	Pump price kr/l	Consumer cost kr/km
Ethanol 1G	4%	0.11	0	0.009	0.17	0.03	0.32	0.40	0.03
Methanol 2G	3%	0.06	0	0.007	0.09	0.02	0.17	0.21	0.02
Gasoline	93%	4.04	0.39	0.226	3.08	1.22	8.74	10.92	0.56
95 octane A7	100%	4.22	0.39	0.24	3.34	1.28	9.22	11.53	0.61

Component	Content %vol	Energy tax kr/l	CO2 tax kr/l	Total tax kr/km	Fuel cost kr/l	Surcharge kr/l	Product cost kr/l	Pump price kr/l	Consumer cost kr/km
Methanol 2G	85%	1.77	0	0.189	2.53	0.54	4.84	6.05	0.64
Gasoline	15%	0.65	0.06	0.037	0.50	0.20	1.41	1.76	0.09
105 octane M85	100%	2.42	0.06	0.23	3.03	0.73	6.25	7.81	0.73

Figure 36 Cost and taxation of methanol blends

9.8. GHG emissions from Biogas

Waste-derived renewable energy is focus of RED II EU regulation from 2020. Biogas solves an important waste issue because it reduces the methane emissions from farm manure. Upgraded biogas utilizes existing European gas grid which has received over €400 billion of investment.

As stated by the European Biogas Association (EBA) as per 22 November 2018:

"Manure if left untreated will emit methane and nitrous oxide emissions as well as a number of other air pollutants or GHG precursors such as ammonia. Instead, if the organic content of livestock manure decomposes in the absence of oxygen in an anaerobic digester, it will decompose into a gas mixture richer in methane. This so-called biogas can be captured, cleaned and combusted for energy production. However, the way in which the biogas is produced – in particular the inputs to the digestion process in the form of type of manure and eventual additional biogenic material such as crops or food waste – can have significant impacts on the efficiency and cost of the process. A by-product is "digestate", a nutrient-rich substance that is usually used as fertiliser. Other options exist to reduce manure emissions but do not produce usable energy: Storage management, air filtering and circulation, composting, nitrification-denitrification treatment, acidification, solid separators and artificial wetlands all shown potential to reduce greenhouse gas emissions from manure."

The EU RED directive (2009/28/EC of 23 April 2009) on the promotion of the use of energy from renewable sources) - **ANNEX V** set out rules for calculating the greenhouse gas impact of biofuels, bioliquids and their fossil fuel comparators.

The Directive currently only mentions wood methanol. Biogas to methanol is not specified in the directive and may therefore be calculated using the Biograce tool.

Biograce can use a default value for biogas and the EU RED directive specifies 3 such values for biogas based on municipal waste, dry manure and wet manure respectably. Danish biogas is practically only certified with default value - a relatively high value. This is because there is not yet a market for biogas with individually calculated emissions.

This means that the calculated emissions from the production of biomethanol can range from below 5 to as much as 26 gCO_{2eq}/MJ using present default biogas values.

The EU has continuously assessed the CO_2 emissions from different fuels and, in its latest proposal for a new directive, sets out the CO_2 emissions for biogas to be as low as -100 gCO_2 / MJ, as shown in Table 13.

Table 13 CO2-emissions of typical bio methane-derivatives /COM/2016/0767/.

Biomethane production system	Technological option	Typical greenhouse gas emissions g CO_{2eq}/MJ	Default greenhouse gas emissions g CO_{2eq}/MJ
Biomethane from wet manure	Open digestate, no off-gas combustion	-22	22

	Open digestate, off-gas combustion	-35	1
	Close digestate, no off-gas combus-tion	-88	-79
	Close digestate, off-gas combustion	-103	-100

As seen in Table 13, biogas carefully manufactured by state of the art, really has no GHG emission. Conversion to methanol is associated with a low greenhouse gas emission and even the waste heat from the conversion is made useful. This makes biomethanol an extremely promising liquid fuel for transport.

9.9. Comparison of EV and methanol car

In Denmark, the government's plan is to ban all sales of new petrol and diesel cars by 2030 and only allow electric cars or other forms of "zero-emission" cars. However, electric cars also cause CO_2 emissions.

Emissions of CO_{2eq} produced by an electric car is based on local footprint of local electricity plus the car manufacturing.

The local footprint of electricity in Denmark is very low, 200 g/kWh ~ 56 g CO2eq/MJ as shown in Figure 37. By comparison, Biograce states for "Electricity EU mix LV" 129 g CO2eq/MJ.

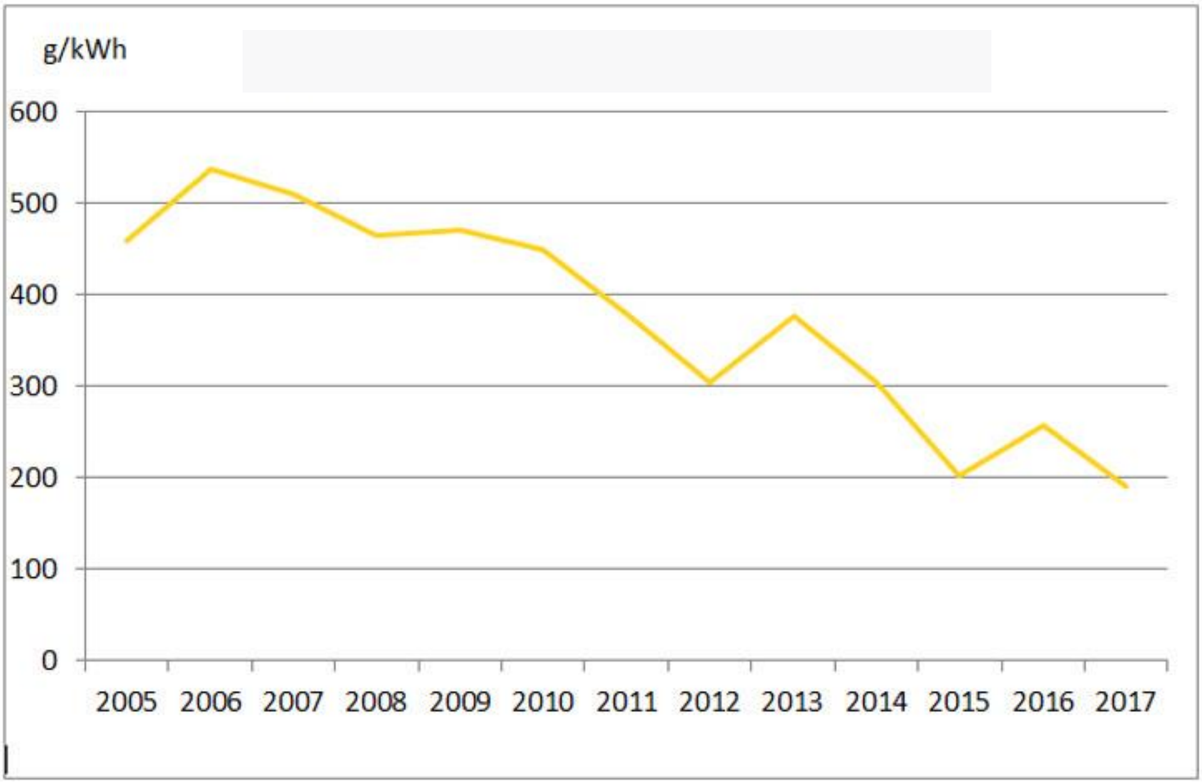

Figure 37 Development in CO_2 emissions per kWh consumed in Denmark

Due to the relatively large CO_2 footprint of manufacturing batteries however, methanol cars still make a strong case in comparison.

The LowCVP (Low Carbon Vehicle Partnership), established in 2003, is a public-private partnership that exists to accelerate a sustainable shift to lower carbon vehicles and fuels and create opportunities for UK business. Nearly 200 organizations are engaged from diverse backgrounds.

LowCVP starts their News Release, 8th June 2011 "*LowCVP study demonstrates the increasing importance of measuring whole life carbon emissions to compare vehicle performance*" saying

> ELECTRIC and hybrid cars create more carbon emissions during their production than standard vehicles – but are still greener overall, according to a new report.
>
> For example, a typical medium sized family car will create around 24 tonnes of CO_2 during its life cycle, while an electric vehicle (EV) will produce around 18 tonnes over its life. For a battery EV, 46 % of its total carbon footprint is generated at the factory, before it has travelled a single mile.

Table 14 LowCVP estimated emissions in vehicle production (tons CO2e)

Standard gasoline vehicle	5.6
Hybrid vehicle	6.5
Plug-in hybrid vehicle	6.7
Battery electric vehicle	8.8

Based on a 150,000 km life cycle we find from Table 14:

Emission <u>during manufacture of an EV</u> 8,8 * 1.000.000 /150.000 = 58,7 g CO_2/km

Emission <u>during manufacture of an FFV</u> 5,6 * 1.000.000 /150.000 = 37,3 g CO_2/km

To these manufacturing figures driving emissions must be added. LowCVP find that an EV generates 65 gCO_2 per km with a 500 g/kWh electricity mix. With the Danish mix of 200 g/kWh that translates to 26 gCO_2 per km. The Danish Climate Counsil uses 35 g/km to account for production of wind turbines etc. We shall use 32,5 g/CO2/km.

Using Real Driving Emission (RDE) measurements from Chapter 3, we find:

- Emission driving a city car on E5: 130 gCO_2/km
- Emission driving a city car on M85: 40 gCO_2/km
- Emission driving a city car on M100: 8 gCO_2/km
- Emission driving an EV: 32,5 gCO_2/km

Summing up

- Life cycle emission of a city car using E5 (37,3+130) = 167,3 gCO_2/km
- Life cycle emission of a city car using M85 (37,3+40) = 77,3 gCO_2/km
- Life cycle emission of a city car using M100 (37,3+8) = 45,3 gCO_2/km
- Life cycle emission of an EV (58,7+32,5) = 91,2 gCO_2/km

A car on M100 thus emits from cradle to grave about half as much CO_2 as an electric car, when the methanol is produced from biogas.

Even an M85 car emits less CO2 than an electric car, as shown in Table 15.

Table 15 Life cycle comparison of gasoline, electric and methanol vehicle

	E5	M85	Electric
Emission in production of vehicle	5.600 kg $CO_{2eq.}$	5.600 kg $CO_{2eq.}$	8.800 kg $CO_{2eq.}$
Emission driving 150.000 km	19.650 kg $CO_{2eq.}$	5.250 kg $CO_{2eq.}$	6.000 kg $CO_{2eq.}$
Life cycle emission	25.250 kg CO_{2eq}	10.850 kg $CO_{2eq.}$	14.800 kg $CO_{2eq.}$
Fuel and energy pathway	Corn fermentation and natural gas in CHP	Wet manure from open digestate with off-gas combustion	From Danish grid

10. Dissemination

Information about this project is available on the following websites:

https://www.iea-amf.org/content/projects/map_projects/56

http://danskbiomethanol.dk/profile/home.html

A contribution to AMFI Newsletter was sent on Jan. 11th, 2019.

As newsletter, two publications were made. One short information sheet and one folder describing the project in more detail. See "CityCarSheet" and "CityCarFolder".

Physical meetings/workshops were held with several Danish stakeholders,

- Shell Refineries on 31/8-2018
- Scantune on 21/9-2018
- Port of Aarhus on 28/9-2018
- Circle-K on 8/1-2019
- Nordic Green on 15/3-2019
- EWII on 22/10-2018
- NGF Nature Energy 15/11-2018
- Dansk Folkeparti 27-11-2018
- Danish Transport and road safety agency on 7/3-2019

Discussions and mail correspondence about this project were also held with several stakeholders,

- Go'on
- FDM
- Scania
- Drivkraft Danmark (Fuel Suppliers Association)
- The government's Commission for Green Transition of Passenger Vehicles
- KL - Local Government Denmark
- City of Aarhus
- City of Skanderborg
- City of Copenhagen

A presentation suitable for a webinar was developed but not deployed. The Transportation Innovation Network TINV was used to create further national interest in the topic.

Figure 38 Magnetic advertising sign for test vehicles says: "We drive on M85 Methanol made from Danish Biogas"

Figure 39 Magnetic sign on test vehicle in public traffic

11. Recommendations for the future

Due to the extremely low conversion cost and low life cycle GHG emissions it is recommended to continue work on methanol fuelled cars as a supplement to electric cars.

A continued effort is needed to convince decision makers, vehicle suppliers and the general public that methanol fuel is as safe and practical as gasoline.

For future work some key aspects should be addressed:

- Demonstrating M85 in a much larger number of vehicles
- Obtaining a general approval of a Flex Fuel kit in Denmark
- Software conversions (ECU flashing) as alternative to flex fuel kits
- Using Direct Injection engines for better cold start
- Establishing physical production of bio-methanol in Denmark
- Removing the barriers mentioned in this report

The authors of this report welcome all Danish stakeholders to make contact in order to establish broader collaboration on future methanol fuelled cars.