

# METHANOL AS A RENEWABLE FUEL – A KNOWLEDGE SYNTHESIS

Report from an f3 project

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## PREFACE

This report is the result of a collaborative project within the Swedish Knowledge Centre for Renewable Transportation Fuels (f3). f3 is a networking organization, which focuses on development of environmentally, economically and socially sustainable renewable fuels, and

- Provides a broad, scientifically based and trustworthy source of knowledge for industry, governments and public authorities,
- Carries through system oriented research related to the entire renewable fuels value chain,
- Acts as national platform stimulating interaction nationally and internationally.

f3 partners include Sweden's most active universities and research institutes within the field, as well as a broad range of industry companies with high relevance. f3 has no political agenda and does not conduct lobbying activities for specific fuels or systems, nor for the f3 partners' respective areas of interest.

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## EXECUTIVE SUMMARY

When the world saw the first spikes in oil price in the 1970s and 1980s, it created an intense activity addressing fundamental issues such as how the western world could become less dependent on crude oil and how that could be realized at the cost of fuels which were in line with products from crude oil-based fuels. The only alternative fuel that attracted fundamental interest at the time was methanol. It could be produced efficiently from alternative energy sources at comparably low production costs, and feedstocks, mainly natural gas and coal, were available on a scale even surpassing crude oil.

The interest in methanol as a fuel resulted in large tests in various car fleets all around the globe. The results were reported as generally very positive and from many test sites like California, methanol was looked at as not only a solution from insecure crude oil prices but also as a potential candidate to combat the bad air quality prevailing in the US Pacific state with its very large cities. Also, in Sweden one of the solutions to less dependency on crude oil was methanol and a large fleet test and project developments took place during the same time period. Large fleets of standard vehicles adjusted to run on M15 (15% methanol in gasoline) and M100 (100% methanol) were operated for an extensive period. When the oil price fell back to low levels in 1986, the interest in finding alternatives to crude oil-based fuels disappeared quickly in Sweden and elsewhere. In California, however, work that had been initiated went on for about another decade and generated considerable experiences in the handling and use of methanol as an automotive fuel, both in cars and in busses and trucks.

During the 1990s, the world started to experience a growing concern regarding the increasing concentration of greenhouse gases (GHG) in the atmosphere. This resulted in a growing interest in finding alternative, renewable automotive fuels. There is (of course) not an exact time when the activity started, but the 1990s is the decade when various countries initiated plans and carried out studies in the area. In this early stage of forming a biofuels agenda, a shift took place which respect to the use of methanol. From being the natural alternative fuel choice during the previous oil crises, it was in most places taken off the agenda. The motivation was often based on the reasoning that methanol is corrosive and that it is toxic.

From the historical background can be discerned a lack of long-term perspective with respect to (a) earlier and current motivation to use/not to use methanol as an alternative fuel, (b) experiences gained from earlier periods of methanol usage, and (c) why interest to use methanol as an automotive fuel has shifted through the past decades. From this, the question also arises of how this lack of long-term perspective may have influenced the potential renewable methanol market of today.

The objective of the report is thus to create a knowledge synthesis with this long-term perspective in mind and to look forward and address the following topics:

1. Lessons learned in the widespread tests of methanol as a fuel in the 1980s and 1990s
2. Recent knowledge about global use of methanol in various fuel applications including health and safety aspects of methanol usage in the fuel sector
3. Current and future production pathways of methanol with focus on renewable production alternatives
4. Current and future use of methanol in various engine applications

5. Methanol production cost economics
6. Production potential of biomethanol in Sweden.

The report also includes subjects that closely relate to renewable methanol as an automotive fuel such as the following: Fossil methanol economics; Renewable methanol competitiveness; Methanol as energy carrier for fuel cells and hydrogen as its replacement; Dehydrated methanol i.e. Dimethyl Ether (DME), a clean and efficient diesel fuel.

In order to carry out the objectives and more specifically to be able to grasp the partly difficult task to explain the “ups and downs” with respect to methanol’s acceptance as an automotive fuel, the report includes information gathered through contacts with a large number of companies and institutions that have been and /or are involved in activities involving methanol.

Maybe the most important factor and the key reason why methanol was investigated and tested in large programs during the 1970s and 1980s, was its cost of production. The fuel industry knew that the production cost of methanol was on the same level as products from crude oil. When the cost of methanol (US Gulf Coast) is compared to two crude oil products, naphtha and No.2 Fuel Oil on an energy basis during the period 1986 to 2015, it can be seen that during long periods the methanol price was very close to that of the two other commodities and even lower during periods. This type of comparison is from one fundamental point of view not fair, because methanol has historically been a chemical commodity and priced as such, and even more important, been produced in quantities relating to the comparably small chemicals market and not to the (compared to chemicals) gigantic fuels market.

Experiences from trials were as said very positive. The numbers of vehicles involved in operation in California were over 15,000 including also busses and a number of heavy-duty vehicles, while in Europe they were a couple of thousands. Methanol’s superior quality as a fuel was well known from racetracks and use in speed motorcycles. It maximized power output from a given engine size. On the racetrack, it was also viewed as a comparably safer fuel than gasoline. After a severe crash with gasoline-fuelled cars in the Indy-500 race in 1964, gasoline was replaced by methanol. In 2005, Indycar changed methanol to ethanol, a result of strong lobbying from the ethanol industry.

When the increasing concentration of GHG in the atmosphere became a subject of increasing concern and society started to seek for alternatives to fossil-based energy sources, the fuel producing industry as well as automakers started to look for renewable fuel alternatives. In this process, methanol was gradually moved out of the picture, although it was the alternative of choice during the oil crises a decade earlier. A number of arguments were brought forth, which earlier were not central in the debate regarding methanol although of course well known. It was now toxic and the risk of exposures could lead to injuries or death. It was also corrosive and would lead to more expensive vehicles. The energy content of methanol was low and would lead to bigger tankage and larger fuel injection systems. Other arguments were also raised in the debate.

The listed concerns are real and need to be addressed with various measures. But the listed issues, and others, also need to be put in comparison with other identified alternative and renewable fuels in order to compare the alternatives as objectively as possible. E.g. the energy content of methanol is 15.9 MJ/litre and for liquid natural gas (LNG) 20.3 MJ/litre. Methanol is handled in ordinary atmospheric tankage, while LNG needs special tankage, distribution equipment, thick insulation and

advanced vehicle adaptation in order to handle the condensed gas at  $-160^{\circ}\text{C}$ . Still LNG is today put forth as an important alternative fuel for e.g. heavy-duty vehicles and ships.

Even if it is difficult to reveal how this, what can be seen as a policy change, actually was motivated and carried through, it is quite easy to follow what became the result. Methanol is since almost two decades often not even mentioned in reports and studies when renewable fuels/advanced biofuels/2<sup>nd</sup> generation biofuels are reviewed. If it is included it is marginalized or included with a negative statement stating one or two of its earlier mentioned qualities, that it is corrosive and toxic.

A similar change from broad acceptance to being marginalized has also happened to methanol as an energy carrier for fuel cells (FC). In the 1980s and 1990s, it was at least one of the key candidates with methanol reforming taking place on board the vehicles. During the late 1990s and early 2000s methanol was gradually moved out from that application and today hydrogen is the preferred energy carrier. It is not at all clear what happened although some strategic decisions were taken, which led to the change. The base for this change can however be questioned. One reason to believe so is that the Japanese automaker Nissan in 2016 declared that they now had developed a FC-based concept based on ethanol reforming on board the vehicles. Nissan use arguments such as; More user-friendly; This solution combats the common hurdle of deployment for traditional fuel cell vehicles: The lack of hydrogen fuelling infrastructure; It uses bio-ethanol derived from renewable crops such as corn or sugarcane and that refuelling infrastructure already exists to a great extent; It claims that the system is expected to be less costly (than traditional hydrogen systems); Ethanol is safer to use than hydrogen because it is not as combustible; The fuel does not have to be pure ethanol. It can also be a mix of up to 55 % water, which further brings down the cost of the operation. All these arguments are true for methanol as well. Methanol is even easier to reform than ethanol.

As an overall observation with respect to health and safety (corrosion risks are here treated as part of safety) it seems that the arguments often used against widespread use of methanol are overemphasized and that measures can be or have been developed to mitigate negative aspects of methanol use. Large commercial use of methanol in various applications going on today is described in this report. The information from these activities is practical evidence that so is the case. Major work done by independent authorities such as the Environmental Protection Agency (EPA), the Society of Automotive Engineering (SAE), Lloyds and others all conclude that methanol is a viable fuel alternative and from most key aspects is to be preferred compared to gasoline.

The report presents a number of potential users of methanol. It elaborates currently applicable, straightforward applications such as blending 3% of methanol into all European gasoline (allowed by the gasoline specification), using renewable methanol in production of biodiesel and as reactant in production of MTBE. It describes the possibility to combine E85 fuel with methanol blending to become so-called GEM fuels where GEM stands for gasoline, methanol, ethanol blends. It also includes pure methanol applications such as using methanol as bunker fuel in ships and methanol as energy carrier in fuel cells. The so-called ED95 fuel (95% ethanol with an ignition improver) is also mentioned as there is a potential to develop that concept with a corresponding MD95 fuel.

Efficient conversion of a feedstock to an acceptable quality syngas (hydrogen,  $\text{H}_2$  plus carbon monoxide,  $\text{CO}$ ) through gasification is the most critical step in the conversion of a feedstock to methanol. When the syngas quality requirement is met, the conversion from syngas to methanol is carried

out basically in the same way as with today's commercially used technologies. Most methanol is currently produced from natural gas, and, in the case of China, from coal. There is however a lack of large plants in which renewable feedstocks such as woody residues is converted from feedstock to pure syngas and further from syngas to a product like methanol. There are a couple of very advanced pilots (small demos), which have shown that conversion of cellulosic material to synthesized products is feasible and that heat and material balances are in line with what has been the result of simulation work upfront. The next step is therefore to scale up to large demos or small commercial sized plants demonstrating the complete chain of processes making up the total plant concept. Most gasification developments are carried out with forest residues of various types as feedstocks, although other interesting routes are also under development or in their commercialization stages. Straw products are under development in Germany and municipal waste gasification to methanol is being commercialized in Canada where the first plant was started up 2016.

Table A 1 shows conversion efficiencies for three different conversion routes from biomass to methanol. Case A shows conversion of biomass, Case B conversion of black liquor (BL) in pulp mills and Case C a combination of BL with pyrolysis oil (PO) in pulp mills. It shows that methanol can be produced from biomass with an energy conversion efficiency between 50 – 70% depending on the conversion route. This report does not have the ambition to describe in detail the best and second best conversion route from the point of view of conversion efficiency but rather to give a well-founded base for what level of efficiency can be reached. These numbers can then be combined with the biomass potential in e.g. Sweden thus giving an overall methanol production potential for the country. The production potential could also be increased considerably via utilization of renewable electricity to produce H<sub>2</sub>, which then can be added to the syngas from the gasification process and as a consequence augment the production capacity. H<sub>2</sub> can also be combined with a carbon dioxide (CO<sub>2</sub>) source and be converted to methanol as is currently being done at a small demonstration plant on Iceland.

**Table A 1. Overall conversion for biomass to methanol for different conversion routes.**

Process step	Gasification	Shift	Methanol synthesis	TOTAL
Conversion from / to	Biomass to H <sub>2</sub> +CO	Non-shifted to shifted syngas	Syngas to methanol product	Biomass to methanol
<u>Conversion route</u>				
<b>Biomass gasification, Case A</b>	0.7-0.8	0.96-0.97	0.79-0.8	0.53-0.62
<b>BLG to Methanol, Case B (Biomass added to compensate)</b>		*		0.65-0.7
<b>Biomass to PO combined with BLG, Case C</b>		**		0.49-0.6
* Conversion of BL to syngas and further on to methanol does not make sense (as for biomass gasification) as the overall calculation as explained in the subchapter about BLGMF concepts relates to the biomass addition to the system to compensate for withdrawal of BL normally being fired in a recovery boiler. See ref. ** When PO is added to a BLGMF system PO energy is converted to methanol with about 70% energy efficiency as described under Case C. Production efficiency of PO from biomass is multiplied with this efficiency to get the TOTAL value.				

The production cost of renewable methanol is benchmarked against natural gas-based methanol production and against cellulosic ethanol. The latter is chosen because it is judged to be the most commonly cited renewable fuel when various renewable biofuels are listed. The production cost

estimates focus on investment, the cost of the feedstock and thirdly the operation and maintenance cost.

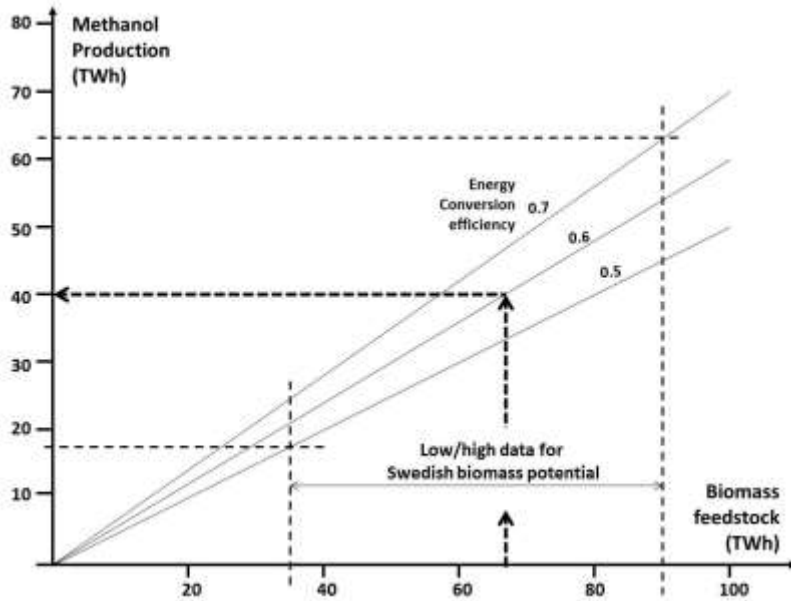
For the base case chosen in this report the production cost of renewable methanol is in the interval 64-71 EUR/MWh or 355-393 EUR/tons of methanol. The key base case data comprises cost of capital corresponding to 20 year/10%, biomass feedstock at 21 EUR/MWh, yearly O&M costs calculated as 3.5-4.0% of total plant investment and cost of electric power at 60 EUR/MWh. The base case and two other cases are presented in Table A 2.

**Table A 2. Production cost of renewable methanol**

Case	<b>Base Case</b> Capital: 20 years/10% Feedstock: 21 EUR/MWh Power: 60 EUR/MWh	<b>Base case plus plus</b> Investment. + 20%	<b>Base case plus</b> Investment: + 20% Capital: 10 years/10% Feedstock: + 20% El. Power: + 17%
EUR/MWh	64-71	68-76	83-98
EUR/ton	355-393	377-421	461-544

When benchmarking against advanced biofuel alternatives like cellulosic ethanol, the highest quoted cost level of bio-methanol in the sensitivity analysis, around 100 EUR/MWh, is still competitive. When benchmarking against today's fossil fuels, gasoline and diesel, the calculated production cost for bio-methanol cannot compete on a pure cost per energy basis. The current gasoline price at refinery gate is in the order of 45 EUR/MWh. This corresponds to about 0.40 EUR/litre gasoline. In today's price scenario for fossil fuels bio-methanol needs a premium of 40-50% to be able to compete when the production technologies have matured.

Depending on different sources of information, biomass availability for conversion to biofuels by 2050 is quoted to be between 30 and up to the level of 100 TWh/year. Energy conversion efficiencies from biomass to methanol vary between 50 and 70% depending on technology. Figure A 1 can be used to identify the production of methanol from certain feedstock potentials for different energy conversion efficiencies (biomass to methanol).



**Figure A 1 Methanol production as a function of biomass potential for different conversion efficiencies**

To avoid internal adjustment of the mole  $H_2/CO$  ratio from about the level of 1 to the level of 2 (which is necessary for methanol synthesis) external  $H_2$  can be added to reach the desired ratio. If the  $H_2$  is produced via renewable electricity the produced methanol will be renewable as well. For typical syngas compositions the total syngas energy flow (and the methanol production) increases by 50 to 60% with this type of  $H_2$  addition. The renewable carbon in the feedstock is in this way utilized to a much larger extent.

As an example in Figure A 1, if average feedstock availability potential is combined with average conversion efficiency 40 TWh/year of methanol could be produced from 67 TWh/year of biomass in 2050. If the PtL concept also would be fully implemented this potential could increase to about 60 TWh/year.



## SAMMANFATTNING

Metanolanvändning i olika tillämpningar ökar globalt och idag finns flera exempel på hur metanol används inom transportsektorn. Av dessa exempel kan bland annat dras slutsatserna att de främsta orsakerna till att metanol som drivmedel vinner terräng är att produktionen är energi- och kostnads-effektiv liksom att användningen av metanol är förhållandevis okomplicerad. Det finns också flera exempel på hur metanol testas som bränsle i olika, ibland nya, typer av motorer.

I dagens debatt finns en brist på långsiktigt perspektiv med avseende på (a) tidigare och nuvarande motiv att ”använda/inte använda” metanol som ett alternativt bränsle, (b) erfarenheter erhållna från tidigare perioder av metanolanvändning och (c) varför intresse för att använda metanol som ett fordonsbränsle har skiftat under de senaste decennierna. Syftet med denna rapport är således att skapa en kunskapsynsnes med detta långsiktiga perspektiv i åtanke och att blicka framåt och belysa metanols potentiella roll som energibärare/motorbränsle i Sverige (och på annat håll).

I diskussioner om användningen av metanol som transportbränsle nämns dess toxicitet och potentiella korrosivitet ofta som viktiga anledningar till att inte införa metanol på bränslemarknaden. Trots många kontakter med företag och institutioner som har långa erfarenheter av metanol som bränsle kom det inte fram några ytterligare orsaker (förutom dess giftighet och korrosivitet) som talade för att inte använda metanol som ett bilbränsle. Genomgången visade snarare att hälso- och säkerhetsfrågor stöder alternativet ”använda”.

Produktion av metanol från fossila råvaror är väl etablerad och mycket av tekniken är tillämplig även då råvarorna är förnybara. Det finns två huvudsteg i produktionen; Syntesgasproduktion (väte plus kolmonoxid) och omvandling av syntesgas till metanol. Det senare steget skiljer sig i princip inte från motsvarande process med fossil råvara. Det är kostnads- och energieffektiv syntesgasproduktion från förnybara råvaror som är nyckeln till framgångsrik produktion av förnybar metanol. Biomassabaserad metanolproduktion kan också kombineras med nya koncept som exempelvis elektrobränslen (Power to Liquids, PtL). Integrering av PtL-konceptet kan öka produktionen av metanol från en given mängd biomassa med >50%.

I ett utvecklat scenario (n:te anläggningen) kan biomassabaserad metanol produceras till kostnader i intervallet 65-70 EUR/MWh vilket motsvarar 40-50% högre produktionskostnad än dagens pris på fossila bränslen på energibasis vid anläggningen. De två huvuddelarna i produktionskostnaden, kapitalkostnaden och kostnaden för råvaran, har studerats och varierats för att förstå produktionsökonomins dynamik. Om t.ex. biomassapriset skulle ligga på ungefär hälften av vad den gör i Sverige idag (vilket skulle motsvara typiskt pris i södra USA) skulle produktionskostnaden minska till 50-55 EUR/MWh, nära dagens fossila bränslepris. Produktionskostnaden för metanol står sig också bra i jämförelse med andra förnybara bränslen. Den är t.ex. endast 50-60% av den för cellulosa-baserad etanol (på energibasis).

Eftersom faktisk tillgång på biomassa är under intensiv diskussion innehåller rapporten en beskrivning av hur metanolproduktionspotentialen kan beräknas utifrån tillgång på råvara och val av omvandlingseffektivitet. Till exempel, om den genomsnittliga, uppskattade tillgängligheten av råvara 2050 kombineras med den genomsnittliga konverteringseffektiviteten, skulle ca 40 TWh/år metanol kunna produceras. Om då också PtL-konceptet utnyttjades fullt ut skulle potentialen öka till ca 60 TWh/år.

## SHORT SUMMARY

Methanol use in various applications is on the rise globally and there are several examples on how methanol is used in the transport sector today. From these examples, it can be concluded that the main reasons to go the methanol route are that the production is comparably efficient and cost effective as well as that use of methanol is carried out without any noticeable problems. There are also several examples of where methanol as fuel is under advanced testing in various, sometimes novel, types of engines.

From the historical background can be discerned a lack of long term perspective with respect to (a) earlier and current motivation to “use/not to use” methanol as an alternative fuel, (b) experiences gained from earlier periods of methanol usage, and (c) why interest to use methanol as an automotive fuel has shifted through the past decades. The objective of this report is thus to create a knowledge synthesis with this long term perspective in mind and to look forward and address methanol’s potential role as energy carrier/motor fuel in Sweden (and elsewhere).

In discussions about the use of methanol as a transportation fuel, its toxicity and potential corrosiveness is often mentioned as key reasons why not to introduce methanol in the fuels market. Despite numerous contacts with companies and institutes who have long term experiences with methanol use as a fuel no new additional concerns (besides being toxic and corrosive) was revealed with respect to not to use methanol as an automotive fuel. The review rather showed that health and safety issues support the “use” alternative.

Production pathways for methanol from fossil feedstocks are very well proven and much knowledge is applicable when renewable feedstocks are used. There are two main steps in the production; the syngas (hydrogen plus carbon monoxide) production and the conversion of syngas to methanol. The latter step does not differ from corresponding process in fossil-based concepts. It is cost and energy efficient syngas generation from renewable feedstocks that is the key to successful production of renewable methanol. Biomass based methanol production can also be combined with novel concepts such as electro fuels (Power to Liquids, PtL). Inclusion of PtL can increase the production potential of methanol from a given amount of biomass with > 50%.

In a developed scenario ( $n^{\text{th}}$  plant economics), biomass based methanol can be produced at costs in the range of 65-70 EUR/MWh, which corresponds to 40-50% higher production cost than today’s price of fossil fuels on an energy basis at plant gate. The two main elements in the overall production cost, cost of capital and cost of feedstock, have been studied and varied to understand the dynamics of production economics. If e.g. the biomass price would be at about half of what it is in Sweden today (which would correspond to the typical price in southern US) cost of production would drop to 50-55 EUR/MWh, close to current fossil fuel prices. Methanol production costs also stand up well in comparison with other renewable fuel and production cost is e.g. typically only 50-60% of that of cellulosic ethanol (on energy basis).

As availability of biomass feedstock currently is strongly debated, the report includes a description of how the methanol production potential can be calculated based on feedstock availability and conversion efficiency. As an example, if the average feedstock availability potential 2050 is combined with the average conversion efficiency, approx. 40 TWh/year of methanol could be produced. If the PtL concept also would be fully implemented, the potential could increase up to approx. 60 TWh/year.

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# 1 INTRODUCTION

## 1.1 HISTORICAL BACKGROUND

Methanol is one of the world's largest chemical commodities. It is very well known in the chemical industry, as it is a component in very many products and therefore is produced, handled and used in a large number of locations all around the world. Besides being an important chemical commodity, it has from time to time been a candidate when developing alternative fuels to the crude oil based gasoline and diesel fuels. Appendix 1 lists some key variables of methanol (incl. blends) and compares them with ethanol (incl. blends), petrol and diesel.

When the world saw the first spikes in oil price in the 1970s and 1980s, this created an intense activity addressing fundamental issues such as how can the western world become less dependent on crude oil and how could that be realized at a cost of fuels that was in line with products from crude oil based fuels, gasoline and diesel. The only alternative fuel that attracted fundamental interest at the time was methanol. It could be produced efficiently from alternative energy sources at comparably low production costs and feedstocks, mainly natural gas and coal, were available on a scale even surpassing crude oil. Also Sweden followed this path and the Swedish political background to the proposal to introduce methanol as an alternative fuel can be found in various protocols from the Swedish government and in recommendations from OED, Oljeersättningsdelegationen (an institution introduced by the government to recommend how to find alternative to crude oil derived fuels) (OED, 1980). See also the report *Why is ethanol given emphasis over methanol in Sweden?* (Grahm, 2004, p. 5)

The interest in methanol as a fuel resulted in large tests in various car fleets all around the globe. Results were reported as generally very positive (MacDonald, 2000) and from many test sites like California methanol was looked at as not only a salvation from unsecure crude oil prices but also as a potential candidate to combat the bad air quality prevailing in the US Pacific state with its very large cities. In Sweden, a large fleet test and project developments took place during the same time period. A large fleet of standard vehicles adjusted to run on M15 (15% methanol in gasoline) and M100 (100% methanol) were operated for an extensive period.



**Figure 1:1. M100 Ford Escort in the Swedish methanol test fleet. Photo: Ingvar Landälv.**

The team that can be seen in Figure 1:1 was heading the coal to methanol project named *Nynäshamnskombinatet* planned to be located south of Stockholm, in Nynäshamn. The methanol production was to be blended into Swedish gasoline to create a M15 fuel. The final report was published

in 1984 and summarizes the project as well as gives a political background to the project plan (Nynäshamnskombinatet, 1984).<sup>1</sup>

Even though there was work done which had the ambition to show that methanol could be produced by domestic feedstocks, mainly forest residues, this was never a real option in the 1980s because the goal at the time was not to change to renewable sources but merely to find cost efficient solutions to crude oil based fuels.

When the oil price fell back to low levels in 1986, the interest in finding alternatives to crude-oil based fuels disappeared quickly in Sweden and elsewhere. In California, however, the work that had been initiated went on for about another decade and generated considerable experiences in the handling and use of methanol as an automotive fuel, both in cars and in busses and trucks. Finally due to that the price difference between gasoline and methanol was not big enough to continue to drive the development and combined with a generally negative attitude from the oil industry led to that activities ceased towards the end of the 1990s.

Besides methanol and ethanol being fuel candidates in the very early stage of the automotive car era in the early 20<sup>th</sup> century, during the oil crises in the 1970s and 1980s they were for the first time regarded as real alternatives to gasoline due to fear of oil shortage combined with high prices. Starting around 2005, the Chinese began to look for domestic alternatives to their rapidly growing car fleet, which resulted in an ever-increasing cost of imported fossil oil. Oil prices were also rising, which made the situation even worse. Their main choice fell on coal-based methanol because China does not have large sources of either oil or natural gas but has vast resources of bituminous coal. The choice to go for methanol was based on efficiency of conversion and cost of production combined with methanol being a good candidate as a complement to gasoline.

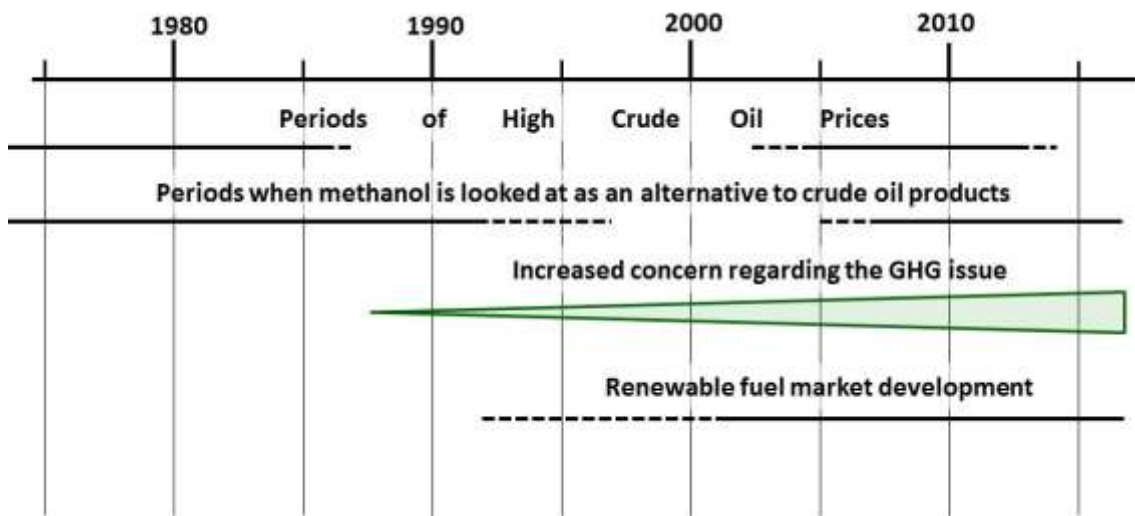
A more recent, and related to Sweden, development with respect to use of methanol as a fuel, is the test of methanol as a bunker fuel. It has become one of the alternatives in those areas of the world where sulfur emission requirement corresponds to maximum 0.1% sulfur in the bunker fuel. To meet this emission requirement with a crude oil based fuel, a low sulfur marine gas oil (MGO) is required. Since 2015, this restriction is imposed in the Baltic, the North Sea and the English Channel. The ship operators have looked into different solutions to cope with the new legislation and one which now is under test in the STENA Germanica ferry running between Gothenburg and Kiel in Germany is conversion of a ship to run on pure methanol (with an diesel igniter). This is thus a second example, besides China, on a decision in favor of methanol when the decision is based on pure economics.

An illustration of time versus periods of high oil prices and increased interest in introducing methanol in the fuel sector is shown in Figure 1:2. The figure also illustrates the growing concern for the increasing concentration of greenhouse gases (GHG) in the atmosphere. That there has been a concern for a long time can be illustrated by the fact that when Nynäshamnskombinatet (see above) dropped its methanol focus and finally became a fossil based energy combine designed to produce power, heat and hydrogen (for the adjacently located Nynäs refinery) part of the location permit in-

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<sup>1</sup> Part of the final report of Nynäshamnskombinatet published in September 1984 can be found in Appendix 4. The full report can be made available through the author of this report.

cluded planting of forest (two locations investigated) to mitigate the emission of fossil carbon dioxide (CO<sub>2</sub>). The growing forest would absorb corresponding quantities of CO<sub>2</sub> as the new plant was to emit. The location permit was granted in the late 1980s.



**Figure 1:2. Illustration of key variables forming a background to the report (author's own visualization).**

As a reaction to the increasing emissions of GHG and continued rising use of fossil energy, a growing interest in finding alternative, renewable automotive fuels also started to develop. There is (of course) not an exact time when the activity started, but as Figure 1:2 illustrates, the 1990s is the decade when various countries initiated plans and carried out studies in the area (Brazil with its special situation and unique potential to use sugar cane for ethanol production had started earlier). Swedish reports which illustrate the interest in this field are e.g. the NUTEK/KFB report *Fossil and bio-based motor alcohols* (Brandberg and Sävbark, 1994) and two reports by Vattenfall Utveckling AB: *Biofuel based Methanol and Ethanol as Fuels – A Survey Study* and *Biofuel based Coproduction of Methanol and Electric Power* (Vattenfall Utveckling AB, 1991, 1992).

## 1.2 REPORT OBJECTIVES

From the historical background can be discerned a lack of long-term perspective with respect to (a) earlier and current motivation to use/not to use methanol as an alternative fuel, (b) experiences gained from earlier periods of methanol usage, and (c) why interest to use methanol as an automotive fuel has shifted through the past decades. From this, the question also arises of how this lack of long-term perspective may have influenced the potential renewable methanol market of today.

The objective of the report is thus to create a knowledge synthesis with this long-term perspective in mind, to look forward and address the following topics:

- 1) Lessons learned in the widespread tests of methanol as a fuel in the 1980s and 1990s (Chapter 2)
- 2) Recent knowledge about global use of methanol in various fuel applications including health and safety aspects of methanol usage in the fuel sector (Chapter 3)
- 3) Current and future production pathways of methanol with focus on renewable production alternatives (Chapter 4)

- 4) Current and future use of methanol in various engine applications (Chapter 5)
- 5) Methanol production cost economics (Chapter 6)
- 6) Production potential of biomethanol in Sweden (Chapter 7).

The report also includes subjects that closely relate to methanol as an automotive fuel such as the following:

- Fossil methanol economics. The report includes the production and economics of natural gas-based methanol. This provides data on a fossil fuel based alternative to today's gasoline and diesel-based systems. It also serves as a comparison to production cost of renewable methanol (Chapter 6).
- Renewable methanol competitiveness compared to other advanced biofuels. Renewable methanol production is benchmarked against lignocellulosic ethanol because ethanol is the most commonly cited renewable fuel alternative and its production economics are therefore interesting to compare to the methanol case (Chapter 6).
- Methanol as energy carrier for fuels cells. Methanol was the fuel of choice for fuel cells in the rapid developments taking place in the 1980s and 1990s. Methanol was moved out of the picture in the US developments and replaced by gasoline somewhere in the mid-1990s which later was dropped as an alternative (Chapter 3).
- Hydrogen as energy carrier. The DOE decision in 2004 to drop "on board reforming" of the energy carrier to hydrogen opened up for hydrogen as energy carrier. A brief description of a hydrogen distribution system is therefore included for the purpose of making a condensed comparison between methanol and hydrogen as energy carriers for fuel cells (Chapter 3).
- Dehydrated methanol becomes DME. DME is dehydrated methanol and the production is close to identical to the production of methanol. As a consequence, the production economics are also close to those of methanol. DME has shown to be a very efficient alternative diesel fuel with a number of important advantages compared to standard hydrocarbon-based diesel fuels (Chapter 3).

### 1.3 METHOD FOR GATHERING OF INFORMATION AND DATA

In order to carry out the objectives and more specifically to be able to grasp the partly difficult task to explain the "ups and downs" with respect to methanol's acceptance as an automotive fuel, the report includes information gathered through contacts with a large number of companies and institutions that have been and/or are engaged in activities involving methanol. Appendix 2 lists the chapter/section headlines of the report and contacts that have been taken to gather information. Most contacts have been in the form of email exchange and phone calls, but the work also includes visits and face to face meetings at conferences and other meeting places.

Examples of meetings held to gather information from the period 1980-1990:

- VW in Wolfsburg regarding methanol history within the company and their current hydrogen-fueled FC-equipped concept cars. The meeting included a meeting with Dr.-Ing. Axel



König, one of the authors of the book *Alkoholkraftstoffe* published in 1982. König and his co-author Dipl.-Ing. Holger Menred were both employees of VW and summarized the VW knowledge at the time when the 270-page book came out.

- Paul Wuebben, deeply involved in the methanol tests in California
- The Methanol Institute, which has a very large database covering the history of methanol production and use.
- Meetings with representatives of Ford, Wärtsilä, VTT, Scania, Stena, Volvo and others to describe the purpose of this report and ask for relevant information that would strengthen the knowledge base.
- Discussions with professionals at e.g. VTT, KTH, Lund University, University of Bath.

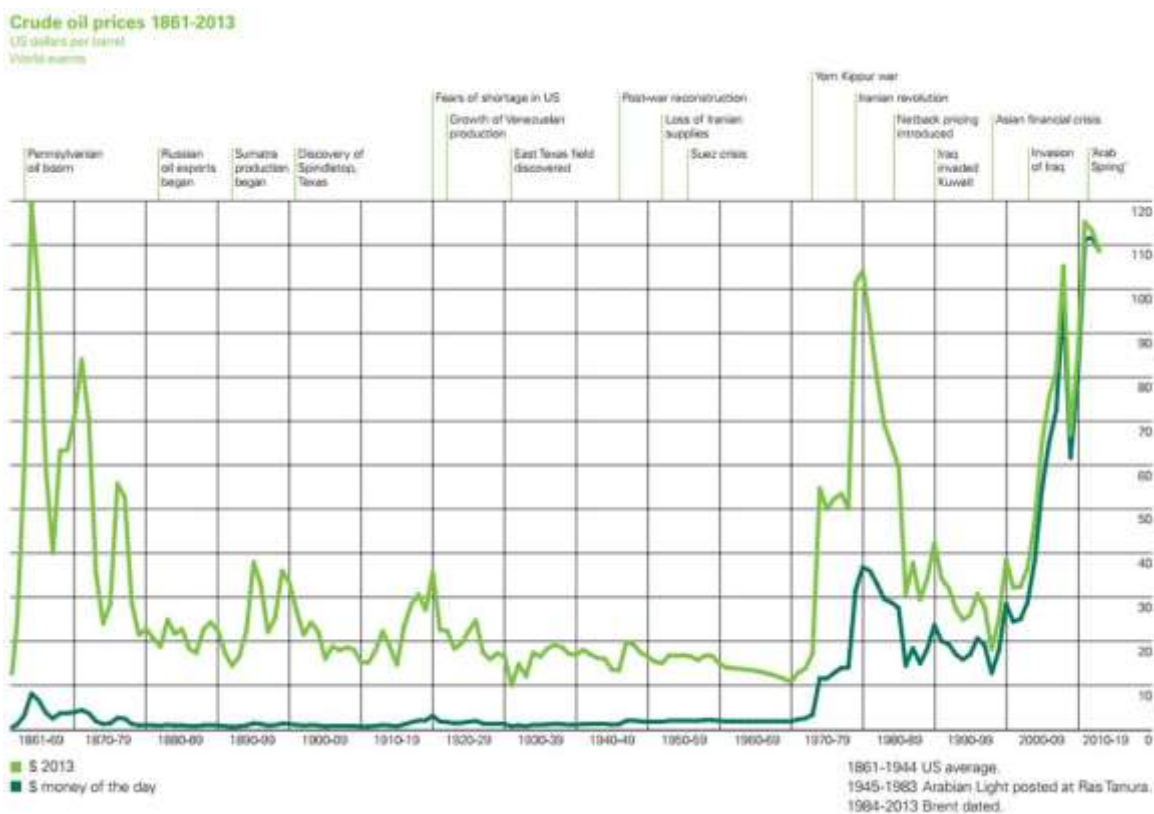
While the matrix is generally correct, it does not reveal the weight of each individual “x”, which may represent anything from a brief communication to extensive exchange of information and discussions.

A specific literature search has not been made addressing the basic causes of the change in policy, which according to the findings in this report took place between the successful methanol tests in the 1980s and 1990s and the absence of methanol as a renewable fuel alternative in the last about 20-year period. The issue was included in the list of questions raised with the approached stakeholders.

## 2 METHANOL AS A FUEL – TIMEFRAME 1970'S TO 1990'S

### 2.1 METHANOL – A NATURAL ALTERNATIVE TO CRUDE BASED FUELS AT THE 1970/80 OIL CRISES

In one of his most striking declarations US president George W. Bush in his speech to the American people in February 2006 said, “America is addicted to oil”. This was not a new discovery but increasing oil prices in 2004-2008 combined with ever-increasing oil consumption for the world as a whole gave extra weight to the statement. Also in the 1970s and 1980s, dependence on crude oil imported from the Middle East to the Western world (USA, Europe and Japan) was very strong. As can be seen in Figure 2:1, the oil price in 2013 USD was very high also in the 1975 to 1985 time frame. The shock that hit the Western world caused by the unrest in the Middle East led to a lot of major activities in order to make the Western world less dependent on the unstable oil region consisting of the nations around the Persian Gulf. IEA was formed with an initial task to make society less depended on crude oil. In Sweden the “Commission for Oil Substitution” was formed with the task to make Sweden less dependent on oil (Kommissionen mot Oljeberoende, 2006).



**Figure 2:1 Cost of crude from 1860s to 2012 in nominal USD and in 2013 USD (Business Insider, 2011).**

In the 1970 and 1980s the by far most commonly proposed alternative to oil derived automotive fuel was methanol. In some countries, ethanol was also carefully examined, as in Brazil, but in most countries that started the investigation and later on trials with alternatives, methanol was the chosen alcohol. It was already one of the world’s largest industrial chemical commodities and its production, storage and handling characteristics were well known. It was also well known that alcohols were good alternatives to gasoline for Otto engines (spark ignition engines) and a lot of

work had been done by various car manufacturers, which carefully examined various aspects of ethanol and methanol either as blend components in gasoline or as pure 100% fuels. One good example is the work done by Volkswagen and compiled in the book *Alkoholkraftstoffe* by two VW engineers (Menrad and König, 1982).

Maybe the most important factor and the key reason why methanol was investigated and tested in great detail during this time period was its cost of production. The fuel industry knew that the production cost of methanol was on the same level as products from crude oil. This was the case although the production volumes of methanol were only a fraction of the crude oil based fuel market. Methanol was an industrial base chemical and new capacities were put on stream to follow the development and increased needs of methanol in the chemical sector. The crude oil production in the 1970s and 1980s was about 8 million tons per day. Methanol production was less than 0.5% of that calculated on an energy basis. Figure 2:2 shows the cost of methanol (US Gulf Coast) and two crude oil products, naphtha (C&F Japan) and No.2 Fuel Oil on an energy basis during the period 1986 to 2015. This type of comparison is from one fundamental point of view not fair because methanol has historically been a chemical commodity and priced as such and even more important, been produced in quantities relating to the comparable small chemicals market and not for the (compared to chemicals) gigantic fuels market. Nevertheless, during long periods the methanol price has been very close to that of the two other commodities and even lower as in the period from the middle of 2008 to the end of 2012.

In some periods, the methanol price climbs considerably higher than for the two other commodities e.g. 1994/1995, 2006/07 and 2007/08. Can these spikes (and others not mentioned) be explained? Figure 2:3 relates the methanol price to various world events and to upsets in the methanol production industry.

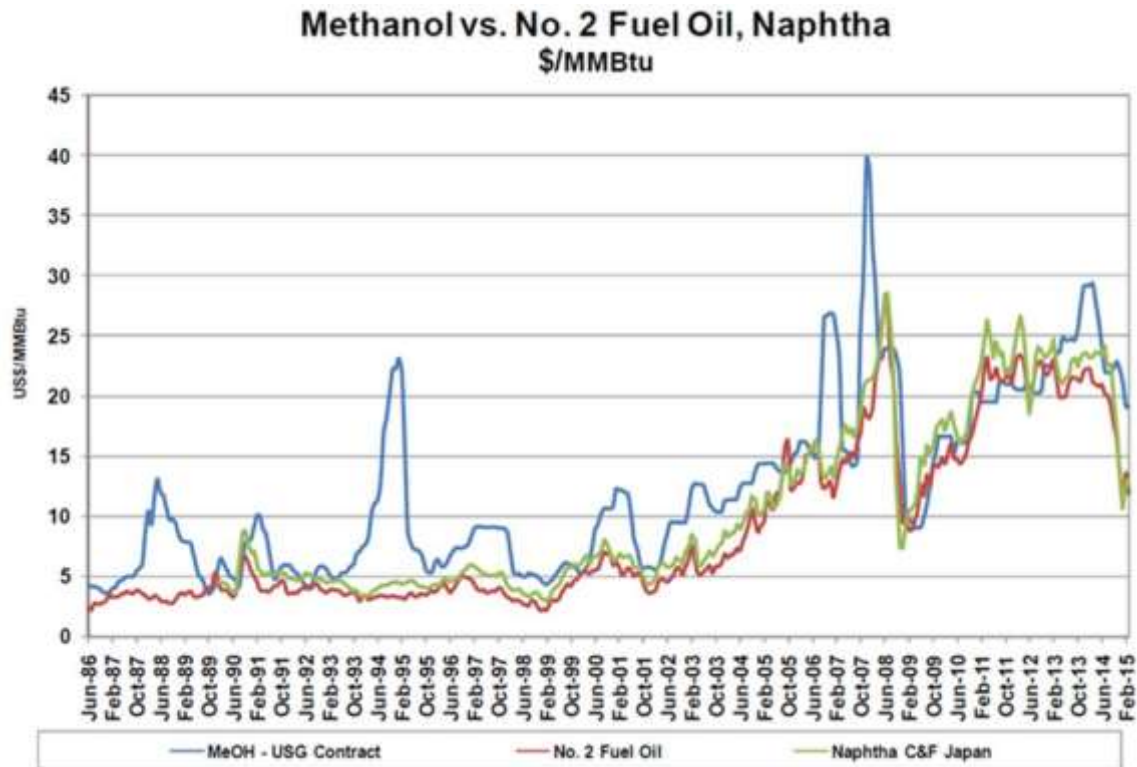


Figure 2:2 Price of methanol versus No. 2 fuel oil and naphtha 2006 to 2015 (MMSA, 2015).

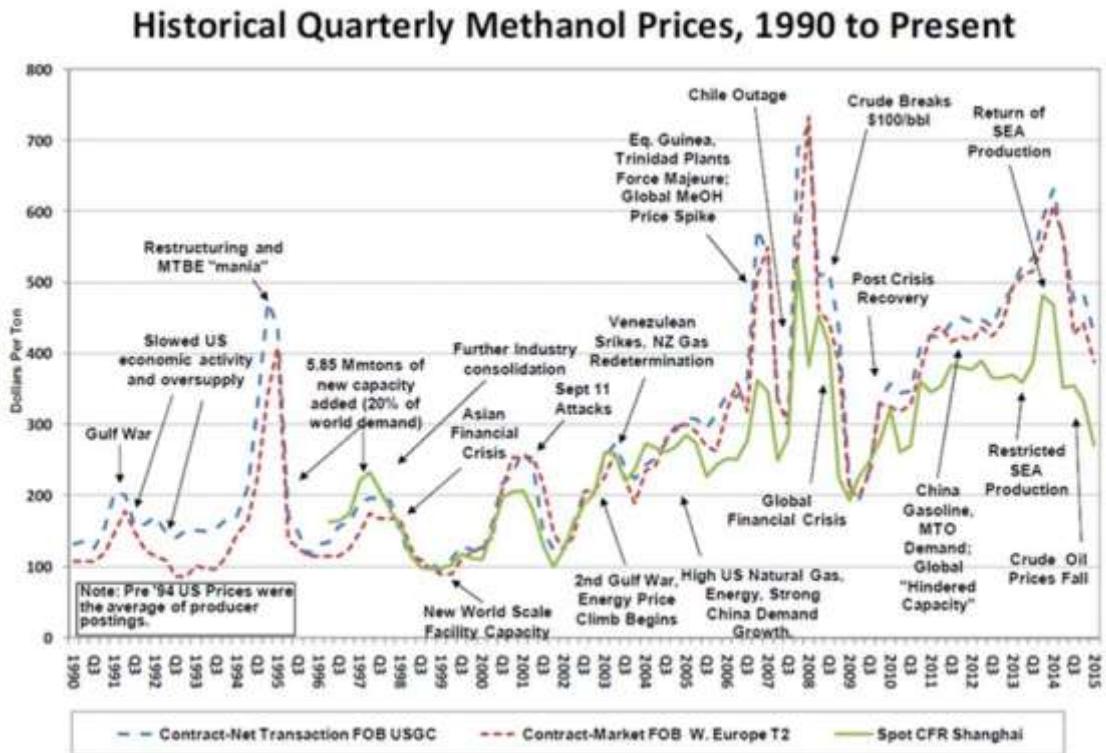


Figure 2:3. Historic methanol price 1990 to 2015 related to various world events (MMSA, 2015).

When comparing Figure 2:2 and Figure 2:3, spikes in the methanol price can be connected to e.g. introduction of the so-called Reformulated Gasoline (RFG) in the US in the early 1990s. RFG demanded some percentage of oxygenates in the gasoline to combat CO emission and reduce ozone formation. The most commonly selected oxygenate became MTBE (methyl tertiary butyl ether)

produced from isobutylene and methanol and the demand for methanol increased dramatically and so did the price. Other price spikes were caused by unscheduled production stops for large plants like 2006 in Trinidad and 2007 in Chile.

From above information, the following can be concluded:

- Methanol has historically been a commodity chemical for the chemical industry and its global production capacity, although large in chemical industry terms, is low compared to production volumes handled in the fuel industry (less than 1% calculated on an energy basis).
- The price of methanol has historically been sensitive to comparably small variations in the supply and demand balance for its major off-taker, the chemical industry.
- The oil industry knew that methanol could be produced comparably cheap and therefore be an alternative to crude-based fuels in the 1970s and 1980s. Production costs could compete with crude-based fuels. This was known prior to the oil crises in the 1970s and 1980s and it is a well-established fact today as well.

## 2.2 OVERALL RESULTS FROM FLEET TESTS IN SWEDEN, NORWAY, GERMANY AND CALIFORNIA

In December 2005, the Swedish Government appointed a commission to “draw up a comprehensive program to reduce Sweden's dependence on oil. There were several reasons. Oil prices affect Sweden's growth and employment; oil continues to play a major role in peace and security throughout the world. There is a great potential for Swedish raw materials as an alternative to oil. But especially the burning of fossil fuels threatens the living conditions for future generations. Climate change is a fact that we politicians have to deal with.”<sup>2</sup>

The Commission had a number of official hearings. One covered various production routes from feedstocks to products and various renewable fuel options. One presentation focused on the methanol and DME (Di Methyl Ether) options and Table 2:1 was presented to show experiences from trials with methanol in the 1980s. Information has been compiled from various sources (e.g. MacDonald, Perez and Mizutani, 1997; Ekbom, Landälv and Brandberg, 2008). Most of the programs ended during the 1980s. Testing in the State of California continued however to the end of the 1990s. The number of vehicles involved in operation was over 15,000 including also busses and a number of heavy-duty vehicles (not mentioned in Table 2:1).

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<sup>2</sup> Cited from the Summary of the report from the “Commission against Oil Dependence” signed by Prime Minister Göran Persson in June 2006 (Kommissionen mot Oljeberoende, 2006).

**Table 2:1. Summary of fleet test with methanol (blends or pure) during the 1980s [compiled from various source, not complete]**

Methanol blend	When?	Where?	How much? Number of vehicles/ Tot. Driving distance	Experiences D: Distribution & Storage F: Vehicles
M4	1980-82	Norway	> 600	D: Only positive results F: No reported incidents
M15	1980-83	Norway	80	D: Phase separation at one occasion F: No disturbances after initial engine adjustments
	1980-82	Sweden	1000 / 20 million km	D: No disturbances reported F: "As driving a gasoline fuelled car"
	1980-82	Germany	900 / 54 million km	D: No disturbances reported (5 oil companies participated) F: In general positive
M100	1985-86	Sweden	22	F: Positive driving experiences. Increased engine wear in non-adopted engines
	1982-86	Germany	86	--
	1982-86	USA(CEC*) USA(BoA)	>500 250	F: In general very positive results (CEC*) F: Very good results (Bank of America) * California Energy Commission

The conclusions that can be drawn from tabled information and from documents that describe the methanol experiences are quite clear. Already the first generation of methanol-adapted vehicles operated quite well or in many cases very well. It could therefore be expected that the second-generation design would have become even better. A condensed summary of results of the California experiences can be found in a presentation given by Paul Wuebben at 2015 Methanol Forum in Brussels (Wuebben, 2015). He has also produced a White Paper named *A New Look a Methanol: Accelerating Petroleum Reduction and the Transition to Low Carbon Mobility* (Wuebben, 2016) which both looks back on lessons learned and paint a picture how the gained knowledge can be explored in future developments.

### 2.3 METHANOL ON THE RACE TRACK

For various reasons methanol has been a preferred fuel for racecar drivers and teams for decades – and still is. The properties of methanol are unique from a couple of important aspects where these may be the most important.

- It has the highest octane of available Otto type fuels (ethanol and methanol are comparable), which translates into improved efficiency.
- For a given amount of air used in engine combustion, energy output increases about 60% when going from gasoline to methanol. That means that for a given cylinder volume the vehicle can get about 60% more power out when changing from gasoline to methanol. This is of course a very important aspect when competing on a racetrack.
- Methanol has a much higher heat of evaporation than gasoline, which has the consequence that the methanol fuel cools the cylinder volume much more, which leads to increased utilization of the available cylinder volume.

Methanol became the preferred fuel in the Indy 500 race (INDIANAPOLIS 500) after a severe incident in 1964 when seven cars were involved in a very serious crash resulting in a major gasoline

fire. The crash prompted the switch from gasoline to methanol. Methanol was not without problems and incidents. The largest concern was fires because methanol burns with an invisible flame. This caused some very severe and stressful situations, which e.g. can be found in a film from the Gold Coast Indy Allmendinger Race in 2006.<sup>3</sup> The film shows how two persons are caught by the invisible methanol flames, but it also reveals that they actually survived without being terribly wounded (which would not have been the case if the fire had been caused by gasoline). Methanol has eight times less heat release than a gasoline flame (EPA, 1994). To avoid the issue of invisible flames a chemical can be mixed with methanol fuel to provide flame luminosity. When blends with ethanol and/or gasoline are used, these will provide a visible orange flame.

In 2005, the Ethanol Promotion and Information Council (EPIC) approached Indycar. EPIC is a consortium of ethanol producers that advocate the increased use of ethanol. EPIC was anxious to address public concerns that ethanol use led to engine damage and poor performance when used in streetcars. As a marketing effort, it was believed that sponsoring an IndyCar could be used as a tool to promote education and awareness of ethanol use, and to curb the spread of erroneous information. The IndyCar Series has since then used ethanol blended with 2% gasoline as standard fuel.

## 2.4 METHANOL AS A RENEWABLE FUEL ALTERNATIVE

As briefly described in section 2.2 the experiences from trials with methanol in a number of countries were very positive. But most of the tests were discontinued after the oil price fell back to low levels in the middle of the 1980s. Nevertheless, California continued to experiment with the use of methanol fuels. Air quality concern was the driving force and methanol as a blend with gasoline or in its pure form continued being used almost up to the year 2000. An event that resulted in a negative burden also for methanol was the discovery of a leaking gasoline tank in California in 1995. During the coming years, MTBE was to be found in a great number of wells in many places in the US and the use of MTBE has been stopped in basically all states in the US since 2005. The so-called reformulated gasoline (introduced by the oil industry as an alternative to alcohol fuels) contained MTBE and because this molecule is water soluble, it started to contaminate the ground water. Methanol is part of the reaction when MTBE is produced. This fact was used to cast a shadow also over methanol although methanol had nothing to do with the MTBE just being a reactant in its formation.

MTBE is not classified as a hazard for the environment, but it imparts an unpleasant taste to water already at very low concentrations. The criticism of it and its subsequent decreased usage, some claim, is more a product of its easy detectability (taste) in extremely low concentrations (ppb) than its toxicity. When dissolved in groundwater, MTBE will lead the contaminant plume with the remaining components such as benzene and toluene following. As a result of the leakage problems and the discussion that follows, MTBE has in many markets been substituted with ETBE. The differences between ETBE and MTBE are small from a biodegradability point of view (Yuan, 2006) with a slight advantage for ETBE. It is however doubtful whether the small difference actually can be taken as an objective reason to go from the cheaper MTBE to the more expensive ETBE alternative. Tank leakages and spillage of gasoline containing ETBE lead to very similar effects as MTBE

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<sup>3</sup> [https://www.youtube.com/watch?v=NQ\\_UufZ0eZk](https://www.youtube.com/watch?v=NQ_UufZ0eZk)

containing gasoline. The route course, storages leaking gasoline, had also a tendency to be forgotten although that was the overarching problem.

When the increasing concentration of greenhouse gases (GHG) in the atmosphere became a subject of increasing concern and society started to seek for alternatives to fossil-based energy sources, the fuel producing industry as well as automakers started to look for renewable alternatives. In this process methanol was gradually moved out of the picture although it was the alternative of choice during the oil crises a decade earlier. A number of arguments were brought forth which earlier were not central in the debate regarding alternatives to crude oil based fuels:

- Methanol is toxic and risk for exposures leading to injuries or death had become a strong concern.
- Methanol is corrosive and will lead to more expensive vehicles.
- The energy content of methanol is low and will lead to bigger tankage and larger fuel injection systems.
- “Methanol is a chemical commodity, not a fuel.”
- Methanol requires a totally new infrastructure.

The listed concerns are real and need to be addressed with various measures. They also need to be put in comparison with other identified alternative and renewable fuels and be compared as objectively as possible. Some examples:

- The energy content of methanol is 15.9 MJ/liter and LNG 20.3 MJ/liter<sup>4</sup>. Methanol is handled in ordinary atmospheric tankage while LNG needs special tankage, distribution equipment and vehicle adaptation in order to handle the condensed gas at -160°C. Methane leakage is very difficult to avoid due to methane evaporation and methane is a highly potent GHG.
- From certain aspects methanol is more toxic than gasoline and diesel. When painting a full picture of how a system based on gasoline, diesel and methanol would result in health and safety risks for human beings the picture switches in favor of methanol. This is further elaborated in section 3.7.
- If a vehicle has been adapted to operate on E85, it is qualified to also operate on M85.<sup>5</sup> Vehicle adaptation was practically tested and associated costs well defined during long-term tests in 1980s and 1990s. See references mentioned in earlier in this chapter (2).
- European Automobile Manufacturer Association (ACEA) states in its position paper on methanol the following: “*Methanol is not allowed due to its nature of being an aggressive material that can cause corrosion of metallic components of fuel systems and the degradation of plastics and elastomers*” (ACEA, 2015). Although methanol is more aggressive compared to gasoline, materials used in modern vehicles have to be able to cope with up to

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<sup>4</sup> The reason for comparing with LNG is that LNG and methanol share areas of application, such as heavy duty vehicles and ships.

<sup>5</sup> Personal communication. Kjell AC Bergström, former CTO of SAAB, responsible for the development of SAAB BioPower. 2005



10% ethanol or higher (e.g. Brazil) as this is standard in many countries throughout the world. ACEA member vehicles are sold worldwide and their main market is often China. Cars exported to China need to be adapted to operate on methanol containing gasoline qualities. In Europe they are designed to cope with 3% methanol (M3) due to the European gasoline specification EN228 (see Appendix 3).

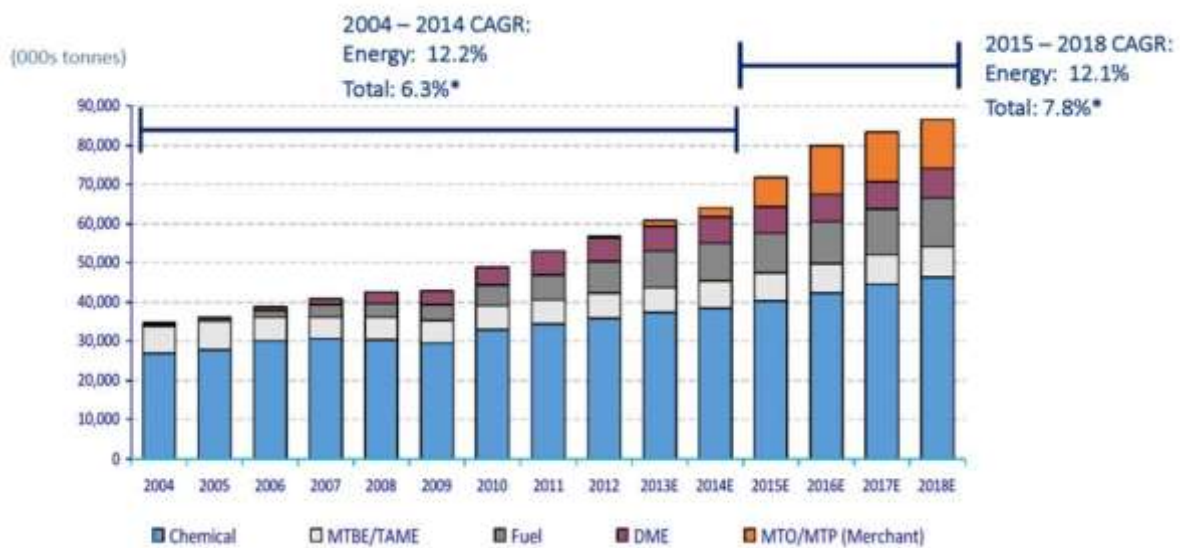
The ACEA document quoted above starts: *“In many of today’s discussions about alternative fuels, the role of methanol continues to be frequently discussed. One of the main reasons for this is that the production of methanol is relatively easy and cheap. Any kind of energy carrier (e.g. biomass, natural gas, coal) can be transferred via synthesis gas (H<sub>2</sub>, CO) into methanol. Given that such feedstock is cheap, methanol might be even cheaper than gasoline on an energy base.”*

The ACEA document continues to list nine reasons why methanol should be banned from gasoline plus that it pays special attention to the toxicity issue. Some of these items are listed in the bullets above in this paragraph. Others are discussed in various chapters of this report and are therefore not addressed “one by one”. A general observation is that despite the concern that ACEA has with respect to methanol use, considerable activities involving methanol take place in various places in the world and in different applications.

Maybe the strong negative concern expressed by ACEA stems from the fact that today’s car fleet needs to follow ever increasing performance demands and environmental restrictions. Deviation in engine performance and disturbances in the car’s exhaust control equipment can become very costly for a car manufacturer and therefore it is better to keep all new, potential threats to vehicle performance on a safe distance. Methanol in the fuel may be such a potential threat.

### 3 REVIEW OF METHANOL AS A FUEL IN A GLOBAL CONTEXT – TODAY/TOMORROW

Methanol production and demand has been steadily increasing during the last two decades and more so during the second half of that period. Figure 3:1 shows how the basic demand for chemicals is steadily increasing but also more specifically how methanol for energy usage (as a blend component in gasoline and as converted to DME) has gone from small numbers to becoming a market of about 20 million tons during a period of 10 years. Another use of methanol as a fuel, namely as a component in MTBE and FAME production, has not increased during the same period. In a longer perspective, it has actually decreased. The big increase in methanol consumption for fuel use almost exclusively relates to use in one country, China.



**Figure 3:1 World demand of methanol divided into main applications. CAGR: Compound Annual Growth Rate (IHS, 2015).**

#### 3.1 NATIONAL INITIATIVES FOR METHANOL BLENDING INTO THE GASOLINE POOL

##### 3.1.1 China

During about the last 15 years the Chinese production and use of methanol has gone from being a marginal activity to becoming a major player in the world's methanol market and even more so in China itself. Why this very strong emphasis on methanol? The key reason is China's interest in using its indigenous coal reserves to lower their dependence on imported fuels. In their evaluation of various conversion routes, they chose the methanol route due to its simplicity and energy efficiency. This road forward has however not hindered the Chinese from also introducing Coal To Liquid (CTL) technology such as utilizing Fischer Tropsch (FT) technology for production of hydrocarbons such as diesel fuel. A major investment of this type is e.g. the Shenhua Ningxia plant planned for start-up during 2016. It will produce diesel, gasoline and Liquid Petroleum Gas (LPG), together 80,000 bbl/day, from 2,300 tons/hour of coal.

The boom in methanol production and blending of methanol into gasoline led in 2013 to methanol corresponding to 7-8% of the fuel pool, which meant that methanol was present in large areas of the distribution system. As an example: The Shanxi province has demonstrated the use of methanol during the last 30 years. Over 1,500 gas station sold M15 and 60 stations were equipped with M85-M100 dispensers. The province has over 80,000 flexi fuel vehicles, mostly taxis. 15,000 taxis consumed 120,000 tons of M85/year (Dolan, 2014). A national standard for M85 and M100 exists in China since 2009. A national standard for M15 is under development but has been delayed a couple of times. Meanwhile various provinces have adopted their own standards and Figure 3:2 illustrates how this process has progressed.



**Figure 3:2. Introduction of M85 and M100 standards in provinces in China (Methanex, 2016, p. 15).**

Domestic car producers supply less than 25% of the vehicles sold in China. This means that cars built by international automakers are running “every day” on M15, because in 2013 about 7 million tons of methanol was blended in gasoline to meet M15 specifications. So, the obvious question to Original Equipment Manufacturers (OEMs) such as VW and Volvo is whether they make any special design alterations on their cars that are sold in China and what the experiences are so far. It is not easy to get any official information from the automakers regarding this issue. Typical answers are<sup>6</sup>:

- We are selling standard products in China. No adaptation to Chinese standards. We see some problems with elastomers but gasoline standards are not as stringent as those in e.g. Europe, so when problems occur we do not know what has caused them.
- Control of engine performance is not at all as strict in China as in e.g. Europe. Therefore knowledge regarding performance is less good.

<sup>6</sup> Personal Communication, Frank Seifried, 2016. Meeting with VW, Wolfsburg.

- We believe that methanol blending first of all is something that is an issue outside the cities. We have no insight into what is going on there (outside urban areas).

The connections between international automakers and the Chinese market are strong, as China is the largest market for many of the international car companies. Therefore, the methanol usage that is currently ongoing in China will over time show in practice how detrimental methanol in gasoline actually is to the current car fleet.

Due to its connection to Volvo Car (Geely owns Volvo Car) the following quote from the Chinese company Geely's chairman is included (Automotive News, 2014), "*methanol fuel is safe, economic and environmentally friendly, and shall be developed as auto fuel for green energy auto development*" (Figure 3:3, left).



**Figure 3:3. Left: Geely's chairman Mr. Li Shufu (Automotive News, 2014). Right: Geely M100 cars at CRI's methanol plant, Island (CRI, 2016).**

In the quoted article he also said that the company had developed methanol engines since 2005. The company has built a factory in the province of Shanxi, which is capable of producing 100,000 methanol-fueled cars per year. Later Geely has established cooperation with the Icelandic company Carbon Recycle International (CRI) and have supplied a number of M100 cars to the company (Figure 3:3, right). CRI produces methanol from geothermal energy and CO<sub>2</sub> and call its product "Vulcanol". Their first plant is a demonstration unit with a production capacity of 4000 ton/y. The production is sold to companies in the Netherlands, Sweden and China.

### 3.1.2 Israel

Israel discovered natural gas reserves in its sector of the Mediterranean Sea in 2000 and has since then developed its domestic-based natural gas system. The country already had a distribution network for natural gas but was totally dependent on imported gas. Israel was also totally dependent on import with respect to crude oil based products. As a consequence of the discoveries the country spent considerable resources on research and on holding national and international hearings on the topic of how best make best use of the newly found resource. One outcome resulted in the decisions to establish a national M15 standard and start to blend 15% methanol into its gasoline. This standard was brought into force in May 2016.

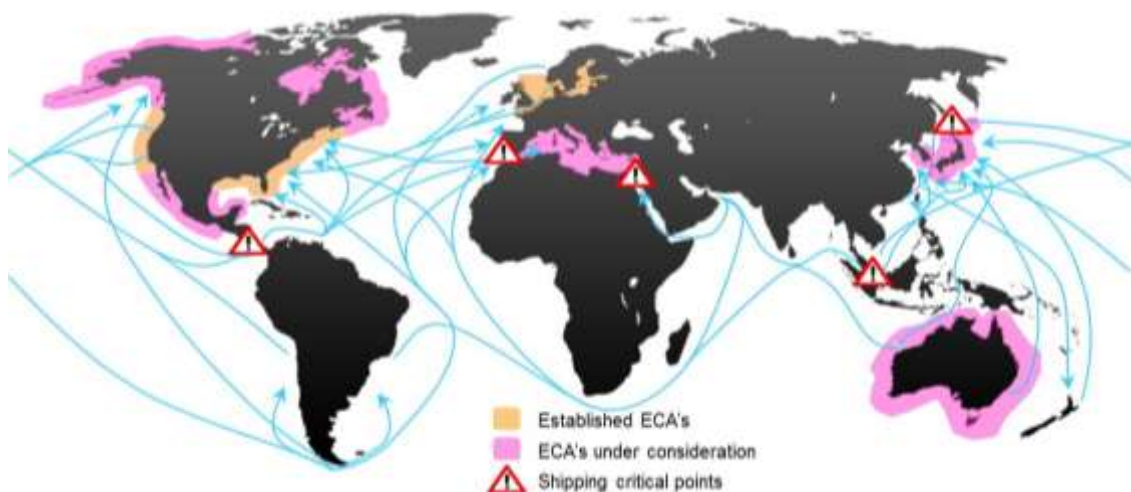
In November 2016 FCA (Fiat Chrysler Automobile) announced that the company has developed the first ever retail-ready vehicle to comply with EU Euro 6 regulations, which is also able to run on a blend of gasoline and methanol from 0 up to 15%. The adapted car model is a Fiat 500. The development is part of a project by the Israeli Government's initiative called IFCI (Israel Fuel Choices Initiative). Another key Israeli partner is the chemicals company DOR Chemicals, one of

Israel's foremost fuel components producers in order to develop methanol in terms of production, blending, infrastructure, regulations and automotive technologies.

### 3.2 METHANOL AS A BUNKER FUEL IN SHIPS

Methanol as bunker fuel for ships comes as a surprise for many who get in touch with the concept for the first time. Bunker oils are known to be the truly cheap left over hydrocarbons from oil refining and how would it then be possible for methanol to compete? During refining impurities are pushed from the light, valuable fuels (some are also removed from the slates) to the more heavy fractions, which make them high in sulfur and metals content.

The impact of bunker fuel burning in coastal waters has become an increasing concern and lately IMO, the International Maritime Organization, has imposed mandatory rules for SO<sub>2</sub> and NO<sub>x</sub> emissions from ships in so-called Emission Control Areas (ECA) around the world. Figure 3:4 illustrates the situation in 2015. The figure shows that areas in Northern Europe, namely the Baltic Sea, the North Sea and the English Channel and coastal waters in part of North America (up to 200 nautical miles from the coast) already have mandatory rules regarding sulfur emissions. From January 2015, all ships moving in these waters must limit SO<sub>2</sub> in the flue gases emitted from the ship to a level corresponding to what flue gases from combustion of a fuel oil with 0.1% sulfur would emit.



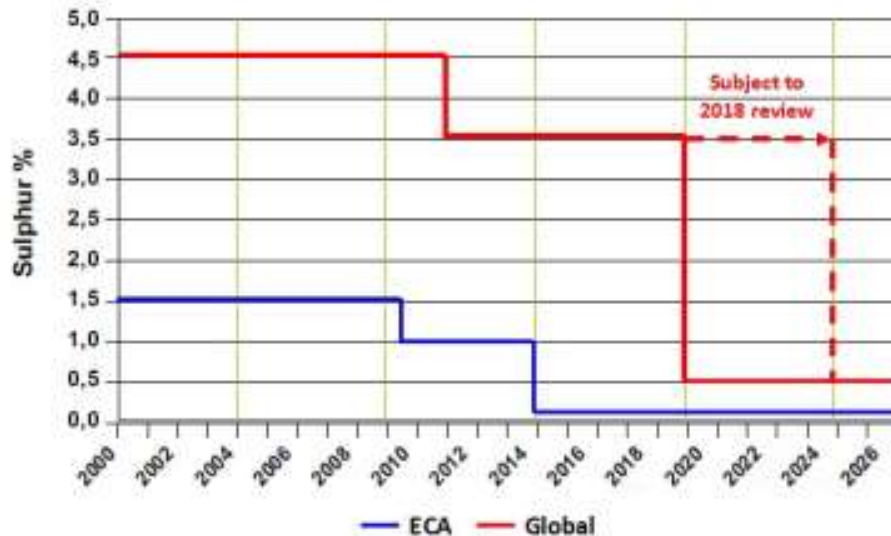
**Figure 3:4. Established and planned Emission Control Areas according to IMO.**

This new regulation has initiated a lot of activities and led to four main ways forward

1. Change fuel to MGO, a Marine Gas Oil with maximum 0.1% sulfur
2. Use high sulfur fuel oils and equip the ship with exhaust scrubbers, a type of desulfurization technology. A system to handle and get rid of waste needs to be part of that solution.
3. Convert the ship to use LNG as fuel
4. Convert the ship to use methanol as fuel

The change in quality of bunker oils for shipping is an ongoing process, which in the coming years will put further pressure on the refining industry to desulfurize their heavier products. Figure 3:5

illustrates the plan for continued desulfurization of bunker fuels. The mentioned ECA areas decreased the sulfur content from 1.0 to 0.1% in January 2015. Sulfur in bunker oils worldwide is currently on the level of 3.5%. The plan is to lower this to 0.5% during the period 2020 to 2025. No decisions are taken yet. About 27 million tons of bunker oil is currently consumed in Northern Europe. When the sulfur content dropped to 0.1%, this corresponded to a decrease of SO<sub>2</sub> emissions of about 500,000 tons /year. 9% of the world's bunker consumption is used in the mentioned area.



**Figure 3:5. Sulfur content in bunker fuels and plans for reduction (IMO).**

Maybe the most surprising outcome referring to the list of four alternatives above is the presence of methanol as a potential bunker fuel. The background lies in the fact described in section 2.1 and illustrated in Figure 2:1. The price of methanol is during long periods not higher than the cost of refined crude oil products. Figure 2:1 shows e.g. that methanol and No.2 Fuel Oil during the period June 2008 to June 2012 had a similar price on an energy equivalent basis. Marine Gas Oil with maximum 0.1% sulfur is thus during periods not cheaper than methanol and during periods it has actually been higher in price.

This lack of price difference during long periods has led to ship owners both in Europe and in the US having started to investigate if a change from crude oil based fuels to methanol can be justified. The Swedish shipping company Stena, through its daughter company Stena Line, operates a large number of ships in the European ECA area (called the SECA area, the Sulfur Emission Control Area), among them about 25 ferry boats. After investigations and tests, they decided to equip one of their largest ferries, Stena Germanica, with engines running on methanol. Actually, it implied changing fuel in existing engines. The first of four engines, each of size 6 MW, started to operate on methanol in April 2015. The other three followed some months later and the ship is currently running on methanol.

A large number of activities are part of such a major shift, not the least issues relating to safety and handling. The ship had to be certified by Lloyds to operate on methanol as bunker fuel. The same type of procedure had been carried out for LNG-fueled ships in the years before and the process was now repeated for methanol. The overall conclusion was very positive. It was e.g. accepted to store the methanol in the double hull bottom of the ship. A spill of methanol is not harmful for the environment. Because methanol dilutes fast in water and is biodegradable it breaks down relatively fast into CO<sub>2</sub> and water. An area that normally cannot be used in a ship can in this way be used for

the bunker fuel storage. Safety precautions led to all piping handling methanol being double walled, something already imposed on LNG bunker fuel (see also section 3.7).

While the Stena trials are currently running, other companies operating ships in ECA areas have ordered new ships where methanol is the bunker fuel while operated in the ECA area. Six chemical carriers are to be delivered during 2016 and they will all be equipped to operate both on methanol or different types of bunker oils (Methanex, 2013). The order contains an option of supplying another three ships.

### 3.3 METHANOL AS A RENEWABLE COMPONENT IN TODAY'S FUEL MIX

Is there already today an inroad for renewable methanol into the European fuel system? An answer to this is yes. There are at least three places where methanol is currently being consumed or could be used in today's system. These could all be of renewable origin.

First, methanol could be blended into gasoline, similar as to what is today already being done in China (see section 3.1.1). According to the gasoline specification EN228 prevailing in Europe (see Appendix 3) gasoline can contain 3% by volume of methanol. According to various sources, small quantities of methanol are found in the European gasoline from time to time. Gasoline in most European countries does not contain methanol however. With gasoline consumption in 2015 corresponding to about 110 million m<sup>3</sup>, approximately 2.5 million tons of methanol could be blended into the gasoline. According to EN228 it would be necessary to have a blend component if methanol were to be used. This blend component can be ethanol already present in the gasoline pool.

Second, biodiesel produced from various biological raw materials such as rapeseed oil is processed into biodiesel via esterification, using methanol in the process. Currently most of this methanol is of fossil origin and could be changed to renewable methanol. The proportion of methanol in biodiesel varies depending of what kind of oil or fat that is to be esterified (typically around 13% but varies between 11 and 16% by volume)<sup>7</sup>. The consumption of biodiesel in Europe during 2013 was 10 million tons or approximately 11.4 million m<sup>3</sup> (EBB, 2016). The esterification required about 1.6 million m<sup>3</sup> of methanol or about 1.3 million tons. This is a very attractive use of renewable methanol, a market already available, which would make the biodiesel have a higher GHG reduction potential than if fossil-based methanol is used in the process. However, there is currently no real incentive to use renewable methanol in biodiesel, because the legislation considers the entire energy content of biodiesel renewable despite the use of a fossil feedstock.

Third, when the oil industry developed the so-called reformulated gasoline in the 1990s, part of the solution was the addition of the octane booster MTBE (see section 2.4). Since then MTBE (methyl tertiary butyl ether) has found its way into most major gasoline markets of the world. During the last decade, it has partly been substituted by ETBE. MTBE is formed by letting iso-butylene react with methanol in a comparably simple conversion process at moderate pressure and temperature. The methanol part in the final MTBE product constitutes approximately 35%. The total European

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<sup>7</sup> There is a need to use excess methanol in order to make the reactions reach close to completion (>95%) and this excess is 50 to 100% more than what the stoichiometry requires. This excess is however separated from the crude product and reused.

MTBE consumption was 3.2 million tons in 2013 and the methanol used in production thus corresponds to 1.1 million tons/year.

Together the three mentioned markets would amount to about 5 million tons of methanol per year or 2.5 million toe<sup>8</sup>/year, which would correspond to a little less than 1% of the fuels consumed in Europe. To produce such an amount of biomethanol would require 25 plants each producing 200,000 tons of methanol per year.

### 3.4 METHANOL AS AN ENERGY CARRIER FOR DME PRODUCTION

DME is included in this methanol report because the production pathway to DME is via methanol and because methanol can become the energy carrier for a market where DME is the desired automotive fuel, especially for heavy-duty applications.

While methanol is a typical Otto engine fuel having a very high octane number its dehydrated sister molecule di-methyl-ether (DME) is a fuel very well suited for the Diesel engine having a very high cetane number. DME is normally produced in a process where two molecules of methanol react over a catalyst bed at 240 -280 °C to form one molecule of DME plus water. The reaction is slightly exothermic and has a very high selectivity. DME can be produced directly from the crude methanol formed in the methanol synthesis reactor or (of course) from the traded purified so-called Grade A or Grade AA methanol. It can also be directly synthesized from the synthesis gas. The H<sub>2</sub>/CO ratio shall then be adjusted to 1.

In a developed DME fuel market methanol may become the energy carrier for DME production. For large production capacities produced far away from the market economic calculation may show it to be more efficient to transport and store methanol (a liquid) than to store and distribute DME which is a gas at atmospheric pressure and therefore is handled at about 5 bar (as a liquid) and handled in principle as LPG. A distributed versus a centralized DME production system needs further evaluation.

DME has first of all been identified as a promising fuel for HD vehicles but could as well be an attractive alternative for e.g. barges in the European channel system. A DME installation on a HD vehicle has very good synergies with existing diesel engine installation in platforms; by changing a limited amount of components, it is possible to develop a DME variant of a diesel vehicle. This possibility reduces the complexity of the system, which is very important to bring down the cost. Because of volume effects, a DME variant will have higher initial costs, but a simple system reduces this effect and gives opportunities for future cost reductions. All parts related to the fuel system need to be replaced, i.e. the tank system and the fuel injection system and piping on the engine. There are also some material issues, e.g. seals, that need to be replaced. The DME engine also requires new engine control functionality, as the physical properties of DME are quite different from those of diesel. Therefore, although the changes are limited, the engine is a dedicated DME engine and cannot be run on diesel (ERTRAC, 2014). Some key aspects regarding DME as a fuel:

- Excellent auto ignition properties, which corresponds to a high cetane number and makes it a suitable fuel to be used in highly efficient diesel engines.

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<sup>8</sup> Tonne of Oil equivalent.



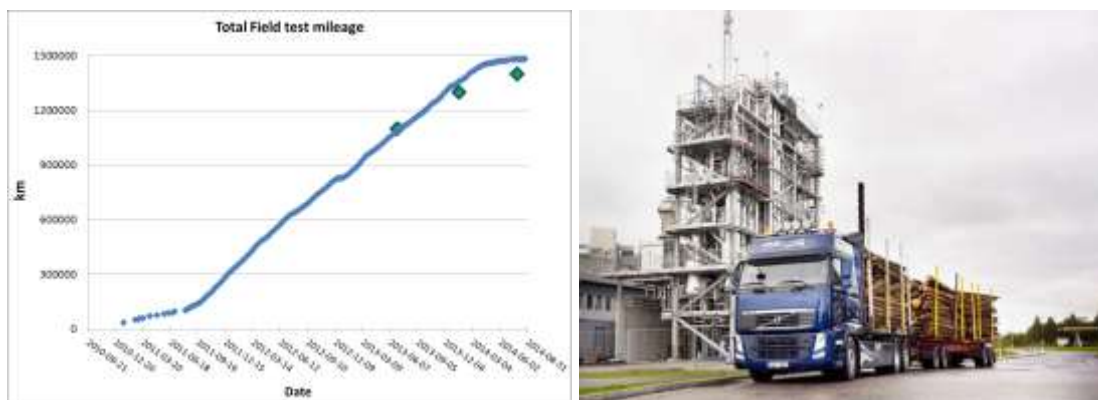
- Produces almost no soot in the combustion process, which means that the particulate matter (PM) emissions are very low even without exhaust after-treatment systems. The reduction of the exhaust after-treatment enables opportunities to increase the vehicle payload and offer better suitability for body works, and the low soot levels also gives the option to apply a high level of exhaust gas recirculation (EGR) to reach low engines NO<sub>x</sub> emissions.<sup>9</sup>
- Although the handling is more complicated than handling diesel, the tank system installation is less complex compared to LNG and CNG fuel systems that must handle very low temperatures (-160°C) or high pressures (> 200 bar).
- Lower energy density compared to diesel, which decreases the possible action ranges by approximately 50%. Comparable action range as an equivalent LNG truck fuel system and is significantly improved compared to CNG.
- DME has poor lubricity, and therefore a lubricity improver needs to be added to the fuel.
- Basically consists of one single molecule which reduces the risk of local market issues related to differing fuel qualities. As a comparison, diesel is a mixture of thousands of different hydrocarbons and the quality varies globally. Nevertheless, a fuel specification is necessary to control impurities and secure the inclusion of lubricity additives.
- Non-toxic with rapid degradation to CO<sub>2</sub> in air and no known environmental impacts.
- More difficult to reach very high injection pressures, due to physical properties.

In the EU FP7 BioDME project, Volvo operated ten DME-fueled HD trucks in commercial services for more than 1,500,000 km as shown in Figure 3:6 (left). The trucks operated almost all the time on BioDME produced from conversion of black liquor (pulp mill intermediate) to BioDME at a site in Northern Sweden shown in Figure 3:6 (right). The project met or exceeded expectations from all important aspects and was described as a success story by EU. A condensed description of two years of operation of the plant and the vehicles can be found in (Landäl *et al.*, 2014).

The connection to methanol in the BioDME project is clear, as the production of DME was based on methanol production, in a novel process. In the process, raw methanol is reacted to DME, after which the formed DME is separated by distillation and the non-reacted methanol recycled to the DME reactor for complete reaction to DME. The DME content in the product is above 99.8% by volume. See also section 4.1, about methanol synthesis.

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<sup>9</sup> The e.g. Volvo BioDME vehicles meet Euro V emission levels by use of EGR and oxidation catalysts.



**Figure 3:6. Left: Accumulated mileage for HD DME trucks 2010-2014 [LTU Green Fuels]. Right: The BioDME plant LTU Green Fuels and one of the Volvo HD trucks in commercial service in the Piteå area [LTU Green Fuels].**

Also Ford is actively working with DME as fuel but first of all for passenger cars. Currently Ford initiated the “xME for Diesel”-project funded by the German Ministry of Economy. The project was kicked off in September 2015 with the objective to look at DME and OME1 (=Methylal or Dimethoxymethane) in passenger cars and HD applications. Engines are being set up and vehicle demonstrators will be available in 2017/2018. In Ford’s presentation material<sup>10</sup> regarding the project, they claim e.g. ultraclean emissions and increased fuel efficiency plus very low greenhouse gas emissions, as low or lower than EV cars when in both cases renewable electricity is the prime source of energy. Ford is also engaged in a parallel project together with Aachen University on Fuel-Generation paths (in particular Electro-Fuels: CO<sub>2</sub> + regenerative electricity => DME/OME1) in order to identify efficient fuel generation possibilities on small, medium and large production scales.

### 3.5 METHANOL AS ENERGY CARRIER FOR HYDROGEN PRODUCTION

Hydrogen is by many viewed as the ultimate fuel for many of our transport needs and it has for a long time received considerable financial support from federal and national funds. In 2002 the US DOE published “A national vision of America’s transition to a hydrogen economy – to 2030 and beyond” and initiated a large number of advanced research projects. In Europe, the “Fuel cell and Hydrogen Joint Undertaking” was initiated in 2008. For the fiscal year 2014 the EU budget was close to 90 MEUR, of which the EU contribution was around 86 MEUR and the industry’s about 2 MEUR.

In 2014 the EU signed a new Directive (2014/94/EU) regarding deployment of alternative fuels infrastructure. In article 1 it states, “*This Directive establishes a common framework of measures for the deployment of alternative fuels infrastructure in the Union in order to minimize dependence on oil and to mitigate the environmental impact of transport. This Directive sets out minimum requirements for the building-up of alternative fuels infrastructure, including recharging points for electric vehicles and refueling points for natural gas (LNG and CNG) and hydrogen (...)*”. The direc-

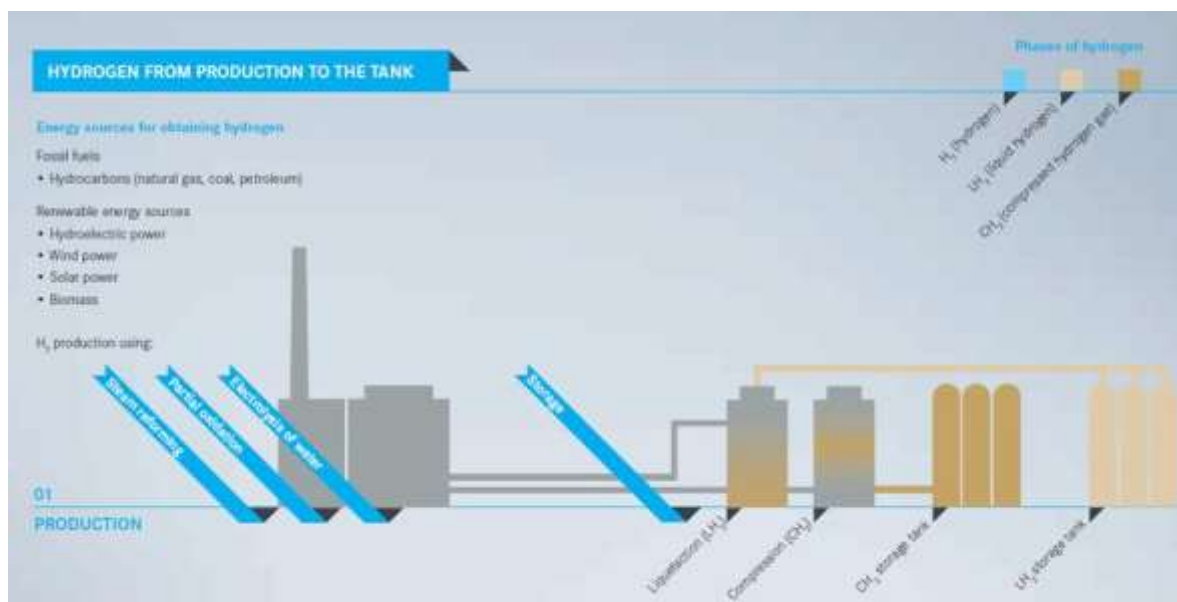
<sup>10</sup> Personal Communication Werner Willems, Ford, 2016 and [https://www.aboutdme.org/aboutdme/files/ccLibraryFiles/Filename/000000003015/Ford\\_DME\\_infographic.pdf](https://www.aboutdme.org/aboutdme/files/ccLibraryFiles/Filename/000000003015/Ford_DME_infographic.pdf)

tive includes a time plan for how the EU member states shall implement the infrastructure alternatives. Extensive work is currently ongoing on state and EU levels. (European Union, 2014)

To develop a complete “well to wheel” solution for a hydrogen fuel system storage and distribution is a true challenge. Gaseous hydrogen is handled at very high pressures (700-800 bar) in order to bring sufficient quantities on board a vehicle. Still at this very high pressure, the energy density is far away from other alternative fuels. Regardless of these drawbacks, since early 2000 the predominant route for bringing fuel to the FC vehicle has been to distribute and store the energy in the form of hydrogen.

Daimler has for more than two decades worked intensively with FC vehicles and they have developed scenarios describing how they see the hydrogen infrastructure to be laid out over a country like Germany. Daimler regularly publishes reports in a series called Daimler TECHNICALITY and issue 2-2010 is named “Fuel cell future” (Daimler, 2010), a report comprising 100 pages of information relating to hydrogen FC vehicles and systems. Other companies involved in hydrogen FC development have joined forces in the so-called Joint Energy Partnership (JEP) and developed sophisticated models for how hydrogen is intended to be produced, distributed and stored in this novel infrastructure. Vehicle manufacturers involved are e.g. Daimler, BMW, GM/Opel, Toyota and VW and oil companies are represented by Shell, Total and Statoil. The engineering contractor Linde is also a member of JEP.

One section is devoted to the description of hydrogen infrastructure and Figure 3:7 illustrates how hydrogen is planned to be produced from fossil and renewable sources and stored in gaseous ( $\text{CH}_2$ : compressed hydrogen) and liquid ( $\text{LH}_2$ ) form.



**Figure 3:7. Hydrogen: from production to the tank (Daimler, 2010, p. 51).**

In the same way three illustrations covering distribution, provision and use show a very sophisticated system including distribution in pipelines ( $\text{CH}_2$ ) and as  $\text{CH}_2$  and  $\text{LH}_2$  on trucks and final cryogenic pumping and compression to 700 bar at the tank station. The technical complexity, low energy density even at very high pressures, cryogenic handling of  $\text{LH}_2$  at  $-253\text{ }^\circ\text{C}$ , and various safety aspects make infrastructure for hydrogen a very complex and expensive business.

Why include information about hydrogen infrastructure and use in this Knowledge Synthesis about methanol?

The reason is that there is a history before the hydrogen concept was adopted and became the prevailing energy carrier for FC systems. Daimler and other developers of FCs spent large efforts on developing vehicles where methanol was the fuel and the concept included reformation of methanol on the vehicle and producing pure hydrogen for the FC. Daimler had parallel efforts where with their so-called NECAR cars 1 to 5 they tested different approaches (Ernst, 2007). The last car in the series, NECAR 5, was operated with a methanol reformer on board (so was also NECAR 3) and in May-June 2002 the car made a journey across North America, in total 5,250 kilometers on its way from San Francisco to Washington, D.C. In 12 days it clocked 85 operating hours with an average speed of about 62 km/h. NECAR 5 consumed about four liters of methanol per 100 kilometers, which corresponds to about two liters of gasoline equivalents per 100 km, a very low consumption figure. During the trip it had:

Snow and ice at temperatures around 0° Celsius; More than 1,300 km over 2000 meters; Highest point at 2,657 meters; Long stretches of superhighway in Nebraska; Heat of up to 35° Celsius; Stop and go in big cities like San Francisco, Chicago and Washington, D.C. Except for fuel filters, V-belts and a water tank there were no repairs worth mentioning.

The US had since the late 1980s been active in FC developments and in the US the choice of fuel was an open issue. Alcohols (methanol and ethanol) and hydrocarbons (gasoline and methane) were all tested with the presumption that the fuel was to be reformed to hydrogen on board the vehicle. During the development process, the fuel of choice was narrowed down and the alcohols disappeared. This can indirectly be seen in a DOE Decision Team Committee Report (US Department of Energy, 2004). In the background of the report it can be read: “*From the late 1980s through the early 1990s, the DOE Fuel Cells for Transportation Program focused on steam reforming of methanol to provide hydrogen-rich reformate for polymer electrolyte membrane (PEM) fuel cells. Methanol possesses high energy density, is simple to store, easy to reform and can be rapidly fueled into a vehicle.*” During the 1990s, the methanol option was dropped (no reason given in the document) and the document does not address the potential Go/No-Go of methanol reforming on board a vehicle but rather for gasoline, a much more demanding fuel to reform into a clean hydrogen fuel for the FC.

Why was methanol ruled out of the picture? This is not clear but it is well known that the oil majors had no interest of introducing methanol in the fuel market and they participated often in conferences and workshops and expressed their negative view of methanol as a fuel. These activities were very intense in the years before and after the year 2000. The common arguments were: Methanol is toxic and methanol is corrosive.

Two partnerships existed in the background during the period mentioned above. It was the FreedomCAR Partnership established in 2002<sup>11</sup> and the FreedomCAR and Fuel Partnership established

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<sup>11</sup> Partners are DaimlerChrysler Corporation, Ford Motor Company and General Motors Corporation.

in 2003.<sup>12</sup> Daimler was in cooperation with Chrysler from 1998 to 2007 and it is easy to come to the conclusion that the German FC development had to follow the very strong signals from DOE and The FreedomCAR and Fuel Partnership view.

When DOE in 2004 officially announced its NO to on board reforming, it became an important milestone for European developers of FC vehicles, not only for Daimler but also for VW as well as for Japanese OEMs such as Toyota. The American market would not continue with on board reforming concepts. The only energy carrier with no need for a reformer on board is then hydrogen.

Recently Nissan has ironically closed the circle when they in June 2016 announced that they developed a fuel cell for on board reforming of ethanol. The arguments are interesting and contradict the phase out of a simple alcohol as energy carrier for FC vehicles (see section 5.7).

### 3.5.1 *Can methanol be brought back into the picture?*

Methanol may still play a role in the “hydrogen economy” as it currently is described e.g. in the above cited Daimler report. An alternative to hydrogen infrastructure is to create a methanol infrastructure and reform methanol to hydrogen at the fueling station. Methanol is a large and well-known chemical commodity and the production, distribution and storage are well known and would be a low cost option compared to a hydrogen infrastructure. As described in chapters 4 to 6 methanol is a strong candidate as energy carrier and fuel with respect to production pathways, utilization in various engines as well as from the production economy’s point of view.

Mitsubishi Gas Chemical (MGC) has developed a methanol to a pure hydrogen process, which operates at relatively low temperatures (240-290°C) and enables rapid start-up and stop. The technology is in use by customers in the electronics, glass, ceramics and food processing industries. In the Japanese Hydrogen & Fuel Cell Program (JHFC) hydrogen is produced at the gas station using steam reforming of various primary fuels and in Kawasaki MGC’s technology for methanol reforming is utilized. According to JHFC methanol is the safest of all materials available for hydrogen production (Olah, Goepfert and Prakash, 2011, p. 190).

An interesting comparison between methanol and liquid hydrogen is the following:

*Hydrogen (H<sub>2</sub>) content in 1 liter of methanol at room temperature contains more hydrogen (98.8 g) than 1 liter of liquid hydrogen does at -253°C (70.8 g) (Olah, Goepfert and Prakash, 2011, p. 191), actually about 40% more!*

<sup>12</sup> Partners the Department of Energy (DOE), BP America, Chevron Corporation, ConocoPhillips, Exxon Mobil Corporation, Shell Hydrogen LLC and the United States Council for Automotive Research (USCAR) — a legal partnership among DaimlerChrysler Corporation, Ford Motor Company.

### 3.6 INFRASTRUCTURE CONSIDERATIONS

Production and use of fuels can be seen as a process in four steps: (1) feedstock identification including availability and various aspect of quality, (2) conversion to a fuel, (3) fuel storage and handling (4) fuel use in engines/vehicles. The base line today is easy to identify. Crude oil feedstock represents step (1) and engines running on gasoline and diesel step (4).

It is a commonly expressed view among today's stakeholders representing the main pathway crude oil to gasoline and diesel that new renewable fuels trying to enter the fuels market should comply with today's infrastructure system, implying that the most costly part of the four steps mentioned is the third one, fuel storage and handling. A commonly used terminology that shows up in many reports and policy document is that the new fuel should be "infrastructure ready" or be a "drop-in fuel" implying it is just to mix into the systems distributing diesel and gasoline today. It is easy to accept this reasoning, which then in turn leads to the new processes either using the thermochemical or the biochemical conversion route should fulfill this boundary condition.

The heavy focus on today's infrastructure has had the following two important consequences with respect to methanol:

- Methanol is not allowed in the USA gasoline standard, which means there is no place for methanol in their fuel system. The European gasoline standard allows for 3% methanol with a co-solvent and methanol is from time to time found in low concentrations in European gasoline but normally there is none.
- With the focus on "drop-in" fuel solutions it has been difficult to have fruitful discussions regarding other promising and efficient renewable alternatives such as methanol as well as for DME. Infrastructure costs have been looked at as a major obstacle.

With EU Directive 2014/94/EU in place, the basic logic of "drop-in" fuels and "infrastructure ready" renewable fuels is overruled by new candidates, which definitely need new and also comparably expensive infrastructure (European Union, 2014; DG MOVE, 2015). The directive calls for EU wide infrastructure for electricity (for electro-mobility), compressed natural gas (CNG), liquefied natural gas (LNG) and hydrogen. The European natural gas grid will be extended to carry CNG at a dense network of CNG fueling stations. Biomethane produced in various ways will be purified and compressed and fed into the CNG network to make the fossil NG over time more and more sustainable. Corridors across Europe will distribute LNG and this system too will over time become more and more renewable via injection of liquefied biomethane into the system. LNG is intended to be used for HD transport and as bunker fuel in ships and barges on the European channels.

The background to the inclusion of hydrogen in the directive has been discussed in section 3.5, while the focus on methane stems from an attempt from the EU Commission to make EU less dependent on crude oil based fuels. NG based fuels were thought to increase due to import of fuels from less stable regions in the world and also lower GHG emissions from fossil fuels. Both arguments have during the last few years lost most of their weight as EU dependence on Russian gas today cannot be seen as a better choice than being oil dependent. Further, investigations (DG ENER, 2015, see Figure ES-2) have shown that leakages along the production and handling route for NG have made a difference in GHG emissions from crude oil based fuels and CNG/LNG fuels to shrink to very little or zero.

The four steps listed above can be used when analyzing introduction of a new fuel in the transport sector, e.g. methanol:

- What is/are the available feedstock(s) for the fuel production?
- How efficient and complex is the fuel production?
- How can the fuel be stored and distributed?
- What are the advantages and disadvantages of the fuel for the vehicle?

In the study *Climate Issue in Focus* (Volvo, 2008) eight different renewable fuels were analyzed with respect to seven different important criteria with respect to being used in heavy duty vehicles. The overall results were presented as a matrix shown in Figure 3:8. The background to the indicators in the matrix is presented in the brochure in the form of data and diagrams.

	Climate impact	Energy efficiency	Land use efficiency	Fuel potential	Vehicle adaptation	Fuel costs	Fuel infrastructure
Biodiesel	4/5	4/5	1/5	1/5	4/5	4/5	4/5
Synthetic diesel	4/5	4/5 / 4/5	3/5	4/5	4/5	4/5	4/5
DME - Dimethyl ether	4/5	4/5 / 4/5	4/5 / 4/5	4/5	4/5	4/5	3/5
Methanol - Ethanol	4/5 / 4/5	4/5 / 4/5	4/5 / 4/5	4/5	4/5	4/5	3/5
Methanol - Ethanol	3/5	3/5	1/5	3/5	4/5	3/5	3/5
Biogas	4/5	3/5	4/5	4/5	1/5	3/5	1/5
Biogas - Biodiesel	4/5	4/5	4/5	4/5	4/5	3/5	1/5
Hydrogen - Biogas	4/5 / 4/5	3/5	4/5	4/5	1/5	3/5	1/5

**Figure 3:8 Summary of results for different criteria and fuels (Volvo, 2008).**

The methanol alternative is one of the eight fuel candidates and as can be seen from the matrix this fuel has high scores for most of the criteria. To the far right the cost and complexity of the fuel infrastructure is indicated on a scale one to five. Volvo presented the following description with respect to infrastructure cost in general and specifically regarding methanol as a fuel.

Volvo acknowledges that the infrastructure is often viewed as a key challenge when discussing introduction of a new fuel but adds: *However, it should be noted that since the infrastructure for conventional fuels is also in need of major investment, infrastructure is a secondary issue in the longer term.*

Three symbols in the matrix stand for “Major Changes (liquid fuel)” and the following comment is given with respect to ethanol and methanol: *When used in pure form, methanol and ethanol require corrosion-resistant materials, additional fire safety measures and a separate infrastructure. Due to the significant health hazards involved, methanol should be handled in completely closed systems.*

In summary methanol as a renewable fuel comes out very strong in comparison with other renewable fuels. A comparison of the EU Directive 2014/94/EU with the Volvo view can preferably be done.

### 3.7 HEALTH AND SAFETY CONSIDERATIONS

As has been described, methanol has both been (one of) the fuels of choice when looking for alternatives during the oil crises in the 1970s and 1980s, and a prime candidate as energy carrier for fuel cells on board vehicles. The reason why methanol was ruled out of these applications is not clear, but it is well known that the oil majors had no interest in introducing methanol in the fuel market and that they often participated in conferences and workshops and expressed their negative view of methanol as a fuel. These activities were very intense in the years before and after 2000. The common arguments were: Methanol is toxic and methanol is corrosive. Both these arguments are of course true, but are they true to the extent that methanol should be ruled out of applications, since it might be a prime candidate if these two arguments were less stressed?

Because methanol is one of the world's largest industrial chemicals and present in numerous applications, it has been carefully examined from health and safety points of view. Also because it has been a candidate to become an automotive fuel it has been investigated in deep detail and compared with currently used fuels, especially gasoline, because methanol has first of all been a candidate as a gasoline replacement.

This chapter will not describe different alternative fuels and make comparisons between them (e.g. ethanol, methanol, methane, CNG, LNG, hydrogen etc.) and compare them with today's dominating fuels, gasoline and diesel with respect to health and safety. Instead, it refers to a number of detailed investigations and reports and to practical experience with respect to health and safety aspects of methanol in need of special attention, some of which have already been addressed in section 2.4.

#### 3.7.1 **Safety: Methanol as compared to gasoline with respect to fire risk**

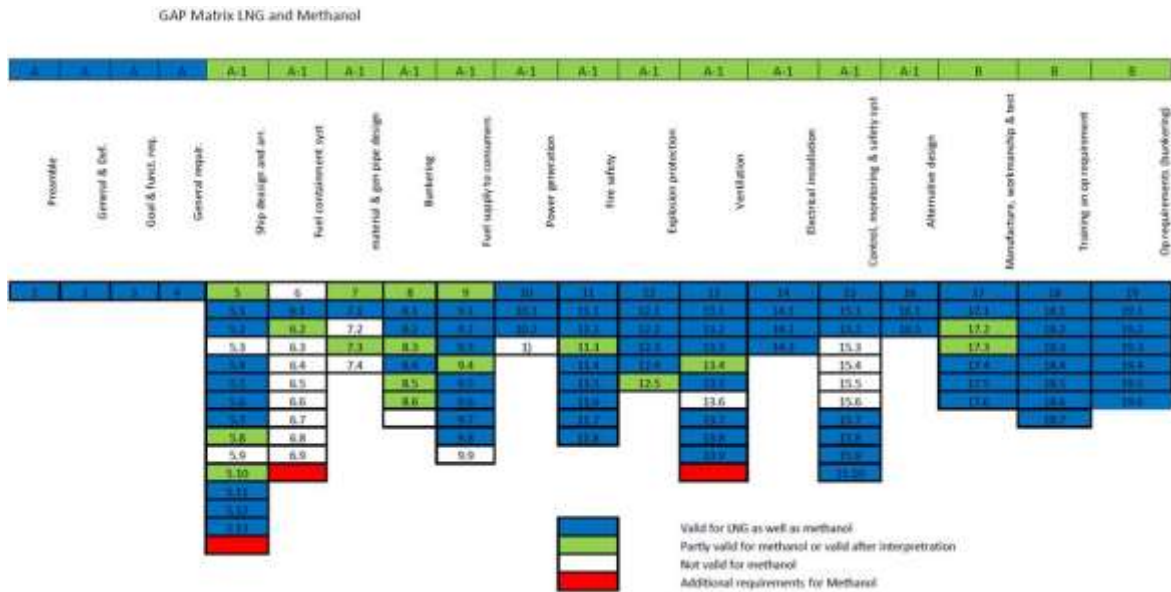
In conjunction with the intense testing of methanol as an alternative to gasoline during the 1980s in the US, both the US Environmental Protection Agency (EPA, 1994) and the Society of Automotive Engineers (SAE) (Machiele, 1990) presented overall conclusions with respect to risks of fire if gasoline was to be exchanged to methanol. In summary the investigation says, "Projections indicate that casualties would drop dramatically if methanol were substituted for gasoline as the country's primary automotive fuel." The short summery gives some of the fundamental reasons why this is the case such as:

- Lower volatility of methanol compared to gasoline
- Higher flammability requirement (four times higher concentration of methanol vapour needed to ignite compared to gasoline)
- Lower vapour density of methanol avoids dens gas clouds along the ground
- Lower heat release rate (an eighth compared to gasoline)



**3.7.2 Safety: Methanol in confined spaces such as engine room in a ship**

Safety is of uttermost importance when allowing a fuel to be used as bunker fuel in ships. Methanol is a low flashpoint fuel and must comply with the so-called IGF Code (International Code of Safety for Ships using Gases or other Low flashpoint Fuels). The practical way to approve methanol according to this code, was to compare how LNG was investigated and approved according to the same code (see Figure 3:9). The work was done by Lloyds and DNV. The rules are still provisional but there are no reasons to believe they will not be passed. The extensive work can be illustrated by a matrix where all aspects of safety and handling are divided into a large number of subheadings.



**Figure 3:9. GAP analysis between LNG and Methanol as bunker fuel in ships (Freudendahl, 2016).**

Figure 3:9 shows 19 such subheadings e.g. Bunkering (#8), Fire safety (#11) and Ventilation (#13). Each topic is then divided into subtopics which can be just a few or quite a number as on the Ventilation topic. As can be seen from the figure only four items (in red) were needed to cover “methanol only” subtopics. White items are not valid for methanol while blue and green are valid or partly valid for both LNG and methanol.

Stena Line has revamped their largest ferryboat to run on methanol (plus an ignition improver). Such a decision would not have been taken if the company had not been convinced that health and safety issues would be handled at a satisfactory level.

**3.7.3 Health: Risks associated with exposure to methanol compared to gasoline**

Methanol is produced in small amounts in the human body as part of the metabolic process, and occurs naturally in some fruits. At high enough concentrations, it is poisonous. Ingestion of 10 ml can cause blindness and 60-100 ml can be fatal if the condition is untreated (Bromberg and Cheng, 2010, Chapter VII and VIII). This risk has been quantified and put in relation to risks associated with use of other fuels, especially gasoline. Such a comparison does not lead to disqualification of methanol. On the contrary, methanol has from many aspects a better risk profile than gasoline. In a

scenario with extensive use of pure methanol, mitigation measures would be put in place to minimize the risk of humans being directly exposed to methanol. See the comparison in chapter VII of (Bromberg and Cheng, 2010).

#### **3.7.4 *Health and Safety: Risk assessment in conjunction with methanol introduction in FC vehicles***

As described at length in section 3.5, methanol has been of interest as fuel for fuel cells, including on-board reforming. The author has been in contact with a number of stakeholders to try to understand the swing in interest with respect to methanol use on vehicles including large car manufacturers and developers of FC technology. Just after the millennium shift (2002), a major report covering risk assessment when moving from gasoline to methanol use on a broad scale was carried out by a well-known risk assessment group on behalf of some car and oil majors (Det Norske Veritas, 2002). This assessment came out in clear favour of methanol but was never published. The author has read the report, which is labelled “For internal use only”. The principal conclusion of the report is that when all impacts on human health and safety are considered and weighted together, the risk is clearly greater for a gasoline based fuel system than for a corresponding methanol based system. The results thus confirm and support what has been concluded also in other detailed investigations.

#### **3.7.5 *Health and Safety: Methanol Safe Handling Manual***

Methanol Institute (MI) is the global trade association for the methanol industry representing the world’s leading methanol producers, distributors and technology companies. From their web site a Methanol Safe Handling Manual is available free of charge (Methanol Institute, 2013). The approximately 150 pages long document describes all kinds of aspects of methanol production, storage and use under headings such as Health and Safety, Process Safety, Fire Safety, Emergency Response, Methanol Incidents and Safeguards.

#### **3.7.6 *Concluding remarks regarding health and safety***

The author claims that the arguments regarding risks relating to health and safety (corrosion risks are treated here as part of safety) are overemphasized and that measures can be or have been developed to mitigate them. Extensive commercial use of methanol in various applications is described in this report and these provide practical evidence that the often-quoted two words (toxic and corrosive) are simply not a sufficiently strong argument to rule out methanol from the fuel application arena. This view is supported by the above mentioned reports and investigations.

## 4 CURRENT AND POTENTIAL FUTURE PRODUCTION PATHWAYS FOR METHANOL

One key to success for converting of an energy feedstock to methanol is the generation of a (sufficiently) good quality syngas, which is a mix of hydrogen (H<sub>2</sub>) and carbon monoxide (CO). Syngas conversion and barriers to efficient conversion of the syngas to various products i.e. methanol are well known by many commercial process providers in that field. Thus, the route to success lies in efficient and not too complicated syngas generation. Therefore, this chapter starts with a description of methanol production and the demands that the upstream processes need to fulfill in order to deliver the required syngas to the methanol synthesis. Thereafter follows sections describing syngas generation from different feedstocks.

This report focuses methanol. From a technology development standpoint syngas can be further converted to almost any kind of fuel and chemical including e.g. hydrogen, methane, FT diesel, ethanol, DME, various base chemicals such as plastics etc.

### 4.1 METHANOL GENERATION FROM SYNGAS

Today methanol is primarily produced from natural gas via synthesis of syngas at high pressure (70-100 bars) and temperature (240 -280 °C) over a fixed bed catalyst. Syngas for methanol production is characterized by the stoichiometric ratio  $(H_2 - CO_2) / (CO + CO_2)$ , often referred to as the module M. M close to 2 defines a stoichiometric synthesis gas for formation of methanol. With an optimum synthesis gas, the conversion of synthesis gas energy to methanol energy is about 80% and the released heat of reaction is converted to steam at about 30 bar. The selectivity to methanol reaches 99.9%.

The synthesis gas to methanol conversion step is very well established, which means that if the quality of the syngas fulfills the requirements for the conversion, then methanol is produced according to well defined rates and circumstances. The point in the process chain which needs to fulfill the quality requirement is indicated with a red circle in Figure 4:1. This implies that it is the synthesis gas generation step that is the challenge when a methanol production route from a new feedstock is established. The methanol conversion catalyst and the efficiency of the methanol conversion process are sensitive to certain impurities with respect to catalyst performance and concentration of inert components in the synthesis gas with respect to process efficiency. The most common impurity that will deactivate the catalyst is sulfur containing molecules such as hydrogen sulfide and carbon oxy- sulfide and the most common inert molecules that will lower the process efficiency are methane, nitrogen and argon. There is a gas recycle loop in the methanol conversion process and inert components will build up in the loop and lead to higher utility consumption, dilution of the reactants and a larger purge gas stream from the loop.

When a new feedstock such as biomass is gasified and converted to synthesis gas this novel feedstock will generate a gas that in detail needs to be analyzed with respect to trace components. Special measures in the form of new gas purification steps may need to be developed in order to cope with traces that have not been found in synthesis gas before when the feedstock was e.g. natural gas or coal.

A new technology for methanol production, developed by Haldor Topsoe, has been tested in the pilot plant owned by LTU Green Fuels, a subsidiary of Luleå University of Technology. The gasification pilot plant was started up in 2005. Until the end of December 2012 the plant was owned and operated by Chemrec AB. A syngas to methanol to further conversion to BioDME process unit was later added downstream the gasifier and was started up in 2011. This 3 MW<sub>th</sub> pilot plant is equipped with a novel syngas to methanol technology, which does not have a gas recycle loop for non-converted synthesis gas. Instead, the conversion from syngas to methanol is carried out in two catalytic steps placed in series. The first step is of conventional design in which part of the synthesis gas is converted to methanol. The conversion is then completed in the second reactor. Even though the methanol reaction is kinetically favored by high temperature, synthesis gas conversion is thermodynamically favored by low temperature, and the second reactor is operated at a lower exit temperature than the first reactor. It operates in a mode that favors continued conversion of the syngas, because the produced methanol is continuously removed from the gas phase where the reaction takes place. This type of reactor is called a CONRAD reactor, because it features a CONDensing RADial flow of methanol internally in the reactor, implying that methanol is condensed when formed. This leads to the reaction equilibrium being moved by increasingly cooler temperature and reaction from syngas to methanol exceeding 98%. This new technology thus eliminates the need for a recycle loop for non-reacted synthesis gas, which leads to a considerably smaller first reactor step. It also means that inert molecules to a larger extent can be accepted in the produced and cleaned synthesis gas. This is an advantage because higher concentration of inerts such as nitrogen may lead to simplifications for the synthesis generation part of the plant.

Typical new methanol plants are very big and can produce up to 10,000 tons of methanol per day in a single train. The energy conversion efficiency from natural gas energy to methanol energy is in the order of 67-68%. The plant size is 5-10 times larger than a plant fed with a renewable feedstock like biomass ever can become. 10,000 t/d of methanol corresponds to 2,300 MW of product, which with a conversion efficiency of 60% from biomass would need about 3,800 MW of feedstock. In a mature scenario, maybe 500-1,000MW of biomass can be gathered to one location, which would lead to a production of 300 – 600 MW of methanol or 1,300- 2,600 tons per day of methanol.

## 4.2 SYNGAS FROM NATURAL GAS

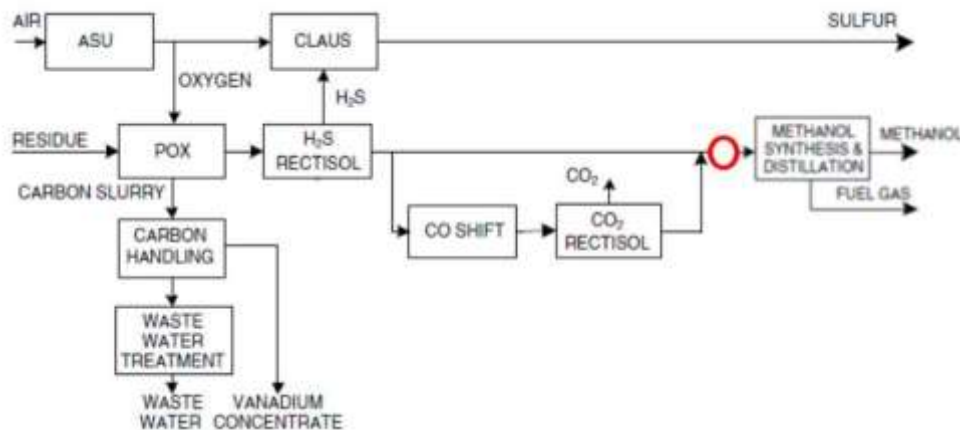
Most of the methanol produced in the world is produced from natural gas. Natural gas is purified from remaining sulfur components and fed to a so-called gas reforming plant where the methane molecules are converted to synthesis gas over a catalyst at very high temperature and pressure around 20-30 bar. Natural gas reforming is the starting process also for other major natural gas based technologies that use synthesis gas as an intermediate such as e.g. ammonia production and FT synthesis and the technology has gone through significant developments. Reformer technology can simply be divided into steam reforming, partial oxidation of methane and a combination of the two called autothermal reforming. Steam reforming (at 800-1000°C) is highly endothermic, partial oxidation (at 1200-1500°C) is highly exothermic and autothermal reforming is balanced in order to either produce or consume much heat. The H<sub>2</sub>/CO ratio for steam reforming is about 3 and for partial oxidation and for autothermal reforming about 2. Before the synthesis gas is fed to the methanol synthesis the H<sub>2</sub>/CO ratio and the amount of CO<sub>2</sub> in the gas need to be adjusted to reach the module value of 2 (see intro to chapter 4). The H<sub>2</sub>/CO ratio is adjusted in a so-called CO shift (carries out the so-called water gas shift reaction (WGS) in which water reacts with CO to form H<sub>2</sub> and

CO<sub>2</sub>) to a degree which fulfills the optimum value of the module M. To reach the right M number most of the CO<sub>2</sub> also must be removed a gas purification plant.

#### 4.3 SYNGAS FROM COAL AND OTHER FOSSIL FEEDSTOCKS (EXCL. NG)

As explained in the first part of this chapter, efficient conversion of a feedstock to an acceptable quality syngas is the most critical step in the conversion of a feedstock to methanol. When the syngas quality requirement is met, the conversion from syngas to methanol is carried out basically in the same way with some variants. All variants are well established.

Figure 4:1 shows a block diagram where the feedstock is named residue, which normally stands for a heavy oil fraction from an oil refinery. Such residues are often rich in sulfur and metals such as vanadium and nickel. The Gasification unit comprises the POX unit (gasification through Partial Oxidation of the feedstock), carbon handling and wastewater treatment. The residue is oxidized with oxygen from the Air Separation Unit (ASU). The non-reacted carbon ends up as soot in a carbon slurry. This is sometimes recycled to the feed stream but in this case, soot and metals are separated from the (waste) water stream. Soot is thereafter separated and sent for combustion and the plant generates a metal rich by-product. Raw syngas leaves the POX unit and is sent to the gas-cleaning unit (Rectisol, a common technology for these types of syngas) where the gas is cleaned to ppb level from sulfur components utilizing methanol at about -50°C. CO<sub>2</sub> is also removed down to typically 3%. Part of the gas has its H<sub>2</sub>/CO ratio adjusted in a CO shift to such a degree that when shifted and non-shifted (bypassed) gas is mixed downstream the ratio of the combined streams will be optimal for the methanol synthesis. See the paragraph regarding the module M in the beginning of section 4.1.



**Figure 4:1 Residue-based methanol plant (Higman and van der Burgt, 2008).**

The combination of gasification, CO shift and gas cleaning described for residue gasification is well developed and a large number of plants are in operation around the world. The plant would look very much the same if the feedstock were pet coke from a refinery. When coal is gasified, the technology differs substantially with respect to how coal is prepared and fed to the gasifier. The coal gasifiers also represent a big variety of concepts and heat recovery downstream the gasifier is also done in quite different ways for different technologies. The carbon handling in the diagram becomes slag and char handling, which comprises wastewater handling and various ways to handle the solid fractions mainly made up by the slag present in the coal feed. The raw syngas leaving the POX unit will however be very similar to the corresponding raw syngas from residue gasification.

The downstream units will therefore also be built up in a similar fashion as for the residue case and this is also true for the methanol production section.

The methanol boom in China described in section 3.1.1 has resulted in construction of a large number of coal to methanol plants (as well as coal to ammonia and other syngas derived products). The Chinese rationale was to use the most efficient and least expensive process to convert the country's indigenous resource coal and make a product that could substitute (part of) the oil import. Initially China bought coal gasification knowhow from large gasification licensors such as Texaco (now GE) and Shell, but as the experience of construction and operation increased, China developed technologies that became part of the plants, also for the gasification step.

Conversion of e.g. coke oven gas from steel mills to useful products and in so doing indirectly lowering GHG emissions has been studied by e.g. (Lundgren *et al.*, 2013). Such a view could be applied also to other fossil energy waste stream. One large such source is so-called associated gas streams that today are mostly flared. Figure 4:2 shows major flaring locations in the world. These type of fossil hydrocarbon streams should rather be converted to a useful commodity like methanol instead of being flared and just add CO<sub>2</sub> to the atmosphere. Such plants would have the additional benefit of very low (or even negative) feedstock costs.



**Figure 4:2. Photo from space showing flaring of various hydrocarbons (SkyTruth, 2016).**

#### 4.4 METHANOL FROM BIOMAS VIA SYNGAS

There is a lack of large plants in which renewable feedstocks such as woody residues are converted from feedstock to pure syngas and further from syngas to a product like methanol. There are however a couple of advanced pilots (small demos), which have shown that conversion of cellulosic material to synthesized products is feasible and that heat and material balances are in line with what has been results of simulation work upfront. The next step is therefore scale up to large demos or small commercial sized plants demonstrating the complete chain of processes making up the total plant concept. Most gasification developments are carried out with forest residues of various types as feedstocks, although other interesting routes are also under development or in their commercialization stages.

Straw to products is under development in Germany in the so-called BioLiq<sup>13</sup> development plant at Karlsruhe Institute of Technology and municipal waste gasification to methanol and ethanol is being commercialized in Canada by the Canadian company Enerkem<sup>14</sup>. While BioLiq is an advanced pilot plant including all steps from feedstock preparation to production of synthetic gasoline via DME, the Enerkem facility in Edmonton, CA is a commercial scale plant producing methanol from municipal waste (see also section 4.4.1 below).

In a Swedish (and also Nordic) perspective forest residues of various kinds are the feedstock that can be made available in large quantities and can have a significant role to play in making Sweden and the Nordic region independent of fossil energy. This report focuses on conversion routes from forest residue to methanol, but it should be noted that when syngas generation is developed and established, the choice of product is in principle an open decision.

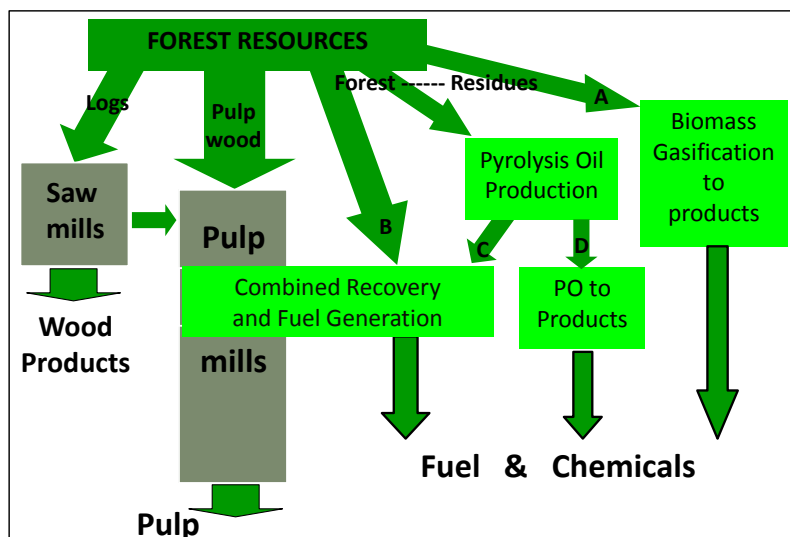
Figure 4:3 illustrates major conversion pathways from the forest resource to key product groups. As the figure shows, two main industries constitute the backbone in the forest industrial sector. These are the sawmills and the pulp (or integrated pulp and paper) mills. The well-developed infrastructure that exists in this mature industrial sector can be further developed as an addition to the existing industry. Not shown in the figure but still well established is yet another user of the forest resource – the existing market for forest residue streams. These flows of renewable energy are utilized in a large number of Combined Heat and Power (CHP) plants and in plants just for heating in communities, industries and in the private sector. This means that the infrastructure for forest residues is also well established and it has been so for many decades.<sup>15</sup>

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<sup>13</sup> BioLiq Project web page. <http://www.bioliq.de/english/>

<sup>14</sup> Enerkem web page. <http://enerkem.com/>

<sup>15</sup> Integration of syngas based biofuel production (e.g. methanol) with e.g. forest industry has been studied for Swedish conditions in a number of previous studies, e.g. (Isaksson et al., 2012; Andersson, Lundgren and Marklund, 2014; Pettersson et al., 2015; Gustavsson and Hulteberg, 2016; Holmgren et al., 2016).



**Figure 4:3.** The four major conversion pathways from forest residues to key product groups (fuels and chemicals). The figure shows four conversion alternatives for the forest residue resource into fuels and chemicals. A) Biomass Gasification to product; B) Biomass for combustion in pulp mills to compensate black liquor energy, which is gasified to products, the Black Liquor Gasification (BLG) concept; C) Biomass to Pyrolysis oil (PO) for further conversion together with black liquor (BL) to products in pulp mills, the PO/BL concept; and D) Biomass to PO for further upgrading to products.

Route D in Figure 4:3 utilizing gasification of PO is in principal the BioLiq concept mentioned above for straw as feedstock. In the BioLiq concept, syngas is converted to DME and further to synthetic gasoline. Route D via gasification of PO will not be dealt with as it is not seen as a sufficiently cost and energy efficient conversion route. Within the Renew project (RENEW, 2008), it was concluded that products generated via the two stage approach (PO production followed by gasification, either distributed production of PO or produced at the place of the gasification plant) had a production cost which was in the order of double the cost compared to direct gasification of biomass. PO could however also be gasified to syngas together with black liquor (BL), route C, and in that way be converted to fuels and chemicals. This concept shows cost and conversion efficiency advantages and is described in section 4.4.4.

#### About Pyrolysis Oil (PO) production:

Fast pyrolysis is thermal decomposition of biomass in the absence of oxygen. Residence time: 1-2 seconds. Temperature: ~500 °C. The process involves heating and subsequent quenching in the absence of oxygen to produce:

- solid char
- pyrolysis oil also-called bio-oil or pyrolysis liquid
- combustible gases

Other conversion routes via PO under intense investigation and development today are focusing PO upgrading to hydrocarbon type of fuels utilizing various technologies developed for the oil refinery industry. These routes also apply to lignin fractions, which can be generated from black liquor in pulp mills or as byproducts from e.g. ligno-cellulosic ethanol production.

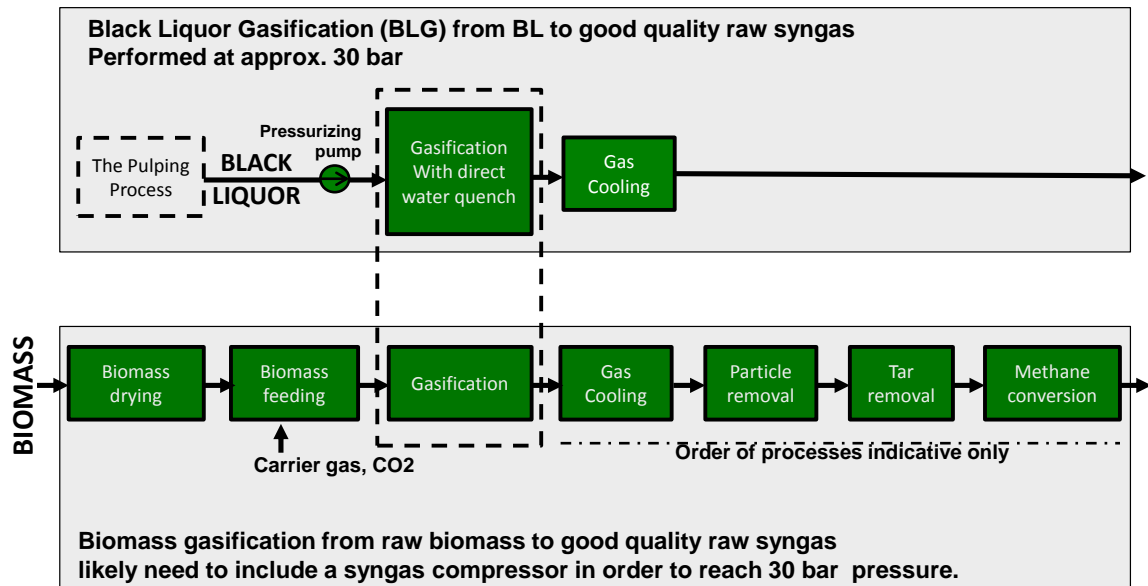
#### 4.4.1 Syngas generation

The key to success for converting biomass to a product lay as described in section 4.1 in the generation of a (sufficiently) good quality syngas. A Strategic Innovation Agenda covering gasification



and pyrolysis from a Swedish perspective was developed during 2015-2016 (Lundgren *et al.*, 2016). It involved a workshop and a detailed survey covering various aspects such as feedstock availability, technical maturity and level of commercial strength. The survey, which involved some 45 specialists in the field, concluded that gasification technologies are ready for full size demonstration, especially BFB technology for solid feedstocks and entrained flow gasification technology for black liquor.

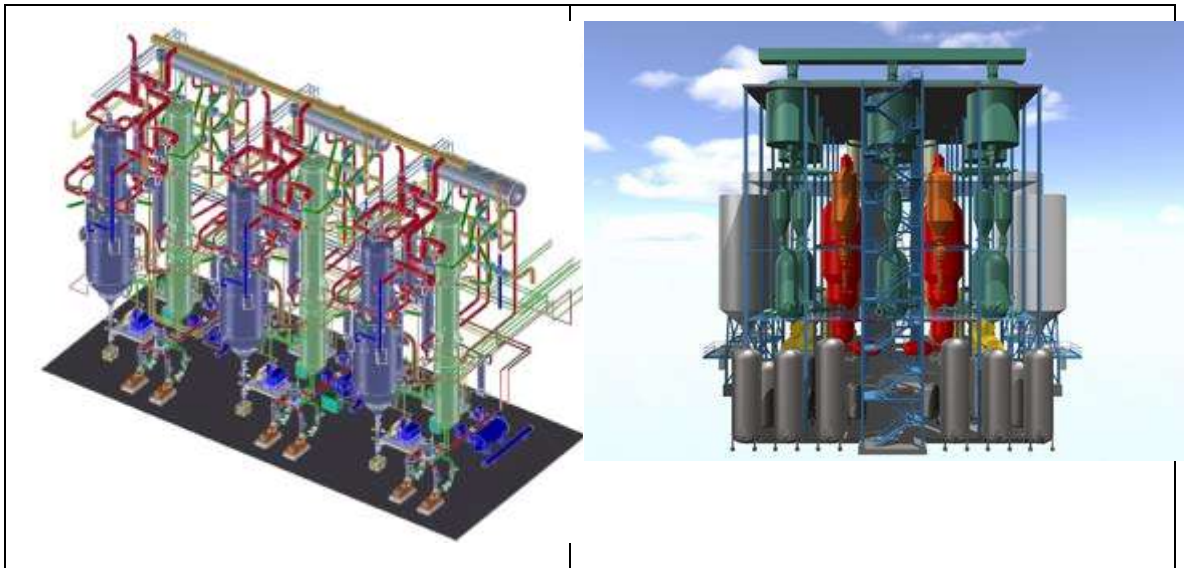
Figure 4:4 illustrates what needs to be included in the syngas generation process step in order to reach an acceptable raw syngas, which thereafter can be further cleaned by conventional syngas cleaning and conditioning technologies.



**Figure 4:4. Main process steps in conversion of feedstock to good quality raw syngas [Landälv].**

For the black liquor gasification (BLG) case three steps are shown: pressurizing via a pump, gasification in an entrained flow gasifier, and gas cooling. The raw syngas is ready for downstream processing by commercially available technologies. The LTU Green Fuels plant in Piteå, Sweden (see above) has during more than 11,000 h successfully demonstrated that the quality of the raw gas is such that it can be converted to methanol and DME during long-term operation.

For the solid biomass case, gasification of wood chips or wood pellets would most likely take place in a Circulating Fluidized Bed (CFB) or Bubbling Fluidized Bed (BFB) gasifier. There is a need for a number of process steps upstream and downstream the gasification step in order to deliver the same type of good quality raw syngas as in the BLG case. The overall system is more complex but developments in Europe and in the US and Canada has come so far that demonstration in large scale is the necessary next step. The best reference to refer to in the case of wood gasification is the GTI BFB development plant in Des Plaines (Chicago). The so-called U-gas gasifier was 2012/13 for about 3,000 hours fed with wood pellets and produced syngas for further conversion to synthetic gasoline. Results were very promising and concepts were developed with the ambition to build large-scale plants. Consequently, also these trials, although shorter in duration than the BLG trials, proved that the BFD-based concept for syngas generation from dry wood material worked well and companies involved judged the technology was ready for scale up. Figure 4:5 illustrates basic engineering efforts for BLG gasification (showing three parallel trains) and BFB biomass gasification (showing two parallel trains).



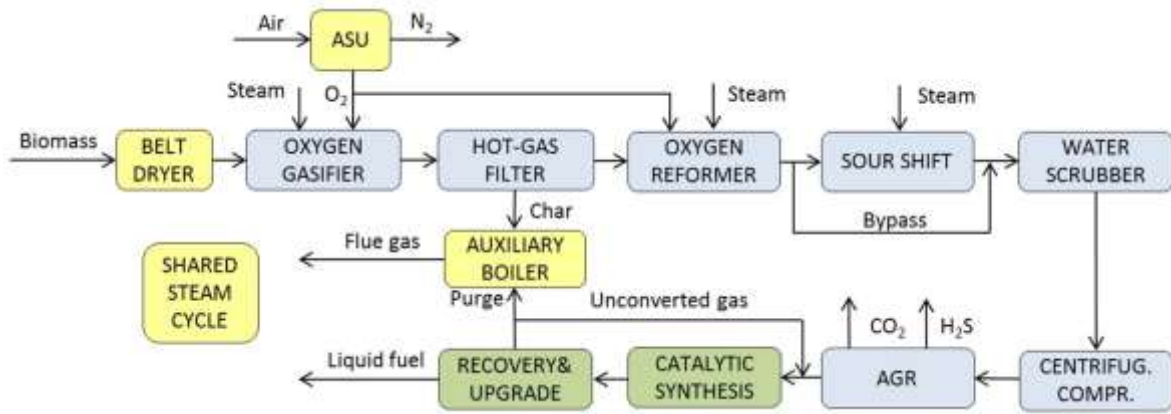
**Figure 4:5** Industrial sized gasifiers for BLG to the left [Chemrec] and biomass [UPM, Andritz, Carbona].

The Canadian company Enerkem has started up a waste to methanol plant in Edmonton, Alberta. The plant converts 300 t/d of dry post-sorted municipal solid waste (after recycling and composting) to methanol and ethanol. It utilizes own developed technology in all its process steps and the gasifier is of BFB-type operating at 2-4 bar pressure. The plant was commissioned producing methanol and completed a performance test in the summer of 2015 with an uptime of 60% over the last month of operation before a planned shut-down to expand the production capacity. The plant resumed operations for biomethanol production in April 2016. The produced biomethanol meets commercial standard for methanol. A biomethanol to bioethanol conversion module is being added in 2016 and will be ready for startup in 2017. At full capacity, the plant will produce 88 t/d of ethanol. Ethanol is expected to be the primary product. Until autumn 2016, the plant has logged 2,600 operating hours. Enerkem is a commercial company with ambition to establish similar plants as the one in Edmonton in various locations. They are currently considering an investment in Europe together with AkzoNobel and other partners. The product is said to be methanol but there are also other alternatives in discussion such as ammonia.

#### 4.4.2 Biomass gasification to methanol (Case A in Figure 4:3)

Practical and theoretical work with a CFB and BFB type of gasification-based system has many connections to VTT, the Finish research center and to industries active in or having relations to Finland. It is therefore relevant to use VTT-sourced material for review of the biomass gasification to methanol pathway. Examples on companies who have been involved from time to time are Andritz Carbona, UPM, Neste, Stora Enso and Foster Wheeler.

A typical block diagram for a plant under this headline is shown in Figure 4:6. It is taken from a VTT report that covers various pathways to methanol, DME and synthetic gasoline. Not all process steps are shown explicitly in this figure, but they are included in other block identifications.



**Figure 4:6. Generalized block diagram of a stand-alone biomass-to-liquids plant (Hannula and Kurkela, 2013).**

Raw syngas conditioning and cleaning in the form of “Oxygen Reforming”, “Sour Shift” and “AGR” (Acid Gas Removal or Gas Cleaning) are blocks shown in the figure before the cleaned syngas is ready to be fed to the “Catalytic Synthesis” which is this case is a methanol synthesis. The “recovery and upgrade” step is for the methanol case a distillation section. The so-called sour shift is a WGS unit as described earlier in this chapter. Steam is required and  $\text{CO}_2$  is generated in the reaction. That the shift is “sour” indicates that the unit is installed before the raw syngas is cleaned from its content of hydrogen sulfide ( $\text{H}_2\text{S}$ ). Sulfur originates from the woody material and (most of) it is converted to the acidic gas component  $\text{H}_2\text{S}$  and the catalyst is thus tolerant towards sulfur containing components. For other solutions the WGS unit is located downstream the AGR unit and is then named a “Sweet Shift”. A disadvantage having the shift in this location is that  $\text{CO}_2$  is formed in the shift and that therefore a second cleaning of the syngas becomes necessary to eliminate the formed  $\text{CO}_2$ .

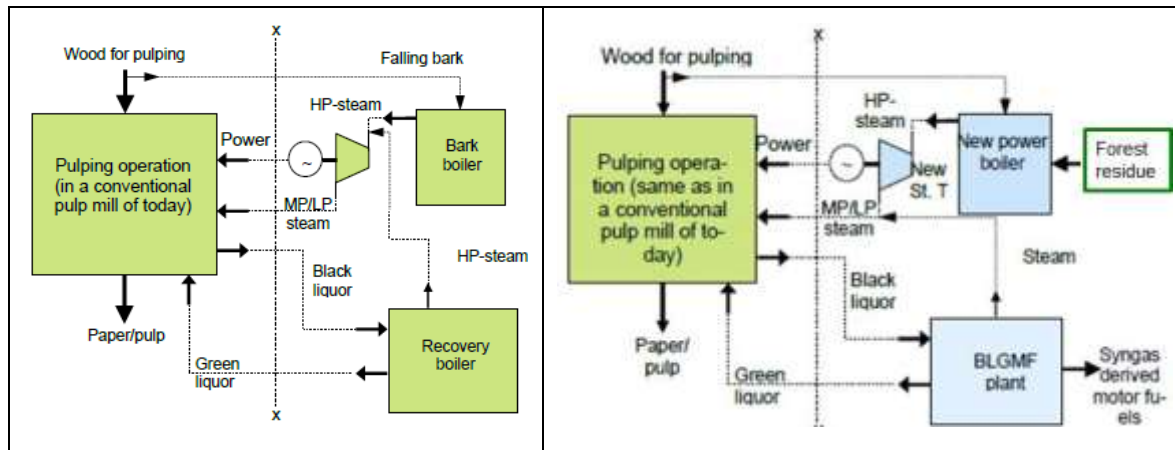
The methanol synthesis step located downstream is sensitive to various trace components (one group being molecules containing sulfur is mentioned earlier). Gasification feedstock from forestry material contains a large number of the elements that are to be found in the Periodic System and therefore long-term operations and comprehensive analysis work will be important for the first large and continuously running plants. Syngas chemistry is however very well established and many of the potential trace components are known from e.g. coal gasification and mitigation steps are known. It is not uncommon that a guard bed is located upstream the methanol synthesis reactor to absorb certain trace components that have not been separated out in the AGR unit. The synthesis unit has a very high selectivity towards methanol and the non-reacted syngas together with some trace components such as methane are bled from the unit and used as fuel.

The crude methanol is purified to desired quality in the distillation section, which separates pure methanol products from a liquid waste stream mainly consisting of water and traces of organic matters. The waste stream is fed to waste water treatment.

The overall plant concept needs a utility plant where the main unit is a CHP plant with its steam and condensate system. This unit balances the steam needs of the overall plant and generates electric power in a backpressure steam turbine. Other utilities are inert gas (normally nitrogen), dry air systems (for instrument operation and other operational needs), water systems etc.

#### 4.4.3 Black Liquor Gasification (BLG) to methanol (Case B in Figure 4:3)

The so-called BLGMF concept (Black Liquor Gasification to Motor Fuels) was invented and patented in early 2000. The pulp mill based conversion concept was then elaborated in two reports (Ekbom, Lindblom and Berglin, 2003; Larson *et al.*, 2007), by the Swedish consultant company Nykomb Synergetics and Princeton University, respectively. Both reports followed the same concept solution, which is illustrated in Figure 4:7.



**Figure 4:7** Main process blocks in a conventional pulp mill (left) and the same mill equipped with a BLGMF concept (right) (Ekbom, Lindblom and Berglin, 2003).

The overall results in the two reports are *in the form of calculation of differences* (in investments, in operations costs, in revenue streams). The base case, the left figure in Figure 4:7, is a modern pulp mill with a modern recovery boiler and a steam system including a bark boiler for falling bark (from the pulp wood preparation). The BLGMF case, the right figure, includes the same mill but in this case, the recovery boiler is changed out to a gasification based fuel generating plant and a large biomass-fed boiler (also firing the falling bark plus extra biomass). The BLG plant gasifies the black liquor and sends back the used coking chemicals, the so-called green liquor to the mill. This is also what the recovery boiler does, but in this case the boiler also generates large volumes of high pressure steam, while in the BLGMF case the gasification plant generates raw syngas and considerably less steam. The necessary steam generation to balance the energy needs for the new combined process solution is instead carried out by a new large CHP plant with extra forest residues fed to the boiler.

What was discovered and what later on has been studied and calculated further by a number of investigators is that the biomass requirement needed (forest residue in the green rectangle in the right figure, Figure 4:7) to compensate for the elimination of steam generation from black liquor combustion is comparably low. The overall biomass to fuel conversion efficiency was defined to be energy in fuel divided by extra biomass fed to the CHP (compared to the base case with mainly bark from the mill's own operation) under the key assumption that the net power balance for the two cases is the same.

The principle for the BLGMF concept has, on a small scale, been demonstrated in Piteå, Sweden for about 11,000 hours of operation (See sections 3.4 and 4.4.1). Besides the differences in syngas generation technology there is one major process difference between biomass and BL gasification, namely that black liquor has a high concentration of sulfur components (stemming from the salts making up the cooking chemicals) and a large portion of that sulfur ends up as sulfur-containing

components in the syngas. Typically 1-1.5 % (v) of the dry raw syngas is hydrogen sulfide (H<sub>2</sub>S). This must be brought to virtually zero before the syngas is fed to the methanol synthesis unit.

Syngas with that amount of sulfur is however nothing new in the world of coal-, petcock- and residual oil gasification. Raw syngas from such feedstocks can easily contain 1% (v) of H<sub>2</sub>S and sometime much more and commercial technologies for gas cleaning are available from several suppliers. In this context it should however be noted that syngas cleaning (from sulfur components and CO<sub>2</sub>) is only the first step in the pulp mill related case. The sulfur must also be recovered and recycled to the mill, as it is part of the cooking liquor cycle. This can be accomplished in various ways but will not be further elaborated in this report.

#### **4.4.4 Biomass to Pyrolysis oil (PO) for further conversion to products in pulp mills, the PO/BLG concept (Case C in Figure 4:3)**

Pyrolysis oil (PO) can be mixed into Black Liquor (BL) from a pulp mill and in that way augment the fuel plant's capacity. The key reason for this concept stems from the fact that BL from a kraft (sulfate) pulp mill is a very efficient gasification fuel due to its content of catalyzing sodium, which constitutes about 20% (wt) of BL on a dry basis. Carbon conversion in BL gasification is very high already at a comparably low gasifier temperature. When making tests on sulfite liquor containing about half as much sodium on a dry basis compared to kraft liquor it was observed that key gasification parameters did not change negatively. They even marginally improved. Pure PO gasification on the other hand is less efficient. The gasifier temperature needs to be considerably higher (several hundred degrees) in order to reach high carbon conversion numbers. These two observations led to the idea of mixing in quantities of PO into the kraft BL main stream and investigating if the present sodium in the BL would act as a catalyst also on the PO part of the fuel.

During 2015 and 2016 various gasification tests with up to 20% PO in BL were run at the Piteå Pilot plant. The trials lasted for totally about 1,100 hours, of which 900 hours also included methanol and DME production. The tests verified the computer model of the mixed feedstock and extrapolation outside the tested interval can therefore be deemed to have a solid base and the most important assumption, namely that gasification temperature could stay low, at around 1,050°C.

Besides the practical verification tests at the pilot plant the concept has been extensively evaluated using techno-economic energy systems analysis (Andersson *et al.*, 2015, 2016).

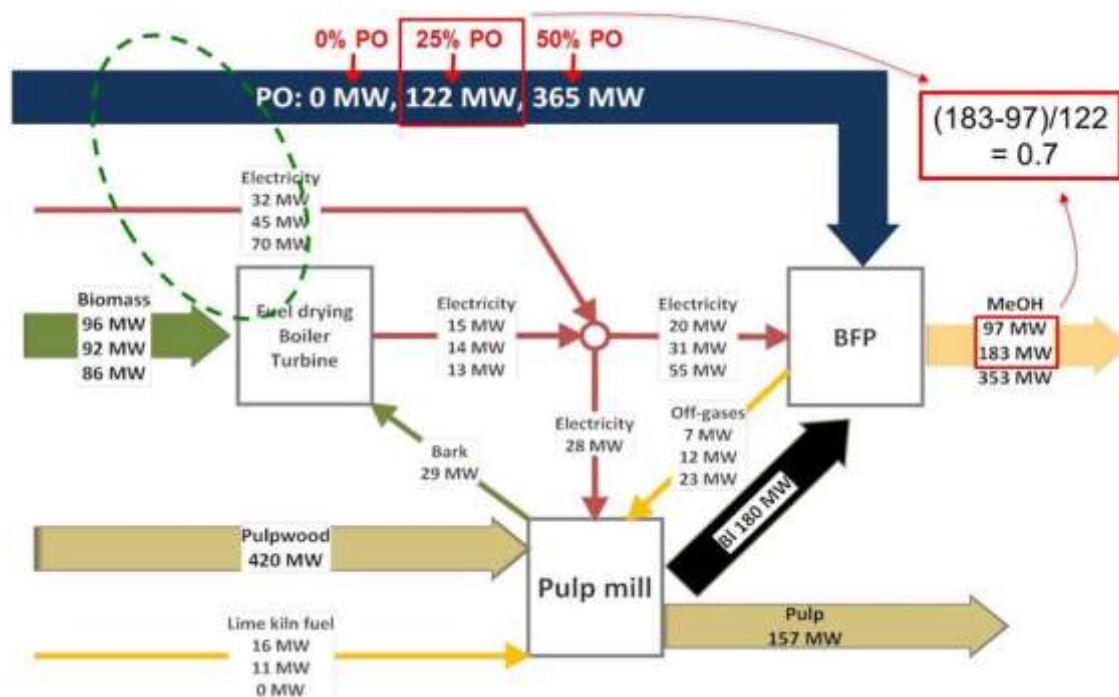
The process technology will be the same regardless of whether PO is blended into the BL or not. The key novel equipment will be a mixing unit in the feed stream to the gasifier. Concentration of sulfur containing components in the syngas will go down in principle in proportion to the degree of PO mixing. This will not lead to a change in process technology. An area that has not been investigated is the potential impact of trace components entering the pulp mill liquor loops via the new PO feedstock. The inorganic fraction in PO is however low (partly process dependent) and traces will still originate from forestry material.

Figure 4:8 illustrates a pulp mill equipped with a BLG to methanol plant that also gives data for how the main stream will vary when the gasifier feedstock consists of 0%, 25% and 50% PO mixed with the BL. The pulp mill operation is constant with respect to pulp wood requirement, pulp production as well as steam and power needs. The following can be e.g. extracted from the information in the figure:

The base case with no PO addition produces 97 MW of methanol and requires 125 MW of biomass (of which 29 MW is falling bark from the pulpwood) to be fed to the boiler in order to generate the required steam for the total plant. The boiler generates 15 MW of electric power at the same time. The plant also needs to import 32 MW of electric power from outside.

When 122 MW of pyrolysis oil is added to the gasification plant, the need for biomass to the boiler slightly decreases to 121 MW and the need to purchase power increases to 45 MW

The conversion efficiency for PO to methanol is 70% as expressed in the red box in the figure. It results in a decrease of limekiln fuel purchase of 5 MW<sub>t</sub> (16 to 11) but with an increased electric power consumption of 13 MW (32 to 45).



**Figure 4:8 Pulp mill with gasification of BL and BL/PO mixes (adapted from Andersson et al., 2015).**

A very positive effect of PO addition to a small mill like the one in the example is that the comparably complex gasification based plant becomes comparably large and thus gains from economy of scale.

The high conversion rate from PO to methanol is very positive but the overall conversion from biomass to methanol via PO is of course affected by the energy loss in the PO production. For a stand-alone PO plant typical biomass to PO efficiency is between 65 and 70% (energy in PO divided by energy in biomass). The conversion efficiency from biomass via PO to methanol in the described concept above would then maximum become 49% ( $0.7 \times 0.7 = 0.49$ ). If the PO production is integrated with a large CHP plant like the one needed in the concept presented in Figure 4:8 (see dotted ellipse in the figure), energy in the biomass needed to produce PO can be used much more efficient. This integrated concept has been developed by VTT and is today a commercial technology. According to (Mckeough *et al.*, 2005) energy utilization of the biomass provided to produce PO can reach around 90% (Page 15, Figure 1) when applying the VTT process. With such a process solution, the earlier described route reaching less than 50% overall conversion efficiency could

reach about 60% depending on how the 10% losses in the PO unit is distributed between PO product and heating energy for the host H&P plant.

#### 4.4.5 Biomass to methanol conversion efficiency

Earlier referred documentation in the form of reports in this chapter includes quite detail analysis regarding mass- and energy balances for the various process concepts both overall balances and also on process unit basis. An overall approximate estimate of the conversion efficiency of a specific process route can be reached by multiplying energy conversion efficiency of each process units involved in the conversion chain. An important observation when carrying out this kind of overall energy balance is to only include those elements which are of interest in the conversion processes, H<sub>2</sub> and CO. Methane is not taking part in the methanol formation. Methane will however play a role in the energy balance of the overall plant. Methane will pass through the methanol synthesis as an inert gas component and leave the process via a purge gas stream from the methanol loop. See “Purge” flow in Figure 4:6. Exothermic reactions take place in (at least) three units from feedstock to product in the gasification unit, the water gas shift unit and in the methanol synthesis. If the gasification generates substantial quantities of methane it can be reacted to syngas in a methane-reforming unit located downstream the gasifier. See “Oxygen Reformer” in Figure 4:6.

Table 4:1 presents approximate overall energy conversion numbers for the three conversion routes described above as Case A to C. The information in the table shows that methanol can be produced from biomass with an energy efficiency of 50 – 70% depending on conversion route.

**Table 4:1. Overall conversion for biomass to methanol for different conversion routes (author’s compilation).**

Process step	Gasification	Shift	Methanol synthesis	TOTAL
Conversion from / to	Biomass to H <sub>2</sub> +CO	Non-shifted to shifted syngas	Syngas to methanol product	Biomass to methanol
<u>Conversion route</u>				
Biomass gasification, Case A	0.7-0.8	0.96-0.97	0.79-0.8	0.53-0.62
BLG to Methanol, Case B (Biomass added to compensate)		*		0.65-0.7
Biomass to PO combined with BLG, Case C		**		0.49-0.6
<p>* Conversion of BL to syngas and further on to methanol does not make sense (as for biomass gasification) as the overall calculation as explained in the subchapter about BLGMF concepts relates to the biomass addition to the system to compensate for withdrawal of BL normally being fired in a recovery boiler. See ref.</p> <p>** When PO is added to a BLGMF system PO energy is converted to methanol with about 70% energy efficiency as described under Case C. Production efficiency of PO from biomass is multiplied with this efficiency to get the TOTAL value.</p>				

This report does not have the ambition to describe in detail the best and second best conversion route from the point of view of conversion efficiency but rather to give a well-funded base for what level of efficiency can be reached. These numbers can be combined with biomass potential estimations in order to assess overall methanol production potential e.g. for Sweden (chapters 7-8).

#### 4.5 THE POWER TO LIQUID CONCEPT

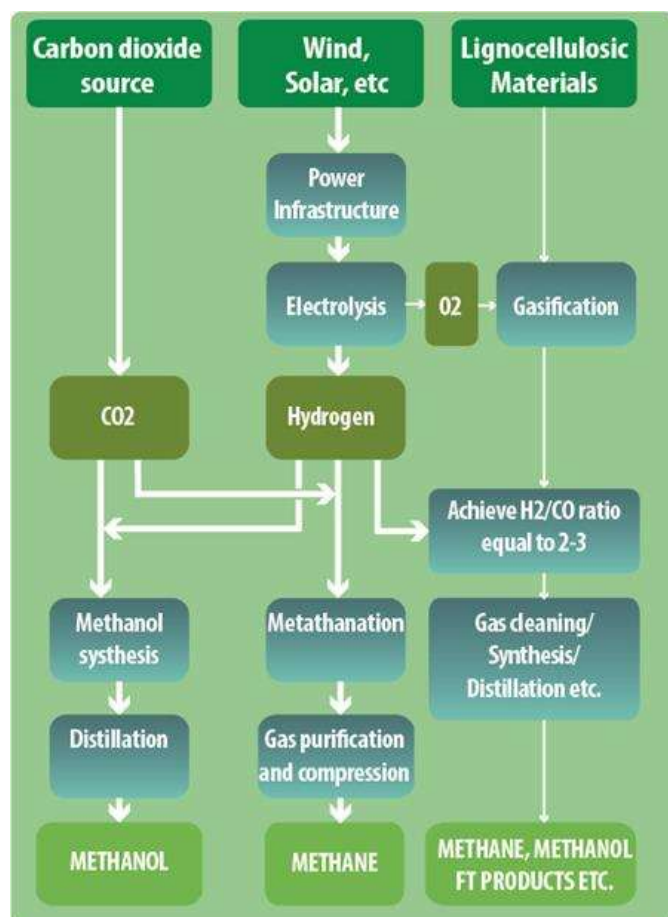
Power-to-Gas (PtG) and Power-to-Liquid (PtL) refer to technologies that convert electric energy into another energy carrier, like for example methane (PtG) or methanol (PtL). Depending on whether the electricity comes from biomass (e.g. co-firing or CHP) or from renewable sources like wind or solar energy. These fuels are either biofuels or ‘renewable fuels of non-biological origin’ as described in the amended to Renewable Energy Directive. In the following power to methanol will be focused on, but in conversion pathways to other products are also included.

Electricity is converted to hydrogen through electrolysis. There are two main electrolysis technologies for the production of hydrogen in power to gas plants. The most common is alkaline electrolysis in which the electrolyte is an aqueous alkaline solution containing either sodium hydroxide (NaOH) or potassium hydroxide (KOH). The alkaline electrolysis technology is well understood and considered robust, with units in reliable operation for decades. It is the current standard for large-scale electrolysis, and systems have been successfully built at megawatt scale, producing up to 200 Nm<sup>3</sup>/hour of hydrogen. In energy applications, conventional alkaline electrolysis technology may have drawbacks, such as the relatively limited ability to respond to fluctuation in electrical input and lower gas purity.

An alternative to alkaline-based technology is the PEM electrolysis technology. It has fast response times to fluctuations in electrical input and can also be operated anywhere between 0 and 100% of nominal capacity, which are important considerations for grid balancing. PEM electrolysis also produces high-purity hydrogen, which can be used directly in many applications with no further purification required.

Sufficiently cheap hydrogen generation from electricity is the enabling technology for the PtG and PtL production routes. This implies that the price for renewable electricity must be low to make this concept feasible. In Figure 4:9, methanol production is illustrated along two pathways, the PtL way (below called PtL – Methanol) where hydrogen from electrolysis is combined with CO<sub>2</sub> from a suitable source and the syngas injection way (below called Methanol via adding H<sub>2</sub>

to syngas), which covers the concept where external hydrogen is used for H<sub>2</sub>/CO adjustment in a syngas-conditioning step. Injection of externally produced hydrogen replaces the WGS unit described earlier e.g. as part of Figure 4:1 or Figure 4:6.



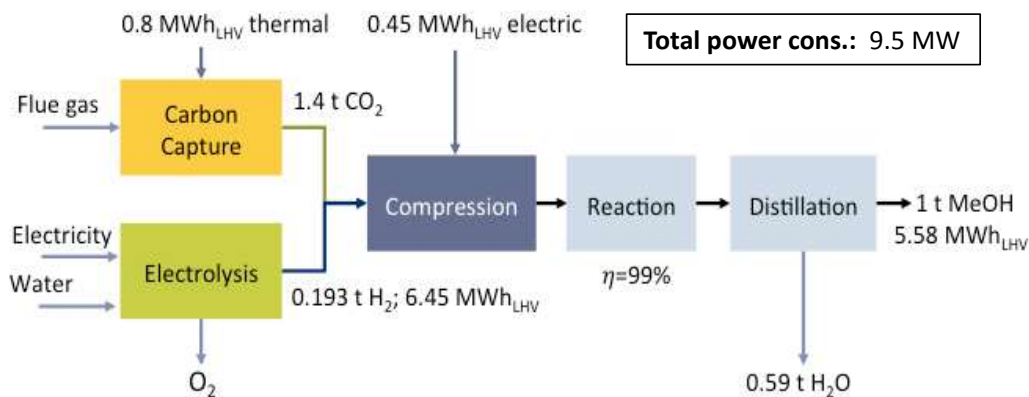
**Figure 4:9. PtG and PtL conversion pathways [ETIP Bioenergy].**



#### 4.5.1 PtL – Methanol

This concept has been described in detail by Nobel Prize winner George Olah and others in the book ‘Beyond Oil and Gas: The Methanol Economy’ (Olah, Goepfert and Prakash, 2011, p. 239-245). PtL-methanol technologies rely in the same way as conventional syngas- based methanol production on catalytic conversion but in this case on the synthesis of CO<sub>2</sub> and H<sub>2</sub> to methanol. The CO<sub>2</sub> can be sourced from an array of different sources, ranging from biogas installations, breweries, power plants, refineries and many other point sources of CO<sub>2</sub>.

The energy balance of a PtL-methanol plant is shown in Figure 4:10 as presented by Carbon Recycle International (CRI). The total electricity, including electricity to the electrolyzer is 9.5 MW and the conversion efficiency from electric power to methanol is thus close to 60% (5.58/9.5).



**Figure 4:10 Energy balance for a PtL-methanol concept utilizing CO<sub>2</sub> from a flue gas stream (Stefansson, 2015).**

The overall efficiency of the PtL-methanol process is determined primarily by three factors:

1. Choice of electrolyzer and compression technologies
2. Recycling of hydrogen from the reaction system
3. Capture of waste heat within the plant.

The overall efficiency of the process (electricity to methanol) is therefore determined by the choice of technology and ranges from 45% to 65%.

#### 4.5.2 Methanol via adding H<sub>2</sub> to syngas

A gasification process typically generates a raw synthesis gas that has a H<sub>2</sub> to CO molar (volumetric) ratio of around 1 (0.8 to 1.3). For most synthesis processes a higher ratio is needed, typically around 2 (methanol) to 3 (methane). In order to accomplish the desired ratio the raw syngas is passed through a CO shift process in which CO is reacted with H<sub>2</sub>O to form H<sub>2</sub> and CO<sub>2</sub>. The reaction is exothermic and the syngas loses about 3-5% of its heating value.

The right ratio can also be accomplished via adding H<sub>2</sub> to the process and the H<sub>2</sub> can be produced in the same way as hydrogen needed for the PtL and PtG concepts. Hydrogen added to the syngas in this way becomes hydrogen in the product in a very energy and investment efficient way. It has the following advantages:

- No investment in CO shift unit.

- No high-pressure steam addition needed for the CO shift reaction.
- No loss of green carbon due to CO becoming CO<sub>2</sub> in the CO shift unit.
- No loss of syngas energy in the exothermic CO shift reaction.
- Increased syngas production in the order of 50% compared to the case with a CO shift.
- Lower operating cost for the gas-cleaning plant due to lower CO<sub>2</sub> load.
- Oxygen produced in the electrolyzer can be used as oxidant in the gasification process, which will make the ASU plant just a fraction of its original size or in some cases obsolete (depending on the type of gasifier and gasifier feedstock).
- Lower relative investment in the syngas and fuel generation parts of the plant due to economy of scale. The gasification plant will stay the same.

The right side of Figure 4:9 shows how the produced H<sub>2</sub> is sent to the syngas stream, and also how the produced O<sub>2</sub> from the electrolyzer is used in the gasification process. If the energy loss in the shift unit is credited the hydrogen addition (which is logical), then added hydrogen energy becomes methanol energy with 88-90% efficiency. The span is due to varying original ratio H<sub>2</sub>/CO.

The conclusion from the above is that the concept of methanol via adding H<sub>2</sub> to syngas results in a number of important improvements:

- Fuel generation potential from a certain biomass resource increases by about 50%.
- Hydrogen is liquefied (into the form of methanol) with close to 90% energy efficiency.
- The relative investment in the syngas train decreases and the plant concept becomes simpler.

The above logic is in all important aspects true for all feedstocks and for all products. It is thus a concept that can be included in any type of syngas production plant that includes a CO shift unit, if H<sub>2</sub> is added in a sufficient amount to fully replace the CO shift unit.

The following example is generated from one of the pulp mills for which Chemrec AB has made heat and material balances. The example can be adjusted to other raw syngas compositions depending on which H<sub>2</sub>/CO ratio the gasifier is generated in a certain case. In this specific case, the raw syngas molar ratio is 1.15. This is brought to the ratio 2.25 downstream the CO shift or after the hydrogen addition, same for both cases. Table 4:2 illustrates main gas flows before the CO shift unit is removed and thus the H<sub>2</sub>/CO ratio is adjusted via use of the WGS process unit. Table 4:2 illustrates when the CO shift has been removed and an electrolyzer producing hydrogen and oxygen from water and renewable electricity has been added.

**Table 4:2. Syngas train with CO shift unit for H<sub>2</sub>/CO adjustment [Chemrec/Landälv]**

Component	(1) Rawgas, Nm <sup>3</sup> /h	(2) Oxygen	Shifted gas, MW	(4) Removed CO <sub>2</sub> , Nm <sup>3</sup> /h	(5) MeOH, MW/Ton/h
H <sub>2</sub>	22,351 (67 MW)		128.1 MW	CO <sub>2</sub> 16,819	102.5 / 18.6
CO	19,416 (67.9 MW)				
O <sub>2</sub>		12,874			

With the CO shift in place the plant produces 102.5 MW of methanol from the 134.9 MW H<sub>2</sub> plus CO in the raw gas. The Air Separation unit (ASU) uses 8.4 MW of electricity to generate the necessary oxygen for the gasification reactions.

**Table 4:3. Syngas train with electrolyzer unit for hydrogen addition [Chemrec/Landälv].**

Component	(1) Rawgas, Nm <sup>3</sup> /h	(2) Oxygen	(3) Shifted gas	(4) Removed CO <sub>2</sub> , Nm <sup>3</sup> /h	(5) MeOH, MW / Ton/h	(6) Gas after H <sub>2</sub> injection, Nm <sup>3</sup> /h	(7) Added H <sub>2</sub> , Nm <sup>3</sup> /h	(8) Added O <sub>2</sub> , Nm <sup>3</sup> /h
H <sub>2</sub>	22,351 (67 MW)		-	CO <sub>2</sub> 11,412	159.3 / 28.9	43,775 (131.2 MW)	21,424 (64.2 MW)	
CO	19,416 (67.9 MW)					19,416 (67.9 MW)		
O <sub>2</sub>		12,874						10,712

When the CO shift is replaced with hydrogen brought in from the outside, the methanol production increases to 159.3 MW (+55%) utilizing the same amount of raw gas, 134.9 MW. Instead, the new plant combination consumes 100.7 MW of electric power for hydrogen production. As a credit, the electrolyzer also produces oxygen resulting in a decrease of power needed for the ASU of 7 MW. The net power requirement is therefore 93.7 MW. The conversion efficiency of net power to methanol is thus 60.6%.

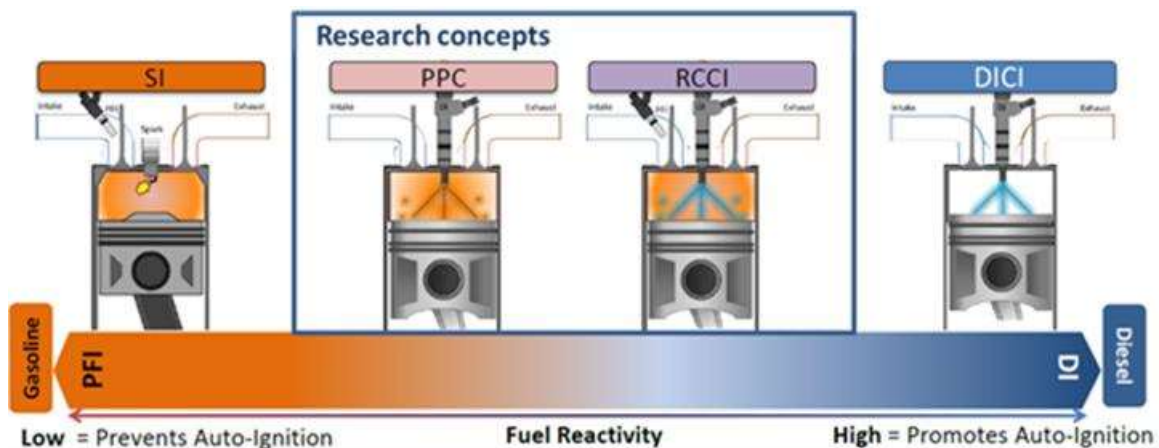
The energy in the added hydrogen corresponds to 64.2 MW and the increase of methanol production to 56.8 MW. Hydrogen therefore becomes liquefied in the form of methanol with an energy conversion efficiency of 88.5%. The energy loss in the CO shift in Table 4:2 is close to 5%. CO<sub>2</sub> losses to the atmosphere go down from 16819 to 11412 Nm<sup>3</sup>/h. The corresponding carbon shows up in the extra methanol production.

## 5 CURRENT AND POTENTIAL FUTURE USE OF METHANOL IN VARIOUS TYPES OF ENGINE APPLICATIONS

This chapter partly overlaps the information provided in chapter 3 where system descriptions are to be found, while this chapter covers information relating to engine development and adaptation.

### 5.1 INTRODUCTION

As any kind of fuel methanol has advantages and disadvantages as motor fuel and the engine needs to be optimized to take advantage of the special feature methanol offers. In Figure 5:1 the two base concepts for commercial internal combustion (IC) engines are illustrated together with two research concepts. The spark ignition (SI), Otto cycle concept is shown to the far left and the compression ignition (CI), Diesel cycle concept to the far right. In modern SI engines, the fuel is often Direct Injected (DI) and the abbreviation for this concept is DISI. For diesel engines, the fuel is always directly injected and the abbreviation used is DICI. The bar at the bottom of Figure 5:1 illustrates the type of fuel: Gasoline-type of fuel, which should prevent auto-ignition to the left and diesel-type of fuel, which should promote auto-ignition to the right. Methanol should be put to the very left on this bar due to its high octane number, an indicator of its ability to withstand auto-ignition under high pressure and temperature.



**Figure 5:1. Engine combustion research concepts compared to conventional SI and DICI. Blue indicates a reactive fuel like diesel while orange indicates a none-reactive fuel like gasoline (Tunér, 2016).**

In this context, it can be of interest to notice that dehydrated methanol becoming DME is a typical diesel fuel with a high cetane number. This measurement of a fuel's suitability as a diesel fuel is an inverse function of a fuel's ignition delay, and the time period between the start of injection and the first identifiable pressure increase caused by the combustion.

Use of pure methanol in a SI engine that is designed to take advantage of the fuel's high octane number leads to a very efficient combustion cycle. Use of methanol in racing cars and speedway motorcycles (operated in SI-mode) is practical proof of this characteristic feature of this fuel. Use of methanol in a DICI is thus not feasible (has a low cetane number) and the fuel needs to be mixed with an ignition additive or the engine needs to have a second fuel that has the necessary diesel characteristic, a high cetane number.

In between the two commercial engine concepts, there are developments that can be described as combining the best features of the two. One of the concepts, Partial Premix Combustion (PPC) is described in section 5.4 and is included in Figure 5:1. The engine applications covered in this chapter will be related to the above overall illustration of different engine combustion concepts. The above description and figure describing today's and tomorrow's potential engine concepts and their suitability for various fuels have been extracted from various works carried out by Lund University (Tunér, 2016).

A real-life illustration of the broad application capability of methanol as a fuel took place at the GreenPilot project kick-off conference in Gothenburg on June 16, 2016<sup>16</sup>. The three-year project will test different methanol fuelled engines in a pilot boat. In order to get all four (potential) methanol users to show up for a joint photo, the event took place just before 09.00 in the morning when the methanol-fuelled ferry Stena Germanic arrived to Gothenburg from Kiel (see Figure 5:2). On the water but at the time not yet rebuilt to methanol operation was also a Swedish Pilot boat. During the coming 2 years the boat will be tested with three different methanol-fuelled engines from different suppliers. The first is a 12 litre engine supplied from Weichai from China which has been tested running on pure methanol M100 and the engine is currently (February 2017) being installed in the boat. A second engine is a 13 litre engine bought from Scania. It has been redesigned to Otto engine mode and operated on M100 on low speed. The pressure ration has been taken down from 17 to 12 but is planned to be raised back to 17 after initial testing. It will be put into a test cell to get well based data on performance and exhaust emissions.



**Figure 5:2. From Seminar with the GreenPilot project June 2016 [Green Pilot].**

At the key there was also a SAAB Biopower E85 car bought in Piteå in late April, serviced and thereafter fueled with M56 fuel (56% methanol in gasoline) during its journey from Piteå to Stockholm and further to Lund University in Southern Sweden where it has been running since then. It has since it started and until February 2017 run well over 10,000 km on M56. The engine was taken apart after 10,000 km for inspection. Detailed inspection protocol is still not finalized but no negative observation was noticed at visual inspection. Finally, there was a M100 speedway motorcycle

<sup>16</sup> GreenPilot web page: [www.GreenPilot.se](http://www.GreenPilot.se)

on show. LTU had been contacted earlier by one of the Swedish speedway racing teams, which resulted in meetings and practical testing and some common information activities e.g. short news by the Swedish Television, SVT.<sup>17</sup> The ambition of the small event on June 16 was to show to the public the broad and comparably simple application possibilities of methanol. Table 5:1 summarizes the reason why the four demonstrators have selected methanol as fuel for their very diverse applications.

**Table 5:1. Key reasons for the selection of methanol for the four applications described above.**

Application	Reason to choose methanol
Large Ship	Comparably cost efficient, engine efficiency, clean, potential to be renewable, comparably simple introduction in the ship, simple infrastructure
Small boat (e.g. Pilot)	Comparably cost efficient, engine efficiency, clean, potential to go renewable, comparably simple introduction in the ship, simple infrastructure
Small car	A flexi fuel car such as E85 can as well be run on M85 or various mixes of gasoline ethanol and methanol, GEM (see section 5.2)
Speedway motorcycle	When designing for power as a function of vehicle weight methanol often becomes the fuel of choice.

## 5.2 LOW BLEND OF METHANOL IN GASOLINE

The European gasoline standard EN228 allows for 3% by volume of methanol and also has a limitation of maximum oxygen concentration of 2.7%. This is for the standard allowing 5% by volume of ethanol. Currently some countries in Europe allow 10% ethanol and then the corresponding maximum content is increased accordingly.

To investigate the issue of low blend of methanol in gasoline the INTROMET (INTroduction of METHanol) project was started in 2003 with financial support from the Swedish Energy Administration (Ecotraffic, 2006). The objective was to study the introduction of methanol as a motor fuel, primarily via low-level blending in gasoline. In addition to low-level blending, many other aspects of the introduction on a long-term horizon were also discussed in the report.

Ten cars participated in the field test according to Table 5:2. The table also describes the total driven distance per car and the total fuel consumption and consumption expressed as liter/100km.

<sup>17</sup> <http://www.svt.se/nyheter/lokalt/sormland/har-testar-smederna-varldsunik-t-bransle>

**Table 5:2. Vehicles tested in the INTROMET project (Ecotrafic, 2006). NOTE: Comma in the table stands for a decimal point. E.g. 7,1 is 7.1.**

Car brand / model	Distance (km)	Fuel tot. (litres)	Fuel cons (l/100 km)
Toyota Yaris	7026	499	7,1
Toyota Yaris	8247	546	6,6
Renault Clio	4786	377	7,9
Renault Clio	8232	534	6,5
Renault Clio	4193	299	7,1
Toyota Yaris Verso	7525	373	5,0
Toyota Yaris	3500	259	7,4
Toyota Yaris	3940	286	7,2
Toyota Yaris <sup>6</sup>	3940	286	7,2
VW Golf	4191	400	9,6
Sum	55580	3859	

The fuel composition used in the INTROMET project was 3% methanol and 3% ethanol, i.e. M3E3. It was anticipated that a co-solvent would be necessary besides the 3% methanol that is permitted according to the EU specification. By adding a maximum of 3% ethanol, the oxygen content was also below the maximum of 2,7% allowed in the specification at that time. The fuel was supplied by Statoil, which was also responsible for the refueling station.

One Toyota Yaris that had run about 30,000 km of which the last about 7,000 km on M3E3 was inspected in detail. The following was concluded:

- No degradation could be found in cylinder heads or in fuel pumps
- The ignition plugs looked normal
- The fuel pump and filter were completely clean
- Oil analysis showed impact of weather conditions (winter) and relatively short driving distances but no apparent negative impact of the blended fuel.

The car was also compared to another car of the same model, which had operated on E5 and run somewhat less mileage. No differences could be noticed.

Various tests were made and the report made the following overall conclusion:

Methanol blending seems to have a certain positive impact on CO and energy efficiency. For HC and NOX no clear impact could be seen. The trend was a small increase for HC for both engine types while NOX decreased for the port-injected engine but increased marginally for the direct-injected engine. The exhaust content of methane, acetaldehyde, formaldehyde and methanol in the exhaust was very low. The catalyst will reduce these levels even further with the exception for methane. In summary, the authors concluded that no objections for blending methanol in gasoline could be found. Optimizing the engine and its injection system would give further improvements.

The authors of the INTROMET report concluded that blending of methanol in gasoline is viable today. The EU specification allows 3% blending and emissions and drivability will not be affected at this blending level. A discussion was also made about introduction at a larger scale, if the fuel specifications of E10 and E85 fuels would allow a certain percentage (higher than 3%) of methanol.

### 5.3 HIGH BLENDS OF METHANOL IN GASOLINE AND SO-CALLED GEM FUELS

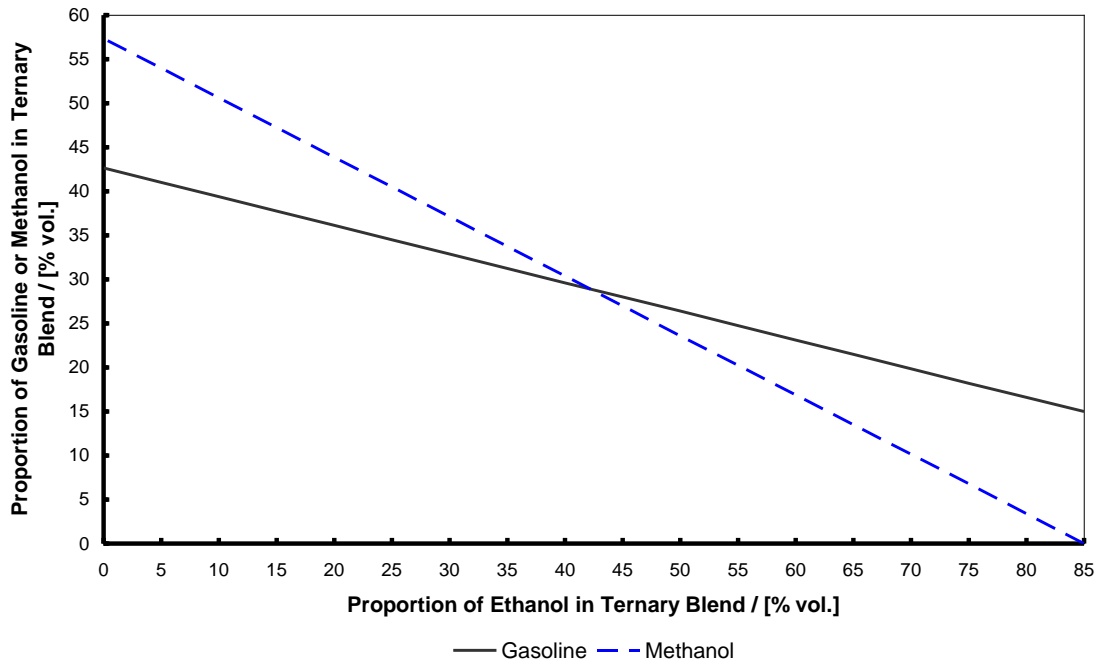
High blends of methanol are used in China as described in section 3.1.1.

Whereas ethanol has been blended with gasoline in the bulk fuel pool for years, methanol can also be introduced because all three (and the other alcohols) are miscible together. If a given target stoichiometric air-fuel ratio (AFR) is used to configure such blends, a significant finding has been that all such blends possess the qualities necessary for them to become ‘drop-in’ alternatives for the binary ethanol-gasoline mixture with the same stoichiometric AFR (Turner *et al.*, 2011). Ternary blends using these components have been termed ‘GEM’ fuels.

This has been shown to be possible by (Turner *et al.*, 2013) who showed that for the extreme case of GEM mixtures with a target stoichiometric AFR equivalent to that of E85 (nominally 85% ethanol and 15% gasoline), all possible blends have nearly identical volumetric lower heating value and octane numbers, together with extremely close enthalpies of vaporization (to +/- 2%). These are the properties that different fuels require to be interchangeable in a spark-ignition (SI) combustion system, including its control. In their testing of a standard production vehicle these authors showed equivalent fuel consumption, CO<sub>2</sub> and criteria pollutant emissions, all with normal engine operation. In fact, the cold-start performance was better when there was methanol in the fuel being tested when compared to the binary ethanol-gasoline equivalent.

Figure 5:3 shows the necessary relationship for the blend components in the extreme high-alcohol-proportion case of E85. As the volume percentage of ethanol is reduced, the rate of increase of the volume of methanol is faster than that of gasoline. This is because, provided the volume proportions of 32.7:67.3 are used for methanol and gasoline, there is equivalence to the proportion of ethanol being removed.





**Figure 5:3 Relationship between proportions of gasoline, ethanol and methanol in ‘GEM’ ternary blends configured to be equivalent to E85. E85 itself is represented at the x-axis, with the equivalent binary gasoline-methanol blend shown on the left-hand side M56 [Univ. of Bath].**

In the mixtures, ethanol is presumed to perform well the function of a co-solvent for the other two components; in early tests there was some evidence of phase separation in the M56 binary blend tested (out of four fuels spanning the range shown in Figure 5:3). However, this was for a fuel system technology level without a physical alcohol concentration sensor. When the minimum ethanol concentration was investigated in later tests in a vehicle equipped with a physical alcohol concentration sensor, no such minimum requirement for ethanol was identified, despite repeated cold soaks and related cold start tests at  $-20^{\circ}\text{C}$  using only the binary methanol-gasoline fuel (at the left-hand side of Figure 5:3) (Turner *et al.*, 2012). Note that in terms of emissions, all of the E85-equivalent ternary blends essentially outperformed gasoline (although aldehyde emissions were not measured).

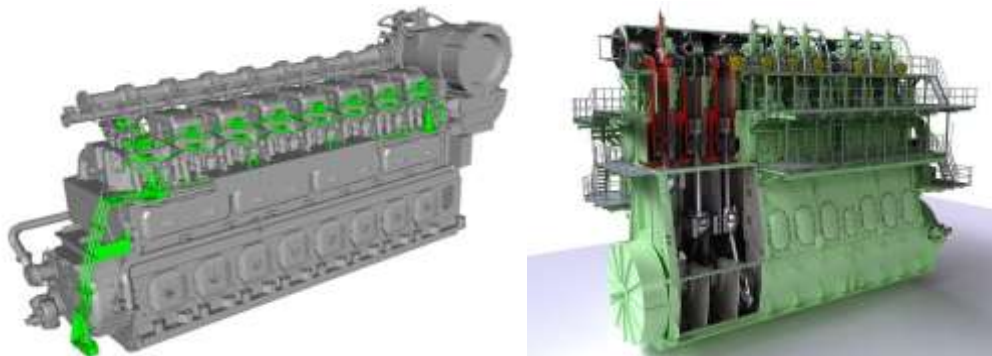
All of the above tests were conducted in port-fuel-injection engines. Pitcher *et al.* studied the blends in an optical direct-injection engine with respect to spray characteristics, important because of the effect of these on emissions and fuel consumption in such engines. They found that there was no significant difference in spray morphology across the blend spectrum of Figure 5:3. A preliminary investigation of materials’ compatibility issues has been reported in another publication, and researchers from other groups have also shown that GEM blends configured in what has been termed this ‘iso-stoichiometric’ manner are effectively invisible in any engine that has been calibrated for the binary ethanol-gasoline limit case.

It is interesting to note that for E85-equivalent blends, energetic efficiency improvements of approximately 5% are possible on a vehicle level. This is because engine thermal efficiency is significantly higher when alcohols are used rather than gasoline (Turner *et al.*, 2007). In itself, this is important with regard to the amount of biomass or renewable energy that needs to be used to make renewable alcohols.

In the US, there are already nine million E85/gasoline flex-fuel vehicles in use. This has been driven by the vehicle manufacturers, because such vehicles exhibit improved fuel consumption performance versus straight gasoline under US CAFÉ regulations, coupled to the fact that the technology is so cost-effective that it has little or no impact on the selling price of vehicles. Consequently, a progressive rollout of GEM fuels, by methanol concentration and region, could allow introduction of methanol as a transport fuel, and straightforward fleet trials could be arranged there. Some government vehicle fleets are already mandated to be flex-fuel capable and provided with suitable pumps and tankage. Such tests could also be conducted in Sweden where until recently E85 flex-fuel cars were on widespread sale, so test vehicles would be readily available. There the large amount of wood waste generated by the forestry industry could be used to make large volumes of methanol and a symbiotic ramp-up of production volume and fuel pool draw could be facilitated by a controlled rollout as discussed above.

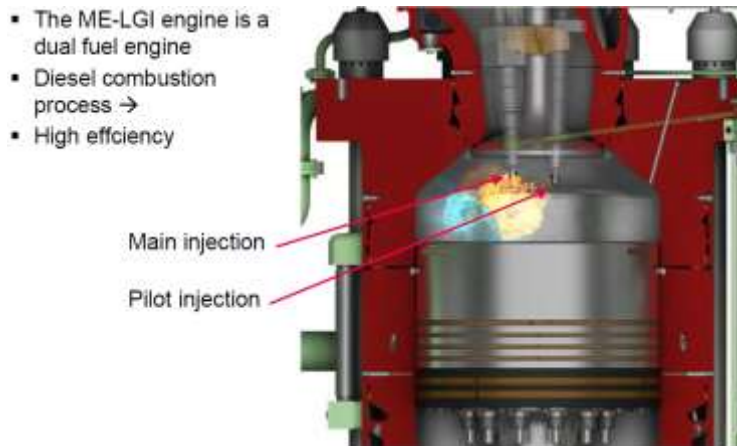
#### 5.4 MARINE APPLICATIONS

The background to introducing methanol as a bunker fuel for ships is described in section 3.2. Two manufacturers are currently testing and also offering methanol-fueled ship engines to the market. Stena Line in Gothenburg has converted its large ferryboat Stena Germanica, which travels the route Gothenburg – Kiel (Northern Germany) to run on methanol. The ship has four Wärtsilä ZA40S engines (See Figure 5:4, left) and Stena first converted one of the four engines and took it in operation in the spring 2015. Two more were converted during spring 2016 and the fourth followed shortly thereafter. This retrofit will make Stena Germanica the first ferryboat ever to run on methanol as the bunker fuel. Another major supplier of ship engines, MAN Turbo and Diesel is a supplier of (mostly) two stroke engines to the marine sector (Figure 5:4, right). Currently nine ships with deadweight of approximately 50.000 ton have been delivered or are under delivery to Methanex' Waterfront Shipping, which all are designed to operate with methanol as bunker fuel.



**Figure 5:4. Left: Wärtsilä ZA40S engine with indication of new equipment for methanol operation [Wärtsilä]. Right: MAN S50ME-B9.3-LGI two-stroke high-pressure gas (methanol) engine [MAN Turbo and Diesel].**

Both mentioned brands are designed for dual fuel operation where methanol is the main fuel and diesel is utilized as ignition fuel. This is caused by methanol not being a fuel suitable for the diesel cycle in which the fuel is ignited by pressurization of the air/fuel mixture. To enable the use of methanol in the diesel engine cycle a conventional diesel fuel is used as igniter. Figure 5:5 illustrates how the two injectors are located in the top of the cylinder in a MAN ME-LGI engine. The design of the dual fuel systems allows the ships to operate also on pure diesel fuel with zero methanol consumption.

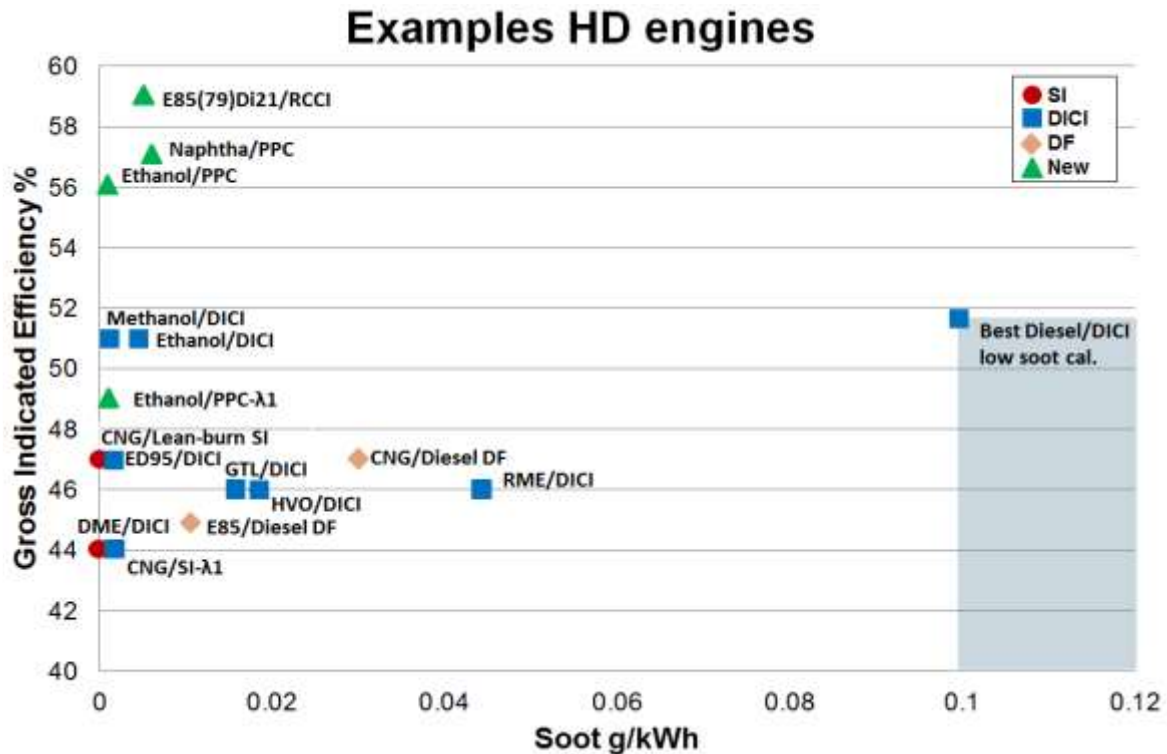


**Figure 5:5 Illustration of dual fuel injection in a MAN ME-LGI engine (Marinvest, 2016).**

## 5.5 PARTIAL PREMIX COMBUSTION (PPC) CONCEPT

PPC is associated with a separation of the direct injection event and the auto-ignition combustion. See Figure 5:1 where the PPC illustration has direct injection (no spark plug). Not shown but what is part of the concept is that part of the fuel is introduced into the cylinder with the combustion air and high amounts of exhaust recycle gases. The (main) fuel injection timing is optimized leading to low emissions of soot, NO<sub>x</sub>, HC and CO together with very high efficiency. PPC exhibits substantial fuel flexibility with liquid fuels by tailoring the injection strategy towards the auto-ignition properties of the fuel.

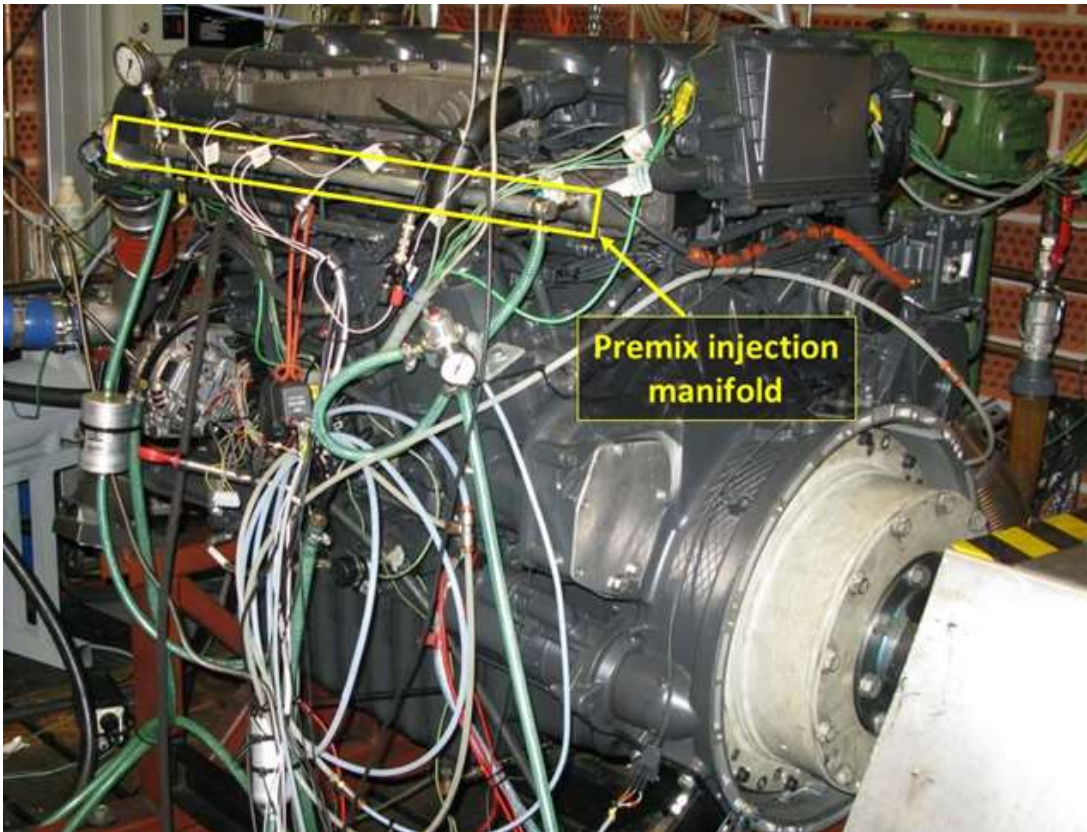
Lund University's work referred to in the beginning of this chapter has published a large number of test results for different engine concepts where the gross indicated efficiency (GIE) of heavy duty (HD) engines is presented versus soot emissions (see Figure 5:6). The best diesel performance is shown to the right (close to 52% efficiency).



**Figure 5:6. Gross indicated efficiency versus soot for different fuel and heavy-duty engine combustion concepts. “New” symbol refers to PPC concepts. [Lund Univ.]**

To the left some very efficient concepts are to be found and among them PPC tests for naphtha and ethanol. Methanol is not in the figure but it would show up approximately on the same level as the two mentioned alternatives. The difference between GIE and the overall efficiency of an engine or Break Thermal Efficiency (BTE) differs depending on fuel. According to the quoted article, the standard diesel fuel has a BTE of 47%, a difference between the two data of 4.6%. For a PPC concept, this difference is higher and the BTE for an ethanol PPC engine is estimated to be 48-50%.

The principle of PPC has been practically tested by VTT, Technical Research Center of Finland, utilizing a 9 liter, 5 cylinder Scania diesel engine adapted for so-called ED95 fuel (Murtonen *et al.*, 2015). The ED95 is an ethanol fuel that is mixed with an ignition improver additive package. VTT’s test program comprised a comprehensive fuel matrix with alternative additive packages, varying water content of the fuel and varying additive dosing percentage. A combination of indirect (into the intake manifold) and direct fuel injection was tested as well. This latter test is in principle practicing the PPC concept as described above. The extra fuel rail for premixing was engineered into the Scania engine as can be seen in Figure 5:7. The engine is equipped with unit injectors, which led to a need for five injection points, one per cylinder. For an engine with a common rail system, it would be very simple to introduce the premix concept.



**Figure 5:7. Test cell at VTT with Scania ED95 diesel engine equipped with manifold for premix fuel injection [VTT].**

The amount of testing with premix combustion was very limited. The result showed that with reduction of the additive package to 25% of normal, impacted engine performance, even when the engine was hot but via premix of fuel into the inlet manifold, the engine performed as with normal dosage of ignition additive and no premix. The fuel consumption however increased by about 10%. VTT concluded that “further testing to optimize, e.g. the amount of pilot fuel and timing of main fuel injection is needed to really show the potential of the concept”.

## 5.6 ADAPTATION OF ED95 TO BECOME A MD95 CONCEPT

The work cited in section 5.5, *Testing of various fuel and additive options in a compression-ignited heavy-duty alcohol engine* by VTT also includes testing of a preliminary alternative to ED95, which can be named MD95. The alcohol was thus methanol and not ethanol.

The work on methanol performed by VTT and presented in this report was acknowledged by Scania and the report’s results are endorsed by Scania for publication, but the report also states that methanol is today not an approved fuel for Scania’s engine family.

The fuel was prepared in the same way as the ED95 fuel, but the alcohol was changed from ethanol to methanol. During this limited test, the performance of the engine on MD95 was as good as or better than its performance on ED95 on most of the tested variables. In total seven fuels were tested of which 1-5 were ethanol-based, number 6 was a ethanol/methanol blend and fuel 7 pure methanol with an additive package as for fuel 1. Figure 5:8 includes two results from the test work and show slightly better energy efficiency and emissions of hydrocarbons (HC) for methanol than for the other six tested fuels.

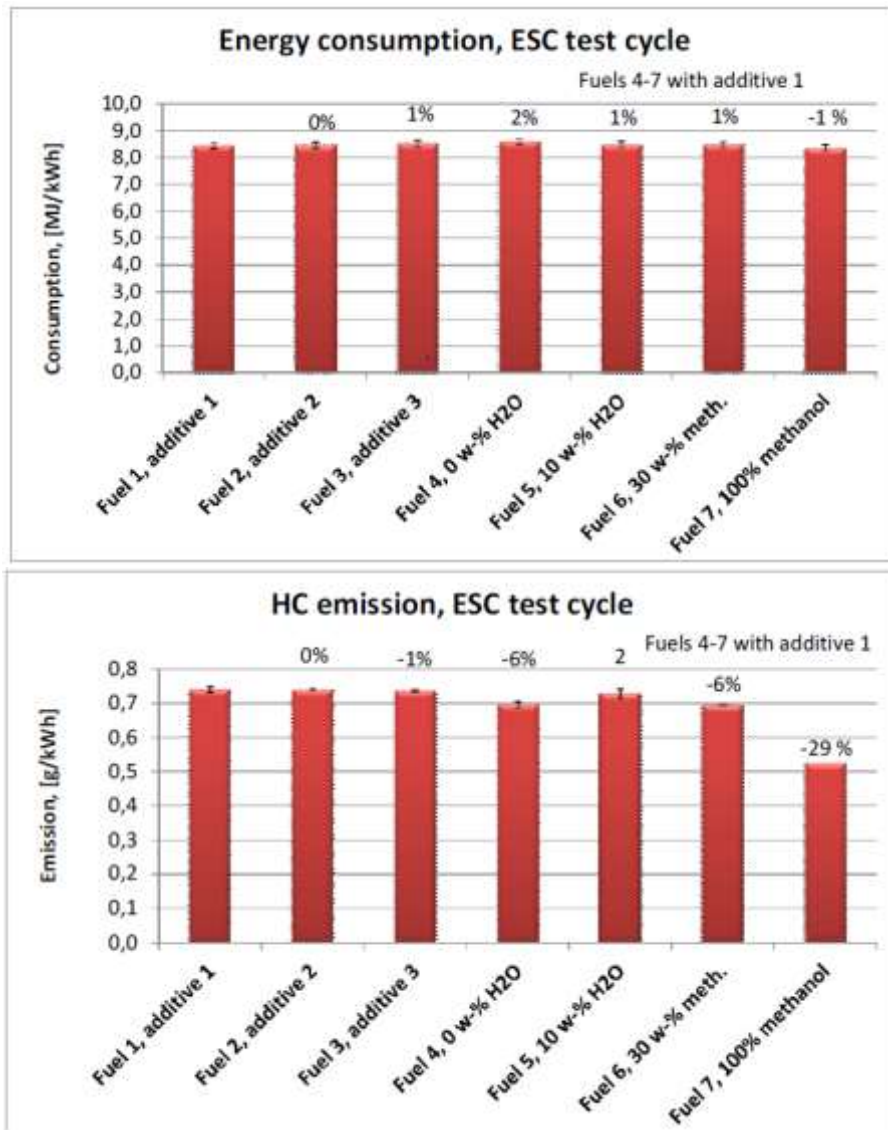


Figure 5:8. Engine efficiency and Hydrocarbon (HC) emissions from test with 7 different fuels [VTT].

Methanol showed better performance also for CO (-54%) and CO<sub>2</sub> (-2%) but higher for NO<sub>x</sub> (+23%) and particulates (+67%). With respect to particles, VTT gave the following comment: “However, as methanol contains no carbon-to-carbon bonds, it is hard to image that methanol would generate carbonaceous particles. The appearance of the test filters, which are quite white, supports this. The result must be an indication of semi volatile components or artifacts. Due to low volumetric heating value the end of injection is delayed compared to operation on ethanol, and this can be one contributing factor” (Murtonen *et al.*, 2015).

In later contacts with Scania’s headquarters (1Q, 2016) with respect to the use of methanol in Scania engines, the following can be summarized<sup>18</sup>:

- Tests with MD95 in Scania’s own test cell have performed well.
- Scania does not see any technical reasons to disqualify methanol.

<sup>18</sup> Personal communication. Eva Iverfeldt, Scania. 2016

- Scania has currently decided to design their engines to operate on five different fuels: diesel, FAME (biodiesel), paraffinic diesel, methane and ethanol. Each fuel requires a major effort from the company from a large number of aspects (from development to service). To add yet another fuel is therefore a decision with quite big consequences.
- Scania lists three key criteria for fuel selection: availability, (acceptable) cost of production, sustainability. These three requirements have led to the five alternatives, which today constitute their fuel portfolio. The development shows that methanol can become more available and at a reasonable cost, comparable to FAME. The buildup of production facilities from woody residues looks promising. It is therefore reasonable to look at methanol as a future viable fuel candidate.
- Clear positive market signals will form the base for Scania to decide whether to develop and include methanol in their portfolio of fuels.

## 5.7 METHANOL IN FUEL CELLS (FC)

The background to the use of methanol in fuel cell (FC) developments is described in section 3.5. That section primarily focuses on the interest and the fading interest in using methanol for FC application, trying to explain why it was moved out of the picture. The FC “energy converter” is normally run on pure hydrogen, but there is an exception in the form of the Direct Methanol Fuel Cell (DMFC).

Regardless the fact that today’s official view regarding infrastructure for FC powered vehicles is based on hydrogen as the energy carrier this may once more change due to various reasons. The Japanese car manufacturer Nissan can serve as an example of a potential change in strategy. In June 2016 (Automotive News, 2016) the following was announced by the company:

- Nissan has developed a new kind of fuel cell drivetrain for cars named e-bio fuel cell, with taps an onboard the tank of ethanol instead of pressurized hydrogen. They claim it to be more user-friendly. See test bench in Figure 5:9.
- Nissan’s system generates its hydrogen inside the car. It does so through an additional step handled by a component called the reformer. The reformer transforms ethanol in the fuel tank into hydrogen, which is then fed into in the fuel stack. In a traditional hydrogen fuel cell car, there is no reformer. The car’s fuel tank carries pressurized hydrogen pumped directly from a fueling station.
- Nissan claims that this solution combats the common hurdle of deployment for traditional fuel cell vehicles: The lack of hydrogen fueling infrastructure. It uses bio-ethanol derived from renewable crops such as corn or sugarcane and that refueling infrastructure already exists to a great extent.
- Nissan claims that the system is expected to be less costly (than traditional hydrogen systems) because it does not require the expensive carbon-fiber storage tanks for pressurized hydrogen or costly precious metals such as platinum catalysts for electricity generation. The FC runs at a higher temperature.
- Nissan claims that ethanol is safer to use than hydrogen because it is not as combustible.

- Nissan says that the fuel does not have to be pure ethanol. It can even be a mix of up to 55% water, which further brings down the cost of the operation.

Nissan's Executive Vice President Hideyuki Sakamoto said while announcing the development. *"We do not require a hydrogen infrastructure. That is the biggest advantage, along with better safety."*

Nissan aims to bring the technology to market in fleet vehicles by around 2020.



**Figure 5:9** The test bench for Nissan's solid oxide fuel cell that runs on bio-ethanol electric power (Automotive News, 2016; photo by Nissan).

On the negative side Nissan explains that it needs to improve the system's heat management, because swings from hot to cold extremes put pressure on durability and because it works best at high temperatures; the driving response lags until the system heats up.

Traditional fuel cell cars also produce zero emissions; that is, they emit only water vapor and heat. Nissan's system emits water vapor, heat and carbon dioxide. That is because carbon dioxide is a byproduct of the onboard reformation of ethanol into hydrogen, but Nissan argues that the system is "carbon neutral" when counted well to wheel.

Despite developing the new technology, Nissan said it has not given up on traditional hydrogen fuel cell systems. In fact, it will continue to develop that technology in parallel with its partners Daimler AG of Germany and Ford Motor Co.

The road from ethanol to methanol is short and the knowledge base within e.g. Daimler for use of methanol as the energy carrier for FC vehicle is extensive.

The principle adopted by Nissan in their new so-called e-bio FC with ethanol as energy carrier is well illustrated by Figure 5:10 showing a block diagram for a corresponding fuel cell with methanol as the energy carrier. A mixture of 2/3 of methanol and 1/3 of water (v/v) reacts and forms hydrogen, water and CO<sub>2</sub> in the reformer unit. For ethanol, the proportion between the alcohol and water is different but the principle is the same.



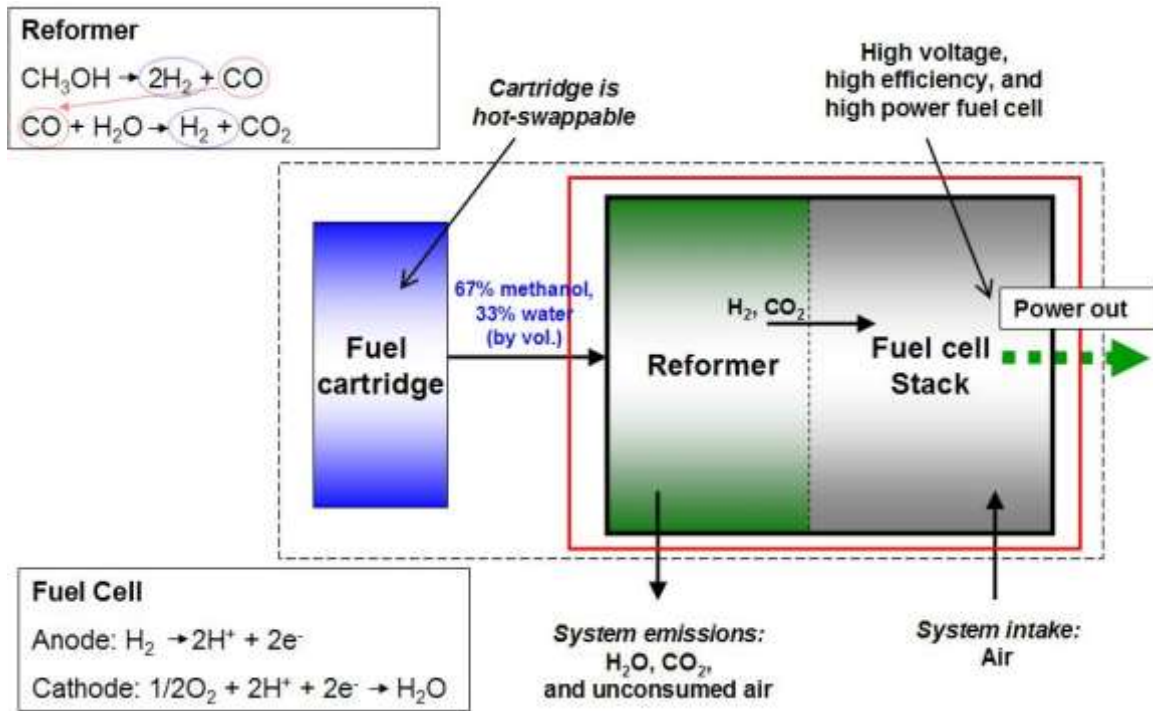


Figure 5:10. Block diagram of a Reformed Methanol Fuel Cell (Wikipedia, no date).

The biggest challenge for on board reforming has been non-converted CO, because CO is a poison for the FC stack. The goal has been to have maximum 10 ppm of CO in the hydrogen fed to the FC stack. This has been a serious issue for the on board reforming concept, but several improvements have been accomplished with reported results where the CO concentration is brought well below 10 ppm and even to zero level (Olah, Goeppert and Prakash, 2011, p. 190).

## 6 PRODUCTION COSTS FOR METHANOL IN THE NORDIC COUNTRIES

With the exception of the newly started Enerkem waste to methanol/ethanol plant in Edmonton, Canada, no large plants are built in which renewable feedstocks such as woody residues are converted from feedstock to pure syngas and further from syngas to a product like methanol (or any other product produced via syngas) as described in section 4.3. Therefore, the cost estimate for a large plant investment for methanol production from renewable resources will have a larger element of uncertainty than an investment calculation for a plant utilizing a technology that already has been constructed and operated on a commercial scale.

Some units and relations used in this chapter:

**1 MMBtu = 0.293 MWh   1 barrel (bbl) = 159 liter   1 US gallon (gal) = 3,785 liter**

**1 ton methanol (LHV): 5.54 MWh   1 ton US gasoline (LHV): 12.1 MWh**

**1 USD = 8.5 SEK   1 EUR = 9.5 SEK   1 EUR = 1.12 USD**

**USD/bbl gasoline equivalent and day = USD/bpd g.e.**

**1 USD/bpd g.e. = 0.01485 EUR/kW (base: 32,67 MJ/liter EU petrol)**

### 6.1 PRODUCTION COST CALCULATION PRINCIPLE AND BENCHMARKING

There are ways in which the production cost can be estimated within a reasonable range and where the uncertainties can be identified and understood. The production cost can be divided into three major elements, feedstock cost, operation and maintenance (O&M) cost and capital cost. The O&M cost is often divided into two parts, fixed and variable cost, where the variable cost relates to the factual operation (e.g. electric power consumption), while the fixed costs are e.g. labor, maintenance, chemicals and catalysts. The feedstock cost together with O&M costs is often referred to as Cash Cost. When the production cost is divided into the three mentioned main elements, it becomes more evident how each key variable influences the total cost of production.

#### 6.1.1 *Objective*

Besides illustrating how the key variables influence production costs, two benchmarking cases are included against which renewable methanol production costs will be compared: (1) production cost of fossil methanol, and (2) production cost of cellulosic ethanol, the dominating so-called second-generation biofuel (or Advanced Biofuel) currently in discussion.

Cost of production of renewable methanol and ethanol can be further studied and compared with other renewable alternatives in the recent Sustainable Transport Forum report “Cost of Biofuel” (Landälv and Waldheim, 2017).

#### 6.1.2 *Analysis of production cost calculation elements*

Main elements making up the total cost of production will be identified.

Feedstock cost will be related to plant conversion efficiency to quantify the impact of feedstock on the total cost of production.

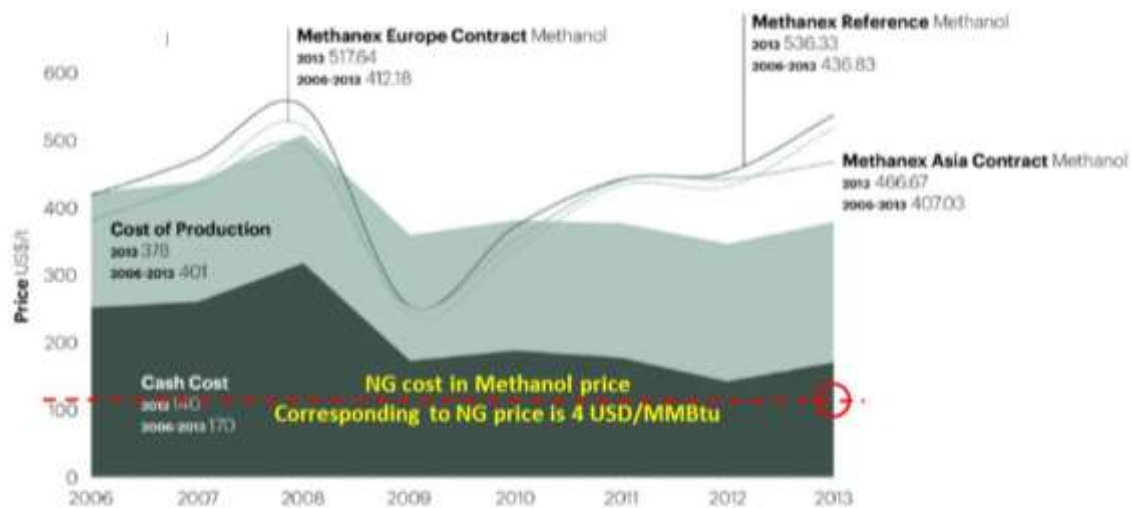
O&M costs will be compared among different plant configurations and an average number will be developed. Maintenance costs will be compared to the standard estimation method often used in the process industry where yearly maintenance is a percentage of the total plant investment cost.

Capital cost will be harmonized for all compared cases and a simple sensitivity check will be included. Investment data will be compared using “investment intensity” numbers (EUR/kW of product). If data differ considerably while plant configuration and size are similar, this will be specially commented on.

## 6.2 PRODUCTION COST BENCHMARKING CASES

### 6.2.1 Methanol from natural gas

The following concept is based on fossil methanol production in large plants fed with domestic natural gas in the US. Only two elements are shown in Figure 6:1 building up the methanol production cost, namely the cash cost and the capital cost.



**Figure 6:1. Methanol production cost (Source: Bechtel Hydrocarbon Solution 2013).**

Although the provided information is limited with respect to these two elements, it is possible to identify a number of important data out of the figure. The largest variable cost in the production cost calculation is the feedstock cost for natural gas. As can be seen in Figure 5:1 the cost of natural gas varied through the years. In 2013 a gas price of 4 USD/MMBtu (12.2 EUR/MWh) was a typical selling price in the US and this was selected for the economic calculation for that year. With a conversion efficiency of 0.65% from natural gas to methanol, the feedstock cost in the production cost of methanol is about 115 USD/ton (illustrated by the lower red, dotted line in Figure 5:1). As the figure illustrates, the cost of feedstock thus constitutes more than  $\frac{3}{4}$  of the total cash cost in 2013. In many parts of the world natural gas is even cheaper than in the US and prices down to 2 USD/MMBtu (6.1 EUR/MWh) and below exist (the pipeline price of natural gas in November 2016 is down to around 3 USD/MMBtu) (CME Group, 2016). These prices are difficult to verify, but e.g. natural gas production in conjunction with oil exploration tends to become very cheap.

Table 6:1 summarizes the main cost elements and the effect of the natural gas price on the production cost. A natural gas price of 4 USD/MMBtu equates a feedstock cost of about 115 USD/ton of methanol.

**Table 6:1. Methanol production cost in the US for various natural gas prices.**

Natural Gas price		USD/ton	USD/MWh	EUR/MWh
4 USD/MMBtu (12.2 EUR/MWh)	Cash Cost	140	25	23
	Capital Cost	238	43	38
	<b>TOTAL</b>	<b>378</b>	<b>68</b>	<b>61</b>
2 USD/MMBtu (6.1 EUR/MWh)	Cash Cost	82	15	13
	Capital Cost	238	43	38
	<b>TOTAL</b>	<b>320</b>	<b>58</b>	<b>51</b>

On an energy basis, the feedstock cost in the methanol production cost corresponds to about 21 USD/MWh (19 EUR/MWh). The total cash cost is 25 USD/MWh (23 EUR/MWh). At a natural gas price of 2 USD/MMBtu the corresponding total cash cost drops to 15 USD/MWh (13 EUR/MWh) of methanol.

As can be seen from the data in Table 6:1 the capital cost part of the total cost of production is dominating and it is important to investigate how this element is calculated. The total investment in large methanol plants is typically reported to be in the order of 50-60,000 USD/barrel and day (USD/bpd), where barrel means the energy equivalent gasoline barrel (USD/bpd g.e.). As an example, published data from a recently started Celanese plant in Southern USA can be reviewed (Oil & Gas Journal, 2016). The investment in this plant corresponded to 59,000 USD/bpd g.e. This way of expressing investment is often called “investment intensity”. This is based on the referred methanol plant producing 3900 t/d ( $1,300,000/8000 * 24$ ) which corresponds to 2453 m<sup>3</sup>/d g.e. or 15,430 bpd g.e. This number multiplied by the investment intensity (59,000 USD/bpd g.e.) gives a total investment of about 910 MMUSD, which is the quoted investment number in the article. As comparison, 60,000 USD/bpd g.e. equals 998 USD/kW or 891 EUR/kW of methanol production capacity.

The information from Figure 6:1 shows a capital cost of 238 USD/t. This level of capital cost, calculated as an annuity for the investment, is paid back in five years with an interest rate of 15% (annuity number of 0.2983 for 5 years and 15%). The plant then is assumed to run at full capacity all 5 years with a methanol price of 378 USD/ton. As a comparison it can be mentioned that straight payback expressed as gross income divided by investment is less than three years for the 4 USD/MMBtu natural gas case presented in Figure 6:1.

If in a sensitivity calculation payback time for capital is increased to 10 years and the interest rate is dropped to 10%, the capital cost of production would be significantly lower. With the 4 USD/MMBtu natural gas price, the production cost would be reduced from 378 to 255 USD/t. Converted into cost of energy this corresponds to 41 EUR/MWh of methanol, which is on par with today’s gasoline cost at around 0.4 EUR/liter.

At a natural gas price of 2 USD/MMBtu, and the lower cost of capital (10 years, 10%), the corresponding number for methanol energy would be 32 EUR/MWh. Comparison with current oil-based

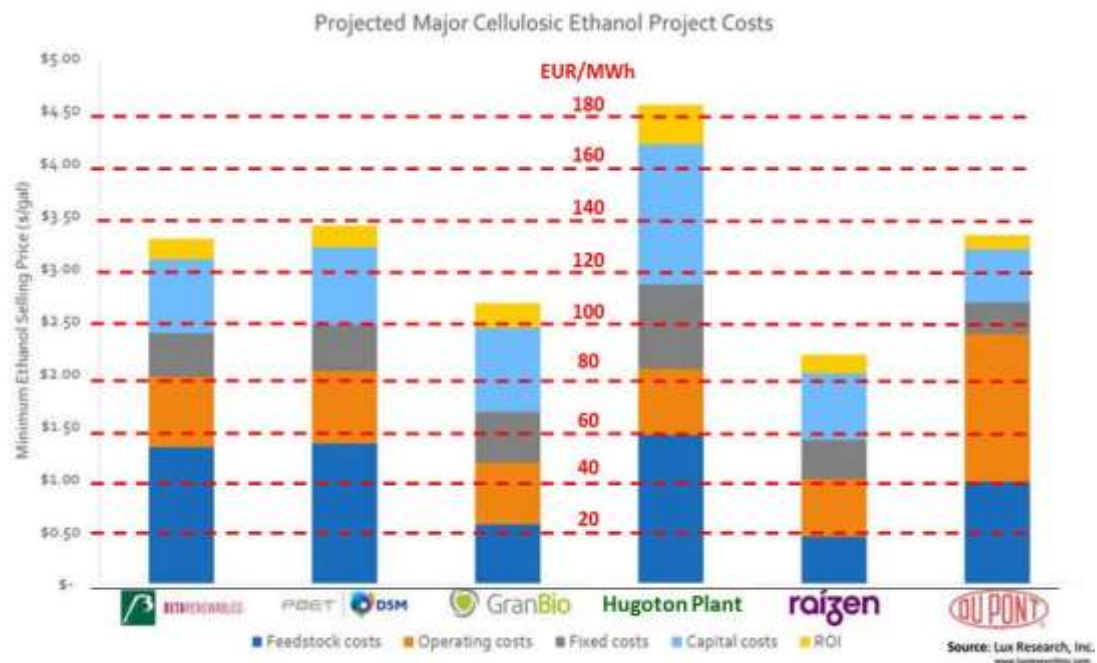
commodities confirms what was described in chapter 2, that methanol can be produced at cost levels where it can compete on an energy basis with current dominating fuels from crude oil.

#### Key conclusions:

- The two most important variables influencing the cost of production of methanol from natural gas are fuel cost and cost of capital.
- Based on capital cost calculated as an annuity with 5 years payback and 15% interest, the fossil methanol price reference level for 2013 ranges between 51-61 EUR/MWh depending on variations in feedstock (natural gas) price between 2-4 USD/MMBtu.
- After five years (when investment capital is paid back) the production cost equals the cash cost. This corresponds to 23 EUR/MWh at a natural gas price of 4 USD/MMBtu
- A sensitivity analysis with capital cost calculated as an annuity with 10 years pay back and 10% interest gives a fossil methanol price level between 32-41 EUR/MWh depending on the same 2-4 USD/MMBtu variation in natural gas price.

### 6.2.2 Cellulosic ethanol

Currently there are quite a number of first of a kind cellulosic ethanol plants up and running and there are data available that give the basic cost structure. One such comparison among plants in operation (or soon coming on stream) is shown in Figure 6:2. For the ethanol plants, the cash costs typically constitute about 70 to 80% of the total production cost, while the capital cost element is 20 to 30% with the exception of the DuPont plant where it is about 15%.



Source: <http://www.pennenergy.com/marketwired-power/2016/02/24/raizen-has-lowest-price-as-cellulosic-ethanol-hinges-on-feedstock-cost.html>

**Figure 6:2 Projected production costs for major Cellulosic ethanol projects (Lux Research, 2016).**

Ethanol plants converting cellulosic sugars have a typical conversion rate of 35% defined as energy in product divided by energy in feedstock. It may vary from some percentage points below 30 up to

close to 40%. Most actors in the field however quote numbers around 33%. In Figure 6:2 one feedstock cost level is about 1.3 USD/gal of ethanol (three plants) and for two plants the feedstock cost is about half of that, 0.6 USD/gal. The DuPont plant indicates 1.0 USD/gal but they also quote an efficiency at the higher end of the interval (about 37%). 1.3 USD/gal of ethanol and 33% efficiency equates a feedstock cost of about 100 USD/ton or 16 EUR/MWh. The two plants with low feedstock cost therefore pay about 8 EUR/MWh for their feedstock if calculated with the same efficiency. Conversion efficiency and cost of feedstock therefore play a significant role in the economy of these plants. For two of the plants feedstock alone represent about 40% of the cost of the product.

It seems clear that the return on capital has been set at a low level. For the Hugoton plant, investment is reported to be 500 MMUSD (minus 21 MMUSD in grant) and the production capacity is stated to be 95,000 m<sup>3</sup>/y of ethanol and 18 MW of green power. The capital part of the selling price is about 1.7 USD/gal (yellow and blue in Figure 6:2).

If the same representation of investment is used for the Hugoton plant investment as was used above for a large methanol plant, the investment intensity of the ethanol plant is about 6240 EUR/kW (refer to produced ethanol and including utility plant investment). The other plants referred to in Figure 6:2 have investment intensities between about 2400 and 6500 EUR/kW.

The plants in Figure 6:2 are the first of a kind of plants and it is evident that operation experience and improved design will move the investment intensity to the lower end of the quoted span and further downwards (see section 6.3).

#### Key conclusions:

- For cellulosic ethanol plants (1) cash cost contributes to a large proportion of the overall production cost with cost of feedstock being the biggest single element and (2) the return on invested capital is low.
- Based on the reported cellulosic ethanol plant data for feedstock, O&M and capital costs of one of the plants reaches a total ethanol production cost below 85 EUR/MWh, four in the interval 105 to 130 EUR/MWh and one more than 180 EUR/MWh.
- The investment intensity is comparably high or in the interval between 2,380 and 6,530 EUR/kW.

## 6.3 PRODUCTION COST OF METHANOL – BIOMASS AND BLG ROUTES

### 6.3.1 *VTT biomass to methanol concept*

Section 4.4.2 presents a biomass to methanol concept developed by VTT (Hannula and Kurkela, 2013). The study contains a detailed description regarding how the investment, feedstock and O&M costs have been calculated. It should however be noted that the cost estimate has not been elaborated from input from various licensors of technology e.g. for the gas cleaning and methanol synthesis technology suppliers.

Key available data from the report are presented in Table 6:2. The base case in the table is data as per the report, while the “normalized” case has been adjusted in order to make the VTT data com-

parable with the other reported plants regarding the most important variables. The reported investment figures are taken as reported. They will be used to create a span in which the investment for a plant of the reported size and nature can be expected to end up.

**Table 6:2. Key plant data for biomass gasification based methanol plant (Hannula and Kurkela, 2013).**

Variable	VTT report Base	VTT report "normalized"	Comment
Plant size, MW <sub>th</sub>	300	300	LHV
Conversion efficiency (biomass to methanol)	0.61	0.61	
Operating hours per year	7889	8000	7889 => 8000
Product methanol			
- MW <sub>th</sub> methanol	183	186	7889 => 8000 op. h
- Ton/year	261,000	265,000	7889 => 8000 op. h
Investment, MEUR	347	347	
Investment intensity EUR/kW	1896	1866	7889 => 8000 op. h
Production cost, EUR/MWh	66	71	7889 => 8000 op. h
- Of which capital (20 years/10%)	29 (44%)	27 (38%)	
- Of which feedstock (Base: 16.9 EUR/MWh)	28 (42%)	35 (49%)	16.9 EUR/MWh => 21 EUR/MWh
- Of which O&M	9 (14%)	9 (13%)	

In Table 6:2, the yearly hours of operation have been increased to 8,000 h leading to some small adjustments in other parameters. The investment intensity is calculated as described in Example 1 above, in this case with 20 years/10% capital charge. VTT has assumed a comparably low biomass price. This has been adjusted to be equal to 20 öre/kWh or 21 EUR/MWh.

From the production cost data it is clear that two variables play a dominating role, namely cost of feedstock and cost of capital.

#### Key conclusions:

- Cost of capital and cost of feedstock are the two dominating elements representing together over 80% of the cost of production.
- Investment intensity is in the order of 2000 EUR per kW of product (methanol)

### **6.3.2 E.ON biomass to biomethane project**

Another project under consideration in Sweden, and which has been approved for financial support from the EU program called NER300, is called The Bio2G project and is run by E.ON Gasification Development AB (EGD). It intends to construct a biomass to biomethane plant in Southern Sweden and feed the biogas into the national natural gas grid. The project is idling due to lack of long-term legislation in support of renewable fuel production, a hindrance it shares with a number of other projects.

The reason why this project is included in this report (although it is not a biomass to methanol project) is that to a large extent it is built up with the same technology as the VTT project presented

above and that it also is very close in size. From data presented it can however be seen that the process calculations lead to deviations that need to be taken into account when dealing with sensitivity. Conversions from biomass to methane alternatively to methanol have somewhat different overall conversion efficiencies.

From an overall investment point of view, the deviations between the two concepts should be fairly small. Both concepts share the same or similar plant sections all through to production from biomass storage and feed system to clean syngas ready for synthesis. The deviation will be dealt with in section 6.3 where the influence of changes of the investment cost will be shown.

Available key data have been provided by E.ON and are presented in Table 6:3. Similar as to for the VTT report, the base case is data from the report and the “normalized” case has been adjusted to make the data comparable to other reported plant data.

**Table 6:3 Key plant data (n<sup>th</sup> plant) for biomass gasification based biomethane plant [E.ON].**

Variable	E.ON report Base	E.ON report “normalized”	Comment
Plant size, MW <sub>th</sub>	334	334	LHV
Conversion efficiency (biomass to biomethane)	0.60	0.60	See comment in text
Operating hours per year	8000	8000	
Product methanol			
- MW <sub>th</sub> biomethane	200	200	LHV
Investment, MEUR	421	421	
Investment intensity EUR/kW	2050	2050	
Production cost, EUR/MWh	69	75	
- Of which capital (Base: 25 years/8%)	25 (36%)	31 (41%)	25years / 8% => 20years/10%
- Of which feedstock (21 EUR/MWh)	35 (51%)	35 (47%)	
- Of which O&M	9 (13%)	9 (12%)	

In Table 6:3, data for n<sup>th</sup> plant has been included. The NER300 project was reported to have a 10% higher investment cost and also some other deviations compared to what is presented in the table. The E.ON projects also included income from export of district heating. This income has not been included in the cost of production in order to minimize differences between concepts.

E.ON gives lower conversion efficiency than the VTT report, which from process kinetics point of view cannot be correct. Part of the reason is that the proposed E.ON concept includes an H&P plant, which consumes part of the feedstock. The actual conversion efficiency from biomass entering the gasifier to biomethane product is 64-67% depending mainly on the inlet of hot filter temperature downstream the gasifier. Therefore 64% should be compared to VTT’s 61%. See the influence of overall energy conversion in section 6.3.

E.ON has specified 25 years with 8% interest for cost of capital (see base case for n<sup>th</sup> plant). This has been normalized to 20 years and 10%. They have specified a span for the cost of biomass fuel (18.9-26.3 EUR/MWh). This has been put at 21 EUR/MWh as in the normalized VTT case.



Key conclusions:

- The costs of capital and feedstock are the two dominating elements together representing over 80% of the cost of production.
- Investment intensity is in the order of 2000 EUR per kW of product (methane)

**6.3.3 The Domsjö Mill with integrated thick liquor to methanol plant**

This project example as well as the following general so-called BLGMF case below are not stand-alone plants as is the case with the above-described two cases.<sup>19</sup> The investments calculations instead expresses differences between two investments (a recovery boiler (RB) based solution and a BLG based solution) and the process data are also differs between two process solutions. Section 4.4.3 describes the BLGMF concept further.

BLGMF is a concept where the spent cooking liquor from a pulp mill is gasified to syngas and converted further to e.g. methanol, and biomass is fired in an H&P boiler to compensate for the loss of steam and power production, which is the result of the elimination of the recovery boiler. The conversion efficiency number given in row two of Table 6:4 shows the conversion efficiency from liquor to methanol. The overall conversion efficiency from extra biomass to methanol is considerably higher, in the order of 90%. It is part of the feedstock cost at the end of the table.

The Domsjö Mill is a sodium sulfite mill. The liquor, which in sulfate (kraft) mills often is called black liquor, is in this case called thick liquor or brown liquor due to its brownish color. The Domsjö mill has two recovery boilers from about 1960, which are close to need to be replaced, and gasification is a very viable option to a new recovery boiler. The methanol production cost case presented in Table 6:4 is based on engineering work carried out during 2008 to 2011.

**Table 6:4 Key plant data for BLG based methanol plant, Domsjö [Chemrec].**

Variable	Domsjö Base (With 53 MEUR grant)	Comment	Domsjö (With 150 MEUR RB credit)
Plant size, MW <sub>th</sub> of black liquor	191	LHV	191
Conversion efficiency (thick liquor to methanol)	0.51	See comment in text	0.51
Operating hours per year	8300	Spare gasifier train	8300
Product methanol			
- MW <sub>th</sub> methanol	98	LHV	98
- Ton/year	147,000		147000
Investment, MEUR	350	300 with grant	200
Investment intensity EUR/kW	3060		2040
Production cost, EUR/MWh	102		88
- Of which capital (20 years/10%)	43 (42%)		29 (33%)
- Of which feedstock	34 (33%)	See comment in text	34 (39%)
- Of which O&M	25 (25%)	See comment in text	25 (28%)

<sup>19</sup> Even though the E.ON plant strictly speaking is integrated with a district heating network, the revenues from district heating are negligible in comparison to the revenues from the produced methane, for which reason it is regarded as stand-alone here.

It comprises negotiated technology licenses for the involved process licensors together with preliminary cost calculations provided by the technology licensors. The Chemrec gasification plant was to a large extent designed and engineered by a company commercially involved in supplying entrained flow gasifiers to other gasification systems (from coal and oil). Costs associated with integration between the new process and the existing plant as well as changes to be done within the mill were estimated by Domsjö's own staff and their consultants. The project was given a grant of 500 MSEK through a grant program headed by the Swedish Energy Agency.

In order to achieve high availability (8,300 h per year in operation) for the plant the gasification unit was equipped with a spare train. Each train can process 50% of the liquor feed. See Figure 4:5 for illustration of the design.

In the cost of production of methanol the cost of capital is calculated as for the other two examples with 20 years' payback and an interest rate of 10%. The overall project included import of steam from a third party. Therefore, the cost of "feedstock" is higher. It actually includes capital and operation costs from the steam generation partner. When the system boundary is moved out to include the addition of extra biomass to operate the entire new system, the conversion efficiency from energy in the extra biomass brought to the H&P boiler to methanol is over 90%. Close to 50% of the O&M costs refer to buying the oxygen and nitrogen "over the fence" from a company building a new facility close to the Domsjö industrial site.

The BLGMF concept has been developed with the aim to substitute the existing boiler-based recovery system with a gasification-based system plus (normally) a new biomass-fed boiler. From an investment point of view such a change of recovery system would lead to the cost of a new recovery boiler being credited to the new plant. Recovery boilers are replaced regularly. Some seven recovery boilers have e.g. been replaced in Sweden since 2000. The Domsjö gasification-based recovery system would have become the first installation of the novel gasification-based technology, and therefore it was agreed to exclude the boiler credit from the calculation. Table 6:4 shows a case where the 500 MSEK grant is not credited to the investment, but instead a tentative cost of a new boiler-based recovery system is credited to the investment. With the assumption that the recovery boiler system would cost 150 MEUR, the net investment would then become 200 MEUR. The investment intensity would become considerably lower and the cost of methanol production would decrease about 14% to 88 EUR/MWh.

#### Key conclusions

- The costs of capital and feedstock are the two dominating elements representing 70-80% of the cost of production.
- Investment intensity is in the order of 3000 EUR per kW of product (methanol) without recovery boiler credit and about 2000 with credit.

#### **6.3.4 A generic sulphate mill with integrated black liquor gasification (BLG) to methanol plant**

The Domsjö project was in many ways unique and therefore the following case is meant to describe an n<sup>th</sup> plant case. Average-sized mills in Scandinavia and in the world generate in the order of 2000-2500 tons of dry black liquor solids per day (tDS/d) and this generic case is calculated for a

mill producing 2500 tDS/d, which corresponds to about 350 MW of liquor. Table 6:5 describes key data for such a plant.

This investment is intended to take place when the existing recovery boiler has been outdated and the mill is ready to invest in a new recovery boiler alternatively in the now commercialized BLG-based technology in order to produce methanol from the generated syngas. The same type of reasoning is of course applicable to a new pulp mill installation. At the time of the investment decision, the comparison for the mill owner stands between a new modern recovery boiler and a BLG-based system with increased use of biomass. The change will result in a need to buy extra electric power, because instead of producing power and heat, as the recovery boiler-based mill would do, the black liquor energy is now used for production of other valuable commodities. Power will be generated on the backpressure steam demand of the combined new facility, utilizing a new comparable large biomass fed boiler. This power production will however not be enough to satisfy the total demand from the new combined plant.

The gasification unit is equipped with an extra spare gasification train (three trains in operation and one spare) in order to meet the demand of availability calculated to be 8,300 operating hours per year. The conversion efficiency from black liquor to methanol is calculated to be 53%. This number can over time be increased a few percentage points e.g. via allowing increased solids content in black liquor and via preheat of gasifier feed streams.

The cost of a new recovery boiler has been calculated at 250 MEUR leading to a net investment of 240 MEUR (influence of the size of the avoided investment is discussed in section 6.5.1).

**Table 6:5 Key plant data (n<sup>th</sup> plant) for BLG based methanol plant [Chemrec].**

Variable	Generic BLG plant	Comment
Plant size, MW <sub>th</sub> of black liquor	366	LHV, 2500 tSD/day
Conversion efficiency (thick liquor to methanol)	0,53	See comment in text
Operating hours per year	8300	Includes 3x50% gasifier train
Product methanol		
- MW <sub>th</sub> methanol	194	LHV
- Ton/year	290000	
Investment, MEUR	490/240	Total/with RB credit
Investment intensity USD/kW	2465/1290	Total/with RB credit
Production cost, EUR/MWh	64	with RB credit
- Of which capital (20 years/10%)	18 (28%)	with RB credit
- Of which biomass feedstock	12 (19%)	At 21 EUR/MWh
- Of which O&M, power	21 (33%)	At 60 EUR/MWh
- Of which O&M, other	13 (20%)	

For this case, the two large variable cost elements biomass feedstock and electricity play a significant role, amounting to about 50% of the total cost of production of methanol. The background to the considerable power purchase is that the internally produced power only comes from the heat and power boiler designed to operate on the backpressure of the mills steam system. The power deficit is purchased from the power net (see also sections 4.4.3 and 7.1).

Key conclusions:

- The costs of biomass and power together make up about 50% of the cost of production. The cost of power is dominating.
- The plant is less capital intensive than other studied conversion routes. Capital costs represent approximately 30% of the total cost of production.

## 6.4 METHANOL PRODUCTION COST COMPARISON AND SENSITIVITY

Data from section 6.3 shows with some variations that the costs of capital and feedstock(s) make up about 70-85% of the total cost of production of bio-methanol. In order to get an understanding of the capital burden for a certain way to produce energy in the form of biofuels, the unit “investment intensity” has been used. A technology with low investment intensity and high conversion rate from feedstock to product will come out positive in a comparison, because these two elements dominate in the total cost of production.

### 6.4.1 *Investment intensity*

Figure 6:3 illustrates the investment intensity data presented in section 6.3 as well as the two benchmarking examples from section 6.2. Regarding cellulosic ethanol plants, a set of data is added from a survey carried out by Bloomberg New Energy Finance (2013)<sup>20</sup> in addition to what is presented in section 6.2.2. Bloomberg has followed the cellulosic ethanol technology development for a long period and in this report they summarized the investment in new plants in that year and predicted improvements for the coming period to 2016. As can be seen in Figure 6:3, these numbers coincide well with the plants having the lowest investment intensity (see Figure 6:2).

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<sup>20</sup> Bloomberg : Cellulosic ethanol costs: Surveying an industry (March 18, 2013)

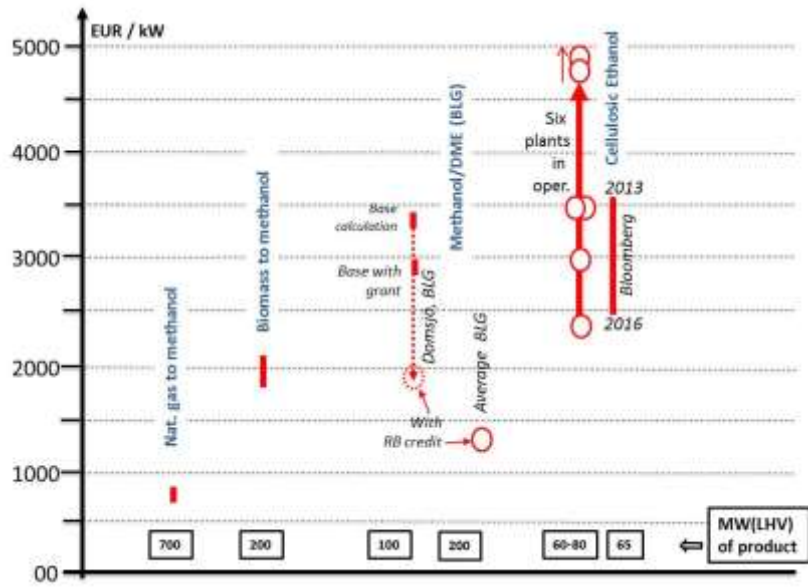


Figure 6:3 Investment intensity (EUR per kW of product) for various conversion routes to methanol (author's own visualization).

Figure 6:3 indicates an expected span for investments in gasification-based plants. An important variable is size of plant because economy of scale is an important factor when calculating the cost of production. The studied plants (not including Domsjö) are of the same size, 200 MW of methanol. A 200 MW product capacity corresponds to close to 300,000 tons per year of methanol if the plant is operated 8,000 h per year. The review of plant data shows investment intensity between 1800 and 2200 EUR/kW of product corresponding to investments between 360-440 MEUR. In the BLG case with a credited recovery boiler investment the investment could come down to approximately 260 MEUR (investment intensity of 1300 EUR/kW).

As shown in figure, the investment intensity for the six cellulosic ethanol plants in operation is 50-100% higher than the presented gasification-based plants, in the lower end of the span. It should be noted that the ethanol plants are also smaller, typically only a third of the size and thus the investment can partly be attributed to the economy of scale, although the actual processes are also very different and therefore not directly comparable in that way.

Natural gas-based methanol on the other hand has low investment intensity, but the plant capacity is also very large (700 MW of methanol) compared to the biomass-based systems.

#### 6.4.2 Overall production cost – influence of key variables

This section presents a sensitivity analysis of how key variables affect the overall bio-methanol production costs. Table 6:6 summarizes the Base Case, which includes production cost data from section 6.3 for two of the presented concepts – one based on gasification of solid biomass and one on gasification of black liquor.

**Table 6:6. Production cost for Base Case (EUR/MWh).**

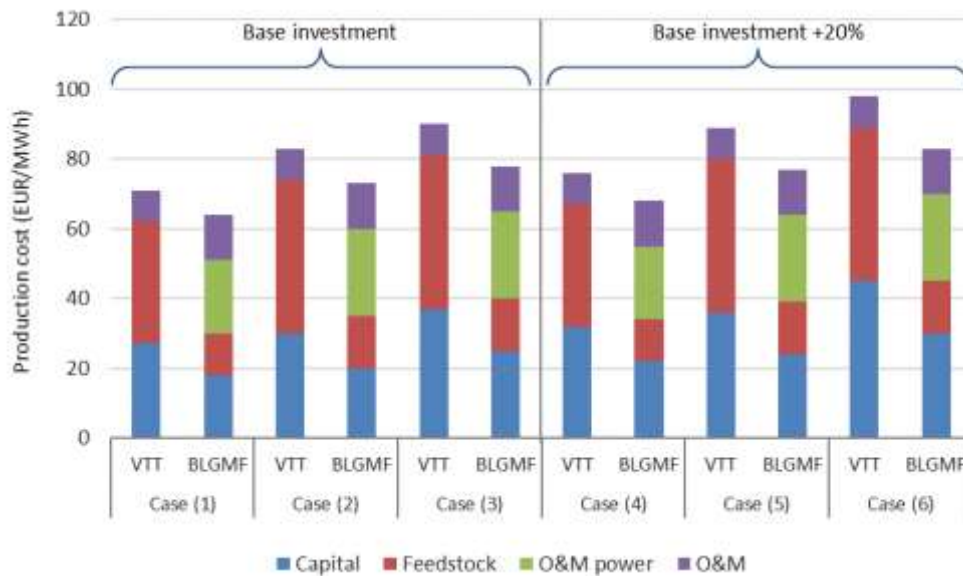
Plant Concept	Total	Capital	Feedstock	O&M Power	O&M
VTT (solid biomass)	71	27	35		9
BLGMF (black liquor)	64	18	12	21	13

In the sensitivity analysis, two levels of investments have been considered. For each of these two investment levels the impacts of costs of capital, biomass and power have been investigated.

For case (2), the base investments for the three concepts have been kept but the cost of capital is chosen with 15 years' payback at 10% interest (annuity 0.1315). At the same time the feedstock cost has increased by 25% to 26 EUR/MWh and the costs of purchased power by 10 EUR/MWh to 70 EUR/MWh. Case (3) equals case (2) with the difference that cost of capital is chosen with 10 years' payback at 10% interest (annuity 0.1627). Cases (4) to (6) correspond to cases (1) to (3) but with an increased overall investment of 20% for each studied case. Table 6:7 gives an overview of the six considered cases.

**Table 6:7 Case definition (numbers in parentheses) for the sensitivity analysis.**

Investment	Capital			Feedstock		O&M		
	20y/10%	15y/10%	10y/10%	Base	+25%	Power 60 EUR/ MWh	Power 70 EUR/ MWh	Other O&M
Base	(1)			(1)		(1)		(1)
		(2)			(2)		(2)	(2)
			(3)		(3)		(3)	(3)
Base +20%	(4)			(4)		(4)		(4)
		(5)			(5)		(5)	(5)
			(6)		(6)		(6)	(6)



**Figure 6:4. Production costs for the two bio-methanol production concepts, for the six studied sensitivity analysis cases (Table 6:7).**

In Figure 6:4 the resulting production costs for the analyzed cases are presented, divided on the included cost components. As can be seen in the figure and as has also been discussed in section 6.3.4 and shown in

Figure 6:3, the BLGMF concept has a benefit in that the investment can be credited with the avoided investment in a new recovery boiler, which results in a lower capital cost. Relatedly, due to the lower need of purchased biomass feedstock, the BLGMF concept is less sensitive to changes in feedstock price.

When comparing the basic data for the different process concepts in section 6.3, some parameters, such as overall conversion rate from biomass to methanol, the total investment for the VTT case, and the cost of recovery boiler replacement in the BLGMF case were specifically highlighted because the presented data could be questioned for various reasons. Table 6:8 thus presents additionally sensitivity analysis regarding the influence of those parameters.

**Table 6:8 Sensitivity when altering certain basic data.**

Parameter	Proposed change: From => To	Change in Cost of Production of methanol
VTT overall conversion efficiency: Minus 4 percentage points	0.61 => 0.57	For case (1): + 2.5 EUR/MWh
VTT total investment: Plus 20%	347 => 416 MEUR	For case (1): + 2 EUR/MWh
Recovery boiler credit: Minus 50 MEUR	Net Investment 240 => 290 MEUR	For case (1): + 4 EUR/MWh

As can be seen in Table 6:8 the effect on the production cost is less than 5 EUR/MWh (in the order of 3-4%) for each of the proposed changes in the three listed parameters.

### 6.4.3 Conclusions regarding bio-methanol production costs

- The base case as chosen in this report concludes that bio-methanol can be produced at cost levels in the interval 64-71 EUR/MWh or 355-394 EUR/tons of methanol.
- If investment costs are 20% higher the production cost increases to 68-76 EUR/MWh or 377-421 EUR/ton of methanol.
- In the highest cost scenario described in this report (corresponding to +20% investment cost, 10 years/10% capital charge, +20% on feedstock cost and +10 EUR/MWh on power purchase), the production cost would end up in the interval of 83-98 EUR/MWh or 460-543 EUR/ton of bio-methanol.
- Reasonable uncertainty about the value of special parameters such as overall conversion efficiency from biomass to methanol (VTT report) and value of recovery boiler credit (the BLGMF concept) influences the total production cost of bio-methanol by less than 4 EUR/MWh or 3-4%.
- When benchmarking against advanced biofuel alternatives like cellulosic ethanol (section 6.2.2), the highest quoted cost level of bio-methanol (around 100 EUR/MWh) would still be competitive. The low production cost level (around 70 EUR/MWh) is lower than the lowest quoted production cost level for cellulosic ethanol showed in Figure 6:2. It should also be noted that the ethanol cases are based on a feedstock price of about 50% of what is used for the gasification-based examples.
- When benchmarking against today's fossil fuels, gasoline and diesel, the calculated production cost for bio-methanol cannot compete on a pure cost per energy basis. The current gasoline price at plant gate is in the order of 0.45 EUR/liter (taxes excluded), which corresponds to 45 EUR/MWh. In today's price scenario for fossil fuels, bio-methanol needs a premium of 40-50% to be able to compete when the production technologies have matured.

## 6.5 METHANOL FROM OTHER RENEWABLE FEEDSTOCKS

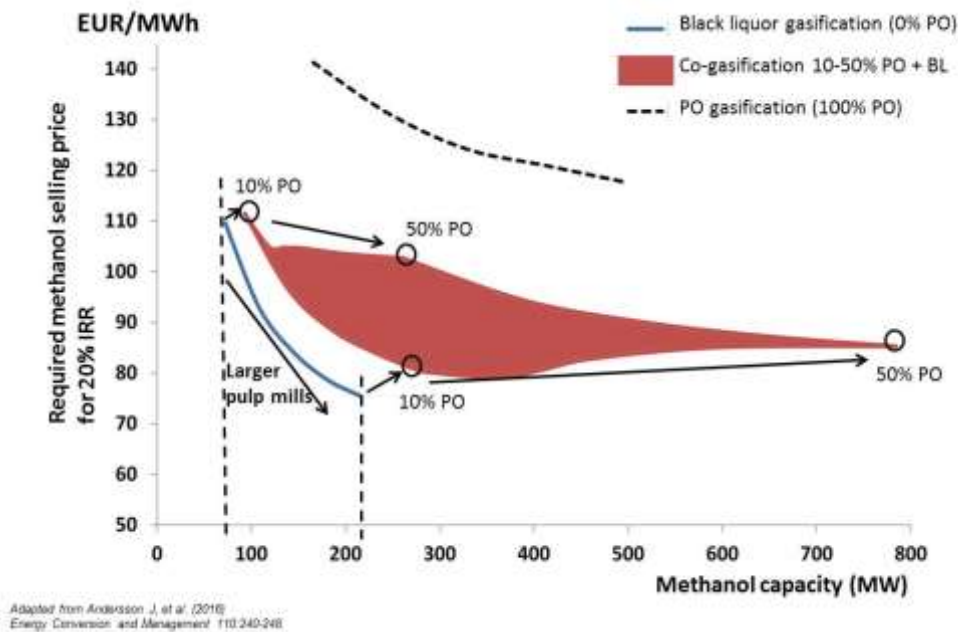
### 6.5.1 Blending of pyrolysis oil into black liquor

Section 4.4.4 describes a route from biomass feedstock to methanol, which involves a feedstock preparation step in the form of conversion of biomass to pyrolysis oil (PO) via fast pyrolysis. Table 4:1 presents overall conversion numbers from biomass to methanol including the route via PO. The



conversion process from biomass to pyrolysis oil introduces an extra cost element for the feedstock. PO will have a cost of energy that reflects the energy loss in the process and the cost of capital for the investment. Compared to a biomass price of 21 EUR/MWh used as base price for woody biomass in this report, the PO price will need a price in the order of at least 40-45 EUR/MWh. It can therefore be concluded that methanol produced via downstream PO gasification, syngas cleaning and synthesis cannot compete with direct biomass gasification. This is indicated with the dotted line in Figure 6:5 (100% PO case).

A separate route for PO conversion to methanol is via blending PO with black liquor in a BLGMF concept. Energy balances for such a concept are also described in section 4.4.4. In (Andersson *et al.*, 2016) the concept of blending 10-50% of PO into black liquor is described in detail. The mixing of the two fuels leads to more favorable gasification conditions than for gasifying them separately. Figure 6:5 elaborates the concept with the economic assumptions put forth in the referred paper.



**Figure 6:5. Production cost for a black liquor – pyrolysis oil combined gasification concept. Basic data used as calculation base: The PO price is assumed to be 42 EUR/MWh; the biomass price 20 EUR/MWh and the power price 58 EUR/MWh (adapted from Andersson *et al.*, 2016).**

The figure shows the required selling price of produced methanol in order to achieve an IRR (Internal Rate of Return) of 20%. Fuel production in small to average sized mills is considered. Their methanol production capacity is between 75 and 220 MW (see two vertical dotted lines) without any PO addition. The lower capacity (75 MW methanol) corresponds to a mill that produces about 200,000 dry tons of pulp per year and the higher capacity (220 MW methanol) corresponds to a mill that produces about 600,000 dry tons of pulp per year.

For the largest pulp mill case (lower side of the red area in the figure, 220 MW of methanol without PO mixing) the methanol production cost varies between approximately 80 and 90 EUR/MWh when mixed with PO, with pure BLG giving the lowest cost (slightly below 80 EUR/MWh). For small pulp mills (upper side of the red area, 75 MW of methanol without PO mixing) blending of BL with PO results in a decreasing production cost. The reason is that the capital cost of the fuel

plants is comparably high, which can be beneficial due to that the blending in of a second feedstock enables economies of scale benefits, also for a relatively smaller mill.

It should be noticed that the calculations in this section were made with cost of capital corresponding to IRR of 20%. If the same cost of capital were applied to the PO/BL blending concept as for the other normalized cases in section 6.3, the production cost would be significantly lowered due to a reduction of the cost of capital of 30-40%. This would also have the effect that all blended cases would become comparably cheaper compared to the black liquor only case, due to all other costs (feedstock, O&M) staying the same with only the capital cost decreasing.

With blending of PO into the black liquor, small mills could become comparably large fuel producers. Instead of producing around 220 MW of methanol the production could increase by a factor of about 3.5 to almost 800 MW with a 50/50 BL / PO mix.

Key conclusions:

- Gasification of pure pyrolysis oil (PO) is comparably expensive and leads to high production costs
- Blending of PO into black liquor is cost-effective due to favorable gasification parameters combined with economy of scale effects.
- Blending of a secondary feedstock, such as PO, can thus make black liquor gasification economically feasible also for small pulp mills.

### **6.5.2 Boosting methanol production in syngas based plants**

EU identifies “renewable fuels” as one of the ways to decrease oil dependence in the transport sector. In the EU Directive (referred to in sections 3.5 and 3.6) 2014/94 and in more recent works like the update of the SET Plan (Strategic Energy Technology Plan), renewable fuels (often referred to as electro fuels) are defined as gaseous or liquid fuels made from renewable electricity and a carbon source, preferably CO<sub>2</sub>. The concepts are often referred to as Power to Gas (PtG) or Power to Liquids (PtL). Cheap electricity is more and more becoming a corner stone in discussions regarding Europe’s energy future.

This chapter connects to the PtG/PtL concepts and refers to a combination of conversion technologies, which are explained in section 4.5 and illustrated in Figure 4:9. Section 4.5.2 describes how hydrogen from an outside source can be combined with a syngas-based fuel production plant and drastically boost the output from such an installation. The chapter also includes an example giving process data for a syngas train with two alternatives, one having the conventional alternative with a CO shift reactor for H<sub>2</sub>/CO adjustment and one with hydrogen addition through electrolysis of water to get to the same ratio, i.e. no need for a CO shift unit. The efficiency numbers presented in the energy balances show that conversion into methanol in a syngas train constitutes an efficient way of “liquefying” hydrogen. In this way, gaseous hydrogen can be safely “stored” with no losses and at very low storage costs, compared to high pressure or liquefied pure hydrogen.

The dominating cost element in the cost of producing renewable hydrogen is the (renewable) electricity. If hydrogen actually can be generated at a comparably low cost, the rest of the conversion to methanol comes with favorable, even negative additional costs. The overarching positive parameter is that the added hydrogen energy is converted to methanol energy with 89-90% energy efficiency.

With a power to hydrogen conversion efficiency of 60-65, the power cost (PC) in the hydrogen production cost would be  $PC/0.60$  to  $PC/0.65$ . Power at 40 EUR/MWh thus corresponds to a power cost element in the hydrogen of 62-67 EUR/MWh of hydrogen. Even though long-term availability of really cheap power is questionable (who would add more capacity if long term power prices were expected to stay very low?), this constitutes the base for the PtG and PtL concepts. With the assumption of long-term cheap power, e.g. around 20 EUR/MWh, the main variable cost element of the hydrogen would be 31-33 EUR/MWh and with 90% conversion efficiency to methanol, this would correspond to a power cost element in the cost of production of methanol of 34-37 EUR/MWh.

In a recent master thesis from Luleå University of Technology (Weddig, 2017), a techno-economic analysis was performed of implementing an electro fuels concept in a black liquor gasification plant with methanol synthesis (similar to the one described in section 4.4.3 of this report). Weddigs thesis shows (Table 10) that the net specific investment (EUR/MW<sub>Methanol</sub>) is about the same for the additional plant producing methanol from renewable power as the specific investment of the base plant. Table 6:6 shows that the investment cost element in the cost of methanol production according to this report is 18-27 EUR/MWh. Using these data results in that that the total cost of extra methanol production (at a power price of 20 EUR/MWh) will be 34-37 EUR/MWh plus 18-27 EUR/MWh. The total cost of production for methanol from the added renewable power would then be 52-64 EUR/MWh. Both reports use the same cost of capital. The production cost is of course very sensitive to the cost of power. 10 EUR/MWh higher power price would increase the total cost of production with 17-19 EUR/MWh.

#### Key conclusions:

- Adding externally produced hydrogen (generated through low-cost renewable electricity) to syngas and in that way substituting the CO shift step in order to reach the desired H<sub>2</sub>/CO ratio can be both cost and energy efficient.
- An average power cost of 20 EUR/MWh can produce methanol at a cost where the power cost element in the methanol product is 34-37 EUR/MWh and the total cost of extra production in the order of 60 EUR/MWh.
- The cost of extra methanol production from renewable power is very sensitive to the power price.
- The principle can be applied to any product (e.g. FT liquids, DME, methane) needing additional hydrogen in the syngas in order to form the right ratio between H<sub>2</sub> and CO for the downstream synthesis.

## 7 POTENTIAL FOR METHANOL PRODUCTION IN SWEDEN

### 7.1 METHANOL FROM BIOMASS

The conversion efficiency from biomass to methanol is described in section 4.4.5. Different conversion routes result in a span of conversion efficiencies between about 50 and 70% calculated as energy in the methanol divided by energy in the feedstock, biomass. The section concluded that:

Direct biomass gasification	53-62%
Biomass via use of black liquor in pulp mills (BLG)	65-70%
Biomass via pyrolysis oil mixed with black liquor (BLG+PO)	49-60%

The potential for methanol production from domestic Swedish biomass resources can thus be calculated via multiplication of the identified bioenergy resources by the conversion efficiency. 60% can be chosen as a “safe” average, as biomass gasification can reach some percentage points above 60%. Integration with pulp mills is an attractive alternative concerning both efficiency and production cost, and would lift the maximum potential substantially.

With respect to the BLG cases above these cases are based on that the power deficit which is result of the change from recovery boilers to BLG in the pulp mill is compensated for by extra power generation from biomass in condensing mode. If that power deficit was to be generated via other renewable power generation than from biomass, the biomass requirement would decrease considerably and consequently the percentage numbers listed above could increase to numbers well above 100%. This can be seen in the case presented in Table 6:5 where power purchase is an important cost in the overall production cost and the biomass purchase thus very low compared to the production of methanol.

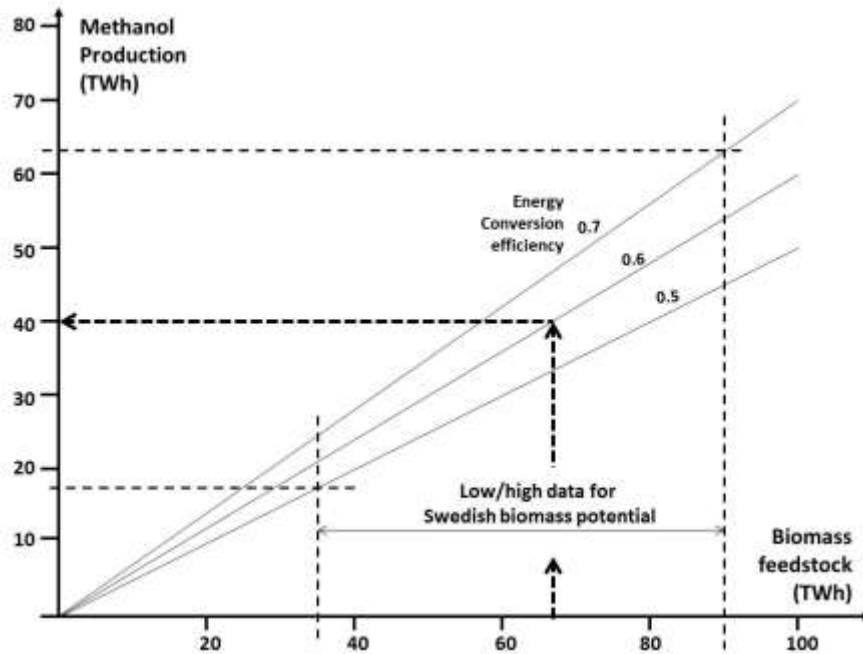
#### 7.1.1 *Biomass potential in Sweden*

The topic of biomass availability has been studied by several groups in recent years, of which only a few are mentioned here.

Thuresson and Johansson (2016) analyzed the actual and potential use of biomass from forests and the Swedish forestry industry up to the year 2050. The study reported that today’s production of biomass could be increased by 62 TWh and by additional 36 TWh by 2050, to reach in total 98 TWh. Börjesson (2016) reported lower levels and summarized today’s potential to 24-33 TWh, and, by 2050, 36-50 TWh, but also identified an uncertainty of additionally 74 TWh. Further increase of these potentials could be accomplished via more purposeful harvesting of biomass for bioenergy purposes and if biomass was to be produced on farm land which today is put in fallow. de Jong *et al.* (2017) investigated the sustainable harvesting potential of forest residues and stumps in order to not get in conflict with other environmental quality objectives, and ended up with a significantly lower potential, about 2.5 times today’s harvesting levels (from 10-12 TWh to around 28 TWh per year in total). With harvesting also of brushwood another 5-10 TWh could be added to the potential (Ebenhard *et al.*, 2017).

### 7.1.2 Methanol production potential

As can be seen from data presented above, both feedstock potential estimations and methanol production efficiencies are subject to considerable uncertainties. In order to visualize future methanol production potentials in Sweden, Figure 7:1 can be used to identify the production of methanol from certain feedstock potentials for different energy conversion efficiencies.



**Figure 7:1. Methanol production as a function of biomass potential for different conversion efficiencies.**

Variables that can impact future production volumes are e.g.:

- Improved conversion efficiency
- Increased or decreased biomass potential due to changes in e.g. forestry and forest management regimes
- Increased or decreased competition from other biomass users, e.g. renewable electricity production or industrial use.
- Externally produced renewable hydrogen (not from biomass energy) for use as methanol production booster (section 6.5.2).

It will take at least a decade before a real impact can be experienced from the construction of new production plants fed with biomass, and during that period new as well as updated knowledge regarding e.g. biomass potentials, conversion routes and technologies etc. will become available, which will alter the overall potential estimations.

A calculation example (see Figure 7:1) for e.g. 2050: 67 TWh of biomass can be converted to 40 TWh methanol with a conversion efficiency of 60%.

## 7.2 INCREASED METHANOL PRODUCTION THROUGH THE USE OF RENEWABLE ELECTRICITY

The syngas conditioning technology, which is used to alter the H<sub>2</sub>/CO ratio, the so-called CO shift or Water Gas Shift (WGS) process, is described in the technology section 4.4.2. In section 4.5.2, addition of externally produced hydrogen is described as a powerful technology concept (PtL) for capacity enhancement of the syngas handling and conversion parts of the gasification based methanol production plant.

In a scenario where sufficiently cheap renewable power is available, the methanol production potential from a given amount of biomass energy can increase with more than 50%. 1 kWh of power would become approximately 0.6 kWh of methanol.

The methanol production potentials shown in Figure 7:1 would thus be multiplied with a factor of 1.5 to 1.6, depending on original H<sub>2</sub>/CO ratio in the raw syngas from the gasifier. Using the example from section 7.1.2, methanol production from 67 TWh/y biomass with a conversion efficiency of 60% could then increase from 40 to 60-64 TWh/y of methanol when fully utilizing the PtL concept.

## 8 CONCLUDING DISCUSSION AND PROPOSAL FOR FURTHER WORK

The main aim of this report has been to create a knowledge synthesis regarding use of renewable methanol as fuel – historically, today and in the future. This chapter aims to summarize the main findings, as well as propose some areas of interest for further work.

### 8.1 CONCLUDING DISCUSSION

#### **8.1.1 Lessons learned; Current situation; Production capabilities**

There is a very comprehensive experience base from use of methanol in various fuel applications both from earlier periods (1980s to 1990s) and from more recent times. Reports from trials, operations of test fleets and fuel handling experiences are to a very large extent positive in nature. As a fact, it has shown to be very difficult to find documents that describe general negative results from practical use of methanol as a fuel. Chapters 2, 3 and 5 thus give a generally positive description of methanol as an alternative fuel to today's gasoline and diesel.

Overall results from health and safety reviews are also pointing in a positive direction, not the least when being compared with alternatives like e.g. gasoline and LNG. The well-known facts that methanol is potentially corrosive and aggressive on many materials used in today's engine concepts and that it is toxic substance for human beings do not change this picture. Other fuel solutions come with other disadvantages which balance the comparisons and result in that methanol often come out as the better candidate.

This report claims that there during periods has been an intense discussion, especially in the late 1990s, with respect to which role methanol should play in the fuels market for vehicles but that this discussion has not always been entirely fact based. From the author's experience, it has rather been statements in various documents and from speakers in conferences stating that methanol is "corrosive and toxic" and not a suitable fuel for use by the general public. It has however not been possible to find scientific publications that support this view.

Regardless of how this negative attitude towards methanol actually was motivated and carried through, it is possible to follow the results of it. Today methanol is often not mentioned in reports and studies when renewable fuels / advanced biofuels / 2<sup>nd</sup> generation biofuels are reviewed. If it is dealt with, it is in general marginalized, not at all included, or included with a negative statement concerning one or two of its earlier mentioned qualities, that it is corrosive and toxic.

Two examples of recent reports are *Energy Carriers for Powertrains, for a clean and efficient mobility* (ERTRAC, 2014)<sup>21</sup> and *State of the Art on Alternative Fuels Transport Systems in the European Union* (DG MOVE, 2015)<sup>22</sup>. In the latter report some production data about methanol is included, data which would not have been there if the author of this report had not been a member of the EGFTF group.

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<sup>21</sup> Compiled by the ERTRAC Working group: Energy and the environment together with the Natural & Bio Gas Vehicle Association (NGVA).

<sup>22</sup> Compiled by the Expert Group of Future Transport Fuels (EGFTF) and headed by DG MOVE.

The reasoning behind excluding methanol from the list of potential renewable fuel alternatives was asked to many of the companies that were contacted during the work with this report, but none of these contacts has been able to provide e.g. scientific documentation that motivates the general negative attitude to methanol. Their motivation has many times been just the generally cited reason mentioned above. Some of the contacts instead provided material supporting methanol. For example, VW provided a copy of the comprehensive book *Alkoholkraftstoffe*, which was produced by VW employees (Menrad and König, 1982).

Production of syngas that meets the quality demand for catalytic conversion of the syngas to methanol is well established for various fossil feedstocks but much less so from feedstocks of renewable origin, as has been described in [Chapter 4](#). Gasification demonstrations in the scale from a few MW to some tenths of MW of feedstock have however been successfully operated for both liquid (black liquor and pyrolysis oil) and solid (wood chips, pellets and municipal solid waste) feedstocks. For some of the demonstrations, methanol has been the final (or intermediate) product, while other projects have aimed at other final products. However, this report emphasizes that it is the syngas generation as such which is the key process step for a successful conversion concept of a feedstock to methanol, rather than the choice of end product.

A novel production route to fuels (Power to Liquids, PtL), which depends on availability of low-cost (renewable) electric power, has received increased attention in the last couple of years. Also, this concept is currently demonstrated with methanol as product.

Even though today's commercial syngas to methanol technology is well established and currently offered by a handful of licensors, novel routes are also under development and are being tested. Results are promising and the step for these technologies into the commercial stage is not too far away.

### **8.1.2 Production cost and potential**

Methanol (fossil origin) is one of the world's largest chemical commodities and as such traded in large volumes. Contract and spot prices are therefore readily available and can be compared with today's main fuels – gasoline and diesel. As shown in [Chapter 2](#), selling prices for methanol are occasionally lower than today's fuels (on energy basis). When the production cost structure is reviewed more closely ([Chapter 6](#)), it can be seen that the cash cost of production of methanol from natural gas can reach levels well below current prices of gasoline and diesel (Table 6:1). 0.4 EUR/lit of gasoline corresponds to about 45 EUR/MWh, while the cash cost for methanol production from natural gas at 2-4 USD/MMBtu corresponds to 13-23 EUR/MWh. There is thus a significant margin between the two levels, which would cover the methanol plant investment.

This report also concludes that renewable methanol can be produced at cost levels around 65 EUR/MWh, with the capital charge and feedstock prices used in this report. With a feedstock price more in line with southern US prices (about half of the European biomass prices); the production cost would drop to about 50 EUR/MWh, which is close to the current fossil fuel prices.

The gasification route to methanol is one of the currently most cost and energy efficient routes for production of advanced biofuels, and cheaper than e.g. cellulosic ethanol production, as shown in section 6.4. This insight has not been gained recently, but has been known since decades (see e.g.



Vattenfall Utveckling AB, 1991, 1992; Brandberg and Sävbark, 1994). Thus, according to this report, the clear “no” to methanol and “yes” to ethanol in the US has not been found to be based on rational scientific grounds but rather on strategic considerations.

There are a number of production pathways to methanol generated from different renewable feedstocks. The report gives a span for energy conversion efficiency (Table 4:1), about 0.5 to 0.7 as well as a span for feedstock availability (chapter 7) in the form of biomass resources (current and future) in Sweden (section 7.1.1). Figure 7:1 visualized the potential production of methanol as a function of feedstock potential, for different energy conversion efficiencies. In addition to this and in the light of current low electricity prices, it is worthwhile to mention that if the Power to Gas (PtG) concept (section 4.5) becomes sufficiently profitable, hydrogen addition to biomass-derived syngas can be an efficient way to generate a fuel like methanol from renewable electricity. A certain methanol production potential can then be increased by at least 50% by utilizing a larger degree of the green carbon atoms and thus generating less CO<sub>2</sub> to the atmosphere from the production facility.

### **8.1.3 Strategic considerations**

The cost of production of methanol, fossil based and renewable, opens up for a discussion regarding potential reasons why the fuel industry and the oil companies, were reluctant to embrace the introduction of methanol in the fuel pool. If in the 1990s a large fuel system based on methanol would had been established in e.g. California as a consequence of the previous oil crises (and the successful fleet tests on methanol) and being complemented by renewable methanol being mixed into the system, an efficient and wide-spread alternative fuel system could have been built up quite rapidly and at a comparably low cost. Methanol was already then a widespread commodity available in harbors all around the globe and it was also well known how to store and handle it. The 1990s was the decade when discussions regarding GHG neutral fuels started to take off.

A similar chain of circumstances can be seen with respect to selection of energy carrier for fuel cell (FC) powered cars. Reforming of methanol on board the vehicles had been shown to function well in long-term operation (section 3.5), but methanol was without evident reasons replaced by gasoline. This gasoline based concept was subsequently judged to be too costly and complicated, which resulted in that on board reforming was dropped in favor of using pure hydrogen as fuel (US Department of Energy, 2004). At the same time, a safety report produced during this period compared methanol and gasoline for wide spread public use as FC fuel in the US. The report pointed clearly in favor of methanol, but was never published (section 3.7.4). The “hydrogen economy” was thus born. In the EU this has led to that the so called Infrastructure Directive (2014/94/EU) (European Union, 2014) which includes an in principle mandatory launching of a hydrogen infrastructure all around the EU member states. Recently, however, Nissan has announced their intention to develop an FC vehicle utilizing ethanol as energy carrier and re-introduce on board reforming of ethanol to hydrogen (Automotive News, 2016). In their statement, they also included a list of reasons why hydrogen should be avoided as energy carrier.

The above mentioned examples indicate that strategic decisions regarding fuel systems, infrastructure etc. have not always been based on apparently rational reasoning, but on a chain of other aspects, which has shaped the system as it is today – with methanol marginalized as alternative fuel.

## 8.2 PROPOSAL FOR FURTHER WORK

Based on the discussions summarized above, a number of areas for further investigation and research have been identified.

### 8.2.1 *Broad comparison of methanol with hydrogen, methane (CNG/LNG) and others*

It is difficult to find sources that compare methanol with other fuel alternatives currently in focus. Proposed work should thus include Well to Wheel (WtW) comparison of methanol with other alternatives like ethanol, hydrogen and methane (CNG/LNG). The WtW approach should include not only energy use and CO<sub>2</sub> emissions along the whole chain from feedstock to use in the vehicle, but also comparison of other characteristics such as cost and complexity of storage, distribution, handling, vehicle adaptation, health and safety etc., similar to the investigation by (Volvo, 2008). In this context, further investigation could be carried out regarding why methanol, being one of the simplest and most efficient alternative fuels to produce and use, was removed from the alternative fuel agenda in the 1990s.

### 8.2.2 *Methanol / gasoline blends' impact on modern car engines*

The attitude from the European car manufacturers (and others as well) is that methanol should not at all be present in the gasoline fuel and that its presence already in very low concentrations is potentially harmful for the engines (section 2.4). As methanol in gasoline blends is extensively used in China (section 3.1.1), which is also one of the largest markets for many of the European auto-makers, it would be interesting to further investigate the apparent discrepancy between the attitudes in China vs. in Europe. Are cars supplied to the Chinese market supplied with special materials in the fuel system? Are there many reports on engine damages? In that case, how is that handled? Similar questions can be asked with respect to the Brazilian market, but in this case relating to high blends of ethanol in gasoline (27%).

### 8.2.3 *Revisiting the energy carrier issue for Fuel Cells (FC)*

The currently preferred fuel infrastructure for FC powered cars consists of pressurized or liquefied hydrogen (section 3.5). As discussed above, this report reveals some of the history behind today's proposed solution and also reports of signs of a move back to on board fuel reforming (section 5.7). In view of the substantial work regarding hydrogen infrastructure currently going on within EU relating to the above mentioned Infrastructure Directive (2014/94/EU), it should be of interest to further investigate methanol (as well as ethanol or mixes of the two alcohols) as an alternative to hydrogen as energy carrier. The work could e.g. include:

- Should energy be distributed to the tank stations in the form of methanol/ethanol and be reformed to hydrogen at the tank station before being fed to the car (as hydrogen)?
- Should onboard reforming of methanol/ethanol be brought back as a concept (not the least in light of what is proposed and developed by Nissan)?
- Can methanol/ethanol contain water (avoiding expensive distillation)?
- Safety considerations for hydrogen versus methanol/ethanol system

- A WtW comparison with respect to energy use, GHG emissions and cost/complexity of the fuel systems.

#### **8.2.4 Making full use of all green carbon in the gasifier feedstock**

The PtG concept can be combined with syngas generation as described in section 4.5.2. If hydrogen from e.g. electrolysis is made available it can be fed to the syngas conditioning as part of the process and thus eliminate the water-gas-shift (WGS) unit. The conversion efficiency of energy in the form of hydrogen to energy in the form of methanol is very high, about 90%. Elimination of the WGS should be a straight forward exercise with few surprises but special attention need to be given to the gas purification process (the AGR unit) and potential needs for other gas conditioning processes (due to that the WGS unit is no longer in place).

A further step to utilize the green carbon from the feedstock could be to include a reversed shift converting  $H_2$  and  $CO_2$  to CO and water. Theoretically, all  $CO_2$  could then become CO and all carbon atoms would finally end up as carbon in the methanol. This technology does not exist commercially but is investigated by catalyst suppliers.

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## 10 APPENDICES

### 10.1 APPENDIX 1: KEY DATA FOR LIQUID FUELS COMPARED TO METHANOL

Table 10:1 provides key data for M85, M100 and a number of other liquid fuels that often are mentioned when comparing methanol with alternatives.

**Table 10:1. Key data for M100 and M85 compared to other liquid automotive fuels [Ecofractic].<sup>23</sup>**

Fuel property	Unit	Ethanol E100	Ethanol E85 <sup>a</sup>	Methanol M100	Methanol M85	Petrol	Diesel EC1
Density, liquid	Kg/m <sup>3</sup>	794	765 - 785	795	780	720 – 775	800 – 820
Density (vapour)	rel. air	1.6	> 1			3-4	5-6
Boiling point	°C	78.5	25 - 205	64,7	25 - 215	25 – 205	180 – ca305
Conductivity	cu	140.000	as E100	30.000.000	30.000.000	3 - 10	50 – 100
Vapour pressure	kPa	17	40 – 50 <sup>b</sup>			45 - 95	0.4
Flash point	°C	12	< - 30	11	- 36	< - 40	56 (60) <sup>c</sup>
Flammability range fuel vapour in air	%	3.3 - 19	1.4 - < 19	6.0 – 36.5	2 – 34	1 - 8	0.6 – 7.5
Flammability range, -summer <sup>d</sup> -winter <sup>d</sup>	°C	12 to 40	-35 to +5 -35 to -5 <sup>e</sup>	10 to 40	- 40 to + 23	- 40 to -10 -45 to -20	50 -
Autoignition temperature	°C	425	360	465	385 - 480	250 – 280	220 – 316
Stoichiometric air/fuel ratio	Kg/kg	9,0	10			14,6	14,8
Heat of vaporisation	kJ/kg	910	850	1100	1044	335	251
Energy of combustion	kWh/lit	5.9	6.3			9.1	9.8
Energy of combustion, LHV	MJ/lit	21,2	22,7			32,8	35,3
CO <sub>2</sub> -formation	g/MJ	71,6				75	72
Flame spread rate	m/s	2 - 4	3 - 5	2 - 4	3 – 5	4 - 6	0.02 – 0.08
Diffusion coefficient	cm <sup>2</sup> /h	293		465	372	186	251
Pool burn rate	Mm/min			1.7		7.3	4.0
Energy of ignition <sup>f</sup>	mJ	0.14 - 0.24	~ petrol	0.14 – 0.22	0.14 – 0.24	0.20 – 0.24	0.20 – 0.24

- a) A new standard for E85 has just recently been enforced in Sweden. The data for a fuel corresponding to this standard might slightly deviate from the data presented here.
- b) The interval is due to the difference between summer and winter qualities of E85 according to the Canadian study cited.
- c) The demand for marine applications is 60°C
- d) The values of the end points are dependent on a variety of factors as, tank fill level, changing fuel composition due to “tank breathing”, etc.
- e) The data for flammability range are taken from a Canadian study cited and might deviate slightly from Swedish and European E85 fuel.
- f) At the stoichiometric air/fuel ratio.

### 10.2 APPENDIX 2: LIST OF CONTACTED COMPANIES AND INSTITUTIONS

In order to carry out the objectives and more specifically to be able to grasp the partly difficult task to explain the “ups” and “downs” with respect to methanol’s acceptance as an automotive fuel, the

<sup>23</sup> Ecotraffic Report. *Methanol blending in gasoline – some Swedish Experiences*. 2013, Table 1.

report includes information gathered through contacts with a large number of companies and institutions who have been and /or are involved in activities involving methanol. Table 10:2 shows a list with the chapter/section headings of the report and an overview of contacts that were taken to gather information. Most contacts were in the form of email exchanges and phone calls but the work also includes visits and face-to-face meetings at conferences and other meeting places.

**Table 10:2. List of topics related to contacts taken.**

CHAPTER/SECTION	VTT-MeOH production	MeOH Inst.	Wärtsilä	MIT	MAN	VW	P. Wuebben	P. Dodd	Methanex	HTAS	VTT-engine/ Scania	AB Volvo and Volvo car	CRI	MIT/D. Cohen	U. o. Bath	Stena	KTH	Prakash	LTH
2.1 Methanol – a natural alternative to crude...		x		x		x	x	x	X	x								x	
2.2 Overall results from fleet tests...		x				x	x												
2.3 Methanol on the race track <sup>a</sup>		x																	
2.4 Methanol as a renewable fuel...	x	x		x				x	X			x				x		x	
3.1 National initiatives for methanol blending into the gasoline pool		X				x						x							
3.2 Methanol as a bunker fuel in ships		x	x		x	x			X							x			
3.3 Methanol as a renewable component...		x																	
3.4 Methanol as an energy carrier for DME... <sup>b</sup>												x							
3.5 Methanol as energy carrier for hydrogen...																	x		
3.6 Infrastructure considerations																			
3.7 Health and safety considerations		x																	
4.1 Methanol generation from syn-gas										x									x
4.2 Methanol from natural gas		x							x	x									
4.4 Methanol from biomass via syn-gas	x	x								x									
4.5 The Power to Liquid concept	x	x								x			x					x	

Table 10:2 (continued).

CHAPTER/SECTION	VTT-MeOH production	E.ON	MeOH Inst.	Wärtsilä	MIT	MAN	VW	P. Wuebben	P. Dodd	Methanex	HTAS	VTT-engine/ Scania	AB Volvo and Volvo car	CRI	MIT/D. Cohen	U. o. Bath	Stena	KTH	Prakash	LTH	
5.1 Introduction																					x
5.2 Low blend of methanol in gasoline			x		(X)		x		(x)												(x)
5.3 High blends of methanol in gasoline and GEM fuels			x				x									x					
5.4 Marine applications				x		x	x										x				
5.5 Partial Premix Combustion (PPC)...															x						x
5.6 Adaptation of ED95 to become a MD95...												x									
5.7 Methanol in Fuel Cells (FC)			x		x		x				x								x	x	
6.2 Production cost benchmarking cases <sup>c</sup>			x							x											
6.3 Production cost of methanol - biomass and BLG routes <sup>d</sup>	x	x																			
6.5 Methanol from other renewable feedstocks	x										x			x							

<sup>a</sup> Also Ikaros Smederna

<sup>b</sup> Also Ford, Germany

<sup>c</sup> Also Bechtel, Lux Inc

<sup>d</sup> Also LTU and Chemrec

## 10.3 APPENDIX 3: AUTOMOTIVE FUELS – UNLEADED PETROL

Table 10:3. Requirements and test methods for unleaded petrol.

Table 1 - Requirements and test methods for unleaded petrol

Property	Units	Limits		Test Method <sup>a</sup> (See 2. Normative references)
		Min.	Max.	
Research octane number, RON		95,0	--	EN ISO 5164 <sup>b</sup>
Motor octane number, MON		85,0	--	EN ISO 5163 <sup>b</sup>
Lead content	mg/l	--	5,0	EN 237
Density (at 15 °C) <sup>c</sup>	kg/m <sup>3</sup>	720,0	775,0	EN ISO 3675 EN ISO 12185
Sulfur content <sup>c</sup>	mg/kg	--	50,0 (until 2008-12-31)	EN ISO 20846 EN ISO 20847 EN ISO 20884
		--	10,0	EN ISO 20846 EN ISO 20884
Oxidation stability	minutes	360	--	EN ISO 7536
Existent gum content (solvent washed)	mg/100 ml	--	5	EN ISO 6246
Copper strip corrosion (3 h at 50 °C)	rating	class 1		EN ISO 2160
Appearance		clear and bright		visual inspection
Hydrocarbon type content <sup>c</sup>	% (V/V)			EN 14517 EN 15553
- olefins		--	18,0	
- aromatics		--	35,0	
Benzene content <sup>c</sup>	% (V/V)	--	1,00	EN 238 EN 12177 EN 14517
Oxygen content <sup>c</sup>	% (m/m)	--	2,7	EN 1601 EN 13132 EN 14517
Oxygenates content <sup>c</sup>	% (V/V)			EN 1601 EN 13132 EN 14517
- methanol <sup>d</sup>		--	3,0	
- ethanol <sup>e</sup>		--	5,0	
- iso-propyl alcohol		--	10,0	
- iso-butyl alcohol		--	10,0	
- tert-butyl alcohol		--	7,0	
- ethers (5 or more C atoms)		--	15,0	
- other oxygenates <sup>f</sup>		--	10,0	
NOTE Requirements in bold refer to the European Fuels Directive 98/70/EC [1], including Amendment 2003/17/EC [2].				
<sup>a</sup> See also 5.8.1				
<sup>b</sup> A correction factor of 0,2 for MON and RON shall be subtracted for the calculation of the final result, before reporting according to the requirements of the European Directive 98/70/EC [1], including Amendment 2003/17/EC [2]. For advice on reporting see 5.7.				
<sup>c</sup> See also 5.8.2				
<sup>d</sup> Stabilising agents shall be added.				
<sup>e</sup> Shall conform to EN 15376 (see 5.2). Stabilising agents may be necessary.				
<sup>f</sup> Other mono-alcohols and ethers with a final boiling point no higher than prescribed in Table 2.				

#### 10.4 APPENDIX 4: EXTRACT FROM NYNÄSHAMNSKOMBINATET FINAL REPORT (IN SWEDISH)

This Appendix contains summary pages of the Final report from September 1984 for the so called Nynäshamnskombinatet (ENERGIKOMBINAT I NYNÄSHAMN).

Front pages	Report front page plus and artistic illustration
FÖRORD (Preface)	Give a summary of why and by whom the report was carried out
ENERGIPOLITISK BAKGRUND (Energy Political Background)	2.1 General 2.2 Alternative Fuels 2.3 District heating of greater city regions

# **ENERGIKOMBINAT I NYNÄSHAMN**

**Metanol – Bränslegas – Fjärrvärme**

## **TEKNISK PROJEKTERING och EKONOMISK UTVÄRDERING**

**Slutrapport till Statens Energiverk  
Projekt 267032-1**

**September 1984**

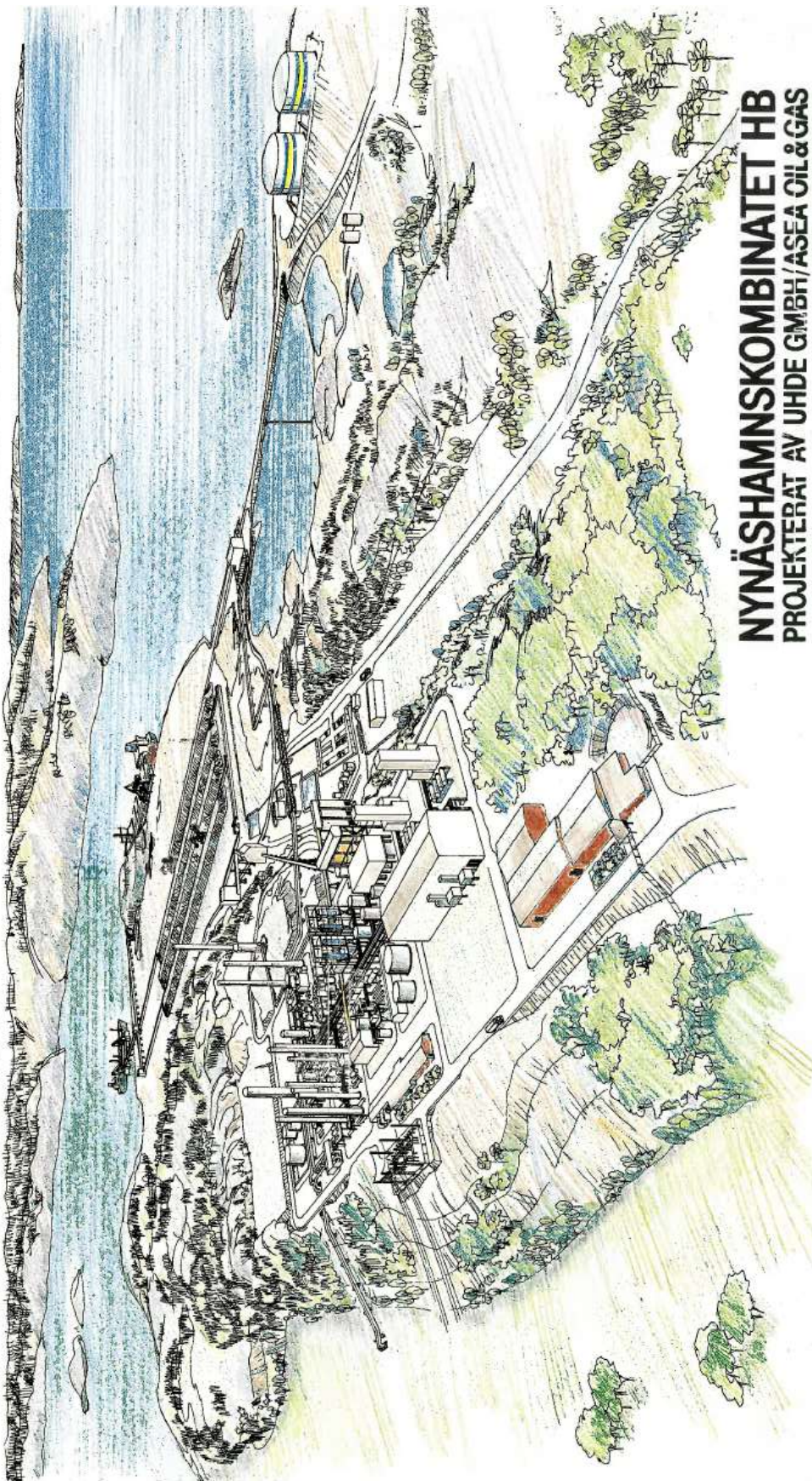
**NYNÄSHAMNSKOMBINATET HB**

**Box 7858 Stureplan 3 103 99 Stockholm 08-788 50 30**

# ENERGIKOMBINAT I NYNÄSHAMN

DRIVMEDEL FÖR SVERIGE

## VÄRME FÖR STOCKHOLM



**NYNÄSHAMNSKOMBINATET HB**  
**PROJEKTERAT AV UHDE GMBH/ASEA OIL & GAS**  
September 1984  
Division of ASEA-ATOM

Idé/text: GDM AB, Västerås/ Tryckproduktion, Västerås 1984



## FÖRORD

Föreliggande rapport utgör slutredovisning av en utredning rörande de tekniska, ekonomiska och miljömässiga förutsättningarna för ett energikombinat i Nynäshamn. Projektet avser anläggningar för tillverkning av metanol, bränslegas och hetvatten samt därtill hörande rörledningssystem för transport av hetvatten och gas till Stockholm.

Ansvariga för utredningen har varit Nynäshamnskombinatet HB (NHK), som ägs av ASEA AB, AB Nynäs Petroleum och AB Svarthålsforsen.

Till grund för utredningen har bl a legat en tidigare projektstudie, NE 1981:6 "Energikombinat Stockholm-Nynäshamn, Metanol-Bränslegas-Fjärrvärme"

Utredningen har genomförts med finansiellt stöd från Statens Energiverk i form av ett villkorslån om 14 MSEK.

Utredningen har genomförts under tiden mars 1982 - september 1984.

Utredningsresultatet är baserat på en sammanlagd arbetsinsats av ca 60.000 mantimmar, varav huvudparten hänförs till den tekniska projekteringen och kostnadsberäkningen av produktionsanläggningarna i Nynäshamn.

I utredningsarbetet beträffande produktionsanläggningarna i Nynäshamn har följande konsult- och ingenjörsföretag varit engagerade:

Huvudkonsult	Konsortium bestående av UHDE GmbH, Dortmund ASEA OIL & GAS, Västerås
Övriga företag	Texaco Development Corporation, New York (Kolförgasningsanläggning)
	Lurgi GmbH, Frankfurt am Main (Metanolanläggning)
	Degrémont, Paris (Avloppsvattenrening)

## 2 (4)

Battelle Research Centre, Geneva  
(Val av kolråvara)

Chem Systems, London  
(Energiprisprognoser)

Purvin & Gertz, London  
(Energiprisprognoser)

ASEA OIL & GAS, Västerås  
(Ekonomiska utvärderingar)

Svensk Drivmedelsteknik AB, Stockholm  
(Förutsättningar för metanol som drivmedel)

Statens Geotekniska Institut, Linköping  
(Slaggundersökningar)

Studsvik Energiteknik AB, Nyköping  
(Analyser av Höganäsokol)

Nycol AB, Stora Vika  
(Rening av Höganäsokol)

Prof Gunnar Svedberg/tekn lic Maria Gårding  
Inst för kemisk apparatteknik, KTH, Stockholm  
(Kvicksilverutredning)

Fil dr Bengt Noläng  
Svensk Energidata, Uppsala  
(Kvicksilverutredning)

Robert & Stintzig Arkitekter AB, Stockholm  
(Beställarens arkitekt)

Tegnér Arkitektgrupp AB, Stockholm  
(Landskapsarkitekt)

Trichem Consultants Limited, London  
(Processteknisk konsult)

Johnson Construction Company, AB Nynäs Petroleum och VIAK har medverkat med projekteringsarbete och kalkylunderlag beträffande kompletterande anläggningsinvesteringar utanför produktionsanläggningen. Underhandskontrakt och diskussioner har ägt rum med representanter för Nynäshamns kommun samt med Naturvårdsverket, Sprängämnesinspektionen, Stockholms Vatten- och Avloppsverk, SMHI, försäkringsbolag m fl.

AB Svarthålsforsen har medverkat med underlag för projektets ekonomiska utvärdering.

Formell beställare av delutredningen beträffande överföringssystem för hetvatten och bränslegas från Nynäshamn till Stockholm har varit Stor-Stockholms Energi AB. Nynäshamnskombinatet HB har fungerat som beställarens ombud och har bekostat utredningen.

Utredningsorganisationen för denna del av utredningen har haft följande sammansättning:

Projektledare	Halvard Gedung, Tumba
Huvudkonsult	Fjärrvärmebyrån AB, Västerås
Ledningsgrupp	Jan-Erik Kignell, Nynäshamnskombinatet HB Lars Nilsson, Nynäshamnskombinatet HB Halvard Gedung Birger Abrahamson Fjärrvärmebyrån AB Björn Andersson, Fjärrvärmebyrån AB
Referensgrupp	Anders Höök, Stockholms Energiverk Lars Jäderberg, STOSEB Per Hansson, Landstingets Regionplanekontor
Underkonsulter	Allmänna Ingenjörbyrån AB (Geologi och geoteknik)  Energiprojekt AB (Systemanalyser)

AB Rollmo Värmeteknik  
(Transienta strömningsförlopp)

Scandiaconsult AB  
(Antikvarisk utredning)

Söderblom & Palm AB  
(Landskapsvård)

Skånska Cementgjuteriet AB och Johnson Construction Company har medverkat med kalkylarbete och analyser av tidplaner och resursbehov.

Informationsmöten och samrådsmöten har hållits med representanter för berörda kommuner och med Länsstyrelsen för Stockholms län och dess berörda enheter, varvid även företrädare för Vägförvaltningen, Lantbruksnämnden och Skogsstyrelsen deltagit. Samråd har även ägt rum med SIND, Sprängämnesinspektionen och Arbetarskyddsstyrelsen.

## 2. ENERGIPOLITISK BAKGRUND

### 2.1 Allmänt

Den energipolitiska bakgrunden till det projekt, som presenteras i denna rapport, är den av regering och riksdag fastslagna övergripande målsättningen att minska Sveriges höga oljeberoende. Projektet syftar till att med kol som råvara producera dels alternativt drivmedel i form av metanol, dels uppvärmningsenergi för storstockholmsområdet i form av bränslegas och spillvärmebaserat hetvatten. Projektet förutsätter således att den energipolitiska målsättningen är inriktad mot att minska Sveriges oljeberoende inom såväl transport som uppvärmningssektorn.

Utöver den energipolitiska målsättningen att minska oljeberoendet innebär det aktuella projektet att även högt ställda miljöpolitiska målsättningar kan uppfyllas, både vad gäller minskade utsläpp av bilavgaser som minskade utsläpp av svavel- och kväveoxider från förbränningsanläggningar.

### 2.2 Alternativa drivmedel

Den svenska oljeförbrukningen uppgick 1979 till drygt 30 milj m<sup>3</sup>, varav i runda tal 70% gick till uppvärmning, industri och kraftproduktion och ca 27% gick till transportsektorn. En analys av motsvarande situation under 1983 visar att den totala oljeförbrukningen sjunkit till drygt 20 milj m<sup>3</sup> samt att oljeförbrukningen inom uppvärmningssektorn, industrin inklusive kraftproduktion sjunkit till knappt 60% av totalförbrukningen. Samtidigt har transportsektorns oljebehov legat kvar i stort sett oförändrat och svarar idag för nästan 40% av den samlade förbrukningen av oljeprodukter.

Dessa siffror vittnar om en imponerande minskning av Sveriges oljekonsumtion med cirka en tredjedel på 4 år, en minskning som nästan helt ägt rum inom industri och uppvärmningssektorn. De faktorer som haft störst betydelse för denna utveckling är

- besparingsåtgärder
- ersättning av olja med el, kol och inhemska bränslen
- låg ekonomisk aktivitet

Oljeersättning med alternativa bränslen har till en stor del skett med hjälp av finansiellt stöd från staten för övergång till fastbränsleeldning. Statens insatser på detta område torde i dagsläget uppgå till ett par miljarder kronor. En annan starkt bidragande faktor till den minskade oljeförbrukningen är den goda tillgången och det internationellt sett låga priset på elkraft i Sverige, som bl a stimulerat till installation av direktverkande eluppvärmningssystem och värmepumpar.

Oljeberoendet inom transportsektorn ligger samtidigt kvar oförändrat högt på en nivå av ca 97%. De statliga insatserna i syfte att åstadkomma oljeersättning på drivmedelsområdet kan räknas i några tiotal milj kronor.

Enligt riksdagsbeslut våren 1981 fastställdes som målsättning för införande av alternativa (ej oljebaserade) drivmedel att år 1990 utnyttja 1-3 TWh (225.000-680.000 m<sup>3</sup>) motoralkoholer, och att metanol därvidlag ansågs utgöra det enda realistiska alternativet för en mer omfattande bensinersättning. Etanol bedömdes kunna utgöra ett komplement i begränsad skala. Detta beslut var grundat på Oljeersättningsdelegationens (OED) rapport DsI 1980:19 "Introduktion av alternativa drivmedel". I denna rekommenderade OED storskalig metanolintroduktion enligt en strategi som i början av 90-talet skulle leda till en metanolförbrukning av ca 700.000 ton/år och därmed ersätta 10% av den svenska bensinförbrukningen.

I en andra rapport, DsI 1982:12 "Strategi för alternativa drivmedel", redovisar OED en förändrad inställning till behovet av oljeersättning inom transportsektorn. Målsättningen är mycket vagare formulerad och tidsperspektivet för storskaliga satsningar skjuts på framtiden med motiveringen att "oljeersättning i första hand även fortsättningsvis bör koncentreras på fasta bränslen medan ersättning av bensin och diesellojla med alternativa drivmedel bör ses som en mera långsiktig möjlighet."

Inte heller i andra länder har påbörjade utvecklings- och demonstrationsprogram lett fram till några konkreta beslut om metanolintroduktion av beredskapsmässiga skäl, vilket kan synas beklagligt, eftersom Västeuropa fortfarande befinner sig i en utsatt position i fråga om drivmedelsförsörjningen.

Tillgången på olja är visserligen för närvarande god men cirka hälften av tillförseln kommer från Persiska viken. Västeuropa svarar för hela 20% av världens oljeförbrukning och är till 80% importberoende. Av världens samlade oljereserver finns endast 4% i Västeuropa (Nordsjön) medan hela 50% av reserverna återfinns i området kring Persiska viken.

Att Sverige i dagsläget köper cirka tre fjärdedelar av sin råolja från Nordsjön ändrar inte på det faktum att Sverige genom sitt medlemskap i IEA åtagit sig att i händelse av försörjningskris medverka till en kvotering av då tillgänglig olja.

Mot denna bakgrund borde en introduktion av alternativa drivmedel fortfarande framstå som lika angelägen som tidigare.

En ny och inte mindre viktig aspekt på en introduktion av motoralkoholer har kommit att bli de allt allvarligare försurningsproblemen. Det finns idag klara belägg för att dessa problem i avgörande grad är förknippade med bilarnas avgasutsläpp av främst kväveoxider. I Västtyskland, där försurningsproblemet blivit akut genom en omfattande skogsdöd, pågår ihärdiga ansträngningar att genomföra krav på katalytisk avgasrening. Detta medför i sin tur krav på blyfri bensin eftersom blyet förgiftar katalysatorerna. Den tyska ståndpunkten innebär bl a att blyfritt bränsle skall finnas tillgängligt från den 1 januari 1986 och att nya bilar snarast möjligt skall utrustas med katalysatorrening för att klara nya avgaskrav, som ligger i linje med de i USA redan gällande bestämmelserna. Inom EG arbetas intensivt för att söka finna gemensamma europeiska lösningar i dessa frågor. I Sverige har den sk bilavgaskommittén framlagt förslag att införa katalytisk avgasrening och blyfritt bränsle i enlighet med de västtyska riktlinjerna.

Eftersom blyets uppgift i bensinen är att höja oktantalet måste vid införande av blyfritt bränsle, antingen blyet ersättas med någon annan oktantalshöjande komponent, exempelvis metanol, eller motorerna konstrueras om till lägre kompression och därmed högre bränsleförbrukning för att fungera med ett mera lågoktanigt bränsle.

Den förändring till blyfria drivmedel, som nu synes vara på väg i Västeuropa, är en unik händelse. En så radikal förändring när det gäller krav på en ny drivmedelskvalitet har aldrig ägt rum tidigare. För Sverige/Västeuropa ger detta en möjlighet att kombinera miljöpolitik och energipolitik genom att under senare hälften av 80-talet införa ett blyfritt alkoholblandbränsle, som kan ges ett väsentligt högre oktantal än vad som skulle vara möjligt med enbart bensin. Som framgår av kapitel 4.1.6 bör detta kunna ske utan några ökade kostnader av betydelse.

Den tekniska genomförbarheten av att introducera ett sådant blandbränsle har demonstrerats i flera länder, bl a i Sverige i en testflotta omfattande 1000 bilar, som under ett drygt år kördes på M15-bränsle (15% metanol i blyfri bensin).

Det är i detta sammanhang intressant att konstatera att låginblandning av metanol påbörjats i flera länder på rent kommersiella grunder.

Mot ovan redovisade bakgrund torde en fortsatt metanolintroduktion i Västeuropa sannolikt komma att styras både av energipolitiska beslut inom EG och av de kommersiella marknadskrafterna.

### 2.3 Storstadsregionernas uppvärmning

Under de senaste decennierna har en snabb övergång till fjärrvärmeuppvärmning ägt rum i Sverige, framför allt i de tre storstadsregionerna. Den mest omfattande uppbyggnaden av stora fjärrvärmenät har skett i storstockholmsområdet, där den totala fjärrvärmelasten idag uppgår till drygt 3.000 MW innebärande en årlig energileverans av nära 8 terrawattimmar (TWh). Enligt de utbyggnadsplaner, som finns för fjärrvärmenäten i stockholmsregionen, kommer den totala värmelasten att i början av 90-talet överstiga 4.000 MW och den årliga energileveransen uppgå till ca 11 TWh, vilket motsvarar energiinnehållet i ca 1 miljon ton eldningsolja.

Hetvattenförsörjningen till dessa fjärrvärmenät har till för några få år sedan till mer än 90% skett i oljeeldade anläggningar. Genom installation av koleldade verk, elpannor och stora värmepumpar minskar den oljeberoendet i snabb takt i detta uppvärmningssystem. Ytterligare konverteringar från



oljeeldning till andra energislag planeras finnas bl a en ombyggnad av kraftvärmeverket i Värtan ( $210 \text{ MW}_e / 330 \text{ MW}_v$ ) från olje- till koleldning. Vidare planeras investeringar i flera nya värmepumpverk.

Utmärkande för fjärrvärmesystemen är den stora flexibiliteten med avseende på att kunna utnyttja olika slag av bränslen och anläggningar för produktion av hetvatten, exempelvis olja, kol, el och biobränslen respektive hetvattenpannor, mottrycksverk, värmepumpar etc. Andra alternativ är gaseldade anläggningar och industriell spillvärme från olika typer av processindustri.

Genom att förlägga processindustrier inom rörledningsavstånd från större fjärrvärmenät uppstår intressanta möjligheter att på ett ekonomiskt sätt tillvarata spillvärme från de industriella processerna för produktion av hetvatten. På detta sätt ökar konkurrenskraften i den industriella tillverkningen genom de intäkter som erhålles från spillvärmeleveranserna.

Fjärrvärmenäten i storstockholmsområdet är av sådan omfattning att spillvärmerna från storskalig processindustri kan tillvaratas under större delen av året. Detta innebär långa utnyttjningstider för spillvärmeenergin och därmed maximalt förbättrad produktionsekonomi i de processindustriella anläggningarna.

