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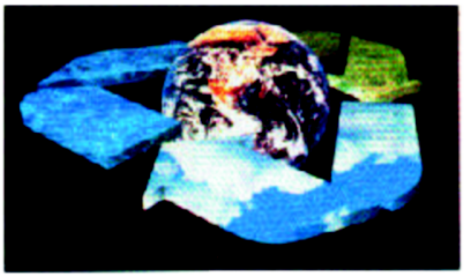
SUSTAINABLE FUELS

Introduction of biofuels



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PREFACE

The emissions of greenhouse gases, such as carbon dioxide, from the road transport system and the measures that should be taken to reduce these emissions are frequently debated in Sweden and in many other countries.

The debate covers several alternative fuels, including those based on biomass, alternative fossil fuels and, in addition, new powertrains that, in their turn require new fuels. In many cases, the present cost is very high. This leads to the need for large tax incentives so that the alternatives will be competitive. Further development of the production methods is therefore necessary.

There is no Swedish strategy for the introduction of biofuels at the present time. This report is intended to be a basis for discussions about such a strategy. Known technical and economic prerequisites for a large-scale introduction of biofuels have been summarised. This has led to the identification and evaluation of a number of fuel alternatives.

The report has been written by Peter Ahlvik and Åke Brandberg, Ecotraffic ERD^3 AB. The authors are liable to the results and the assessments in the report.

Borlänge, November 2002.

Swedish National Road Administration, Vehicle Standards Division

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EXECUTIVE SUMMARY

Introduction and background

A reduction of the climate gases from the transport sector has become an important issue in Europe during the last years as part of a strategy to meet the commitments in the Kyoto agreement. A proposal for a directive covering the introduction of alternative fuels and biofuels in particular has been put forward by the EU Commission. On the long-term, there is also an increasing awareness of the diminishing oil resources and the risk for problems with the energy supply. In view of these issues, the use of resources (feedstock and energy) other than crude oil have to be developed.

This report has its main focus on bio-based motor fuels that have the potential to become future sustainable fuels for general use, i. e. easily handled liquids such as alcohols and Fischer-Tropsch hydrocarbons with highest system energy efficiency and lowest costs. Niche fuels such as fatty acid methyl esters (FAME), dimethyl ether (DME), methane, hydrogen and electricity are only briefly discussed. The findings are based on a previous report from the Swedish National Road Administration (SNRA) “Well-to-wheel efficiency[1].

Fuel production and energy efficiency

In the study mentioned above, Ecotraffic examined and assessed 98 combinations of fuels (feedstock from crude oil, natural gas and biomass) and drivetrains. The identified combinations of biofuels and energy converters (engines) with the highest efficiency were.

Dimethyl ether (DME)	/diesel engine/
Gaseous hydrogen	/fuel cell/
Methanol	/diesel engine, fuel cell/

Liquid hydrogen (LH_2), ethanol and Fischer-Tropsch diesel fuel (FTD) from biomass had somewhat lower efficiency.

On a longer timeframe, it will be possible to obtain very low emissions of hazardous emission components with all types of fuels. Therefore, feedstock availability, energy efficiency and cost will be the most crucial issues for new fuel candidates.

Fuel distribution

A finely branched, low cost distribution network to make a fuel available everywhere will require liquid fuels that are easily handled (such as petrol and diesel oil today). Duplication of such a network for handling liquefied gases under pressure or cryogenic liquids will hardly be acceptable, due to cost reasons. Niche applications of such fuels will be the remaining possibility. In addition, distribution in large central pipelines has to be arranged for maximum flows, since buffer stores can only be small, and will be vulnerable to distur-

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[1] Ahlvik P. and Brandberg Å. (Ecotraffic): “Well-to-wheel efficiency for alternative fuels from natural gas or biomass” Swedish National Road Administration, Publication 2001:85, available at the Internet site of SNRA at www.vv.se, 2001.

bances of the supply. These drawbacks, including costs, do not apply to the distribution of easily storable liquid fuels from large and efficient production plants and terminals built for average consumption. The problems in hydrogen distribution are so severe that a recent study proposed a shift of focus from “hydrogen economy” towards “methanol economy”. Nevertheless, the hydrogen option is still considered in this study.

The necessary large market penetration needed to achieve the long-term targets could only be met by using easily handled liquid fuels and by focusing on light-duty vehicles and long distance heavy goods vehicles.

Cost

Cost estimates have been made for fuel production and distribution and based on these results the total cost for the fuels to the vehicle tank (well-to-tank cost) can be estimated. The results from these calculations have been summarised in **Table ES.1.**

Table ES.1. *Estimations of pump price (without taxes and VAT) for some biofuels*

Cost of some biofuels (incl. distribution, excl. tax)	**Time-frame**	**Prod. price** €c/l	**Price, distributed product**[a]		
			€c/l pet. equiv.	€c/l die. equiv.	**Notes**
Petrol	2001	21,7	31,0		Avg. cost 2001
Diesel fuel	2001	21,7		30,9[a]	Avg. cost 2001
Ethanol, grain	2000	65	109		Actual cost
Ethanol, cellulosic matter	2010	50	86		Eng. studies.
	2020	41	73		Eng. studies.
Methanol, natural gas	2000	12	37		Actual cost
Methanol, bio-syn	2010	27	67		Eng. studies.
	2020	22	57		Eng. studies.
FTD, bio-syn	2010			83	Rough estimate
	2020			68	Rough estimate
DME, natural gas	2000			46	Eng. studies.
DME, bio-syn	2010			75	Eng. studies.
	2020			63	Eng. studies.
RME	2000	65		80	Actual cost
Hydrogen		?			Diff. to estimate

Notes:

[a] The price comparison has been carried out for two different cases, the first as a substitution for petrol and the second as a substitution for diesel fuel. Since the energy content differs between petrol and diesel, the two columns cannot be directly compared.

[b] The price of the distribution of diesel fuel has been carried out for private customers and for large-scale use in passenger cars. This is valid only for countries with relatively high share of diesel cars (i.e. the assumptions are not valid for Sweden with the present penetration of diesel cars).

[c] The cost for hydrogen has not been estimated. The primary reason is that the assessment of the costs for fuel distribution and storage has been very difficult.

It should be noted that the basis for the calculations varies and therefore, there are many uncertainties in several of the estimations. Therefore, comments regarding the estimations listed in **Table ES.1** have been added to show data and methodology used (actual cost, engineering studies or rough estimates).

First, it should be noted that the cost estimates for the biofuels in **Table ES.1** do not consider (possible) utilisation of waste heat. If this is taken into account – and if heat sinks for space heating (e.g. district heating) are available – the cost of some of the fuel options could be somewhat reduced. It is notable that the efficiency in several cases would also increase for these options in that case.

The basis for the estimation of the production cost for FTD is small, which implies that a cost in proportion to the lower yield in comparison to methanol has been anticipated. An analogous estimate based on the calculated cost for DME gives a similar figure.

In spite of the higher distribution cost for DME in comparison to liquid fuels, the cost is still lower than for FTD. This might be considered a remarkable finding but is due to the fact that the production cost for DME will be significantly lower than for FTD.

The production cost of RME is difficult to estimate due to sizeable subsidies at the feedstock production stage. A distribution cost of the same magnitude as for diesel fuel has been used but with a compensation for the lower energy content. A large-scale distribution would be a necessary presumption for this methodology. Due to the constraints mentioned, the listed cost has to be considered somewhat unreliable.

Drivetrains

Biofuels are more costly to produce than conventional fossil fuels. In the opinion of the authors, a large-scale introduction of biofuels should be based on a reduction of the fuel consumption in the vehicle in order to limit the incremental cost for the customer.

Considerable investments are currently made in energy efficient vehicles and drivetrains by the auto industry and their suppliers. However, it is not clear today which development options that will “win” this race. Consequently, a large-scale introduction of alternative fuels must be made in such a way that these are compatible with the new engine and vehicle technology. A first step must consider alternatives intended for conventional petrol and diesel engines, while fuel cells should be taken into account at a second stage.

Summary of fuel assessments

A simplified way of presenting the results and recommendations in the previous sections is to grade and summarise the findings in Tables. An important condition is that the strategy proposed should have a long-term main priority but also include a short-term action program in line with the mentioned priority.

Three important factors to note are: Possibilities for low-blending, which could provide large volumes on a short-term for a small incremental cost in the fuel distribution. The long-term goal to introduce biomass-derived principal fuels is the most important criterion. In areas with poor air quality, niche programs could be of interest on a short and medium term. Such activities could give a possibility to gain knowledge about new fuels (e.g. DME) that have not been tested before under real operating conditions.

Two matrices of the type mentioned above have been prepared; one for petrol substitution and one for diesel substitution. The matrices are shown in **Table ES.2** (petrol substitution) and **Table ES.3** (diesel fuel substitution). It could be noted that most of the assessments refer to the biomass-based alternatives of each fuel. However, the opportunity to use both fossil and non-fossil feedstock is seen as an advantage. As reference in each case, petrol and diesel fuel are shown in the columns to the right. Virtually "sulphur-free" petrol and diesel fuel (ULSD[2]) qualities are foreseen. The grade has been set from 0 (impossible, in principle) to 5 (best).

Table ES.2. *Summary of conclusions regarding use of biofuels as petrol substitution*

	Petrol subst.	**Ethanol**	**Methanol**	**Methane**	**H_2**	**Petrol**
Intro-duction	Bio & fossil	No	Yes	Yes	Yes	-
	Fuel infrastr	4	4	2	0	5
	Low-blending	5	3	▨ [a]	▨	▨
Future	Dedic. engine	5	5	5	4	4
	Emissions	3	3	4	-	2
	Efficiency	3	4	4	3	5
	FC fuel	2	3	1	5	1
Economy	Volume 2005	1	0	1	0	5
	Volume 2020	2	3	1	2	5
	Price 2005	1	▨	1	▨	5
	Price 2020	2	3	1	1-2	4
Critical factor		Process technology	Synthesis gas production	Fuel distribution	Fuel distribution	Finite resource
Assessment		Dev. of cellulosic prod. Principal fuel (FFV)	Syngas production Principal fuel (FFV)	Niche fuel Dual-fuel vehicles[c]	Future fuel DFV[c] difficult	Should be phased out on long term

Notes:

[a] A crosshatched box indicate an impossible combination.

[b] Hydrogen in fuel cells gives zero emissions (which should give grade 5) but NO_X formation in otto engines is a potential problem, although not investigated in detail.

[c] Dual Fuel Vehicle (DFV), an engine that could run on two fuels

When all the factors have been taken into account for fuels intended for petrol substitution (**Table ES.2**), ethanol and methanol appear to be the primary fuel candidates, with a small advantage for methanol. The alcohols could be used in low-blending, which could enable the use of large quantities rapidly. Fuel-flexible vehicles running on alcohol fuels can be developed and produced at a very small incremental cost. The incremental cost for fuel distribution is also manageable.

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[2] ULSD: Ultra-Low Sulphur Diesel fuel.

Gaseous fuels have too many drawbacks to be used as main fuel candidates for principal fuels. These fuels are better suited for niche applications and one goal could be to identify these niches.

Table ES.3. *Summary of conclusions regarding use of biofuels as diesel fuel substitution*

	Diesel subst.	**Ethanol**	**Methanol**	**DME**	**FTD**	**RME**	**H_2**	**Methane**	**ULSD**
Intro-duction	Bio & fossil	No	Yes	Yes	Yes	No	Yes	Yes	-
	Fuel infrastr.	4	4	2	5(4)	5	0	0	5
	Low-blending	1	1	▨[a]	5	5	▨	▨	▨
Future	Dedic. engine	2-4[b]	2-5[b]	5	4	3	1-2	2	3
	Emissions	4	4-5	5	4	3	?	4-5	3
	Efficiency	3	4	4	3	2	?	4	5
	FC fuel	2	3	3	1	0-1	5	0-1	0-1
Economy	Volume 2005	1	0	1	1	1	0	1	5
	Volume 2020	2	3	2	3	1	2	1	5
	Price 2005	1	▨	▨	▨	1	▨	1	5
	Price 2020	2	3	3	2	1	3	1	4
Critical factor		Process technology	Synthesis gas production			Feed-stock avail-ability	Fuel distribu-tion	Fuel distribu-tion	Finite resource
Assessment		Develop-ment of cellulosic production	Development of synthesis gas production processes	Growing niche	Principal fuel	No high priority	Future fuel	Niche fuel	Should be phased out on long term

Notes:

[a] A crosshatched box indicate an impossible combination.

[b] The large interval for alcohols indicates that a dedicated diesel engine is necessary. Similarly, the alcohols have better properties than diesel fuel, such as lower soot and NO_X formation and that gives a higher rank. However, ethanol with EGR has had such high particulate emissions that particulate filters could hardly be avoided in the future. Since methanol is better in this respect, the upper interval for the ranking has been set as high as 5.

DME and FTD are better adapted for diesel engines and therefore, these two fuel candidates are primary options for diesel fuel substitution (**Table ES.3**) DME is the “superior” fuel of the two but it is more difficult to distribute and cannot be used for low-blending. In spite of other advantages, DME is likely to be considered a niche fuel for the near future.

The alcohols could be used as diesel fuel substitute on the condition that engines are developed for these fuels. Drawbacks such as difficulties in utilising the fuels in low-blending in diesel fuel and the lack of fuel flexibility imply that these fuels, in most cases, will have problems to compete with other fuel candidates in the near future. Since the interest to develop dedicated diesel engines that can run on alcohol fuel has been low on an international level, these fuels are not considered for large-scale diesel fuel substitution in the near future.

RME and the gaseous fuels are likely to be destined for niche applications for a long time.

Strategy and priorities

A strategy for renewable motor fuels must be based on sufficient feedstock availability, foreseeable technical development and reasonable economy. In several studies, renewable power by wind and solar power is projected to have a high supply potential. Wind power in Europe from hundreds of thousands of 4-5 MW wind mills is difficult to imagine and new solar power mainly based on import from African deserts can hardly be acceptable from the viewpoint of supply security. Even if cost hurdles for such power production could be overcome, the question remains concerning the distribution of the gaseous hydrogen produced. Biomass is considered a more promising feedstock with both a much higher availability than assumed and a potential for development.

A chain containing distribution on a large scale in pipelines is, on paper, an energy efficient route but seems to be an uneconomic proposition when costs are included. Refuelling of gaseous hydrogen at much higher pressures (up to 700 bar) than assumed or liquefaction before distribution and refuelling will considerably deteriorate the system efficiency.

The best use of hydrogen produced from renewable power might be to use it as a supplementary hydrogen source in central, biomass-based gasification plants. Due to the composition of the biomass, the primary gas is deficient in hydrogen, and by introducing hydrogen, the operation will be somewhat simplified. With biomass as feedstock, the pathway via gasification and synthesis to DME, methanol or FT-hydrocarbons is more efficient than that via power and electrolysis to hydrogen. However, DME is excluded as a principal, generally available fuel and is considered only as niche fuel.

The results from previous studies on energy system efficiency by the authors lead to the conclusion that methanol produced via gasification and synthesis has an efficiency advantage over FT-hydrocarbons, and most likely, even a cost advantage. However, FTD could substitute diesel fuel without any change in fuel infrastructure and therefore, this option is also of interest. The gasification is not fully developed and demonstrated in commercial scale. *There is therefore an urgent requirement to prioritise such development work, which is common to several end products (DME, methanol, hydrogen, FT-hydrocarbons).*

It is somewhat surprising that studies led by oil and auto industry have come up with statements that methanol (based on NG and used in FC) does not provide any advantage over oil-based fuels, diesel fuel in ICE or petrol FC, or CNG in dedicated ICE. Biomass-based methanol is therefore seldom studied − in spite of high efficiency and, next to renewable hydrogen, lowest GHG-emissions. Instead, renewable hydrogen and fuel cells are proposed as means to solve GHG-issues in spite of the problems with fuel infrastructure.

The basis for the much talked-about “hydrogen economy” seems not to be a practical proposition, since too many weaknesses are involved, these being due to the properties of hydrogen itself. Hydrogen is the lightest element on earth and has the lowest energy density of all fuels, which leads to high costs and low efficiency at production, transport, storage and refuelling. Hydrogen may not be an acceptable practical solution as a future motor fuel for general use. *Has the time come to shift to a “methanol economy” and to direct resources to this pathway for future sustainable motor fuels?*

Conclusions

In previous Ecotraffic studies, the most efficient biofuels from the point of view of well-to-wheel efficiency have been identified. High efficiency is usually synonymous with low cost although this cost is still significantly higher than for conventional fossil fuels. Fuels such as DME, hydrogen and methanol have been identified as the fuels of highest efficiency.

When fuel distribution is considered, high incremental cost in this stage is added for fuels that are gaseous at normal pressure and temperature. The distribution of gaseous and cryogenic fuels on a larger scale tends not to be realistic for general use. Consequently, within the foreseeable future, these fuels will be devoted to niche applications. The necessary large market penetration needed to achieve the long-term targets could only be met by using easily handled liquid fuels and by focusing on light-duty vehicles and long distance heavy goods vehicles.

In order to be able to implement large-scale activities on biofuels, consensus between Governments (in member states and on the EU level), the agriculture/forest, vehicle and fuel/energy sectors is necessary. The assessment of the authors is that such a consensus, in the short and medium term (<10 years) should be possible to be reached concerning the low-blending of bioalcohols and FTD in petrol and diesel fuel. These fuels would be implemented for in-use vehicles and the large-scale introduction of fuel-flexible vehicles for increasing the use of bio-alcohols.

Methanol and FTD could be produced from synthesis gas. Both these processes are commercial with natural gas feedstock. Concerning the production of synthesis gas from biomass, an intensification of research and development will be necessary before this technology can be optimised for commercial use. Therefore, a dedicated program, aiming at the erection of a demonstration plant for synthesis gas production from biomass, is a very important requirement.

In parallel to the above proposed activities regarding fuel production, the development of direct-injection otto engines intended for alcohol fuels (“ADI” in analogy to “GDI”) with fuel-flexible capabilities are essential parts of the proposed strategy. In addition, alcohol-fuelled diesel engines are of importance on a somewhat longer timeframe.

Biofuels are, due to natural reasons (starting with virgin feedstock), more costly to develop than those produced from fossil feedstock (crude oil, natural gas). A prerequisite for industrial stakeholders to take part in the development towards long-term sustainable transportation is that the overall conditions (goals, taxes, administrative incentives) will be established on a long-term basis and that they are internationally harmonised.

The utilisation of biomass for heating purposes or for the generation of electricity, are two alternatives to motor fuel production. The potential in the former sector is rather limited and other cost-effective options are available in order to reduce the heating requirements. As the efficiency in motor fuel production is significantly higher than for electricity generation, biomass-based motor fuels are a realistic alternative that should be investigated in parallel with the two other options.

SAMMANFATTNING (SWEDISH SUMMARY)

Inledning och bakgrund

En minskning av utsläppen av klimatgaser från transportsektorn har blivit en viktig fråga i Europa under de senaste åren som en del av en strategi för att klara Kyotoavtalets åtaganden. Ett förslag till ett direktiv som behandlar introduktionen av alternativa drivmedel och i synnerhet biodrivmedel har föreslagits av EU Kommissionen. På lång sikt finns det också en ökande medvetenhet om de minskande råoljetillgångarna och riskerna för problem med energitillförseln. Mot bakgrund av dessa frågor måste användningen av andra resurser (råvaror och energi) utöver råolja utvecklas.

Det främsta målet med denna rapport har varit de biobaserade drivmedlen som har en potential att bli framtida hållbara drivmedel för allmän användning, dvs. lätthanterliga vätskor som alkoholer och Fischer-Tropsch kolväten som uppvisar den högsta systemeffektiviteten och de lägsta kostnaderna. Nischbränslen som metylestrar av vegetabiliska och animaliska oljor (t.ex. RME), dimetyleter (DME), metan, väte och elektricitet behandlas bara översiktligt. Resultaten i denna rapport har främst baserats på två tidigare rapporter för Vägverket, dels den svenska förlagan till denna rapport[3], dels en rapport om systemeffektivitet för alternativa drivmedel[4].

Drivmedelsproduktion och energieffektivitet

I den studie av Ecotraffic som nämndes ovan, undersöktes och bedömdes 98 olika kombinationer av drivmedel (råvara från råolja, naturgas och biomassa) och drivsystem. De kombinationer av biodrivmedel och energiomvandlare (motorer) med de högsta verkningsgraderna identifieras. Dessa var:

Dimetyleter (DME)	/dieselmotor/
Vätgas i gasform	/bränslecell/
Metanol	/dieselmotor, bränslecell/

Något lägre systemverkningsgrad hade vätgas i flytande form (LH_2), etanol samt Fischer-Tropsch dieselolja (FTD) från biomassa.

I ett längre tidsperspektiv kommer det att bli möjligt att nå mycket låga hälsofarliga avgasemissioner med alla typer av drivmedel och därför kommer tillgången på råvara, verkningsgrad och kostnaderna på lång sikt att bli de viktigaste frågorna för nya drivmedelsalternativ.

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[3] Ahlvik P och Brandberg Å.: "Med hållbarhet i tankarna – Introduktion av biodrivmedel." Vägverket Publikation 2002:83, 2002.

[4] Ahlvik P. and Brandberg Å. (Ecotraffic): "Well-to-wheel efficiency for alternative fuels from natural gas or biomass" Swedish National Road Administration, Publication 2001:85, available at the Internet site of SNRA at www.vv.se, 2001.

Distribution

Ett fint förgrenat distributionsnät karakteriserat av låga kostnader kommer att kräva flytande drivmedel som kan hanteras enkelt (som bensin och dieselolja i dag) för att kunna göra ett drivmedel allmänt tillgängligt. En dubblering av denna infrastruktur för att hantera förvätskade gaser under tryck eller kryogeniska vätskor kommer knappast att bli allmänt acceptabelt av kostnadsskäl. Nischapplikationer av sådana bränslen kommer att vara den enda kvarvarande möjligheten. Dessutom måste distribution i stora centrala rörledningar dimensioneras för maximalt flöde, eftersom buffringskapaciteten bara kan vara mycket liten, och de kommer att vara sårbara för störningar i tillförseln. Dessa nackdelar, merkostnaderna inkluderade, gäller inte för distribution av enkelt lagringsbara flytande drivmedel från stora och effektiva produktionsanläggningar och terminaler byggda för en medelförbrukning. Problemen med vätgasdistributionen är så stora att en nyligen publicerad studie föreslog en ändring av fokuseringen från ”vätgasekonomi” till ”metanolekonomi”. Likväl behandlas i alla fall vätgas i denna studie.

Den nödvändiga stora marknadspenetrationen som förutsättning för att nå de långsiktiga målen kan bara nås med lätthanterliga vätskeformiga drivmedel och genom en fokusering på lätta fordon och långväga tunga lastbilar.

Kostnader

Kostnadsuppskattningar har gjorts för drivmedelsproduktion och distribution och baserat på dessa resultat har en beräkning av den totala kostnaden för dessa bränslen fram till fordonets bränsletank gjorts (well-to-tank kostnad). Resultaten från dessa beräkningar har summerats i **Tabell S.1.**

Det bör noteras att underlaget för beräkningarna varierar från fall till fall och därför finns många osäkerheter i uppskattningarna. Därför har kommentarer gällande uppskattningarna i **Tabell S.1** lagts till för att visa vilka data och vilken metodik som använts (verklig kostnad, ingenjörsberäkningar och grova skattningar).

Det bör påpekas att kostnadsuppskattningarna för biodrivmedlen i tabellen i **Tabell S.1** inte tar hänsyn till ev. användning av spillvärme. Om detta beaktas – och om värmesänkor finns för uppvärmning (t.ex. fjärrvärme) – kan kostnaden för dessa alternativ minska något. Det kan även nämnas att verkningsgraden i flera fall också skulle öka för dessa alternativ i detta fall.

Underlaget för uppskattningen av produktionskostnaderna för FTD är litet, vilket betyder att en kostnad i proportion till det minskade utbytet i jämförelse med metanol har förutsatts. En liknande uppskattning baserad på den beräknade kostnaden för DME ger ett snarlikt värde.

Trots den höga distributionskostnaden för DME i jämförelse med flytande bränslen är kostnaden fortfarande lägre än för FTD. Detta kan tyckas som ett anmärkningsvärt resultat men beror på att produktionskostnaden för DME kommer att vara mycket lägre än för FTD.

Produktionskostnaden för RME är svår att uppskatta genom de stora subventioner i produktionsledet som förekommer. En distributionskostnad av samma storleksordning som för dieselolja har använts men med en kompensation för det lägre energiinnehållet. En storskalig distribution vore nödvändig för att denna metodik skall kunna användas. På grund av de nämnda förutsättningarna kan den angivna kostnaden anses som något otillförlitlig.

Tabell S.1. *Kostnadsuppskattningar (Kr)*

Kostnader för biodrivmedel (inkl. distribution exkl. skatt)	**Tidsram**	**Prod. pris** kr/l	**Pris, distribuerad produkt**[a]		
			kr/l bensinekv.	kr/l dieselekv.	**Anmärkningar**
Bensin	2001	2	2,85		Medelpris 2001
Dieselolja	2001	2		2,84[b]	Medelpris 2001
Etanol, spannmål	2000	6	10,0		Faktisk kostnad
Etanol, cellulosa	2010	4,6	7,9		Ingenjörsber.
	2020	3,8	6,7		Ingenjörsber
Metanol, naturgas	2000	1,1	3,4		Faktisk kostnad
Metanol, bio-syn	2010	2,5	6,2		Ingenjörsber.
	2020	2	5,2		Ingenjörsber.
F-T-diesel, bio-syn	2010			7,6	Grov skattning
	2020			6,3	Grov skattning
DME, naturgas	2000			4,2	Ingenjörsber.
DME, bio-syn	2010			6,9	Ingenjörsber.
	2020			5,8	Ingenjörsber.
RME	2000	6,5		7,4	Faktisk kostnad
Vätgas[c]		?			Svårt att uppsk

Anmärkningar:

[a] Prisjämförelser görs i två fall, jämfört med bensin respektive dieselolja. Eftersom energiinnehållet per liter är olika för bensin och diesel kan inte de båda kolumnerna jämföras direkt.

[b] Priset för distribution av dieselolja till dieseldrivna personbilar har beräknats för en tänkt distribution till privatkund i stor skala. Detta är tillämpbart endast för länder med en relativt hög andel dieselbilar (vilket inte är fallet i dag i Sverige med nuvarande penetration av dieselbilar).

[c] Någon kostnad för vätgas har inte uppskattats. Främst beror det på svårigheten att bedöma kostnaderna för distribution och lagring.

Drivsystem

Biodrivmedel verkar bli avsevärt dyrare än konventionella drivmedel. Författarnas bedömning är därför att en storskalig introduktion av biodrivmedel förutsätter bränslesnålare fordon för att minimera merkostnaden för kunden.

Bilindustrin och deras underleverantörer investerar nu stora resurser i utveckling av energieffektivare fordon och framdrivningssystem. Det är dock inte klart vilket eller vilka utvecklingsspår som kommer att ”vinna” denna tävling. Det innebär att en storskalig introduktion av alternativa bränslen måste göras så att de är kompatibla med ny motor och fordonsteknik. I första steget måste alternativ introduceras som passar bensin och dieselmotorer och i ett andra steg bör även bränsleceller beaktas.

Summering av bedömningar

Ett förenklat sätt att presentera resultat och rekommendationer från tidigare avsnitt är att göra en sammanfattning av dem i form av två tabeller. En viktig förutsättning är att den föreslagna strategin skall ha en långsiktig huvudsaklig prioritet men också inkludera kortsiktiga åtgärdsprogram som ligger i linje med den nämnda prioriteringen.

Tre viktiga faktorer att notera är: Möjligheter till låginblandning, vilket kan möjliggöra stora volymer på kort sikt för en liten merkostnad i distributionsledet. Det långsiktiga målet att introducera biomassebaserade huvuddrivmedel är det viktigaste kriteriet. I områden med dålig luftkvalitet kan nischprogram vara av intresse på kort och medellång sikt. Sådana aktiviteter kan erbjuda en möjlighet att insamla kunskap om nya drivmedel (t.ex. DME) som inte har testats förut under verkliga driftsförhållanden.

Två matriser av ovan nämnda slag har sammanställts, en för bensinersättning och en för dieselersättning. Matriserna visas i **Tabell S.2** (bensinersättning) och i **Tabell S.3** (dieselersättning). Det kan vara värt att nämna att de flesta bedömningarna avser de biomassebaserade varianterna av respektive drivmedel. Emellertid ses även möjligheterna att använda både fossil och icke-fossil råvara som en fördel. Som bas för bedömningarna visas bensin respektive dieselolja längst till högra kolumnen. Praktiskt taget svavelfria kvaliteter (ULSD[5]) har förutsatts. Skalan har satts från 0 (i princip omöjligt) till 5 (bäst).

När alla faktorer beaktas för de drivmedel som lämpar sig som bensinersättning (**Tabell S.2**) framstår etanol från cellulosaråvara och metanol som de främsta kandidaterna, med ett litet försteg för metanol. Alkoholerna kan användas för låginblandning, vilket kan möjliggöra an snabb introduktion av stora kvantiteter. Bränsleflexibla fordon som körs på alkoholbränslen kan utvecklas och produceras till en mycket liten merkostnad. Merkostnaden för drivmedelsdistributionen är också hanterbara.

Gasformiga drivmedel har för många nackdelar för att vara kandidater till huvudbränslen. Dessa bränslen passar bättre för nischapplikationer och ett mål kan vara att identifiera dessa nischer.

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[5] ULSD: Ultra-Low Sulphur Diesel fuel.

Tabell S.2. *Summering av slutsatser angående biodrivmedel för bensinersättning*

	Bensinersättning.	**Etanol**	**Metanol**	**Metan**	**H_2**	**Bensin**
Intro-duktion	Bio & fossil	Nej	Ja	Ja	Ja	-
	Infrastruktur	4	4	2	0	5
	Låginblandning	5	3	▨ [a]	▨	▨
Framtid	Dedicerad motor	5	5	5	4	4
	Emissioner	3	3	4	-	2
	Verkningsgrad	3	4	4	3	5
	BC-bränsle	2	3	1	5	1
Ekonomi	Volym 2005	1	0	1	0	5
	Volym 2020	2	3	1	2	5
	Pris 2005	1	▨	1	▨	5
	Pris 2020	2	3	1	1-2	4
Kritisk faktor		Proces-steknik	Syntesgas-produktion	Bränsle-distribution	Bränsle-distribution	Ändlig tillgång
Bedömning		Utv. cellulosapro-cess. Hu-vudbränsle (FFV)	Syntesgas-produktion Huvud-bränsle (FFV)	Nisch DFV[c]	Möjligt bränsle DFV[c] svårt	Måste fasas ut på lång sikt

Anmärkningar:

[a] En linjerad ruta avser en omöjlig kombination eller att tillförlitliga uppgifter saknas.

[b] Emissionerna för vätgas är noll (vilket skulle rendera 5 i betyg) för bränsleceller men NO_X bildning i ottomotorer är ett problem som ej analyserats närmare.

[c] DFV: Dual Fuel Vehicle, eller tvåbränslemotor.

DME och FTD är de drivmedel som är bäst lämpade för dieselmotorer och därför är dessa två bränslekandidater de främsta alternativen som dieseloljeersättning (**Tabell S.3**). DME är det ”bättre” dieselbränslet av de två men är svårare att distribuera och kan inte användas för låginblandning. Trots alla andra fördelar är det troligt att DME måste anses som ett nischdrivmedel inom den närmaste framtiden.

Alkoholer kan också fungera som dieselersättning under förutsättning att motorer utvecklas för dessa bränslen. Nackdelar som svårigheterna att använda bränslena i form av låginblandning i dieselolja och avsaknaden av bränsleflexibilitet antyder att dessa drivmedel, i de flesta fall, kommer att ha svårigheter i konkurrensen med andra drivmedelalternativ på kort sikt. Eftersom intresset för att utveckla anpassade dieselmotorer som kan köras på alkoholer internationellt varit lågt ses inte dessa drivmedel som alternativ för en storskalig ersättning av dieselolja inom den närmaste framtiden.

RME och de gasformiga drivmedlen kommer sannolikt att vara hänvisade till nischapplikationer för lång tid framöver.

Tabell S.3 *Summering av slutsatser angående biodrivmedel för dieseloljeersättning*

	Dieselersättn.	Etanol	Metanol	DME	FTD	RME	H_2	Metan	ULSD
Intro-duktion	Bio & fossil	Nej	Ja	Ja	Ja	Nej	JA	JA	-
	Infrastruktur	4	4	2	5(4)	5	0	0	5
	Låginblandning	1	1	▨ [a]	5	5	▨	▨	▨
Framtid	Dedicerad motor	2-4[b]	2-5[b]	5	4	3	1-2	2	3
	Emissioner	4	4-5	5	4	3	?	4-5	3
	Verkningsgrad	3	4	4	3	2	?	4	5
	BC-bränsle	2	3	3	1	0-1	5	0-1	0-1
Ekonomi	Volym 2005	1	0	1	1	1	0	1	5
	Volym 2020	2	3	2	3	1	2	1	5
	Pris 2005	1	▨	▨	▨	1	▨	1	5
	Pris 2020	2	3	3	2	1	3	1	4
Kritisk faktor		Proces-steknik	Syntesgasproduktion			Begränsad tillgång	Bränsle-distribution	Bränsle-distribution	Ändlig tillgång
Bedömning		Utveckla cellulosa-process	Utveckling av processer för syntesgasframställning	Växande nisch	Huvud-bränsle	Inga satsningar	Framtids-bränsle	Nisch	Måste fasas ut på lång sikt

Anmärkningar:

[a] En överkryssad ruta avser en omöjlig kombination eller att tillförlitliga uppgifter saknas.

[b] Det stora spannet för alkoholer illustrerar det faktum att en speciellt konverterad dieselmotor behövs. Samtidigt har alkoholerna bättre egenskaper än dieselolja – t.ex. mindre sotbildning och NO_X – vilket renderar ett högre betyg. Etanol har dock uppvisat så pass höga partikelemissioner vid användning av EGR att partikelfilter i framtiden knappast kan undvikas. Eftersom metanol är bättre i detta avseende har det övre intervallet satts så högt som 5.

Strategi och prioriteringar

En strategi för biodrivmedel måste bygga på tillräcklig råvarutillgång, överblickbar teknisk utveckling och ekonomisk rimlighet. I flera studier har förnybar el via vindkraft och solenergi förutsatts ha en stor potential till drivmedelsförsörjning. Vindkraft i Europa från hundratusentals 4-5 MW stora vindkraftverk är svåra att föreställa sig och ny solenergi baserad i huvudsak på import från Afrikanska öknar kan knappast vara acceptabla lösningar när det gäller försörjningstrygghet. Även om kostnadsbarriärerna för sådan elproduktion skulle klaras kvarstår frågan om distributionen av den gasformiga vätgas som produceras. Biomassa anses som en mer lovande råvara med mycket större tillgång än förmodat och en potential för utveckling.

En distributionskedja baserad på storskaliga rörledningar är, på papperet, en energieffektiv väg men verkar vara ett ofördelaktigt alternativ när kostnaderna inkluderas i bedömningen. Tankning av gasformig vätgas vid mycket högre tryck (upp till 700 bar) än som tidigare använts eller förvätskning före distribution och tankning kommer att minska systemeffektiviteten avsevärt.

Den bästa användningen av vätgas producerad från förnybar el kan vara att använda den som komplementär vätekälla i centrala biomassebaserade förgasningsanläggningar. På grund av biomassans sammansättning kommer primärgasen att vara vätefattig och genom då introducera vätgas, kommer processen att förenklas något. Med biomassa som råvara är vägen via förgasning och syntes till DME, metanol och FT-kolväten mer effektiv än att gå via el och elektrolys till vätgas. Emellertid har DME uteslutits som allmänt tillgängligt huvudbränsle utan bedöms bara bli ett nischbränsle.

De resultat från tidigare studier om systemeffektivitet som författarna utfört har lett till slutsatsen att metanol producerad via förgasning och syntesgas har en effektivitetsfördel över FT-kolväten och, mest troligt, även en kostnadsfördel. Emellertid kan FTD ersätta dieselolja utan någon förändring av infrastrukturen och därför är även detta alternativ av intresse. Förgasningssteget är inte fullt utvecklat och demonstrerat i kommersiell skala. *Därför är det ytterst viktigt att prioritera detta utvecklingsarbete som är gemensamt för flera slutprodukter (DME, metanol, vätgas, FT-kolväten).*

Det synes något förvånande att studier ledda av olje- och bilindustrin har kommit fram till konstaterandet att metanol (baserat på naturgas och använt i bränsleceller) inte ger några fördelar jämfört med oljebaserade drivmedel, dieselolja i ICE eller bensin i FC, eller CNG i anpassad ICE. Biomassebaserad metanol har sällan studerats – trots den höga effektiviteten och som har, näst efter vätgas, de lägsta emissionerna av växthusgaser. Istället föreslås förnybar vätgas och bränsleceller som lösningen på denna fråga trots problemen med bränsleinfrastrukturen.

Förutsättningarna för den mycket omtalade ”vätgasekonomin” verkar vara sådana att detta inte är ett praktiskt förslag, eftersom det finns så många svagheter och dessa beror på vätgasens inneboende egenskaper. Vätgas är det lättaste grundämnet på jorden och har det lägsta energiinnehållet av alla drivmedel, vilket leder till höga kostnader och låg effektivitet i produktion, transport, lagring och tankning. Vätgas kanske inte är en acceptabel lösning för ett framtida drivmedel för allmän användning. *Har tiden kommit för att byta till en ”metanolekonomi” och för att överföra resurserna till denna väg till hållbara drivmedel?*

Slutsatser

I tidigare studier som Ecotraffic utfört har de mest effektiva biodrivmedlen utifrån systemverkningsgrad från produktion till slutanvändning identifierats. En hög effektivitet är normalt synonymt med låga kostnader även om kostnaden fortfarande är avsevärt högre än för konventionella fossila drivmedel. Drivmedel som DME, vätgas och metanol har identifierats som de drivmedel som har högst systemverkningsgrad.

När man tar hänsyn till drivmedelsdistributionen tillkommer stora merkostnader i detta led för drivmedel som är gasformiga vid normalt tryck och normal temperatur. Distributionen av gasformiga och kryogena drivmedel i större skala tenderar inte att bli realistiska för allmän användning. Följaktligen kommer dessa drivmedel att förbli hänvisade till nischanvändning inom överblickbar framtid. Det nödvändiga stora genomslaget som behövs för att nå de långsiktiga målen kan bara klaras med lätthanterliga flytande drivmedel och genom att man fokuserar på lätta fordon och tunga fordon för fjärrtransporter.

För att det skall vara möjligt att implementera storskaliga insatser på biodrivmedel är en koncensus mellan myndigheter (i medlemsländerna och på EU-nivå) och sektorer som jord/skogsbruk, fordon och drivmedel/energi nödvändig. Författarnas bedömning är att en sådan koncensus på kort och medellång sikt (<10år) bör vara möjlig att nå för låginblandning av bioalkoholer i bensin och FTD i dieselolja. Dessa drivmedel kan användas i den befintliga fordonsparken och i en storskalig introduktion av bränsleflexibla fordon för ökad användning av bioalkoholer.

Metanol och FTD kan produceras från syntesgas. Båda dessa processer är kommersiella med naturgas som råvara. När det gäller produktionen av syntesgas från biomassa är en intensifiering av forskning och utveckling nödvändig innan denna teknologi kan optimeras för kommersiell användning. Därför är ett riktat program som syftar till att uppföra en demonstrationsfabrik för syntesgasproduktion från biomassa en mycket viktig förutsättning.

Parallellt med de ovan föreslagna aktiviteterna gällande drivmedelsproduktion är utvecklingen av direktinsprutade ottomotorer avsedda för alkoholbränslen (”ADI” i analogi med ”GDI”) med bränsleflexibla egenskaper en väsentlig beståndsdel av den föreslagna strategin. Dessutom är alkoholdrivna dieselmotorer av betydelse på en något längre tidshorisont.

Biodrivmedel är, av naturliga orsaker (börjande från jungfrulig råvara) mer kostsamma att utveckla än de som producerats från fossila råvaror (råolja, naturgas). En förutsättning för att industriella företrädare skall delta i utvecklingen mot långsiktigt hållbara transporter är att de övergripande förutsättningarna (mål, skatter, administrativa incitament) kan fastställas på lång sikt och att de är internationellt harmoniserade.

Användningen av biomassa för uppvärmningsändamål eller för att generera el är två alternativ till framställning av drivmedel. Potentialen i det förra fallet är ganska begränsad och andra mer kostnadseffektiva alternativ finns tillgängliga för att minska uppvärmningsbehovet. Eftersom effektiviteten i framställningen av drivmedel är påtagligt högre än för elgenerering är biomassebaserade drivmedel ett realistiskt alternativ som bör undersökas vidare parallellt med de båda övriga alternativen.

1 INTRODUCTION AND BACKGROUND

Emissions of greenhouse gases (GHG), with the focus on fossil carbon dioxide, have become a concern due to their steady increase in the atmosphere with possible negative consequences for the climate of the earth. An agreement to abate these risks by a policy for reductions is underway (Kyoto) by setting the first targets (8% on average in the EU for around 2010) in this area. Scientists, however, suggest that much higher reductions, well above 50% and possibly approaching 80%, are required to stabilise the carbon dioxide level in the atmosphere.

The transport sector accounts for an increasing amount and share of emissions of GHG and this trend is expected to continue due to increased trade and personal mobility, the latter particularly in third world countries. In Europe, the liberalisation of trade and the integration of several new member candidates in the EU are expected to increase goods transport, particularly on roads in spite of the policy of having more goods on rail and water. The transport sector is almost entirely based on motor fuels originating from fossil oil resources. Other sectors, such as power and space heat, do not show the same trend of increased GHG emissions but rather stagnation or even some reduction. Furthermore, the possibilities in these sectors of using a wider range of fuels, including renewable biomass and the direct use of sun radiation, geothermal and industrial waste are greater than in the transport sector. This is particularly evident for heating purposes.

Improvement of the fuel economy of vehicles is always ongoing, sometimes enforced by regulations (CAFE in the US or voluntary commitments (ACEA) in Europe). However, this development is counteracted by the growth of the road traffic and by the preferences of vehicle buyers for high performance over fuel economy. Obviously, efficiency improvements, which should always be part of the measures, are not sufficient to achieve long-term GHG reduction goals.

The factors above indicate the necessity of including the transport sector now in the efforts to reduce GHG. This is the background to a proposed directive [1][6] on alternative motor fuels (not only biofuels) aimed to include and promote the use of biofuels. This would also be a measure to ensure an available energy supply of alternatives to oil based motor fuels by 2020, the primary target being 20%. In parallel an amendment of the mineral oil directive to equalise biofuels to mineral oil fuels and to apply a reduced rate of excise duty on biofuels.

Issues on agricultural policies are often apparent in discussions on alternative motor fuels. This is also evident in the proposed EU directive (ethanol from grains and fatty oils mainly from rapeseed).

Decisions on future fuels for the transport sector, concerning both ecology and economy, must be sustainable in the long-term. However, short-term decisions are needed and might be in conflict with long-term conditions. These can be exemplified by issues on the supply of renewable energy resources (concerning biomass, a land use issue) and on the practical possibility of conversion to a hydrogen energy economy. Short-term issues often deal with more cost-effective efficiency improvements or the use of components for blends with existing fuels for existing (and new) vehicles. Balanced prioritisation in such situations

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[6] Numbers in brackets refer to references that are listed in the reference section at the end of the report.

should be based on the motto "*think long-term when acting in the short-term*" to set the direction of the development of road transport systems in the decades following 2020.

The purpose of this study has been to compile a pool of knowledge, which can be used in discussions on the future development and introduction of biofuels. The study is mainly based on a previous study "Well-to-wheel efficiency" [2]. Agricultural policy matters are, however, not included in the considerations in this report.

Some delimitation has been made in order to "classify" the fuel options discussed in this report. It may be of interest to consider the following "threshold-limits" for the penetration of motor fuels, in fully accomplished scenarios, when anticipating calculations of system efficiencies:

- >1% but <10% of the market (niche fuel)
- >10% of the market (principal fuel, i.e. for general use everywhere)

2 PRESUMPTIONS AND METHODOLOGY

2.1 General criteria for the introduction of new fuels/engines

Any change in motor fuel supply or engine technology must fulfil a number of criteria:

- The resource base must be large and durable so that a substantial market can be maintained in the long term.
- Regarding land use, the yield of energy carrier must be as high as possible.
- The efficiency of conversion to marketable motor fuel and of conversion to transport work must be as high as possible; the entire chain from feedstock recovery/production to end use in the vehicle must be considered (LCA, Life Cycle Assessment).
- Renewable origin of the fuel is important in order to achieve the highest possible GHG reductions.
- The fuel must be available everywhere and be readily refuelled in a short time to achieve customer acceptance, i.e. be easily distributed in a finely branched network as is in the case of petrol and diesel oil today.
- The fuel must allow sufficient range of driving between refills, e.g. min. 500 km.
- International standardisation and international trade must be possible
- Emissions other than GHG must be nearly nil (to meet future very strict emission limits) or acceptable with regard to health and environment and not impose unacceptable safety risks.
- The cost must be the lowest possible.

2.2 Some issues to consider

In the preparation of this work, some critical issues were put forward for discussion. Within the framework of this study, it was not possible to come up with answers to all these questions. However, identifying the most important issues is an important first step.

One of the most important issues is the potential market penetration for alternative fuels, and biofuels in particular. This is of interest both in a short and medium term (2-5 years) as well as in the long-term (>10 years).

The incremental cost for biofuels must be kept at a reasonably low level. A level of 22 €c per litre (petrol fuel equivalent) has been suggested by the SNRA as a reasonable target for full-scale production.

Gaseous fuels, such as natural gas and biogas, could be converted to liquid fuels. The rationale for this conversion (compared to the use as gaseous fuels) should be assessed.

Several fuels such as hydrogen, dimethyl ether, methanol and Fischer-Tropsch fuels could be produced from synthesis gas from biomass or natural gas. The technical status for these production processes should be clarified.

Methanol is acutely toxic if ingested and it can be mistaken for ethanol. This issue has raised concern about the widespread use of methanol as a motor fuel. Several issues regarding methanol distribution and its low-blending in petrol should be highlighted and potential solutions to these problems should be discussed.

Several of the fuel candidates could be classified as niche fuels due to their small market potential. However, some of these fuels could provide substantial environmental benefits regarding local air quality. The rationale for priorities in this area should be discussed.

The fuel introduction strategy for alternative fuels should be compatible in both the short and the long term. Similarly, the number of fuel candidates and different fuel specifications should be kept to an absolute minimum.

New combustion concepts and new types of energy converters create new demands on fuels. The question as to whether alternative fuels could have advantages or disadvantages in this respect should be investigated.

There is competition concerning the available feedstock, and biomass in particular, from other sectors, e.g. the energy sector. The best use of various feedstocks is an important issue to consider.

2.3 Methodology

This report is partly based on a previous study by Ecotraffic that was funded by SNRA. The report was published in Swedish in June 2002 [3]. The study reported here is an update of the mentioned work. Special concern was taken to better elucidate the European perspective in this work, as the previous report was more focused on the conditions in Sweden.

The background material in this study is based on data previously collected and prepared in various other projects. A major part of the background material originates from a well-to-wheel study [2]. Therefore, no specific literature search was carried out in this study. However, in areas where new reports were available, these have been taken into account.

3 RESULTS

3.1 Feedstock availability – fossil resources

The future availability of crude oil, natural gas and other fossil energy feedstocks is in principle limited. The recovery of conventional oil (above about 20°API) is expected to reach a plateau within one or two decades depending on the level of ultimately recoverable oil presumed as is indicated in **Figure 1**. The background data for **Figure 1** have been collected from the Energy Information Administration (EIA) in the USA and a report from DOE (with contribution from DOE's federal laboratories and consultant companies) [4].

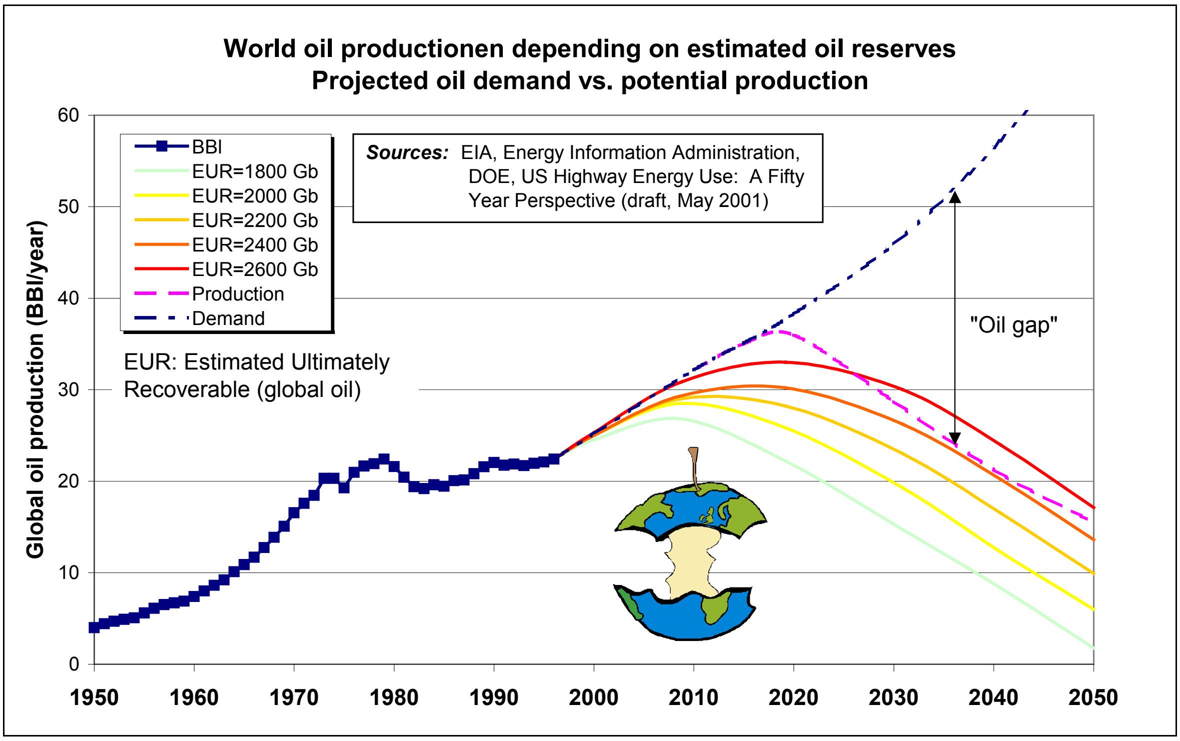

Figure 1. Global oil production and demand depending on the size of oil reserves (sources: EIA, DOE)

When coupled to the forecasted demand on oil it is evident that an oil gap is expected to emerge that must be filled from another feedstock. An oil gap roughly equal to the recovery of conventional oil in 2035 is indicated **Figure 1**. The recovery of conventional natural gas is expected to follow a similar path with a delay of about a decade.

Fossil hydrocarbon resources are, however, far from being exhausted since other types are potentially available in many times larger quantities as indicated in **Table 1** (Rogner [5]). The biggest resource used today is coal, exemplified in the transportation sector by conversion plants in South Africa since 1955. Coal, however, has the highest content of carbon per energy unit and expanded utilisation is not desirable. Methane hydrates, an estimated even larger resource, is the most unknown and difficult to recover resource. Today, there is no technique known for its utilisation. Conventional natural gas is the feedstock for a few plants (New Zealand, Malaysia and South Africa for production of LPG, petrol, kerosene and diesel oils.

Fuels from unconventional oil resources such as very heavy oil (VHO) in Venezuela and tar sands in Canada are examples of resources now being tapped in fairly large scale in operations that are similar to the mining of coal. Therefore, their recovery is more cumbersome and costly. These feedstocks are hydrogen-poor and the upgrading to finished products is also more cumbersome and costly than for conventional crudes. Utilisation of these resources would lead to still higher emissions of fossil carbon dioxide and will only be possible if the carbon dioxide is recovered and sequestered in natural aquifers in the crust of the earth. The technology is presently being exploited and commercially used in sandstone formations but further development is still needed in this area. This might be applied at suitably situated big scale conversion sites to other energy carriers but not if spread as motor fuels. A consequence will therefore be that a hydrogen distribution net must be established as supplement (discussed under section 3.2.4).

Table 1. *World fossil fuel potential (source: H. H. Rogner [5])*

Energy source	Resource (terabarrels)
Methane hydrates	137,5
Coal	45,78
Unconventional natural gas	6,14
Conventional natural gas	3,08
Unconventional oil	17,17
Conventional oil	2,163
Oil used	0,81

The conclusion is that continued use of conventional fossil fuels might lead to ecological disaster and in a long-term perspective (>50 years) fuels from renewable resources have to used. It has been argued that a reduction of fossil carbon dioxide emissions well above 50%, maybe approaching 80%, is needed to stabilise the climate. In such a scenario, the reduction of the carbon dioxide emissions from transport sector cannot be avoided.

3.2 Well-to-wheel efficiency

3.2.1 Motor fuels candidates

Calculation of efficiencies and costs for all steps in the chain, from feedstock to end use, for new motor fuels and drive systems must be carried out. These should be based on the presumption that production, distribution and end use will occur on a very large scale, corresponding to the road traffic market today and that foreseeable, future condition will be considered. Thus, to satisfy demands for high potential in use, new systems must be generally available everywhere and must include only few new fuels, preferably only one. Those fuels must be possible to produce from many feedstocks including renewable ones. Limited niche applications of certain other fuels might be justified under certain conditions particularly during transition phases.

Scenarios considered as possible for immediate application but with potential to become the future motor fuels satisfying the above mentioned presumptions are:

- Production of alcohols (methanol, ethanol) for systems with high energy efficiency, cheap distribution in the form of easily handled liquid fuels, to be used firstly as a component in petrol for existing and new vehicles and increasingly as fuels for optimised, fuel flexible vehicles (FFV) and eventually as pure fuels for future dedicated drive systems (DI- HCCI-diesel engines and electrochemical fuel cells).
- Production of synthetic hydrocarbons (FT-hydrocarbons) for cheap distribution as easily handled liquid fuels to be used firstly as quality improving component in diesel oils and eventually as separate independent fuels for future optimised DI- and HCCI-diesel engines and possible hydrogen carriers for electrochemical fuel cells.

Niche applications of other motor fuels, with limitations, for the transport sector can be envisioned, providing their own merits are adequate (they already exist to some extent):

- Fatty oil of RME-type for low-level blending in diesel oil; the limitation is technically a low potential (2-4% of the diesel oil use in the EU) for production by intensive cultivation on agricultural land.
- Ethers of DME-type as fuel for local diesel engine driven fleets for health and environmental reasons; the limitation is technically that, in spite of the highest system efficiency for diesel fuels from alternative feedstocks, no general distribution network can be expected and that they are not suitable for otto-engines.
- Methane, fossil natural gas, synthetic natural gas from biomass (SNG) and biogas, for local/regional fleets; the limitation is technically that no general distribution net for natural gas (or as cryogenic liquid) can be expected and that the potential for locally produced biogas is insufficient for general use. Large scale production of synthetic methane has lower energy efficiency in the entire chain than other alternatives.
- Hydrogen for possible local fleets of zero-emission vehicles with fuel cell power; the limitation is that a general distribution network for gaseous hydrogen (or cryogenic liquid) cannot be expected. The limitation is removed if easily handled liquid hydrogen carriers (methanol, synthetic hydrocarbons) are used at distribution and converted to hydrogen onboard the vehicle.
- Electricity from renewable resources via the existing power grid for battery operated special vehicles in urban areas; the limitation is technically that performance of batteries, technology for storing electricity and for rapid recharging is insufficient for vehicles in common use and no breakthrough of new techniques can be seen.

3.2.2 Feedstock

Natural gas (NG) and biomass are feedstocks with considerable potential in the relatively short-term and on a large scale as a supplement to/replacement of the conventional crude oils with the aim of reducing the emissions of fossil carbon dioxide. Natural gas is a fossil resource of the same magnitude as the conventional crudes. Both are, however, not sufficient in the larger consumption areas (West and Central Europe, North America) but have to be imported. Conversion to easily transportable energy carriers (LNG, methanol, hydrocarbons) at (remote) recovery sites is the mode for long-term future utilisation.

Biomass, mainly lignocellulosic plants, is a renewable resource, the potential of which in the European and global context has not yet been adequately investigated. Direct sun radiation to the earth represents an energy flow of the magnitude 10,000 times the total energy presently used in the world. The annual build-up of land biomass by photosynthesis is estimated to be of the magnitude of 10 times the energy used in the world. Food crops are estimated to account for 1/10 of the land biomass. Forestry, including wood as fuel, handles yearly about 3,500 million m^3 of solid wood, which in energy terms corresponds to somewhat more than 1% of the yearly biomass growth [6].

Discussions in the EU [1] usually restrict the use of biomass for energy carriers to the transportation sector to seasonal annual crops (rapeseed, grains, sugar beets) from set-aside agricultural land, resulting in a potential for replacing less than 10% of the present petrol and diesel oil consumption. This seems to be a substantial underestimate of the biomass potential. Firstly, there are good arguments [7] against the use of intensively cultivated crops for energy purposes and secondly, other much higher yielding crops should be considered for such purposes. An example of this is, for instance, semi-extensive cultivation of lignocellulosic crops (SRF, short rotation forestry) yielding 10 tons or more of dry substance (DS) per hectare and year and requiring replanting at 20-25 years intervals. Salix-species are often mentioned but also others such as Miscanthus and switchgrass have been considered. Amplification factors (yield of DS in energy terms over input of fossil based energy) of 20-30 have been quoted. Moreover, lignocellulosic feedstocks can also be obtained from the forestry and the forest industries as tree residues from cuttings of timber and pulpwood and from thinnings not used today. In the forest industry, bark and black liquor at sulphate pulp production represent a substantial resource. In many countries, the feedstocks of forest origin constitute a much larger resource (for instance the Nordic countries) than can be obtained from agricultural land. Not all countries in Europe have, of course, such favourable conditions, as there is less available land. Surplus agricultural land, however, seems to be similar per capita. Southern, Western and Central Europe cannot obtain self-sustained fuel markets based on biomass although the biofuel market can be considerable. In conferences on Bioenergy by the EC [18], the standing closed forests in the world were estimated to amount to >320,000 million m^3 solid wood (>140,000 Mt DS or >730,000 TWh). For Western Europe 10,000 million m^3 were estimated, whereas figure for the former Soviet Union was 84,000 million m^3. The annual growth in Europe is about 4%, considerably higher than cuttings. Improved forest management is expected to augment the growth and planted forests and short rotation forests might increase available biomass resources substantially. There is an urgent need to investigate future development of land use.'

The potential of biomass as a fuel feedstock is in principle an issue of how land can be used and developed for production. Preferably, lignocellulosic material that seems to give the highest yields, yet requires the least inputs of fertilisers, pesticides and fuels, should be utilised. Although a few studies have been made, a systematic, thorough investigation is recommended as to how land use can be developed taking into consideration the ecological and social restrictions of safeguarding bio-diversity and sustainable, environmental impacts. It is then important that the investigations are carried out by professional bodies in the area and that decisions are not based solely on the compiled statistical data on present land use within that field. Examples can be taken from Sweden, i.e. in a first study by the Forestry division of the Swedish University of Agricultural Sciences (SLU) [8, 9], which revealed a much higher than expected availability, and a study from a developing country, Thailand [10]. These studies exemplify how new land use for woody energy crops can be developed.

Waste that contains organic matter from agriculture, industry and the community should be included in the biomass resource base, as well as peat as long as it not exceeds its growth.

In many studies, renewable, long-term sustainable feedstocks include solar (photovoltaic, thermal), wind and hydropower as indirect sources to hydrogen by electrolysis [11, 12]. However, it is difficult to understand how such a power excess of any magnitude over direct power use could emerge particularly in Europe. Only a limited production from such new power can be expected [13]. Imports from areas with high sun radiation and very low cloudiness, such as the often discussed the Sahara desert, have to be included.

Artificial photosynthesis by sun radiated, gene-modified micro-organisms to produce hydrogen from water is an interesting research area in an early stage but as yet very low productivity is indicated. The same goes for light-sensitive metal oxide catalysts.

Nuclear-based power cannot be considered as a long-term sustainable source until breeder or fusion reactors become available. This alternative, if accepted at all, is not part of any scenario.

3.2.3 Production

The main pathway to alternative motor fuels involves conversion to liquid products (alcohols, hydrocarbons). The energy efficiency in this production step is important and is highest for DME, hydrogen and methanol, of which only methanol is an easily handled liquid fuel. The primary step is gasification to synthesis gas and thereafter, catalytic synthesis to the desired product, possibly followed by some secondary up-grading to specified market products. The technology is well known and commercially used on a large scale (methanol, FT-hydrocarbons) with natural gas as the feedstock. With biomass (lignocellulosics, wood) the gasification step to synthesis gas is not yet fully developed or demonstrated in commercial scale. However, it is considered as ready for this stage, based on knowledge from earlier pilot plant work and experiences from the commercial use of similar feedstocks (peat, brown coal). The up-grading of the raw gas to finished synthesis gas can be considered as known, commercially available and already used technology, exemplified by the use of hard coals of various kinds as feedstocks [14].

For cellulose containing feedstocks, there is another conversion pathway, i.e. chemical/biochemical hydrolysis to simple sugars for fermentation to ethanol. It is commercially used for sugar and starch containing raw materials and has earlier been used with wood feedstock but needs to be refined to obtain high yields. For best results, the hydrolysis should be accomplished bio-chemically with enzymes according to American studies. Achievable yield of ethanol will depend on the content of hemicellulose and cellulose of the feedstock, setting an upper limit [14, 15].

Preliminary engineering studies are the basis of the efficiencies given in **Table 2** for energy self-sufficient plants used to produce liquid fuels (natural gas as feedstock and hydrogen as product is included for comparison).

Table 2. Production yield in percent (based on LHV), including feedstock production and transport

Product / Feedstock	METHANOL/ /DME	ETHANOL	FT-FUEL	HYDROGEN
NATURAL GAS	**68/72**	--	**55**	**73**
BIOMASS	**52/55**	**45**	**43**	**54**

The gaseous fuels DME and hydrogen give the highest yields while methanol is the liquid fuels with the highest yield. The production of methanol yields 15-20% more motor fuel energy than the FT-hydrocarbon production and the yield of ethanol is limited by the content of cellulose and hemicellulose. There is some uncertainty about the yields of FT-hydrocarbons as it is not clear if yield figures are given for the broader mix of hydrocarbons that is typical for the FT-synthesis or only for the diesel oil fraction. The methanol synthesis is very selective to almost 100% methanol. Some improvements of the FT-hydrocarbon production have been reported in recent studies [16], and in the following discussion, an energy yield value of 45% has been anticipated[7]. It seems likely that the improvements might be applicable to the production of DME, methanol and hydrogen as well. Total yields of useful energy carriers can be improved if surplus heat can be utilised for space heating (district heat) or drying. This potential can only be investigated when considering concrete local projects, which are beyond the scope of this report.

High-octane otto-engine petrol is complex to produce via the FT-route (is simpler and more efficient via methanol, Mobil process). The yield of such petrol will be lower than that of the diesel oil fraction and presumes the use of the less efficient otto-engine compared to the diesel engine or fuel cell. Possible production of FT-naphtha might give yields as for FT-diesel oil and thus lower than for methanol, which is better suited as fuel for fuel cells. The yield advantage of the simplest product, hydrogen, is lost at distribution and refuelling. The distribution of DME is considerably simpler than that of hydrogen but has to be handled under moderate pressure (5-10 bar) to provide a liquid.

3.2.4 Fuel distribution and refuelling

The distribution of liquid fuels from terminals to many retail stations requires little energy, about 1% of the energy content of the hydrocarbons and about 2% of that of methanol. The refuelling operation with liquids requires negligible energy (liquid pumping in low-pressure systems) in contrast to gases. Gaseous fuels require energy corresponding to 10-30% of the energy content of the fuel in high-pressure or cryogenic systems, for operation of compressors (up to 700 bar is considered with hydrogen) or liquefaction units (at 20 degrees above absolute zero, i.e. -253°C). Gases that can be liquefied at ambient temperatures (DME and LPG) represent intermediates from distribution viewpoint.

Pipeline distribution of gases is accomplished on a very large scale with natural gas, requiring energy for operation of the compressors corresponding to about 2% of the energy content of the gas moved per 1,000 km. Hydrogen, due to its low energy density, would need several times more energy to move the same amount of energy in the same pipe. A

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[7] For clarification, it should be noted that the higher value for FT-hydrocarbons has been used in the discussion but not in **Figure 2**, which is based on results from a previous study by the authors [2].

larger diameter pipe would be an optimised solution for roughly doubled transport energy use.

Fuels, which are liquid at ambient conditions, carry the lowest cost of distribution (somewhat higher for liquefied gases) and gaseous fuels the highest costs, with hydrogen costing the most. Cryogenic liquids carry the highest costs because of the more expensive equipment and boil-off losses of product, while the advantage would be the possibility of better area coverage. The costs of creating a finely branched distribution network, as that which exists for the present motor fuels, would be prohibitive.

3.2.5 Use and efficiency in various engines/drivetrains

A summary of the system efficiency for combinations of various *biomass* based fuels, energy converters and drive systems is given in **Figure 3** (taken from the underlying study [2] for SNRA, Swedish National Road Administration). In the study, a total of 98 combinations were investigated, including natural gas as a feedstock. Vehicle acceleration, i.e. 0-100 km/h in 11 s ± 0,1 s, was kept constant as a performance criterion for all vehicles. The study comprised only passenger cars (LDV) and the results cannot be simply applied to heavy-duty vehicles without further investigation.

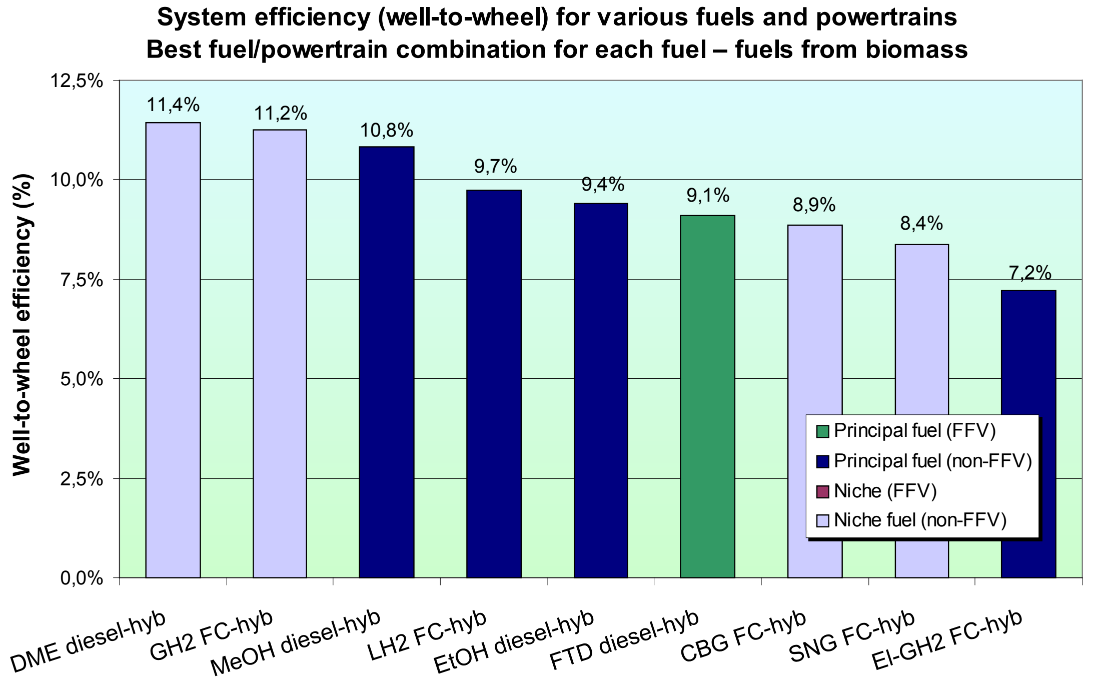

Figure 2. *Well-to-wheel efficiency for the best combinations of fuel/drivetrains. Fuels from biomass feedstock.*

Table 3. *Explanations to the abbreviations in* ***Figure 2***

Abbreviations	Explanations
DME diesel-hyb	DME, diesel engine hybrid
GH_2 FC-hyb	Compressed hydrogen, fuel cell hybrid
MeOH diesel-hyb	Methanol, diesel engine hybrid
LH_2 FC-hyb	Cryogenic (liquid) hydrogen, fuel cell hybrid
EtOH diesel-hyb	Ethanol, diesel engine hybrid
FTD diesel-hyb	Fischer-Tropsch diesel fuel (synthetic fuel), diesel engine hybrid
CBG FC-hyb	Compressed biogas, fuel cell hybrid
SNG FC-hyb	Compressed synthetic natural gas,
El-GH_2 FC-hyb	Compressed hydrogen, produced from electr. (local), fuel cell hybrid

In the Figure, only the best combinations (as explained in **Table 3**) have been included and divisions has been made between principal fuels (with a potential for widespread use everywhere) and niche fuels (limited to local/regional use). A further division is made between the possibility for fuel flexibility or blending with existing fuels (designated FFV, lacking a better conception), as these possibilities might be useful during a long transition period. A list of the categories in prioritised order will be:

- Principal fuel, FFV
- Principal fuel, not FFV
- Niche fuel, FFV
- Niche fuel, not FFV

The efficiency measure used is the energy efficiency (LHV-basis) in the entire chain from biomass feedstock production to performed work at the wheels. As there are great losses in several steps of the chain the total efficiency in absolute numbers is low, around 11% for best cases (a few %-units higher with natural gas feedstock). It is hardly surprising that all the best options comprise hybrid drive systems. It also is not surprising that no otto-engine is among the best combinations since there is a fuel cell and/or a diesel engine in best combinations for all fuels. However, a hybrid combination with the best otto-engine fuel, methanol, ranks higher than a conventional diesel engine on any alternative fuel and nearly equal to direct fuel cell drive with hydrogen [2].

The six top-ranking fuels are:

- DME
- Gaseous hydrogen, GH_2
- Methanol
- Liquefied Hydrogen, LH_2
- Ethanol
- FTD

It might be considered logical to limit the list of fuel candidates above (e.g. to three fuels). However, as will be shown later, fuel distribution is a limiting factor for the gaseous and cryogenic fuels. It would also be an advantage if both petrol and diesel fuel could be substituted. It is worth noting that if the FT-route becomes somewhat more efficient, as mentioned above, FTD may become equal to or marginally better than ethanol.

In the opinion of the authors, the motor fuels above should be given the highest priority if energy efficiency and the reduced emissions of GHG are the most important criteria. In some investigations, local emissions with impact on health and environment have been considered as most important and these studies have resulted in recommendations for biogas. This has often been based on the present day status of the aftertreatment technology. Little (or no) consideration has been paid to future improvements of such techniques, which in the near future will reduce the difference between various fuels to almost negligible level. *Energy efficiency and GHG emissions will remain as the future decisive criteria for principle fuels.*

3.3 Low-blending in petrol and diesel fuel

The two possibilities of introducing a new motor fuel are to use it for the existing car park without any alteration of the vehicles and to use it for new, modified vehicles or a new drive system. Low level blending into present petrol or diesel oil are examples of the first mentioned and an immediate route to the entire car park is opened with possibility for alternating refuelling of existing petrol or low level blends. Modified and new systems that can use the new fuel and be optimised for it are discussed under section 3.4. There are also transitional solutions that are fuel flexible and can use both the existing and the new fuel.

3.3.1 Petrol

Low level blending of oxygenates (alcohols, ethers) has been used since the 70'ies and is controlled by standards and regulations. The oxygenates can be seen as normal components in petrol with high octane numbers and non-aromatic character, yielding a petrol with less harmful emissions and some replacement of crude oil based products. In the US use of oxygenates was introduced by legislation for "reformulated gasoline" and "oxygenated gasoline" in order to improve the air quality in areas with bad air. The effect of a 2% by weight oxygen level was for the then modern (1989) cars with catalytic aftertreatment found to give a reduction of CO emissions by about 25%, HC emissions by 10% without increased NO_X emissions. Furthermore, a 15-25% lowered potential for ozone-formation and cancer risk by emissions of gaseous "air toxics" (carcinogenic gases) was shown. A higher level than 2,7% oxygen might lead to increased NOx-emissions. Whether this is also valid for modern cars today has not been investigated and is not known.

The specification for future petrol with oxygenates is proposed in the World-Wide Fuel Charter (WWFC) [17] by the motor industry and it sets a limit of 2,7% oxygen. It is also stated that "methanol is not permitted" but does not give any reason. In old cars in the 80's there might have been material problems in the fuel system but not for present day cars which can tolerate higher levels than are considered as low level blends.

Alcohol-containing petrol can have a problem with sensitivity to the presence of too much water, which might cause phase separation. This was thoroughly investigated in the 80's and the experiences have been compiled in a report from co-operative work under the IEA umbrella [18] and form the basis of the rules for low level blending laid down in directive 85/36/EEG. Only methanol alone at low levels is not permitted but here the presence of a higher alcohol (which could be ethanol) is required. Properly formulated blends with alcohols in petrol have been and are today in safe use. The storage system has to be amended to prevent the inflow of liquid water. Problems with water sensitivity can be avoided by converting the alcohol to ether by reacting it with isobutene (MTBE, ETBE), a solution preferred by the oil industry. However, ethers have a disadvantage of leaving contaminated water drainage from the distribution system. The availability of sufficiently low-cost isobutene from steam crackers and refineries is, however, not high enough to allow full utilisation of the potential for oxygenates in petrol and supplementary direct alcohol blending will anyway be needed.

The possibility of successively increasing the level of alcohols to expand the market has been discussed, since modern cars can technically operate on higher level blends. With regard to uncertainties about their use in older cars and possible emission disadvantages, this is probably not a recommendable proposition. Other ways to expand the market are discussed in section 3.4.

The conclusion is that low level blending of oxygenates in petrol is a suitable proposition and an immediately available part of an introduction strategy. By the general use of oxygenates as components of petrol the refiners can utilise their properties to lower the costs of production of the hydrocarbon part and meet demands for lower harmful emissions. Under the directive and specifications in force today the market as exemplified by Sweden (petrol market of 5,4 million m^3 *yearly) can be 400,000* m^3 *of ethanol or about 140,000* m^3 *of methanol together with 200,000* m^3 *of ethanol. Part of these can be as ethers. Western Europe represents, of course, a many times larger market.*

3.3.2 Diesel fuel

The components for blending into diesel oil, that can have a bio-origin, are mainly fatty acid esters, FAME (vegetable and animal oil and fats, which have been re-esterified with methanol or ethanol to obtain acceptable properties) and synthetic (Fischer-Tropsch, FT) hydrocarbons. Alcohols are to a lesser extent miscible with diesel oil. Examples are emulsions with contents of alcohols that are higher than can be designated as “low level blends” and have been used for alternative refuelling with the diesel oil, for example 15% of ethanol or 12% of methanol. The use of co-solvents (high amounts are required) has also been tested. The conclusion is that blends of alcohols and diesel oil can hardly become a generally used, independent motor fuel but only a niche fuel.

The most common re-esterified vegetable oil in Western Europe is RME, rapeseed oil methyl ester. The primary rapeseed oil is too viscous and high-boiling for direct use but is re-esterified with methanol and glycerol is obtained as a by-product. In the U.S. soybean oil is the most common base oil. RME and similar can be blended with diesel oil to rather high contents without any noticeable change of the properties of the blend fuel or performance of the engine. RME can be as such in diesel engines with seals properly adapted and adjustments to maintain performance data are made.

The use of pure cold-pressed vegetable oil, such as rapeseed oil, has been proposed as an alternative to re-esterification of RME[8]. The poor cold-flow properties and various other

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[8] In fact, this alternative was proposed some two decades ago by the German inventor L. Elsbett.

characteristics of cold-pressed vegetable oils necessitate considerable (and expensive) modifications of the engine and its fuel system. Such modifications of products still under warranty might lead to that the loss of the warranty. Furthermore, such "tampering" is not allowed on modern engines, unless the conversions are homologated. The use of cold-pressed oil is not recommended, since re-esterification is a simpler and cheaper option.

The limitation for the use of RME is that the availability is low and the fact that it is a product from the intensive cultivation of annual crops on agricultural land. The potential in Sweden is considered 2-4% of the use of diesel oil and RME cannot be anything but a niche fuel and is used best if blended at that level in diesel oil. Estimates for Europe also yield a potential of a few percent.

FT-hydrocarbons can, at least if they have been produced from methane (natural gas) and have the same boiling range, FTD, be blended with present-day diesel oil to rather high contents. The limitation will be the lowered density (affecting engine power) since the FTD has a low density, <0.78 kg/litre. As the FTD contains no sulphur, has very low content of aromatics and a has high cetane number, it can advantageously be used for quality improvement of low-grade diesel oil. FT-products produced from other feedstocks (coal in South Africa) have somewhat different properties but are miscible with conventional diesel oils.

3.3.3 Concluding remarks on low-blending

Conclusions of what is said above are (from the technical viewpoint):

- *The same fuel components that can be used for low level blending in petrol and diesel oil, can be developed to self-existent, new motor fuels for drivetrains used presently and in the future. Alcohols (methanol, ethanol) and FT-hydrocarbons are leading candidates with methanol having the most energy efficient system (and probably also the least costly system).*
- *Production processes that lead to easily handled, liquid fuels from bio-feedstocks must be given a priority for development as a commercial demonstration. This applies particularly to the gasification route with biomass feedstocks with methanol and/or FT-hydrocarbons as final products. Introduction of these as motor fuels can be started early using existing and commercially available technologies with natural gas as feedstock and, at present oil prices, lower costs.*
- *Continued development of drivetrains with diesel engines, fuel-flexible otto engines and eventually fuel cells must be encouraged and be given long-term goals.*

3.4 Large scale use of alternative fuels

Firstly, some definitions should be given. An *energy converter* is an "engine" that can convert chemical energy (fuel) to some other form of energy, e.g. mechanical energy or electricity, which can be used to propel a vehicle. The energy converters covered here are the conventional internal combustion engines of otto and diesel type, as well as the fuel cell. The denotation *drivetrain* is used for the transmission or its electric counterpart, the electric drivetrain. A *powertrain* is the whole drive system, comprising the energy converter and the drivetrain (including energy storage, if included in the system).

Conventional fuels, such as petrol and diesel fuel will continue to dominate in the foreseeable future. Therefore, the future development of the energy converters for these fuels must be described here as well as the adaptation of these energy converters to alternative fuels. In fact, most of the development resources today are allocated to the conventional internal combustion engines for petrol and diesel fuels, since these options totally dominate the market.

Large scale use of alternative fuels is limited to the so-called principal fuels, i.e. fuels defined as being able to reach a market penetration of more than 10% of the petrol and diesel fuel use. Niche fuels are only covered here if they have the same properties as other fuels (e.g. methane is the main component of both biogas and natural gas).

3.4.1 Possible market penetration of energy converters and fuels

Combinations of energy converters and fuels

First, it is of interest to provide an overview of the possible combinations of energy converters and fuels. The fuel origin (i.e. feedstock) is of little interest in this case. In **Table 4**, the combinations of principal fuels and energy converters are shown.

Table 4. *Possible combinations of fuels and energy converters*

Fuel	Otto	Diesel	Fuel cell
Petrol	Yes	Not cons.[a]	Yes[b]
Diesel fuel	No	Yes	Not cons.[a]
Synthetic diesel fuel (FTD)	No	Yes	Yes
Ethanol	Yes	Yes	Yes
Methanol	Yes	Yes	Yes
DME	No	Yes	Yes
Methane (CNG, LNG, CBG and SNG)	Yes	Only heavy-duty veh.[a]	Yes
Hydrogen (GH_2 och LH_2)	Yes	Not cons.[a]	Yes

Notes:

[a] "Not considered" refers to that the fuel in mind theoretically might be used in the energy converter but that this would require a considerable change in fuel specification or else significant development of the energy converter.

[b] Petrol should in this case not be considered as "conventional" petrol but a special fuel quality practically free from sulphur and aromatics. It is notable that the contemporary "best" EU fuel specification (2005) has relatively high aromatic content. Consequently, it would be a completely new petrol specification for fuel cells in contrast to the petrol sold today. Naphtha is often considered as a fuel for fuel cells but its potential from crude oil is limited.

Not all combinations in **Table 4** are practically possible, as the fuel properties do not fit the particular energy converter, or else the technology needed would be too sophisticated to be economically feasible.

Petrol and diesel fuel will remain as primary fuel in the foreseeable future. Petrol is linked to use in otto engines and a similar relationship exists between diesel fuel and diesel engines. Diesel fuel is not considered for fuel cells due to the difficulties in the reformation process. Likewise, the petrol specification must be tailored to enable reformation although it should be noted that this is also a very difficult task.

DME is an ideal fuel for diesel engines (provided that a dedicated injection system is used) but is not feasible for use in otto engines. The use of DME in fuel cells could also be feasible. FTD cannot be used in otto engines but is ideal for diesel engines. FTD, or actually a "lighter" Fischer-Tropsch fuel (sometimes called Fischer-Tropsch Naphtha) could be used in fuels cells on condition that a reliable reformer could be developed.

The otto engine technology for all methane-based fuels does not discriminate (in principle) between fuel origin[9]. Methane could be used in diesel engines as well, but this has only been considered for heavy-duty vehicles. Some ignition-source other than a spark plug has to be used and a glow plug or diesel fuel as a pilot fuel are possible solutions.

Hydrogen has not been considered for use in diesel engines, although this could be theoretically possible using a somewhat similar solution as for methane-fuelled diesel engines. With hydrogen, a fuel cell is much more efficient than an otto engine, and presumably than a diesel engine, as well.

Limiting factors concerning fuel distribution

A few comments on the limiting factors in the fuel distribution should be added, as feedstock potential and efficiency are not the only factors of importance. As previously mentioned a market penetration of more than 10% for a certain fuel was the target, and this applies to the energy converters as well. Synergies and potential problems in this area have to be identified.

The large-scale distribution of CNG in pipelines for widespread use would be only feasible in densely populated areas, due to cost aspects. LNG has a far greater potential than CNG, since it is a liquid fuel and could be transported in ships and distributed by tank trucks. LNG could possibly be introduced on a large scale from a technical standpoint even in countries with low population density, such as e.g. Sweden but it seems as the cost is prohibitive.

Biogas produced using anaerobic digestion would have difficulties in meeting the target penetration since the price of the feedstock will be a limiting factor[10]. Due to the small-scale production of biogas, utilisation as compressed biogas (CBG) is the only feasible alternative. The biomass feedstock for SNG is the largest of all feedstocks for methane fuels from biomass. The problem with SNG is that production should preferably be carried out in relatively large facilities (for maximum efficiency) and this is difficult to combine with small-scale local distribution. Liquefaction of SNG is in principal possible as well as of natural gas but this alternative has been excluded due to efficiency and cost reasons. Co-distribution of CBG and SNG with CNG is in principle possible and is already utilised on a small scale in Sweden at sites where a natural gas pipeline is available. Since CBG and SNG in that case would have to assume some of the cost of the pipeline, this is a more expensive alternative than local distribution. If both CBG and SNG are produced, it could be

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[9] The methane number (MN: knock resistance of methane containing fuels) and Wobbe index (relative heating value), etc. must be taken into consideration but new technology could make these engines somewhat fuel flexible in this respect. Furthermore, it is anticipated that the fuel specification for the gaseous methane-containing fuels (CBG and SNG) must be kept within relatively tight limits.

[10] This refers to the phase after the cheapest feedstock has already been utilised.

possible to meet the target of 10% penetration. If CNG and LNG were also included, the total potential for methane would be well above the 10% target. However, the cost is a limiting factor.

Fuel distribution of hydrogen is an even more difficult task than distribution of methane. Pipeline distribution would be significantly more expensive (and energy demanding) than for natural gas, the cost of which is already somewhat prohibitive. As in the case of natural gas, LH_2 would be an option for a widespread use of hydrogen, yet at a significantly higher cost than for LNG. Local hydrogen production via electrolysis is an option, but studies have showed poor efficiency for this option [2]. Electricity production from renewable sources (wind, sun) is not yet viable due to the high cost and questionable excess potential in Europe. The problems in hydrogen distribution are so severe that one recent study proposed a shift of focus from “hydrogen economy” towards “methanol economy” [19]. In summary, it could be concluded that hydrogen could be distributed from a technical standpoint but that the cost is prohibitive today. Nevertheless, the hydrogen option is still considered in this study.

For the liquid fuels, there are no limitations in fuel distribution.

Market penetration for energy converters

It is of interest to give a brief comment on the possible market penetrations of the three energy converters, since this also has a crucial impact on the use of alternative fuels.

Today, diesel fuel is more or less the sole fuel for heavy goods vehicles and its market share is increasing for the light commercial vehicles. Consequently, the diesel engine, with more than 99% market share, totally dominates the market for heavy-duty vehicles. In niche applications (e.g. city buses), otto engines are used for CNG, biogas and LPG as an alternative to diesel engines. Fuel cell buses will be field-tested beginning in next year, but the market penetration for this energy converter in heavy-duty vehicles is likely to be low within the next 1-2 decades. *Based on these presumptions, a significant market penetration in this category of vehicles could only be achieved for alternative fuels suitable for diesel engines within the indicated timeframe.*

For passenger cars and the smallest light commercial vehicles, the situation is completely different to that for heavy-duty vehicles, as both petrol and diesel fuels are main fuels. Differences in government policies (e.g. taxation) in the EU member states have a great influence on the market penetration of each fuel. Therefore, it is easier to estimate the future market penetration for the whole EU, than for individual member states. Such an estimate has been made by the authors and the result is shown in **Figure 3**[11].

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[11] The calculation model does not exactly replicate the statistical data from 1997 to 2002.

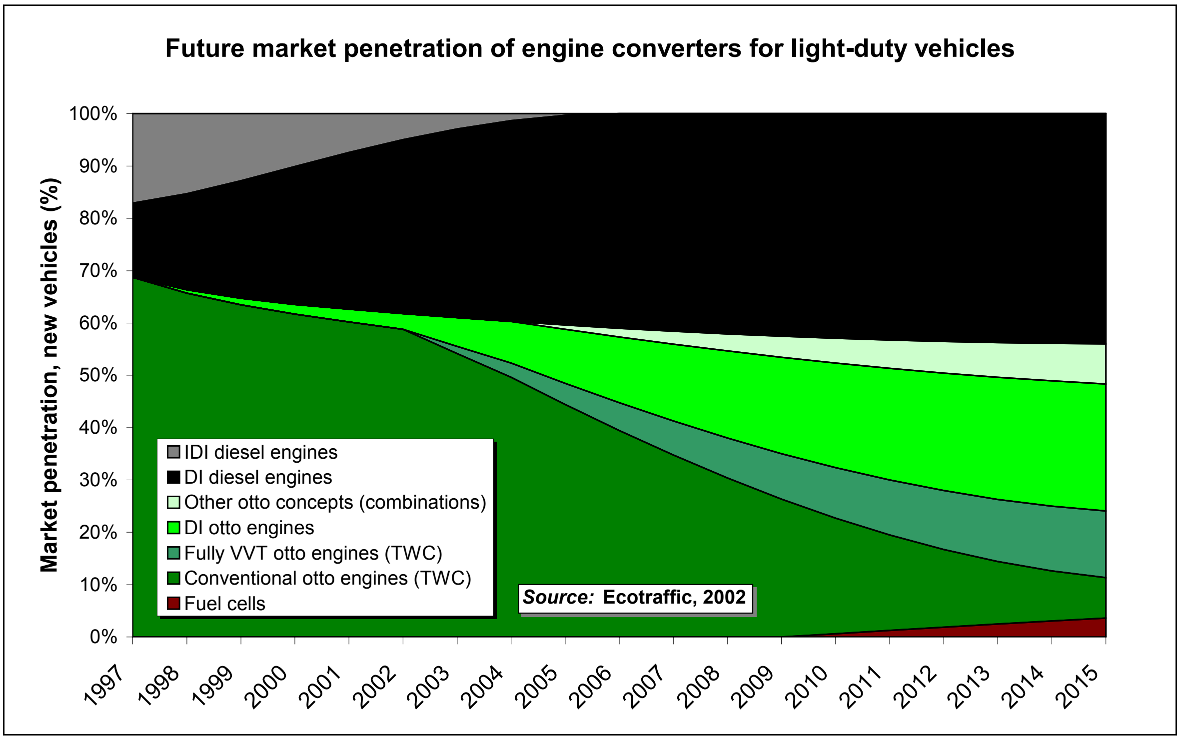

Figure 3. *Future energy converters for passenger cars*

The technology shift from indirect injection (IDI) to direct injection (DI) for diesel engines is evident from **Figure 3**. The current trend is that the market penetration of diesel cars is increasing. In our view, the rate of increase will diminish at the end of the period and stabilise at a level slightly above 40%. The share of diesel fuel from crude oil cannot increase to an arbitrary level with contemporary refinery technology. An increase in the demand for jet fuel and diesel fuel for heavy-duty applications is also likely. Likewise, long-term investments in the refinery business have to pay-off before new commitments are made. Therefore, an increase in the demand for diesel fuel will lead to higher prices and this will stabilise the market penetration for diesel cars at a “natural” level. An increase in fuel trade with countries having a low share of diesel fuel (e.g. the USA) could be one option to offset the anticipated problems in diesel fuel supply. In general, it is plausible that the price on diesel fuel will increase in the future in comparison to the petrol price. It is also likely that the current tax incentives, that currently favour diesel fuel in most EU member states, will diminish in the future.

Conventional petrol-fuelled otto engines will decrease in favour of direct injection engines and engines with fully variable valve timing, as well as combinations of the two technologies. The denotation “other concepts” in **Figure 3** refers to combinations of VVT and/or DI with other options, such as e.g. supercharging and/or variable compression. It can be concluded that a metamorphosis of the otto engine will be necessary to fulfil the commitments to reduce fuel consumption and CO_2 in the anticipated timeframe. The difference in fuel consumption between diesel and otto engines will most likely decrease in the future. Similarly, the use of more sophisticated technology will reduce the price difference between these options. In general, the technical differences between the engines will also diminish and the synergies regarding the development will increase.

In the opinion of the authors, fuel cells will not receive a commercial breakthrough in the near future. Some prototype vehicles are about to enter a field test phase soon. A limited production might start in 2010 but these vehicles will (presumably) be restricted to certain niches, due to cost issues and the lack of fuel infrastructure. Possibly, a large-scale introduction cannot be made before 2020.

Drivetrains were not included in **Figure 3** above (i.e. only energy converters were covered). Electric hybrid drivetrains could have a significant market penetration in the future. A decisive factor is the incremental cost in comparison to conventional drivetrains.

3.4.2 The otto engine

Development trends for otto engines

The otto engine is characterised by the fact that it generally uses premixed homogenous air/fuel preparation and a spark plug as ignition source. A stoichiometric air/fuel ratio (λ=1) is used for the greatest part of the operating range. This enables the use of the so-called three-way catalyst (TWC) that can simultaneously reduce all the three regulated emission components (CO, HC and NO_X). The air/fuel preparation is made before the engine cylinder using indirect ignition of the fuel.

With direct injection of the fuel, a stratification and overall lean air/fuel ratio could be accomplished. Due to the reduction of the throttling losses and some other effects, the fuel consumption could be reduced by some 12% (our estimate) for the contemporary systems in comparison to TWC. The problem with a lean mixture is that a conventional catalyst for TWC does not give any NO_X reduction. New NO_X storage types of catalysts have been introduced on the market and they are reducing this handicap compared to the conventional otto engines.

Another concept of reducing the fuel consumption could also be mentioned. The German car manufacturer BMW has introduced fully variable valve timing and lift, which can control the air/fuel supply to the engine. Thus, the throttling losses could be reduced to a very low level although the air/fuel ration could be kept at the stoichiometric level. The principal advantage over lean mixture and direct injection is that the conventional TWC emission control system can be maintained. Therefore, the emission potential is greater. The authors estimate that the fuel consumption could be reduced by about 8% with contemporary systems[12].

In the analysis of future energy converters, the authors have anticipated that otto engines in a long-term perspective (2010 and later) will use direct injection and that the penetration of fully variable valve timing initially will be small. A combination between this system and direct injection does not imply that the reduction in the fuel consumption could be added in. However, some minor synergy effect could be anticipated for future development of these systems.

Alternative fuels in otto engines

Alcohol fuels have some attractive properties for otto engines but also some problems. The high octane number and a high latent heat of evaporation could increase engine power and

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[12] BMW claim some 10% reduction of the fuel consumption for the 3-series car but in this case, other improvements (friction, 4-valve cylinder head, downsizing etc.) also contribute, since the concept is used on a completely new engine family.

efficiency. Furthermore, an alcohol engine could be fuel-flexible, a considerable advantage during an introduction phase for a new fuel. Cold start at low temperature has been a serious problem for alcohol-fuelled otto engines, similarly to petrol engines. Higher emissions during the cold start phase and even problems to start the engine have been noted. In the future, an alcohol engine could utilise direct injection in a way similar to petrol engines. With future development of direct injection, the cold start problems could be resolved. An important issue to study is whether this engine could be fuel flexible. Early research data indicate that this could be possible [20].

Gaseous fuels, such as, i.e. methane and propane, have a high octane number, which is desirable for otto engines. Furthermore, gaseous fuels could have a decisive advantage during the cold start phase since the fuel is in a gaseous state during air/fuel preparation[13]. A disadvantage is that gaseous fuels displace air in the cylinder and consequently, the engine power is reduced in comparison to petrol engines. Another issue seems to be that the long-term stability of the emission control system could be problematic, which has been indicated by emission test programs on in-use vehicles.

Concerning the use of gaseous fuels in heavy-duty vehicles, it could be noted that these engines, in general, have been converted from diesel engines to otto engines. Certain advantages regarding emissions could be mentioned but the efficiency in comparison to the original diesel engine is lower. In most cases, gaseous-fuelled engines utilise lean-burn combustion but TWC is also used. The main advantage of lean-burn is a higher efficiency, while the TWC concept has lower emissions. Theoretically, direct injection could be used on gaseous-fuelled engines as well as on alcohol engines, but the technical problems are greater in the former case.

3.4.3 The diesel engine

Development trends for diesel engines

Contrary to (conventional) otto engines, diesel engines use excess air. Furthermore, modern diesel engines have direct injection of the fuel and the ignition is accomplished by the high temperature at the end of the compression stroke. Generally, the efficiency is higher for diesel engines than for otto engines, primarily due to the low pumping losses (no throttling) and the high compression ratio. The heterogeneous air/fuel preparation, due to contemporary injection systems, causes soot formation. An advantage is that the late injection reduces the amount of fuel in crevices around the combustion chamber, giving lower engine-out emissions of CO and HC in comparison to otto engines.

CO and HC emissions can be oxidised in an oxidation catalyst while the NO_X emission cannot (yet) be reduced by contemporary catalysts. In the near future (probably in 2003), a NO_X reduction technology similar to the technology used in direct injection petrol engines will be introduced. Particulate filters have been used on the after-market for heavy-duty engines since mid 90's and in 2000, Peugeot introduced a filter on a passenger car. Other manufacturers are expected to follow this trend. The use of particulate filters and NO_X reducing catalysts will enable the diesel engine to achieve a similar emission level as the petrol engine in the future.

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[13] This advantage is lost if the engine is started on petrol only, which seems to be the contemporary strategy for some bi-fuel engines in light-duty vehicles.

Alternative fuels in diesel engines

RME and FTD are “natural” diesel engine fuels, since they have a sufficient cetane number and they are miscible with diesel fuel. These fuels enable fuel flexibility, a particular advantage during an introductory phase. The NO_X emissions are generally higher for RME and somewhat lower for FTD in comparison to diesel fuel. Soot emissions are lower in both cases. For a dedicated engine, lower soot emissions could be advantageous as the recirculation of exhaust gas (EGR) could be increased. A higher EGR rate decreases the NO_X emissions.

DME is an excellent diesel fuel that presumably, has better emission properties than all other alternative diesel fuels. Soot formation is practically eliminated with DME and NO_X emissions decrease considerably in comparison to diesel fuel. The advantage of using higher EGR rate is greater than for RME and FTD. DME is not miscible with diesel fuel and a dedicated injection system has to be used, as well as special solutions for fuel tanks and refuelling equipment. DME will be introduced in dedicated fleets but this fuel has to be considered as a niche fuel for the foreseeable future.

Alcohols could be used in diesel engines, on the condition that some kind of ignition aid (ignition improver in the fuel, glow or spark plugs, etc.) is used. Advantages for alcohol fuels are low levels of NO_X and particulate emissions. These advantages are greater than for RME and FTD but not as significant as for DME. On the international market, very little development work is carried out on alcohol-fuelled diesel engines and no engines are commercially available for light-duty vehicles. In Sweden, Scania has produced some 400 ethanol-fuelled buses but recently they announced that production would be discontinued due to low market demand. A specific problem with alcohols is that they are not miscible with diesel fuel and consequently, this engine/fuel combination is only applicable in niche solutions until a new fuel infrastructure has been built.

As mentioned above, gaseous fuels, such as methane and propane, are “natural” otto engine fuels due to their high octane number. Thus, a conversion of diesel engines to otto engines is a possible solution. In contrast to the light-duty engines, lean-burn combustion seems to be preferred over stoichiometric combustion (with TWC) for heavy-duty engines. The advantage of TWC is lower emissions than with lean-burn. Thermal stress is reduced for the lean-burn and hence, the power level can be higher. There is also available technology to use these fuels in a diesel engine, as well[14]. The advantage is a higher efficiency than in an otto engine. The drawback is that the classic diesel engine problems with NO_X and particulate emissions arise, albeit somewhat less accentuated than with diesel fuel. Commercial engines for heavy-duty vehicles are available in the USA (e.g. Caterpillar). Westport Innovations, is developing an advanced combustion system with direct injection and a Cummins Westport engine with this system will be available in 2004 [21].

3.4.4 Unconventional combustion concepts for otto and diesel engines

It is interesting to note that new combustion concepts are currently being investigated for both diesel and otto engines. It could be mentioned that there are several acronyms to the concepts mentioned below. The authors have used the most common acronyms CAI (Con-

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[14] In principal, this technology could be used on light-duty diesel engines as well but it is doubtful if the option is as attractive in this case due to cost and complexity issues.

trolled Auto Ignition) for otto engines and HCCI (Homogenous Charge Compression Ignition) for diesel engines.

The HCCI concept is of great interest for diesel engines and is probably the more well-known of the two concepts mentioned here. The HCCI concept is based on evaporating and premixing the fuel and air *before* ignition in a somewhat similar manner as in an otto engine. However, contrary to the otto engine, ignition is carried out using compression ignition. HCCI could significantly reduce – or eliminate – NO_X and particulate emissions, two of the main emission problems for diesel engines.

The new concept for otto engines, CAI is somewhat similar to HCCI, since it also uses air/fuel premixing and compression ignition. Due to the poor compression-ignition properties of otto engine fuels, ignition must be enhanced in some way. Massive use of hot residual gases is one possibility to promote compression ignition of a fuel with very low cetane number.

Regarding the fuel demand imposed by HCCI and CAI concepts, it is notable that different properties than for the conventional petrol and diesel fuels are necessary to fully optimise each concept. Presently, very little is known about the new demands that these concepts will impose on fuel specifications. Whether alternative fuels could have significant advantages over conventional fuels is another issue to consider. The US institute SwRI and the University of Lund in Sweden have conducted some pioneering work on fuel properties for HCCI engines. Brunel University and Ford have been investigating the impact of alcohol fuels and petrol formulations on a CAI engine [22]. In a recent study, it was found that alcohols had a considerably larger CAI operating area than petrol. The following order was established: methanol>ethanol>petrol. Similar findings have been noted previously on 2-stroke engines. In contrast, petrol fuel quality had very little effect on CAI operation.

Although few data are still available, it is worth noting that considerable development efforts are conducted on these combustion concepts and, therefore, bringing alternative fuels and fuel specifications into the optimising process would be a logical next step.

3.4.5 Fuel cells

Fuel cells can convert chemical energy directly to electricity. Thus, the limitations imposed by the Carnot cycle could be circumvented and this would result in a potential for higher efficiency than internal combustion engines. The most likely fuel cell candidate for vehicle applications, the Proton Exchange Membrane Fuel Cell (PEMFC), use hydrogen fuel. Other fuels have to be reformed to hydrogen in a fuel processor, or reformer. Methanol and DME are straightforward to reform and the most difficult fuel candidates are methane, petrol and diesel fuel. Other fuels are ranked in-between these categories. Significant fuel reformulations (or naphtha) are necessary to utilise petrol and diesel fuel in fuel cells.

With methanol, and possibly, also with DME, it could be theoretically possible to use internal reforming, i.e. a DMFC (Direct Methanol Fuel Cell) or a DDMEFC (Direct DME Fuel Cell). So far, the efficiency for a DMFC is significantly lower than for a PEMFC but under the condition that the technical problems could be solved, there is a potential that the same efficiency as the latter could be achieved. A significant simplification of the system could be accomplished with DMFC or DDMEFC in comparison to a PEMFC with reformer.

The efficiency in the fuel cell is, as previously mentioned, high and it is highest at low loads. The necessary accessories (pumps, fans, etc.) decrease the efficiency, particularly at low loads, which reduces the potential advantage under these operating conditions. The efficiency in the electrical drivetrain is lower than for conventional manual transmissions. If some kind of energy storage is used in the electrical drivetrain, it could be characterised as a hybrid drivetrain (see below). A hydrogen-fuelled fuel cell and a DMFC have practically zero emissions. When a reformer is used, there are some emissions from the reformer but it appears that there is a great potential to reduce these emissions to very low levels. The greatest problems for the fuel cells are the high cost and that the preferred fuels (hydrogen and methanol) are not readily available today.

It is clear that an introduction of fuel cells at the market would favour fuels that either could be used directly without reforming (in PEMFC, DMFC or DDMEFC), or fuels that could be reformed with high efficiency (methanol and DME).

3.4.6 Drivetrains

The denotation "drivetrain" is used here as a generic term for various types of gearboxes and electrical drivetrains. Although most of them are more or less well known, it could still be of interest to add some short comments about them.

Conventional drivetrains

Three different main types of transmissions are of interest today. The conventional mechanical transmission has a number (5-6) of fixed ratios (gears). A development trend of this type of gearbox is that it is equipped with automatic shifting, which reduces the fuel consumption. Possibly, a dual clutch is also included to increase the comfort and enable faster shifts without torque interruptions. The automatic transmission uses a torque converter instead of a clutch and this is the cause of higher losses in this transmission in comparison to the former. The development trend is an increasing number of gear ratios (from 4 to 6) that significantly reduces the fuel consumption. The third option is a continuously variable transmission (CVT). This transmission is practically as efficient as the conventional mechanical gearbox. New CVT concepts have recently been introduced and in series production they could be expected to increase their market share in comparison to the conventional automatic transmission.

Hybrid electric drivetrains

An electric drivetrain could be of direct or hybrid type. The first option mentioned has no energy storage. Electricity is generated (using combustion engine-generator or a fuel cell) and transmitted to an electric motor that drives the wheels. In a hybrid system, electricity storage is used and, in most cases, a chemical battery is the preferred option, although supercapacitors and flywheels are conceivable future solutions. The electric hybrid systems can be characterised as series or parallel hybrids but combined hybrids are also possible. In a series hybrid, the system is in series (e.g. the chain of engine-generator-motor) and all propulsion power is provided by electric motors at (or near) the driving wheels. In a parallel hybrid, the power is transmitted both mechanically (through a transmission) or electrically (via an electric motor and, possibly, a reduction gear). A fuel cell vehicle with energy storage has to be characterised as hybrid vehicle. Only a series hybrid drivetrain is conceivable in this case, since the fuel cell cannot generate any mechanical work.

The fuel consumption was generally lower for hybrid systems in passenger cars with combustion engines in our simulations [2]. This is also the main advantage with hybrid systems. Lower emissions could theoretically also be obtained with hybrid systems but these advantages are probably relatively small. In heavy-duty vehicles, the potential for reducing the fuel consumption is generally lower, except in special cases, such as for vehicles in city traffic. Since future hybrid-electric systems, due to cost considerations, will have relatively small energy storage, the possibilities to "refuel" with electricity are small. Consequently, this option has not been considered.

3.4.7 Priority of fuels for widespread use

Constraints imposed by fuel distribution

As previously discussed, the list of biofuels with the highest priority could be extended to six different fuel/distribution alternatives. Since hydrogen distribution was considered in both gaseous and liquid form, the list could be reduced to five fuel alternatives. If the target penetration is set to more than 10%, as proposed in section 3.4.1 above, several fuels could meet this target. However, it is likely that the distribution of fuels that are gaseous at normal temperature and pressure will become too expensive to be competitive[15]. The cost of fuel distribution is discussed in more detail below (3.6.8). In some less densely populated countries in Europe, such as the Nordic countries, it is not technically and economically feasible to build a pipeline infrastructure for gaseous fuels that would be able to serve a large proportion of the population. With the restrictions mentioned, the list of main fuel candidates could be reduced to three:

- Methanol
- Ethanol
- FTD

Efficiency

It is of interest to study the w-t-w efficiency for the three fuel candidates, as mentioned above, in somewhat more detail. It is not possible to use all the energy converters for each fuel, so the number of combinations is limited to eight, i.e. FTD is not technically feasible in otto engines.

In **Figure 4**, the relative energy use in a w-t-w perspective is shown for the combinations mentioned. The baseline (index=100) in the chart has been set for the best combination (methanol in a diesel engine hybrid). Only hybrid drivetrains are considered, as the efficiency is higher for these than for drivelines with direct drive. Results from the previously mentioned w-t-w study have been used as input data for the figure [2].

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[15] Another comment of interest to add is that LH_2 in a previous section (**Figure 2**) was classified as a principal fuel. Eventually, this classification was made only according to the potential to distribute the fuel in large quantities. In principle, this could be possible for cryogenic fuels, as well, due to the liquid state. However, if the high distribution cost is taken into consideration, it is much more difficult to reach the widespread use anticipated for principal fuels.

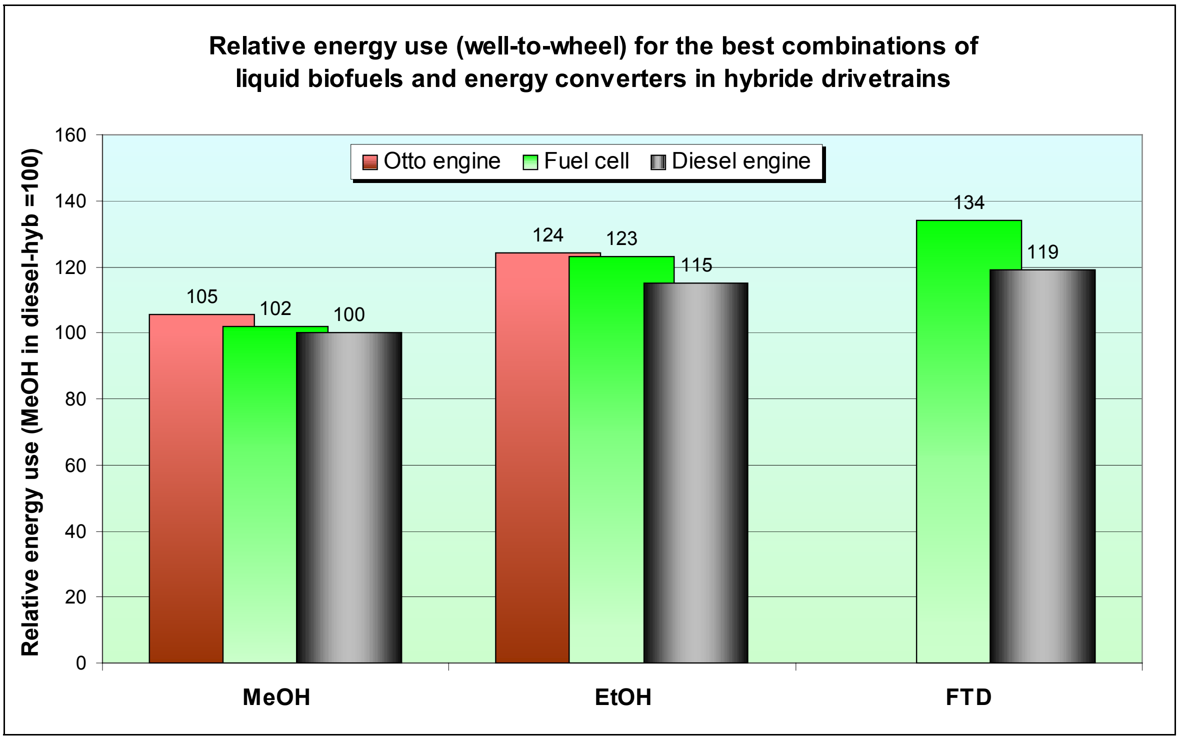

Figure 4. *Well-to-wheel energy use of some liquid biofuels*

As can be seen from **Figure 4**, methanol has the lowest energy use in general of all three energy converters. The relatively small differences between the various energy converters for this fuel are somewhat surprising. The difference between otto and diesel engines is smaller for methanol in comparison with petrol-diesel, since the DI otto engine is anticipated to be optimised for methanol. Thus, the advantages provided by methanol are fully utilised. Another note is that the use of hybrid drivelines reduces the differences between otto and diesel engines, in general. In hybrid systems, the average load is shifted towards higher loads, which reduces the relative difference between these two engines. Methanol reforming causes smaller losses compared to other fuels and therefore, the difference between fuel cells and diesel engines is small in this case.

In general, the energy use for ethanol and FTD is higher than for methanol, regardless of energy converter. An important observation is that *FTD in a diesel engine has a lower energy use than ethanol, both in a fuel cell and in an otto engine*. However, the yield (in energy terms) for FTD *could* be somewhat higher than we had anticipated in our calculations (section 3.2.3). It is also worth noting that the energy use in otto engines would be higher *if* these were not optimised for alcohols. The same conclusions could be drawn for low-blending. Therefore, FTD may not be as "inferior" regarding efficiency on a short-term horizon, as could be anticipated from the results in **Figure 4**. On the long-term, a considerable market penetration is foreseen, and consequently, as high an efficiency as possible is aimed at. **Figure 4**

It could be argued that ethanol would remain a niche fuel, since the energy use and cost will be higher than for methanol. In the short-term ethanol could be used for low-blending, in fuel-flexible vehicles and in dedicated fleets (e.g. buses). The feedstock potential is high enough to make this fuel a principal fuel but other factors might limit the market penetration.

FTD and methanol, being simple to handle and distribute, could become principal fuels. Ethanol could supplement in certain areas but it is difficult to motivate as high priority for this fuel as for the previously mentioned fuels. *With the long-term conditions as the basis for short-term actions, the authors propose that the activities should be concentrated on methanol and FTD.* Furthermore, methanol could be used in low-blending and a similar opportunity is obvious for FTD in diesel fuel. Thus, both fuels have certain fuel flexibility. The aim of introducing biofuels in both types of (contemporary) energy converters (otto and diesel), as well as in light-duty and heavy-duty vehicles could be fulfilled. In our analysis, ethanol has a slightly higher efficiency than FTD when diesel engines are used in both cases. However, as has been pointed out above, this deduction might have to be re-evaluated if the potential improvements in FTD production are realised and consequently, these fuels could be about equal from an efficiency standpoint. In ethanol-fuelled otto engines, the efficiency is lower than in FTD-fuelled diesel engines. When ethanol is used in diesel engines, a similar fuel-flexibility as for FTD cannot be obtained. In comparison with methanol, the lower efficiency for ethanol is decisive for the priority between these fuels.

Potential problems

In this section, some potential problems for the three fuels mentioned above are discussed. Only the aspects dealing with their use as “neat” fuels are covered here. In low-blending and niche applications, some problems disappear but new issues arise. This is covered in separate sections later on.

A much-debated issue concerning methanol is the acute toxicity. This is also valid for the ingestion of petrol and diesel fuel but in these cases, experience from about a century of use has been accumulated. The number of incidents with petrol and diesel is low. The acute toxicity of methanol is somewhat higher than for petrol and in addition, methanol could be mistaken for ethanol. Methanol is used in model engines and in racing vehicles but this could hardly be considered as a general use. In northern America, methanol is used as an anti-freeze for windshield washer fluid, whereas isopropanol is mostly used in northern Europe. It is evident that methanol can be handled in this application in northern America without significant fatalities.

In a potential large-scale introduction of methanol as a motor fuel, some precautions must be taken to avoid intentional or unintentional misuse of methanol. A Swedish company of fuel dispensers, Identic, is currently developing a new spill-free and safe dispensing system for methanol refuelling for the Methanol Fuel Cell Alliance (MFCA) [23, 24]. A prototype system has been installed in the Necar 5 fuel cell prototype car by DaimlerChrysler.

In contrast to the acute toxicity, the health and environmental impact from fuel spill could be significantly lower for methanol than for petrol and diesel fuel. Methanol is ubiquitous (naturally present) in the environment due to various biological processes in plants, micro-organisms and animals. Consequently, the biodegradation of methanol is generally faster than for fuels of crude oil origin, as these substances are not naturally present in the nature.

For the use of methanol in otto and diesel engines, denature, bitterant, odorant and flame visibility additives are available. The engines are compatible with these additives. However, the fuel reformer used in fuel cells is very sensitive to such additives[16]. In a recent study by Xcellsis, a couple of issues have been identified [25]. Many of the additives under

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[16] It could be possible to develop reformers (of a similar kind as for petrol) that are not sensitive to additives but then the advantage of high reforming efficiency for methanol in comparison to other fuels would be lost.

discussion for conventional engines have been shown to degrade the catalyst in the fuel reformer within a very short timeframe in laboratory tests. Therefore, it is important to determine whether additives are necessary and if there are ways to solve the problems mentioned. Contamination (e.g. by other fuels) in the fuel distribution chain might also be an issue.

The acute toxicity of ethanol is significantly lower than for methanol. Ethanol is present in beverages and is used (or misused) for intoxication. Additives are necessary to avoid the neat ethanol fuel being used for this purpose. As ethanol is used as a beverage, this need is even more evident than for methanol. Again, the problem for fuel cell reformers is somewhat similar as for methanol.

The potential problems with FTD are few. Initially, the preferred use of FTD would be for blending in diesel fuel and in this case, no specific problems are expected. For the use of neat FTD, a compromise between specific energy content (related to density[17]) and cold flow properties must be made. It is likely that a somewhat lower energy content has to be accepted, and this will result in lower engine power, unless a certain fuel flexibility in future engines could be foreseen. A fuel specification for FTD must be adopted in EU. Some problems with material compatibility (polymers and elastomers) could be expected with neat FTD. However, there are materials available to handle this issue in new vehicles and new fuel infrastructure. The (potential) impact on old equipment should be assessed.

3.5 Niche programs for improved local air quality

3.5.1 Preconditions

The rationale of initiatives involving niche fuels would primarily be to improve local air quality. If these fuels are less cost-effective than other solutions, there must be other objectives to justify investment in niche fuels. In those cases, when such fuels could be introduced “on their own merits”, there are no reasons for specific incentives. However, this is not the case for any known alternative fuel today. Instead, the problem is that the incremental costs are very high and other incentives than CO_2 tax would have to be identified to justify investments for these fuels. Some, but far from all, objectives are:

- Local air quality and (in some cases) reduced noise
- The fuel could be part of a greater, and more comprehensive, introduction strategy
- Research and development
- Political objectives

Local air quality

Local air quality is often referred to as a rationale for introducing alternative fuels. Without doubt, this was the case in the past, since the alternative fuels usually had significantly lower emissions that the conventional fuels, such as petrol and diesel fuel. However, the development has now reached a state that, provided that the best available technology is used (BAT), the difference in comparison to the best alternative fuels is small. Even if the

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[17] A typical density of FTD could be 780 kg/m^3 or less. This is significantly lower than the level of 820-840 kg/m^3 that is under discussion for future “clean” diesel fuels.

relative difference remains, the absolute difference in societal value of the emission reduction will be relatively small in economical terms. For example, if the societal cost of NO_X emissions for a Euro IV car (0,08 g/km) is 8 € per kg, the cost in one year (yearly driving range of 15 000 km) amounts to only 9,6 €. Future emission reductions would further reduce this cost to an almost negligible level. Larger differences could be expected for heavy-duty vehicles but also in this case, the cost will be drastically reduced in the future.

Noise

Some fuels could reduce the noise emissions and this is often considered as a significant advantage in densely populated areas. However, the noise emissions could also be reduced for conventional fuels if this is desired, and in many cases (e.g. for passenger cars), this is also a customer preference. In practice, the advantage of the alternative fuels is often simply a lower cost for sound insulation in comparison to conventional fuels. At higher speed (e.g. on rural roads and motorways), it is tyre noise, which is dominant. Consequently, the difference between various fuels is marginal in these cases.

Future introduction strategy

The use of niche vehicles could be part of a future introduction strategy. Since no such strategy has yet been defined in the EU or on a member state level, it is difficult to identify possible initiatives involving niche solutions based on this position. However, this could change in the future, on the condition that the mentioned strategy is developed.

Research and development

Another objective for alternative fuels in short-term niche applications would be to stimulate technical research and development to enable the alternative fuels to develop at the same pace as petrol and diesel fuel. This work will generate knowledge that could be used as the basis for decisions on future large-scale introduction. The cost of these activities could be characterised as “life insurance premium”. The side effect would (presumably) be an improved air quality – albeit at a higher cost than more cost-effective solutions for conventional (fossil) fuels.

Political objectives

It is impossible to avoid the so-called “political” motives being part of the picture when activities regarding alternative fuels are discussed. Different political parties represent various different groups in the society (e.g. farmers, oil industry, etc.) and consequently, the position of the politicians is influenced in such matters. The popularity of a particular alternative fuel tends to change as fast as the support for a certain politician or a party. Considerations are influenced by industry positions as a certain decision could have a substantial influence on various branches of the industry. Lobbying is frequent in such cases.

Strategy for niche fuels

Among the various motives for activities related to niche solutions according to the list above, the authors recommend the three first objectives are considered as main objectives and that the activities must be motivated from these standpoints.

Some of the fuels that could be of interest for niche programmes are:

- Natural gas and biogas
- FTD and DME from synthesis gas

- Electric vehicles

Regarding activities on niche fuels, there are reasons to stress that a consensus between the interests of the society, vehicle manufacturers and fuel producers and distributors is essential. It is of great importance that these stakeholders could reach a common position regarding the main priorities on these issues.

3.5.2 Natural gas and biogas

The main objective for using natural gas and biogas is local air quality. Biogas is indeed a biofuel but as such, it is much simpler to use in other sectors than the transport sector. Furthermore, the efficiency in these other applications is higher and consequently, the reduction of the climate gases will be greater than in the transport sector. Natural gas has in some cases (otto engines) lower emissions of climate gases (about 20%) than other fossil fuels (petrol), but the substitution in other sectors might be at least as beneficial regarding emissions of climate gases. As previously pointed out, gaseous fuels are not particularly well suited for a large-scale introduction in the near future, and therefore, these fuels could only be a small part of an introduction strategy. In the biogas case, there are also limitations regarding the (commercially attractive) feedstock. Since air quality is the remaining main (potential) advantage for biogas, stricter emission levels than the EU “base level“ should also be used in procurements in this area. For example, Euro IV could be used instead of Euro III.

3.5.3 FTD

FTD could be blended in diesel fuel today, but it could also be used as a neat fuel. The lower energy content of FTD in comparison to conventional diesel fuel, implies that the engine power is reduced somewhat. If a high energy content is desirable, the cold start flow properties have to be compromised. In dedicated vehicle fleets, a lower energy content is not a significant problem, since the engines could be optimised for the fuel. If the vehicles also have to use conventional diesel fuel an adaptive control must be used, or else lower power when using FTD must be accepted.

As mentioned above, FTD has some emission advantages regarding NO_X and particulate emissions. When EGR is used, this advantage could be utilised to further reduce NO_X emissions further since particulate formation is lower than for conventional diesel fuel. When significantly lower emissions are the aim, aftertreatment for both NO_X and particulate emissions is necessary. Since FTD is virtually sulphur free, the use of such devices is enabled. However, since conventional diesel fuel is improving in this aspect (<10 ppm S), as in future EU regulations, the advantage of FTD is diminishing. Presumably, FTD (possibly with altered composition[18]) could enable the development of new combustion systems. Regarding emission components that pose health hazards, FTD should be significantly better than European diesel fuel but the difference compared to Swedish environmental class 1 diesel fuel is likely to be marginal.

Summarising, FTD has several advantages regarding exhaust emissions but these advantages are not decisive when compared to ultra-low sulphur diesel fuel. In spite of that, the authors suggest that the preconditions for using FTD in dedicated fleets should be investi-

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[18] For example, FTD emission properties could be improved by using oxygenated additives, such as e.g. heavy ethers.

gated. The main reason is that there are relatively few experiences from the use of this fuel. Furthermore, FTD is commercially available on the market, although it is presently only produced from fossil resources. It is also reasonable to anticipate that the use of FTD is combined with the use of new emission control technologies to achieve lower emissions than with “sulphur-free” diesel fuel (such as the Swedish environmental class 1 fuel).

3.5.4 DME

DME has a greater emission potential than FTD and it has a significantly higher well-to-wheel efficiency. DME is cheaper to produce but it is more expensive to distribute and the vehicle cost is increased. Today, there is no field experience from DME-fuelled vehicles and this, in combination with the previously mentioned advantages, is one of the main objectives for introducing niche vehicles on this fuel. The cost of building the fuel infrastructure for DME is likely to be high and since fuel flexibility is not possible, general use is excluded in the near future. However, fuel distribution is much simpler for dedicated fleets and efforts should therefore be concentrated on this area. Since DME was the fuel that had the highest well-to-wheel efficiency in our study, this is also a reason for further investigations in this area. Stakeholders from vehicle and fuel industries must be involved in such project, since DME, as a gaseous fuel necessitate a new fuel infrastructure (contrary to FTD). DME is commercially available on the market but, as for FTD, only fuel of fossil origin is currently produced.

3.5.5 RME

RME is non-toxic and biologically degradable. Accidental spill on land and water pose fewer hazards than petrol and diesel fuel. However, other fuels for diesel engines, e.g. FTD, also have these advantages. One strategy in utilising the mentioned advantages would be to identify the niches where these properties are very crucial and direct the use of RME to these applications.

RME does have a certain advantage regarding CO_2 emissions and the use of fossil energy contrary to many claims. The ratio between output and input of energy is generally in the order of a factor of two to four, depending on the conditions [26]. The use of process energy from straw gives the higher level. Climate gases are reduced by about the same factor as the mentioned energy ratio.

RME has certain advantages and disadvantages regarding exhaust emissions. RME is virtually sulphur-free, but this is already the case for Swedish diesel fuel and such diesel fuel will be introduced in the EU as well. CO and particulate emissions are generally lower than for diesel fuel, although an oxidation catalyst is sometimes needed to achieve this reduction for the particulate emissions. The advantage for particulate emissions is of no significance if a particulate filter is used in both cases. Also the HC emissions are generally lower for RME but this is more or less an impact of the emission sampling than a real effect. RME has a very high boiling point and not every organic compound in the exhaust can be measured, since they are trapped in the sampling system.

NO_X emissions are generally higher for RME than for diesel fuel, although some experts claim that these emissions could be lowered by using an optimised engine [27]. It is of interest to analyse this issue in somewhat more detail. For injection pumps with no closed loop control of the injection timing, the dynamic injection timing is more advanced with RME, due to the higher viscosity. A compensation of this advance could be made by retarding the static injection timing. The increase in NO_X emissions with RME for modern engines appears to be relatively small due to the control of the injection event. It is often claimed that the NO_X emissions could be reduced in comparison to diesel fuel by further retarding the injection timing. The disadvantage of retarded injection is higher fuel consumption. Furthermore, the injection event is already so late in modern engines that there is virtually no room for any further retardation. Likewise, RME does not have a higher cetane number than diesel fuel that could enable this adjustment. It thus seems that it would be difficult to achieve any reductions in NO_X emissions with RME compared to diesel fuel.

In the future, it could be possible to reduce the NO_X emissions with RME if the potential to increase the EGR rate, due to the lower particulate emissions[19], is utilised. However, certain development efforts will be necessary before this potential could be fully utilised.

Summarising, the emission advantages for RME are relatively small. In addition, the lower ratio of energy output in comparison to that of the best biofuels implies that RME should not have as high a priority as the best options. Furthermore, it should be noted that the environmental impact (use of herbicides, pesticides, fertilisers, etc.) due to the intensive cultivation is much greater that for the fuels produced from feedstocks using less intensive cultivation.

3.5.6 Alcohols

In the opinion of the authors, the best use of alcohols today would be blending in petrol and the use of fuel flexible vehicles (which is actually also a form of blending).

The interest from the industry for the use of alcohols in heavy-duty vehicles has been small. The Swedish manufacturer Scania is the only manufacturer that has supplied any great number of vehicles during the last 10 years. However, Scania has now announced that they will discontinue the production of ethanol engines. The significantly lower emissions achieved by utilising exhaust aftertreatment (particulate filter) and EGR on diesel-fuelled engines has probably also had some influence on customer preferences. Since methanol was phased out in California, the use of methanol has not been of interest in USA in recent years.

A similar relationship as for the heavy-duty vehicles is also seen for the light-duty vehicles. Ford Focus Flexifuel, which can run on blends from neat petrol to E85, is the only exception from this rule in Europe. About 4000 of these vehicles are now introduced in Sweden. Some other fuel flexible vehicles are available in the USA but the European car manufacturers have been very hesitant regarding the use of alcohols in light-duty vehicles. Some manufacturers advocate the use of methanol in fuel cell vehicles. However, it will be many years until fuel cells can be introduced on a larger scale. The problem is to bridge over the gap before fuel cells are of interest. Introducing alcohols first as a blending component in petrol and later in fuel flexible vehicles could be one way of starting to build the fuel infrastructure.

Summarising, the present interest in using alcohols is very low in Europe, apart from their use in fuel flexible vehicles in Sweden. Therefore, any specific activities to introduce vehicles fuelled by neat alcohols cannot be recommended in the near future. Instead, the re-

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[19] Note that the particulate emissions before a particulate filter are referred to in this case. Lower in-cylinder particulate emissions enable the use of higher EGR rates, and this is the cause for the (potential) reductions of NO_X emissions.

sources should be concentrated on long-term research and development efforts on dedicated engines for these fuels.

Regarding ethanol production, it should also be added, that any greater activities on ethanol production from grain or other agriculture products cannot be recommended. The low crop yield and the relatively low output ratio of energy imply that there are better alternatives, which should receive a higher priority.

3.5.7 Electric vehicles

Electricity has a very low tax as a “fuel” today in comparison to conventional fossil fuels and this is also valid in the case of the proposal for (long-term) taxation of alternative fuels now under discussion in the EU. Therefore, it is somewhat difficult to justify further economic incentives for electric vehicles. Field tests have been carried out in several of the member states in the EU during the last decade. The cost of electric cars is still high and the problems with short range and slow charging are far from being solved. In addition, the emission advantage will be considerably reduced in the future. If the energy losses in the production of electricity are taken into account, the well-to-wheel efficiency is not significantly higher than for the best alternatives with combustion engines. In certain niche applications, initiatives for the use of electric vehicles could be justified. These applications should be identified. In view of this background, electric vehicles could not be written off completely.

3.6 Cost

Contrary to petrol and diesel fuel, the data available for assessing the cost for the alternative fuels is significantly less. For example, no verified cost for the production of biofuels from lignocellulosic matter – the non-fossil feedstock considered to have the greatest potential – are unknown, as no such production exist today. The cost in these cases can only be estimated from engineering studies that have been conducted. Note that the cost referred to in this section is without taxes and VAT.

3.6.1 Bioethanol

Ethanol from grain

In order to sell ethanol from grain in Sweden, a complete tax exemption, i.e. about 50 €c/l[20], plus VAT, is necessary. This indicates a cost of over 65 €c/l (6 SEK/l). The main reason is the high cost of the feedstock (up to 3,3 €c/kWh), which, if a high credit contribution from feedstock cannot be received, gives a high cost for the ethanol produced. Furthermore, current plants are relatively small, which is also a contributing factor to the high cost.

Ethanol from cellulosic feedstock

The Swedish organisation for alcohol development, BAFF, refers to a cost for ethanol from cellulosic matter for the years 2000 and 2010 respectively to an interval of 41 – 34 €c/l (63 – 51 €c/l in petrol equivalents). This is based on a feedstock cost of 0,87 €c/kWh (DS), 9,5% annuity and contribution from solid fuel by-products. (At the same feedstock cost

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[20] The cost in € has been calculated on an exchange rate of SEK 9,2 per €.

and annuity that has been used for biomethanol below, the interval would be 0,50 – 0,41 €c/l ethanol (0,75 – 0,62 €c/l in petrol equivalent.) The production plant would be created as a combined ethanol plant (with solid fuel as the main product) and a combined power and heating plant. The products would be ethanol, electricity and hot water for district heating with internal trade of solid fuel and by-products between the parts of the plant (a somewhat questionable way to assess the future large-scale production cost of ethanol). The ethanol yield is in energy terms (TS-LHV) only 19% of the feedstock input.

BAFF refer to a study by NREL, a national laboratory under the Department of Energy (DOE), which estimated the cost in 2000 of about 30€c/l ethanol, based on a significantly lower feedstock cost and a several times larger plant [15]. In addition, the yield was much higher but the contribution from by-products (electricity) was very small. Furthermore, an extrapolation to 2010 would give the considerable cost reductions of 17€c/l, due to process and plant development that seems to be totally unrealistic based on European conditions. A specific analysis of this report and an adaptation of the results to Swedish conditions have been carried out by Ecotraffic. The assessment for a self-supported and fully developed plant resulted in an ethanol yield of 43% (LHV-base) and about 45% when the electricity surplus was included. BAFF has used the same report in their cost estimates.

Similar data (same cost per energy unit) as for ethanol has been stated for methanol produced by gasification of biomass but, according to the opinion of the authors, this is based on the use of totally unrealistic technology.

3.6.2 Biomethanol

Biomethanol through gasification has, in the Swedish engineering studies, yielded a cost of up to 27 €c/l (about 55 €c/l petrol equivalent) at a feedstock cost of 1,1 €c/kWh and 12% annuity. This was without compensation for by-products (district heating, potentially dried solid fuel, as well). How far the compensation and potential future cost reduction by learning could reduce the cost has not been discussed in detail. Perhaps about 22 €c/l could be achievable on a long-term horizon.

As a comparison, it could be mentioned that methanol produced from natural gas has a typical price of about 150 €/ton (about 11€c/l or about 22 €c/l petrol equivalent) in Rotterdam. Depending on market supply and demand, the price has generally been in the range of 100 – 200 €/ton[21]. The EU has 0 – 7% import duty on methanol depending on origin (in contrast to the situation for petrol, where no duty is applied!).

3.6.3 Bio-DME

The cost of DME produced from natural gas should, according to the engineering company Haldor Topsøe in Denmark, be about 5% lower than the cost for methanol from natural gas (about 24€c/l in petrol equivalents). The difference in cost is primary in the synthesis gas stage. Since the cost will generally be higher for both DME and methanol from biomass and the process stages before the synthesis stage are equal, the cost difference in relative numbers will be somewhat lower in this case. This difference in price is at the refinery gate. The advantage for DME is changed to a disadvantage if fuel distribution is taken into

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[21] The list price for the first two quarters of 2002 has been about 112 €/ton but was rising during the third quarter and is now at 208 €/ton.

account. The difference in fuel distribution (and dispensing) is about 3 times higher for DME than the difference in production cost (3.6.8).

3.6.4 Hydrogen from biomass

It is difficult to estimate the production cost for hydrogen from biomass, since the basis regarding engineering studies and cost estimates is significantly less than for DME, methanol and ethanol. Based on the condition that the hydrogen yield is between that of methanol and DME, the cost of hydrogen production should be on the same order of magnitude as for both the other mentioned fuels. The incremental cost for hydrogen distribution is likely to be significantly higher than in the two other cases so that the cost at the refuelling station must also be considerably higher.

3.6.5 Bio-FTD

No well-founded estimate of the production cost for FTD from biomass has yet been found. Based on good engineering practice, it could be concluded that a lower yield than for the other fuels from synthesis gas should also result in a higher cost. Furthermore, the synthesis stage is somewhat more complicated and at the same time, yet another process stage has to be added for the final process of the fuel after the synthesis stage. When the development of the production processes has advanced, it will be interesting to see how the cost for FTD will be in relation to ethanol from cellulosic matter.

3.6.6 RME

It is complicated to estimate the cost of RME production. EU has estimated the incremental cost to about 300 € per m^3 of substituted diesel fuel. The average price of Swedish environmental class 1 diesel fuel at the pump was, according to statistics from the branch organisation SPI, 92 €c/l in 2001. The production price was 42 €c/l and the rest was attributable to distribution cost (incl. profit), taxes and VAT. However, these data have been collected without taking normal rebates into account, and in addition, large customers receive significantly greater discounts than private car owners do. Likewise, customers with their own tanks and dispensers receive even higher discounts. It should also be noted that the Swedish EC1 fuel is “cleaner” and more expensive than future ultra-low sulphur (<10 ppm) diesel fuel in the EU. Furthermore, the very small market for diesel cars in Sweden has also an impact on the diesel fuel price for private customers. In comparison, the average diesel fuel price in Rotterdam was about 22 €c in 2001. An incremental cost of 33 €c/l for RME should give a production cost of over 65 €c/l, even taking rebates into account. In large-scale RME distribution, the distribution cost would hardly be higher than for diesel fuel. A problem in the estimation of the production cost for RME is that neither subsidies nor taxes in agriculture are taken into account.

Re-esterification of rapeseed oil is a relatively simple process that is also rather cheap and therefore, a major share of the cost can be attributed to the production of the rapeseed feedstock. This condition, together with the problems in taking subsidies and taxation in production into account, makes the estimate of the RME price very difficult. Presumably, the real cost could be even higher than the estimate above. Thus, RME would be one of the most expensive biofuels. An in-depth study of the production cost of RME should be carried out before decisions on large-scale investments in this fuel are made.

3.6.7 Comparison with conventional fossil fuels

The cost for methanol and ethanol should be compared with typical data of about 22 €c/l for petrol (average in 2001) at the refinery gate or import harbour (Rotterdam price). The variations were great, since the highest level was 30 €c/l in May and the lowest was 15 €c/l in December. The corresponding average price for diesel fuel was at a similar level but with lower variations. Thus, the diesel fuel price was lower in energy terms.

Fuel distribution cost and taxes increase the price for the average customer considerably. It is also notable that current taxes in the member states vary considerably. The only reasonable universal fuel tax would be to use the energy content as the basis. Differentiation from that level should take emission properties and fuel origin (fossil or non-fossil) into account.

In view of the target for maximum incremental cost proposed by SNRA of 22 €c/l petrol equivalent, a petrol price in Rotterdam of 22 €c/l would necessitate a petrol-equivalent production cost of 22 €c/l. This happens to be the projected future (after 2010) cost for methanol; the fuel with the lowest total cost as distributed product. Assuming that the engine efficiency could be raised, the target cost could be met with a small margin although the distribution cost is higher for methanol than for petrol. Other fuels are more expensive but could come reasonably close to the target, in particular if an efficiency gain in the engine is foreseen.

The conclusion of the discussion above is that a relatively high level of carbon tax corresponding to 22 €c/l of petrol could possibly be met on a long-term horizon for methanol from biomass. Other fuels could come relatively close to this target.

3.6.8 Fuel infrastructure cost

Previously, the production cost for various fuels has been discussed. The fuel distribution cost is also a very important issue. In two reports for the Swedish Governmental Authority KFB (now called Vinnova), the distribution of motor alcohols [28] and DME [29] was investigated by Ecotraffic. Petrol and diesel fuel were also part of these studies. Petrol was the basis for the comparison with the alcohol fuels in the first study, while diesel fuel and DME were compared in the second study. In order to be able to compare all the fuels, a recalculation of the cost of diesel fuel and RME in the two mentioned studies has been carried out as a substitution for petrol instead of diesel fuel. Since the first study was completed in 1996 and the second in 1997, the cost was representative for the situation in the mid 1990's. Presumably, the cost would be somewhat higher today, primarily due to inflation. It should also be noted that the cost was estimated for fully developed systems. For rebuilds of old petrol stations and during an initial phase, the cost will most likely be higher but on the other hand, such cost is not relevant on a long-term horizon. All cost that is independent of volume has been set similar to petrol.

The results from the mentioned study are shown in **Table 5** but in Euro (€) compared to Swedish crowns (SEK) in the original calculation. The conversion factor from SEK to Euro has been set to 10, i.e. somewhat higher than the exchange rate, to take some inflation into consideration.

Table 5. *Fuel distribution cost for some selected fuels. Calculated as substitution for petrol (€c per litre petrol equivalent of substituted petrol)*

Distribution stage	Petrol	Diesel	Methanol	Ethanol	DME
Volume dependent					
Sea transport	0,60	0,55	1,10	8,50	1,64
Land transport	0,70	0,64	1,30	1,00	2,00
Partly volume dependent					
Storage, handling at depot	0,70[a]	0,64[a]	1,70	1,60	1,46[b]
Storage at station	2,0	1,82	2,70	2,35	5,00
Not volume dependent					
Distributor	2,00	2,00	2,00	2,00	2,00
Refuelling station	2,50	2,50	2,50	2,50	2,50
Total cost	***8,50***	***8,14***	***11,30***	***10,30***	***14,60***

Notes:

[a] About 0,3 €c per litre of this cost is capital cost for storage value.

[b] About 0,5 €c per litre of this cost is capital cost for storage value.

As can be noted in **Table 5**, the distribution cost for substituting one litre of petrol is 11,3 €c for methanol and 10,3 €c for ethanol, i.e. an advantage of 1 €c for ethanol. As reference, the cost of distributing petrol was estimated to 8,5 €c per litre. Consequently, the incremental cost of distributing methanol is 2,8 €c per litre petrol substituted. If the fact that the engine efficiency can be increased by using methanol in comparison to petrol is taken into account, the incremental cost should decrease marginally. A methanol engine would have to utilise direct injection, or else be converted to diesel cycle, to achieve an increase in (relative) efficiency. In the best case, this could offset the increase in distribution cost. On the other hand, in comparison with diesel fuel, methanol offers no efficiency benefits.

The incremental cost of replacing petrol (or diesel fuel) by DME is significantly higher than for methanol simply because DME has to be handled under pressure. Since DME is primary a fuel for diesel engines, the comparison was initially made with diesel fuel [29]. However, as the previous figures for motor alcohols were compared with petrol, the results in the mentioned report have been recalculated for a substitution of petrol (using the conversion factor of 10 between € and SEK). The recalculation gives a cost of 14,6 €c per litre of substituted petrol, i.e. a difference of 6,1 €c. This is more than 3 €c higher than for methanol and more than twice the difference between methanol and petrol. As diesel engines are more efficient than otto engines, the comparison with petrol would be more favourable if this was taken into account. The comparison with methanol depends on whether the methanol engine is of the otto or diesel type. As discussed above, diesel engines can also be adapted to methanol.

If DME is compared with diesel fuel, the difference (6,5 €c) is somewhat higher than in the comparison with petrol. The greater difference in this case is due to the higher energy content of diesel fuel in comparison to petrol. This give a lower distribution cost per energy unit for diesel fuel compared to petrol and therefore, the comparison between DME is less favourable for DME than the previous comparison with petrol.

3.6.9 Total cost

Based on the cost for fuel production and distribution, as discussed in previous sections, the total cost for the fuels to the vehicle tank (well-to-tank cost) can be estimated. It should be noted that the basis for the calculations varies and therefore, there are many uncertainties in several of the estimations. Some fuels are produced today, which implies that the knowledge about the cost in these cases is relatively comprehensive. The cost for other fuels or the calculated future costs have some smaller or larger uncertainties, depending on the available input data. Therefore, comments regarding the estimations listed in **Table 6** below have been added to show data and methodology used (actual cost, engineering studies or rough estimates). A somewhat more prudent timetable than indicated in the engineering studies has been anticipated (e.g. 2020) to allow new technology to mature[22].

Table 6. *Estimations of pump price (without taxes and VAT) for some biofuels*

Cost of some biofuels (incl. distribution, excl. tax)	**Time-frame**	**Prod. price** €c/l	**Price, distributed product[a]**		
			€c/l pet. equiv.	€c/l die. equiv.	**Notes**
Petrol	2001	21,7	31,0		Avg. cost 2001
Diesel fuel	2001	21,7		30,9[a]	Avg. cost 2001
Ethanol, grain	2000	65	109		Actual cost
Ethanol, cellulosic matter	2010	50	86		Eng. studies.
	2020	41	73		Eng. studies.
Methanol, natural gas	2000	12	37		Actual cost
Methanol, bio-syn	2010	27	67		Eng. studies.
	2020	22	57		Eng. studies.
FTD, bio-syn	2010			83	Rough estimate
	2020			68	Rough estimate
DME, natural gas	2000			46	Eng. studies.
DME, bio-syn	2010			75	Eng. studies.
	2020			63	Eng. studies.
RME	2000	65		80	Actual cost
Hydrogen		?			Diff. to estimate

Notes:

[a] The price comparison has been carried out for two different cases, the first as a substitution for petrol and the second as a substitution for diesel fuel. Since the energy content differs between petrol and diesel, the two columns cannot be directly compared.

[b] The price of the distribution of diesel fuel has been carried out for private customers and for large-scale use in passenger cars. This is valid only for countries with relatively high share of

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[22] It is assumed that a number of plants have to be erected before the cost advantage of new technology can be fully utilised.

diesel cars (i.e. the assumptions are not valid for Sweden with the present penetration of diesel cars).

[c] The cost for hydrogen has not been estimated. The primary reason is that the assessment of the costs for fuel distribution and storage has been very difficult.

First, it should be noted that the cost estimates for the biofuels in **Table 6** do not consider (possible) utilisation of waste heat. If this is taken into account – and if heat sinks (e.g. district heating) are available – the cost of some of the fuel options could be somewhat reduced. It is notable that the efficiency in several cases would also increase for these options in that case.

The basis for the estimation of the production cost for FTD is small, which implies that a cost in proportion to the lower yield in comparison to methanol has been anticipated. An analogous estimate based on the calculated cost for DME gives a similar figure.

In spite of the higher distribution cost for DME in comparison to liquid fuels, the cost is still lower than for FTD. This might be considered a remarkable finding but is due to the fact that the production cost for DME will be significantly lower than for FTD.

The production cost of RME is difficult to estimate due to sizeable subsidies at the feedstock production stage. A distribution cost of the same magnitude as for diesel fuel has been used but with a compensation for the lower energy content. A large-scale distribution would be a necessary presumption for this methodology. Due to the constraints mentioned, the listed cost has to be considered somewhat unreliable.

3.7 Proposed strategy

3.7.1 Present use of biofuels

The EU Commission has identified only six countries that make a real contribution to the biofuels production in Europe. These countries are France, Austria, Germany, Sweden, Italy and Spain. A rough calculation by the authors indicates that up to 0,6 TWh of biofuels will be used in Sweden in 2002. Most of this volume is ethanol and some the ethanol is imported. The use of petrol and diesel fuel in 2001 was 83 TWh. The biofuel use amounts to about 0,7% of the use of petrol and diesel fuel. A similar share was indicated for France in 1999 by the EU Commission [1]. As the current use of biofuel appears to be lower in most member states, meeting the proposed target of 2% in 2005 seems to be a difficult task.

3.7.2 Summary of fuel assessments

A simplified way of presenting the results and recommendations in the previous sections is to grade and summarise the findings in Tables. An important condition is that the strategy proposed should have a long-term main priority but also include a short-term action program in line with the mentioned priority. Three important factors to note are: Possibilities for low-blending, which could provide large volumes on a short-term for a small incremental cost in the fuel distribution. The long-term goal to introduce biomass-derived principal fuels is the most important criterion. In areas with poor air quality, niche programs could be of interest on a short and medium term. Such activities could give a possibility to gain knowledge about new fuels (e.g. DME) that have not been tested before under real operating conditions.

Two matrices of the type mentioned above have been prepared; one for petrol substitution and one for diesel substitution. The matrices are shown in **Table 7** (petrol substitution) and **Table 8** (diesel fuel substitution). It could be noted that most of the assessments refer to the biomass-based alternatives of each fuel. However, the opportunity to use both fossil and non-fossil feedstock is seen as an advantage. As reference in each case, petrol and diesel fuel are shown respectively. The grade has been set from 0 (impossible, in principle) to 5 (best). The columns to the right refer to virtually "sulphur-free" petrol and diesel fuel (ULSD[23]) qualities.

Table 7. *Summary of conclusions regarding use of biofuels as petrol substitution*

	Petrol subst.	**Ethanol**	**Methanol**	**Methane**	**H_2**	**Petrol**
Intro-duction	Bio & fossil	No	Yes	Yes	Yes	-
	Fuel infrastr	4	4	2	0	5
	Low-blending	5	3	▨ [a]	▨	▨
Future	Dedic. engine	5	5	5	4	4
	Emissions	3	3	4	-	2
	Efficiency	3	4	4	3	5
	FC fuel	2	3	1	5	1
Economy	Volume 2005	1	0	1	0	5
	Volume 2020	2	3	1	2	5
	Price 2005	1	▨	1	▨	5
	Price 2020	2	3	1	1-2	4
Critical factor		Process technology	Synthesis gas production	Fuel distribution	Fuel distribution	Finite resource
Assessment		Dev. of cellulosic prod. Principal fuel (FFV)	Syngas production Principal fuel (FFV)	Niche fuel Dual-fuel vehicles[c]	Future fuel DFV[c] difficult	Should be phased out on long term

Notes:

[a] A crosshatched box indicate an impossible combination.

[b] Hydrogen in fuel cells gives zero emissions (which should give grade 5) but NO_X formation in otto engines is a potential problem, although not investigated in detail.

[c] Dual Fuel Vehicle (DFV), an engine that could run on two fuels

When all the factors have been taken into account for fuels intended for petrol substitution (**Table 7**), ethanol and methanol appear to be the primary fuel candidates, with a small advantage for methanol. The alcohols could be used in low-blending, which could enable the use of large quantities rapidly. Fuel-flexible vehicles running on alcohol fuels can be developed and produced at a very small incremental cost. The incremental cost for fuel dis-

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[23] ULSD: Ultra-Low Sulphur Diesel fuel.

tribution is also manageable. Gaseous fuels have too many drawbacks to be used as main fuel candidates for principal fuels. These fuels are better suited for niche applications and one goal could be to identify these niches.

Table 8. *Summary of conclusions regarding use of biofuels as diesel fuel substitution*

	Diesel subst.	**Ethanol**	**Methanol**	**DME**	**FTD**	**RME**	**H_2**	**Methane**	**ULSD**
Intro-duction	Bio & fossil	No	Yes	Yes	Yes	No	Yes	Yes	-
	Fuel infrastr.	4	4	2	5(4)	5	0	0	5
	Low-blending	1	1	▨[a]	5	5	▨	▨	▨
Future	Dedic. engine	2-4[b]	2-5[b]	5	4	3	1-2	2	3
	Emissions	4	4-5	5	4	3	?	4-5	3
	Efficiency	3	4	4	3	2	?	4	5
	FC fuel	2	3	3	1	0-1	5	0-1	0-1
Economy	Volume 2005	1	0	1	1	1	0	1	5
	Volume 2020	2	3	2	3	1	2	1	5
	Price 2005	1	▨	▨	▨	1	▨	1	5
	Price 2020	2	3	3	2	1	3	1	4
Critical factor		Process technology	Synthesis gas production			Feed-stock avail-ability	Fuel distribu-tion	Fuel distribu-tion	Finite resource
Assessment		Develop-ment of cellulosic production	Development of synthesis gas production processes	Growing niche	Principal fuel	No high priority	Future fuel	Niche fuel	Should be phased out on long term

Notes:

[a] A crosshatched box indicate an impossible combination.

[b] The large interval for alcohols indicates that a dedicated diesel engine is necessary. Similarly, the alcohols have better properties than diesel fuel, such as lower soot and NO_X formation and that gives a higher rank. However, ethanol with EGR has had such high particulate emissions that particulate filters could hardly be avoided in the future. Since methanol is better in this respect, the upper interval for the ranking has been set as high as 5.

DME and FTD are better adapted for diesel engines and therefore, these two fuel candidates are primary options for diesel fuel substitution (**Table 8**). DME is the "superior" fuel of the two but it is more difficult to distribute and cannot be used for low-blending. In spite of other advantages, DME is likely to be considered a niche fuel for the near future. The alcohols could be used as diesel fuel substitute on the condition that engines are developed for these fuels. Drawbacks such as difficulties in utilising the fuels in low-blending in diesel fuel and the lack of fuel flexibility imply that these fuels, in most cases, will have problems to compete with other fuel candidates in the near future. Since the interest to develop dedicated diesel engines that can run on alcohol fuel has been low on an international level, these fuels are not considered for large-scale diesel fuel substitution in the near future. RME and the gaseous fuels are likely to be destined for niche applications for a long time.

3.7.3 Program for the development of fuels from synthesis gas

First, it should be noted that the feedstock base for fuels from synthesis gas is the broadest base among all fuels. Hydrogen is the most versatile of the four main fuels from synthesis gas in the respect that the resource base is greater than the other fuels. Hydrogen can be produced from electricity via electrolysis. However, this is not the whole story. The possible role of hydrogen in fuel production and use should be commented on in more detail. In **Figure 5**, the pathways for hydrogen and biofuels produced from synthesis gas is shown schematically[24].

In the synthesis process, a certain ratio of H_2 and CO is necessary. Since biomass has relatively low hydrogen content, a water-gas shift is essential. However, if hydrogen were readily available, it could be introduced before the synthesis step[25]. The efficiency increases when the shift reaction is reduced or eliminated. If CO_2 is available from some source (industry, air, etc.) more hydrogen could be "absorbed". As can be seen in **Figure 5**, a "detour" by using hydrogen directly is also possible. Due to the obvious problems with hydrogen infrastructure, the use of hydrogen (if available from renewable resources) as a source for the production of fuels from synthesis gas could be an alternative in the near and mid-term future.

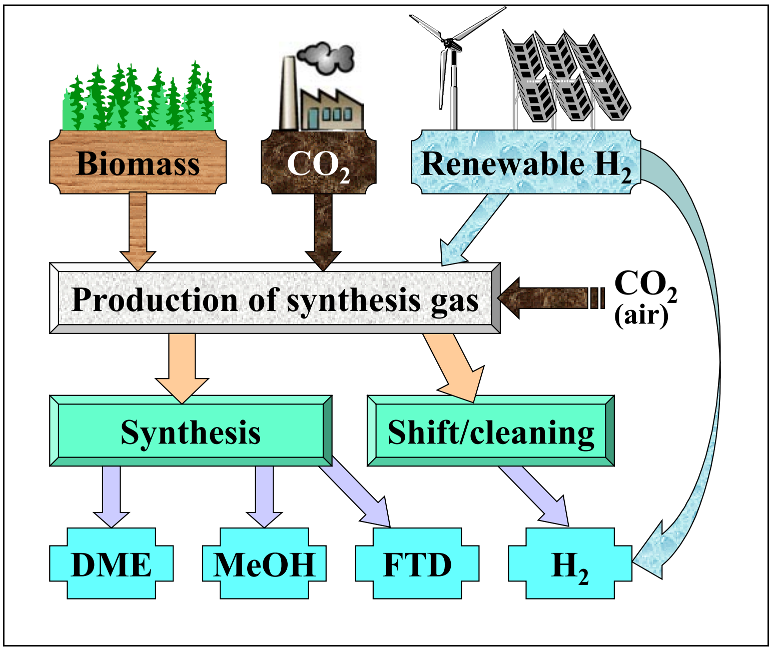

Figure 5. Production of fuels from synthesis gas

The gasifier should be an oxygen/steam driven pressurised gasifier of fluid-bed type and the plant should be equipped with pre-treatment of the feedstock and have primary raw gas cleaning. Ideally, the demonstration plant should be located near a pulp and paper plant having immediate access to feedstock, infrastructure and the possibility to export purified gas as a fuel. At a later stage, the plant could be fitted with more trains and units for conditioning the gas to synthesis gas, synthesis stage and final cleaning of the resulting product. Since no preparations have yet been made for this development, a principal decision should be taken before the end of this year to enable the preparation of the first phase before 2006.

Regarding new fuel components for petrol and diesel fuels and new neat fuels from other feedstock resources than crude oil, it is apparent that the pathway of utilising biomass and synthesis gas seems to be an option that could be further developed. With the knowledge

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[24] Nuclear energy and exotic energy sources have not been considered.

[25] It is notable that the demand for hydrogen in crude oil refineries is likely to increase in the future, as hydrocracking, desulphurisation and hydrogenation will increase. This is primarily due to the increasing demand for "clean" fuels and an increasing share of diesel fuel and aviation fuel. The use of renewable hydrogen in this application could also be plausible.

base available and previous research and development carried out in the Nordic countries, development and demonstration of the gasification stage in relatively large scale should be initiated as soon as possible. A recently initiated co-operation in Germany between Choren Industries, Volkswagen and DaimlerChrysler aiming at the development of production of methanol and FTD from biomass should also be mentioned [30]. Currently, a plant in Schwarze Pumpe in eastern Germany produces methanol from waste and part of the feedstock is of biomass origin. Therefore, part of the methanol produced could be classified as a biofuel. The methanol is sold on the world market at world market prices. Although mainly based on low-cost feedstock, this is presumably the cheapest biofuel available on the world market today.

The rationale for such a strong commitment to fuel production from synthesis gas is as proposed here is, of course, that the results from well-to-wheel efficiency studies have shown that this is the most promising route. Furthermore, the usefulness of the products, primarily the liquid fuel options, in all future energy converters is notable.

3.7.4 Ethanol from lignocellulosic matter

It is reasonable that the on-going development of ethanol from lignocellulosic matter should be completed. The pilot plant under construction in Sweden and similar work in the USA are necessary to gain knowledge as the basis for assessing the potential of the hydrolysis route and for the planning of a commercial plant. In order to erect a plant before the end of this decade, a scientific breakthrough is necessary within the next two years. In addition, a fast implementation of these results in a pilot plant is necessary to complete the first commercial plant before the end of this decade.

3.7.5 Ethanol from grain

The question of additional plants for ethanol from grain or other agricultural feedstock is more or less one of principal, i.e. whether annual energy crops from this sector should be used or not. Some w-t-w analyses on ethanol production have shown a very low energy yield factor (output/fossil input), i.e. about 1:1. The use of biomass process energy, as in the Swedish ethanol plant in the city of Norrköping, could facilitate an improvement resulting in a factor of up to 4:1. However, levels as high as 20:1 have been indicated for biofuels from lignocellulosic feedstock[26] [2]. An increased focus on these options is recommended. From an economical standpoint, the conditions for ethanol from grain are at best as long as the protein fodder by-product can find a market as a substitute for imported protein. This would limit the additional number of plants in Sweden to about two.

3.7.6 RME

The same conclusions as for ethanol from grain could also be used for RME.

3.7.7 Biogas

The available supply of the cheapest feedstock for biogas, e.g. sewage sludge, organic waste etc., is rather limited[27]. It is roughly proportional to the population. However, the use of biogas for vehicle application necessitates the plant having a reasonable size due to eco-

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[26] In fact, these levels could increase even further if the use of fossil fuels in feedstock collection and transport as well as fuel distribution is replaced by the use of biofuels.

[27] Sometimes the cost of this feedstock is negative.

nomic constraints. A certain size is necessary for making the up-grade to fuel quality a realistic option. In sparsely populated areas, this imposes a limitation on the utilisation of biogas in vehicles. The current use of biogas in vehicles in Sweden is estimated to 0,06% of the petrol and diesel fuel market. Doubling of this volume could be a reasonable near-term target. A large-scale increase in the production could provide biogas for about 1-2,5% substitution of petrol and diesel fuel if economy is the limiting factor. This would be some 20-40 times the current volume. It is likely that the potential in the whole EU could be in the same order but the ultimate potential is very dependent on the feedstock cost.

3.7.8 Strategy

Ethanol and RME

In order to fulfil the recommendations for the use of biofuels in the proposal by the EU Commission in 2005, 3-4 ethanol plants would be necessary in Sweden and/or an increase in the production/import of RME. In some EU member states, the 2% target could be met by utilising the mentioned fuels but for the whole EU, this seems to be a very difficult task. The use of these fuels in low-blending (possibly supplemented by fuel flexible vehicles running on ethanol) is the simplest short-term alternatives. However, ethanol from grain and RME cannot compete with the best fuel options from cellulosic matter, regardless of whether the crop yield (per hectare), the efficiency or climate gases are of concern. Likewise, the environmental impact of intensive cultivation is greater for the mentioned two alternatives in comparison to extensive cultivation. In addition, the economical constraints seems to be less favourable, in spite of subsidies and other economic support that is difficult to take into account in cost estimates.

Biogas

A substitution using biogas is an option but in this case, dedicated vehicles are necessary, contrary to the case for low-blending of ethanol and RME. However, a relatively large number of vehicles adapted to the use of natural gas are now available on the European market and these vehicles can also run on biogas. In Sweden, the potential for biogas could double (to 0,1 TWh) relatively easily, i.e. to more than 0,1% of the market and it is likely that this could also be achieved in the whole EU. The feedstock potential is roughly proportional to the population. A large-scale expansion of the production could provide biogas for 1-2,5% substitution of petrol and diesel fuel if economy is the limiting factor. In order to achieve this potential, a large-scale investment in production facilities would be necessary. Alternative use of the biogas (other than in vehicles) should also be considered.

Fuels from synthesis gas

The production of fuels from cellulosic matter via synthesis gas seems, according to previous discussion, be the most favourable option on a somewhat longer horizon. In order to simplify the distribution and to minimise the cost, methanol and FTD appear to be the alternatives that should be given the highest priority on the short and mid-term timeframes. The gasification stage is the most critical step and it is common for all fuels produced from synthesis gas. The other major production stages (shift and synthesis) are, in principal, commercial technology today. In order to deploy this technology in commercial plants before the end of the decade, in intensification in research and development in this area is crucial.

Concluding remarks

Based on the long-term perspective that a significant reduction (~80%) of the emissions of climate gases has to be made, and the forecast of increasing energy use in the transport sector, research and development initiatives have to be initiated now. It would be better to increase the priority for the fuels with a potential for a long-term large market penetration instead of promoting short-term solutions.

3.8 Competition with use of biomass in other sectors

Biomass could be used as an energy source in sectors other than the transport sector. It is often stated that it would be better to burn (e.g. for heating purpose) the biomass instead of using it as feedstock for biofuels. Motor fuels require the highest quality standards of any large-scale use of fuels, implying that the use of biomass energy in other sectors might be more beneficial. However, the situation is not as simple as that. Therefore, some comments on this issue might be necessary to shed some light on the subject.

A very effective use of biomass is to use it for space-heating purposes (direct or district heating). However, large quantities of biomass are already used for this purpose and in Sweden, further increase is rather limited. Environmental concerns limit the use for direct heating, although recently, pellet fuel has enabled significant improvements in this area. Moreover, there are other very cost-effective alternatives for reducing the use of energy in this sector, e.g. insulation. An option in the heating sector would be the export of the biomass for coal substitution.

Electricity could be generated from biomass and, as in the previous case, coal substitution could be beneficial. However, it is important to note – which is not generally known – that the efficiency in electricity generation is lower than that for motor fuel production. In the previously cited report by the authors, an advanced (future) technology for electricity generation, a so-called HAT[28] cycle was anticipated. The efficiency of 55% was significantly higher than for a conventional steam cycle. However, there are also other losses in the pathway (from feedstock production to delivered electricity). This gives a total efficiency of 33% for distributed electricity from biomass. In comparison, DME (with highest efficiency of all biofuels) has an efficiency of 54%, i.e. a factor of 1,6 higher! Of course, it is difficult to directly compare efficiencies of electricity and motor fuel production but these data indicate that fuel production should be considered. In neither of the cases is the utilisation of waste heat considered. Taking this into account, could alter the comparison somewhat but DME would still have much higher efficiency.

In general, the substitution of coal by biomass (e.g. for electricity and/or heating purpose) is very favourable, since coal is the "worst" fuel regarding GHG. On an international level, coal could also be substituted by natural gas – an application well suited for the natural gas infrastructure.

As can be concluded from the discussion above, there are examples of the use of biomass that could be more advantageous regarding GHG emissions and energy efficiency than motor fuel production. Besides electricity generation, the potential is relatively limited and far lower than the biomass potential. Electricity generation and/or export of biomass (in-

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[28] HAT, a Humid Air Turbine utilises a combination of the steam cycle (rankine cycle) and the gas turbine cycle (brayton cyle) by using steam injection.

cluding electricity export) are other options for an increased utilisation of biomass. In view of these options, biomass-based motor fuels are a realistic alternative that should be investigated in parallel with the two other options.

4 DISCUSSION AND CONCLUSIONS

4.1 Presumptions - Resources

The starting points for the considerations in this Chapter are the summaries in the previous Chapters and the goal which has been recognised for long-term, far-reaching reductions (>>50%) of GHG that must include the transport sector [2]. The largest categories of vehicles are passenger cars (LDV in general) and heavy vehicles for long range transport of goods. These target groups must be the main focus of a strategy for sustainable transports. Mass transit by urban buses has instead its focus on the lowest emissions of harmful gases and particles, from the point of view of health and the environment. Transport needs are forecast to grow considerably in the future. The distribution of motor fuels in large volumes is a key factor for reducing the total incremental cost of the fuels. Reduced fuel consumption by advanced vehicles (and drivetrains) will not be sufficient, particularly not when considering customer preferences on a free market. Renewable fuels have to enter the fuel market and their resource base will be a key issue. Direct or indirect utilisation of solar energy flow and use of accumulated biomass by the photosynthesis are the two viable options.

4.2 Fuel distribution

A finely branched, low cost distribution network to make a fuel available everywhere will require liquid fuels that are easily handled (such as petrol and diesel oil today). Duplication of such a network for handling liquefied gases under pressure or cryogenic liquids will hardly be acceptable, due to cost reasons. Niche applications of such fuels will be the remaining possibility. Distribution of gaseous fuels must be assessed similarly on the same grounds. In addition, distribution in large central pipelines has to be arranged for maximum flows, since buffer stores can only be small, and will be vulnerable to disturbances of the supply. These drawbacks, including costs, do not apply to the distribution of easily storable liquid fuels from large and efficient production plants and terminals built for average consumption.

The alternative is the local production on a small scale of gaseous fuels, for instance hydrogen from renewable power, and associated refuelling stations. Costs would most likely be prohibitive for such alternatives.

4.3 Strategy and priorities

A strategy for renewable motor fuels must be based on sufficient feedstock availability, foreseeable technical development and reasonable economy. In several earlier studies (referenced in [2] and [12]), renewable power by wind and solar power is projected to have a high supply potential. Wind power in Europe from hundreds of thousands of 4-5 MW wind mills is difficult to imagine and new solar power mainly based on import from African deserts can hardly be acceptable from the viewpoint of supply security. One reference [13] estimates that less than one quarter of the motor fuel demand could have its origin in renewable power in Europe. Even if cost hurdles for such power production could be overcome, the question remains concerning the distribution of the gaseous hydrogen produced. Biomass is considered a more promising feedstock with both a much higher availability than assumed and a potential for development.

A chain containing distribution on a large scale in pipelines is, on paper, an energy efficient route but seems to be an uneconomic proposition when costs are included. Refuelling of gaseous hydrogen at much higher pressures (up to 700 bar) than assumed or liquefaction before distribution and refuelling will considerably deteriorate the system efficiency.

The best use of hydrogen produced from renewable power might be to use it as a supplementary hydrogen source in central, biomass-based gasification plants. Due to the composition of the biomass, the primary gas is deficient in hydrogen, and by introducing hydrogen, the operation will be somewhat simplified. With biomass as feedstock, the pathway via gasification and synthesis to DME, methanol or FT-hydrocarbons is more efficient than that via power and electrolysis to hydrogen. However, DME is excluded as a principal, generally available fuel and is considered only as niche fuel.

The results of the studies on energy system efficiency ([2], and **Figure 3**) lead to the conclusion that methanol produced via gasification and synthesis has an efficiency advantage over FT-hydrocarbons, and most likely, even a cost advantage. However, FTD could substitute diesel fuel without any change in fuel infrastructure and therefore, this option is also of interest. The gasification is not fully developed and demonstrated in commercial scale. *There is therefore an urgent requirement to prioritise such development work, which is common to several end products (DME, methanol, hydrogen, FT-hydrocarbons).*

It is somewhat surprising that studies led by oil and auto industry (e.g. [2]) have come up with statements that methanol (based on NG and used in FC) does not provide any advantage over oil-based fuels, diesel fuel in ICE or petrol FC, or CNG in dedicated ICE. Biomass-based methanol is therefore seldom studied – in spite of high efficiency and, next to renewable hydrogen, lowest GHG-emissions. Instead, renewable hydrogen and fuel cells are proposed as means to solve GHG-issues in spite of the problems with fuel infrastructure.

The basis for the much talked-about “hydrogen economy” seems not to be a practical proposition, since too many weaknesses are involved, these being due to the properties of hydrogen itself. Hydrogen is the lightest element on earth and has the lowest energy density of all fuels, which leads to high costs and low efficiency at production, transport, storage and refuelling. Hydrogen may not be an acceptable practical solution as a future motor fuel for general use. *Has the time come to shift to a “methanol economy”* [19] *and to direct resources to this pathway for future sustainable motor fuels?*

4.4 Energy converters

The second best use of bioalcohols (after low-blending) would be in fuel-flexible vehicles, that do not cost significantly more to produce than the corresponding petrol-fuelled version of the same vehicle. Such vehicles are already in operation, albeit in small scale. Niche use of fuel-flexible vehicles, e.g. as in the passenger cars available today, could be considered to be a parallel measure to low-blending in petrol and it could also be a pathway for phase-in of larger quantities of bioalcohols. This could be initiated already today. Future fuel-flexible vehicles should be optimised for the alcohol fuel to take advantage of the possibilities for higher efficiency and thus, gaining customer acceptance. Fuel-flexible vehicles are necessary during an introductory phase lasting a couple of decades in order to maintain maximum flexibility during the phase-in period.

Further development of direct-injection otto and diesel engines running on alcohols should be given a high priority but cannot be introduced commercially on a large scale before the proper economical conditions[29] have been established. Until the large-scale production of bioalcohols has been initiated, both engine development and adaptation of the distribution chain could be accomplished with fossil methanol as the basis. The incremental cost in comparison to petrol for this option will be small.

4.5 Possibilities to fulfil the targets of the EU Commission

Today, there are only limited quantities of bio-alcohols (almost only ethanol) available, quite insufficient to reach the 2%-goal for 2005 proposed in the EU. Additional quantities could, in the short-term, only be produced with grains as feedstock although they would still be insufficient to fill the commercial potential that low level blending in all petrol creates. The production of methanol and/or DME based on black liquor at sulphate pulp plants will likely be the next stage in the development but not within the next 4-5 years. Production from wood residues cannot be a reality until the end of this decade, which presumes renewed studies in areas where such studies have hardly even been prepared at the present time.

In continental Europe, short-term emphasis is laid on FAME but this fuel does not have supply-potential at a longer range and it is mainly based on annual crops from intensive cultivation. Development efforts seem to make more benefits elsewhere.

4.6 Cost

Production costs of bioalcohols based on lignocellulosic feedstocks (costing about 55 €/ton DS or 0.3 €c/MJ) are estimated to be at least twice (methanol 22€c/l [14]) those of crude based petrol (typically 22 €c/l at refinery gate or import terminal) and diesel oil today on energy basis. It seems doubtful if the costs could be lowered below this doubled cost by further development. At the retail pump, the petrol price would be 31 €c/l and corresponding price of methanol 57 €c/l petrol equivalent.

Differentiation of the taxes on motor fuels must be applied recognising the bio-origin with a lower tax. Halving of the taxes (on energy basis) at present levels, as suggested by the EU-commission, will probably not be sufficient to create incentives for the industries to act. It will be easier to adjust the taxes on petrol for equal-selling price of the biofuel than for diesel oil due to the not quite understandable lower tax level on diesel oil.

4.7 Conclusions

In previous Ecotraffic studies, the most efficient biofuels from the point of view of well-to-wheel efficiency have been identified. High efficiency is usually synonymous with low cost although this cost is still significantly higher than for conventional fossil fuels. Fuels

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[29] Economical long-term conditions as taxes, incentives etc. have to be set to justify a long-term commitment of stakeholders in this area.

such as DME, hydrogen and methanol have been identified as the fuels of highest efficiency.

When fuel distribution is considered, high incremental cost in this stage is added for fuels that are gaseous at normal pressure and temperature. The distribution of gaseous and cryogenic fuels on a larger scale tends not to be realistic for general use. Consequently, within the foreseeable future, these fuels will be devoted to niche applications. The necessary large market penetration needed to achieve the long-term targets could only be met by using easily handled liquid fuels and by focusing on light-duty vehicles and long distance heavy goods vehicles.

In order to be able to implement large-scale activities on biofuels, consensus between Governments (in member states and on the EU level), the agriculture/forest, vehicle and fuel/energy sectors is necessary. The assessment of the authors is that such a consensus, in the short and medium term (<10 years) should be possible to be reached concerning the low-blending of bioalcohols and FTD in petrol and diesel fuel. These fuels would be implemented for in-use vehicles and the large-scale introduction of fuel-flexible vehicles for increasing the use of bio-alcohols.

Methanol and FTD could be produced from synthesis gas. Both these processes are commercial with natural gas feedstock. Concerning the production of synthesis gas from biomass, an intensification of research and development will be necessary before this technology can be optimised for commercial use. Therefore, a dedicated program, aiming at the erection of a demonstration plant for synthesis gas production from biomass, is a very important requirement.

In parallel to the above proposed activities regarding fuel production, the development of direct-injection otto engines intended for alcohol fuels (“ADI” in analogy to “GDI”) with fuel-flexible capabilities are essential parts of the proposed strategy. In addition, alcohol-fuelled diesel engines are of importance on a somewhat longer timeframe.

Biofuels are, due to natural reasons (starting with virgin feedstock), more costly to develop than those produced from fossil feedstock (crude oil, natural gas). A prerequisite for industrial stakeholders to take part in the development towards long-term sustainable transportation is that the overall conditions (goals, taxes, administrative incentives) will be established on a long-term basis and that they are internationally harmonised.

The utilisation of biomass for heating purposes or for the generation of electricity, are two alternatives to motor fuel production. The potential in the former sector is rather limited and other cost-effective options are available in order to reduce the heating requirements. As the efficiency in motor fuel production is significantly higher than for electricity generation, biomass-based motor fuels are a realistic alternative that should be investigated in parallel with the two other options.

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