Vägverket
Swedish National
Road Administration

Publikation 2001:85

WELL-TO-WHEEL EFFICIENCY

For alternative fuels from natural gas or biomass

Ecotraffic

Titel: Well-To Wheel Efficiency for alternative fuels from natural gas or biomass

Keywords: alternative fuels, hydrogen, methanol, ethanol, electricity, DME, alcohols, hybrids, fuel cell, Fisher-Tropsch, synthetic gas, biomass, methane, natural gas, CNG

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Publication number: 2001: 85

ISSN: 1401-9612

Printed: October 2001

Edition: 100 copies. Also available for downloading at http://www.vv.se/publ_blank/bokhylla/miljo/lista.htm

Distributor: SNRA, Head Office, SE-781 87 Borlänge, phone +46 243-755 00,

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WELL-TO-WHEEL EFFICIENCY

For alternative fuels from natural gas or biomass

A report for
the Swedish National Road Administration

Ecotraffic ERD^3 AB

Peter Ahlvik
Åke Brandberg

October 2001

PREFACE

The emissions of climate gases from the transport sector and the measures that should be taken to reduce these emissions are debated both in Sweden and in Internationally. Alternative fuels from renewable sources, new powertrains, etc. are discussed as possible options. Since there are only few studies available on this issue, it was of interest to carry out a project that would highlight some of these issues.

In April 2001, the Swedish National Road Administration, SNRA, published a report over a well to wheel efficiency study, which had been carried out by the Swedish consultant company Ecotraffic. The report was published in Swedish. After the report was published, it became clear that there was an international interest for an English version of this report. While the work on the Swedish version of the report was in progress, and after the report was finished, several interesting international reports on the subject were published. Therefore, it was felt that a pure translation of the report without considering the most recent publications would have been somewhat negligent. It was also of interest to make some comparisons with the results from the most interesting studies.

In order to keep the major part of the original Swedish report relatively intact, it was decided to translate that report and to put the comparisons in an appendix.

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, October 2001

Swedish National Road Administration, Vehicle Standards Division

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Introduction

The interest in alternative fuels, and biofuels in particular, appears to be increasing due to the ever-increasing problems associated with the emissions of climate gases from road traffic. Eventually, the fossil fuels will also be exhausted and the question is no longer *if* than *when* this will happen. In principle, the fossil fuels will not be completely exhausted but the cost of exploitation of the resources will become prohibitively high. Alternative fuels are also of interest from an energy security point of view in order to be prepared for a certain crisis.

Two different kinds of feedstocks for the production of alternative fuels are of special interest to investigate, i.e. (fossil) natural gas and biomass. The availability of natural gas is vast and in the future, this feedstock could become a substitute for crude oil. On a longer-term horizon, biofuels will be of greater interest in order to decrease the emissions of climate gases. A classification of the fuels in gaseous and liquid fuels has been made to take into account the significant difference in infrastructure for the distribution and refuelling that are needed for these two categories of fuels. A different kind of classification of interest would be to classify them according to the potential market penetration (in a fully developed scenario). The following definitions have been used:

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

Motor fuels and powertrain combinations with a potential use less than 1% have not been considered as such fuels would be of little interest with regard to effect of greenhouse gases (by definition <1%).

The following types of motor fuels have been considered to be of interest to study for final use (not in priority order but in density order):

- Synthetic hydrocarbon fuels (hereafter referred to as “synfuel”): diesel oil and /or fuel cell fuel, i.e. special quality adapted for fuel cells)
- Ethanol
- Methanol
- DME (dimethyl ether)
- Methane
- Hydrogen

As reference, petrol and diesel fuel have also been evaluated. Both these fuel qualities have been considered to be reformulated and virtually sulphur-free (<10 ppm). Hence, the possible advances in the refining processes for these fuels will be counteracted by the additional processing that will be necessary to fulfil the anticipated future fuel specifications.

Methodology

Since the production of alternative fuels in several cases still is not fully developed, a future scenario has been used to show a more realistic potential for this technology in comparison the conventional fuels. In order to make the comparison of new powertrains, such as fuel cells and hybrid drivetrains more realistic, the focus has to be on a future use of these systems as well. A timeframe of 2012 was chosen as a reasonable compromise between various possible timeframes. First, it was considered essential not to choose a too distant future to make it impossible to predict what could happen within this timeframe. Second, it is also of importance to satisfy the criterion that new technology should have had a development time long enough to mature. It has also been considered that the conventional powertrains will be further developed during the timeframe.

The fuel converters investigated have been otto[1] (SI) and diesel (CI) engines as well as fuel cells. The drivetrains have been an automated mechanical gearbox, and electric hybrid systems of parallel (combustion engines) and serial (fuel cells) types. In total, 98 different combinations of fuels, energy converters ("engines") and drivetrains have been studied.

A literature search was carried out to supplement the data that was already available regarding fuel production and technology for powertrains for light-duty vehicles. Concerning the production of fuels, an update of an earlier study by Ecotraffic, the "Life of Fuels" was made. For the powertrains, input data was collected for the use in simulating the efficiency and fuel consumption for the vehicle. These simulations were carried out in the Advisor® (release 3.0) software package from NREL in the USA.

Results

Powertrains

The results from the study shows that fuel cells and diesel engines are the fuel converters that provide the highest efficiency and that the otto engine has a lower efficiency that these two. A significant improvement of the system efficiency could be achieved if the internal combustion engines are used in hybrid drivetrains. The relative improvement for the fuel cells in a hybrid drivetrain is somewhat smaller. However, the differences between these electric drivetrains are significant, since the fuel cell must use a series hybrid drivetrain (this is the only possible solution), while the internal combustion engines are anticipated to use a parallel hybrid drivetrain. The choice of the latter system was made, since the efficiency is higher than for the former.

Well-to-wheel efficiency

In summarising the results on efficiency for the whole system in a lifecycle (well-to-wheel) perspective, two figures are shown. **Figure ES-1** shows the results for the best powertrain for each fuel option, where the fuels have been produced from natural gas. Similar results are shown in **Figure ES-2,** but in this case, the fuels have been produced from biomass. The results for most of the fuel/powertrain combinations are also summarised in **Tables ES-1** and **ES-2** at the end of the Executive Summary.

[1] In general, "otto" is usually written with "O" as a capital letter in English and "diesel" is written with the "d" as a small letter. We have used small letters in both cases.

To add another dimension to the figures mentioned, a classification of the fuels into four different groups has been made. The first criterion has been to distinguish between the fuels according to their market potential, i.e. principal fuels (>10%) or niche fuels (<10%), according to the definition mentioned above. The second criterion has been to differentiate between fuels, which may be "flexible fuels" in any sense and fuels that do not enable this flexibility. Such ones are fuels that can be utilised in FFV (e.g. methanol and petrol) or in dual-fuel vehicles (e.g. biogas and petrol). Another example, which has been included among the flexible fuels, is synthetic hydrocarbons (synfuel), as it is miscible with diesel oil in any proportion. Since no better acronym than "FFV" has been found, this designation has been used although it might be somewhat ambiguous. During an introduction phase for new fuels, fuel flexibility can be an important property, and, therefore, it is of interest to identify such advantages. Since the figures mentioned do shown only a fraction of all investigated combinations, one of the four categories (niche fuel, FFV) is missing in the figures but to make the legend boxes complete, this alternative has been listed anyway.

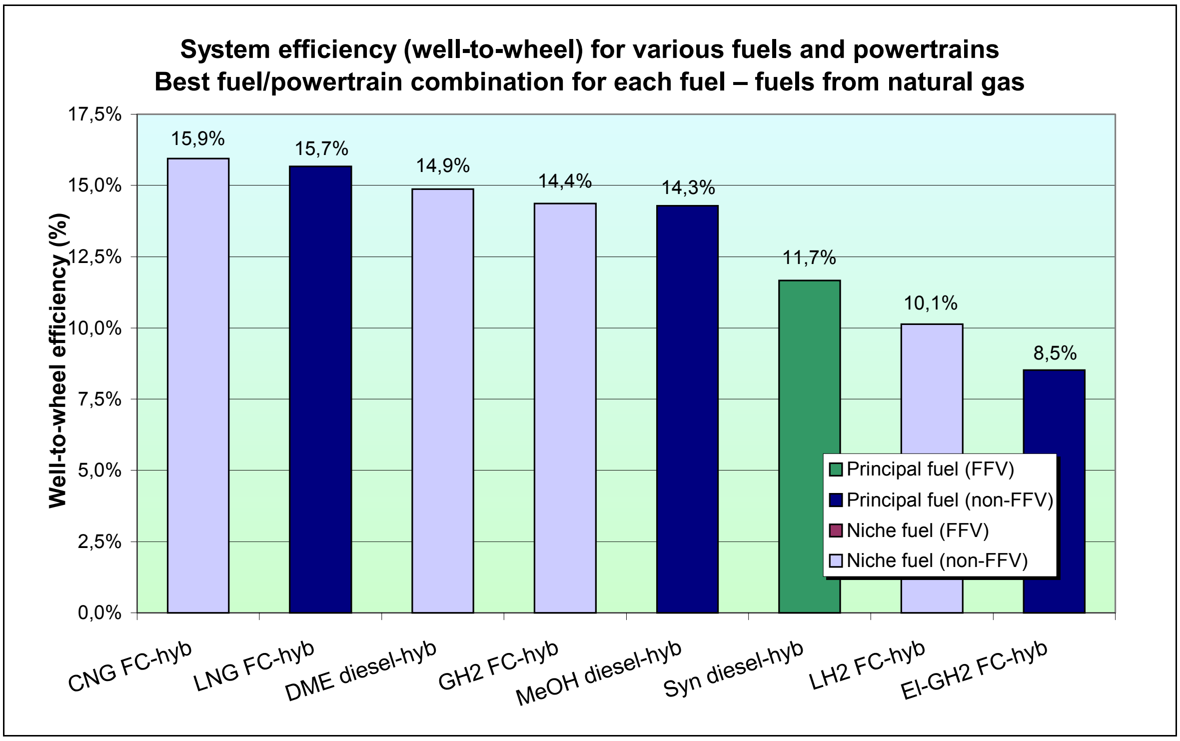


Figure ES-1. *System efficiency for the best combinations of fuel/powertrain. Fuels from natural gas feedstock.*

The results show that various fossil fuels (from crude oil and natural gas), as could be anticipated, have a higher efficiency than the biofuels. This is due to that the latter category is based on original, renewable feedstock but the fossil fuels are made from a "semimanufactured" feedstock. This feedstock is not renewed and therefore, it has an impact on the climate change, which the biofuels do have only to a small extent. For the biofuels, only about 11% of the energy content of the feedstock is obtain as transport work, which is somewhat lower than for the baseline petrol-fuelled otto-engined passenger cars (model year 2012). In general, it can be stated that the less conversion necessary for the feedstock to receive a useful motor fuel, the higher the efficiency will be. However, this is only achievable for natural gas and crude oil, since a relatively extensive conversion process is always necessary for biomass.

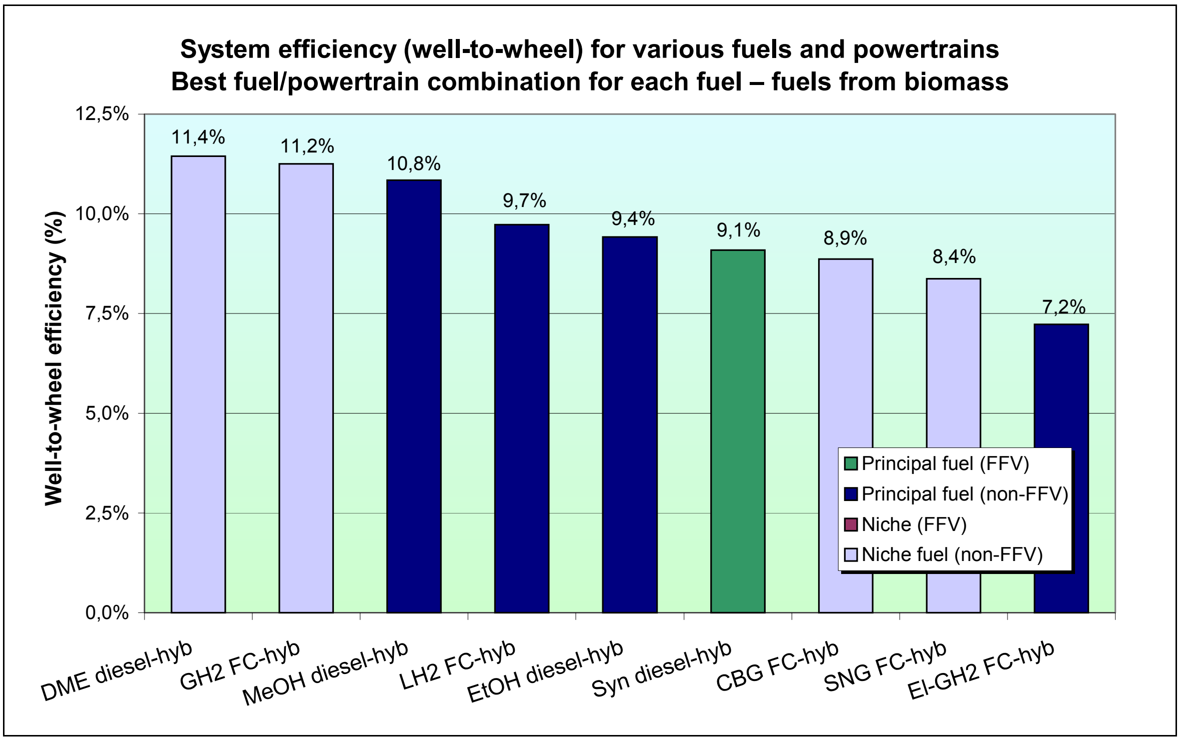


Figure ES-2. *System efficiency for the best combinations of fuel/powertrain. Fuels from biomass feedstock.*

The mutual order between the fuels for the best combinations of all fuels is varying depending on if the feedstock is fossil natural gas or biomass. Three fuels, DME, GH_2 and methanol (of which two are in gaseous state and one in liquid), have been identified as fuels that provide high efficiency when produced *both* from natural gas and from biomass, provided that the best powertrains are used. It could also be mentioned that the feedstock and production processed for DME and methanol are, in principle, similar.

Sustainability

As the issue of sustainability will be more important in the future, it is also of interest to show some results on the use of fossil and non-fossil energy. **In Figure ES-3**, a split between the two types of energy use has been shown for the three "best" motor fuels (DME, methanol and hydrogen) in combination with the best powertrains (fuel cells and diesel engine hybrids). In addition to the best powertrains, a methanol-fuelled otto engine hybrid is also shown, since this might be an interesting transitional solution (fuel-flexible vehicle). The options mentioned are compared with a conventional petrol-fuelled car (index = 100).

As **Figure ES-3** shows, and as already has been mentioned, it is not possible to reach the high system efficiencies for biomass based fuels as for fuels from (already partly converted) fossil feedstocks. This is quite natural as the conversion path to motor fuels is longer and more complex (and energy demanding) for fuels based on biomass. On the other hand, it is evident that very substantial decrease of the fossil energy use can be accomplished with the biomass based motor fuels compared to those based on fossil feedstocks. The use of fossil fuels in the chain for biomass based between the various alternatives, varying between 4,2 and 6,0%. This means that about 95% (93,6-96,2) of the fossil energy could be replaced with bio-energy compared to the reference case.

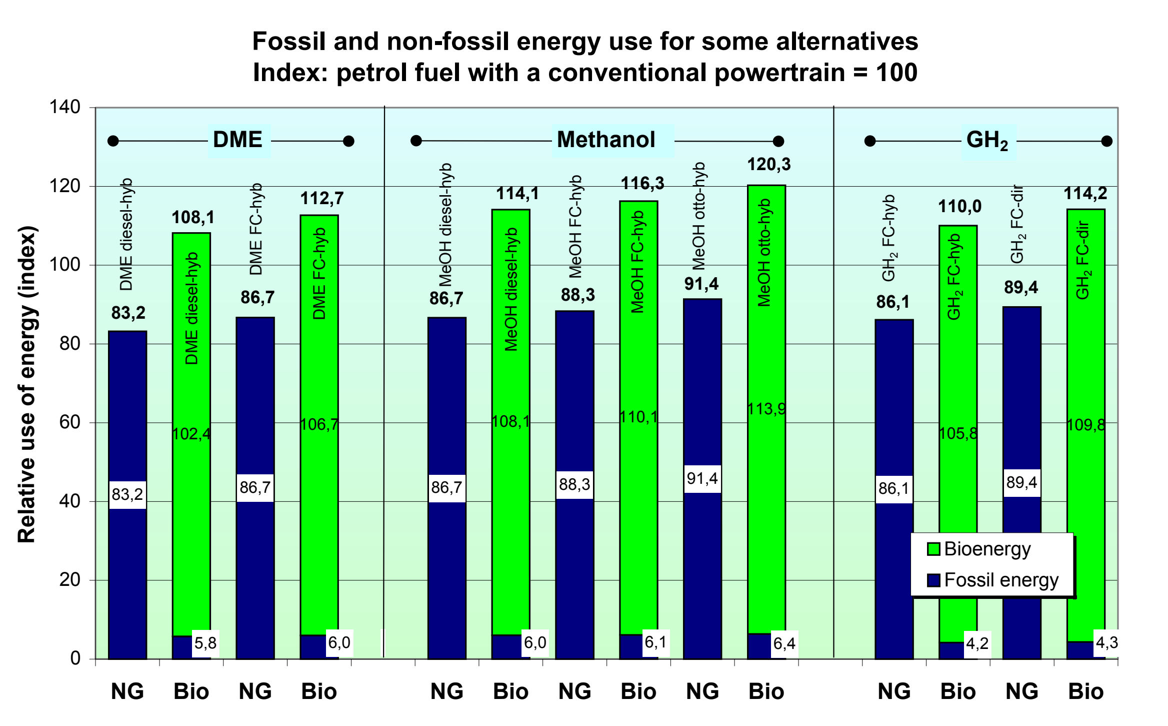


Figure ES-3. Fossil and non-fossil energy use.

Comparison with other studies

After the Swedish version of this report was published, it was found that an international interest in the report could motivate a translation into English. While the work on the Swedish version of this report was in progress and after the report was finished, several interesting international reports on this subject were published. Therefore, it was felt that a pure translation of the report without considering the most recent publications would be somewhat negligent. It was also of interest to make some comparisons with the results from the most interesting studies. Therefore, a comparison with these results was made separately. This addendum to the Swedish version of this study is attached in Appendix 1. Studies by MIT, GM and a German study were considered of most interest, although the final report was not available in the last case. Several other studies have also been discussed.

Methodology and assumptions

In general, it can be concluded that a comparison of results from different studies is difficult due to the various conditions chosen and the assumptions made. Most studies seems to have the ambition to picture at least a medium term time frame, 2005-2020, and focus on principal motor fuels marketable in large volumes. Not all studies have been successful in upholding this ambition throughout. Long term sustainability has only been discussed by a few.

The assumptions made for the vehicles and powertrains seems to differ considerably in several cases. Mostly, an evolutionary or advanced (future) vehicle and improvements in conventional drivetrains and, in addition, the option of hybridisation seems to be in common of most studies. Comparisons of relative vehicle weight between the studies by MIT and Ecotraffic showed reasonable agreement in most cases. Vehicle range and assumptions about the drivetrain and fuel converters could explain most of the differences. In some cases, the criteria for vehicle performance showed a considerable difference between various studies, although most studies have tried to keep the vehicle acceleration constant.

Powertrains

It is trivial to state that that systems based on the diesel engine in all relevant studies are found to have some 21-24% system efficiency advantage over the reference vehicle (evolved petrol driven otto engined vehicle). It is, however, remarkable that no study but Ecotraffic's has tried to analyse alcohols as fuels (particularly in diesel engine drivetrains), in spite of the potential they have among the alternative fuels and that they can be produced on bio-basis.

Fuel cells are without doubt efficient energy converters, with hydrogen as fuel more than 50% better than the reference vehicle (GM quotes >100%). Fair comparisons cannot, however, be made without considering the energy used for refuelling, which is high for hydrogen and reduces the powertrain efficiency to be "only" about 25% better. When considering also the production and distribution steps, the efficiency advantage will be further reduced. Fuels that require onboard-conversion to hydrogen must include this step in the powertrain, which will reduce the energy efficiency advantage to 18-22% (highest for methanol) in the Ecotraffic study. GM quotes higher figures for both petrol and alcohols. The vast difference between the petrol-fuelled (naphtha in one case) fuel cell vehicles in the MIT and GM studies could be noted.

Hybridisation in general, seems to increase the efficiency of the powertrain. The improvement potential is at least 20-24% for internal combustion engines and one study (MIT) found an even greater difference. The potential of hybridisation for fuel cells, at 6-12%, seems to be somewhat smaller.

Well-to-wheel efficiency

CNG/LNG systems usually rank high due to the low energy needs to process NG to pipeline-NG (and to LNG), assuming that large-scale distribution systems are in place. Hydrogen from NG is also an efficient option due to the high efficiency of the fuel cell powertrain. Depending on the assumptions made DME and methanol could be efficient options as well.

Although some fuels in gaseous form (NG, H_2) have shown a high efficiency in several studies, they have also been considered as niche fuels (however, important) in many studies. DME is easier to handle and has almost the same efficiency with NG as feedstock. LNG and LH_2 are liquid options but, as cryogenic fuels, increased cost and, in the latter case, a decrease in efficiency are drawbacks. Methane has the drawback that there does not seem to be any efficient way to produce it from biomass resources (on a large scale). Liquid fuels, easily handled as petrol and diesel oil today, will have a great advantage in distribution and refuelling efficiencies and allow retaining of the refuelling habits of the public. Of the liquid non-cryogenic fuels, methanol seems to be the fuel that has the highest efficiency. Considering these facts, it seems remarkable that this fuel has not been more thoroughly studied.

Sustainability

To maintain the hydrocarbon base feedstocks in a scenario with great reductions of GHG, sequestration of CO_2 in deposits in the crust of the earth would be necessary and is often discussed as technically not an infeasible solution. The unavoidable consequence is, however, a distribution system for hydrogen, which we cannot see as the general future system (above). For GHG-reductions of the magnitude of 80-90%, only biomass-based fuels have such potential, as has been demonstrated in several of the studies.

Discussion and conclusions

As a summary of the results from this study, it can be stated that it is not trivial to find a final “winner” among the 3 to 5 best candidate fuels. On the contrary, it is easier to exclude some of the options where the system efficiency is comparatively low. Hydrogen produced from electricity is such a case.

It is also of importance to mention that there are various criteria available for choosing fuels that have not been disseminated in this study. A very important criterion is, for example, the cost for fuel production, distribution and end use. However, an assessment of this kind has been beyond the scope of this study.

Table ES-1. *Relative system efficiency for systems based on crude oil and natural gas feedstocks*

FUEL, fuelled as	Petrol	Diesel	DME	Methanol	Ethanol	FTD	CNG	CNG	GH_2	GH_2	GH_2	GH_2	GH_2
DISTRIBUTED as	Petrol	Diesel	DME	Methanol	Ethanol	FTD	CNG	LNG	GH_2	LH	DME	Methanol	El
Powertrain	**System efficiency for crude oil / natural gas-based systems in relation to the conventional petrol-fuelled car (=100)**												
Diesel eng. - hybrid		150,7	120,2	115,4		94,3							
Fuel cell - hybrid			115,3	113,2		81,5	128,8	126,6	116,1	81,9	91,7	93,0	68,8
Fuel cell - direct			107,8	107,5		78,5	124,1	122,0	111,9	78,9	88,4	88,3	66,3
Otto engine - hybrid	124,0			109,5			128,1	125,9	90,1	63,5	71,2	70,0	53,4
Diesel eng. – conv.		125,0	99,7	95,7		78,2							
DMFC - hybrid				93,8									
Otto engine – conv.	***100***			88,3			104,5	102,7	73,5	51,8	58,1	57,1	43,6

Table ES-2. *Relative system efficiency for systems based on biomass feedstocks*

FUEL, fuelled as	Petrol	Diesel	DME	Methanol	Ethanol	FTD	CNG	CNG	GH_2	GH_2	GH_2	GH_2	GH_2
DISTRIBUTED as	Petrol	Diesel	DME	Methanol	Ethanol	FTD	CNG	LNG	GH_2	LH	DME	Methanol	El
Powertrain	**System efficiency for biomass-based systems in relation to the conventional petrol-fuelled car (=100)**												
Diesel eng. - hybrid			92,5	87,7	76,1	73,5							
Fuel cell - hybrid			88,7	86,0	71,2	65,4	71,6	67,6	90,9	78,6	72,4	72,8	58,4
Fuel cell - direct			82,9	81,6	67,6	62,1	69,0	65,2	87,6	75,8	69,7	69,1	56,3
Otto engine - hybrid				83,1	70,7		71,2	67,3	70,5	61,0	56,1	54,8	45,3
Diesel eng. – conv.			76,7	72,7	63,1	61,0							
DMFC - hybrid				71,2									
Otto engine – conv.				67,0	57,0		58,1	54,9	57,5	49,8	45,8	44,7	37,0

SVENSK SAMMANFATTNING (SWEDISH SUMMARY)

Introduktion

Ökade utsläpp av klimatgaser från trafiken har lett till att intresset för alternativa drivmedel och för biodrivmedel i synnerhet ökat. På lång sikt kommer också de fossila drivmedlen att ta slut men innan det händer kommer kostnaderna för att exploatera tillgångarna att öka markant. Rent principiellt kommer inte de fossila bränslena att ta helt slut men kostnaden för att exploatera resurserna kommer att bli oöverkomligt höga. Alternativa drivmedel är också av intresse ur försörjningssynpunkt för att kunna hålla en viss beredskap för en krissituation.

Två olika typer av råvaror för produktion av alternativa drivmedel är av speciellt intresse att undersöka, nämligen fossil naturgas och biomassa. Tillgången på naturgas är stor och kan i framtiden bli ett komplement till råolja som råvarubas. På längre sikt är dock biodrivmedel av störst intresse för att minska utsläppen av klimatgaser. En indelning av drivmedlen i gasformiga och flytande drivmedel har gjorts för att ta hänsyn till den väsentliga skillnad i infrastruktur för distribution och tankning som föreligger mellan dessa två kategorier av drivmedel. En annan typ av indelning som är av intresse är att dela in bränslena efter deras potential till penetration på marknaden (i ett fullt utbyggt scenario). Följande definitioner har använts:

- >1% men <10% av marknaden (nischbränsle)
- >10% av marknaden (huvudbränsle, dvs. ett bränsle för allmän användning)

Alternativ som inte har potential att klara mer än 1% har uteslutits eftersom en så låg penetration är av litet intresse ut klimatgassynpunkt.

Följande olika typer av bränsle har ansetts vara av intresse att studera (ej i prioritetsordning utan i densitetsordning):

- Syntetiska kolvätebränslen (i forts. ofta förkortat till ”syntetiskt bränsle” eller ”syntetiskt drivmedel”): dieselolja och/eller ”bränslecellsbränsle” (dvs. speciell kvalitet anpassad för bränsleceller)
- Etanol
- Metanol
- DME (dimetyleter)
- Metan
- Vätgas

Som referens har också bensin och dieselolja utvärderats. Båda dessa drivmedelskvaliteter har ansetts vara ”reformulerade” och praktiskt taget svavelfria (<10ppm). Därför kommer de möjliga förbättringarna i framställningsprocessen för dessa drivmedel att motverkas av den ytterligare raffinering som kommer att vara nödvändig för att uppfylla framtida bränslespecifikationerna.

Metodik

Eftersom produktionen av alternativa drivmedel i flera fall ännu inte är fullt utvecklad har ett framtida scenario använts för att visa en mer realistisk potential för denna teknik i jämförelse med de konventionella drivmedlen. För att nya drivsystem som bränsleceller och hybriddrift skall vara realistiska alternativ krävs också att en användning av dessa system fokuseras på framtida fordon. En tidshorisont till 2012 har valts som en lämplig kompromiss mellan olika tänkbara tidshorisonter. För det första har det varit viktigt att inte välja en allför avlägsen framtid för att det skall vara möjligt att förutspå vad som kan tänkas hända. För det andra är det viktigt att tillfredsställa kriteriet att den nya tekniken skall ha haft tillräckligt lång utvecklingstid för att mogna. Hänsyn har naturligtvis tagits till att även de konventionella drivsystemen och motorer kommer att utvecklas vidare under tidsperioden.

De energiomvandlare som undersökts är otto- och dieselmotorer samt bränsleceller. Drivsystemen har varit en mekanisk växellåda med växlingsautomatik och elhybridsystem av parallell- (för förbränningsmotorerna) och serietyp. Totalt har 98 olika kombinationer av drivmedel, energiomvandlare (”motorer”) och drivsystem studerats.

En litteratursökning har utförts för att komplettera befintligt underlag när det gäller produktion av drivmedel och teknik för drivsystem i lätta fordon. Vad gäller produktionen av drivmedel har en uppdatering av underlag och beräkningar i en tidigare studie från Ecotraffic, ”Life of Fuels”, gjorts. För drivsystemen har dataunderlag samlats i för att sedan kunna utföra simuleringar av verkningsgrad och bränsleförbrukning för drivsystemet i fordonet. Dessa simuleringar har utförts i programmet Advisor® (version 3.0) från det federala laboratoriet NREL i USA.

Resultat

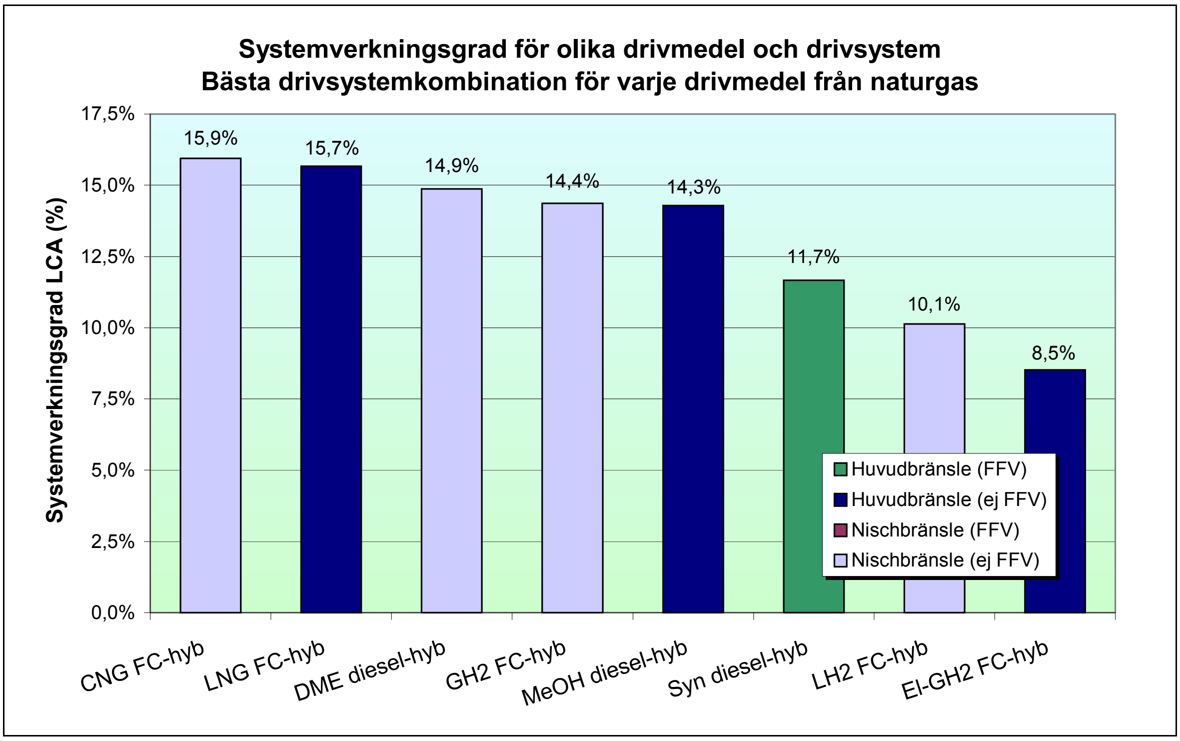
Drivsystem

Resultaten från studien visar att bränsleceller och dieselmotorer är de energiomvandlare som ger den högsta verkningsgraden och att ottomotorn har en lägre verkningsgrad än dessa två. En väsentlig förbättring av systemverkningsgraden erhålls om kolvmotorerna används i ett hybridsystem medan förbättringen av hybridsystemet är mindre för bränsleceller. Skillnaderna i eldrivsystemet mellan dessa två alternativ (bränsleceller resp. kolvmotorer) är dock stora eftersom bränslecellen använder ett seriehybridsystem (enda möjligheten) och kolvmotorerna förutsätts använda ett parallellhybridsystem. Valet av hybridsystem i det senare fallet har gjorts för att verkningsgraden för detta är högre än för ett seriehybridsystem.

Systemeffektivitet

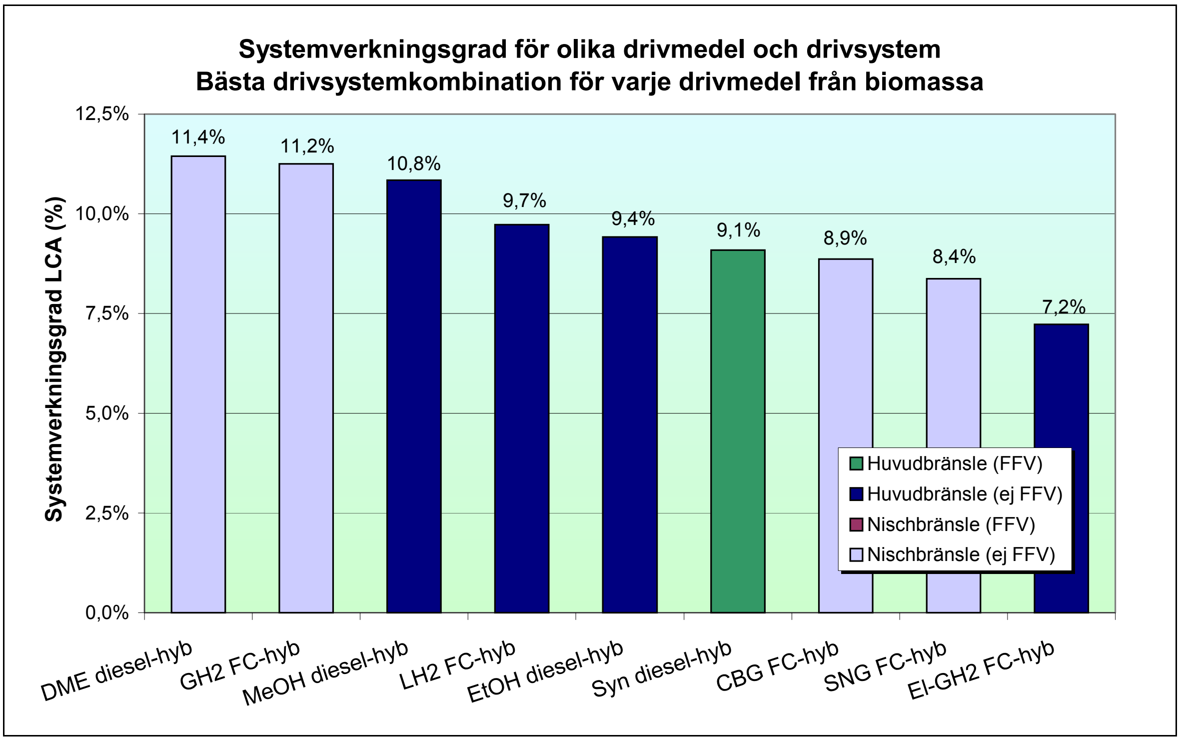
För att på ett enkelt sätt summera resultaten för hela systemet i ett livscykelperspektiv visas två olika figurer. **Figur S-1** visar resultaten för den bästa alternativet av drivsystem för varje bränslealternativ där drivmedlen i detta fall producerats från (fossil) naturgas. Liknande resultat visas i **Figur S-2** men i detta fall har drivmedlen producerats från biomassa. Resultaten för de flesta bränsle/drivsystem kombinationerna har också summerats i **Tabellerna S-1** och **S-2** i slutet av sammanfattningen.

För att införa ytterligare en dimension i de nämnda figurerna har en klassificering av de olika drivmedlen i 4 olika grupper gjorts. Det första kriteriet har varit att skilja mellan drivmedlen i förhållande till deras marknadspotential, dvs. med en indelning i huvudbränslen (>10%) och nischbränslen (<1%) i enlighet med definitionerna som nämnts ovan. Det andra kriteriet har varit att skilja mellan drivmedel som kan betecknas som ”bränsleflexibla” i någon mening och de som inte tillåter denna flexibilitet. Sådana bränslen är de som kan användas i FFV (t.ex. metanol och bensin) eller i tvåbränslefordon (t.ex. biogas och bensin). Ett annat exempel på bränslen som har inkluderats bland de flexibla bränslena är syntetiskt dieselbränsle, eftersom det är blandningsbart med dieselolja i godtyckliga proportioner. Eftersom ingen bättre benämning än ”FFV” har hittats har denna beteckning använts även om den kan tyckas något tvetydig. Under en introduktionsfas av nya drivmedel är bränsleflexibiliteten en viktig egenskap och därför är det av intresse att identifiera sådana fördelar. Eftersom de nämnda figurerna visar endast en bråkdel av alla undersökta kombinationer saknas en av de 4 kategorierna (nischbränsle, FFV) i figurerna, men för att göra förklaringsrutorna kompletta har detta alternativ listats i alla fall.



Figur S-1. *Systemverkningsgrad för den bästa kombination för respektive drivmedel. Drivmedel med naturgas som råvara*

Resultaten för de olika drivmedlen visar att de på fossil bas (råolja, naturgas) självfallet uppvisar högre systemverkningsgrader än de på biomassebas beroende på att de senare utgår från en ursprunglig, förnybar råvara medan de fossila startar från ett ”halvfabrikat”, som ej återbildas och därför påverkar växthuseffekten, vilket de biomassabaserade gör bara i mycket liten grad. För de sistnämnda erhålls i bästa fall drygt 11% av råvarans energiinnehåll som utfört transportarbete, vilket är något lägre än för bilar med bensindrivna ottomotorer (modellår 2012). Generellt gäller att ju mindre konvertering som behövs för råvaran för att få användbart drivmedel desto högre är verkningsgraden. Detta är dock bara aktuellt för fossilgas och råolja eftersom en relativt sett mer omfattande konvertering alltid är fallet för biomassa.



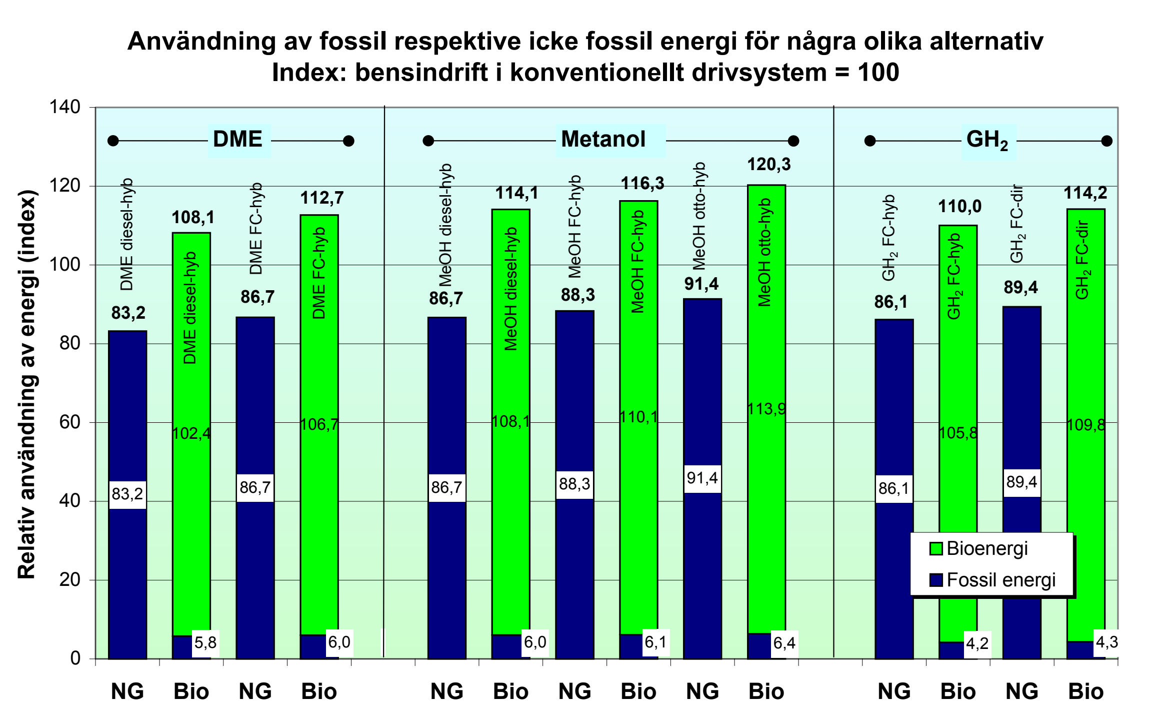
Figur S-2. *Systemverkningsgrad för den bästa kombination för respektive drivmedel. Drivmedel med biomassa som råvara*

Den inbördes ordningen mellan drivmedlen för de bästa kombinationerna av alla drivmedel varierar beroende på om råvaran är fossil naturgas eller biomassa. Tre drivmedel, DME, GH_2 och metanol (varav två är gasformiga och ett är flytande), har identifierats som drivmedel som har hög systemverkningsgrad då *både* fossil naturgas och biomassa används som råvara förutsatt att bästa drivsystem används. Det kan också nämnas att råvara och produktionssystem för DME och metanol i princip är desamma.

Långsiktig hållbarhet

Eftersom frågan om långsiktig hållbarhet kommer att bli alltmer viktig i framtiden är det också av intresse att visa några resultat om användningen av fossil och icke-fossil energi. I **Figur S-3** visas en uppdelning av de två olika typerna av energianvändning för de tre ”bästa” drivmedlen (DME, metanol och vätgas) i kombination med de bästa drivsystemen (bränsleceller och dieselhybrider). Som komplement till de bästa drivsystemen visas också en metanoldriven ottomotorhybrid, eftersom detta kan vara en intressant övergångslösning (en bränsleflexibel bil). De nämnda alternativen har normerats i förhållande till en konventionell bensindriven bil (index = 100).

Som framgår av **Figur S-3**, och som redan tidigare påpekats, är det inte möjligt att erhålla lika hög systemverkningsgrad för de bränslen som framställs från biomassa som för de fossila bränslena. Detta är naturligt eftersom konverteringen till ett drivmedel är mer komplicerad (och energikrävande) för de bränslen som framställs från biomassa. Däremot är det uppenbart att en väsentlig minskning av den fossila energianvändningen kan åstadkommas med biomassebaserade bränslen jämfört med de som baserats på fossil råvara. Användningen av fossila bränslen skiljer sig inte speciellt mycket mellan de olika alternativen emedan variationen är mellan 4,2 och 6,0%. Detta innebär att ca 95% (93,6%-96,2%) av den fossila energin kan ersättas med bioenergi i jämförelse med referensfallet.



Figur S-3. *Fossil respektive icke fossil energi*

Jämförelse med andra studier

Efter det att den svenska versionen av denna rapport publicerats kunde man notera ett internationellt intresse som motiverade en översättning till engelska. Medan arbetet med den svenska versionen pågick och efter att rapporten färdigställts, publicerades flera intressanta internationella rapporter inom detta område. Därför ansågs att enbart en översättning av rapporten utan att ta hänsyn till de senaste publikationerna vore något nonchalant. Det var också av intresse att göra några jämförelser med resultaten från vår studie och de mest intressanta studierna. Därför gjordes en jämförelse med dessa resultat separat. Denna utökning av den svenska versionen av studien finns i Appendix 1. Studier utförda av MIT, GM och en tysk studie ansågs som de mest intressanta, även om slutrapporten inte fanns tillgänglig ännu i det sista fallet. Ett antal andra studier har också diskuterats.

Metodik och förutsättningar

Generellt kan man konstatera att en jämförelse mellan resultat från olika studier är vansklig eftersom förutsättningar och antaganden varierar kraftigt. De flesta studierna verkar ha haft ambitionen att beskriva ett scenario på minst medellång sikt, 2005-2020, och har en fokusering på huvudbränslen som kan kommersialiseras i stor skala. Alla studier har inte kunnat upprätthålla denna ambition fullt ut. Långsiktig hållbarhet har bara diskuterats av några få.

De antaganden som gjorts för fordon och drivsystem verkar skilja sig åt påtagligt i flera fall. För det mesta har ett vidareutvecklat eller avancerat (framtida) fordon med förbättringar av drivsystemet, och som dessutom ofta utnyttjar möjligheterna till hybridisering, varit gemensamma förutsättningar för de flesta studierna. Jämförelser av den relativa vikten för fordonen i MIT och Ecotraffic studierna visade en rimlig överensstämmelse i de flesta fall. Fordonens räckvidd och antaganden för drivsystem och energiomvandlare kan förklara de flesta av skillnaderna. I några fall uppvisar kriterierna för fordonens prestanda stora skillnader mellan olika studier, även om de flesta studierna har valt att försöka hålla accelerationen konstant.

Drivsystem

Det är trivialt att hävda att system som baseras på dieselmotorer i de flesta studier har visats ha en fördel på 21-24% jämfört med referensfordonet (en utvecklad bensindriven bil med ottomotor). Det är emellertid anmärkningsvärt att ingen studie utom Ecotraffics har närmare försökt analysera alkoholbränslen (framförallt i drivsystem baserade på dieselmotorer), trots den potential de har bland de alternativa drivmedlen och att de kan produceras från bioråvara.

Bränsleceller är utan tvekan energiomvandlare med hög verkningsgrad, med vätgas som bränsle mer än 50% bättre än referensfordonet (GM anger >100%). Rättvisande jämförelser kan emellertid inte göras utan att ta hänsyn till den energi som används vid tankningen, vilken är hög för vätgas, och detta minskar fördelen till ”endast” omkring 25%. När också produktion och distribution tas hänsyn till minskar fördelen ytterligare. Bränslen som kräver en reformering i fordonet måste inkludera detta steg i drivsystemet, vilket minskar fördelen vad gäller verkningsgraden till 18-22% (högst för metanol) i Ecotraffics studie. GM anger högre värden för både bensin och alkoholer. Den stora skillnaden mellan den bensindrivna (nafta i ett fall) bränslecellfordonen i MIT och GM studierna kan noteras.

Hybridisering verkar generellt öka effektiviteten för drivsystemen. Förbättringspotentialen är åtminstone 20-24% för förbränningsmotorer och en studie (MIT) har visat en ännu högre skillnad. Potentialen för hybridisering av drivsystem baserade på bränsleceller är 6-12% och verkar därför något mindre än i det förra fallet.

Systemverkningsgrad

CNG/LNG baserade system ligger bra till på grund av de låga energibehoven för att omvandla naturgas till en kvalitet för rörtransport (och till LNG), förutsatt att storskaliga distributionssystem finns tillgängliga. Vätgas från naturgas är också ett effektivt alternativ på grund av den höga verkningsgraden för bränslecelldrivsystemet. Beroende på valda förutsättningar kan även DME och metanol vara alternativ med hög verkningsgrad.

Även om vissa drivmedel i gasform (metan och vätgas) kan ha en hög verkningsgrad enligt flera studier har de också blivit beaktade som nischbränslen (även om viktiga sådana) i många studier. DME är enklare att hantera och har nästan samma verkningsgrad med naturgas som råvarubas. LNG och LH_2 är flytande alternativ men, eftersom de är kryogeniska bränslen, medför de nackdelar som ökade kostnader, och i det sista fallet även en minskning av verkningsgraden. Metan har nackdelen att det inte verkar finnas någon effektiv metod att producerad den från biomassa (i stor skala). Flytande bränslen som enkelt kan hanteras som bensin och dieselolja i dag kommer att ha en stor fördel i effektivitet vid distribution och tankning och tillåter att allmänheten kan behålla sina vanor för tankning av fordonen. Av de icke-kryogeniska flytande bränslena verkar metanol vara det bränsle som ger den högsta verkningsgraden. Vid beaktande av dessa fakta verkar det förvånande att detta drivmedel inte har studerats mer noggrant.

Långsiktig hållbarhet

För att kunna behålla kolvätebaserade råvaror i ett scenario med stora reduktioner av växthusgaser torde deponering av CO_2 i jordskorpan vara nödvändigt och det har ofta ansetts att detta inte är någon omöjlighet. Den oundvikliga konsekvensen är emellertid att detta nödvändiggör ett distributionssystem för vätgas, vilket vi inte kan se som ett generellt framtida system för allmän användning (se ovan). För att minska växthusgaserna med i storleksordningen 80-90% har endast biomassebaserade bränslen en sådan potential, vilket också visats i flera av studierna.

Diskussion och slutsatser

Som sammanfattning av resultaten från denna studie kan man säga att det inte är trivialt att hitta någon definitiv “vinnare” bland de 3-5 främsta kandidaterna till drivmedel. Däremot är det lättare att utesluta något alternativ där systemverkningsgraden är förhållandevis låg. Vätgas från el är ett sådant fall.

Det förtjänar också att nämnas att det finns ett flertal olika kriterier för val av drivmedel som inte berörts i denna rapport. Ett mycket viktigt kriterium är t.ex. kostnaden för produktion, distribution och användning. Sådana analyser har emellertid legat utanför ramarna för denna studie.

Tabell S-1. *Relativ systemverkningsgrad för system baserade på råolja och fossil*

DRIVMEDEL, tankat	Bensin	Dieselolja	DME	Metanol	Etanol	FT-brän	CNG	CNG	GH_2	GH_2	GH_2	GH_2	GH_2
DISTRIBUERAT som	Bensin	Dieselolja	DME	Metanol	Etanol	FT-brän	CNG	LNG	GH_2	LH	DME	Metanol	El
Drivsystem	**Systemverkningsgrad för råolje-/fossilgasbaserade system relativt den för konventionell bil med bensindriven ottomotor (=100)**												
Dieselmotor - hybrid		150,7	120,2	115,4		94,3							
Bränslecell - hybrid			115,3	113,2		81,5	128,8	126,6	116,1	81,9	91,7	93,0	68,8
Bränslecell - direkt			107,8	107,5		78,5	124,1	122,0	111,9	78,9	88,4	88,3	66,3
Ottomotor - hybrid	124,0			109,5			128,1	125,9	90,1	63,5	71,2	70,0	53,4
Dieselmotor – konv.		125,0	99,7	95,7		78,2							
DMFC - hybrid				93,8									
Ottomotor – konv.	***100***			88,3			104,5	102,7	73,5	51,8	58,1	57,1	43,6

Tabell S-2. *Relativ systemverkningsgrad för biomassabaserade system*

DRIVMEDEL, tankat	Bensin	Dieselolja	DME	Metanol	Etanol	FT-brän	CBG	SNG	GH_2	GH_2	GH_2	GH_2	GH_2
DISTRIBUERAT som	Bensin	Dieselolja	DME	Metanol	Etanol	FT-brän	CBG	SNG	GH_2	LH	DME	Metanol	El
Drivsystem	**Systemverkningsgrad för biomassabaserade system relativt den för konventionell bil med bensindriven ottomotor (=100)**												
Dieselmotor - hybrid			92,5	87,7	76,1	73,5							
Bränslecell - hybrid			88,7	86,0	71,2	65,4	71,6	67,6	90,9	78,6	72,4	72,8	58,4
Bränslecell - direkt			82,9	81,6	67,6	62,1	69,0	65,2	87,6	75,8	69,7	69,1	56,3
Ottomotor - hybrid				83,1	70,7		71,2	67,3	70,5	61,0	56,1	54,8	45,3
Dieselmotor – konv.			76,7	72,7	63,1	61,0							
DMFC - hybrid				71,2									
Ottomotor – konv.				67,0	57,0		58,1	54,9	57,5	49,8	45,8	44,7	37,0

1 INTRODUCTION

The interest in alternative fuels, and biofuels in particular, appears to be increasing due to the ever-increasing problems associated with the emissions of climate gases from road traffic. Eventually, the fossil fuels will also be exhausted and the question is no longer *if* than *when* this will happen. In principle, the fossil fuels will not be exhausted but the cost of exploitation of the resources will become prohibitively high. A scenario of this kind is of course very far in the future (~50 years) and consequently, the present generation will not be particularly affected by these problems.

Alternative fuels are also of interest regarding the energy supply in order to be prepared for a crisis situation. This could refer to smaller crises as, e.g. a crisis related to political reasons, such as a war in the Middle East. Longer and deeper crises are also likely to occur emerging from a demand that is higher than the production capacity. Under such as scenario – that presumably should be referred to as a price crisis – will of course lead to an increase in the fuel price until demand and supply meet. During 2000 and part of 2001 such a crisis (though relatively mild) was experienced. The energy crisis that were seen twice in the 1970's, the first in the beginning of the 1970's and the second in the later part of that decade, could also be regarded to be of this character. In the relative near term (this decade), larger crisis of this kind might be expected since the production capacity, and not the energy resources, are the problem. Calculations show that the current production rate can only be increased up to a certain maximum level. The production (pumping rate) from an oil well simply cannot be increased more than up to a certain level without interruptions in the production. This is due to the physical limitations in the oil containing layers in the bedrock, which in this case sets the maximum production rate (with current technology). A similar scenario, as described above could, according to reliable calculations, occur already between 2010 and 2015. The result of this crisis could be significantly increased cost and/or a temporary lack of crude oil and oil products with a corresponding risk for a decline in the world economy. An interesting study that elaborates these problems in more detail is a report by US Department of Energy (DOE) and several of its national laboratories and other organisations [1][2]. Although, at this date (September 2001), the report is only available as a draft report, it is plausible that the report, and the subsequent studies that are planned, will have a significant impact on the energy policy in the USA.

Due to the reasons mentioned above, it could be strategically advisable (to secure the energy supply) and economically profitable (bearing in mind the international competition) to invest in an increased knowledge in this area. In a somewhat longer perspective, the investment in production and distribution capacity for alternative fuels might be an issue to consider.

In the debate about alternative fuels, the question about which fuel is the best is frequently asked. The alternative fuels can be divided into two different categories. The first category is fuels produced from fossil feedstock and the second category is fuels produced from biomass. Even if many countries in Europe, and the Nordic countries, such as Sweden in particular, have a surplus of biomass, the same conditions do not exist for all countries. There is also a competition about the biomass on a local level and likewise, it is not economically feasible to collect all available biomass (e.g. such as remote biomass). However,

[2] Numbers in brackets designate references that are listed in the reference section at the end of the report.

the competition regarding the available biomass is not so though as it seems, since the pulp and paper industry and the energy sector do not have the same demands (fibres contra energy). In summary, the limitations imposed as described, implying that the commercially available biomass would be substantially lower than the theoretically possible.

Since the automotive and fuel industries are international, it is not plausible that Sweden, or any other country in Europe, would be able to introduce a fuel on a large scale that is not used in the rest of the world. Consequently, this reality imposes several limitations on the near-term fuel candidates. A possibility to broaden the feedstock base for new fuels would be if fossil, in addition to non-fossil, feedstock could be used.

A very important factor in the choice between fuels will be the total efficiency for the complete system (on a well-to-wheel basis). This is usually referred to as a life-cycle perspective. The distinction in this study is though, that the vehicle production and the scrapping of the vehicles have not been taken into account. The reason for that these stages have been omitted is twofold. First, the energy use in these stages is relatively small in comparison to the fuel energy used. Second, no significant differences could be expected between the various powertrains investigated in this study. It has been of interest to elucidate the differences between the options but not necessarily the absolute level.

In addition to the factors mentioned above, cost is the most important factor to consider. However, in order to impose some limitations on the volume of the work, this factor has been omitted from the study. An expansion of the work reported here could be added later where this is taken into account.

The scope of the work reported here has been to elucidate the system efficiency for alternative fuels, taking into account that this comparison is to be carried out according to a simplified life-cycle perspective. In order to be able to consider future improvements in the processes for fuel production and distribution of the fuels for the least developed fuels, it is necessary to use a reasonably long time horizon for the study. A scenario that could occur between 2010 and 2015 has been chosen as a realistic timeframe. The real outcome will, of course, be dependant on a number of various factors – among them e.g. political decisions – but what was important in this study, was to show the technical possibilities that might be applicable in the future. In view of the large number of combinations studied, it should be noted that, in practice, only a few of them would be commercially exploited in the future. Obviously, there is no need either to develop options that have considerable drawbacks. By using the results generated in this study, it will be possible to make rough assessments between the various alternatives (i.e. excluding the least favourable alternatives) and consequently, this has been the main goal of the study.

In order to provide a better overview of the main results, short summaries has been made in special summary boxes (see example below) in the main chapters.

Ecotraffic's summary

In the summary boxes a synopsis of the conclusions that can be drawn from the results generated in this study, or the results from other studies cited, is made.

2 BACKGROUND

In the past, Ecotraffic has carried out several studies of relevance to the work reported here. The first, and probably the most important study that could be mentioned in this respect is the life-cycle analysis, "Life of Fuels" (in the following abbreviated LoF), which was one of the first more comprehensive studies in this area [2]. Several of the fuel and powertrain combinations assessed in the present study were also studied in the LoF study. Within the framework of an earlier work for the Swedish Communications and Transportation Research Board (KFB), and with some additional internally funded work, the computational model used in the LoF study[3] has been implemented in MS Excel [3]. Consequently, alterations can now be made considerably easier than before. In general, it can be stated that input data and results from the study regarding fuel production and distribution still are reasonably valid for some fuels, whereas additional work is needed for other fuels. However, data for vehicle energy use and exhaust emissions are outdated. In a report that Ecotraffic carried out for KFB, the impact on environment and health were investigated [3]. Some prognoses for exhaust emissions from various fuels were also made in that report, which gives some guidance for the assumptions made in this report. A more general report about alternative fuels commissioned by the Swedish EPA [4], and report carried out for MTC [5, 6] have also been useful as the basis for this study.

The Swedish National Energy Administration (STEM) and its predecessors[4] in the field of energy research have been responsible for the governmental support in the field of research, development and demonstration regarding energy supply and energy use. Among the incentives made by STEM, a multiyear support for research and development in the area of ethanol production from cellulosic matter could be mentioned. Similar support for developing production methods for methanol from biomass has also recently been discussed by STEM. Support for production of biogas has also been granted and a continuous support in this area by STEM and other authorities can be anticipated in the future. In addition to the support for the production of biofuels, STEM has also granted support for research, development and demonstration in fields as increased energy efficiency, new drivetrain concepts, etc.

The Swedish governmental agency KFB had a 6-year program (1992-1998) with the aim of demonstrating the use of biofuels, the so-called Biofuels programme. Similar support has also been granted for electric and electric hybrid vehicles in a separate programme. The new Governmental Agency Vinnova, which was created in 2001 through the merger of KFB with several other governmental agencies, is likely to continue these efforts.

Several other incentives and support in the area of alternative fuels and powertrains of interest in this respect could also be mentioned, but have been left out in this summary. Some of these measures have also included fossil alternative fuels, such as e.g. natural gas. No overview of these programmes and projects will be made here but it is worth mentioning that there is some documentation available that could be referred to if there is an interest in these fields.

In summary, it can be that concluded that considerable efforts have been made in this area in Sweden. For example, Stockholm has the largest fleet of ethanol-fuelled buses. A tech-

[3] The calculations in the LoF study were carried out without any computer spreadsheet.
[4] Previous Swedish governmental agencies in this field were NUTEK and STU.

nology procurement of about 3 500 fuel-flexible cars has been made and the delivery of these vehicles will start in the fall of 2001. The result of these efforts will be that Sweden will have one of the largest fleets of this kind of vehicles in the world[5]. An important ingredient, which is still missing, is an introduction strategy for alternative fuels in Sweden. A decision on this important matter could provide vastly improved conditions for long-term investments in alternative fuels. The reasons why this strategy is still missing is subject to speculation but the opinion of the authors is that the necessary documentation for such a strategy is still not comprehensive enough for the development of a detailed plan. The rules and regulations within the EU are also potential barriers of non-technical character that could be problematic in this respect. It is conceivable that this type of regulations will be at least as difficult to change as it will be to find solutions to the technical problems that still are unsolved.

The work described in this report has been carried out for the Swedish National Road Administration (SNRA). In the spring of 2001, a Swedish version of the report was published. Due to the considerable interest the report, it was decided to make an English version[6]. This version also contains a comparison with some findings in reports that have been published lately on this subject (see Appendix 1). The main scope of the present work has been to address some of the issues described above.

[5] One could add that the number of FFVs in the USA is significantly greater but on the other hand, many of these vehicles are running on petrol

[6] Two minor errors have been found in the previous Swedish version of the report and corrections have been made in this report. First, there was a small numerical error regarding hydrogen produced from electricity. Second, there was an error in Figures 8 regarding the results for LH_2, since a direct drive fuel cell had been shown instead of the hybrid version.

3 METHODOLOGY

The scope of the study was to generate data that could be used to make a rough ranking between the selected alternative motor fuels based on the well-to-wheel efficiency for the total system. The definition used by the authors for this efficiency is the efficiency in the full fuel cycle from the production of the feedstock for the fuel to the end use in the vehicle. As mentioned before, the production, scrapping, maintenance etc. of the vehicle is not included in the analysis.

The strategy in the study has been to, in as many cases as could be applicable, use results from earlier studied and data that has been collected earlier. Such examples are life-cycle analyses, strategies for the introduction of new motor fuels, studies on vehicle technology, and so on. However, the collection of new data has also been necessary in several cases. Through literature search in databases, the essential literature has been found and subsequently ordered from the publishing organisations.

In the case of the efficiency of various powertrain concepts, the primary problem is that data in the literature in general is based on different presumptions in various studies. Consequently, it is difficult to make correct comparisons based on using available data. The vast number of variations for the technology used add further complication and this highlights the difficulties of comparing data from different studies. Instead of attempting to collect and assess all this information, another approach has been used. The simulation software Advisor®, release 3.0[7] (an application in Matlab/Simulink™) from the US National Laboratory NREL has been used to simulate the energy use for the various powertrain and fuel combinations. The necessary input data have been collected from this programme and from other sources in the literature. In addition, some careful considerations of the authors have been used to make some modifications when necessary.

3.1 Timeframe

The choice of timeframe for the analysis is a very important consideration for a study of this kind. First, it is essential that the technology for production, distribution, end use etc. must be fully developed for the alternative fuels in order to make the comparison as neutral as possible. Unless this approach is used, the comparisons will not be relevant. Undoubtedly, this implies that the comparison have to be carried out for future systems, as many of the combinations studied are not fully developed yet. Certainly some of the systems could be compared on the present commercial level, e.g. such as vehicle emissions, but to make the comparison more relevant, a future perspective is essential. The time horizon of 2010 to 2015 has been chosen due to two main reasons. First, the timeframe is not distant enough to preclude extrapolations of known technology and the presumed commercialisation of advanced research results. Second, the timeframe must be set distant enough to allow a relevant comparison of mature commercial systems according to the discussion above. This is of relevance for, e.g. several biofuels, where the production technology is not fully developed today. An example is the previously cited LoF report [2], where several of the production processes had to be regarded as technologies that were not fully de-

[7] After the simulations were carried out, version 3.1 was released and the current version of Advisor®, as this report is written (September 2001), is 3.2.

veloped at that time. In the present study, we have of course taken into account that these production processes will be further developed in the future and that the processes anticipated will be possible to commercialise within the timeframe foreseen.

In Europe, the present situation is that emission limits for passenger cars have been set for a time horizon of 2005/2006 (Euro IV). In the USA and in California, the limits are more far-reaching[8]. In view of these limits, it is likely that the future emission limits in Europe will be more stringent as well. It is also likely that the difference in emission limits between fuels (petrol and diesel fuel) will become smaller or diminish, as in the USA. Consequently, the difference in emission level (in absolute levels) between various engine/fuel combinations will be of less importance in the future. This is of course on the condition that it will be possible to meet the emission limits from a technical standpoint and that this could be made at a reasonable cost. However, with the timeframe of the study, *the authors have not been able to conclude that this would be impossible for any of the engine/fuel combinations assessed.*

3.2 Literature survey

Since a couple of years, Ecotraffic has had access to the "Global Mobility Database" (GMD) from SAE, which is a very valuable tool in this kind of work. The database contains abstracts and biographies from more than 105 000 papers and articles published by SAE, its sister organisations world-wide and other partners of SAE. The GMD database is available in two versions, one on CD-ROM and the other with Internet access. Ecotraffic use the latter version, since it has a decisive advantage due to the monthly update instead of a yearly update for the former version. As SAE is an organisation for engineers in vehicle technology, the database is dominated by literature within this area. However, some literature on the production of fuels and on life-cycle analysis is also available. These areas have received an increased interest during the past years.

Besides the SAE database, other literature sources must also be used, since this area is somewhat broader than the main focus of the database. Therefore, a limited search has been made at organisations that are active in this area. This search has mainly been performed on the Internet. Literature of basic interest has been the literature used as input data for similar studies as the one reported here.

3.3 Literature evaluation

A comprehensive summary of the literature found in the search has not been made, since this work could not be accomplished within the limitations of the study. Instead, the most important studies that have been used as input data for the calculations have been cited. Assessments and considerations of the authors have been made in the cases where the input data have been scarce or missing. Comments about these estimates have been made when necessary.

[8] This refers to both the lower emission level (compared to Euro IV) and the timeframe (2009).

3.4 Lifecycle perspective

The production processes for some the alternative motor fuels, bio-based fuels in particular, still are underdeveloped. In extreme cases, production schemes for bio-fuels may even lead to increases of emissions of greenhouse gases. Such schemes, which have often been implemented by agri-political reasons, have lead to an undeserved bad reputation for bio-fuels. Such projects had probably not been implemented if adequate knowledge had been available before the decisions were taken. It is therefore important to improve the processes to attain commercial status.

3.4.1 Feedstock production

Crude oil and natural gas (fossil gas) have been formed from dead plants and marine organisms. The energy use to exploit these resources is thus limited to exploration and recovery. Moreover, crude oil as liquid (sometimes after heating) can be easily transported in bulk. This is also a condition required for the comprehensive world trade of the feedstocks.

The conditions are, of course, entirely different for bio-feedstocks. The highest efficiency in the production is attained by extensive cultivation while intensive cultivation (farming) by definition is worse in this respect. Conventional forestry (silviculture) exemplifies extensive cultivation and SRF (short rotation forestry) takes an intermediate position to farming. These lignocellulosic feedstocks are more difficult to convert to motor fuels than for example feedstocks from fatty oil plants (to RME) or sugar and starch containing plants (to ethanol). The transport of the bio-feedstocks to conversion plants naturally is more cumbersome and expensive compared to crude oil. It might be of some advantage if conversion plants could be situated to minimise transports from the cultivation areas compared to remote oil fields.

3.4.2 Production processes

During millions of years, crude oil has been converted in the crust of the earth to a composition that allows conversion (refining) to motor fuels (and other products) in an efficient way. For example, petrol can be produced with an efficiency of around 80% (crude oil recovery included) and diesel oil with around 90% efficiency.

One reason for the relatively low efficiency in the production of many alternative motor fuels is the lower system efficiency of the conversion process compared to the conventional fossil fuels. The background is that the conversion of, for example, a bio-feedstock is more far-going in a process chain that is more energy demanding than the refining of crude oil, and the production of the feedstock itself requires energy. Crude oil can be considered as an intermediate conversion product from the alterations of the virgin raw material in the crust during millions of years that is favourable at the following refining. Moreover, in several of the process steps in the production of bio-fuels, fossil auxiliary fuels may be used. These may be replaced by bio-fuels but the basic problem with low efficiency in the entire process chain remains. Simply put, low efficiency in the production leads to lower yield of motor fuel and less fossil fuel can be replaced. It therefore is as important to have as high system efficiency for alternative motor fuels as for the conventional motor fuels. An exception from low efficiency is illustrated by rapeseed-oil-methyl-ester, RME (and other fatty acid products), for which the production mainly involves only a re-esterification of primary oil obtained by mechanical pressing. The disadvantage for RME is low efficiency of the rape production through intensive cultivation and low hectare yields.

New production processes for bio-fuels are, however, under development and particularly promising fuels are methanol and ethanol that can be produced from lignocellulosic feedstocks. The availability of such feedstocks is large. The problem is that the conversion processes not yet are fully demonstrated with low yields and too high costs.

It is important to note that the production plants that have been studied in this report have not been integrated with any other production but are energy-wise self-sustained greenfield plants. Thus, no recovery of surplus low-grade heat for district heating purposes has been included. If consideration to possible use of such a heat carrier, the system efficiency might improve somewhat (particularly for bio-fuels). A study of such cases would be comprehensive, as consideration must be taken to local circumstances and demands for district or other low-grade energy carriers.

3.4.3 Distribution and refuelling

The distribution of motor fuels is an important part of the fuel chain due to the high costs connected to the construction of finely branched systems for general availability. There will be great advantages for such alternative motor fuels that can be distributed in the existing net without or with only moderate adaptations of it.

At normal pressure and temperature, liquid, easily handled motor fuels naturally are simplest and cheapest to distribute. Synthetic hydrocarbon motor fuels (petrol and diesel oil) can be distributed in existing net with no or very minor adaptations as blend components or as a new, separate fuel quality. Methanol and ethanol would require measures in the net (for example to prevent corrosion) to be able to be distributed but the adaptations are relatively small and there are earlier experiences from fleet demonstrations can be utilised.

Gaseous fuels and cryogenic liquids should present the greatest difficulties and the highest costs at distribution. This goes particularly for the Nordic countries due to the low population density. In this case, the conditions for large market penetration are of greatest interest, i.e. how large part of the energy usage in passenger cars (and possibly heavy vehicles) that can be replaced by the alternative motor fuel. Particular consideration must, of course, be paid to our low population density compared to countries on the continent and for example the USA. A scenario in which distribution net for natural gas covering more than 90% of the population in Sweden (which is the case in other countries, for example the USA), would be entirely unrealistic considering the low population density in our country. For methane, the distribution as LNG (sea, rail and road) must instead be considered.

The following “threshold-limits” for penetration of motor fuels in fully accomplished scenario may be of interest to anticipate at calculations of system efficiencies:

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

Motor fuels and powertrain combinations with a potential use less than 1% might be investigated but such alternatives have been excluded, as such low penetration would be of little interest with regard to effect of greenhouse gases (by definition <1%).

3.4.4 End use

In order to achieve high system efficiency it is important that the interaction between the motor fuel and the powertrain (energy converter + energy transmission + possible energy store) of the vehicle is considered. Undoubtedly there are examples that energy converters with higher mean efficiencies can be used compared to the petrol driven otto engine today (the reference case), e.g. a fuel cell. Nevertheless, it is also important to observe that the efficiency in other parts of such a system might be lower. To operate a fuel cell with petrol the latter must be reformulated from the present market petrol. Moreover, the petrol must be reformed to generate the hydrogen gas required by the cell. This implies increased losses compared to use in a piston engine. The electrical transmission also has a lower efficiency compared to a mechanical transmission for an internal combustion engine (ICE). On the other hand, an electrical drive system makes regenerative breaking possible if there is adequate battery capacity (i.e. power density) installed. However, this could also be accomplished by a hybrid system with a conventional ICE. A fuel cell should therefore be compared to an ICE-hybrid. At such a comparison, the efficiency improvement for a vehicle with fuel cells will not be as high as it looks at first glance.

On the whole, it is important to compare the alternative drive systems with developed conventional systems to make the comparison as relevant as possible. The reasonable time-frame should be at least 10 years ahead. During that period the conventional drive systems will also be developed and this must be considered, and an important part of this process is to adapt and optimise the powertrain systems for alternative motor fuels. By this development, the full potential of the alternative fuels can be utilised.

3.5 Examined systems

3.5.1 System definition

Systems for energy supply, here with emphasis on motor fuels, shall comprise the entire chain from feedstock to and including end use from the aspects of energy utilisation and of the greenhouse effect by fossil CO_2. In order to be able to correctly judge and fairly compare different alternatives, it is necessary to know the origin of the energy carriers. The systems should also be able to produce the same amount of end use services of various kinds for a complete and fair comparison.

Our present supply of motor fuels is based on a semi-finished, fossil product, stored in and recovered from the crust of the earth, mainly crude oil having its origin in biomasses at times tenths or hundreds of million years ago, which then have been converted (fossilised) under conditions that no longer exist on the earth. Systems that shall be sustainable, must be based on recyclable and renewable raw materials and not have larger scope than nature (with assistance of mankind) can accomplish (that potential yet is far from being fully utilised). It is then obvious that neither energy efficiencies nor the influence on the greenhouse effect can be compared without considering the paths of formation of the feedstocks. The longer process chain for conversion of young biomasses results naturally and unavoidably in differences that must not be considered negative.

Energy efficiencies or yields are always given on basis of the lower heating value (LHV) of water-free feedstock and product, as this has been customary in Sweden, though reporting on basis of the higher heating value (HHV) is more correct and gives a more complete accounting. It is most important to clearly state on which basis results are given in order not to give misleading figures. Yield figures will be higher on HHV-basis if the product is richer in hydrogen than the feedstock (or contains bound oxygen as in alcohols) and lower if it is poorer in hydrogen.

In the study, fossil motor fuels and auxiliary process fuels have been used in the different part of the process chain, though it would be possible and reasonable to use renewable fuels to describe the potential of the alternatives, although they are not used in many cases today. The motor fuel used within the chain decreases the fuel for sale but the chain appears to be better from greenhouse point of view.

Based on the discussion above, different systems have been chosen for deeper study. Two basically different classifications of the systems can be done to improve the lucidity. They are:

1. Classification based on feedstock. It can be fossil (natural gas) or biomass.
2. Classification based on the state of the fuel, gaseous or liquid. This has a substantial influence on conditions and costs for distribution, storage, and fuel capacity onboard the vehicles.

In the project design, the latter classification has been used as being more lucid and automatically giving focus on the problems at distribution and refuelling, two of the most important factors for the possibilities to achieve a widespread, general use of alternative motor fuels. It is sometimes of interest to separately see the efficiencies for fossil and non-fossil feedstocks respectively at accounting the results, and this sub-classification have been chosen.

3.5.2 Fuel production pathways

The fuel production is of two principal types, thermo-chemical and bio-chemical respectively. In the thermo-chemical conversion pathway, the biomass feedstock (after drying) is gasified and yields after treatment of the raw gas (purification, shift, etc) a synthesis gas, from which the motor fuel is synthesised. The synthesis gas may also be used for power production. There are also other possibilities for power production from biomass, e.g. via the conventional steam cycle (low efficiency), wood powder fired gas turbines and systems with heat exchangers. For the two latter systems, there are great technical, not yet solved difficulties and are not further considered here. The power produced here can only be seen as a form for distribution of hydrogen (electrolysis at the refuelling site). Electric, battery power vehicles can, by definition, be classified as a small niche with a potential below 1% of the energy usage in the transport sector and therefore, they are not considered here.

There are two different routes for the bio-chemical conversion, namely via saccharification of cellulosic feedstocks and fermentation to ethanol or by anaerobic digestion to methane (biogas). The first process route still needs further development to attain higher efficiency and acceptable costs. The second route is commercial with certain feedstocks but needs further development to a broader range of feedstocks.

The following types of motor fuels have been considered to be of interest to study for final use (not in priority order but in density order)

- Synthetic hydrocarbon fuels (hereafter referred to as "synfuels"): diesel oil (Fischer-Tropsch diesel, FTD) and /or fuel cell fuel, i.e. special quality adapted for fuel cells

- Ethanol
- Methanol
- DME
- Methane
- Hydrogen

As reference, petrol and diesel fuel have also been evaluated. Both these fuel qualities have been considered to be reformulated and virtually sulphur-free (<10 ppm). Hence, the possible advances in the refining processes for these fuels will be counteracted by the additional processing that will be necessary to fulfil the anticipated future fuel specifications. In the diesel fuel case, Swedish Environmental Class 1 (EC1) diesel fuel has been used as the basis for the assessments. It should be noted that this fuel is lower in density and end boiling point than current European diesel fuel. Although it is likely that future diesel fuel specification might decrease density and end boiling point somewhat (as indicated by the proposal by the engine and automotive manufacturers ACEA, AAM, EMA and JAMA [7]), it is not likely that it will become as low as the EC1 fuel. Therefore, the efficiency for the production of a future European diesel fuel might be somewhat higher than we have anticipated.

Compared to the original project proposal, which was discussed with the Swedish National Road Administration, synfuels and DME have been added in the final scope of the project. This does not mean that these motor fuels should be given particularly high priority but rather that they must be included in an introductory discussion. The interest in DME has for instance now and then (among others from Volvo Truck) been high, and a growing interest for synfuels (hydrocarbons) can also be noted, particularly in the USA.

Electricity is not treated as a separate fuel, as the potential for battery powered cars is considered too small. No break-through for the battery technology that could justify widespread application can be noted within foreseeable time. Refuelling with electricity in hybrid vehicles could possibly have a large potential (as most trips are short) but this would imply rather large battery capacity onboard these vehicles. This presumes principally that the hybrid vehicles would be of series hybrid configuration, but indications are that the auto industry will prioritise parallel hybrids with minimised battery capacity for cost reasons. Fuel cell vehicles is an application, which *maybe* will require a larger battery capacity than parallel hybrids and the potential for external electricity supply might be larger in this application. It has, however, been neglected in order to somewhat reduce the number of cases. The most interesting possibility to use electricity is to produce electricity to generate hydrogen by electrolysis at the refuelling site. This is a rather simple and well-established operation and may, at least in an introductory phase, be of interest to avoid the difficulties at distribution of gaseous hydrogen. Any use of power (in vehicles or for hydrogen production) that has been produced during night has not been investigated.

3.5.3 Vehicle powertrains

The various types of drivetrain concepts of interest to study are primarily electric hybrids of conventional piston engines and fuel cells. The piston engines can be subdivided into “otto-cycle” and “diesel-cycle” engines but it is also conceivable that options that strictly speaking are hybrids of these two options (i.e. something in-between otto and diesel) could be possible for some fuels.

The fuel cells could also be subdivided into two groups, hybrid fuel cell systems and direct fuel cell systems. In the latter case, no battery that has a capacity required for high power would be necessary, but on the other hand, the fuel cell stack must be considerably greater than in the former case. In addition, the direct drive system has to be able to follow the dynamics of the driving cycle. The only fuel that enables such dynamic performance for the fuel cell drivetrain is hydrogen. Fuel cells based on direct reforming of methanol (DMFC) are discussed but it is not clear whether it will be possible to achieve dynamic performance high enough to be able to avoid a large battery. Therefore, the direct fuel cell alternative of the DMFC has not been assessed. An alternative of the direct fuel cell system worth discussing is a system where the battery capacity is relatively high but lower than a hybrid system. On the one hand, it could be necessary to have a certain battery capacity for start-up and to provide acceptable performance during the cold start phase. On the other hand, a larger battery capacity enables regenerative braking. The battery capacity foreseen here is of the same order of magnitude as the capacity that is necessary for parallel hybrid vehicles with piston engines. This corresponds to a battery weight of about 50 kg for advanced battery concepts (to be compared to 10 to 20 kg for conventional 12-V lead-acid batteries). Consideration about the cost will be a very important aspect regarding this matter and there are many reasons for not allowing too high battery capacity due to this standpoint.

3.5.4 System selection

In order to provide a better overview of the variety of different systems, a couple of graphical illustrations have been made according to an original idea from Olle Hådell at the SNRA. In the discussions preceding this work and while the work was carried out, the original idea was somewhat refined. It should be noted that the aim of the figures has not been to provide a complete view of the energy system but instead the intention was to show straightforward overviews that would simplify the description of the subject.

Possible routes for gaseous and liquid fuels respectively are shown in Figures 1 and 2. The criteria for the choices between the various options should be that the system must have a number of necessary characteristics to be able to succeed in the future. In this respect, the most important aspects are that it should qualify for general use and it should be user-friendly. This indicates that the fuel must have properties that enable it to be distributed for widespread use and it must be possible to use by ordinary people without specific education (an aspect that is often forgotten). Other criteria are that the fuel should be available on the international market; it should be possible to use by several powertrain concepts; it should have a broad feedstock base and the fuel production and use must be economically acceptable. Bearing these constraints in mind, the energy efficiency and the use of fossil energy has been investigated.

Gaseous fuels

A graphical illustration of the "gaseous" system is shown in **Figure 1**. As can be seen in the figure, four different gaseous fuels are produced: natural gas (methane), dimethyl ether (DME), hydrogen (H_2) and biogas (methane). The authors have chosen to classify DME as a gaseous fuel although it is can be liquefied at a moderate pressure. DME is generally liquefied for distribution and vehicle use, but the fact that the fuel is in gaseous state at normal conditions (atmospheric pressure), it has been regarded as a gaseous fuel. The complications due to these restraints are of similar magnitude as for liquefied petroleum gas (LPG). Electricity is only considered as a means of distributing hydrogen.

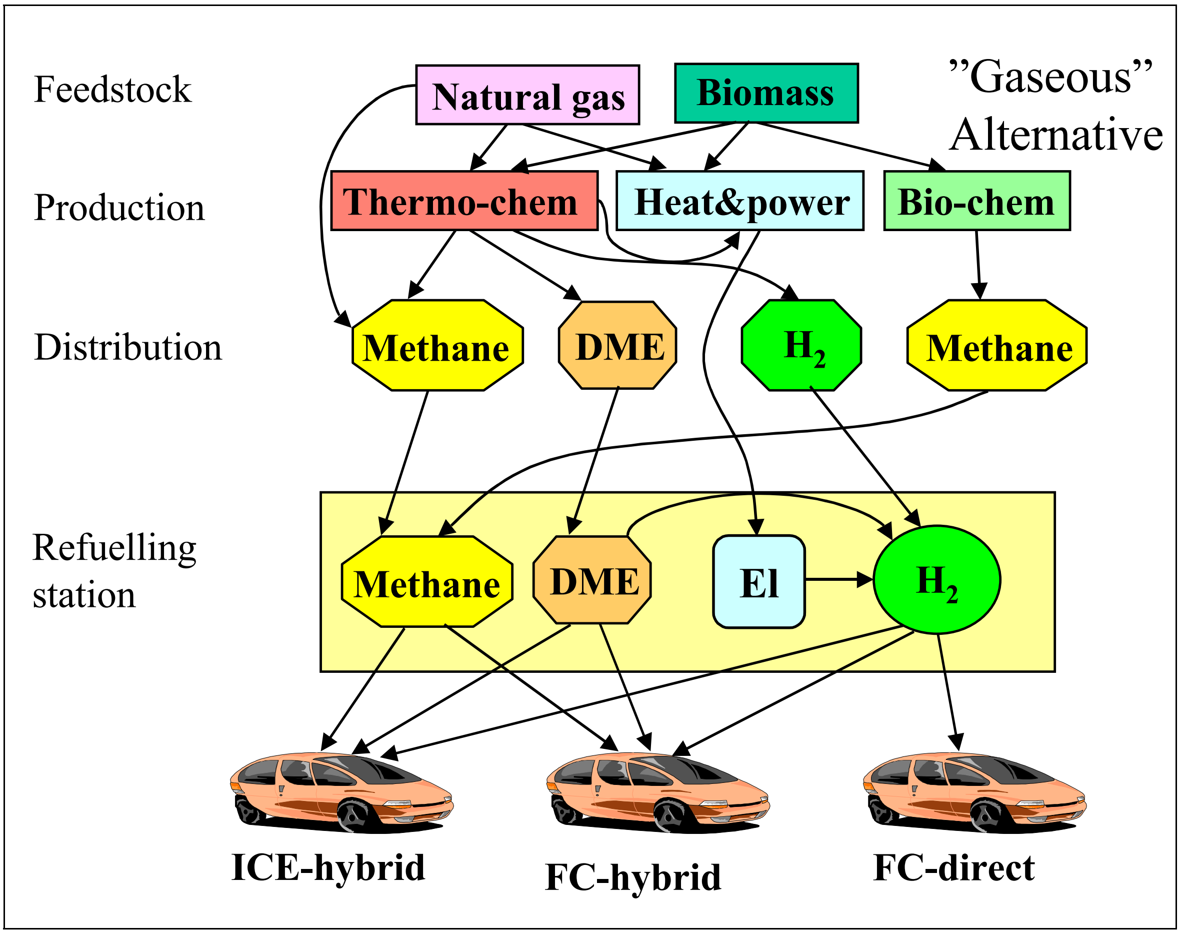


Figure 1. *Alternative "gaseous" fuels*

The co-distribution of various sources methane, whether it is in the form of natural gas or biogas, seems to be an obvious rationalisation in the cases where it is possible. The option of distributing methane in cryogenic state (LNG) is an alternative that cannot be overlooked and potentially, this could provide the opportunity for a broader introduction and general use of this gaseous fuel. It should be noted that this form of distribution could provide an opportunity to either fill LNG or CNG at the refuelling station without too much added complication. The most likely problem seems to be the cost. The various options of distributing methane have not been indicated in the figure.

Hydrogen can be produced from DME by reforming at the refuelling station in a similar fashion as in the methanol case, and this could be another option of simplifying the distribution of hydrogen. This is on the condition, however, that DME will be an interesting fuel for fuel cells (on-board reforming) and that it will be of interest for piston engines as well during a transitional period. Production of DME solely as a means for distributing hydrogen does not seem to be a viable option. Methanol should be a more suitable solution for this purpose, since methanol is a liquid fuel and therefore, simplifies the distribution considerably in comparison to DME. It should also be noted that DME is not an ideal fuel for otto engines, which implies that this alternative has not been considered for this engine type.

Hydrogen can be produced from electricity through electrolysis at the refuelling station. This is a system of interest to study as an alternative to the production of hydrogen directly (thermo-chemical route) or by (on-site) reforming of methanol or DME. The production of electricity is anticipated to be made at a plant that either has a very efficient combination of a gas and a steam turbine (combi-cycle) or, as an alternative, an advanced so-called HAT cycle (Humid Air Turbine). The fuel for the plant is either fossil natural gas or gasified biomass (thermo-chemical route). Direct production of hydrogen at the power plant through electrolysis is hardly of interest, since the hydrogen can be produced at a lower cost and with higher efficiency by using the thermo-chemical process. Localised production of hydrogen at the refuelling station (through electrolysis, methanol or methane reforming) is possible but it should be noted that this production is more complex than to handle conventional filling pumps and therefore, needs attention from educated personal.

The distribution of gaseous fuels, hydrogen and methane, through pipelines is based on the assumption that a pipeline grid is already available, since the transportation sector alone will not be able to bear the cost for this infrastructure. Initially, this might not be an issue in countries that already have a pipeline grid that covers most of the population. However, a considerable additional investment in the infrastructure would be necessary for general widespread use of these fuels in the transportation sector. In some countries, such as Sweden, where the natural gas grid only covers a small proportion of the populated areas, this problem is even more pronounced. However, since cost has not been the main issue in this study, it can be concluded that this form of distribution *could* be possible (although it might be impractical) for distributing gaseous fuels. Nevertheless, distribution by pipeline to areas with low consumption tends to be an absurd solution. Therefore, distribution systems for gaseous fuels through pipeline tend to become niche solutions. The distribution for a general use of these fuels would have to be made with liquefied fuels even if the end use of the fuel is carried out in its gaseous form. Cryogenic methane (LNG) or hydrogen (LH_2) by tankers and tank vehicles could be systems that would be generally applicable and that could be combined in a system for use as gaseous fuels (LNG and LH_2) for heavy-duty vehicles (commercial use) and in vaporised and compressed form (CNG and GH_2) for light-duty vehicle (general use). DME, as well as LPG, are also examples of this kind of distribution but with less complication and risk, since they are not cryogenic although under (moderate) pressure. Cryogenic fluids are presumably produced in large, centralised plants, e.g. such plants that are based on remote natural gas (RNG). Refuelling of cryogenic fluids by the public must be considered doubtful due to safety concern as well as storage of these fluids in light-duty vehicles. These options are not considered in this study. The refuelling time is another important factor to consider. It takes longer time to refuel with gaseous fuels than with liquid fuels and presumably, this is also the case for cryogenic fuels.

Liquid fuels

A graphic illustration of the liquid system is shown in **Figure 2**.

Using the thermo-chemical process route, either a synthetic liquid fuel (e.g. Fischer-Tropsch fuel, or “synfuel”), or methanol can be produced (**Figure 2**). The latter fuel gives a higher efficiency in the production process but a marginally more expensive fuel distribution. Methanol is also a very suitable fuel for fuel cell vehicles, since it can be reformed easier than other fuels. A higher energy density and the simplified distribution (as blending components) are advantages for the synfuel that cannot be overlooked. If the synfuel is to be used in fuel cells, it is plausible that it has to be distributed separately from the other conventional fuels as diesel fuel and petrol. It will be a new fuel quality. The on-board reforming process imposes new constraints on the fuel (sulphur, aromatic content, etc.) that the present petrol and diesel fuels do not fulfil. On the other hand, some simplifications in the production process compared to petrol are possible if the fuel is only to be used in fuel cells. In order to optimise the fuel for fuel cell use, a hydrogen content as high as possible is desirable and in such perspective, e.g. the reforming of petrol in the refinery where the hydrogen content is decreased, is detrimental. This process increases the octane level of the fuel by increasing the aromatic content. Consequently, otto engines and fuel cells should not use the same fuel. A synthetic diesel fuel is well suitable for diesel engines and, with some further development work of the reformer, this fuel might also be appropriate for fuel cells.

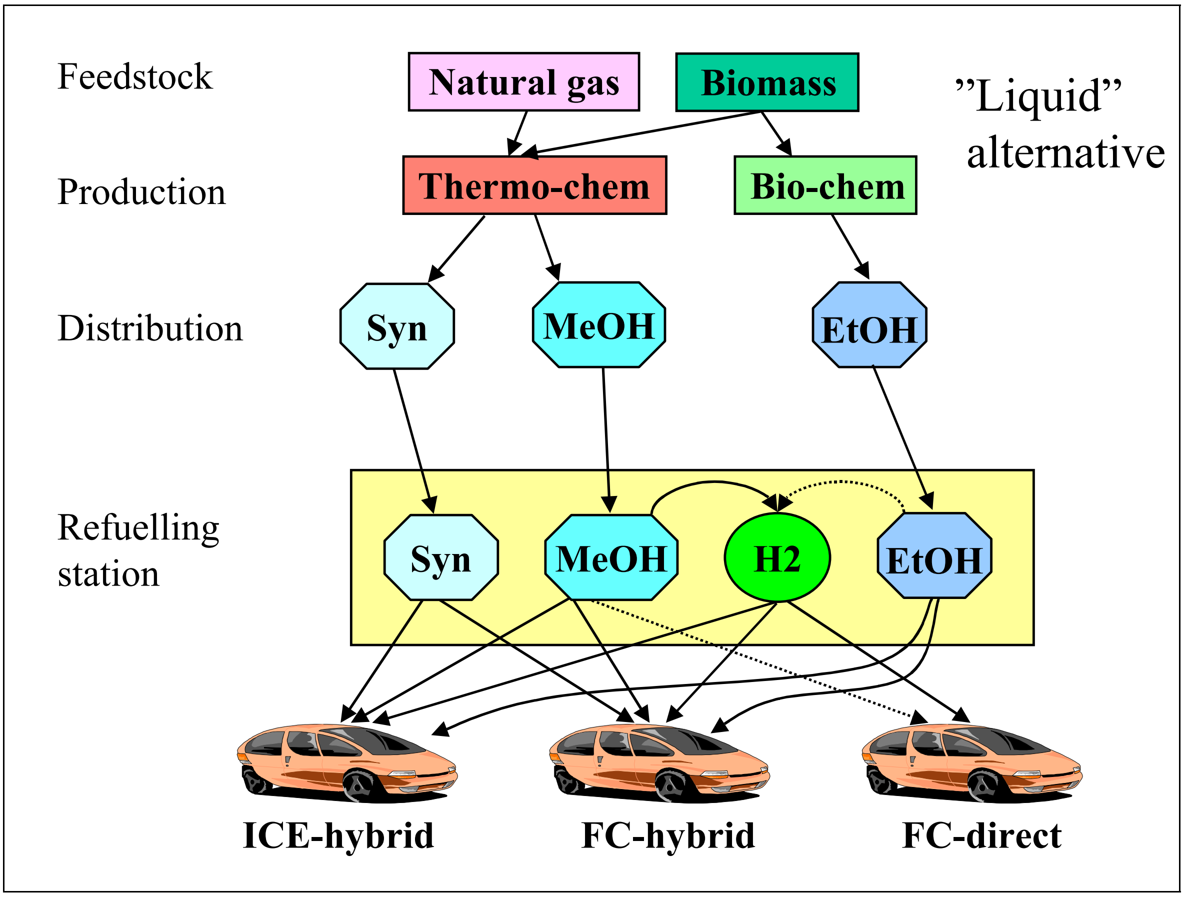


Figure 2. *Alternative "liquid"*

Reforming of methanol to hydrogen at the refuelling station is, as mentioned above, a possibility that could be appropriate for resolving the distribution of hydrogen during an introduction phase. The problems with hydrogen storage in the vehicle have to be considered anyway and it is likely that a shorter range for the vehicle is something that has to be accepted in this case. For fleets of special vehicles, and for heavy-duty vehicles in particular, this could be a solution that, at least in an initial phase, would be of interest. On-board reforming of methanol could provide a range on a similar level as for conventional fuels and this would be an interesting long-term option if the hydrogen storage cannot be satisfactory solved. Reforming of ethanol for the production of hydrogen at the refuelling station has not been considered as a practical alternative, as it is more complicated than for methanol (or DME) and consequently, increases the losses.

The systems (well-to-wheel) that have been selected for a more thorough analysis are:

Gaseous fuels:

- Fossil natural gas (methane) that is imported and distributed through pipeline (niche solution) or as LNG using tanker ships. This methane could be supplemented (or extended) by biogas (CBG) from digestion and by synthetic natural gas (SNG) produced thermo-chemically from biomass. Refilling could be made as compressed gas (CNG) or as liquified gas (LNG), mainly for heavy-duty vehicles.
- Fossil natural gas converted to DME or hydrogen (GH_2 for general use, LH_2 in niches). Supplementing these fuels of fossil origin by fuels from derived biomass is possible. Refuelling in liquid state (DME), in gaseous form (hydrogen, general use) or as a liquid (commercial use).

Liquid fuels:

- Fossil natural gas converted to methanol or synthetic hydrocarbon fuels (synfuels) according to Fisher-Tropsch, Mobil or similar processes.
- Biomass thermo-chemically converted to the same fuels as above.
- Biomass bio-chemically converted to ethanol.

Ecotraffic,s summary

It is of importance to conclude that a "fair" comparison cannot be made at the technology level of today, since the production processes for several fuels has not yet been fully developed. Therefore, the timeframe must be longer but not so long that it would lead to pure speculations.

A classification of fuels into categories that are pure niche fuels and such fuels that could be of interest for general use, i.e. "main" fuels is necessary, since the potential for the reduction of exhaust emissions and greenhouse gases is limited for niche fuels. The availability of feedstock and the cost for distribution and use are limiting factors. Gaseous fuels are fuels that per definition are niche fuels due to these reasons.

A practical classification of fuels could be the following: 1) feedstock origin (fossil or non-fossil), 2) the distribution forms (gaseous or liquid).

4 RESULTS

It may be important to emphasise that the classification of the production chains are the same as in the previous study “Life of Fuels) by Ecotraffic. The interested reader is referred to this publication for a more comprehensive description of presumptions and results. Even though the structure is the same in both cases, a number of alterations of input data have been made in the present study compared to the previous one to reflect the progress that has been made about improved efficiencies of the production processes. There also are differences in data for the vehicles, as future models (year 2012) have been presumed.

4.1 Feedstock production

Only natural gas is included in the study as fossil feedstock for motor fuels and biomass of lignocellulose type (wood) and lucerne as digester feedstock as renewable feedstocks.

4.1.1 Natural gas

Natural gas has its origin in biomasses tenths or hundreds of million years ago and they have been converted (fossilised) in the crust of the earth under conditions that no longer are existing on the earth. Recovery occurs from accumulations in the crust by drilling on land or off-shore at sea. The raw gas contains except the main constituent methane varying amounts of higher hydrocarbons and sometimes nitrogen, carbon dioxide and sulphur containing compounds. The raw gas is usually named “wet gas”. Part of the natural gas is recovered at the recovery of crude oil, so called associated gas, which sometimes is flared if there is no market available.

To obtain an in pipe transportable gas (dry gas), corrosive and compounds condensable to liquids have to be removed in an up-grading terminal. Recovery of light oils, LPG (propane, butanes) and ethane is also made from economical reasons. Recovery and up-grading requires energy and losses by leaks cannot be entirely avoided. The conditions vary much between different gas fields depending on the pressure in the field and on the composition of the wet gas. In the study, the energy use for recovery (including some flaring) and transfer to terminal typically require 3% of the energy content of the final dry gas and 2% for the up-grading to dry gas. In the North Sea area, the first mentioned figure probably is somewhat lower due to strict rules against flaring.

The gas is presumed to have a typical composition as that of the Danish natural gas used in the south-west part of Sweden. It has an energy content (LHV) of 10,8 kWh (38,9 MJ) per Nm^3 and emits 56 g of fossil CO_2 per MJ at combustion. The higher heating value (HHV) is 12,0 kWh (43,1 MJ) per Nm^3. A typical composition of the gas is given in **Table 1** (in percent by volume)

Table 1. *Composition of Danish natural gas*

Compound	Chem.	Volume (%)
Methane	CH_4	91,1
Ethane	C_2H_6	4,7
Propane	C_3H_8	1,7
Butane+	C_4H_{10}	1,4
Carbon dioxide	CO_2	0,5
Nitrogen	N_2	0,6

If there is no pipeline for transport from terminal to market, which often is the case at remote fields, the natural gas has to be transformed to liquid state for transport by ocean tanker. This is accomplished by cooling (<–162°C) so that the gas is condensed to liquid (LNG, liquefied natural gas) or chemically by conversion to methanol or hydrocarbons (Mobil, Fischer-Tropsch). Such plants are expensive and must be large.

4.1.2 Biomass – lignocellulosic matter

Tree residues from forestry and forest industries constitutes the big biomass resource and are presumed to have a typical heating value (LHV) of 19,2 MJ/kg dry substance (DS) in average at an ash content of 2%$_m$ (5,33 kWh) and yields at combustion 90 g CO_2 per MJ, entirely of renewable origin. The higher heating value (HHV) is typically 20,5 MJ/kg DS. Variations of the heating values of various types of biomass-DS are small and the factor of greatest influence is the ash content. Short Rotation Forests (SRF) such as Salix is presumed to have the same heating value (LHV) of 19,2 MJ/kg DS. Typical elementary composition is in average presumed to be 49,0%$_m$ C, 5,8%$_m$ H, 43,0%$_m$ O, 0,2%$_m$ N, and 0,05%$_m$ S at 2%$_m$ ash.

In the bio-chemical route to ethanol as motor fuel, the content of cellulose and hemicellulose is decisive. In average feedstock, the total content is about 60% of the DS. With selected feedstock, e.g. stem wood or sorted biomass for enrichment of the stem wood, the content may be increased to about 66%. It has been discussed (in American studies) to use genetically modified feedstock with very high content of cellulose (80%) to increase the yield of ethanol. The consequence might, however, be that the conversion residues will not be sufficient to cover the energy needs of the conversion plant but additional feedstock has to be used for this purpose.

The biomass feedstock is presumed to have moisture content of 50% as delivered to the conversion plant.

Silviculture and recovery of tree residues at final cuttings needs energy for some use of fossil-based fertilisers and motor fuels for forestry machines. This energy has been presumed to correspond to 3% (3/4 as diesel oil) of the energy content of dry biomass (DS). At more intensive cultivation of energy crops, such as Salix, more fertiliser and motor fuel are required and presumed to be 6,5% of energy content of the DS. If the conversion occurs with a yield of the motor fuel of 50% (in energy terms LHV), the production of feedstock will require 6% or 13% respectively of the energy content of the motor fuel.

The methods for recovery and transport of forestry feedstocks need further development as is described by the forestry division of the Swedish National University of Agriculture, and a presumption for this is a new, big volume and stable use of the feedstock.

4.1.3 Biomass for digestion

Feedstock for bio-chemical digestion to methane is primarily sludge from wastewater purification supplemented by wet wastes from agriculture, food industries and similar. These feedstocks are sufficient for a niche application. For more widespread use, cultivated feedstocks, such as for instance lucerne (i.e. a crop that is assimilating nitrogen from the air), must be considered. Cultivation and harvest is somewhat less energy demanding than for instance wheat cultivation and is presumed to correspond to 3% of the energy content of the dry biomass.

4.2 Feedstock transport

4.2.1 Natural gas transport

The transfer of the natural gas to the plant for up-grading to dry gas is included in the energy use for the recovery, as it is presumed to be situated in the vicinity of the gas field.

4.2.2 Transport of biomass – lignocellulosic feedstock

Biomass from the forest is a dispersed and voluminous feedstock (unless compacted by baling or bundling at the recovery). Transport to the conversion plant must occur over a certain distance, as the size of the plant must be considerable (>0,5 Mt/yr DS) from economical reasons. The fuel consumption (diesel oil) is conservatively estimated to correspond to 1,5% of the energy content of the feedstock-DS, which allows transport over an average distance of more than 100 km one way. The same presumption is made for cultivated energy crops (SRF) though a more concentrated biomass production seems reasonable. (In American studies, very concentrated biomass cultivation is often presumed to obtain low feedstock costs also for very big conversion plants.) A chain of 10-15 plants in Sweden would result in the transport distance mentioned as a reasonable assumption,

4.2.3 Transport of biomass – lucerne

Fuel consumption for transport of harvested lucerne feedstock by farm tractor to a plant nearby for bio-chemical digestion and for transport and spreading of the residue (nitrogen fertiliser) is estimated to correspond to about 4% of the energy content of the biomass-DS.

4.3 Fuel production

The production processes in both classification alternatives, "gases" or "liquids", are to great extent common as is the case for the thermo-chemical route based on primary gasification of the feedstock and up-grading to synthesis gas or hydrogen. The following synthesis step is designed to yield the desired products, methane, methanol, DME, hydrocarbons (synfuel). Gasification and synthesis occurs integrated with heat recovery for drying and power production to obtain an energy-wise self-sustained plant, and optimisation can only be made for the entire plant taken together. Self-sustained plats must be anticipated as the normal case to be able to conduct fair comparisons between alternative products. In reality, there will often be special local circumstances. No regard has been taken to possible use of waste heat. Surveys of production of motor fuels from natural gas have been published by among other ANL [8] and $(S\&T)^2$ Consultants/Methanex [9].

The synthesis requires a gas with a hydrogen/carbon monoxide-ratio of about 2 as hydrogen-rich products are desired. With natural gas as feedstock, this will not be a problem, as it already has high hydrogen content. Hydrogen-poor feedstocks, such as coal and biomass, yields at gasification low hydrogen/carbonmonoxide-ratio, which has to be corrected in order to attain highest possible yield of the desired product by the so called shift-reaction. Part of the carbonmonoxide is then reacted with steam to form hydrogen and carbon dioxide, which is removed from the synthesis gas and released to the atmosphere. These processes are energy demanding and results in lower yields of end product compared to a hydrogen-rich feedstock. This is particularly evident for biomass, which is the most hydrogen-poor feedstock. At hydrogen production, the shift-reaction is accomplished in two steps to only hydrogen and carbon dioxide.

In the synthesis step, DME and methanol have the highest theoretical yield, while hydrocarbons gives lower yields. In addition, only products without carbon chain (methane, methanol, DME) are obtained as 100% of the desired product, while the synthesis to (liquid) hydrocarbons unavoidably results in compounds of a broad spectrum from gases to waxes. Lower yields of motor fuels are then obtained and aftertreatment is needed to improve the yields of these products. The synthesis of higher alcohols (ethanol, butanols) also results in lower energy yields compared to methanol.

In the bio-chemical systems the conversion, with assistance of enzymes, yeast and bacteria, is controlled by the content of convertible compounds and the selectivity of the micro-organisms. In biomass, not all material is available for conversion, and in the case of ethanol the content of cellulose and hemicellulose put up a limit. The anaerobic methane-producing bacteria seem to be less particular about the feedstock.

4.3.1 Methane

The *natural gas* is ready from terminal and refuelling occurs as CNG after pipe distribution. If distribution shall be made as LNG, the liquefaction is accomplished at the terminal. The liquefaction is energy demanding and in modern plants, about 10% of the energy of the LNG produced is consumed at power driven compressors when the power is produced from natural gas in combined-cycle systems.

The *biogas* production occurs in digesters at somewhat elevated temperature and power is needed operation of stirrers and pumps. The yield of methane is presumed to be 70% of the energy content of the organic DS fed, and for the operation primary energy for power and heat is estimated to correspond to 18% of the energy in the methane product. Purification of the gas the remove CO_2 and impurities and compression to 200 bar requires additional 16% of energy.

SNG, methane produced via thermo-chemical gasification to synthesis gas and methane synthesis is a route to supplement/substitute natural gas, thereby the acronym SNG. It is produced on basis of coal in the USA and South Africa. The efficiency should be close to or somewhat lower than at methanol synthesis and is estimated to be 50% in an energy-wise self-sustained based on biomass. Such a plant can produce some heat for district heating and similar to improve the total efficiency, but no such use of waste heat has been assumed in the calculations.

4.3.2 Methanol

Most of the world capacity for methanol production, about 35 Mt/yr, is based on natural gas, although some production occurs from residual oils, hard coal and lignite and marginally from landfill gas.

The energy efficiency with hydrogen-rich natural gas as feedstock can be over 70% in new plants (an optimisation against the gas cost) in energy-wise self-sustained units, which means that 0,42 $MJ/MJ_{methanol}$ is consumed to operate the plant. A small surplus of electricity for export can appear. Hydrogen-rich gas that is not converted is used to cover the energy needs. The carbon conversion from feedstock to methanol is over 90% and the emission of fossil carbon dioxide in the production step is low, about 8 $g/MJ_{methanol}$.

With hydrogen-poor feedstocks, the efficiency will be lower by the need to increase the hydrogen content at expense of the content of carbonmonoxide through the shift-reaction and the excess of carbon is removed as carbon dioxide and released to the atmosphere. Studies on biomass based production by engineering companies have resulted in yield of methanol of about 54% (LHV-basis) in optimised, energy-wise self-sustained plant using oxygen/steam gasification. This corresponds to use of 0,85 $MJ/MJ_{methanol}$ to operate the plant. By-product may be hot water for district heating and possibly drying of pellets. Including the district raises the total yield to about 65% (this potential is not included here as the plant shall be free-standing). The emission of CO_2, entirely of renewable origin, is 104 $g/MJ_{methanol}$ at complete combustion of the ash.

The methanol synthesis can be modified for co-producing part of the product as higher alcohols, ethanol, propanol, butanols, etc. This is not discussed here as the energy yields as motor fuels will be lower than in the dedicated methanol synthesis and the interest in the product is more specific (as blend component) and small.

4.3.3 DME

Production of DME is exactly the same as for methanol up to the synthesis step, which has modified catalyst for direct dehydratisation of the methanol formed to DME, and the separation of the gaseous DME-product and recycling of methanol that is not converted is differently designed. By more favourable conditions at the synthesis, the conversion is more complete and the yield somewhat higher, about 5%, than with methanol as end product. The energy efficiency with natural gas as feedstock is calculated to 74% (LHV-basis) in a self-sustained plant and 57% with biomass as feedstock. Feedstock use of 0,35 and 0,75 $MJ/MJ_{methanol}$ thus is used to operate the plant.

4.3.4 Ethanol

Only the bio-chemical route from lignocellulose (wood) is considered here, although other routes via thermo-chemical conversion are possible and may be developed. Homologation of methanol has been investigated but the degree of conversion and selectivity has not yet been found acceptable. The route via DME and ethene to ethanol (as is applied at petrochemical production of ethanol), which should have possibility to good selectivity, is not satisfactorily investigated. In both cases will, however, the energy efficiency be worse than with methanol as the end product.

The yield of ethanol in bio-chemical conversion is dependent on the content of hemicellulose and cellulose of the feedstock. With a typical average total content of $60\%_m$ the theoretical yield will be 435 litres/tonne or in energy terms 48% of the energy content of the feedstock-DS (LHV-basis). With the presumption that the development of the enzymatic hydrolysis and the fermentation of both C_5- and C_6-sugars leads to that 85% of the theoretical yield of ethanol can be attained (this has not yet been proven; in the latest American evaluation of future technology a figure of 81% was obtained) the ethanol yield will be just below 41% or about 370 litres/tonne DS [10]. The residual products are sufficient to cover the power and steam needs of a plant and yield a small surplus of solid fuel ("lignin") or power for export, which raise total yield of energy carriers to 49% (lignin) or 43% (power) respectively. To operate a self-sustained plant feedstock corresponding to more than 1,0 MJ per MJ of sum of products has to be used in the lignin case. The greater part must be allocated to the ethanol, which requires the most energy demanding sub-processes. Reasonable partition can only be preliminary estimated, as a complete process scheme and energy balances are needed for a true partition. In the study 1,15 $MJ/MJ_{ethanol}$ and 0,45 MJ/MJ_{lignin} respectively have been used.

The emission of CO_2 (from the fermentation step and firing of fuels like biogas and lignin), entirely of renewable origin, amounts to 157 $g/MJ_{ethanol}$ at presumed yields and conversion of the residual products to power at complete combustion of ash and digester sludge.

4.3.5 Synthetic hydrocarbons

Instead of producing methanol or DME using the thermo-chemical route, the choice of other catalytic systems enables the synthesis to be directed towards production of hydrocarbons according to Fischer-Tropsch- or Mobil-processes. The hydrocarbon synthesis is more exothermal than the methanol synthesis, which leads to lower energy efficiencies to products desired. General overviews of the Fischer-Tropsch technologies can be found on the Internet web-sites of the companies SASOL [11], Syntroleum [12] and Rentech [13] and a report from Howard Weil, Labusse, Friedrichs, Inc. [14].

According to the Mobil technology, primarily formed methanol is directly converted to mainly petrol-hydrocarbons and this has been used at a large natural gas based plant in New Zealand (now moth-balled). Although the loss of total energy products is only a few percent, the yield of petrol is less than 80% of the energy content (LHV) of the methanol (the remainder is LPG). The Mobil-technology has been developed to produce also middle distillate but it is still without commercial application.

The Fischer-Tropsch (FT) technology is used in South Africa by SASOL for coal and natural gas based synthesis gas and by Shell in Malaysia on natural gas basis. The FT-synthesis has the advantage over the methanol synthesis by the fact that it can be accomplished at lower pressure and greater conversion per pass through the reactor. However, the catalyst systems used are not very selective and yield a broad product mix with everything from gases (methane) over olefin-rich hydrocarbons with straight carbon chains to oxygen containing compounds and waxes, which require comprehensive aftertreatment to obtain marketable products. Unless the methane produced does have a market but has to be recycled for conversion to synthesis gas, the yield of fuels in a self-sustained plant will be less than 40% of energy (LHV) of the feedstock coal. With other gasification than used by SASOL and developed reactor technology (slurry phase) and catalyst, the FT-technology is estimated to yield up to about 50% (LHV-basis) as liquid motor fuels. With biomass as feedstock, the yield of motor fuels is estimated to be about 5 %-units lower.

With natural gas as feedstock (then often called GTL, gas-to-liquids, in the USA), a hydrogen richer synthesis gas is obtained and the products have paraffin character. In order to obtain low share of gases, the synthesis is controlled to yield high molecular hydrocarbons, which then will be refined by hydrocracking to yield products which may be motor fuels with middle distillate (diesel fuel) as main product. The naphtha fraction may be suitable as petrochemical feedstock for production of ethene, propene, etc. The cracking is needed to obtain a diesel fuel with acceptable winter properties [15, 16]. The product has been emphasised on basis of freedom from sulphur, nitrogen and aromatic hydrocarbons and very high cetane number. It differs, however, from the present diesel oil by having very low density, about 0,78 kg/litre, and therefore is a new quality that cannot directly be interchangeable with present qualities but must within foreseeable time be seen as a niche fuel or blend component to improve worse conventional diesel oils. FT-hydrocarbons have been discussed as possible product to generate hydrogen onboard vehicles with fuel cells.

It has also been suggested that the FT-technology would fit for production of alkylates, but this must be a cumbersome route for a small fraction of the products involving isomerisation and dehydrogenation of primary paraffinic gases before alkylation process.

No complete energy balances for these modern natural gas based FT-plants have been found in the available literature. Yield numbers in energy terms with only liquid motor fuels as end products are estimated to be nearly 15 %-units below those for methanol production with natural gas as feedstock, i.e. about 57% and about 45% (LHV-basis) with biomass as feedstock. To operate a self-sustained plant, 0,75 MJ or 1,2 $MJ/MJ_{hydrocarbon}$ respectively of each feedstock will be required. There might be small side products, e.g. power for export, produced in parallel. Allocation of auxiliary energy between products should be made but data for this is missing.

4.3.6 Hydrogen

The least expensive route to the hydrogen that is used today for hydrogenation processes in the oil and chemical industries is generated from refinery gases or natural gas, at which methane, ethane, etc are reformed by reaction with steam using the gas as process fuel, or by electrolysis of water. The electrolysis yields directly very pure hydrogen, whereas hydrogen from reformed hydrocarbons have to undergo aftertreatment to eliminate carbon-monoxide formed by shift reaction with steam and removal of carbon dioxide formed, which is released to the atmosphere.

The shift reaction at hydrogen production must be more far going than at generation of synthesis gas for methanol synthesis and demands more steam. The absence of the exothermic synthesis step leads all together to somewhat higher yield of hydrogen in energy terms, about 4% compared to methanol production, i.e. about 75% (LHV-basis) in big natural gas based plants. In small plants that are considered for decentralised production at refuelling sites, the yield will be 3-4 %-units lower. In self-sustained plants about 0,33 and 0,40 $MJ/MJ_{hydrogen}$ of the natural gas is consumed for the operation. In both cases, the total yield of energy carriers can be raised if there is a market for low-grade heat (district heat, low-pressure steam). The hydrogen can be available at a pressure of 20-30 bar.

With biomass as feedstock, the yield is estimated to be 57%. Thus, 0,75 $MJ/MJ_{hydrogen}$ of the feedstock is consumed for the operation of the plant.

If the transport shall be as cryogenic hydrogen (LH_2), the liquefaction demands energy that amounts to 12-13 kWh/kg H_2, which means that the energy efficiency decreases from 75% (natural gas case) to 48% (LHV-basis) at compressor operation with power generated in combined cycle or HAT-cycle systems for natural gas. Moreover, unavoidable losses occur at storage and during transport by evaporation (“boil-off”), which in the chain are estimated to a few percent of the product. The loss at the production site is presumed to be 1,5%.

Electrolysis of water to hydrogen (and oxygen) requires about 1,25 $kWh_{elec.}$ per kWh of hydrogen, i.e. an energy efficiency of 80%. When electricity is produced from natural gas 2,5 MJ_{NG} per MJ of hydrogen is consumed. Liquefaction consumes 0,75 MJ_{NG} per MJ hydrogen with power driven compressors and power from NG. In total 3,25 MJ of NG are consumed per MJ of hydrogen as LH_2. Electrolysis is presumed to be used only as local production at refuelling sites, as centralised production and distribution in pipes seems unlikely.

The energy needs given above must be corrected for possible losses of target product later in the chain, e.g. by evaporation.

4.4 Distribution and reforming

Transport from the production sites and distribution to refuelling stations demands energy and sometimes losses occur by leaks and evaporation, which is particularly evident and most often unavoidable for cryogenic liquids.

4.4.1 Methane

Pipeline transport is usually accomplished by compression of the gas to about 80 bar, and the sizing of the pipe for designed pressure drops that requires compressors along the pipeline with a consumption in gas-engine driven compressors corresponding to 2% of the gas flow per 1 000 km. This figure has been used in the study.

Transport of LNG is accomplished in big tankers (100 000 m^3 or more in the future) with well-insulated tanks over oceans. Losses by evaporation are calculated to 0,15% per day or 1,5% per voyage of 10 days one way, as LNG is presumed to originate from remote gas fields. The consumption of fuel for the operation of the ship is presumed to be twice that at transport of oil due to the lower energy content of equal tank volume. The same presumption is made for transport to refuelling stations. Evaporated products may possibly be recovered in cooling systems or be used as part fuel for the ship machinery but is not included in the study.

Biogas is presumed to be consumed near the production site without additional fuel consumption for transport.

4.4.2 Methanol

Import of methanol produced from fossil gas at remote plant is in the future considered to be accomplished by large tankers over oceans to terminals as for crude oil or oil products (so far the biggest methanol tanker built has a capacity for 100 000 m^3). The energy usage for the ship operation is calculated to be 1,2% of transported energy as methanol. Losses are presumed to be negligible. For distribution from terminal to refuelling stations with road tankers the fuel consumption (incl. 0,2% evaporation loss) is presumed to be 1%.

Domestically produced methanol from biomass is presumed to be distributed only with road tanker or possibly a combination of coastal ship and road tanker consuming motor fuel corresponding to 2% of the energy in transported methanol.

4.4.3 Ethanol

Only domestically produced ethanol is presumed with distribution as for methanol and with motor fuel consumption somewhat lower, 1,5% of the energy in transported ethanol.

4.4.4 Synthetic hydrocarbons

FT/GTL-hydrocarbons from natural gas are presumed to have been produced at remote gas fields and to be transported as for crude oil in big ocean tankers at eventually large scale future scenario even if transports in the early phases occurs with smaller ships. The lower density of the FT-product compared to crude oil results in slightly higher transport fuel consumption. The figure 0,008 MJ/MJ_{FT} have been used in the study.

The distribution from terminal to refuelling station occurs as for conventional oil products with a motor fuel consumption of 0,01 MJ/MJ_{FT}.

4.4.5 Hydrogen

Pipeline transport of gaseous hydrogen requires more transport energy in comparison to natural gas, due to its much lower energy content in spite of the lower density. Transport energy need about 75% higher than for NG have cited, and the figure 3,5% of the transported hydrogen energy is used in the study.

Transport as liquefied hydrogen, LH_2, from a plant at a remote gas field is presumed to be accomplished by shipping in big tankers to terminals in the consuming region. The relative motor fuel consumption will be much larger, i.e. about 5 times, than for liquid hydrocarbons, due to the low energy density of the product, about 8,5 MJ/litre compared to about 40 MJ/litre for oil even when the ships would transport the same volume, which is not likely for cryogenic liquids. Moreover, evaporation losses will occur during the transport, about 0,3% per day or 3% during a 10 day trip on way. This is considerably more than the fuel consumption of the tankship machinery.

Storage at the terminals and transport with road tanker to the refuelling sites adds, on top of a motor fuel consumption about 5 times higher than for oil products, further evaporation losses, which are estimated to 3% of energy content in the hydrogen delivered.

4.4.6 Electricity

Power is presumed to be generated in regional power stations with combined cycle system or advanced HAT-cycle with efficiency for the turbine machinery of about 55% (LHV-basis). At the distribution to the user, a loss of 5% is calculated.

4.5 Refuelling

Energy required for refuelling of motor fuels that are liquid at normal atmospheric conditions is negligible in the chain, and nor are spills or evaporation losses noticeable. Gaseous and cryogenic motor fuels require energy and may suffer from losses at refuelling.

4.5.1 Methane

Natural gas must be compressed to about 250-280 bar for quick filling of the vehicle tank to a pressure level of 200 bar and the gas at the station is taken from the low pressure net. Power driven compressors are presumed to consume electricity corresponding to 4% of the energy content of the gas or 8% calculated as NG-resource in combined-cycle power stations.

Refuelling of LNG as such to the vehicle tank is estimated not to require energy that is noticeable in the chain, but to prevent losses at storage cooling compressors may be needed. Refuelling as CNG requires pump work before the vaporisation but no compressor for cooling at normal turnover. The power need for the pump work is calculated to 0,004 MJ/MJ_{NG}, which is almost negligible. The reason for the much lower pump work in this case compared to “normal” CNG is that the pumping occurs as LNG and that the vaporisation is performed after the high pressure has been attained. The considerably smaller volume of the liquid reduces the pump work.

4.5.2 Hydrogen

A refuelling station for hydrogen to vehicles can be equipped for generation of the hydrogen gas by electrolysis at the station and for compression of the gas to over 400 bar for quick filling of the vehicle tank to 350 bar pressure. Alternatively, the station receives gaseous hydrogen from a pipeline and only compression is made for filling with as gaseous fuel. General pipeline distribution of hydrogen seems, however, not likely. As third alternative, the station receives cryogenic hydrogen (LH_2) for storage and refuelling as such or as gaseous hydrogen to the vehicle tank.

Electrolysis of water to hydrogen requires, as previously mentioned (4.3.6), typically about 2,5 MJ natural gas per MJ hydrogen, which is true also for small plants. Compression to over 400 bar requires for the power driven compressors electricity corresponding to about 10% of the energy content of the hydrogen or 20% as NG in combined cycle power stations or 0,25 MJ NG per MJ hydrogen.

Refuelling of cryogenic hydrogen requires only negligible electrical energy, but losses of hydrogen at storage and transfer is probably unavoidable and is estimated to 1%. Alternatively, cooling compressors must be used to prevent the evaporation losses but necessitates power, which constitutes a loss. Refuelling as gaseous hydrogen requires energy for pumping and heat for vaporisation.

4.6 End use

4.6.1 Technology shift for gasoline and diesel engines

The description of the technology used in passenger cars could be begun by drawing the conclusion that a technology shift is currently taking place for both otto and diesel engines. In both cases, the necessary alterations are vast regarding the combustion system and the aftertreatment of the exhaust gases. Most of these modifications cannot be seen from the outside. It has been assumed that the technology shift will be more or less completed in the time horizon that the study is considering.

In the previously cited report by these authors about exhaust emissions and their effect, an illustration (**Figure 3**) showing possible scenarios for the technology shifts for each fuel was shown [3].

As can be seen in **Figure 3**, the technology shift for the diesel-fuelled engines has been proceeding for a couple of years now and it is about to be completed. This does not necessarily imply that the full potential for a reduction of the fuel consumption is exploited yet, since the concept will presumably be further developed for several years to come. The technology shift for petrol-fuelled otto engines has just recently begun and the authors has foreseen a transitional period about as long as for the diesel engines also in this case. An assessment of the available data on the vehicles that already have been introduced on the market implies that there is still a vast development potential for this new technology for petrol-fuelled engines. It is likely that this development will lead to that the difference in fuel consumption between cars with diesel and otto engines will decrease in the future (seen as an average consumption for the car population in each case). Since **Figure 3** was prepared a couple of years ago, it has to be mentioned that the technology shift has not been quite as fast as the authors anticipated. The slow penetration of low-sulphur petrol and the associated problems with aftertreatment devices might have contributed to the somewhat slower–penetration as the record shows today.

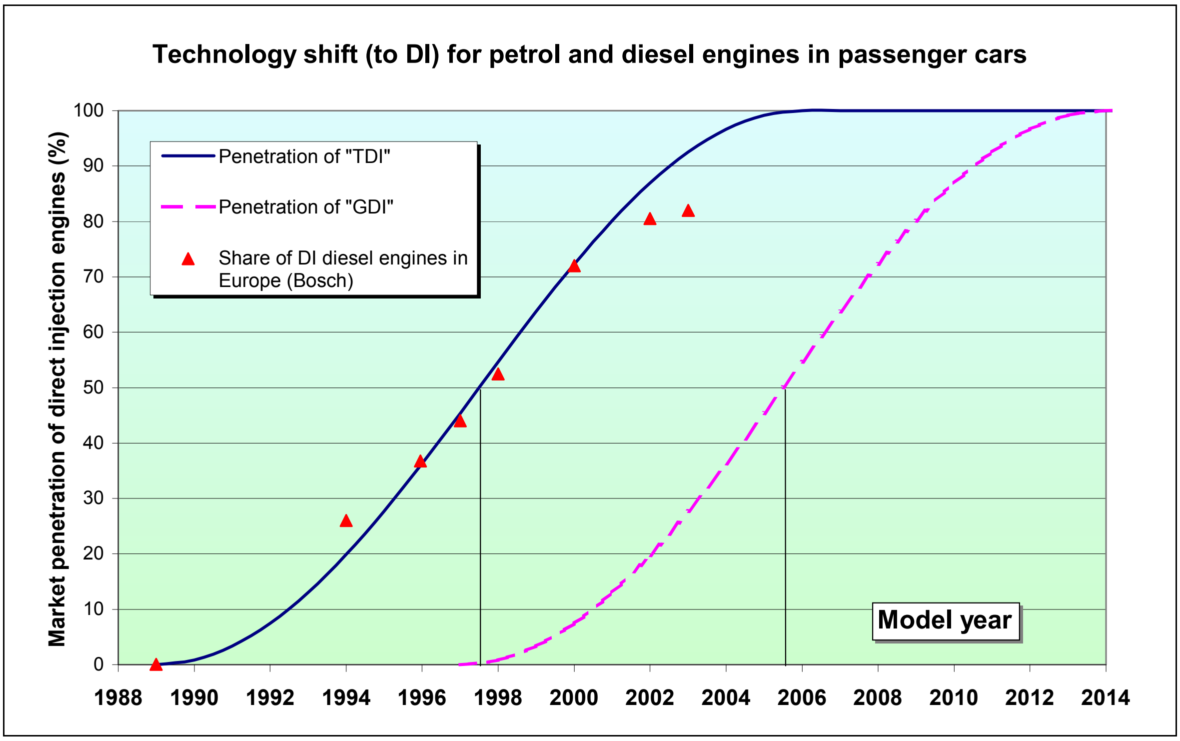


***Figure 3**. Technology shift*

Petrol-fuelled otto engines

Today, most otto engines use the three-way catalyst aftertreatment to clean the exhaust. The injection for the new generation of engines will be made directly in the cylinder instead of in the inlet manifold (or inlet port) for the conventional engines. The Japanese manufacturer Mitsubishi introduced this technology first at the Japanese market and subsequently, this technology has also been introduced in Europe in several of the car models of this company. The European car manufacturers have also developed similar technology and they have just recently introduced this technology, or else, they will introduce this technology in the near future.

The principal advantage by using direct injection on otto engines is that the fuel consumption is considerably reduced. The primary cause for this is that the so-called pumping losses are reduced due to less throttling (excess air). The consequence of this strategy is that a conventional three-way catalyst cannot be used to reduce the NO_X emissions and this is the main drawback of the concept. The most technology that seems to have the greatest potential is based on the storage of NO_X in the catalyst. At a proper interval, the catalyst is regenerated by running the engine in a rich mode for a few seconds so that the stored NO_X can be reduced in a similar fashion as in the three-way catalyst. The main problem with this type of catalyst is that they need low-sulphur or sulphur-free fuel, since sulphates are adsorbed more easily than nitrogen dioxide in the catalyst.

The concepts that are about to be introduced on the market do in fact tolerate a certain level of sulphur in the fuel but it is clear that they could operate better with low sulphur fuel. Furthermore, new catalyst concepts with greater reduction efficiency could be introduced if low-sulphur fuel was available. The sulphur problem has most likely delayed the development an introduction of the new technology compared to the projection in **Figure 3** above. However, it is likely that several new engine generations will be introduced in the near future, which presumably implies that the technology shift could take place at the pace predicted by the authors in the previously cited report [3].

Diesel-fuelled diesel engines

More than a decade ago, direct injection was introduced in diesel engines for passenger cars but the technology is not new, since it was introduced in a larger scale in engines for heavy-duty vehicles more than 50 years ago. It could be of interest to note that of the three engines that were introduced in the 1988-1989 timeframe (Audi, Rover and Fiat), only one of these (Audi) was a commercial success. Later, the technology of this engine was passed on to other companies in the VW group, thus providing these car manufacturers with a lead over their competitors. However, it has not been until the last three years that the development has accelerated and this is attributable to the new high-pressure injection technology (common rail, high-pressure rotary pumps and unit injectors). It is well-known that direct injection for diesel engines demand very high injection pressure to utilise the full potential for reducing emissions and fuel consumption.

The greatest obstacle for diesel engines is still the NO_X and particulate emissions. Particulate traps are now being commercialised by one car manufacturer (Peugeot-Citroën) while other manufacturers have announced that they are developing filter systems that will be mature for production in the 2002 – 2003 timeframe. The technology for reducing the NO_X emissions will not be introduced in larger scale until low-sulphur fuel is available on several markets in Europe. Although Sweden has a diesel fuel with very low sulphur level (<10 ppm), the market for diesel cars in Sweden probably is too small to motivate the early introduction of this technology here. It could be noted that the most promising technology for NO_X removal (NO_X adsorber catalyst) is more or less similar for both otto and diesel engines in the future. Therefore, the NO_X emissions will be on a similar level for these engine types in the future.

Experiences from the US PNGV program

In the US PNGV programme, the potential of reducing the fuel consumption by using hybrid drivetrains has been investigated. The aim of the programme is to reduce the fuel consumption to about 3 litres/100 km (i.e. 80 miles/gallon) for a vehicle of a comparable size to a full-sized US passenger car. This size of the PNGV car is considerably larger than the (commercial) European cars that were introduced on the market recently (VW Lupo 3L and Audi A2 3L). Other advanced targets in the PNGV programme are for emissions, safety, performance, comfort, cost etc. The ten-year programme started in 1994 and it will be completed in 2004, when production-ready prototypes should be presented. In a review of the programme about two years ago, an estimation of the potential for fuel consumption reductions was made for various powertrain options [17]. The results from this study are shown in a figure that was adapted by Ecotraffic (**Figure 4**). Each bar in **Figure 4** represents an interval of uncertainty. The line showed just below 3 l/100 km represents the development target (in petrol equivalents).

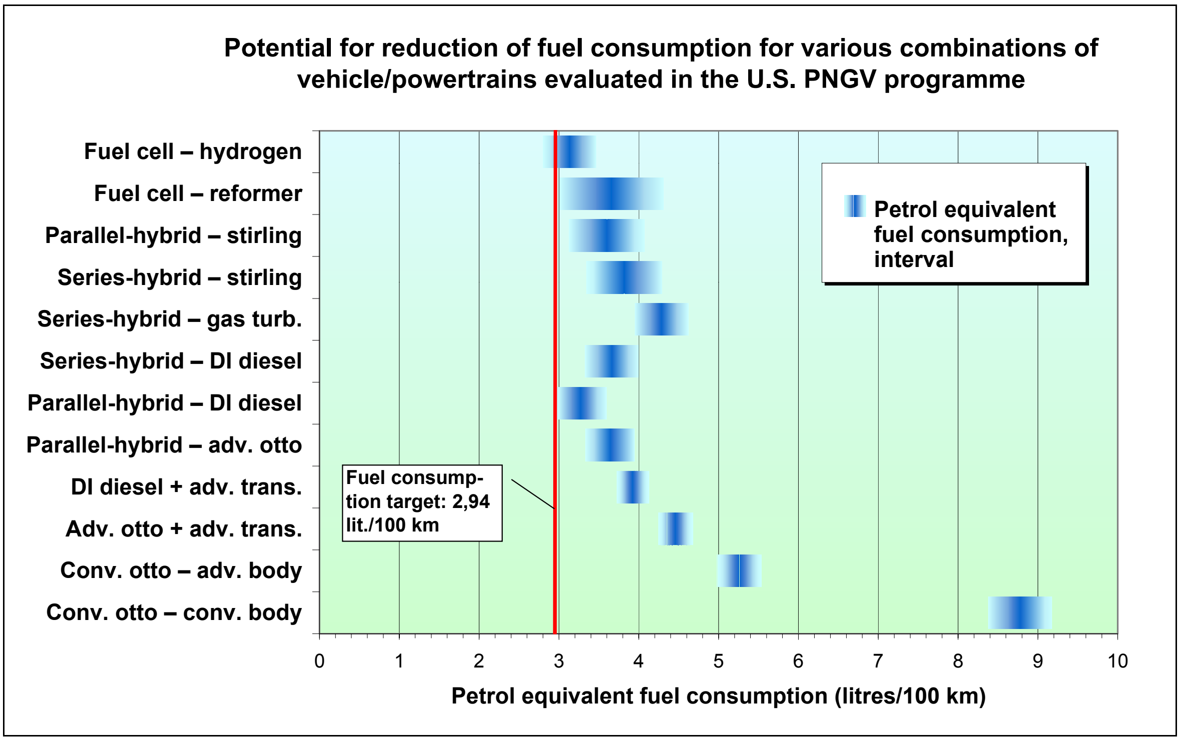


Figure 4. *Fuel consumption potential for various powertrains and fuels (PNGV)*

The first observation to be made in **Figure 4** is that the on-going development of chassis and vehicle body in order to reduce the vehicle *resistance* gives the largest contribution to the reduction of the fuel consumption. The development target to reduce this resistance has been set very high. A diesel-electric hybrid (parallel hybrid) and the two fuel cell options are the only powertrains that seem to approach the fuel consumption target. Recently, the possibilities of using an advanced otto engine in PNGV concept has also been discussed. Even if this powertrain concept does not meet the target for fuel consumption, it would still be of interest to study from a purely commercial standpoint. It could also be speculated that the fuel consumption target could be changed if diesel engines and fuel cells do not seem to meet the other targets (emissions in the first case and cost in the second case).

Recently, strong criticism has made against the PNGV programme due to the specific focus on diesel engines, since several US air quality authorities and environmental organisations consider these engines to produce more harmful emissions than petrol engines. As particulate emissions are of primary concern for diesel engines, it could be noted that the limit for particulate emissions has been set to 0,01 g/mile (0,0062 g/km), which most likely will call for a particulate trap. Current limits in Europe (2001) is at 0,05 g/km and the future regulations (Euro IV, 2005/2006) are at 0,025 g/km. In spite of that the emission targets in PNGV must be regarded as a very low level, environmental organisations prefer other concepts (e.g. petrol) instead of diesel.

4.6.2 Choice of vehicle type

In order to calculate the energy use in the vehicles, some simulations have been carried out using the computer program Advisor® from the federal laboratory NREL in USA. The software should actually not be considered as a program but instead it is an application in the program library Matlab/Simulink™. The driving cycle chosen for the simulations was the new European driving cycle (NEDC), which is used in the certification of vehicles in Europe. The simulations have not been carried out for all vehicle/fuel combinations, but instead the "rule of thumb" and data from other investigations have been used in some cases to calculate the energy use. These cases differ very little from the combinations that have been simulated. It is also appropriate to point out that much more effort could have been spent on the simulations and the collection and assessment of the input data used. However, a thorough analysis of this kind was beyond the scope of this study.

The selection of vehicle types was made so that the base case vehicle type should be representative of vehicles that could dominate the market for new vehicles in the timeframe of 2010 to 2015. To make the model year more concrete within the interval, the model year 2012 was chosen. The vehicle should be representative of an "average" new vehicle in Sweden (for that model year). The previously mentioned voluntary limits for CO_2 emissions for light-duty vehicles in Europe are shown in **Table 2**.

***Table 2**. Voluntary limits for CO_2 emissions in Europe*

Year	CO_2 (g/km)	Red. (%)	Remarks
1995	185	0%	Base level for the comparison
2003	165 – 170	-9,9%	Indicative target range
2008	140	-24,7%	Target for 2008
2012	120	-35,5%	Indicative target for 2012

The first important issue to note about the data in **Table 2** is that the new vehicles sold in Sweden in 1995 were significantly larger and had more powerful engines than the average car in Europe. Consequently, the fuel consumption and CO_2 for the cars sold in Sweden was higher than the average level for whole of Europe. This is still valid and it is questionable whether this habit will change significantly until 2012. It should also be noted that the voluntary agreement mentioned above in for whole EU and for all ACEA members and it is not applicable to specific markets and car manufacturers. It is somewhat unclear how ACEA will allocate the CO_2 emissions between its members, or if some other procedure will be used. However, the means of achieving the goal is of little relevance in this respect *if* the goal is achieved. Some reservations have been made by ACEA, such as the free penetration of new technology in all member countries. This aspect will most likely be considered in the review process.

In the assessment by the authors about the new vehicle population in Sweden, it has been assumed that the cars will be somewhat larger than the European average but that the difference in engine size and power will decrease. Another assumption is that the penetration of diesel cars will not be as great in Sweden as in the rest of Europe. Today, the market penetration has decreased in Sweden (about 5% in mid 2001) in comparison to the situation two years ago and it appears to stabilise at about this level. Even if the penetration in 2012 would be higher, it is not likely that the increase will be as great as in the rest of Europe. Therefore, we have assumed that this effect and the influence of the reduction in engine power (in relation to the EU average) will more or less cancel out each other. The conclusion is that the fuel consumption for new cars in Sweden would have to be reduced by as much as in the whole of Europe, i.e. by 35,5%.

The reduction of the fuel consumption could be achieved in by two different routes. One route would be that the driving resistance is reduced and the other possibility would be to increase the powertrain efficiency. Energy recovery by using regenerative braking is included in the drivetrain in this case. We have assumed that the relative improvement of the powertrain and the driving resistance would be about equal. The parameters for the average vehicle are (**Table 3**):

Table 3. *Some important vehicle parameters*

Parameter	Value	Unit	Remarks
Rolling resistance (r_0)	0,007	dim. less	Tyres w. low rolling resistance
Aerodyn. drag coefficient (C_d)	0,25	dim. less	~10% less than best cars today
Frontal area (A)	2,1	m^2	Equal to an average car today
Aero. drag index (C_d • A)	0,525	m^2	
Vehicle weight (conv.)	1 088	kg	Including powertrain, etc.
Acceleration (0-100 km/h)	11,0	s	PNGV: 12 s for 0-96,6 km/h
Otto engine improvement	17,6	%	As average in the driving cycle

Regarding the data in **Table 3**, some interesting remarks can be made:

- The tyres with low rolling resistance that are assumed to be used are, in principal, available already today, since these tyres are used in e.g. electric cars, and cars with low fuel consumption. In general, these tyres are narrower than average tyres for these vehicle categories and they often have some drawbacks (noise, handling, etc.). However, it does not seem impossible to obtain the improvement in the future that we have anticipated.
- The aerodynamic drag coefficient is considerably lower than for the average new car today of this size but still it has to be stated that the anticipated improvement is not at all as great as for some concept cars. For example, the prototype cars from the PNGV programme are at or below 0,20.
- Any significant reduction of the frontal area has not been anticipated, since the passenger compartment has to remain unchanged. A considerably lower and longer car body would provide an opportunity to reduce the frontal area but since this would hardly be accepted, this possibility has not been excluded. Advanced concepts, such as, e.g. active boundary layer control, are not foreseen within the timeframe.
- The weight of the cars has to be reduced significantly in comparison to the level today. A weight of only 1 088 kg for a gasoline-fuelled car that uses a conventional drivetrain might seem low but this is a necessity if the fuel consumption target should be reached with a reasonably efficiency for the drivetrain. In order to achieve as low weight as about 1 100 kg, new light materials (e.g. aluminium) will be necessary in the construction of the car body. In addition, the weight of the drivetrain and other components must be considerably reduced compared to contemporary cars of the same size.
- The necessary improvement of the otto engine that is referred to in **Table 3** has been derived from basic data for the previously cited report for KFB [3]. These data should be interpreted primarily as an improvement of the fuel consumption in the most rele-

vant area of operation regarding the load and speed. In general, corresponds to a brake mean effective pressure of about 2 bar (about 20% load) at 2000 r/min for conventional petrol-fuelled cars today. The potential of increasing the maximum efficiency at full load or at the point with the highest efficiency is not as great as it is at low load.

Table 4. *Aerodynamic drag for some passenger cars*

Car, model	C_d	A (m^2)	$C_d \bullet A$ (m^2)
Audi A2, 1.4 TDI	0,28	2,20	0,616
Audi A2, 3L	0,25	2,18	0,544
Audi A4	0,31	2,04	0,632
Audi A6	0,31	2,19	0,679
VW Passat	0,27	2,15	0,581

In order to further elucidate the possibilities to reduce the aerodynamic drag, data for some Audi/VW cars are shown in **Table 4** [18]. First, it is worth noting that a drag coefficient significantly below 0,30 should be possible to achieve in the future. Furthermore, is also clear that a tall car as the Audi A2 is hampered by the large frontal area. In fact, the Audi A2 without the aerodynamic features (1.4 TDI in (**Table 4**) actually has a greater drag index ($C_d \bullet A$) than such a large car as the VW Passat. The conclusion is that a conventional body is better than a tall and short car regarding the air resistance.

Since the choice of drivetrain and fuel has a significant influence on the vehicle weight in some cases (e.g. fuel cell vehicles), it could be of interest to show the weight for the various options. Some approximations have been made in order to simplify the analysis, which implies that errors of a few tens of kg is likely to occur in the table in comparison to a more comprehensive analysis. In order to achieve similar performance as the reference car, the size of the engine (and drivetrain) has been increased (or decreased), and this has affected the weight of the car. However, no corresponding increase in body weight (and vehicle components) has been anticipated to compensate for an increase in powertrain weight, which tend to somewhat underestimate the total weight of the vehicles with the heaviest powertrains. It is evident that a more thorough analysis of conditions and input data could refine the analysis but the difference compared to the relatively simple analysis carried out here, are not likely to be great except in some special cases. Some examples are the fuel cell cars, where the uncertainty is greatest. This is particularly a problem for the DMFC car, where data are scarce. The results for the weight with some of the combinations of drivetrains and fuels are shown in **Table 5**.

The first observation to be made regarding the results in **Table 5** are that both petrol and diesel fuel with the conventional drivetrains has the lowest weight. Since it has been anticipated that the hybrid drivetrain is of the parallel hybrid type, relatively small batteries are used. Therefore, the weight increase in the electric drivetrain is more or less compensated for by the weight reduction of the fuel converter. Other types of hybrid drivetrains are significantly heavier. The difference between diesel and petrol engines should be – according to general experience – of an advantage for the petrol engine. The reason for that the difference did not turn out that way might be that the base petrol engine was smaller (1 litre) than the corresponding diesel engine (1,9 litre). The scaling made for simulation in Advisor® was greatest for the diesel engine, especially for the hybrid system and this could also contribute to the results. The question remain whether it is possible to reduce an diesel engine as much as necessary without changing the weight to power ratio. Another cause for the somewhat unexpected results might be that the base diesel engine is a relatively light engine that is only a few kg heavier than a petrol engine of the same size (assuming that the same engine block and cylinder head material is used in both cases).

Table 5. *Vehicle weight with various drivetrains and fuels*

Fuel	Fuel converter	Drivetrain	Weight
Petrol	Otto engine	Conventional	1 088
Petrol	Otto engine	Hybrid	1 097
Diesel fuel	Diesel engine	Conventional	1 102
Diesel fuel	Diesel engine	Hybrid	1 096
Methane	Otto engine	Conventional	1 195
Methane	Otto engine	Hybrid	1 204
Hydrogen	Otto engine	Conventional	1 195
Hydrogen	Otto engine	Hybrid	1 204
Hydrogen	Fuel cell	Direct	1 270
Hydrogen	Fuel cell	Hybrid	1 323
Methanol	Fuel cell	Direct	1 244
Methanol	Fuel cell	Hybrid	1 272
Methanol	DMFC	Hybrid	1 438
DME	Fuel cell	Direct	1 270
DME	Fuel cell	Hybrid	1 296

The alternative liquid fuels, such as the synthetic diesel fuel, methanol and ethanol, and in addition DME, as well, have been anticipated to have the same weight as diesel fuel and therefore, these fuels are not shown in **Table 5**. This approximation is reasonable if the same tank volume is used (the difference in density is not that decisive) but it is not correct if the same range for the cars is desirable. Likewise, a tank for DME with the same energy content weigh more than a tank for the liquid fuels but instead, we have anticipated a somewhat reduced volume. This assumption leads to a somewhat shorter range for DME than for the conventional liquid fuels.

The gaseous-fuelled cars have a somewhat higher weight than petrol and diesel fuel, due to the higher tank weight, although a shorter range has also been anticipated in this case. It is hardly reasonable to increase the weight and volume so much that and equal range is obtained. The question is raised instead, whether the customers would be prepared to accept a significantly shorter range than the interval of 600 to 1 000 km that is common for passenger cars of today. This is a factor that, in general, would tend to limit the market penetration of gaseous-fuelled vehicles.

The weight of the fuel cell equipped cars is considerably higher than for the other drivetrains and this is a cause of the somewhat higher fuel consumption than expected. The most outstanding heavyweight car is the car with the DMFC fuel cell but in this case, no other input data (on system weight) than those available in Advisor® have been used as the basis for the assumptions. These figures are (most likely) very uncertain, since this is the least developed type of a fuel cell. It is likely that the weight of this drivetrain could be significantly reduced in the future, provided that a breakthrough is made in the development of the fuel cell stack. Some recent literature, as e.g. a paper by Moore et al., indicate that a DMFC vehicle could be competitive in weight and volume with a hydrogen fuelled fuel cell vehicle, if future development is successful [19].

By using the input data for the base vehicle as described above, simulations have been performed in Advisor® to estimate the fuel consumption. In a similar way, the fuel consumption has been calculated for the other powertrain and fuel combinations. In addition to the description above, some further comments regarding the fuel converters and the integration in a hybrid electric drivetrain are made below.

4.6.3 The otto engine

The engine technology used for the engine in a conventional drivetrain or a hybrid-electric drivetrain does not differ very much and therefore, the improvements of the otto engine are more or less general for this engine type. The petrol-fuelled otto engine is the base alternative and therefore, it is described first.

Petrol

The direct injection technology, as described above, is by no means the only possible technology to reduce the fuel consumption from otto engines, although this technology has tended to attract most of the interest lately. An overview of future technologies is shown in **Figure 5**. This figure was originally prepared by the consultant company AVL but has been modified somewhat by Ecotraffic (inclusion of several lines) [3]. A direct injection diesel engine is also shown as reference in the figure.

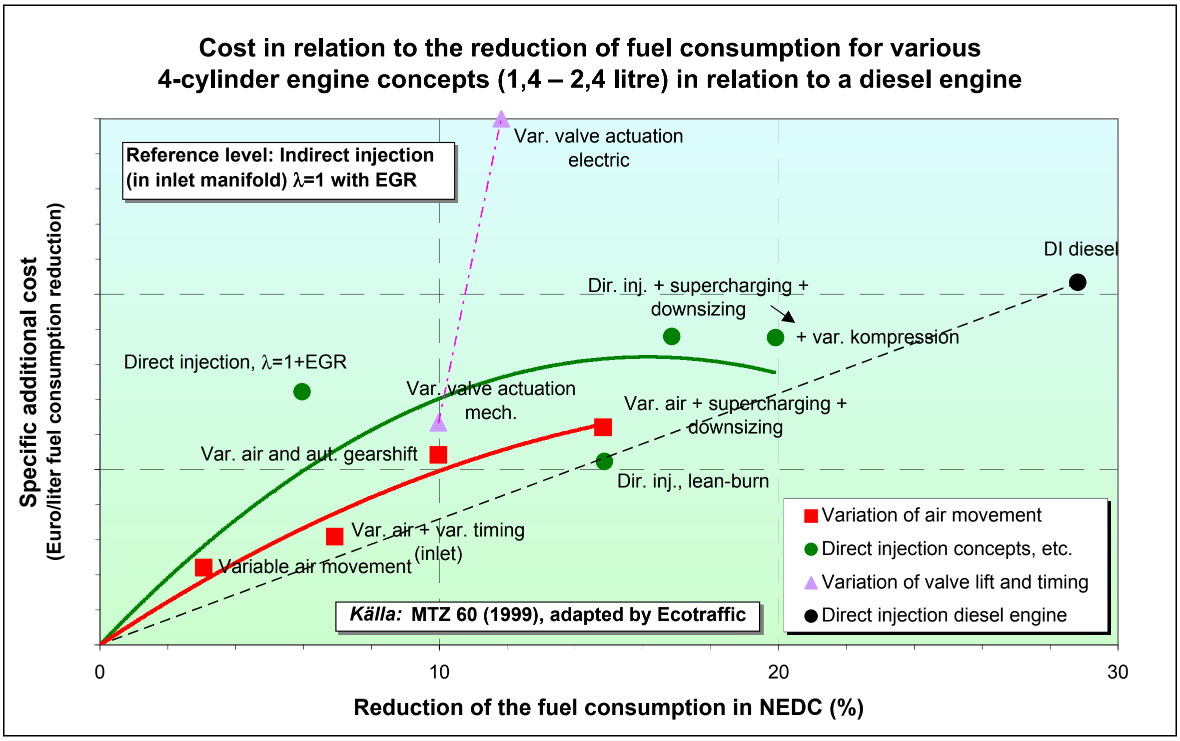


Figure 5. *Reduction of fuel consumption for otto engine in relation to cost (figure adapted from a publication by AVL)*

As can be seen in **Figure 5**, there are many different alternatives to reduce the fuel consumption for petrol-fuelled otto engines. Several of the alternatives shown have almost the same potential as the direct injection technology. Some of the alternatives tend to be too expensive by today's standards to be realistic, but further development will certainly lead to that those alternatives will be of interest in the future. One example is that the difference in fuel consumption between the direct injection engine with lean-burn concept and the engine with electrically actuated valves (fully variable valve control) is not great. On the contrary, the difference in cost is considerable.

Direct injection improves the fuel consumption for an engine primarily at low load. Therefore, the potential to a *relative* improvement for a hybrid drivetrain will not be as great for these engines as for the conventional otto engine. This should be taken into consideration even if we only have accounted for this impact by a rough estimation.

In order to make the simulation of a future concept as correct as possible, a fuel consumption map for the load and speed range of the engine would be necessary. Since the estimation of this map is an extensive work, an approximation has been made instead in order to estimate the relative improvement in the most relevant operating area (load and speed) of the engine. The improvement potential is, as described above, greatest at part load but some improvement can also be expected at full load. Consequently, a *higher* than realistic maximum efficiency for 2012 has been used, knowing that this does not have a decisive impact in the driving cycle investigated, since the engine load is low in this cycle. One of the engines in Advisor® (1 litre cylinder volume) has been used as the basis for the simulations. The maximum efficiency "island" in the engine map has been increased from 34% to 42% in order to achieve the efficiency at lower engine load that has been estimated to be realistic. Even if this increase in efficiency might not be too impressive, it is still possible that the fuel consumption is overestimated due to the vast potential for improvements at low engine load. This would be further accentuated if supercharging of the engines would receive a higher penetration than today.

An important improvement of the fuel consumption is that it is foreseen that future otto engine concepts will have a significantly reduced idling. We have anticipated that this strategy will be applied when the engine has reached a certain temperature level. It is foreseen that the idling could be reduced by 75% compared to the situation today, when the engine is not shut off at all. A higher output starter motor, alternator (preferably combined) and battery will be necessary to achieve this objective. This kind of a system is already used to some extent today on the (diesel-fuelled) VW Lupo and Audi A2 cars that have a fuel consumption of 3 litres per 100 km. A combined belt-driven alternator and starter (the alternator is used for starting as well) is a possibility that will be commercialised soon. A factor that hitherto has prevented the strategy of shutting off a petrol engine instead of idling is the increase in emissions resulting from the start. Even if this contribution is small in comparison to the cold start, there are many starts in a driving cycle and the contribution would not be negligible for conventional engines. Future engine technology will not have these limitations.

Electric hybrid systems of parallel and series types are conceivable for the combustion engines. The parallel hybrid version has been used extensively in this study, since investigations both by NREL and the authors have shown that this system has a greater potential to reductions in fuel consumption. Furthermore, the parallel hybrid does not need as sizeable battery as the series hybrid and consequently, the cost is lower for the former. A special variation of the parallel hybrid system is the system that Toyota uses in the Prius. This system has at least the same potential to a reduction of the fuel consumption as the "conventional" parallel hybrid but seems to be much more expensive. The parallel hybrid system used in this study is anticipated to have a starter-alternator that can reach an (intermittent) power of 15 kW. An energy storage with half the weight to power ratio of the advanced lead-acid battery provided in the Advisor® files has been foreseen. A battery type that has this potential is a lithium battery or an advanced nickel-metal hydride battery. The combustion engine has been scaled down to achieve the same acceleration performance target. No deterioration of the efficiency has been anticipated although a small deterioration could be the case in practice. It is also worth mentioning that hybrids of the described type presumably will have a potential for a significant market penetration in 2012, since the increase in cost (compared to a conventional drivetrain) should be acceptable for most applications.

Alternative fuels

An important question regarding the use of alternative fuels is the level of optimisation of the engines to the fuels and consequently, whether the alternative fuels have specific advantages that could be utilised in the development. It is plausible that the full potential of these fuels has not been exploited today. Some estimations and assumptions are used to elucidate these issues.

Alcohols

It is well known that the alcohols, ethanol and methanol, have specific advantages in otto engines – these fuels are simply "natural" otto engine fuels. First, the octane number is higher than for petrol, which is advantage for an engine where the maximum compression ratio is limited (knocking) by the octane level. Second, the alcohols have a higher latent heat of evaporation than petrol and since the energy content (per litre or per kg) is lower, a total evaporation of the alcohols would give a considerably lower temperature of the air-fuel mixture than petrol. A lower temperature implies a higher volumetric efficiency although this is somewhat counteracted by the fact that the alcohol molecules are smaller than the average petrol molecule and therefore they have a greater volume than the latter. However, the air-fuel preparation is not as simple as indicated, since the evaporation is not completed in the inlet manifold (with indirect injection). Nor is it so that all energy for evaporation is taken from the air, which might be expected. A considerable contribution to the evaporation comes from the hot surfaces in the inlet system (due to evaporation from the walls) and from the hot surfaces surrounding the combustion chamber (fuel impinging on the walls). The result is a lower volumetric efficiency and increased heat transfer. It is notable that alcohol engines have a higher volumetric efficiency than petrol-fuelled engines, which implies that the physical properties of the fuel have an impact. Yet another advantage for the alcohols is a slightly increased mass flow rate per unit of energy caused by the lower energy density of the fuel. This also gives a small contribution to increased power and efficiency.

The greatest problem with alcohol fuels in otto engines today is the substantial increase in emissions when the engine is cold started at low ambient temperature. This problem should be possible to solve in the future when new engine technology (e.g. direct injection) will be available. In a direct injection otto engine, the injection at higher load is made during the inlet phase. The objective with this strategy is on the one hand to obtain a homogenous charge and on the other hand to utilise the charge cooling effect due to fuel evaporation. In direct injection gasoline engines, an increase in power and torque can be obtained with this strategy compared to conventional port injection. With port injection, some heat for evaporation comes from the hot surfaces (before inlet valve closure) and this problem is (partly) avoided by using direct injection, hence the increase in volumetric efficiency in this case. It is plausible that alcohol fuels could have a further advantage in this respect, due to the increase in latent heat of evaporation. The cooling effect of the charge by direct injection also permits a higher compression ratio compared to conventional injection. In early experiments with direct injection of alcohols, several interesting observations of potential advantages with this system have been made. The enhanced cold start ability at low ambient temperatures seems to be the most important feature.

Perhaps the most interesting question about future alcohol engines with direct injection is whether these engines can be made fuel flexible (FFV). Even if this concept is a compromise in comparison to a dedicated engine, FFV is a concept that must be used during an introduction phase. It is well known that the injection system and air-fuel preparation in a diesel engine is not particularly well suited for FFV operation, since the differences in fuel density (volume) for the fuels in mind (diesel and alcohol) are vast. Furthermore, the time allowed for the injection phase and the air fuel preparation is very short in these engines. Although the parallel to direct injection otto engines might seem far-reaching, these engines are also limited by a short period for injection and fuel preparation in the lean-burn stratified charge mode. This is not a particular problem for conventional otto engines that have indirect injection, since the period for injection and fuel preparation can be longer due to the port injection. No particular study of modern[9] direct injection systems on an alcohol engine is known to the authors but a recently published study from the Technical University in Zwickau shows the influence of direct injection with methanol fuel [20]. The results from this study, which were performed on petrol, methanol and mixtures of these two fuels, indicated that there should be a fair chance of success for an FFV concept with direct injection. The model tests made showed that the penetration of the spray decreases with methanol, due to the difference in physical properties in comparison to petrol fuel. In general, the penetration should increase when methanol is used but the better atomisation and the increase in evaporation counteracts this trend. This should be a considerable advantage, since wall-wetting is a particular problem in direct injection engines (especially at cold starts). In summary, we have anticipated that the future alcohol-fuelled otto engine will be equipped with direct injection and that it will be a FFV type. Instead of using M85 and E85 fuels, we have anticipated "clean" alcohols (besides denaturants), i.e. M100 and E100. The vastly improved cold start properties of the direct injection should enable blending with petrol. *By using this fuel strategy, the option of using the same fuel quality for both alcohol-fuelled diesel and otto engines is created under the condition that the diesel engines do not need blending with an injection improver.*

In the future, NO_X reduction on petrol fuelled direct injection otto engines will most likely be achieved by so-called NO_X storage catalysts. These catalysts are very sensitive to sulphur poisoning and consequently, since alcohols are sulphur-free fuels, they have a fundamental advantage in this respect over petrol and diesel fuel. A proposal for the reduction of sulphur levels in both these fuels was made by the EU prior to the publishing of this re-

[9] The development company FEV in Aachen developed a direct injection otto engine based on an old VW-concept of an direct injection petrol-fuelled engine. However, this concept was so vastly different from the new direct injection engines that no conclusions can be drawn from that concept that can be directly applied to modern direct injection engines.

port[10]. A NO_X storage catalyst must be regenerated periodically from the stored NO_X. This is achieved by running the engine under rich condition for a short period (typically a few seconds). During this regeneration, the reduction of NO_X is accomplished by utilising CO and HC in a similar manner as for "normal" three-way catalysts. This is possible, since there is no oxygen excess during the rich "spike". It is known that the composition of the HC emissions is important to achieve a high NO_X reduction (regeneration) and the question arise whether the unburned "HC" emissions from alcohol fuels would work as a reductant. Limited results from such catalysts and lean-NO_X catalysts indicate that alcohols, and methanol in particular, has better properties than HC from petrol and diesel fuel regarding NO_X regeneration. Another advantage of alcohol fuels in direct injection otto engines would be the foreseen reduction in soot and particulate formation in comparison to petrol. The particulate formation in direct injection petrol engines is a particular problem (especially at low ambient temperatures), since these emissions are approaching those of modern diesel engines *without* particular filters.

Methane

In theory, methane is an excellent fuel for otto engines. First, methane has a very high octane number, which increases the efficiency compared to petrol. Second, since methane is in gaseous state, low emissions can be achieved at cold start – the fuel has already evaporated. Drawbacks can be found in the area of air-fuel control. Since the fuel is in gas-phase, the influence of pressure and temperature on the injection quantity (through variation of the density) is more detrimental than for liquid fuels. Furthermore, the so-called λ-window for the catalyst is generally smaller than for gasoline even if the on-going catalyst development has aimed at reducing this drawback in comparison to petrol catalysts. The long-term stability of the emission control system for methane-fuelled vehicles has still not been well-documented and some results indicate an inferior emission deterioration in comparison to petrol [21].

Heavy-duty methane-fuelled engines are often run with air excess in order to reduce the fuel consumption (the so-called lean-burn system) and thermal load. This concept appears to be difficult to utilise for methane-fuelled light-duty vehicles due to the relatively though NO_X emission limits in the future for this category of vehicles. This is mainly due to the difficulties of reducing NO_X emissions in a catalyst at excess air ratios. This problem remains if direct injection of gas[11] is utilised (in analogy with direct injection of petrol). The direct injection petrol engines also have the same problem but the catalyst used initially (i.e. Mitsubishi GDI) do reduce NO_X to a certain degree, since petrol is used as a reducing agent. Future catalyst technology utilising NO_X storage is likely to create some problems for methane. Methane is presumably one of the poorest hydrocarbon reducing agents for these catalysts and therefore, it would be necessary that CO alone is used as reductant. No published results are known to the authors that would indicate the potential of methane with this type of catalysts but it could be anticipated, as indicated above, that certain problems will arise. In practice, there also appears to be some problems to combine direct injection of methane with direct injection of petrol (see further elaboration of this issue below).

[10] The low-sulphur diesel fuel used in Sweden is below the future limit of 10 ppm.

[11] Maybe the term "injection" is not the best in this case, since methane is in gaseous state, but it is used anyway due to the lack of a better denotation.

It should be noted that systems for direct injection of methane are in the development phase for heavy-duty engines, which implies that the problems with direct injection of gaseous fuels will be solved in the future. However, these engines use diesel fuel, or a glow plug, as the ignition source and a very high compression ratio (similar to diesel engines) and this implies that these engines should be classified as diesel engines. As described above, it has not been fully shown that the problems indicated for a direct injection methane engine will be solved within the timeframe of the vehicles studied. In order to keep the comparison on a technology neutral level, we have nevertheless anticipated that the future methane-fuelled engine will be a direct injection (spark ignited) otto engine. If the technical problems cannot be solved, as indicated above, the possibilities of using a conventional engine with indirect injection remain. However, this would imply that significantly higher fuel consumption than we have anticipated would be the outcome of this strategy.

It should be mentioned that there are several practical difficulties in the development of a so-called “dual-fuel” engine, i.e. an engine that (in this case) should have direct injection of both fuels (petrol and methane). The available space in a modern 4-valve cylinder head is very limited. It is difficult enough to find the necessary space for both a spark plug and an injection nozzle for petrol. Since an injector for a gaseous fuel, per definition, will be larger than for liquid fuels, and as a dual-fuel engine has to use two injectors, this solution seems almost impossible. Whether it would be possible to integrate both nozzles in a combined injector remains to be seen. However, a combination in which one injector is used for direct and the second is for indirect injection seems possible. Increased fuel consumption with the system that has indirect injection is inevitable. We have foreseen that the fuel consumption for a methane engine would be as low as for a dedicated engine with direct injection, which has to be considered as an ideal case. If this option cannot be made fuel-flexible in some way (e.g. dual-fuel), a significant drawback arise in the introductory phase. Another problem is the relatively low range for a methane-fuelled car, which will lead to certain limitations in the market penetration.

In spite that the high octane number for methane gives a higher efficiency for this fuel than for petrol, which potentially also should increase the power, there are other factors that decrease the power level. The volumetric efficiency is lower than for petrol and alcohol fuels, since methane is in gaseous form and displaces fresh air in the cylinder. This could possibly partly be compensated by later injection (after inlet valve closure) when direct injection is used but this is associated with an increase in the injection work (higher injection pressure would be needed). Late injection also results in reduced time for mixing, which could be of importance at high load. To compensate for the power loss, the engine should be resized. It is also worth noting that the vehicle weight increases for methane fuelled vehicles, although in this case, the range is reduced in comparison to petrol and alcohols. This fundamental feature cannot be overlooked in the calculation of fuel consumption.

Hydrogen

There are some published results where hydrogen has been used in engines both of otto and diesel type. The available data material is not comprehensive enough to make a satisfactory estimation of the potential of hydrogen in these engines. There are possibilities of running an engine on a very lean air-fuel mixture with hydrogen, which is essential for obtaining a high efficiency. However, this strategy is also used on the direct injection engines running on other fuels. On the other hand, lean-burn combustion in combination with the problem that hydrogen displaces more air than other fuels, leads to a considerable reduction of engine power. An increase in engine capacity and/or supercharging is necessary to recover the power. This increases the weight of the powertrain. We have assumed that the influence of several of these parameters cancel out each other and therefore, the same efficiency as for a petrol-fuelled engine has been anticipated.

4.6.4 Diesel engine

A diesel engine optimised for diesel fuel is the basis for diesel engines fuelled with alternative fuels. No decisive differences in efficiencies have been anticipated for the fully developed diesel engines running on alternative fuels.

Diesel fuel

A significant increase of the specific power, which can be achieved by supercharging and a simultaneous reduction in cylinder capacity, would be the primary measures to reduce the fuel consumption of this engine type. Whereas the maximum brake mean effective power for contemporary turbocharged and aftercooled diesel engines is between 12 and 20 bar, lets say on average about 16 bar, future engines would have to achieve more than 20 bar on average. By these measures alone, the fuel consumption at light loads decrease. Further reduction of friction, pumping losses and heat rejection are other areas where certain scope of improvement remains. The maximum efficiency is foreseen to increase only marginally, from the level of today between 43 and 45% to about 46%. By the way, this mentioned level is the development target for 2004 in the US PNGV programme. A correction of the increase in fuel consumption due to cold start as received from the simulations in Advisor® has been made, since the model apparently is not correct in this respect. (The same model as for petrol engines has been used, which is not supported by experimental data.)

In order to fulfil future NO_X emission limits – that are anticipated to be significantly stricter in the future for diesel-fuelled cars, presumably similar to petrol cars – a NO_X storage catalyst will be necessary. There is some increase in fuel consumption associated with the NO_X regeneration (this regeneration could be simultaneous to the regeneration of the particulate filter). An increase of the fuel consumption by 2% due to the regeneration[12] has been anticipated, although recently published data indicate that this penalty might be reduced to less than 1%, provided that the sulphur content is below 10 ppm [22]. An increase in the fuel consumption of the same order as above (2%) has also been anticipated for the diesel engines fuelled by other fuels than diesel fuel, since these engines must use the similar type of catalyst.

Synthetic hydrocarbons

A synthetic hydrocarbon fuel, such as the Fischer-Tropsch diesel fuel (FTD), has several properties that differ from conventional diesel fuel. The formation of NO_X and particulate emissions is reduced, although these problems remain as an inherent feature of the diesel engine. The FTD fuel is essentially sulphur-free, which is a considerable advantage regarding the use of effective exhaust aftertreatment. Furthermore, the cetane number is high for the FTD fuel, which is a considerable advantage for contemporary diesel engines. Since the fuel is also free of polycyclic aromatic hydrocarbons (PAH), olefines and cycloparaffines, the emission components (possibly) causing health hazards should (presumably) be

[12] Desulphatisation, however small for low-sulphur fuels, is anticipated to be included in this figure.

considerably lower than for Swedish Environmental Class 1 diesel fuel (EC1) and European diesel fuel. The density for FTD is lower than for both EC1 and conventional diesel fuel, which would reduce the engine power unless countermeasures are taken. The FTD can be readily mixed with conventional diesel fuel and, possibly, it could have a higher value as a blending component in such use than used separately. Blending could also be interpreted as certain fuel flexibility for the FTD fuel.

DME

DME is a ”natural” fuel for diesel engines due to the exceptionally high cetane number. Therefore, the same efficiency as for diesel fuel is possible for a diesel engine adapted for DME. DME is non-toxic and should have an inherent property of significantly reducing the toxic emissions in the exhaust in comparison to conventional diesel fuel. A significant reduction of the NO_X emissions for DME in comparison to diesel fuel has been found in several studies. Particulate formation is largely avoided with DME in comparison to hydrocarbon fuels. DME also provide the opportunity for using higher rate of EGR, which further reduced the NO_X emissions compared to diesel fuel. Deducing from the limited number of studies available, it seems that the use of a NO_X reducing catalyst should be a viable solution for this fuel. Since DME is sulphur-free, the use of effective aftertreatment devices in general is more easily facilitated with DME than with sulphur containing fuels.

A DME engine cannot be made fuel flexible, without too large compromises and at a reasonable cost. This is of course a significant disadvantage during an introduction phase and, in particular, this is of importance for general use of this fuel, as in case of passenger cars.

Ethanol and methanol

The experience from heavy-duty vehicles has shown that ethanol and methanol could be used in diesel engines. An external ignition source, such as a glow plug, is foreseen to avoid the use of an ignition improver. Even if the development of glow plugs for diesel-fuelled passenger cars has been rapid, it is likely that further development will be necessary to increase the reliability and the useful life (i.e. the life of the engine) for the use in alcohol engines. The necessity to use an external ignition source for the alcohols is a significant disadvantage in comparison to other alternative fuels, such as DME and FTD.

The NO_X emissions will be lower for the alcohol engines than for diesel fuel and simultaneously the rate of EGR can be increased, which further reduces the NO_X emissions. In general, the soot and particulate formation is significantly reduced with alcohols, although an increase in particulate formation has been seen with high rates of EGR on a heavy-duty ethanol engine. It is not clear if the same problem will be seen for methanol but, in theory, this molecule should be better in this respect than ethanol due to the absence of carbon-carbon bonds and a higher content of oxygen. The application of a NO_X reducing catalyst should be easily facilitated on methanol according to limited test data, due to the excellent properties of methanol as a reducing agent. Ethanol should also be possible to use in combination with this catalyst technology, although ethanol is less suited as a reductant in a catalyst than methanol.

As in the case with DME, there are no practical opportunities to make alcohol diesel engines fuel flexible.

4.6.5 Direct fuel cells

A direct fuel cell system in Advisor® has been used as the primary input data for the simulation of this option. These input data are based on experimental data for a prototype fuel cell that has been developed by ANL in the USA. The fuel cell model in Advisor® has a maximum net efficiency (including auxiliaries) as high as 60%, which is one of the highest figures published for fuel cell systems. (Bearing in mind that the efficiency for a single cell is always higher than for a whole system).

A special characteristic of the fuel cell system in Advisor® is that the efficiency at zero power is as high as 20%, which is technically impossible[13] (in analogy with a perpetual motion machine), since the system is depending on auxiliaries. Furthermore, the fuel cell is atmospheric, which implies that a large and expensive stack (high platinum use) would have to be used. It is more realistic to use a pressurised stack, which necessitates the use of a compressor-expander with an associated electric drive. It seems inevitable that a vehicular system would need further "parasitic" losses in comparison to the relatively simple system in Advisor®. Therefore, a revised fuel cell system has been calculated on the condition that an additional auxiliary loss of 4 kW at full power (50 kW) and 2 kW at zero power would be necessary. Scaling of the system to reach the same power as the original system (50 kW) will be necessary to compensate for the additional losses. In **Figure 6**, the efficiency for some fuel cell systems has been plotted.

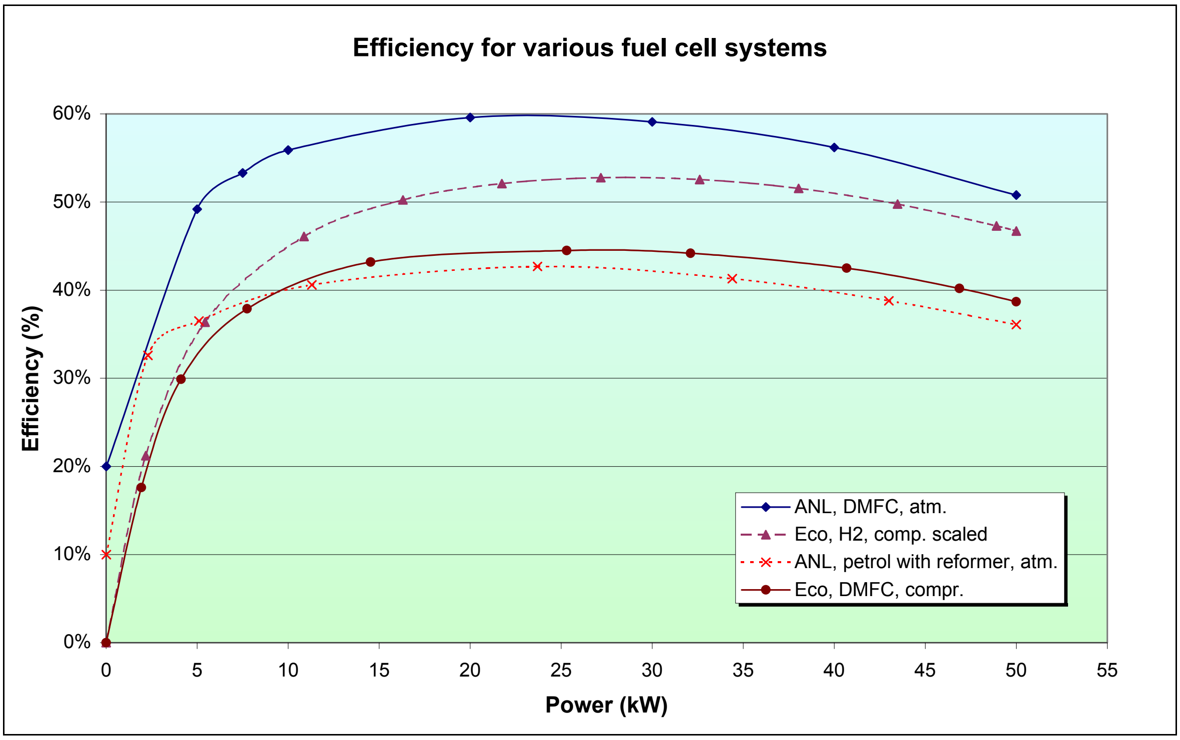


Figure 6. *Efficiency for fuel cell systems*

The direct fuel cell drive system has no large energy storage and therefore, the fuel cell stack has to be sized to slightly above 66 kW. Furthermore, no regenerative braking can be used (due to the limited battery capacity). Therefore, the total efficiency will be somewhat

[13] At zero load, the efficiency must be zero according to definition.

lower than a hybrid fuel cell system (energy storage). There are also other concerns. If, for example, the start period cannot be sufficiently short, there are no practical possibilities to do without a larger battery capacity. Under these conditions, the direct drive fuel cell system would have to be abandoned in favour of the fuel cell hybrid.

In general, **Figure 6** shows that the efficiency for the fuel cell systems is high at low load in comparison to internal combustion engines. It is also clear that the deterioration of the efficiency due to the "parasitic" losses is relatively larger at the lowest loads for the fuel cell used in the simulations ("Eco, H_2, comp. scaled" in the figure). A fuel cell from ANL with petrol reforming and a fuel cell with internal reforming of methanol (DMFC) are also shown where the efficiencies have been estimated by Ecotraffic.

4.6.6 Fuel cell hybrids

In this case, the same model for the fuel cell stack has been used as in the previous case (direct driven fuel cell), except that the power has been reduced by about 50%, i.e. to 35 kW.

Batteries that have the same performance as for the other hybrid drive systems has been foreseen also in this case, but since the power requirement is higher, the battery size has been increased. Since the start-up period presumably will be relatively long, there is certain risk that an even higher battery capacity could be necessary than what we have anticipated.

4.6.7 Fuel cell – internal reforming (DMFC)

Today, there is little information available about direct methanol fuel cells (DMFC) and their performance. Up to now, the reported efficiency for these fuel cells has been very low (seldom more than 15%) but it could be expected that a maximum efficiency of more than 40% is possible with new technology. Significant improvements of this system have been made recently, and therefore, this alternative cannot be overlooked. However, the efficiency anticipated for the DMFC fuel cell is only indicative. On the condition that a high efficiency can be achieved in the future, this option would be very interesting, since it is a notably simpler system than a fuel cell with reformer. The DMFC technology can only be applied on methanol and consequently, other fuels are of little interest for DMFC.

4.7 Total system efficiency

The total number of combinations of feedstock, fuels, fuel converters and drivetrains investigated is 98, of which six represent conventional fuels as petrol (4) and diesel fuel (2). It is difficult to present an overview of these data. We have chosen to make a classification in gaseous and liquid fuels, which subsequently have been divided after the feedstock used. In total, the results are summarised in four tables and as complementary information, diagrams are shown for some selected alternatives. In order to simplify the presentation of the results, the various smaller steps in the pathways have been lumped together in the following larger steps:

- Production (”Prod.”) comprising the three following steps: feedstock production; feedstock transport and fuel production
- Distribution, local reforming (in applicable cases) and refuelling (”Distr.”)
- On-board reforming of the fuel in the vehicle (Ref.)

- The powertrain (“P-train”), which comprise the fuel converter (engine) and the drivetrain (mechanical and electrical)
- Total system efficiency for the whole well-to-wheel chain (“Total”)

The four first steps in the pathway are logical steps in the life-cycle and in addition, the total efficiency is shown. Furthermore, another comparison is shown and this is a relative comparison using the petrol-fuelled car with a conventional drivetrain as the baseline (Rel.). It should also be mentioned that the efficiency for the powertrain is *not* the efficiency directly obtained from the simulation program. Using this efficiency would not be relevant in this case, since the fact that the weight is varying between the vehicles is not taken into account. Instead, a “corrected” efficiency is used, where the correction is based on the energy used in the vehicle in relation to the energy used in the conventional vehicle.

In order to calculate the efficiency for the whole vehicle, we have first summarised the energy used for rolling resistance, aerodynamic drag and the kinetic energy lost during braking. Then this sum is related to the fuel energy provided and this yields the efficiency for the powertrain. Other definitions of the efficiency are sometimes used and for example, Advisor® uses a definition that does not include the last term (kinetic energy).

4.7.1 Gaseous fuels

Feedstock: natural gas

In **Table 6** the well-to-wheel efficiency for the gaseous fuels derived from natural gas are shown. Some of the conclusions are more or less general and therefore, they are only discussed in connection to this table and not in the tables shown later.

From the results in **Table 6** for gaseous fuels from natural gas and for the conventional fuels, such as petrol and diesel fuel, the following conclusions can be drawn:

- In general, electric hybrids fuelled by petrol and diesel fuel have higher efficiency than the conventional drivetrains. The same conclusion is also applicable for the other fuels used in combustion engines. The relative advantage of hybridisation is somewhat greater for otto engines than for diesel engines. For fuel cell vehicles, the advantage of a hybrid drivetrain is not as great as for the combustion engines.
- The fuel cell is the fuel converter that has the highest efficiency and in combination with a hybrid drivetrain, it has the highest efficiency of all powertrains. Of the fuel converters, the diesel engine has the second highest efficiency and the otto engine has the lowest efficiency. It is also notable that the difference in efficiency between the best piston engine (diesel hybrid) and the fuel cell hybrid is not remarkably great (21,2% vs. 23,5%). The *relative* difference is not more than about 10%. This might seem controversial but it appears to be in line with the findings from the PNGV programme as shown above (**Figure 5**). The improvement potential by a factor as high as 2 to 3, which is often cited for fuel cells powertrains, seems very unlikely in view of our results and the results from the PNGV programme. One reason for the relatively small differences in our case is due to that the comparison is between hybrid systems in both cases. The second reason is that we have anticipated a continuous development of the combustion engines in the future. Since fuel cell vehicles have not yet been commercialised in a larger scale, the comparison must be carried out for future vehicles. It is worth noting that the average efficiency (in the driving cycle) of the fuel cell engine

is as high as 43,3% but "only" 29,6% for the diesel engine and 26,1% for the petrol fuelled otto engine[14]. Since the fuel cell powertrain is a series hybrid that has significantly lower efficiency in its electric drivetrain than a parallel hybrid drivetrain, the total efficiency of the powertrain is reduced. The significantly higher weight for the fuel cell vehicle also contributes to a reduction in the total efficiency of this vehicle.

- The total efficiency is considerably higher for diesel fuel than it is for petrol. This is partly dependent of the higher efficiency of the engine, partly dependent on the higher efficiency in the fuel production. The relative difference between the engine types in a conventional drivetrain are 12,7% and 15,2% for the hybrid system – in both cases of course an advantage for the diesel engine. However, these differences are smaller than the difference of 18,1% of the vehicles of today, as a recent evaluation (September 2000) of an updated material from the previously cited report has shown. As described before, future development of both engine types will reduce the difference between them [3].
- The use of methane in the form of CNG has the highest efficiency of all fuels based on natural gas. The total efficiency of CNG in an otto engine hybrid and in a fuel cell is practically identical. The losses caused by the conversion in the fuel reformer – a loss not incurred for the combustion engine – is the primary reason for the relatively poor results for the fuel cell. Methane distributed and used in the vehicle as LNG does not have much lower efficiency than CNG. The reason for these results are that the vast compression work needed for CNG, which in principle are equal to the losses in the liquefaction of natural gas to LNG. The refuelling of LNG does not incur the same losses as refuelling of CNG.
- Hydrogen from natural gas (GH_2) used in an otto engine results in a significantly lower efficiency than to use the natural gas (as CNG) directly in this engine. Fuel cells improve the results but the efficiency is still lower than for CNG and LNG in an otto engine. In spite of that, hydrogen used in fuel cells is the best alternative of all options that use hydrogen from natural gas. Hydrogen from electricity is the alternative that has the lowest efficiency and next is hydrogen as LH_2 and hydrogen distributed as DME but reformed at the refuelling station.
- DME in a diesel engine is better than all hydrogen alternatives for an otto engine and consequently, better than all alternatives but some that use methane directly (CNG and LNG). The higher efficiency of a diesel engine does not fully compensate for the losses in the conversion of natural gas to DME. DME has marginally higher efficiency in a diesel engine than in a fuel cell. The advantage of DME in comparison to the gaseous (CNG, GH_2) and cryogenic (LNG, LH_2) fuels is that the fuel distribution is considerably simplified. For example, the distribution of hydrogen in gaseous form (via pipeline) hardly is a solution that could be used on a large scale and for general use.
- Natural gas distributed as LNG (dispensed as LNG or CNG), is a fuel that can provide both a high efficiency and at the same time is not limited to a niche, since a large-scale distribution is possible. A large-scale enlargement of the natural gas pipe grid is not likely in Sweden but the distribution of natural gas as LNG would be a possible solution for broad use of this fuel. Unfortunately, this alternative tends to be very expensive in comparison to the distribution of conventional liquid fuels.

[14] The efficiency of the otto engine is somewhat higher when fuelled by alcohols than by petrol.

Table 6. *System efficiency for gaseous fuels from (fossil) natural gas*

				Efficiency					
	Fuel	**Fuel con.**	**D-train.**	**Prod**	**Distr.**	**Reform.**	**P-train.**	**Total**	**Rel.**
Oil	Petrol	Otto	Conv.	0,841	0,986	1,000	0,149	0,124	1,000
	↑	Otto	Hybrid	0,841	0,986	1,000	0,185	0,153	1,240
	↑	FC	Direct	0,841	0,986	0,780	0,226	0,146	1,184
	↑	FC	Hybrid	0,841	0,986	0,780	0,235	0,152	1,228
	Diesel	Diesel	Conv.	0,888	0,990	1,000	0,176	0,155	1,250
	↑	Diesel	Hybrid	0,888	0,990	1,000	0,212	0,186	1,507
Gaseous fuels from (fossil) natural gas	Methane, CNG	Otto	Conv.	0,957	0,909	1,000	0,149	0,129	1,045
	↑	Otto	Hybrid	0,957	0,909	1,000	0,182	0,159	1,281
	↑	FC	Direct	0,957	0,909	0,780	0,226	0,154	1,241
	↑	FC	Hybrid	0,957	0,909	0,780	0,235	0,159	1,288
	Methane, LNG	Otto	Conv.	0,887	0,963	1,000	0,149	0,127	1,027
	↑	Otto	Hybrid	0,887	0,963	1,000	0,182	0,156	1,259
	↑	FC	Direct	0,887	0,963	0,780	0,226	0,151	1,220
	↑	FC	Hybrid	0,887	0,963	0,780	0,235	0,157	1,266
	Hydrogen, GH_2	Otto	Conv.	0,770	0,794	1,000	0,149	0,091	0,735
	↑	Otto	Hybrid	0,770	0,794	1,000	0,182	0,111	0,901
	↑	FC	Direct	0,770	0,794	1,000	0,226	0,138	1,119
	↑	FC	Hybrid	0,770	0,794	1,000	0,235	0,144	1,161
	Hydrogen, LH_2	Otto	Conv.	0,471	0,916	1,000	0,149	0,064	0,518
	↑	Otto	Hybrid	0,471	0,916	1,000	0,182	0,079	0,635
	↑	FC	Direct	0,471	0,916	1,000	0,226	0,098	0,789
	↑	FC	Hybrid	0,471	0,916	1,000	0,235	0,101	0,819
	El, GH_2	Otto	Conv.	0,451	0,820	1,000	0,149	0,055	0,444
	↑	Otto	Hybrid	0,451	0,820	1,000	0,182	0,067	0,544
	↑	FC	Direct	0,451	0,820	1,000	0,226	0,084	0,676
	↑	FC	Hybrid	0,451	0,820	1,000	0,235	0,087	0,702
	DME, GH_2	Otto	Conv.	0,754	0,641	1,000	0,149	0,072	0,581
	↑	Otto	Hybrid	0,754	0,641	1,000	0,182	0,088	0,712
	↑	FC	Direct	0,754	0,641	1,000	0,226	0,109	0,884
	↑	FC	Hybrid	0,754	0,641	1,000	0,235	0,114	0,917
	DME	Diesel	Conv.	0,725	0,967	1,000	0,176	0,123	0,997
	↑	Diesel	Hybrid	0,725	0,967	1,000	0,212	0,149	1,202
	↑	FC	Direct	0,725	0,967	0,840	0,226	0,133	1,078
	↑	FC	Hybrid	0,725	0,967	0,840	0,242	0,143	1,153

Feedstock: biomass

In **Table 7** the system efficiencies for gaseous fuels produced from biomass are shown. The results for the conventional powertrains and fuels are similar as previously only the results for the other liquid fuels are discussed here. The following conclusions can be drawn:

- In this case, methane (biogas or CBG and SNG) must be produced from biomass using a conversion process, which was not the case for natural gas. Therefore, the efficiencies are generally significantly lower for the biomass derived fuels and this is the reason why methane is not one of the best alternatives in this case. SNG is somewhat less efficient than biogas (CBG).
- Hydrogen in a fuel cell where the hydrogen is distributed in gaseous form is the best hydrogen alternative and the second best alternative (after DME in a diesel engine) of all assessed alternatives. At the same time, one has to note that the distribution of hydrogen for widespread use hardly is an attractive alternative. The same relations as for the alternatives that are distributed in gaseous phase are also valid for the fuels that are distributed in liquid phase (LH_2), as well as for DME and distribution using electricity. The last alternative (electricity) is the least efficient alternative of all biomass based fuel options. However, the distribution possesses no serious problems in this case in contrary to the other alternatives to distribute hydrogen or simple hydrogen carriers in gaseous phase.
- DME in a diesel engine is the best alternative of all options using DME as a fuel and at the same time, this is the best alternative of all gaseous fuels produced from biomass. The fuel cell has a lower efficiency than the diesel engine due to the necessity to reform DME to hydrogen on-board the vehicle.
- In general, the system efficiency is lower for the fuels produced from biomass compared to the fuels produced from natural gas or crude oil. This is conceivable, since the fuel production stage is more difficult in the former case (i.e.. higher losses are incurred) depending on the character of the feedstock.

Table 7. System efficiency for gaseous fuels from biomass

				Efficiency					
	Fuel	**Fuel con.**	**D-train.**	**Prod**	**Distr.**	**Reform.**	**P-train.**	**Total**	**Rel.**
Oil	Petrol	Otto	Conv.	0,841	0,986	1,000	0,149	0,124	1,000
	↑	Otto	Hybrid	0,841	0,986	1,000	0,185	0,153	1,240
	↑	FC	Direct	0,841	0,986	0,780	0,226	0,146	1,184
	↑	FC	Hybrid	0,841	0,986	0,780	0,235	0,152	1,228
	Diesel	Diesel	Conv.	0,888	0,990	1,000	0,176	0,155	1,250
	↑	Diesel	Hybrid	0,888	0,990	1,000	0,212	0,186	1,507
Gaseous fuels from biomass	Methane, CNG	Otto	Conv.	0,527	0,917	1,000	0,149	0,072	0,581
	↑	Otto	Hybrid	0,527	0,917	1,000	0,182	0,088	0,712
	↑	FC	Direct	0,527	0,917	0,780	0,226	0,085	0,690
	↑	FC	Hybrid	0,527	0,917	0,780	0,235	0,089	0,716
	Methane, SNG	Otto	Conv.	0,502	0,909	1,000	0,149	0,068	0,549
	↑	Otto	Hybrid	0,502	0,909	1,000	0,182	0,083	0,673
	↑	FC	Direct	0,502	0,909	0,780	0,226	0,081	0,652
	↑	FC	Hybrid	0,502	0,909	0,780	0,235	0,084	0,676
	Hydrogen, GH_2	Otto	Conv.	0,598	0,800	1,000	0,149	0,071	0,575
	↑	Otto	Hybrid	0,598	0,800	1,000	0,182	0,087	0,705
	↑	FC	Direct	0,598	0,800	1,000	0,226	0,108	0,876
	↑	FC	Hybrid	0,598	0,800	1,000	0,235	0,112	0,909
	Hydrogen, LH_2	Otto	Conv.	0,436	0,950	1,000	0,149	0,062	0,498
	↑	Otto	Hybrid	0,436	0,950	1,000	0,182	0,075	0,610
	↑	FC	Direct	0,436	0,950	1,000	0,226	0,094	0,758
	↑	FC	Hybrid	0,436	0,950	1,000	0,235	0,097	0,786
	El, GH_2	Otto	Conv.	0,375	0,820	1,000	0,149	0,046	0,370
	↑	Otto	Hybrid	0,375	0,820	1,000	0,182	0,056	0,453
	↑	FC	Direct	0,375	0,820	1,000	0,226	0,070	0,563
	↑	FC	Hybrid	0,375	0,820	1,000	0,235	0,072	0,584
	DME, GH_2	Otto	Conv.	0,586	0,650	1,000	0,149	0,057	0,458
	↑	Otto	Hybrid	0,586	0,650	1,000	0,182	0,069	0,561
	↑	FC	Direct	0,586	0,650	1,000	0,226	0,086	0,697
	↑	FC	Hybrid	0,586	0,650	1,000	0,235	0,090	0,724
	DME	Diesel	Conv.	0,550	0,980	1,000	0,176	0,095	0,767
	↑	Diesel	Hybrid	0,550	0,980	1,000	0,212	0,114	0,925
	↑	FC	Direct	0,550	0,980	0,840	0,226	0,103	0,829
	↑	FC	Hybrid	0,550	0,980	0,840	0,242	0,110	0,887

4.7.2 Liquid fuels

Feedstock: natural gas

In **Table 8** the system efficiency for the liquid fuels produced from natural gas is shown. The fuel options in this case are not as many as for the gaseous fuels presented above, and for both fuels (Fischer-Tropsch fuel and methanol), they are based on the thermo-chemical production route from synthesis gas.

Table 8. *System efficiency for liquid fuels from fossil natural gas*

				Efficiency					
	Fuel	**Fuel con.**	**D-train.**	**Prod**	**Distr.**	**Reform.**	**P-train.**	**Total**	**Rel.**
Oil	Petrol	Otto	Conv.	0,841	0,986	1,000	0,149	0,124	1,000
	↑	Otto	Hybrid	0,841	0,986	1,000	0,185	0,153	1,240
	↑	FC	Direct	0,841	0,986	0,780	0,226	0,146	1,184
	↑	FC	Hybrid	0,841	0,986	0,780	0,235	0,152	1,228
	Diesel	Diesel	Conv.	0,888	0,990	1,000	0,176	0,155	1,250
	↑	Diesel	Hybrid	0,888	0,990	1,000	0,212	0,186	1,507
Liquid fuels from natural gas	FTD	Otto	Conv.	0,556	0,989	1,000	0,176	0,097	0,782
	↑	Otto	Hybrid	0,556	0,989	1,000	0,212	0,117	0,943
	↑	FC	Direct	0,556	0,989	0,780	0,226	0,097	0,785
	↑	FC	Hybrid	0,556	0,989	0,780	0,235	0,101	0,815
	Methanol	Otto	Conv.	0,688	0,978	1,000	0,162	0,109	0,883
	↑	Otto	Hybrid	0,688	0,978	1,000	0,201	0,135	1,095
	↑	Diesel	Conv.	0,688	0,978	1,000	0,176	0,118	0,957
	↑	Diesel	Hybrid	0,688	0,978	1,000	0,212	0,143	1,154
	↑	FC	Direct	0,688	0,978	0,860	0,230	0,133	1,075
	↑	FC	Hybrid	0,688	0,978	0,860	0,242	0,140	1,132
	↑	DMFC	Hybrid	0,688	0,978	1,000	0,172	0,116	0,938
	Methanol, GH2	Otto	Conv.	0,719	0,661	1,000	0,149	0,071	0,571
	↑	Otto	Hybrid	0,719	0,661	1,000	0,182	0,087	0,700
	↑	FC	Direct	0,719	0,661	1,000	0,230	0,109	0,883
	↑	FC	Hybrid	0,719	0,661	1,000	0,242	0,115	0,930

The following conclusions can be drawn from the results in **Table 8**.

- The difference in efficiency between the otto and diesel engines is less for the alcohols than in the case for petrol and diesel fuel. This is simply because the efficiency in the engine can be increased when it is optimised for alcohols rather than for petrol, while the same efficiency has been anticipated in the diesel engine case.
- Methanol has generally the highest efficiency of all fuels. The best combination of engines and drivetrains is a diesel engine and an electric hybrid drivetrain but a fuel cell hybrid has only fractionally lower efficiency.

- The fuel cell with internal reforming of methanol (DMFC) has a lower efficiency than both the other fuel cell alternatives on methanol but it is uncertain how high the efficiency could be for a practical system of this kind. The relatively high weight of the vehicle is one of the reasons for the comparatively poor result in this case, and the question remains to what extent it would be possible to reduce the weight in the future.
- The FTD fuel generally has lower system efficiency than methanol due to a lower efficiency in the fuel production chain and a lower efficiency for the on-board fuel reformer in comparison to a methanol reformer.
- Hydrogen from methanol, where the reforming is made on-site at the refuelling station, does not get as high efficiency as with an on-board methanol reformer. This might be surprising but the reason is that an on-board reformer has a higher efficiency, since it can be integrated in the fuel cell system and thus use waste energy (heat) and tail gas from the anode. An on-site reformer does not have the same opportunities for an optimised and integrated system as an on-board reformer. However, certain possibilities might remain for the on-site reformer to utilise waste energy but this has not been included in the calculations, since the refuelling station is considered a stand-alone unit.
- The otto engine fuelled by hydrogen produced from methanol by local reforming has the lowest system efficiency of all combinations that use liquid fuels from natural gas.

Feedstock: biomass

In **Table 9**, the system efficiency for the liquid fuels from biomass is shown. The fuel options are less in this case than for the gaseous fuels above and in two cases (FTD and methanol), they are bases on the route using synthesis gas and in one case on fermentation (ethanol). Some of the general conclusions are similar as for natural gas based fuels and the additional conclusions are:

- Methanol is the fuel that has the highest system efficiency of all liquid fuels from biomass. The efficiency of the diesel engine hybrid system is somewhat higher than for the fuels cell hybrid on the same fuel. For the direct drive systems the results is the opposite, i.e. the fuel cell is better than the diesel engine. As expected, the otto engine hybrid has a lower efficiency that the fuel cell hybrid, but the difference (0,831 vs. 0,860) is not striking. This seems to be one case where the otto engine could be acceptable regarding the efficiency. The DMFC has a lower efficiency than the fuel cell with a reformer and similarly, it has a lower efficiency than the piston engines.
- Ethanol, both in a diesel engine and a fuel cell, has lower system efficiency than methanol. Compared to the FTD fuel, ethanol is somewhat better (both in a diesel engine and in a fuel cell).
- The FTD fuel has generally lower efficiency compared to methanol. Even if the comparison is made using a diesel engine for the FTD fuel and an otto engine for methanol, the former combination has a lower efficiency than the latter.
- Hydrogen in an otto engine where the hydrogen has been produced by methanol reforming at the refuelling station has the lowest efficiency of all alternatives that are – distributed as liquid fuels. (However, hydrogen from electricity has an even lower efficiency, see above.) This is not very surprising, since this alternative is not of particular interest from a practical point of view. In a fuel cell, the efficiency increases and in fact, it is higher than for alternatives as ethanol and FTD fuel in a fuel cell.

Table 9. System efficiency for liquid fuels from biomass

				Efficiency					
	Fuel	**Fuel con.**	**D-train.**	**Prod**	**Distr.**	**Reform.**	**P-train.**	**Total**	**Rel.**
Oil	Petrol	Otto	Konv.	0,841	0,986	1,000	0,149	0,124	1,000
	↑	Otto	Hybrid	0,841	0,986	1,000	0,185	0,153	1,240
	↑	FC	Direkt	0,841	0,986	0,780	0,226	0,146	1,184
	↑	FC	Hybrid	0,841	0,986	0,780	0,235	0,152	1,228
	Diesel	Diesel	Konv.	0,888	0,990	1,000	0,176	0,155	1,250
	↑	Diesel	Hybrid	0,888	0,990	1,000	0,212	0,186	1,507
Liquid fuels from biomass	FTD	Diesel	Konv.	0,433	0,990	1,000	0,176	0,075	0,610
	↑	Diesel	Hybrid	0,433	0,990	1,000	0,212	0,091	0,735
	↑	FC	Direkt	0,433	0,990	0,780	0,230	0,077	0,621
	↑	FC	Hybrid	0,433	0,990	0,780	0,242	0,081	0,654
	Methanol	Otto	Konv.	0,522	0,980	1,000	0,162	0,083	0,670
	↑	Otto	Hybrid	0,522	0,980	1,000	0,201	0,103	0,831
	↑	Diesel	Konv.	0,522	0,980	1,000	0,176	0,090	0,727
	↑	Diesel	Hybrid	0,522	0,980	1,000	0,212	0,108	0,877
	↑	FC	Direkt	0,522	0,980	0,860	0,230	0,101	0,816
	↑	FC	Hybrid	0,522	0,980	0,860	0,242	0,106	0,860
	↑	DMFC	Hybrid	0,522	0,980	1,000	0,172	0,088	0,712
	Methanol, GH2	Otto	Konv.	0,562	0,662	1,000	0,149	0,055	0,447
	↑	Otto	Hybrid	0,562	0,662	1,000	0,182	0,068	0,548
	↑	FC	Direkt	0,562	0,662	1,000	0,230	0,085	0,691
	↑	FC	Hybrid	0,562	0,662	1,000	0,242	0,090	0,728
	Ethanol	Otto	Konv.	0,449	0,988	1,000	0,159	0,070	0,570
	↑	Otto	Hybrid	0,449	0,988	1,000	0,197	0,087	0,707
	↑	Diesel	Konv.	0,449	0,988	1,000	0,176	0,078	0,631
	↑	Diesel	Hybrid	0,449	0,988	1,000	0,212	0,094	0,761
	↑	FC	Direkt	0,449	0,988	0,820	0,230	0,084	0,676
	↑	FC	Hybrid	0,449	0,988	0,820	0,242	0,088	0,712

In order to obtain a somewhat better overview, the results in the previous tables for the relative energy use (the column on the far right) are shown in matrixes in two tables below. The rows have been organised, as far as possible, in a descending order. This order is somewhat ambiguous, since the efficiency for an otto engine hybrid for the fuels most suitable for otto engines actually are higher than for a direct drive fuel cell. The results, as described above, are shown in **Table 10** (crude oil and natural gas) and in **Table 11** (biomass).

Table 10. Relative system efficiency for systems based on crude oil and natural gas feedstocks

FUEL, fuelled as	Petrol	Diesel	DME	Methanol	Ethanol	FTD	CNG	CNG	GH_2	GH_2	GH_2	GH_2	GH_2
DISTRIBUTED as	Petrol	Diesel	DME	Methanol	Ethanol	FTD	CNG	LNG	GH_2	LH	DME	Methanol	El
Powertrain	**System efficiency for crude oil / natural gas-based systems in relation to the conventional petrol-fuelled car (=100)**												
Diesel eng. - hybrid		150,7	120,2	115,4		94,3							
Fuel cell - hybrid			115,3	113,2		81,5	128,8	126,6	116,1	81,9	91,7	93,0	68,8
Fuel cell - direct			107,8	107,5		78,5	124,1	122,0	111,9	78,9	88,4	88,3	66,3
Otto engine - hybrid	124,0			109,5			128,1	125,9	90,1	63,5	71,2	70,0	53,4
Diesel eng. – conv.		125,0	99,7	95,7		78,2							
DMFC - hybrid				93,8									
Otto engine – conv.	***100***			88,3			104,5	102,7	73,5	51,8	58,1	57,1	43,6

Table 11. Relative system efficiency for systems based on biomass feedstocks

FUEL, fuelled as	Petrol	Diesel	DME	Methanol	Ethanol	FTD	CNG	CNG	GH_2	GH_2	GH_2	GH_2	GH_2
DISTRIBUTED as	Petrol	Diesel	DME	Methanol	Ethanol	FTD	CNG	LNG	GH_2	LH	DME	Methanol	El
Powertrain	**System efficiency for biomass-based systems in relation to the conventional petrol-fuelled car (=100)**												
Diesel eng. - hybrid			92,5	87,7	76,1	73,5							
Fuel cell - hybrid			88,7	86,0	71,2	65,4	71,6	67,6	90,9	78,6	72,4	72,8	58,4
Fuel cell - direct			82,9	81,6	67,6	62,1	69,0	65,2	87,6	75,8	69,7	69,1	56,3
Otto engine - hybrid				83,1	70,7		71,2	67,3	70,5	61,0	56,1	54,8	45,3
Diesel eng. – conv.			76,7	72,7	63,1	61,0							
DMFC - hybrid				71,2									
Otto engine – conv.				67,0	57,0		58,1	54,9	57,5	49,8	45,8	44,7	37,0

4.7.3 Highest system efficiency

There are, of course, other ways to present the results than those used in previous sections. A classification that might be of interest is to group them as niche-fuels and principal fuels. Niche-fuels are, according to the definition in this study, those that cannot attain a market share over 10% of the total motor fuel use. The definition of principal fuels is that they should have potential to broad general use everywhere. Such fuels are those with a broad feedstock basis and distribution as liquids, though not necessarily be used as liquids at the end use. As example of the latter kind is LNG, which is distributed as liquid but could be used in gaseous form as CNG in light duty vehicles (and with advantage also as LNG in heavy duty vehicles).

Another classification that is used is differentiation between fuels, which may be “flexible fuels” in any sense. Such ones are fuels that can be utilised in FFV (e.g. methanol) or in dual-fuel vehicles (e.g. biogas and petrol). Another example, which has been included among the flexible fuels, is synthetic hydrocarbons (synfuel) as miscible with diesel oil in any proportion. Even though the properties of the synfuel departs somewhat from conventional diesel oil, it seems likely that engine and control system to take care of the differences. The synfuel can also be used for low level blending in a similar way as for alcohols in petrol. Lacking a better acronym “FFV” has been used for all the various examples mentioned although it has to be noted that duplicated fuel systems are needed onboard for the dual-fuel alternatives. During an introductory phase, fuel flexibility can be an important property, and it therefore is interesting to particularly demonstrate such properties.

A classification according to fuels from natural gas and from biomass feedstocks has been used below. To reduce the number of alternatives only the ten best combinations of motor fuel, energy converter and transmission have been shown in diagrams.

Feedstock: natural gas

In **Figure 7** the system efficiency (in the entire chain from feedstock to end use) for the 10 best combinations of motor fuel, energy converter and transmission have been shown.

DME in diesel engine (hybrid and conventional), hydrogen in fuel cell hybrid, and methanol in diesel engine hybrid also are on the list for the 10 best combinations. DME is in fact the fuel, which shows the highest system efficiency of those fuels that have a step of chemical conversion at the production. Methanol is the only one of these fuels that is liquid at normal atmospheric temperature and pressure.

Another interesting way of accounting is to show the best combination (energy converter and transmission) for each fuel. In **Figure 8** a comparison is shown for these alternatives, which include 8 different drivetrains for the fuels that are produced from natural gas.

As is indicated in **Figure 8,** CNG, LNG, DME, GH_2 and methanol are the best alternatives. The differences between these fuels are not very great, while synfuel, LH_2 and electricity have considerably lower system efficiency compared to the first mentioned motor fuels.

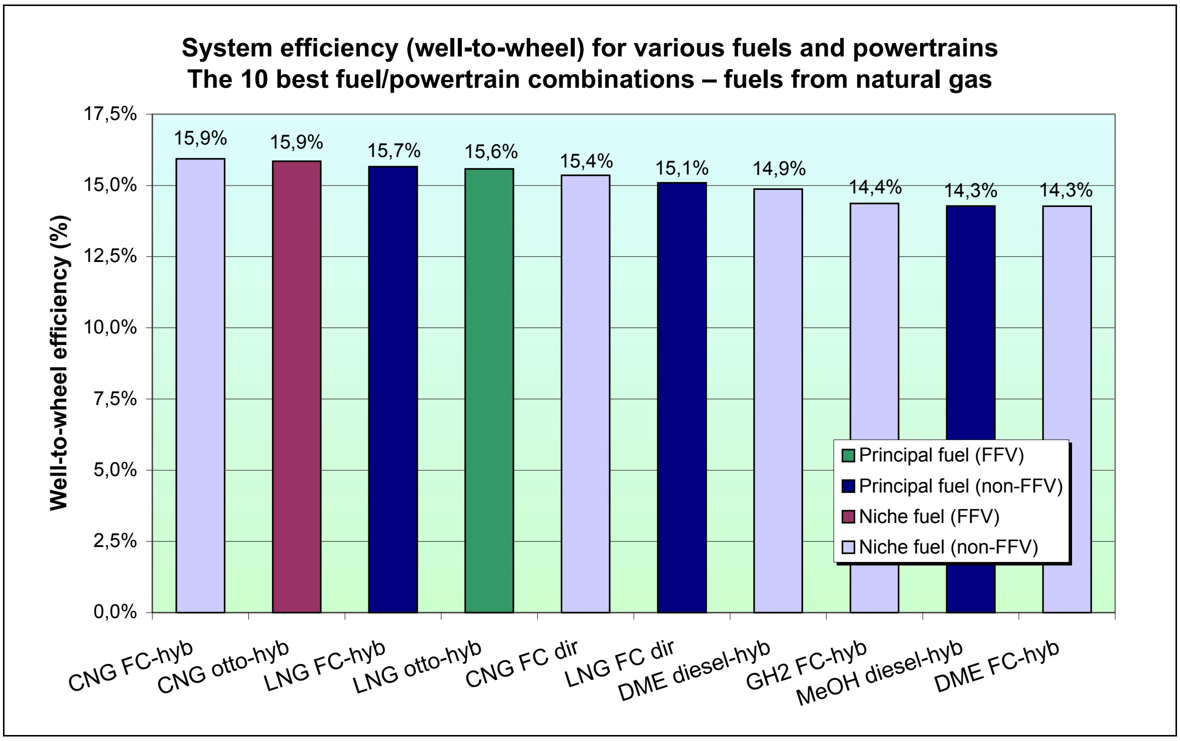


Figure 7. *System efficiency for the 10 best fuel/powertrain combinations. Fuels from natural gas feedstock.*

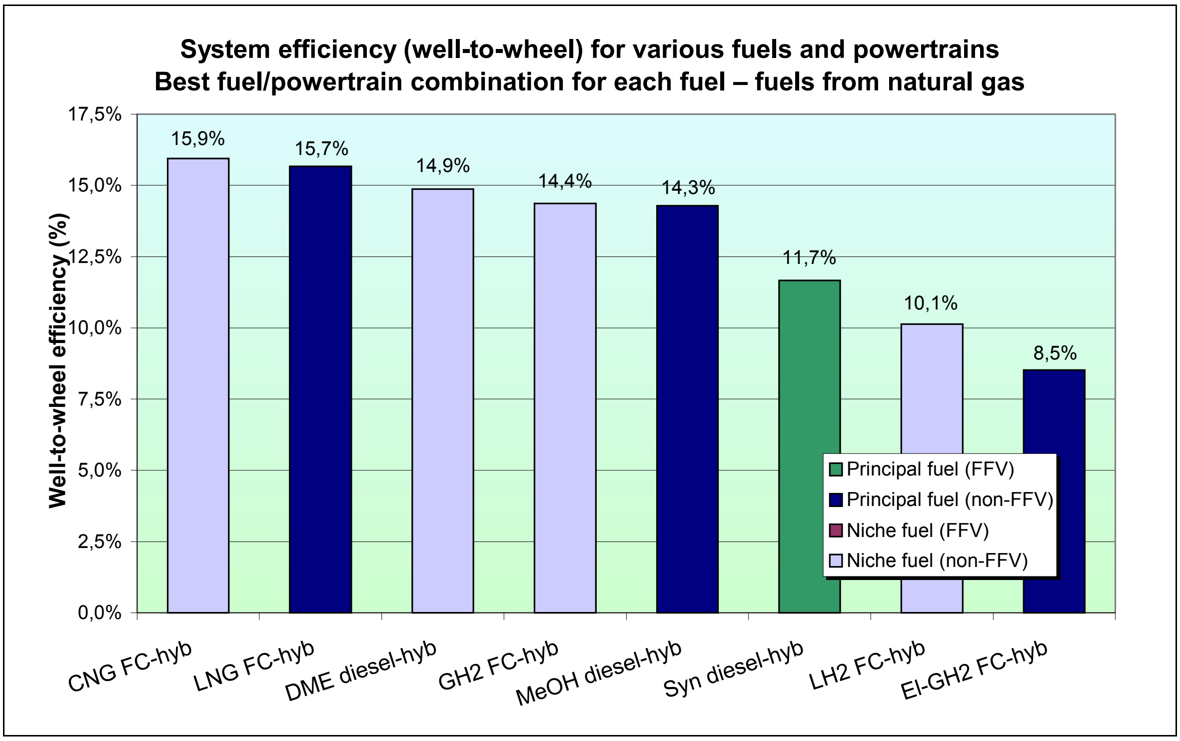


Figure 8*.* *System efficiency for the best combinations of fuel/powertrain. Fuels from natural gas feedstock.*

Feedstock: biomass

In **Figure 9** the system efficiency (entire fuel chain from feedstock to end use) for the 10 best combinations of motor fuel, energy converter and transmission are shown for fuels from biomass feedstock. As only the 10 best combinations are included in the figure, not all four fuel sub-alternatives entered the figure, but “Niche fuel (FFV)” is missing.

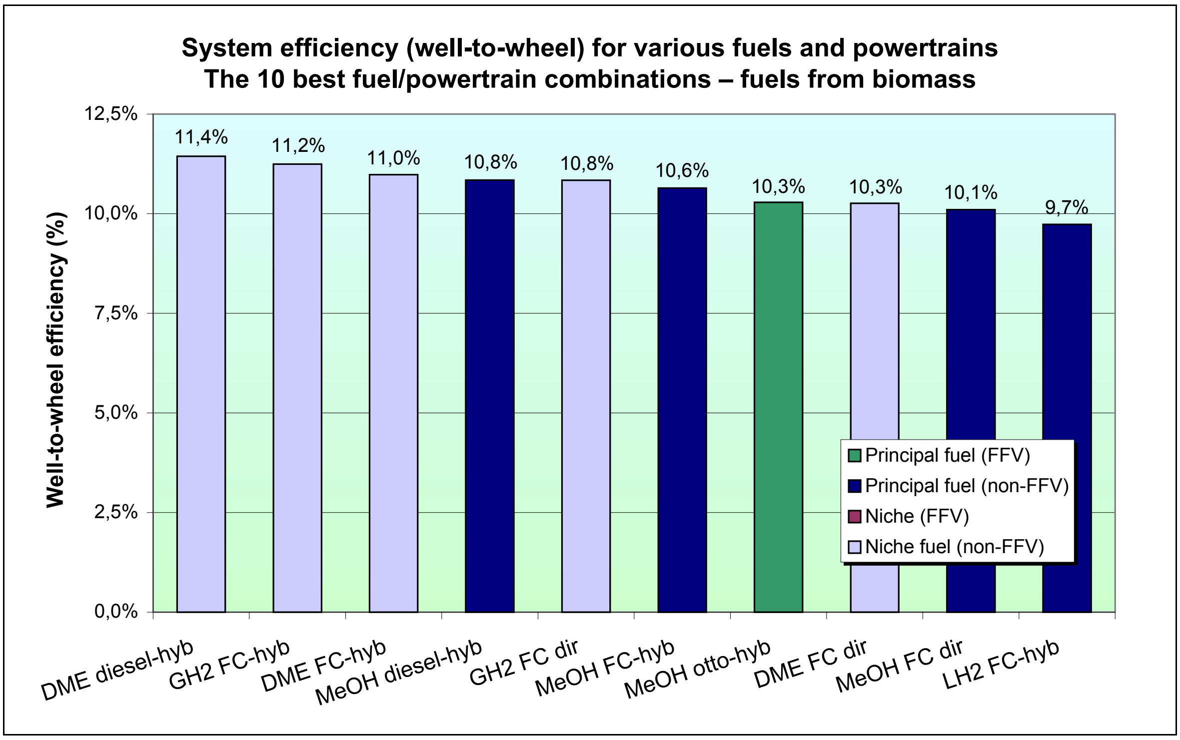


Figure 9. *System efficiency for the 10 best fuel/powertrain combinations. Fuels from biomass feedstock*

It might be interesting to note that methane as motor fuel (biogas and SNG) is not found among the ten best combinations when biomass is the feedstock (**Figure 9)**. With fossil natural gas as feedstock, methane scored the highest system efficiency. Instead, DME, hydrogen and methanol are the top ranking motor fuels. It might again be interesting to note that methanol is the only fuel that is liquid at normal conditions.

In the same way as above for the motor fuels from natural gas, a comparison is shown in **Figure 10** between the best alternatives with fuels from biomass. Nine different combinations qualify.

Figure 10 shows that the ranking between the motor fuels is not the same as for the fuels produced from fossil natural gas. For instance, methane as CBG and SNG now are among the worst alternatives – only electricity as distribution form for hydrogen is a worse alternative. As a coarse ranking, it might be stated that there are three different groups of motor fuels. The first top ranking includes DME, GH_2 and methanol; the second LH_2, ethanol and synfuel; while electricity ends up in the last group.

An important aspect, which might be decisive for which fuel has qualifications to become a principal fuel in the future and at the same time make a transition to bio-based motor fuels possible in the long term, is that the fuel must have high system efficiency *both* with biomass and with natural gas as feedstock. Among those fuels, which have the highest system efficiency, DME, GH_2 and methanol are found among the 5 best on each list (**Figure 8** and **Figure 10** respectively). In an effort to summarise the results, these alternative motor fuels should be given top priority based on the criteria highest system efficiency with both feedstocks.

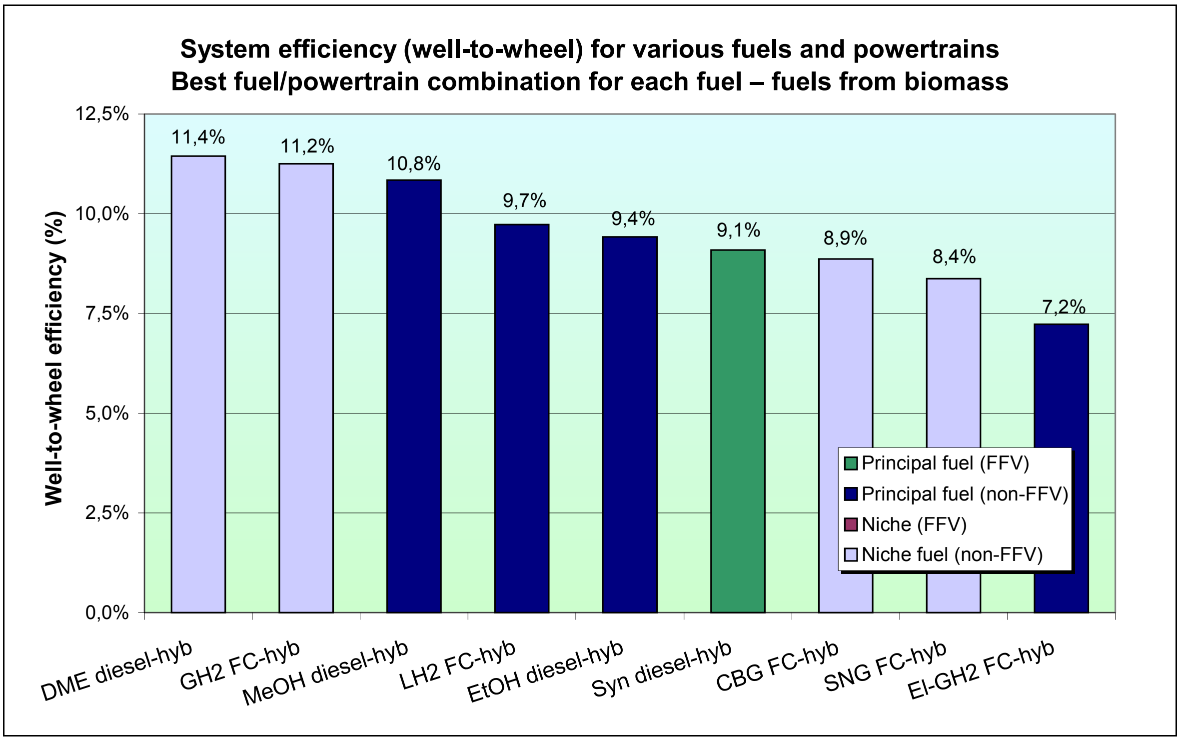


Figure 10. *System efficiency for the best combinations of fuel/powertrain. Fuels from biomass feedstock*

In a somewhat broader interpretation of the results to include the 6 best fuels for each feedstock also synfuel appears among the 4 with top priority. It might also be interesting to note that all these fuels (3 or 4 depending on the criteria chosen) are based on a process that uses gasification of biomass when this type is the base. The processes for production of DME and methanol are very similar and those motor fuels might even be produced in the same plant at a certain additional investment. This strategy might be preferable for a (commercial) prototype or demonstration plant, as both fuels could be investigated, although not simultaneously.

It is also important for this study to have a continuation to supplement with an analysis of costs for production, distribution and end use. It is possible that cost criteria will lead to elimination of some alternatives due to unreasonable high costs in the system.

Another important aspect to note is that the alternative of using an otto-engine as fuel converter is not included in any "best" alternative for any fuel. As has been described above, the otto-engine is, however, the only energy converter that in a rather simple way can be made fuel flexible. This is a significant advantage over diesel engines and fuel cells. Indeed, it has been argued that a fuel reformer (for fuel cell vehicles) might be made fuel flexible, but it must be a considerable cost increase to use a reformer from so complex and different fuels as synfuel and/or petrol to fuels that are simpler to reform, such as for instance methanol and DME. It is still too early determine if a powertrain with fuel cell can be made fuel flexible in a simple and cost effective way. For a diesel engine, it is almost impossible except for the specific case when synfuel will be used.

In a scenario where the diesel engine would have a much higher market penetration due to its higher efficiency compared to the otto-engine, the challenge to considerably reduce harmful emissions yet remains. Certainly, the fuel alternatives discussed here (DME, alcohols, synfuel) have improved prospects to low emissions compared to diesel oil, but further development is still needed to reach the low levels of NO_X, which have been commercially demonstrated for the best otto-engines. Such an example is the petrol driven cars, which meet the so-called SULEV-limits in California. A NO_x-reducing catalyst *is a necessity* with diesel engines (irrespective of motor fuel used) to meet this emission level, unless a revolutionary new combustion technology (HCCI[15]), presently still on the research level, can be developed to commercial use. The particle emissions can, if necessary (not quite certain to be needed for the alternative motor fuels), be handled with particle filters, for which the development has a reached higher status than for the NO_X-reduction.

During a transition phase, some fuel flexibility probably will be required for vehicles that shall be able to have general and common use. Therefore, it seems likely that otto-engines will play a great role during this phase, partly because fuel cells will hardly have any great penetration during the next 10 years and in a simple way can provide fuel flexibility, and partly because the diesel-engines may hardly meet the demand on fuel flexibility and, moreover, not yet have attained sufficiently low NO_X-levels. In summing the discussion above, the otto-engine will thus play a decisive role also as fuel converter for alternative motor fuels during foreseeable future. Its disadvantage is lower efficiency than for the two other energy converters but the other advantages seem obvious during a transition phase.

4.7.4 Fossil and non-fossil energy use

In this report, energy efficiency and energy usage has so far been discussed irrespective of the origin of the energy carrier, fossil or renewable. A diagram showing the split between the to types of the energy usage in relative terms for the three best motor fuels (DME, methanol, and hydrogen) and the best powertrain (fuel cell and diesel engine hybrids) is shown in **Figure 11**. As in the previous figures, an index of 100 is given to the conventional petrol fuelled otto-engine (the reference case).

Fuels based on both natural gas and biomass are shown in **Figure 11** and in the latter case fossil and biomass energy usage are separated. For a presentation that is more complete, the otto-engine hybrid vehicle for methanol has been included, as this combination almost has as high system efficiency as the fuel cell hybrid vehicle.

As **Figure 11** shows, and as already has been mentioned, it is not possible to reach the high system efficiencies for biomass based fuels as for fuels from (already partly converted) fossil feedstocks. This is quite natural as the conversion path to motor fuels is longer and more complex (and energy demanding) for fuels based on biomass. On the other hand, it is evident that very substantial decrease of the fossil energy use can be accomplished with the biomass based motor fuels compared to those based on fossil feedstocks. The use of fossil fuels in the chain for biomass based between the various alternatives, varying between 4,2

[15] HCCI: Homogenous Charge Compression Ignition, a combustion system with capabilities for significant reduction (eventually complete elimination) of NO_X and particulate emissions.

and 6,0%. This means that about 95% (93,6-96,2) of the fossil energy could be replaced with bio-energy compared to the reference case.

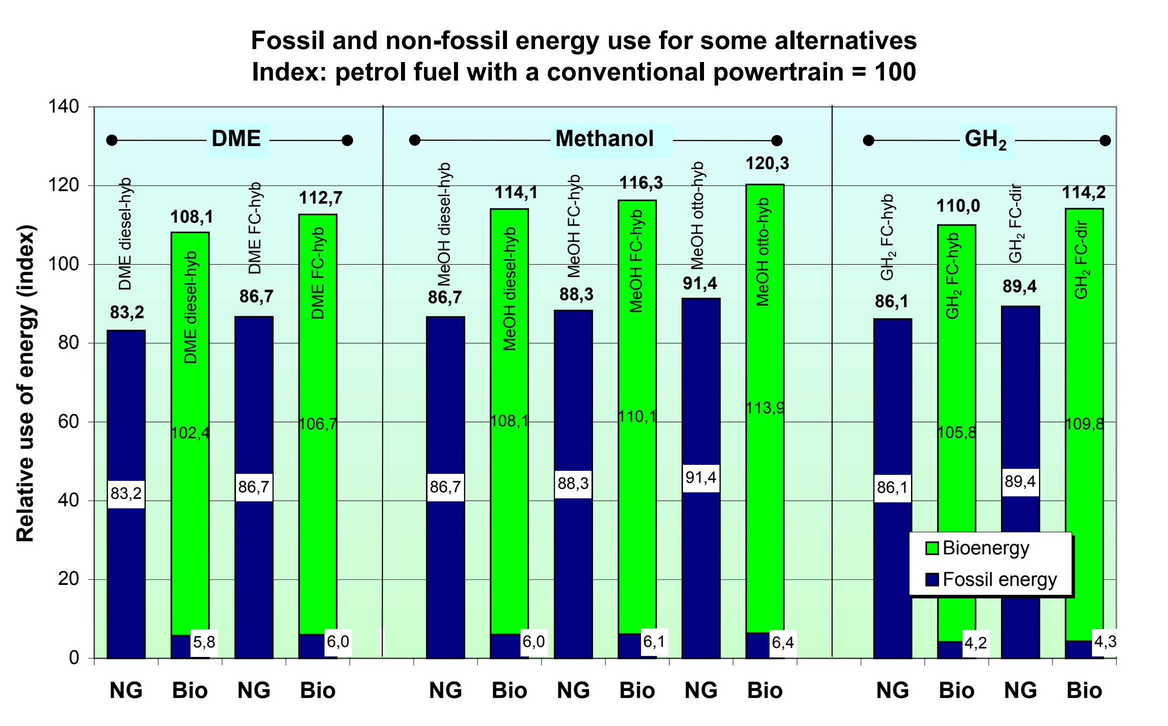


Figure 11. *Fossil and non-fossil energy use.*

Ecotraffic's summary

As summary of the results of this study, it can be said that it is not trivial to find any definitive "winner" among the 3 to 5 foremost candidates. It is easier to exclude some of the alternatives, for which the system efficiency is rather low. Hydrogen from electricity is such a case.

Fuel cells and the diesel engine present the highest efficiency among the various fuel converters and in both cases it is presumed that hybrid systems are applied. The differences of the electric drive systems of these alternatives are, however, great as the fuel cell utilises a series hybrid system while the diesel-engine (and the otto-engine) both are presumed to use parallel hybrid systems.

The internal ranking between motor fuels for the best combinations of all fuels varies depending on the feedstock being fossil natural gas or biomass. Three motor fuels, DME, GH_2 and methanol (wherof two are gaseous and one is liquid), have been identified as motor fuels, which have high system efficiency when both fossil natural gas and biomass are utilised as feedstocks. Feedstock and production system for DME and methanol are the same.

The usage of fossil energy can be reduced very substantially for the best alternatives. A reduction by 95% seems to be achievable compared to a petrol driven conventional otto-engine.

5 DISCUSSION AND CONCLUSIONS

5.1 Results from this study

From the results of calculations carried out on the energy efficiencies of various systems, the end results have been compiled in **Table 6** to **Table 9** and in **Figure 7** to **Figure 10**. It must be said that the system efficiency, of course, not is the only decisive factor but the ability of the system to far-going penetration of market (general widespread use everywhere), costs and influence on the greenhouse effect must be included at the final assessment.

For vehicles with different powertrains, the tables and figures show that

- only 12% –15% of the energy content (LHV) of the crude oil resource is obtained as transport work with the present concepts, further developed to 2012, powered by piston engines of otto or diesel type and by petrol and diesel oil respectively,
- vehicles with diesel-engine running on diesel oil show higher system efficiency than with petrol driven otto-engine,
- improvement by close to 25%, i.e. to over 15% and up to nearly 19% respectively (petrol and diesel), is possible for both systems with piston engines by use of hybrid system as combination of a smaller combustion engine and electric motor drive and a small battery as power buffer,
- hybrid with fuel cell/electric motor with best fuel has a system efficiency of about 16%, which is not appreciably higher than for a hybrid system with an internal combustion engine of diesel type but somewhat higher for hybrids with otto-engine,
- the ranking between drive systems is (with one exception) the same independent of motor fuel type, namely:
  - hybrid with diesel-engine
  - hybrid with fuel cell
  - direct operation with fuel cell
  - hybrid with otto-engine
  - conventional diesel-engine
  - (hybrid with direct-methanol fuel cell)
  - conventional otto-engine.

  (The exception is the hybrid with otto-engine, which with for this engine particularly suitable fuels has higher efficiency than for system with direct fuel cell operation.)

For assessing the sustainability of the system alternatives it is necessary to begin with the biomass based systems and then note if the choice of the alternative motor fuel also is suitable for the fuel when based on fossil natural gas during a very long transition period. The tables indicate that

- DME used in diesel-engine has highest system efficiency with methanol ranking second and that the efficiency for those systems is considerably higher than for the alternative with, for instance, synfuel (FT-fuels),
- gaseous hydrogen with fuel cell also has high system efficiency but, as it hardly can be made generally available in gaseous state, it has be distributed as cryogenic liquid to achieve this with considerable reduction of the efficiency as consequence,
- distribution of easily handled hydrogen carriers and conversion at the refuelling stations leads to further reduced efficiency, which is lowest for electricity and local electrolysis,
- conversion (reforming) of hydrogen carriers onboard the vehicle integrated with the operation of the fuel cell is more efficient than separate conversion at the fuelling site,
- for fossil based motor fuel CNG has the highest system efficiency even when it has to be distributed as LNG to be generally available,
- biomass based methane, SNG or CBG, are not the best alternative but stands behind DME, hydrogen (GH_2) and methanol,
- gasification of biomass gives possibility to production of motor fuels such as DME, hydrogen (GH_2), methanol and synfuel (hydrocarbons) in rather similar processes/plants and the first three fuels are top-ranking also with natural gas as feedstock,
- among the principal fuels only DME and methanol can be produced from both types of feedstock (fossil natural gas and biomass),
- fuel flexibility (FFV), which is a great advantage during an introduction phase for a new motor fuel, is possible only for methanol among the best motor fuels,
- only methanol is possible to use in all concepts of drive systems,
- the use of fossil energy can be reduced by about 95% for the best alternatives compared to a petrol driven conventional otto-engine.

Energy lost at conversions can partly be recovered as low-grade heat for instance for house heating (district heating) but this is not included in the accounting of the systems above.

5.2 Comparison with other studies

As an addendum to the Swedish version of this study, a comparison has been made in Appendix 1 between our results and some of the results from other studies. Studies by MIT [23], GM [24] and a German study [25, 26] has been of most interest, although the final report was not available in the last case. A summary of appendix 1 is made here.

5.2.1 Methodology and assumptions

In general, it can be concluded that a comparison of results from different studies is difficult due to the various conditions chosen and assumptions made. Most studies seems to have the ambition to picture at least a medium term time frame, 2005-2020, and focus on principal motor fuels marketable in large volumes. Not all studies have been successful in upholding this ambition throughout. Long term sustainability has only been discussed by a few.

The assumptions made for the vehicles and powertrains seems to differ considerably in several cases. Mostly, an evolutionary or advanced (future) vehicle and improvements in conventional drivetrains and, in addition, the option of hybridisation seems to be in common of most studies. Comparisons of relative vehicle weight between the studies by MIT and Ecotraffic showed reasonable agreement in most cases. Vehicle range and assumptions about the drivetrain and fuel converters could explain most of the differences. In some cases, the criteria for vehicle performance showed a considerable difference, although most studies have tried to keep the vehicle acceleration constant.

5.2.2 Powertrains

It is trivial to state that that systems based on the diesel engine in all relevant studies are found to have some 21-24% system efficiency advantage over the reference vehicle (evolved petrol-driven otto-engined vehicle). It is, however, remarkable that no study but Ecotraffic's has tried to analyse alcohols as fuels (particularly in diesel engine drivetrains), in spite of the potential they have among the alternative fuels and that they can be produced on bio-basis.

There also is common agreement that hybridisation of systems based on ICE brings about an efficiency improvement of at least 20-24% (the MIT study quotes values above 40%).

Fuel cells are without doubt efficient energy converters, with hydrogen as fuel more than 50% better than the reference vehicle (GM quotes >100%). Fair comparisons cannot, however, be made without considering the energy used for refuelling, which is high for hydrogen and reduces the powertrain efficiency to be "only" about 25% better. When considering also the production and distribution steps, the efficiency advantage will be further reduced (below). Fuels that require onboard-conversion to hydrogen must include this step in the powertrain, which will reduce the energy efficiency advantage to 18-22% (highest for methanol) in the Ecotraffic study. GM quotes higher figures for both petrol and alcohols. The vast difference between the petrol-fuelled (naphtha in one case) fuel cell vehicles in the MIT and GM studies could be noted.

The hybridisation effect with fuel cells seems to be considerably less than in with ICEs, about 6% or about 12% in the studies of Ecotraffic and GM respectively, which were the only ones to analyse the effect. In fact, no study gave a fuel cell system higher system efficiency than the diesel engine hybrid combination.

5.2.3 Well-to-wheel efficiency

CNG/LNG systems rank high due to the low energy needs to process NG to pipeline-NG (and LNG) assuming that large-scale distribution systems are in place. In the GM study, NG-based GH_2, even when produced decentralised at refuelling stations, with fuel cells is ranked even higher due to the assumed high efficiency of the fuel cell and absence of an optimised CNG-engine. For the same reason, NG-GH_2 achieves higher system efficiency than with methanol as hydrogen carrier, to which the low production efficiency is contributing. Ecotraffic's more optimistic assumptions for the methanol route results in only slight difference of efficiency between the two routes. GM did not consider methanol as otto engine fuel, which Ecotraffic finds to be equal or better in hybrid combination than the direct fuel cell system. In the Ecotraffic-study, the efficiency advantage of the hydrogen fuel cell vehicle is only about 10% over the reference vehicle on well-to-wheel basis while GM quotes 35%.

Although some fuels in gaseous form (NG, H_2) have shown a high efficiency in several studies, they have also been considered as niche fuels (however, important) in many studies. DME is easier to handle and has almost the same efficacy with NG as feedstock. LNG and LH_2 are liquid options but, as cryogenic fuels, increased cost and, in the latter case, a decrease in efficiency are drawbacks. Methane has the drawback that there does not seem to be any efficient way to produce it from biomass resources (on a large scale). Liquid fuels, easily handled as petrol and diesel oil today, will have a great advantage in distribution and refuelling efficiencies and allow retaining of the refuelling habits of the public. Of the liquid non-cryogenic fuels, methanol seems to be the fuel that has the highest efficiency. Considering these facts, it seems remarkable that methanol has not been more thoroughly studied.

Liquid fuels, easily handled as petrol and diesel oil today, will have a great advantage in distribution and refuelling efficiencies and allow retaining of the refuelling habits of the public. Among the liquid alternative fuels, the alcohols with emphasis on methanol, fares best in the long term by high efficiency in production, efficient distribution and refuelling, high efficiency at conversion to hydrogen onboard FCV, and they are possible to use efficiently in all types of powertrains. Motor fuel production based on biomass feedstocks (wood) seems to yield methanol as the most efficient liquid fuel. Considering these facts, it seems remarkable that methanol has not been more thoroughly studied.

The production of FT-fuels is in all studies found to be less efficient than that of hydrogen or methanol (and DME, although this fuel has only been assessed by few studies). The GM study indicates nearly 30% lower system efficiencies compared to petroleum based fuels and 15-20% lower than methanol, the MIT study about 20% lower compared to methanol, and the Ecotraffic study 20-25% lower compared to methanol.

5.2.4 Sustainability

To maintain the hydrocarbon base feedstocks in a scenario with great reductions of GHG, sequestration of CO_2 in deposits in the crust of the earth would be necessary and is often discussed as technically not infeasible. The unavoidable consequence is, however, a distribution system for hydrogen, which we cannot see as the general future system (above). For GHG-reductions of the magnitude of 80-90%, only biomass-based fuels have such potential, as has been demonstrated in several of the studies.

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Appendix 1
Comparison with other studies

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1 INTRODUCTION

In the fall of 2000, Ecotraffic was commissioned by the Swedish National Road Administration to carry out a well-to-wheel system efficiency study. The report was published in April 2001. The literature survey was carried out in the fall of 2000 and most of the analysis and preparation of the report was made early 2001. The report was published in Swedish. After the report was published, it was found that an international interest of the report could motivate a translation into English. While the work on the Swedish version of this report was in progress, and after the report was finished, several interesting international reports on this subject were published. Therefore, it was felt that a pure translation of the report without considering the most recent publications would be somewhat negligent. It was also of interest to make some comparisons with the results from the most interesting studies.

In order to keep the major part of the original Swedish report relatively intact, it was decided to translate that report and to place the comparisons in an appendix. The primary modifications of the original study were that the discussion part of the report and the summary were extended.

This appendix summarises the comparisons made with some of the recent publications in this field. Whenever it was felt necessary, references to some other studies have also been made.

2 STUDIES SELECTED FOR COMPARISON

In principal, three studies were selected for a more thorough scrutiny and in addition to these reports, some recent publications from an on-going project in Germany and some previously published results that study were considered to be of interest. The reports selected were:

- "On the Road in 2020." This report on life-cycle analysis of new automobile technology and fuels was published in late 2000 by the Energy Laboratory of MIT in the USA [1].
- "New concepts for biofuels in transportation." This report (Jan. 2001) by VTT (Technical Research Centre of Finland) assesses the use of biomass-based methanol in advanced vehicles [2].
- "Well-to-Wheel energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems – *North American Analysis* – ". The "GAPC[1]" report (or the GM report as it is referred to here) was published in draft final version in April 2001 as the documentation from a joint project by GM, ANL, BP, Exxon/Mobil and Shell. [3].
- In addition to the studies above, some reports published from a comprehensive project in Germany are also of interest. A summary of the findings has been published in a paper by the IFEU institute titled "Finding the best option for the environment – A comparison of 22 combinations of conventional and alternative fuels and drive systems. This paper was presented at the ISAF XIII Symposium in Stockholm, 2001 [4].

[1] GAPC: Global Alternative Propulsion Center at GM. This was the department at GM, which initiated the study.

The complete report from the German project listed above [5][2] was not available when this report was prepared, so a thorough investigation of the results from this project was not possible. A working report summary is provided on the Internet page of the Office of Technology Assessment at the German Parliament (TAB) [6]. Another German project about fuels worth mentioning is the so-called "VES[3]" co-operation between auto manufacturers and oil companies.

In addition to the papers listed above, several other reports were of interest. Some have focussed on lifecycle assessment of several fuels and powertrain combinations while others have concentrated more on some fuels or powertrains (mostly fuel cells and fuels for fuel cells).

A paper by the Paul Scherrer Institute (PSI) of Switzerland compared methanol, hydrogen, CNG and gasoline [7]. Methanex and (S&T)[2] Consultants has prepared a report about the production and use of methanol [8]. The U.S. Federal laboratory ANL has carried out a lifecycle analysis of fuels produced from natural gas [9]. A. D. Little and Cambridge Consultants compared various fuels for fuel cell vehicles [10].

Researchers at German DLR has compared fuel cell vehicles with conventional and hybrid vehicles running on petrol and diesel fuel [11]. A paper by researchers at the Princeton University provides insight to the characteristics of a fuel cell powertrain and compares gasoline, methanol and hydrogen [12]. Several papers published at the SAE Congress in March 2001 also provide more insight about reformers [13, 14] and/or the integration of reformers in fuel cells [15, 16].

It should also be mentioned that numerous other reports on specific subjects in this field have been published during the last year. However, in this appendix, the focus has been on publications that cover at least a couple of different options, or else publications that provide some specific information necessary for the dissemination or interpretation of the results.

3 CONDITIONS AND METHODOLOGY

The studies briefly referred to have somewhat different focus. Ecotraffic's main focus was to discuss alternative fuels that could have the potential to become principal motor fuels for general use everywhere in the long term and to analyse conditions when the system has been fully developed. This seems necessary in order to make a comparison with the system of today using petrol and diesel oil on a fair basis. Unless these can be kept in a sustainable way, it should be desirable to discuss whether there is another "universal" fuel(s) that can be produced and used in an efficient and sustainable way rather than accepting a number of different fuels, which have potential only as niche fuels. In the Ecotraffic study, 98 combinations of motor fuels and powertrains have been studied. When and if (a) best system(s) has been identified and has been accepted as future goals, the work to find the pathway(s) towards the goal may start.

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2 The final report was published in July 2001, as a first edition, but this set of books was soon out of order. The second set of books was still in press when we first tried to order it and therefore, it was too late to be taken into account in preparing this appendix.

3 VES: Verkehrswirtschaftliche Energiestrategie. The name of the study indicates that this study is about a strategy for economy and energy use in transportation, although a straightforward translation to English using only a few words is not trivial.

The GM study also considered fuels and vehicles that might be commercialised in large volumes and not systems viable only in niche markets. Out of 75 fuel pathways, 13 were selected to be analysed together with 15 powertrains and this yielded 27 pathways for specific analysis in the study. Mostly, current petroleum and NG are feedstocks with corn and lignocellulose as only renewable one for ethanol. The perspective was a North American analysis with focus on what might be favourable in the near future (2005 and beyond) and what might be used during transition phases.

The MIT study discusses a new quasi-steady state in 2020 for low emission, large volume vehicle technologies and not often-crucial transition problems, but fuels are limited to those on petroleum and NG basis. ICE, ICE-hybrid and FC-hybrid cars are analysed in life-cycle comparisons on energy, GHG and costs.

The Methanex study discusses in the 2010 perspective the possibilities for Canada and the U.S. to reduce GHG-emissions by use of FC-vehicles and NG-based hydrogen via different hydrogen carriers in various fuel pathways.

The VTT study only discusses wood biomass as feedstock for methanol production (and more briefly hydrogen) and for use in ICE and ICE-hybrid cars.

The IFEU study discusses 22 combinations of 15 fuels of fossil and renewable origin and ICE and FC powertrains in LCA-perspective. The work, supported by the German Parliament and the EU Commission, was the basis for co-operative work between German auto and energy companies resulting in recommendation to continue work on introduction strategy for three selected fuels: LNG, methanol and LH_2. One criterion is that the selected fuels must be possible to produce from renewable feedstocks. The detailed background report was not available when this appendix was prepared.

The Princeton study, which is a summary of several earlier reports (Ph.D. thesis work) does also provide some information about fuel production and powertrain.

4 RESULTS

4.1 Feedstock – recovery, production and transport

Although there are a number of vast, *fossil* hydrocarbon feedstocks (VHO, bitumen, tar sands, oil shales) and coals possible to use for conversion to motor fuels when conventional crude oils (petroleum) are dwindling, they are heavier (i.e. hydrogen-poor), more contaminated and more costly to up-grade. Therefore, the focus is on the very hydrogen-rich *natural gas* (NG, fossil gas), which is a resource of equal size as that of conventional oils but yet less utilised.

Few industrialised regions have sufficient domestic NG (especially if the transportation sector is considered). Therefore, the scenario for NG as principal motor fuel/feedstock is focussed on import from remote gas fields with low cost and low site-value of NG. The challenge is how to bring the NG to the markets.

In most studies, remote natural gas (RNG) is discussed as future motor fuel or feedstock for large-scale use. Transport in pipelines on land or seaboard over long distances is quite feasible and used, but often not applicable. Conversion to transportable forms (liquids: LNG, methanol, FT-oils, LH_2) has to be applied.

Renewable, long term sustainable feedstocks have been discussed briefly in most reports and more thoroughly in a few. Solar, wind and hydropower as indirect sources to hydrogen are indicated but not included in any scenario except the IFEU study due to too high costs presently. Biomass feedstocks containing sugar (sugar cane, sugar beet) or starch (corn, wheat) are being used for ethanol production but are, as agricultural crops, limited by land availability. Lignocellulosic feedstocks (wood) have been considered for conversion to methanol or ethanol but are often seen as limited to tree residues from saw mills or pulp plants. We consider that tree residues from forestry and purpose grown woody crops (SRF, short rotation forestry) are a much larger potential resource, since these can be produced from non-agricultural land. *The size of this potential still is an open issue considering the huge gap between figures mentioned in some studies and estimates claiming that each year solar energy bound in land biomass amounts to more than ten times the total energy usage in the entire world. The issue of how to develop land use must be thoroughly investigated!*

Biomass must be *produced* in conventional silviculture, developed SRF or agriculture, which require input of energy. As a more diffuse feedstock, energy for its transportation to conversion plants must also be considered and will be greater than for petroleum feedstock.

4.1.1 Energy use

Recovery of *petroleum* has by Ecotraffic been assigned a typical energy usage of 0,03 MJ/MJ of petrol/diesel oil plus 0,007 MJ/MJ for ocean transport to refineries. The MIT study assumed a total of 0,040-0,042 MJ/MJ or an efficiency of 96,5%. In the GM study, efficiencies of 96%-99% for these steps of the fuel chain were assumed with the high figure for US petroleum to US refineries and the low figure (0,042MJ/MJ of petrol) for imported petroleum. Ocean transport in large tankers was assumed to be 99% efficient. In the Methanex study, an efficiency of 89% (0,12 MJ/MJ of petrol) was given for the two steps.

Recovery of *NG* has by Ecotraffic been estimated to typically require 0,03 MJ/MJ of CNG in the chain from well to tank and up-grading to pipeline quality (dry gas) another 0,02 MJ/MJ. For pipeline transport, a figure of 0,02 MJ/MJ per 1000 km was used, giving a total of 0,07 MJ/MJ. In the GM study, midpoint efficiencies corresponding to 0,025 and 0,025 MJ/MJ for the recovery and processing respectively and 0,007 MJ/MJ for transfer from North-American gas fields to refuelling terminals. The Methanex study did not state any figure for a CNG-case but figures for methanol and hydrogen cases indicate an energy use for recovery/processing of about 0,05 MJ/MJ. The MIT study did not give figures for separate steps but only for recovery and transfer to the refuelling station together, amounting to 0,13 MJ/MJ of NG. Conversion to liquids does not require production of dry gas, but preferably, this should be accomplished with wet gas. Conversion to LNG yields a product consisting almost only of methane and higher hydrocarbons as separate products. LNG needs power for the liquefaction in refrigeration compressors. The figure of a midpoint efficiency of 91% in the MIT study, corresponding to NG-energy use (for power in CC-system or efficient gas engine) of 0,098 MJ/MJ agrees well with the Ecotraffic-figure 0,102. Ocean transport energy of LNG was in the GM study estimated to 0,015 MJ/MJ after crediting the ship fuel consumption for boil-off. The figure in Ecotraffic's study was 0,035 MJ/MJ and no credit was given for boil-off.

Biomass feedstocks need to be produced, which requires energy. The GM study refers to an energy input for tree farming (SRF) of 273 MJ/tonne (DS assumed, not stated) corresponding to about 0,015 MJ/MJ of wood-DS (assumed; value is not given). In the Ecotraffic study energy, uses in silviculture and recovery of forestry residues were estimated to be 0,03 MJ/MJ of wood-DS (LHV 19,2 MJ/kg DS) and 0,065 MJ/MJ at SRF farming. The VTT study did not state any figures for energy used for biomass feedstock production. Transports from forests or SRF-plantations to conversion plants were in the Ecotraffic study calculated to consume motor fuel corresponding to 0,015 MJ/MJ of wood-DS. It seems uncertain if this step has been considered in the GM study.

4.2 Fuel production

The motor fuels considered in most studies are, except for reference future petrol and diesel oil, CNG, LNG, methanol, bio-methanol, DME, bio-ethanol, FT-hydrocarbons (synfuel), GH_2 and LH_2. Bio-methanol was for unknown reason not included in the GM study and, similarly, DME was excluded as too small niche fuel. For the same reason, the Ecotraffic study did not include petroleum naphtha. Ecotraffic also considered hydrogen, DME and FT-synfuel on biomass basis. IFEU did not include NG-based methanol and considered renewable hydrogen only on power (hydro, solar, wind) basis. MIT excluded all biofuels as too costly.

Reference fuels are petrol or diesel oil and future qualities should, or must, be chosen for fair comparisons. This means very low sulphur content (5-10 ppmw) for both fuels. For petrol, low benzene content (<1%v) and as low volatility as feasible are important properties. For diesel fuel, limits on heavy aromatics, particularly polycyclic aromatics, and lowered T95-point (340°C, acc. to the WWFC specification [17] by the auto- and engine manufacturers, though not to the extreme Swedish EC1 fuel with T95 below 300°C).

4.2.1 Energy use

Petrol and diesel fuel

Allocation of energy use in the refinery on the different products should be done on basis of how various processes have to be used. In the GM study, the adopted values of refinery efficiency for future petrol is in the range 83%-86%, i.e. 0,205-0,16 MJ/MJ of petrol. For diesel oil, the corresponding figures are 85%-89% or 0,18-0,12 MJ/MJ. In the MIT study energy use was 0,157 MJ/MJ of petrol (86,5%) and 0,089 MJ/MJ of diesel oil (92%). The Methanex study quotes 0,148 MJ/MJ of petrol (87%). In the DLR study assumes 0,16 MJ/MJ of petrol. The Ecotraffic study assumes 0,155 MJ/MJ of petrol (86,5%) and 0,090 MJ/MJ of diesel oil (91,5%). Only the Princeton study seems to be out of line, quoting about 95% efficiency for petrol. There are a number of reasons why studies differ somewhat, such as different crude slates, product mixes, refinery configurations, allocation schemes, etc.

Natural gas

NG and LNG are finished fuels at import terminals and only need distribution to refuelling stations.

Methanol

Methanol from natural gas was in the Ecotraffic study given a conversion efficiency for future plants of above 70%, corresponding to 0,42 MJ/MJ of methanol. This is consistent with the figure given by Methanex, the world's largest methanol producer, and still far below theoretically possible efficiencies. This level of efficiencies has also been supported by ICI, world scale methanol producer, in earlier work, which also showed a small surplus of power for export. (Additional low-grade heat as low-pressure steam or hot water for district heat could be recovered but this was not included in any of the studies). The GM study also mentioned 70% efficiency for future plants but they had used a mix of existing and future plants with average 67,5% efficiency (0,48 MJ/MJ) in their calculations. The rationale for choosing a mix of old and new technology was the present surplus of methanol on the world market, which has been forcing some plants to idle [18]. The MIT study relates an efficiency of 68% or 0,47 MJ/MJ of methanol in the conversion step, and the Princeton study indicated 66% (recalculated from 67,4% on HHV-basis) based on an old (1995) literature reference.

Methanol from wood biomass via oxygen/steam, pressurised gasification has by Ecotraffic been given a conversion efficiency of 54% (0,85 MJ/MJ of methanol). This estimate has been based on engineering studies within EU development program and it is founded on test work in large pilot scale in the Nordic countries. In the Finnish VTT study on two cases of plants, efficiencies of 50,5% and 52,7% to methanol were reported, increasing to around 60% if combustible by-products were included. Black liquor at sulphate pulp plants has been discussed as additional source for methanol via gasification and will be studied in a new EU-project where the authors organisations is participating. The IFEU study has treated wood-based methanol (and ethanol) but the detailed study has not been available for details of the processing steps. None of the other studies has evaluated wood as feedstock except for indications on possibilities in the future and cost indications in the Princeton study.

Ethanol

Ethanol from wood biomass via enzymatic hydrolysis and fermentation of both C5- and C6-sugars has, after extrapolation of present performance data for improvements in the future, by Ecotraffic been given a yield of ethanol corresponding to nearly 41% (LHV-basis). Together with a surplus of solid fuel ("lignin"), this is raising the total energy yield to about 49% (or about 45% when converted to power) or 1,0 MJ/MJ of sum of products. The ethanol path is more energy demanding and allocating gives 1,15 MJ/MJ of ethanol and 0,45 MJ/MJ of lignin. In the GM study, a yield of 409 litres of ethanol per tonne of wood-DS was anticipated in the optimistic (=future?) case. This is somewhat higher than in the Swedish study, probably dependent on a higher content of cellulose/hemicellulose (not stated in the GM study). In energy terms, this would mean a yield of about 45%, assuming a LHV of 19,2 MJ/kg DS (also not stated in the study). Together with a surplus of solid fuels converted to power, a total yield of energy carriers of 48-49% was indicated. A herbaceous feedstock, yielding 5% more ethanol but less excess power, was also studied.

Fischer-Tropsch fuels

Fischer-Tropsch fuel (naphtha/diesel mix) was in the Ecotraffic study assumed to be produced from NG with an efficiency of 57% (0,75 MJ/MJ of FT-fuel) with no recovery of low-grade heat included. Using wood biomass as feedstock, an efficiency of 45% (1,2 MJ/MJ of FT-fuel) was assumed based on extrapolation of actual operation data from South African coal based plants and improved gasification technology. The GM study referred to data for NG-based plants and inputs from among others the three energy company partners. An efficiency of 61%-65% was obtained, with no steam or energy production and other less desirable side-products. In calculations, a conversion efficiency of 63% was used, which was the midpoint figure in the interval mentioned. This is a relatively high efficiency in comparison to other studies, and previous results from the GREET model by ANL. The basis for the calculations was (yet) unpublished data from Shell, one of the participants in the study [18]. These results were based on assumptions for an advanced future process technology, indicating that the technology level assumed for this fuel was not quite the same as for the other fuels produced from synthesis gas. The MIT study indicated a conversion efficiency of about 53% (0,90 MJ/MJ), and the Methanex study about 57%.

Gaseous hydrogen

Gaseous hydrogen from NG was in the Ecotraffic study assumed to be produced with an efficiency of close to 75% (0,336 MJ/MJ of hydrogen) in large centralised plants and somewhat less efficiently, 71%-72%, in small decentralised steam reforming units (0,40 MJ/MJ of hydrogen). With biomass from wood as feedstock, an efficiency of 57% was estimated (0,75 MJ/MJ of hydrogen). The VTT study gave a preliminary estimate of 61% efficiency for hydrogen from wood. In the GM study the efficiency for NG-based hydrogen was estimated to be in the range of 66%-73% in big centralised plant (0,515-0,37 MJ/MJ) on basis of literature data and comments from the three energy company partners. The plants will yield an excess of recovered heat as steam that can be converted to power for export (not included in the efficiency figures). Production in small decentralised units (refuelling stations) was assumed to be accomplished with about 3-4 %-units lower efficiency (0,60-0,44 MJ/MJ). The MIT study quoted for small local plants a conversion efficiency of 70% with NG feedstock (0,43 MJ/MJ of NG). Methanex estimates for large scale plant a conversion efficiency of about 69,5% (recalculated from 74% on HHV-basis). DLR assumed an efficiency of 64,5% (0,55 MJ/MJ of hydrogen; uncertain if up-stream steps were included). The Princeton study gave a NG-conversion efficiency of 79,5% (recalculated from 84,4% on HHV-basis) or 0,26 MJ/MJ, which is the highest figure among all studies.

Cryogenic hydrogen

Cryogenic hydrogen, LH_2, requires a large amount of power for operation of refrigeration compressors. In the Ecotraffic study, an efficiency of about 57% (0-75 MJ/MJ) was assumed for this process, when power is produced from NG in HAT (humid air turbine) or (possibly) by combined cycle (CC) systems. Moreover, boil-off losses will occur and these were assumed to be 1,5% at the production site and several percent (0,3% per day) during ocean transport from remote plants to terminals. In the GM study, liquefaction efficiencies in the 65%-77% range were assumed for central plants depending on the degree of integration with the hydrogen production. Boil-off rates of 0,3%/d were assumed during transport and storage, but 50% could be recovered as process fuel at the production plant. Liquefaction efficiency at refuelling stations was assumed to be 5 %-units lower than that in central plants. (Not considered case in the Ecotraffic study.) In the Methanex study, liquefaction diminished the efficiency from 69,5% to 44%, i.e. operated with an efficiency of 63% when power for the compressors is produced from NG in CC-system. Boil-off at the production was assumed at 1,3%. ADL indicated 64% efficiency (0,57 MJNG/MJ of hydrogen. LH_2 was not considered in the MIT study.

Electrolytic hydrogen

Electrolytic hydrogen was estimated to require 1,25 kWhel per kWh of hydrogen in future plants by Ecotraffic, i.e. 80% efficiency was assumed. When the power is produced in efficient CC-system from NG, the resource consumption is 2,5 MJ of NG per MJ of hydrogen. Inclusion of liquefaction increases this figure to 3,25 MJ/MJ. In the GM study, literature data indicated efficiencies in the range 67%-76%. Power was assumed to be produced in NG-fired CC-systems with 50%-60% efficiency and transmission losses were assumed at 8%. The MIT study used 32% production efficiency and this was based on the US primary fuel mix and assumed 9% transmission loss. In the Methanex study, an efficiency of 69% (recalculated from 81% on HHV-basis) in future plants was assumed.

4.3 Fuel distribution/refuelling and on-site reforming

Fuels distributed in gaseous form require compression to fill the vehicle tank for sufficient range (CNG, GH_2). Transformation to liquid at the station has been discussed (GM) only in one case, LH_2. Production at the station has been considered for electrolytic hydrogen. Transformation to hydrogen at the station has been considered for NG and fuels distributed as liquids (naphtha, petrol, methanol, diesel oil, FT-fuel) by reforming/POX.

4.3.1 Energy use

Pipeline transport of natural gas, NG, was in the Ecotraffic study assumed to consume 2% of the transported flow per 1,000 km for operation of gas engine driven compressors, and this distance was used in the calculations. Refuelling as CNG requires power for compression and was calculated to consume 0,08 MJNG/MJ of CNG with power produced in efficient HAT or CC-systems. LNG transport in big ocean tankers was assumed to consume twice the ship fuel use for petroleum due to the lower energy density, i.e. 0,014 MJ/MJ. Furthermore, a boil-off loss of 0,15% per day was assumed and 10-day trips were anticipated. No credit for recovery as substitute fuel in the ship's machinery was given. The distribution from terminals to refuelling stations was also assumed to consume twice the fuel used for oil products, i.e. 0,02 MJ/MJ. Refuelling of LNG requires very little energy. In the GM study, distribution of gaseous NG from gas fields to refuelling stations was assumed to be 99,3% efficient. LNG transport from remote gas fields to U.S. terminals was assumed to be 98,5% efficient (0,015 MJ/MJ).

Methanol produced at remote plants and transported in big ocean tankers was in the Ecotraffic study assumed to consume 1,2% of the transported methanol energy as bunker fuel and 1% for the distribution to refuelling stations. Domestically produced bio-methanol was assumed to consume motor fuels corresponding to 2% of energy in transferred methanol (0,02 MJ/MJ). For bio-ethanol, this figure was set to 1,5%. Energy for refuelling is negligible, as for all liquids. In the GM study, distribution from central plants/terminals to refuelling stations was assumed to be 98% efficient and including ocean transport in tankers 96,8% (0,033 MJ/MJ). The MIT study referred to a distribution stage-efficiency of 89%-97% or fuel consumption of 0,027-0,12 MJ/MJ of methanol (clean tanker transport from conversion site to regional port in addition to normal distribution to vehicle). In the Methanex study, distribution was exemplified as mainly land transport by rail and truck (Canada) and this was calculated to consume 0,05 MJ/MJ of methanol.

FT-synfuels are generally assumed to require only slightly more fuel for transport than for diesel fuel because of the somewhat lower density.

Hydrogen is the end fuel for all fuel cell vehicles (FCV). The pathways to the energy converter of the vehicle are many: pipeline transport to the retail station and refuelling as compressed hydrogen (GH_2); transport as liquefied hydrogen (LH_2), and refuelling as such or after re-gasification as compressed hydrogen; transport as hydrogen rich fuel (sulphur-“free” petrol or diesel oil, NG, methanol, FT-synfuel) and conversion to gaseous hydrogen and refuelling as compressed hydrogen.

Pipeline distribution of hydrogen from a central unit requires more energy than for NG. In the Ecotraffic study, 3,5% (96,6% efficiency) was allocated to this stage, and compression (to >400 bar) for quick filling of the vehicle tank was, with power driven compressors, estimated to use NG in HAT or CC-systems. This corresponds to 20% of the energy content of the hydrogen (0,20 MJ/MJ of hydrogen or 83% efficiency). In the GM study, the efficiency of the pipeline transfer was assumed to be 96,3%, and about 94% for the station compressor with power driven units and about 86% for gas engine driven units. Figures in the Methanex study were not explicitly mentioned, but indicated an efficiency <94% with power driven compressors for 350 bar end pressure. The same goes for the MIT study for which an efficiency of about 88% may be indicated (including power for the NG-conversion and assuming CC-power.)

Liquefied hydrogen, LH_2, is considered as product from conversion at remote gas fields with ocean transport in well-insulated tanks onboard ships to terminals in similar mode as occurs for LNG today. Due to the low energy density, Ecotraffic assumed transport fuel consumption to be about 5 times larger than for petroleum or 0,035 MJ/MJ of LH_2. Additionally, boil-off losses at a rate of 0,3%/d were estimated or 3% during a 10-day trip (no credit was given for hypothetical recovery as ship fuel). Land transport in road tankers to refuelling stations was likewise assumed to consume 5 times the transport energy for oil products and further boil-off losses of 3% were assumed at transport and storage. Refuelling the vehicle with LH_2 will require very little pumping energy even when it is stored onboard the vehicle as compressed gaseous hydrogen, but some additional boil-off (1%) must be assumed. In the GM study, 50% recovery of the 0,3%/d boil-off and the entire transport from a remote plant to refuelling stations was assumed to be 95,8% efficient (0,044 MJ/MJ of LH_2) and 98,9% for transport from a North American plant.

Conversion to hydrogen decentralised at the refuelling station has been considered by Ecotraffic for methanol and DME (except from power via electrolysis discussed above). On-site conversion of ethanol or hydrocarbons such as petrol and FT-synfuel seems pointless, as the conversion efficiency will be worse on top of lower production efficiency. Conversion from methanol at the refuelling station was by Ecotraffic assumed be 79% efficient (0,265 MJ/MJ of hydrogen); somewhat lower from DME (77%). In all the cases, hydrogen compression has to be added. In the GM study, only local conversion from NG already distributed via a pipeline system and hydrogen by electrolysis at the refuelling stations have been discussed. Conversion efficiencies in small reforming plants and electrolysers and energy use for compression were estimated above. In the MIT study, 70% efficiency (0,43 MJ/MJ of hydrogen) was quoted for NG reforming in decentralised stations plus energy for compression (above).

4.4 Summing up resource-to-tank routes

Among the numerous routes from feedstock to vehicle tank, the most promising ones (in the Ecotraffic study) are compiled in **Table 1** and compared with the results from other studies. The most long-term promising routes from an energy-efficiency point of view (or interesting to elucidate) seem to be:

- NG to GH_2 in centralised plants and pipeline distribution to refuelling stations; presumes domestic NG (or imported LNG, though not included)
- RNG to LH_2 in large remote plants and shipment and distribution as cryogenic liquid to refuelling stations
- RNG to methanol in large remote plants and shipment and distribution to refuelling stations for use as methanol or as GH_2 after on-site reforming
- RNG to FT-synfuel in large remote plants and shipment and distribution to refuelling stations for use as such
- NG to power in regional plants for distribution to electrolysis plants at refuelling stations; presumes domestic NG
- Wood to hydrogen in regional plants and pipe distribution to refuelling stations and use as GH_2
- Wood to methanol in regional plants and distribution to refuelling stations for use as such or as GH_2 after on-site reforming
- Wood to ethanol in regional plants and distribution to refuelling stations.

Comparisons between studies are not always straightforward as the fuel chains are not built in the same way and sometimes refer to specific near term situations in a region and not to the long-term scenario. Among the routes for alternative fuels the route RNG to DME or methanol is the most efficient and the one from NG to compressed hydrogen via electrolysis the least efficient. The route from RNG to cryogenic hydrogen, LH_2, shows low efficiency. There is an agreement about the lower efficiency of the route via FT-synfuel compared to DME/methanol route although the FT-route fares better than that for LH_2. There are considerable differences in data for hydrogen compression and liquefaction among the studies although this does not influence entire fuel chain too much or changes the ranking.

The data shown in **Table 1** sums up the results for the well-to-tank energy use and efficiencies for the comparisons between the various studies.

In **Figure 1**, a comparison between the studies by Ecotraffic, MIT and GM is made regarding some of the fuels, when there has been some information available about the production of those fuels. As expected, the fossil fuels will be dominating in a comparison of this kind. The data from the German study were not available at the time this comparison was made.

Table 1. *Resource to vehicle tank, RtoT (or "well-to-tank"). Energy use in MJ per MJ of finished product, efficiency in percent (% LHV).*

	Feedstock recov./prod	Transport	Production	Distribution	On-site conversion	Refuelling	Total	% LHV Efficiency	Remarks
(R)NG to GH_2									
Ecotraffic	0,04		0,336	0,04		0,219	0,636	61	Regional NG
GM			0,44			0,18	0,855	54	Imported NG via LNG
MIT	0,13				0,43	0,13	0,69	59	Corrected to CC-power
Methanex					0,58	0,21			Regional NG
Princeton			0,258			0,132	0,39	72	Resource recovery/trp data not
ADL						0,091			
DTI			0,39						Incomplete data
IFEU									No breakdown data for WtoT)
DLR							0,55	65	No NG-upstream data
RNG to LH_2									
Ecotraffic	0,068		1,16	0,092			1,43	41	
GM							1,43	41	
Methanex	0,1		1,3	0,1			1,5	40	
IFEU									No breakdown data for WtoT
ADL			0,53						Liquefaction data only
RNG to Methanol									
Ecotraffic	0,043		0,42	0,022			0,485	67	
GM			0,48	0,033			0,59	63	
MIT			0,47	0,027-0,12			0,50-0,59	63-67	No explicit NG-recovery data
Methanex	0,07	0,005	0,42	0,055			0,55	65	
Princeton			0,52	0,01			0,53	65	No NG recovery data
ADL									
DTI			0,56						Incomplete data
RNG to FT-synfuel									
Ecotraffic	0,053		0,754	0,011			0,818	55	
GM	0,052		0,59	0,018			0,694	59	
MIT			0,9	0,013-0,061			0,91-0,96	51-52	No explicit NG-recovery data
Methanex			0,75						
(R)NG to Power to GH_2									
Ecotraffic	0,074		1,466			0,219	1,769	36	
GM	0,15				1,72	0,18	2,1	32	
Methanex					1,9	0,21	2,1	32	
Wood to Methanol									
Ecotraffic	0,056	0,028	0,852		0,02		0,955	51	Forestry residue data
VTT			0,92						Only conversion energy need
IFEU									No breakdown data for WtoT
Wood to Ethanol									
Ecotraffic	0,06	0,03	1,15		0,012		1,252	44	Forestry residue data
GM	0,033		1		0,02		1,05	49	Incl. electricity; no allocations
IFEU									No breakdown data for WtoT
Wood to GH_2									
Ecotraffic	0,053	0,026	0,761		0,03	0,219	1,089	48	Forestry residue data
VTT			0,64						Only conversion energy need

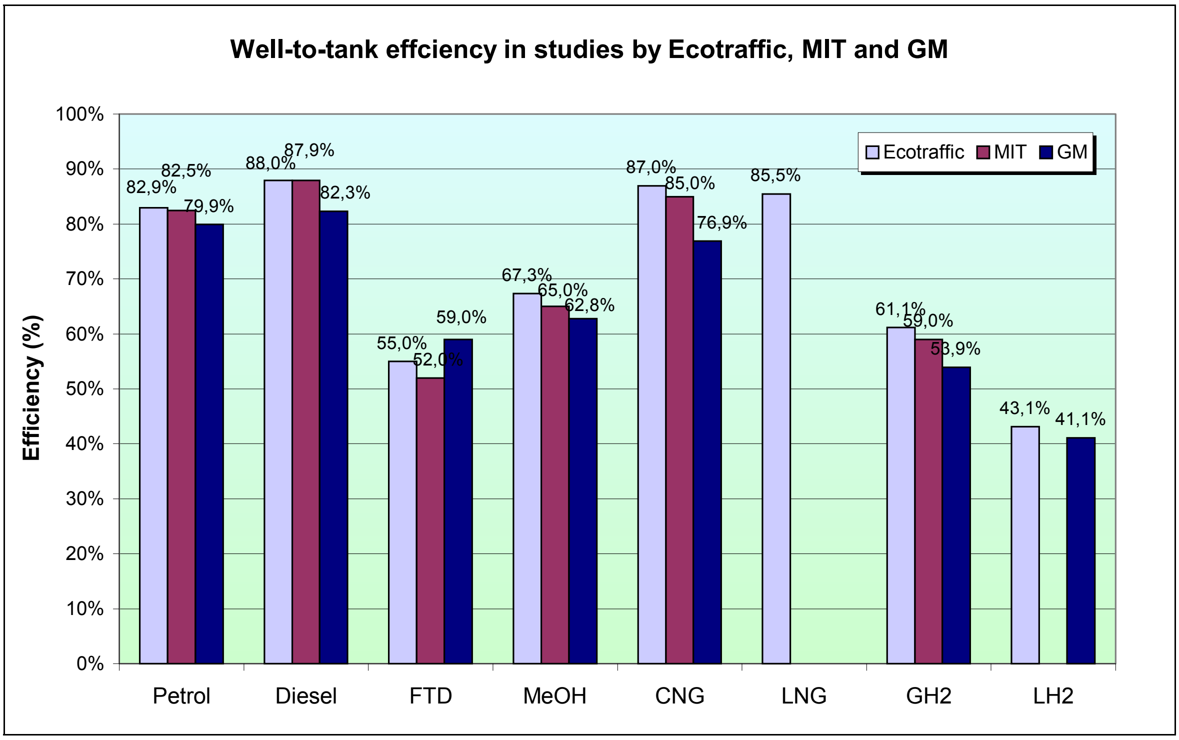

Figure 1. *Fuel production and distribution (well-to-tank)*

The following conclusions can be drawn from **Figure 1**:

- The results for petrol and diesel are very close for Ecotraffic and MIT. The GM study shows a somewhat lower efficiency, in particular for diesel fuel.
- MIT has the lowest efficiency for FT-synfuel, GM has the highest and Ecotraffic is in between. The high efficiency in the GM study can be explained, since they anticipated an advanced future plants based on (yet) unpublished data from Shell. Consequently, the efficiency was considerably higher than the two other studies.
- Ecotraffic has a somewhat higher efficiency for methanol than the two other studies. This is primarily due to more advanced processes assumed, as is likely in new plants; the other studies seem to refer to today's plants, or an average of present and future technology.
- The route for CNG is slightly more efficient in the Ecotraffic study than in the MIT study, while the efficiency for GM is lower. In the latter case, the explanation is that remote natural gas was the source. Since this route is via LNG, the lower efficiency is plausible.
- GH_2 follows a similar trend as the methanol production for Ecotraffic and MIT. The lower efficiency in the GM study is mainly attributable to the fact that natural gas in their study is imported as LNG but transported from the terminal as CNG.
- The efficiency is low for LH_2 for both Ecotraffic and GM. In view of the different conditions and production processes, as explained before, the difference between Ecotraffic and GM seems reasonable.

4.5 End use

4.5.1 General assumptions

Timeframe

The timeframe for studies of this kind is very important and, in particular, this is of considerable importance for the vehicles and powertrains. The development has been fast during recent years and now it appears that several new vehicle and powertrain technologies are close to the (technological) breakthrough stage. The timeframe has to be far enough to allow the technology to be fully developed and commercialised but not too far to lead to pure speculations[4].

The opinion at Ecotraffic was that a timeframe of about 2010 to 2015 would be appropriate and to be more specific, 2012 was chosen. MIT chose 2020 for similar reasons. GM focused on “2005 and beyond” although no specific model year was mentioned in the report. Most of the publications studied have a future perspective and in particular, this applies to fuel cell vehicles. The projection of future development of current internal combustion engine technology, often in combination with a hybrid driveline is a common methodology for the majority of the publications on this subject. Some researchers also compare the new powertrains with conventional powertrains of today but some do not make projections of the development of conventional technology at all, but compare to contemporary vehicles instead. Most of the studies appear to focus on the timeframe between 2005 and 2020.

Vehicle type

Ecotraffic used a European (i.e. Swedish) size of a family car as the basis for the vehicle simulations. Further assumptions were that the European new car vehicle fleet should meet a CO_2 limit of 120 g/km. However, it was also assumed that the Swedish average car would be somewhat larger than the European average car, as has been the case in the past as well. Therefore, the CO_2 emissions in 2012 would still be higher for Swedish cars (i.e. about 129 g/km) than for the average European car.

MIT used an evolutionary car similar to a mid-size car as the Toyota Camry. Several U.S. researchers have used cars (body, chassis, etc.) according to the PNGV specifications and development goals. Some European researchers have focused on very small and light cars. The GM study deviates from most other studies, since they chose a light-duty truck instead of a car. It is well-known that this vehicle category, together with sport utility vehicles (SUVs), account for about 50% of the sales of light-duty vehicles in the USA and, consequently, it is an important vehicle category. It is also worth mentioning that GM provided very little data about the car and the powertrains used (proprietary information?).

The differences between the vehicles, driving cycles and other assumptions in the studies are sometimes so great that it is difficult to draw any firm general conclusions about the differences in the results generated. Furthermore, it is doubtful to make *direct* comparisons between the results from the studies, although, at this moment, this was the only possibility to highlight the findings.

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[4] This does not necessarily mean that *all* the options studied will be developed and commercialised within the timeframe. Such diversification would definitely be a much too costly scenario and, in general, it is plausible to believe that only a few of the options will be commercialised.

Vehicle range

An important factor to consider is the range of the vehicle. Since many of the fuels have a considerably lower energy density than petrol and diesel fuel, or else need high pressure vessels or cryogenic storage, the range will be reduced if a constant volume or mass is anticipated for the fuel tank. Ideally, a constant range would be desirable but this cannot be accomplished meeting reasonable targets for cost, volume and weight for all fuel/powertrain options. A fuel subjected to this problem is hydrogen (in particular in otto engines). For pure electric vehicles, a short range is the only option.

Ecotraffic has used a combination of limitations for range, weight and volume, although it has to be noted that this analysis was based on a relatively simple scheme and not an engineering analysis. The range for the conventional petrol-fuelled car was 818 km. It is the opinion of the authors that a range that long, or longer, has to be the goal for a future family car of this size to satisfy the customer needs. For liquid fuels, the same weight of fuel and tank was used, implying that the range would be somewhat different compared to the baseline. A weight increase has been permitted for the gaseous and cryogenic fuels in conjunction with an associated increase in space demand. In spite of that, a somewhat reduced range in comparison to the base case still has to be accepted, since the stored energy will be less than for petrol and this cannot be fully compensated by an increased efficiency. In some cases, the difference in energy use in comparison to petrol is negligible (e.g. the hydrogen fuelled otto engine). The associated weight increase for some of the options has been compensated by an increase in powertrain size, in order to maintain the vehicle performance and this is further increasing the weight penalty for these options.

Many U.S. studies use the goal for range in the PNGV programme, which is 611 km (380 miles). Bearing in mind the very progressive fuel consumption target of about 3 l/100 km (combined fuel economy, city and highway) in this programme, the tank weight and volume for conventional liquid fuels is very low for this type of car. In comparison, the conventional petrol-fuelled car in our study had a fuel consumption of 6 l/100 km in the NEDC cycle. MIT used a more or less constant range meeting the PNGV target and the fuel storage size was adjusted to meet this target. The problem with this methodology is that it increases the number of simulations that has to be carried out, since several iterations has to be made in order to meet the performance target as well. (In addition, an optimisation of final drive ratio might be necessary if the modifications are great.)

4.5.2 Calculations of fuel consumption

Driving cycle

Ecotraffic used the current European driving cycle (NEDC) for the vehicle simulations. It is well-known that this driving cycle does not reflect current European driving style very well but since there are no better options available that are based on extensive investigations, it was felt that the chosen driving cycle was appropriate. An advantage of using the NEDC cycle is that the future limits for CO_2 in Europe have been set according to this driving cycle.

U.S. studies generally use the U.S. FTP-75 driving cycle. The IFEU study used a combination of the NEDC cycle and a high-speed highway driving cycle. Since the driving cycles differ, it is obvious that the relative difference between various options also differ from study to study.

Calculation methodology

There are basically two options available for calculating the fuel consumption for new vehicles and powertrains. The first method is to carry out a critical review of published data on fuel consumption. The second method is to use a simulation model. VTT used the former method but most of the other studies have used some kind of simulation tools. Ecotraffic used the Advisor® from NREL. There are also other simulation-tools available. GM used a proprietary simulation model (HPSP) developed in-house. The authors state that the model has been thoroughly validated for numerous vehicles and consequently, there are reasons to believe that this model should be one of the best for this purpose. Besides the mentioned statement about validation, very little information is provided about this software.

Performance targets

Some performance targets have to be set for the vehicles. Ecotraffic used the acceleration from 0 to 100 km/h (11 seconds) as the sole criterion for vehicle performance that had to be met. It was anticipated that reasonable goals for passing acceleration, driveability and other criteria could be met by all powertrains in the future. The acceleration performance was kept as constant as possible, allowing for a tolerance of less than +/– 0,1 seconds.

GM used a set of engineering targets that all had to be met. The powertrain was resized to meet these criteria and in general, it was the maximum acceleration of 5 m/s^2 that was the dominant constraint. Surprisingly, the acceleration from 0 to 60 mph differs very much between the vehicles. The slowest acceleration was 10 seconds but the fastest car (otto-hybrid fuelled with petrol and E85) could reach this speed in only 6,3 seconds. This is of the same order of magnitude as a difference between a family car and a sporty car. Most of the other studies have some kind of performance target and generally, it seems to be the acceleration from 0 to 60 mph or 0 to 100 km/h.

Some studies use emission goals but often it is stated that future emission levels could be met by all options, provided that enough development time and effort is spent. However, Ecotraffic did take into account the increase in fuel consumption that is attributable to some new aftertreatment devices needed to meet future emission goals (e.g. particulate trap and NO_X storage catalyst).

4.5.3 Fuel converter

As in the previous cases, GM provides little information about the fuel converters. As the final German report was not available at the time this paper was written, it has not been possible to comment on the choices made in that project. Therefore, only the MIT report is discussed here and the similarities and differences in comparison to our study are commented.

Otto and diesel engines

Most studies foresee significant improvements of petrol and diesel engines in the future. Relatively sparse information is usually provided from the authors about these options, probably because the focus usually is on alternative fuel converters.

Ecotraffic foresee an extensive use of direct injection in both otto and diesel engines. Reduction in engine friction and pumping losses (particularly for the otto engine) are two important factors. Direct injection for otto engines running on alternative fuels has also been anticipated. For the diesel engine, a significant increase in the brake mean effective pressure (BMEP), associated with downsizing, is also foreseen as an effective means of reducing the fuel consumption. An increase in BMEP to over 20 bar[5] will be necessary to obtain the anticipated reduction of fuel consumption. Ecotraffic made a correction of the increase in fuel consumption at cold start for the diesel engines. The cold start model in the version of Advisor® (3.0) that was used overestimates the additional fuel consumption at cold start, since it was based on data for petrol engines. The cold start increase was reduced in Ecotraffic's study by 50% based on relatively limited cold start test data and a validation of the simulation against published results on a diesel car (Audi A2 1.4 TDI). It is not known if any of the other studies did consider this potential problem in the simulations.

MIT extrapolated the BMEP level by 0,5 % per year for both engine types and this extrapolation is based on historic trends. The rated speed (maximum power) was also increased for the petrol engine but not for the diesel engine. It is interesting to find that MIT was much more prudent in extrapolating the maximum BMEP level for the diesel engine in comparison to Ecotraffic. MIT did foresee about 15 bar (compared to 20 bar in the Ecotraffic study), based on the same assumption as for petrol, and this assumption was also made on a longer time horizon (2020) than in Ecotraffic's study (2012).

GM did not scale the engine down for the hybrid drive systems. Consequently, the acceleration performance was significantly higher for these powertrains than for the conventional powertrains.

Fuel cells

Ecotraffic used a fuel cell model provided by Advisor® as the basis for the simulations. Additional parasitic load was anticipated to compensate for pressurising the fuel cell stack (it was atmospheric to start with) and for additional subsystems in the fuel cell system. Thus, the original maximum efficiency for the system was reduced from 60% to about 52%. It is also interesting to note that the relative impact on the efficiency was greatest at light loads – a load region where the efficiency of a fuel cell stack generally is very high.

MIT used an efficiency curve for the fuel cell system that had a higher maximum efficiency than Ecotraffic and in particular, the efficiency was higher at light loads. It has to be noted that the input data for simulations on fuel cell systems is very limited today. Consequently, the results might change if the systems are assessed in the future when new input data are available.

4.5.4 Drivetrain

Ecotraffic used an automated mechanical gearbox for the non-hybrid otto and diesel engines. Such concepts are now becoming increasingly popular on the European market and in addition to the higher powertrain efficiency, they enable the possibility of engine shut-off at standstill. The final drive ratio and the number of gears (5 or 6) were varied to obtain the lowest possible fuel consumption, while the engine was scaled to keep the acceleration constant. For the otto engines, there was no significant difference in fuel consumption between 5 or 6-speed gearboxes, but for the diesel engine, 6 gears provided a small advantage. The use of a larger than usual alternator (belt, chain or gear driven), presumably in combination with a 42 V electric system, could also replace the starter motor. A start and

[5] This level is foreseen as an average for all engines. Some engines reach this level already today but the average level is considerably lower.

stop strategy was anticipated, since this is enabled by the feature mentioned. Thus, it is assumed that engine idling could be avoided for 75% of the driving cycle for the non-hybrid conventional (future) powertrains. For the hybrid systems, no idle at all was anticipated, implying that the engine should be stopped at every standstill. However, the mentioned strategy for the non-hybrid engines decreases the *relative* advantage of the hybrid concepts considerably. The mentioned assumption for the conventional drivetrain is an area where the Ecotraffic study differs from most other studies.

MIT used a continuously variable transmission (CVT) for the hybrids. This is an interesting solution, since it should increase the driver's comfort, a very important parameter in the USA, where most of the cars use automatic transmissions today. It is also clear that the comfort issue will be of increasing importance in Europe in the future. On the condition that the mechanical efficiency of the CVT transmission is high, the powertrain using this transmission could eventually be more efficient than an automated mechanical gearbox. The CVT concept was considered but not investigated by Ecotraffic, since the potential for efficiency improvement over the automated mechanical gearbox was assumed relatively small.

GM used an automatic 4-speed transmission with a torque converter in the base case. The hybrid versions used a 4-speed automated transmission without a torque converter. GM stated that they used validated electrical components from the PNGV Precept automobile for the hybrids.

4.5.5 Vehicle weight

Since the vehicle weight is a factor that has a decisive influence on the fuel consumption and performance, it is of interest to compare the weight of vehicles in the studies evaluated. As no data was provided in the GM report and the complete final German report was not available at the time this report was written, the comparison between the studies of Ecotraffic and MIT remain as the only option. This comparison is shown in the graph of **Figure 2**. Since the vehicles in the two studies differ, the only reasonable comparison that can be made is to relate the weight to the petrol baseline vehicle (index = 100) for each study.

As can be seen in **Figure 2**, the difference in weight between the two studies is very small for the petrol hybrids. The difference is also relatively small for all the other options. Ecotraffic used a somewhat more optimistic assumption for the weight of the fuel processor, which might be the reason for the difference seen in these cases. Ecotraffic also anticipated a higher specific output for the diesel engines, which might explain the difference that can be seen for these options. The longer range foreseen by Ecotraffic could be a reason for that the weight is higher for CNG and GH_2 in our case. The MIT case for the evolutionary car (designated "base" in **Figure 2** is also shown to illustrate the impact of a weight reduction strategy for the more advanced vehicles. Overall, in view of the various assumptions made in each study, it must be considered that the difference in weight is relatively small between the studies.

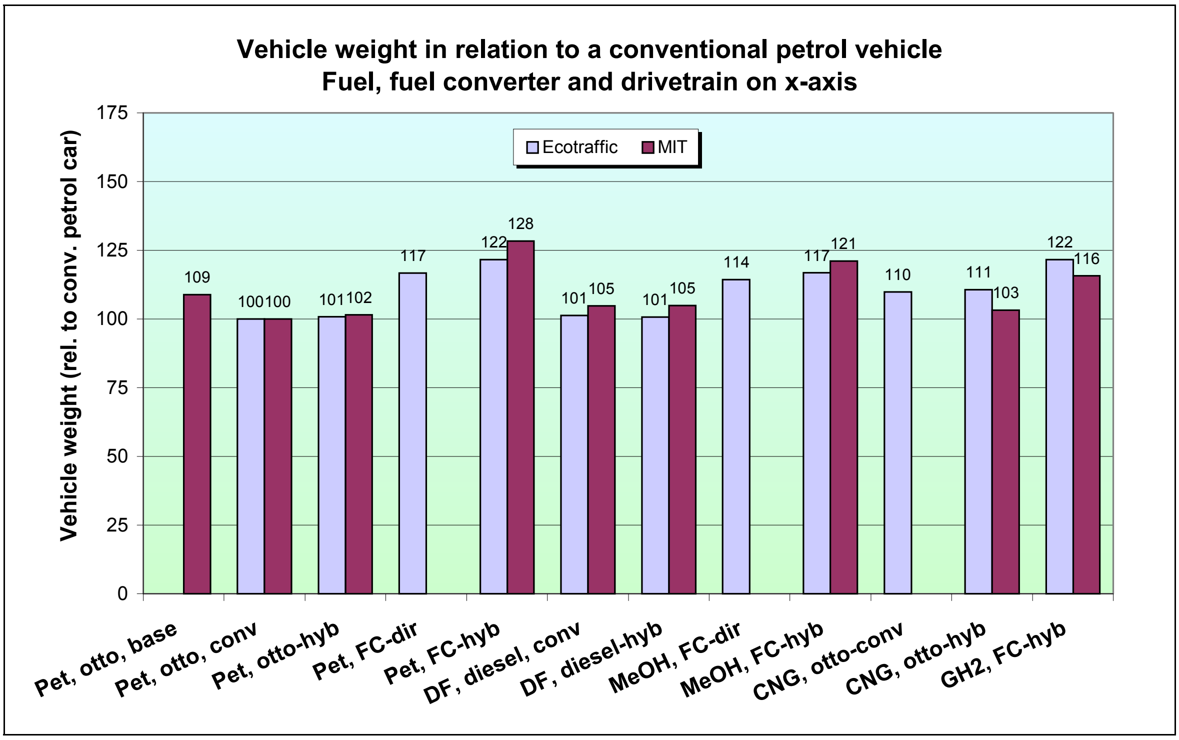

Figure 2. *Vehicle weight for some fuel, fuel converter and drivetrain options. Comparison between studies by Ecotraffic and MIT.*

4.5.6 Powertrain efficiency

Using the available data on powertrain efficiency (and fuel consumption), a calculation of the relative efficiency has been carried out for the MIT and GM studies and these results are compared with the results from our study. The comparison is shown in **Figure 3** to **Figure 5**. Note that there is no difference between fossil and non-fossil fuels regarding the efficiency in the vehicle (tank-to-wheel).

Petrol and diesel fuel

In **Figure 3**, the powertrain efficiencies for the petrol and diesel options are shown.

In **Figure 3**, the evolutionary petrol car by MIT (called "base" in the figure) is shown for reference. The efficiency is 12% lower than the more advanced vehicle, which has been set as the reference case (index = 100) for the comparisons.

It is notable that MIT has foreseen a significant higher efficiency for the hybrid versions using otto and diesel engines in comparison to Ecotraffic and GM. One reason for the relatively small impact of hybridisation in our study was, as mentioned before, the significantly reduced idling (-75%) for the conventional drivetrain due to the anticipated start and stop strategy. GM and MIT did not consider this strategy and hence, a greater advantage by hybridisation could be expected in their studies. Regarding the results in the GM study, it is notably that they did not scale down the engine for the hybrid drivetrain. Thus, there is a considerable performance difference between the hybrid and the non-hybrid versions. MIT used a CVT transmission for the hybrids and this might affect the results in favour of the hybrids. Similarly, GM used an automatic transmission with torque converter for the conventional drivetrain. These drawbacks for the conventional powertrain due to the torque converter losses and the weight penalty for not scaling down the engine for the hybrid powertrain are counteracting each other. This could be the reason why GM obtained practically the same impact of hybridisation as in our study.

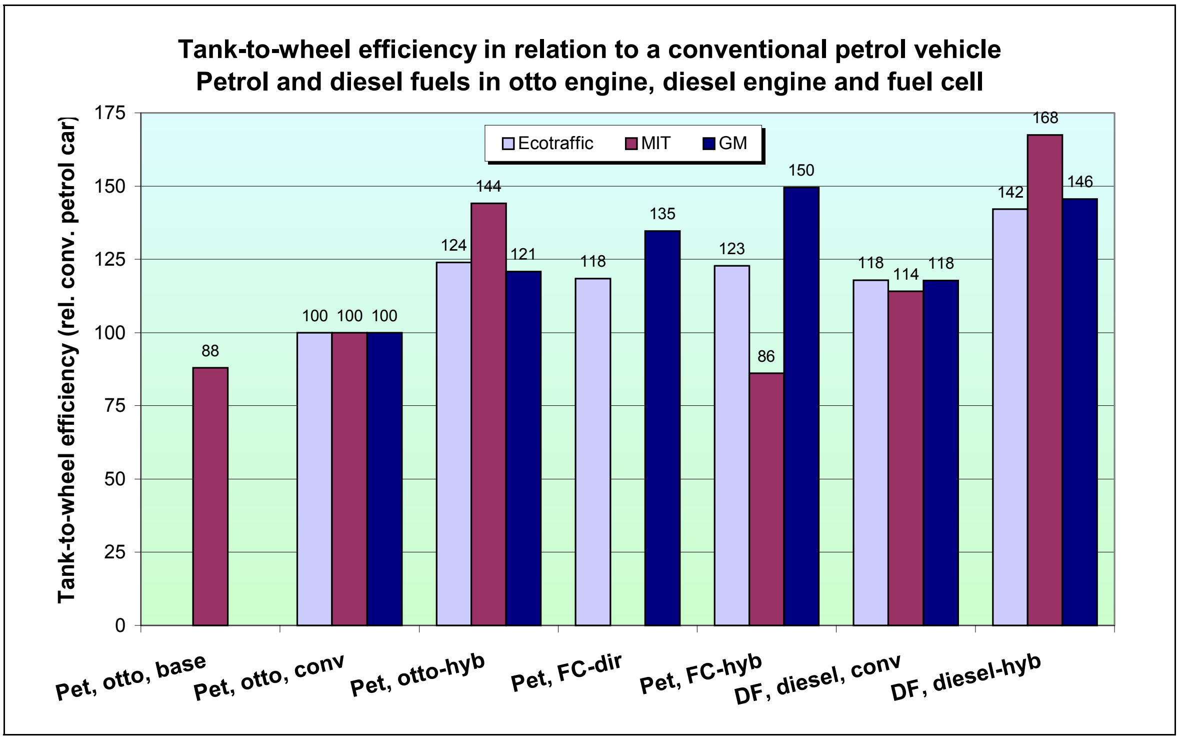

***Figure 3**. Tank-to-wheel efficiency for petrol and diesel fuel*

Regarding the petrol fuel cell hybrids, there is a significant gap between the three studies. GM has the highest efficiency, MIT has an even lower efficiency than the conventional petrol powertrain and Ecotraffic is in between, although the efficiency is higher than for the conventional drivetrain. Several factors, such as weight, fuel cell and reformer efficiency and other assumptions must affect the results but it is not simple to make a thorough explanation of the vast differences in this case. We did not consider the increase in fuel cell stack size that should be necessary when the fuel cell is run on reformate instead of hydrogen. This resizing could increase the weight by some 10 kg or maybe slightly more depending on the impact on the auxiliary devices, but the weight penalty should not be decisive.

In contrast to the former comparison, the difference for the conventional diesel engine is small. The relatively prudent assumption about specific power (and the associated fuel consumption penalty at low loads) in the MIT study might be one explanation for the lower efficiency in their case compared to our study.

Alcohol fuels

The tank-to-wheel efficiency for the alcohols is shown in **Figure 4**. MIT considered only methanol in a fuel cell hybrid, so this limits the possible combinations that could be shown in the figure.

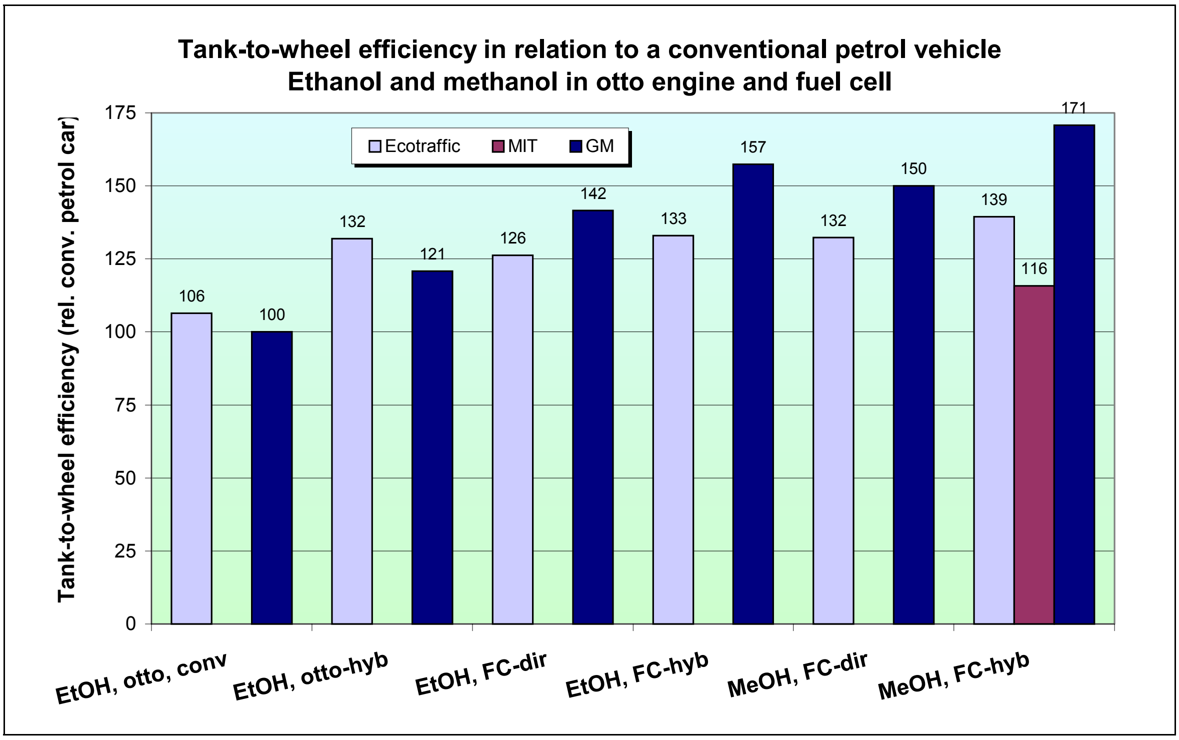

Figure 4. *Tank-to-wheel efficiency for alcohols*

For the alcohols, many of the same conclusions as in the former case are valid also for the results in **Figure 4**. In Ecotraffic's study, a higher efficiency for ethanol and methanol in an otto engine was obtained regardless whether it was a hybrid or a conventional powertrain. We had anticipated an advanced dedicated alcohol engine taking advantage of direct injection, higher octane level of alcohols, increased power (downsizing), utilisation of the evaporation cooling effect, etc. Apparently, GM used the same efficiency for the alcohol-fuelled otto engines as for the petrol engines. In the fuel cell cases, GM had a higher efficiency than Ecotraffic. Partly, this could be because GM had anticipated a higher efficiency for the fuel cell powertrain. However, since very little information about the powertrains used by GM is provided, it is difficult to comment on the differences found. Regarding the methanol fuel cell hybrid, all three studies provided data. GM had the highest efficiency, MIT had the lowest and Ecotraffic was in between.

Note that neither MIT, nor GM, did consider the possible use of alcohols in diesel engines. According to our estimations, a fully developed alcohol-fuelled diesel engine could have the same efficiency as a diesel engine fuelled with diesel fuel, i.e. significantly higher efficiency than both petrol and alcohol-fuelled otto engines. Ecotraffic obtained the highest efficiency for methanol (and DME) in this kind of powertrain (i.e. higher than for a fuel cell).

Gaseous fuels

The tank-to-wheel efficiency for the gaseous fuels (i.e. CNG and GH_2) is shown in **Figure 5**. As in the former figure, there were not many options where all studies provided results.

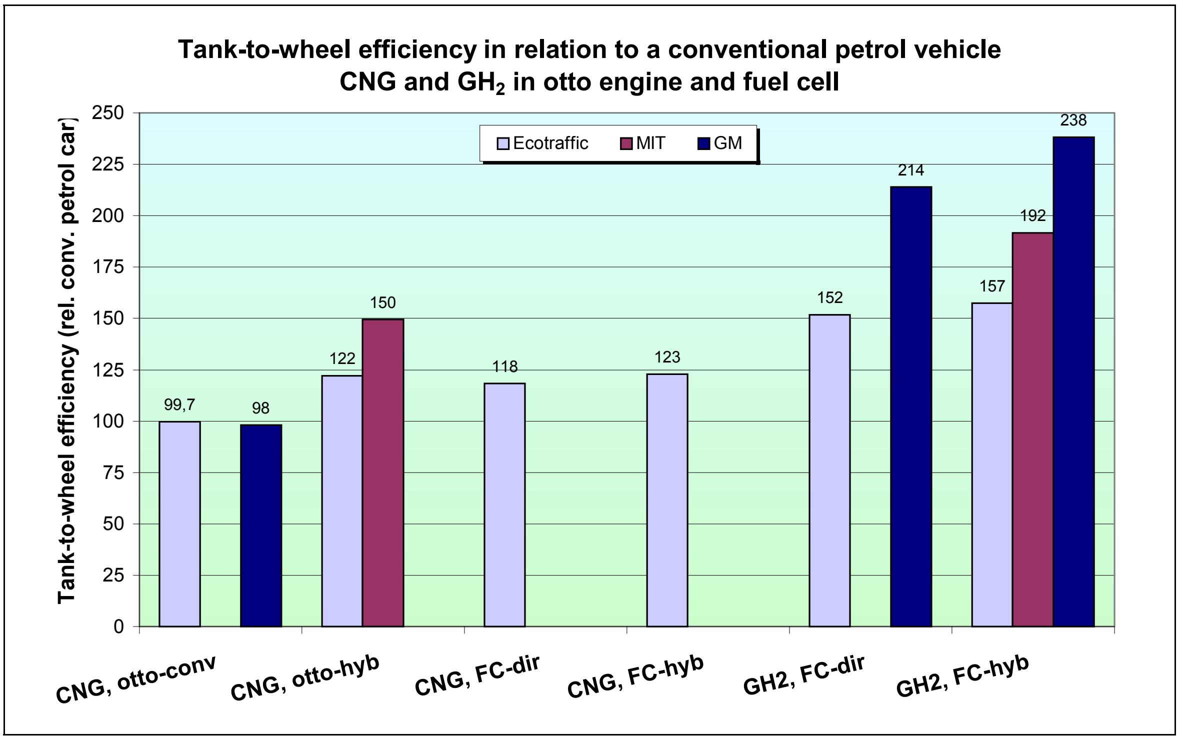

Figure 5. *Tank-to-wheel efficiency for the gaseous fuels*

Ecotraffic anticipated a higher maximum efficiency for a CNG-fuelled otto engine in comparison to the petrol alternative. However, the specific output decreases (necessitating a larger engine, which decreases the part-load efficiency) and there is a weight penalty due to the heavier fuel tanks. Scaling of the engine is necessary to maintain the performance due to the weight increase. The resulting fuel efficiency was practically the same as for petrol. It should be noted that Ecotraffic anticipated the use of direct injection for all otto engines including the CNG engine (although several potential problems were identified in this case). It is not likely that this approach was used in other studies. GM assumed a marginally higher efficiency for the CNG engine (the average efficiency increased from 16,7% to 16,9%) but apparently, the higher weight of the vehicle reduced the efficiency more than the gain in the powertrain efficiency.

The efficiency for the CNG-fuelled otto engine hybrid was considerably higher in MIT's case than in our study. As in the previous case for petrol, the strategies for stop and start, as well as the different range could be the largest contributors to the divergence found.

GM had the highest efficiency for the hydrogen-fuelled fuel cells, Ecotraffic had the lowest efficiency and MIT was in between. There are several assumptions that influence these results. The weight penalty was highest in Ecotraffic's case, due to a demand for a longer range than in the other studies. It is also apparent that GM and MIT had assumed a higher efficiency for the fuel cell powertrain. Approximately the same *relative* difference is the case also for the direct drive fuel cells of GM and Ecotraffic. A more detailed analysis of the differences has not been possible.

4.6 Total system efficiency

In summing up the total system efficiency for the various options, one particular problem is that the same options are not covered in all studies. Since most studies have covered fossil fuels, the most comprehensive comparisons of the results can be made for these fuel options. IFEU provided results for the total efficiency but not for the well-to-tank and tank-to-wheel stages. Therefore, the results from IFEU could be added in this case.

In **Figure 6**, the results for petrol and diesel fuels from crude oil are shown.

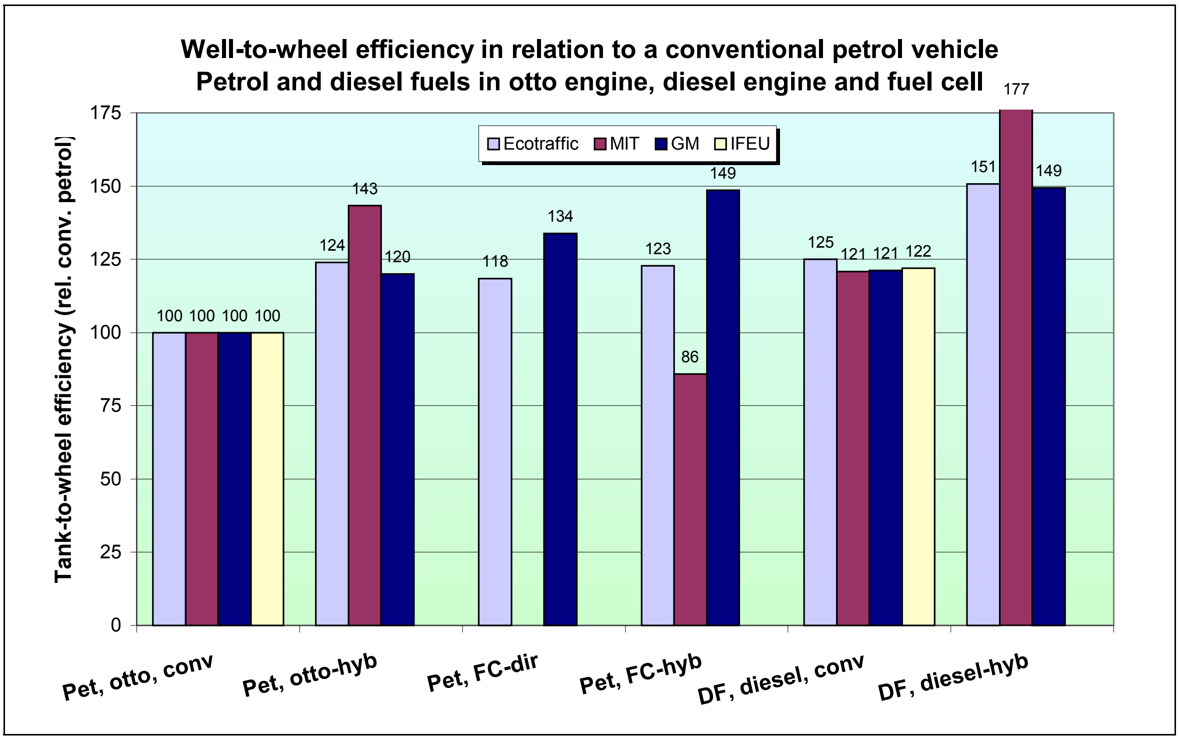

Figure 6. *Well-to-wheel efficiency, conventional crude-oil based fuels*

Compared to the well-to-tank efficiencies shown before, the results in **Figure 6** are quite similar. The most important difference is that the higher efficiency for diesel fuel production improves these options in comparison with petrol. The IFEU results for diesel fuel in a conventional powertrain are on a similar level as the other results.

In **Figure 7**, the results for methanol and DME are shown.

As mentioned before, GM had obtained better efficiency for the fuel cell options, so the difference in comparison to Ecotraffic's is not surprising for methanol. Somewhat surprising are that the results from IFEU show a significantly lower efficiency than the other results. The same trend is also obvious for DME. As the complete report from the German project was not available at the time this report was written, it is difficult to speculate about possible reasons for the outcome.

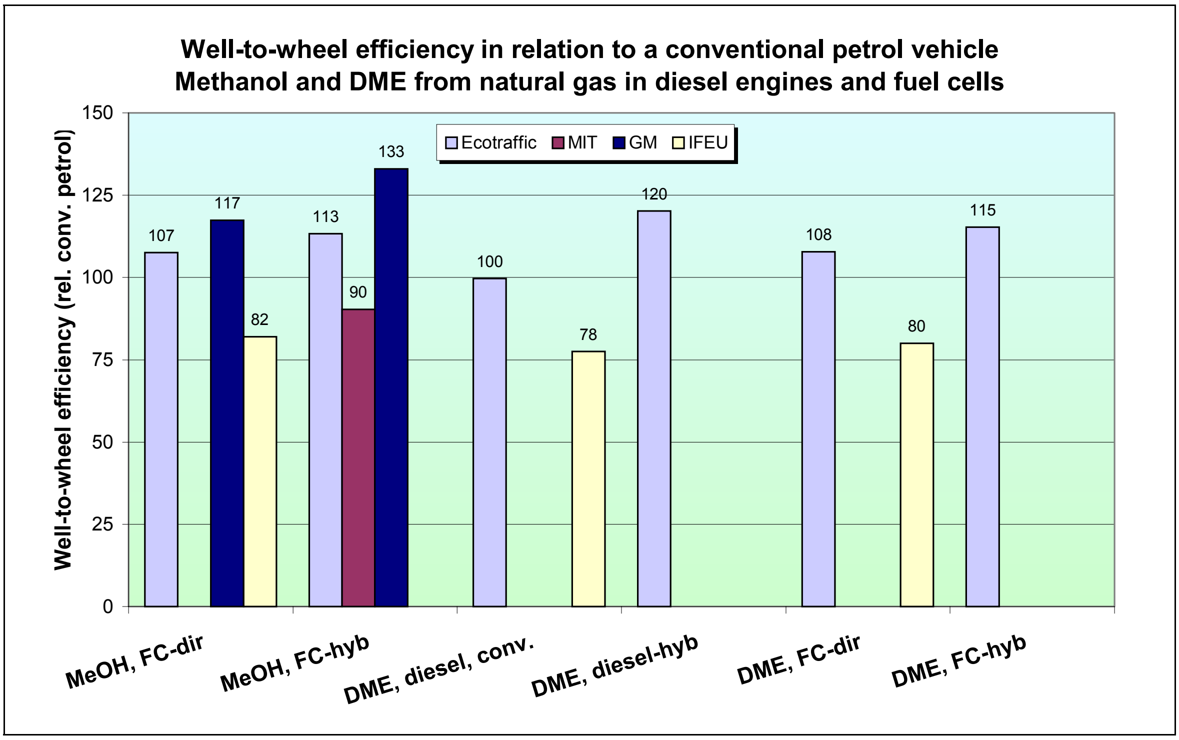

Figure 7. Well-to-wheel efficiency, methanol and DME from natural gas

In **Figure 8**, the results for some selected CNG, LNG and GH_2 options are shown in the same graph.

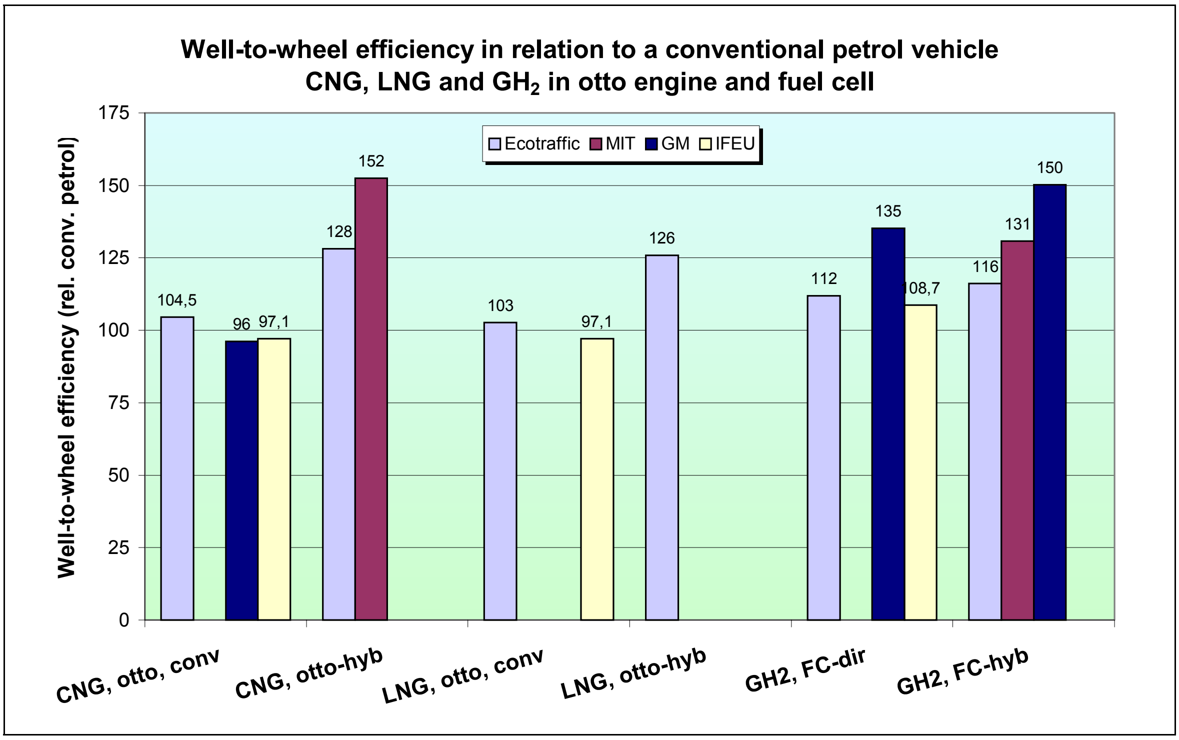

Figure 8. Well-to-wheel efficiency, some selected natural gas based options

In **Figure 8**, Ecotraffic has a higher efficiency for the CNG option than GM and IFEU. The fact that Ecotraffic used a direct injection dedicated CNG engine (otto type) to obtain the highest possible efficiency from this option is the likely reason for the higher efficiency than the other studies. The difference between IFEU and Ecotraffic is somewhat smaller in the LNG case.

Hybridisation generally increases the efficiency and this has been most pronounced in the MIT study. Therefore, it is not surprising that MIT has the highest efficiency for the CNG otto-hybrid.

As in the tank-to-wheel case, GM has the highest efficiency for the GH_2-fuelled fuel cell vehicles. IFEU has a slightly lower efficiency than Ecotraffic for the direct driven hybrid fuel cell.

5 DISCUSSION AND CONCLUSIONS

5.1 Methodology and assumptions

Most studies have the ambition to picture at least a medium term time frame, 2005-2020, and focus on principal motor fuels marketable in large volumes. Few have been successful in upholding the ambition throughout. Long term sustainability has only been discussed by a few. The Ecotraffic study deals only with energy efficiencies in systems considered as technically feasible and when fully implemented, whereas others often refer to adaptations to regionally/locally existing systems and costs, which inevitably means a rather near term view. This does not necessarily imply that we are considering our conditions for the comparisons to be more correct than the other studies – we can only say that the results in the studies are different. Comparisons of results from different studies may rarely be completely correct, as the systems are not often built in an entirely similar way. The attempts that have been made here to compare the results highlight this issue and, as such, the results should be viewed while bearing this problem in mind.

5.2 Powertrains

It is trivial to state that that systems based on the diesel engine in all relevant studies are found to have an 21-24% system efficiency advantage over the reference vehicle (evolved petrol driven otto engined vehicle). It is, however, remarkable that no study but Ecotraffic's has tried to analyse alcohols as fuels (particularly in diesel engine drivetrains) in spite of the potential they have among the alternative fuels and that they can be produced on bio-basis.

There also is common agreement that hybridisation of systems based on ICE brings about an efficiency improvement of at least 20-24% (the MIT study quotes values above 40%).

Fuel cells are without doubt efficient energy converters, with hydrogen as fuel more than 50% better than the reference vehicle (GM quotes >100%). Fair comparisons cannot, however, be made without considering the energy used for refuelling, which is high for hydrogen and reduces the powertrain efficiency to be "only" about 25% better. When considering also the production and distribution steps, the efficiency advantage will be further reduced (below). Fuels that require onboard-conversion to hydrogen must include this step in the powertrain, which will reduce the energy efficiency advantage to 18-22% (highest for with methanol) in the Ecotraffic study. GM quotes higher figures for both petrol and alcohols. The vast difference between the petrol-fuelled (naphtha in one case) fuel cell vehicles in the MIT and GM studies could be noted.

The hybridisation effect with fuel cells seems to be considerably less than in with ICEs, about 6% or about 12% in the studies of Ecotraffic and GM respectively, which were the only ones to analyse the effect. In fact, no study gave a fuel cell system higher system efficiency than the diesel engine hybrid combination.

5.3 Well-to-wheel efficiency

CNG/LNG systems rank high due to the low energy needs to process NG to pipeline-NG (and LNG) assuming that large-scale distribution systems are in place. In the GM study, NG-based GH_2, even when produced decentralised at refuelling stations, with fuel cells is ranked even higher due to the assumed high efficiency of the fuel cell and absence of an optimised CNG-engine. For the same reason, NG-GH_2 achieves higher system efficiency than with methanol as hydrogen carrier, to which the low production efficiency is contributing. Ecotraffic's more optimistic assumptions for the methanol route results in only slight difference of efficiency between the two routes. GM did not consider methanol as otto engine fuel, which Ecotraffic finds to be equal or better in hybrid combination than the direct fuel cell system. In the Ecotraffic-study, the efficiency advantage of the hydrogen fuel cell vehicle is only about 10% over the reference vehicle on well-to-wheel basis while GM quotes 35%.

Although motor fuels in gaseous form (NG, hydrogen) may be important niche fuels we cannot see them as widespread principal fuels to be available everywhere. This either leads to a multi-fuel scenario, which is hardly rational, or would make fuel-flexible vehicles desirable, or the need to transform the fuels to liquids for distribution. This still is an efficient proposition for LNG but not for cryogenic hydrogen, LH_2. Methane has, however, the drawback that there does not seem to be any efficient way to produce it from biomass resources (on a large scale).

Liquid fuels, easily handled as petrol and diesel oil today, will have a great advantage in distribution and refuelling efficiencies and allow retaining of the refuelling habits of the public. Among the liquid alternative fuels, the alcohols with emphasis on methanol, fares best in the long term by high efficiency in production, efficient distribution and refuelling, high efficiency at conversion to hydrogen onboard FCV, and they are possible to use efficiently in all types of powertrains. Motor fuel production based on biomass feedstocks (wood) seems to yield methanol as the most efficient liquid fuel. Considering these facts, it seems remarkable that methanol has not been more thoroughly studied.

The production of FT-fuels is in all studies found to be less efficient than that of hydrogen or methanol (and DME, although this fuel has only been assessed by few studies). The GM study indicates nearly 30% lower system efficiencies compared to petroleum based fuels and 15-20% lower than methanol, the MIT study about 20% lower compared to methanol, and the Ecotraffic study 20-25% lower compared to methanol.

5.4 Sustainability

To maintain the hydrocarbon base feedstocks in a scenario with great reductions of GHG, sequestration of CO_2 in deposits in the crust of the earth would be necessary and is often discussed as technically not an infeasible solution. The unavoidable consequence is, however, a distribution system for hydrogen, which we cannot see as the general future system (above). For GHG-reductions of the magnitude of 80-90%, only biomass-based fuels have such potential, as has been demonstrated in several of the studies. In some studies, hydrogen from resources such as hydro- and wind-power and solar cells is the only truly renewable fuel. We have not included those in our study as the two first-mentioned have low potential and the direct solar route is not feasible to reasonable cost in the foreseeable future. Moreover, a distribution net for hydrogen, suitable for widespread motor fuel refuelling everywhere, does not seems possible with known technology today, and is uncertain in the future.

Ecotraffic's summary

In summary, it can be concluded that a comparison between studies in this area is a difficult task. The main problem is that the assumptions made in the studies often are quite different. However, many of the differences found can be explained and, in most cases, it is surprising to find how close the results are after all. In several cases, it is obvious that the input data used in the calculations could be significantly improved.

Some general conclusions based on the results from our own study and the other studies can be made.

- **Hybridisation appears to be a preferred way to increase the fuel efficiency and it seems that this potential is greater for combustion engines than for fuel cells. Fuel cells can be more efficient than conventional otto-engine powertrains, but the advantage over diesel hybrids is relatively small or nil.**
- **CNG/LNG rank high due to low conversion losses but these fuels cannot be produced in an efficient way from biomass. Hydrogen, DME and methanol have high efficiency whether produced from natural gas or biomass. FT-fuels seem less efficient than these fuels. Hydrogen produced from electricity appears to be the least efficient fuel pathway, although this fuel is used in a fuel cell vehicle.**
- **In view of a (likely) future focus on a widespread use of biofuels, it is somewhat surprising that methanol and DME, being liquid at ambient (methanol) or moderate (DME) pressure, have not been examined more thoroughly.**

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Results in tables

In order to provide a better overview of the results, the fuel production data have been compiled in the form of tables, which are shown below. In order to reduce the necessary space or to avoid using a too small font size, the energy use in the vehicles has been omitted from the tables. The results for fuel production and for the energy use in the vehicles are provided in **Tables 5 – 8** in the main report anyway.

The results attached below show the energy use divided into the use of bioenergy, fossil energy and the total use of energy. The energy use is expressed in MJ energy (for each step respectively) that is used to provide one MJ of energy in the vehicle tank. In addition, data are provided for the efficiency in the fuel production stage (well-to-tank). As an example, it can be mentioned that if the total energy use for the fuel production is 1,0 MJ, this means that for every MJ of energy used in the vehicle, an additional 1,0 MJ is used in the fuel production; i.e. in total: 2 MJ. This can also be regarded as if the energy use in total is a factor of 2 higher than in the vehicle. This is equal to efficiency in the fuel production stage of 50%.

Table 1. Production of gaseous fuels from natural gas

		Energy use in various steps of the fuel production (MJ_b/MJ_p) and energy efficiency (dim. less)																		
		Feedstock prod.			**Feedstock transp.**			**Production**			**Distribution**			**Refuelling & prod.**			**Sum fuel production**			
	Bränsle, dist.	Tot	Bio	Foss	Tot	Bio	Foss	Tot	Bio	Foss	Tot	Bio	Foss	Tot	Bio	Foss	Tot	Bio	Foss	η_{tot}
Oil	Petrol	0,030	0	0,030	0,007	0	0,007	0,155	0	0,155	0,014	0	0,014	0	0	0	0,206	0	0,206	0,829
	Diesel fuel	0,030	0	0,030	0,007	0	0,007	0,090	0	0,090	0,010	0	0,010	0	0	0	0,137	0	0,137	0,880
Gas-fuels., foss.	Methane, CNG	0,030	0	0,030	0,000	0	0,000	0,020	0	0,020	0,020	0	0,020	0,080	0	0,080	0,150	0	0,150	0,870
	Methane, LNG	0,030	0	0,030	0,000	0	0,000	0,102	0	0,102	0,035	0	0,035	0,004	0	0,004	0,170	0	0,170	0,855
	Hydrogen, GH2	0,040	0	0,040	0,000	0	0,000	0,336	0	0,336	0,040	0	0,040	0,219	0	0,219	0,636	0	0,636	0,611
	Hydrogen, LH2	0,068	0	0,068	0,000	0	0,000	1,160	0	1,160	0,092	0	0,092	0,000	0	0,000	1,320	0	1,320	0,431
	El, hydrogen, GH2	0,074	0	0,074	0,000	0	0,000	1,466	0	1,466	0,000	0	0,000	0,219	0	0,219	1,760	0	1,706	0,362
	DME, GH2	0,053	0	0,053	0,000	0	0,000	0,456	0	0,456	0,043	0	0,043	0,518	0	0,518	1,070	0	1,070	0,483
	DME	0,041	0	0,041	0,000	0	0,000	0,351	0	0,351	0,034	0	0,034	0,000	0	0,000	0,426	0	0,426	0,701

Table 2. Production of gaseous fuels from biomass

		Energy use in various steps of the fuel production (MJ_b/MJ_p) and energy efficiency (dim. less)																		
		Feedstock prod.			**Feedstock transp.**			**Production**			**Distribution**			**Refuelling & prod.**			**Sum fuel production**			
	Bränsle, dist.	Tot	Bio	Foss	Tot	Bio	Foss	Tot	Bio	Foss	Tot	Bio	Foss	Tot	Bio	Foss	Tot	Bio	Foss	η_{tot}
Oil	Petrol	0,030	0	0,030	0,007	0	0,007	0,155	0	0,155	0,014	0	0,014	0	0	0	0,206	0	0,206	0,829
	Diesel fuel	0,030	0	0,030	0,007	0	0,007	0,090	0	0,090	0,010	0	0,010	0	0	0	0,137	0	0,137	0,880
Gas-fuels., bio	Methane, CBG	0,054	0	0,054	0,074	0	0,074	0,850	0,850	0,000	0,010	0,000	0,010	0,080	0,080	0,000	1,068	0,930	0,138	0,484
	Methane, SNG	0,060	0	0,060	0,030	0	0,030	1,000	1,000	0,000	0,020	0,020	0,000	0,080	0,080	0,000	1,190	1,100	0,090	0,457
	Hydrogen, GH2	0,053	0	0,053	0,026	0	0,026	0,761	0,761	0,000	0,030	0,030	0,000	0,219	0,219	0,000	1,089	1,010	0,079	0,479
	Hydrogen, LH2	0,068	0	0,068	0,034	0	0,034	1,261	1,261	0,000	0,052	0,000	0,052	0,000	0,000	0,000	1,415	1,261	0,154	0,414
	El, hydrogen, GH2	0,087	0	0,087	0,044	0	0,044	1,902	1,902	0,000	0,000	0,000	0,000	0,219	0,219	0,000	2,251	2,121	0,131	0,308
	DME, GH2	0,077	0	0,077	0,030	0	0,030	0,980	0,980	0,000	0,020	0,000	0,020	0,518	0,518	0,000	1,624	1,498	0,127	0,381
	DME	0,053	0	0,053	0,026	0	0,026	0,754	0,754	0,000	0,020	0,000	0,020	0,000	0,000	0,000	0,853	0,754	0,099	0,540

Table 3. *Production of liquid fuels from natural gas (foss.) and biomass (bio)*

		Energy use in various steps of the fuel production (MJ_b/MJ_p) and energy efficiency (dim. less)																		
		Feedstock prod.			**Feedstock transp.**			**Production**			**Distribution**			**Refuelling & prod.**			**Sum fuel production**			
	Bränsle, dist.	Tot	Bio	Foss	Tot	Bio	Foss	Tot	Bio	Foss	Tot	Bio	Foss	Tot	Bio	Foss	Tot	Bio	Foss	η_{tot}
Olja	Petrol	0,030	0	0,030	0,007	0	0,007	0,155	0	0,155	0,014	0	0,014	0	0	0	0,206	0	0,206	0,829
	Diesel fuel	0,030	0	0,030	0,007	0	0,007	0,090	0	0,090	0,010	0	0,010	0	0	0	0,137	0	0,137	0,880
Foss	FTD (synfuel)	0,053	0	0,053	0,000	0	0,000	0,754	0	0,754	0,011	0	0,011	0,000	0	0,000	0,818	0	0,818	0,550
	Methanol	0,043	0	0,043	0,000	0	0,000	0,420	0	0,420	0,022	0	0,022	0,000	0	0,000	0,485	0	0,485	0,673
	Methanol, GH2	0,058	0	0,058	0,000	0	0,000	0,532	0	0,532	0,028	0	0,028	0,485	0	0,485	1,103	0	1,103	0,475
Bio	FTD (synfuel)	0,067	0	0,067	0,033	0	0,033	1,222	1,222	0,000	0,010	0,000	0,010	0,000	0	0,000	1,332	1,222	0,110	0,429
	Methanol	0,056	0	0,056	0,028	0	0,028	0,852	0,852	0,000	0,020	0,000	0,020	0,000	0,000	0,000	0,955	0,852	0,103	0,511
	Methanol, GH2	0,079	0	0,079	0,019	0	0,019	1,078	1,078	0,000	0,025	0,000	0,025	0,485	0,485	0,000	1,687	1,563	0,123	0,372
	Ethanol	0,060	0	0,060	0,030	0	0,030	1,150	1,150	0,000	0,012	0,000	0,012	0,000	0,000	0,000	1,252	1,150	0,102	0,444

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