Well-to-wheels Analysis of Future Automotive Fuels and Powertrains in the European Context

WELL-to-WHEELS Report
Version 3c, July 2011

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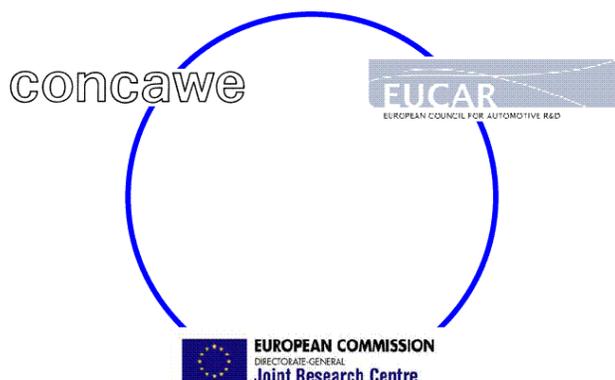
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WELL-TO-WHEELS ANALYSIS OF FUTURE AUTOMOTIVE FUELS AND POWERTRAINS IN THE EUROPEAN CONTEXT

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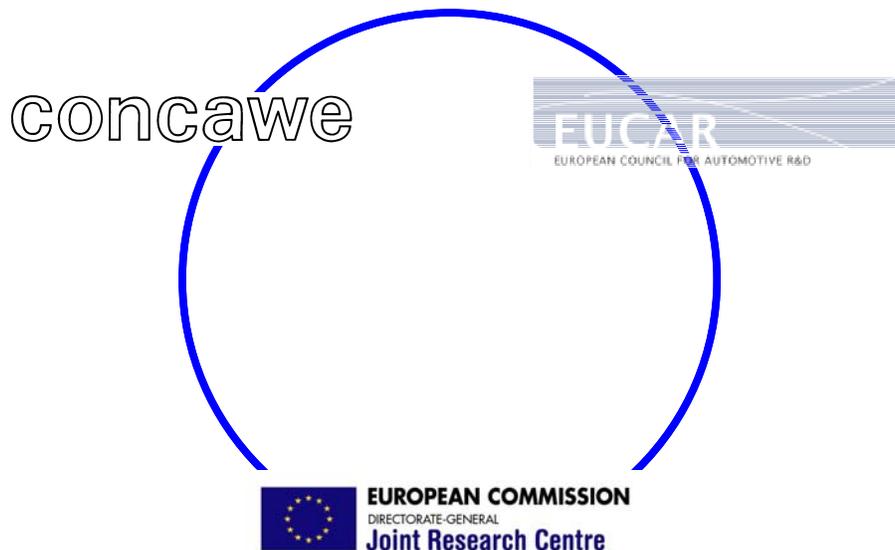
WELL-to-WHEELS Report

Version 3c, July 2011

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Notes on version number:

This document reports on the third release of this study replacing version 2c published in March 2007. The original version 1b was published in December 2003.

This is a partial revision of version 2c in that it does not include an update of section 8 on cost and availability.

Key Findings

EUCAR, CONCAWE and JRC (the Joint Research Centre of the European Commission) have updated their joint evaluation of the Well-to-Wheels energy use and greenhouse gas (GHG) emissions for a wide range of potential future fuel and powertrain options, first published in December 2003. The specific objectives of the study remained the same:

- Establish, in a transparent and objective manner, a consensual well-to-wheels energy use and GHG emissions assessment of a wide range of automotive fuels and powertrains relevant to Europe in 2010 and beyond.

- Consider the viability of each fuel pathway and estimate the associated macro-economic costs.

- Have the outcome accepted as a reference by all relevant stakeholders.

The main conclusions and observations are summarised below. We have separated the points pertaining to energy and GHG balance (in normal font) from additional points involving feasibility, availability and costs (in *italic*).

GENERAL OBSERVATIONS

A Well-to-Wheels analysis is the essential basis to assess the impact of future fuel and powertrain options.

Both fuel production pathway and powertrain efficiency are key to GHG emissions and energy use.

A common methodology and data-set has been developed which provides a basis for the evaluation of pathways. It can be updated as technologies evolve.

A shift to renewable/low fossil carbon routes may offer a significant GHG reduction potential but generally requires more total energy. The specific pathway is critical.

❑ Large scale production of synthetic fuels or hydrogen from coal or gas offers the potential for GHG emissions reduction via CO_2 capture and storage and this merits further study.

➢ *Advanced biofuels and hydrogen have a higher potential for substituting fossil fuels than conventional biofuels*

➢ *High costs and the complexities around material collection, plant size, efficiency and costs, are likely to be major hurdles for the large scale development of these processes.*

Transport applications may not maximize the GHG reduction potential of renewable energies

Optimum use of renewable energy sources such as biomass and wind requires consideration of the overall energy demand including stationary applications.

CONVENTIONAL FUELS / VEHICLE TECHNOLOGIES

Developments in engine and vehicle technologies will continue to contribute to the reduction of energy use and GHG emissions:

Within the timeframe considered in this study, higher energy efficiency improvements are predicted for the gasoline and CNG engine technology (PISI) than for the Diesel engine technology.

Hybridization of the conventional engine technologies can provide further energy and GHG emission benefits.

Hybrid technologies would, however, increase the complexity and cost of the vehicles.

COMPRESSED NATURAL GAS, BIOGAS, LPG

Today the WTW GHG emissions for CNG lie between gasoline and diesel, approaching diesel in the best case.

Beyond 2010, greater engine efficiency gains are predicted for CNG vehicles, especially with hybridization.
> WTW GHG emissions become lower than those of diesel.
> WTW energy use remains higher than for gasoline except for hybrids for which it becomes lower than diesel.

❐ The origin of the natural gas and the supply pathway are critical to the overall WTW energy and GHG balance.

❐ LPG provides a small WTW GHG emissions saving compared to gasoline and diesel.

➢ *Limited CO_2 saving potential coupled with refuelling infrastructure and vehicle costs lead to a fairly high cost per tonne of CO_2 avoided for CNG and LPG.*

➢ *While natural gas supply is unlikely to be a serious issue at least in the medium term, infrastructure and market barriers are likely to be the main factors constraining the development of CNG.*

➢ *When made from waste material biogas provides high and relatively low cost GHG savings.*

ALTERNATIVE LIQUID FUELS

A number of routes are available to produce alternative liquid fuels that can be used in blends with conventional fuels and, in some cases, neat, in the existing infrastructure and vehicles.

The fossil energy and GHG savings of conventionally produced bio-fuels such as ethanol and bio-diesel are critically dependent on manufacturing processes and the fate of by-products.
> The GHG balance is particularly uncertain because of nitrous oxide emissions from agriculture.
> Land use change may also have a significant impact on the WTW balance. In this study, we have modelled only biofuels produced from land already in arable use.

❐ When upgrading a vegetable oil to a road fuel, the esterification and hydrotreating routes are broadly equivalent in terms of GHG emissions.

❐ ETBE can provide an option to use ethanol in gasoline as an alternative to direct ethanol blending. Fossil energy and GHG gains are commensurate with the amount of ethanol used.

❐ Processes converting the cellulose of woody biomass or straw into ethanol are being developed. They have an attractive fossil energy and GHG footprint.

High quality diesel fuel can be produced from natural gas (GTL) and coal (CTL). GHG emissions from GTL diesel are slightly higher than those of conventional diesel, CTL diesel produces considerably more GHG

In the medium term, GTL (and CTL) diesel will be available in limited quantities for use either in niche applications or as a high quality diesel fuel blending component.

New processes are being developed to produce synthetic diesel from biomass (BTL), offering lower overall GHG emissions, though still high energy use. Such advanced processes have the potential to save substantially more GHG emissions than current bio-fuel options.

BTL processes have the potential to save substantially more GHG emissions than current bio-fuel options at comparable cost and merit further study.
> *Issues such as land and biomass resources, material collection, plant size, efficiency and costs, may limit the application of these processes.*

DME

DME can be produced from natural gas or biomass with better energy and GHG results than other GTL or BTL fuels. DME being the sole product, the yield of fuel for use for Diesel engines is high.

Use of DME as automotive fuel would require modified vehicles and infrastructure similar to LPG.

The "black liquor" route which is being developed offers higher wood conversion efficiency compared to direct gasification and is particularly favourable in the case of DME.

HYDROGEN

Many potential production routes exist and the results are critically dependent on the pathway selected.

If hydrogen is produced from natural gas:

WTW GHG emissions savings can only be achieved if hydrogen is used in fuel cell vehicles.

The WTW energy use / GHG emissions are higher for hydrogen ICE vehicles than for conventional and CNG vehicles.

In the short term, natural gas is the only viable source of large scale hydrogen. WTW GHG emissions savings can only be achieved if hydrogen is used in fuel cell vehicles albeit at high costs.

Hydrogen ICE vehicles will be available in the near-term at a lower cost than fuel cells. Their use would increase GHG emissions as long as hydrogen is produced from natural gas.

Electrolysis using EU-mix electricity results in higher GHG emissions than producing hydrogen directly from NG.

Hydrogen from non-fossil sources (biomass, wind, nuclear) offers low overall GHG emissions.

Renewable sources of hydrogen have a limited potential.

More efficient use of renewables may be achieved through direct use as electricity rather than road fuels applications.

Indirect hydrogen through on-board autothermal reformers offers little GHG benefit compared to advanced conventional powertrains or hybrids.

On-board reformers could offer the opportunity to establish fuel cell vehicle technology with the existing fuel distribution infrastructure.

❐ For hydrogen as a transportation fuel virtually all GHG emissions occur in the WTT portion, making it particularly attractive for CO_2 Capture & Storage.

Acknowledgments

This work was carried out jointly by representatives of EUCAR (the European Council for Automotive R&D), CONCAWE (the oil companies' European association for environment, health and safety in refining and distribution) and JRC (EU Commission's Joint Research Centre), assisted by personnel from L-B-Systemtechnik GmbH (LBST) and the Institut Français de Pétrole (IFP).

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1   Study objectives and organisational structure

EUCAR, CONCAWE and JRC (the Joint Research Centre of the European Commission) have updated their joint evaluation of the Well-to-Wheels energy use and greenhouse gas (GHG) emissions for a wide range of potential future fuel and powertrain options, first published in December 2003. The original objectives of the study were:

- Establish, in a transparent and objective manner, a consensual well-to-wheels energy use and GHG emissions assessment of a wide range of automotive fuels and powertrains relevant to Europe in 2010 and beyond.

- Consider the viability of each fuel pathway and estimate the associated macro-economic costs.

- Have the outcome accepted as a reference by all relevant stakeholders.

Cost and potential availability of alternative pathways were evaluated in version 1 and 2 of this study. With the development of specific legislation on introduction of alternative fuels, these issues have been receiving a lot of attention and generated a lot of debate. In this version 3 we opted out of this and concentrated on the evaluation of energy and GHG balances.

Notes:
- The study is not a Life Cycle Analysis. It does not consider the energy or the emissions involved in building the facilities and the vehicles, or the end of life aspects. It concentrates on fuel production and vehicle use, which are the major contributors to lifetime energy use and GHG emissions.
- No attempt has been made to estimate the overall "cost to society" such as health, social or other speculative cost areas.
- Regulated pollutants have only been considered in so far as all plants and vehicles considered are deemed to meet all current and already agreed future regulations.

This study was undertaken jointly by the JRC (Joint Research Centre of the European Commission), EUCAR and CONCAWE. It was supported by the structure illustrated in the diagram below.

Supporting structure
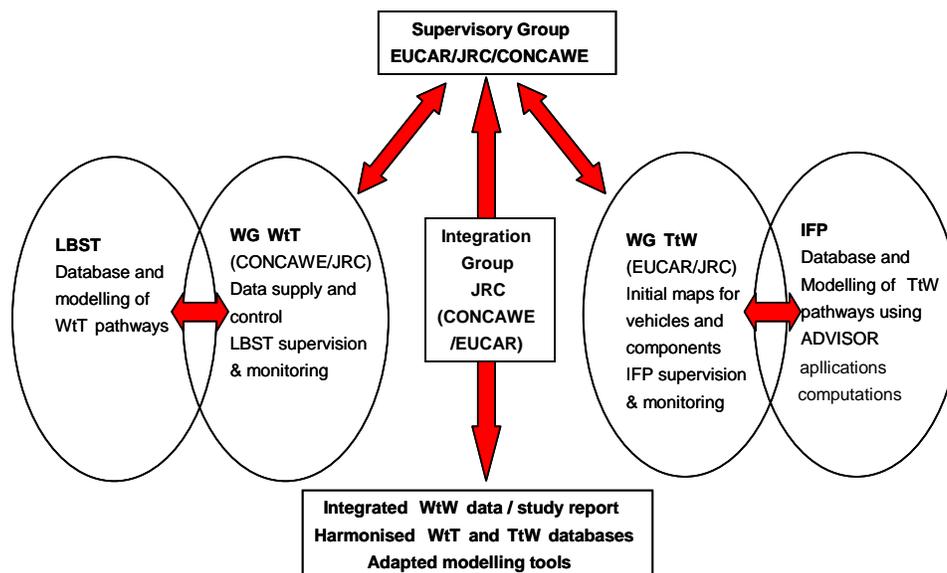
The *"Well to Tank" Working Group* was coordinated by CONCAWE/JRC assisted by LBST[1], a consultancy firm with a proven track record in WTW assessment and which had a major involvement in previous work by General Motors[2] and the TES consortium[3]. JRC provided a major contribution to the bio-fuel pathways characterization and the estimation of future biomass availability.

The *"Tank to Wheels" Working Group* was coordinated by EUCAR/JRC. EUCAR supplied the vehicle data, the engines energy efficiency maps and adaptation procedures. The simulation code adaptation (ADVISOR) and the simulated fuels-vehicle assessments were contracted to the Institut Français du Pétrole (IFP). JRC contributed to the initial ADVISOR code assessment and its adaptation to European market conditions.

The *Integration Group* was chaired by JRC and supervised by a Scientific Advisory Board representing the three partners.

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[1] E^2 database by LBST

[2] GM Well-to-Wheels Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuels/Vehicles Systems. A European study. LBST, September 2002.

[3] Transport Energy Strategy Partnership

2   Scope and methodology

The **Well to Tank (WTT)** evaluation accounts for the energy expended and the associated GHG emitted in the steps required to deliver the finished fuel into the on-board tank of a vehicle. It also considers the potential availability of the fuels, through their individual pathways and the associated production costs.

The **Tank to Wheels (TTW)** evaluation accounts for the energy expended and the associated GHG emitted by the vehicle/fuel combinations. It also includes an assessment of the expected relative retail prices of the various vehicle configurations.

The related methodologies and findings are fully documented and discussed in the companion "Well-to-Tank" and "Tank-to-Wheels" reports. The main assumptions are summarised in *sections 2 and 3* of this report respectively.

This report describes the **Well to Wheels (WTW)** integration for the fuel/vehicle combinations considered, including:
- An overall assessment of the energy required and the GHG emitted per unit distance covered,
- An estimate of the costs associated with each pathway and the resulting costs of fuel substitution and of CO_2 avoidance,
- A discussion of practicality, potential and availability for the main alternative fuels and specifically for biomass-related fuels,
- Considerations of alternative (outside the road transport sector) and optimum use of limited energy resources.

Sections 3 to 6 cover the different fuel/vehicle groups from conventional fuels and powertrains to hydrogen fuel cells. *Section 7* is dedicated to CO_2 capture and storage. *Section 8* gives an overview of the costs of substitution and CO_2 avoidance and of the potential availability of alternative fuels. *Section 9* covers alternative uses of energy resources.

The evaluation of individual pathways calls for sound comparison of the various options from a variety of angles. We have endeavoured to shed some light on this by answering the questions:
- What are the alternative pathways to produce a certain fuel and which of these hold the best prospects?
- What are the alternative uses for a given primary energy resource and how can it be best used?

Our aim has been to evaluate the impact of fuel and/or powertrain substitution in Europe on global energy usage and GHG emissions balance, i.e. taking into account induced changes in the rest of the world..

Throughout this study we have endeavoured to remain as neutral and objective as possible. In any such study, however, many choices have to be made at every step. These cannot always be based purely on scientific and technical arguments and inevitably carry an element of personal preference. While we do not pretend to have escaped this fact, we have endeavoured to make our choices and decisions as transparent as possible.

Among the data that were available we chose what we judged to be the most appropriate sources. Some of the selected assumptions, such as the set of minimum driving performance criteria, are real and tangible. Others, relating to emerging technologies, extrapolated to 2010 and beyond, are closer to expectations than assumptions. The choices made are referenced, justified and documented. The

details of the calculations have been to the largest possible extent included in the appropriate appendices to allow the reader to access not only the results but also the basic data and the main calculation assumptions.

Data sources are referenced in the WTT and TTW reports but are, as a rule, not repeated in this WTW integration document.

In such a study, there are many sources of uncertainty. A large part of the data pertains to systems or devices that do not yet exist or are only partly tested. Future performance figures are expectations rather than firm figures. In each step of a pathway there are usually several options available. The main options have been singled out by defining a separate pathway but this has practical limits and is therefore another important source of variability. The variability ranges selected are identified in the respective WTT and TTW sections and as much as possible justified.

As an energy carrier, a fuel must originate from a form of primary energy, which can be either contained in a fossil feedstock or fissile material, or directly extracted from solar energy (biomass or wind power). Generally a given fuel can be produced from a number of different primary energy sources. In this study, we have included all fuels and primary energy sources that appear relevant for the foreseeable future. The number of conceivable fuels and fuel production routes is very large. We have tried to be as exhaustive as possible but, inevitably, certain combinations that we considered less relevant have been left out at this stage. The database is structured in such a way that new data from scientifically established changes, progress, or new applications can be easily taken into account in future updates. The following matrix summarises the main combinations that have been included.

Table 2-1 Primary energy resources and automotive fuels

Resource		Gasoline, Diesel, Naphtha (2010 quality)	CNG	LPG	Hydrogen (comp., liquid)	Synthetic diesel (Fischer-Tropsch)	DME	Ethanol	MT/ETBE	FAME/FAEE	HVO	Methanol	Electricity	Heat
Crude oil		X												X
Coal					X[1]	X[1]	X					X	X	
Natural gas	Piped		X		X[1]	X	X					X	X	X
	Remote		X[1]		X	X[1]	X[1]		X			X	X	X
LPG	Remote[3]			X					X					
Biomass	Sugar beet							X						
	Wheat							X	X					
	Wheat straw							X						
	Sugar cane							X						
	Rapeseed									X	X			
	Sunflower									X	X			
	Soy beans									X				
	Palm fruit									X	X			
	Woody waste				X	X	X	X				X		X
	Farmed wood				X	X	X	X				X	X	X
	Organic waste		X[2]										X	X
	Black liquor				X	X	X					X	X	
Wind													X	X
Nuclear													X	X
Electricity					X									

[1] with/without CCS
[2] Biogas
[3] Associated with natural gas production

A common vehicle platform representing the most widespread European segment of passenger vehicles (compact 5-seater European sedan) was used in combination with a number of powertrain options shown in *Table 2-2* below. ADVISOR, an open source vehicle simulation tool developed by the US-based National Renewable Energy Laboratory (NREL), was used and adapted to European conditions.

Key to the methodology was the requirement for all configurations to comply with a set of minimum performance criteria relevant to European customers while retaining similar characteristics of comfort, driveability and interior space. Also the appropriate technologies (engine, powertrain and after-treatment) required to comply with regulated pollutant emission regulations in force at the relevant date were assumed to be installed. Finally fuel consumptions and GHG emissions were evaluated on the basis of the current European type-approval cycle (NEDC).

It is important to recognise that:
- The model vehicle is merely a comparison tool and is not deemed to represent the European average, a/o in terms of fuel consumption
- The results relate to compact passenger car applications, and should not be generalized to other segments such as Heavy Duty or SUVs.
- No assumptions or forecasts were made regarding the potential of each fuel/powertrain combination to penetrate the markets in the future. In the same way, no consideration was given to availability, market share and customer acceptance.

Table 2-2 Automotive fuels and powertrains

Powertrains	PISI	DISI	DICI	Hybrid PISI	Hybrid DISI	Hybrid DICI	FC	Hybrid FC	Ref. + hyb. FC
Fuels									
Gasoline	2002 2010+	2002 2010+		2010+	2010+				2010+
Diesel fuel			2002 2010+			2010+			2010+
LPG	2002 2010+								
CNG Bi-Fuel	2002 2010+								
CNG (dedicated)	2002 2010+			2010+					
Diesel/Bio-diesel blend 95/5			2002 2010+			2010+			
Gasoline/Ethanol blend 95/5	2002 2010+	2002 2010+			2010+				
Bio-diesel			2002 2010+			2002 2010+			
DME			2002 2010+			2010+			
Synthetic diesel fuel			2002 2010+			2010+			
Methanol									2010+
Naphtha									2010+
Compressed hydrogen	2010+			2010+			2010+	2010+	
Liquid hydrogen	2010+			2010+			2010+	2010+	

PISI: Port Injection Spark Ignition

DISI: Direct Injection Spark Ignition

DICI: Direct Injection Compression Ignition

FC: Fuel cell

2.1 WTT approach

This part of the study describes the process of producing, transporting, manufacturing and distributing a number of fuels suitable for road transport powertrains. It covers all steps from extracting, capturing or growing the primary energy carrier to refuelling the vehicles with the finished fuel. All details of

assumptions and calculations are available in the *WTT report* and its appendices. We briefly discuss below some basic choices that have been made and that have a material impact on the results.

2.1.1 Pathways and processes

Our primary focus has been to establish the energy and greenhouse gas (GHG) balance for the different routes. The methodology used is based on the description of individual processes, which are discreet steps in a total pathway, and thereby easily allows the addition of further combinations, should they be regarded as relevant in the future.

2.1.2 Costing basis

Cost data as published in version 2b are considered obsolete and have not been updated in this version.

2.1.3 Incremental approach

The ultimate purpose of this study is to guide those who have to make a judgement on the potential benefits of substituting conventional fuels by alternatives. It is clear that these benefits depend on the *incremental* resources required for alternative fuels and the *incremental* savings from conventional fuels saved.

In order to estimate the implications of replacing conventional fossil transport fuels with a certain alternative fuel (one at a time) in terms of energy use, GHG emissions and cost, we calculated the *difference* between two realistic future scenarios: one in which the alternative fuel was introduced or expanded and one "business as usual" reference scenario which assumed that demand was met by the forecast mix of conventional fossil fuels in 2010-2020. The transport demand (number of km driven) and all other factors remained the same in both scenarios. We then derived metrics such as the conventional replacement cost per km or per tonne conventional fuel, the GHG savings per km or per tonne and (by combining these) the GHG mitigation cost.

At the 2010-2020 horizon substitution is only plausible up to a limited level, say up to a maximum of 10-15% depending on the option considered. The incremental energy, GHG emissions and costs estimated through the above process must also be consistent with this level of substitution.

In order to estimate the savings from conventional fuels the question to consider was what could be saved by using less of these rather than how much they cost in absolute terms. We thus considered that the energy and GHG emissions associated with production and use of conventional fuels pertained to the marginal rather than the average volumes. Marginal production figures representative of the European situation were obtained through modelling of the EU-wide refining system (see figure below and more details in *WTT Appendix 3*).

Figure 2.1.3   Impact of a marginal reduction of conventional gasoline demand

"Business-as-usual" scenario
Meeting 100% of future demand

Alternative scenario
Marginal reduction of gasoline production

❑ Other product volumes unchanged
❑ Change in energy, GHG, crude intake
    "charged" to decremental gasoline
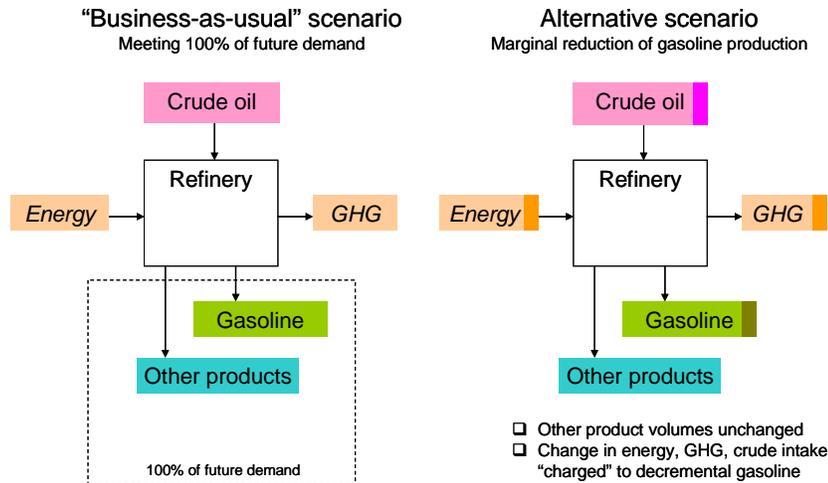
Distribution energy was taken as proportional to volumes. In monetary terms, however, most of the infrastructural costs attached to production and distribution of conventional fuels would not be significantly affected by a limited substitution, particularly as distribution of alternative fuels would rely on the existing network. Therefore only variable distribution costs were taken into account.

Within the scope of substitution mentioned above and the timeframe considered, production costs of alternative fuels could reasonably be taken as proportional to volumes. Infrastructure costs, which are significant for fuels that are not fungible with conventional ones (e.g. gaseous fuels), critically depend on the scale envisaged. In order to compare the various options on an equal footing we developed, for the most significant fuel options, a production and distribution cost scenario based on satisfying 5% of the future passenger car transport demand.

2.1.4 By-product credits

Many processes produce not only the desired product but also other streams or "by-products". This is the case for biofuels from traditional crops such as bio-diesel from rapeseed. In line with the philosophy described above we endeavoured to represent the "incremental" impact of these by-products. This implies that the reference scenario must include either an existing process to generate the same quantity of by-product as the alternative-fuel scenario, or another product which the by-product would realistically replace.

The implication of this logic is the following methodology (*Figure 2.1.4*):
- All energy and emissions generated by the process are allocated to the main or desired product of that process.
- The by-product generates an energy and emission credit equal to the energy and emissions saved by not producing the material that the co-product is most likely to displace.

For example, in the production of bio-diesel from oil seeds, protein-rich material from e.g. oil seeds pressing are likely to be used as animal fodder displacing soy meal.

We strongly favour this "substitution" method which attempts to model reality by tracking the likely fate of by-products. Many other studies have used "allocation" methods whereby energy and emissions from a process are arbitrarily allocated to the various products according to e.g. mass, energy content, "exergy" content or monetary value. Although such allocation methods have the attraction of being simpler to implement they have no logical or physical basis. It is clear that any benefit from a by-

product must *depend on what the by-product substitutes:* all allocation methods take no account of this, and so are likely to give flawed results.

Figure 2.1.4   By-product credit methodology
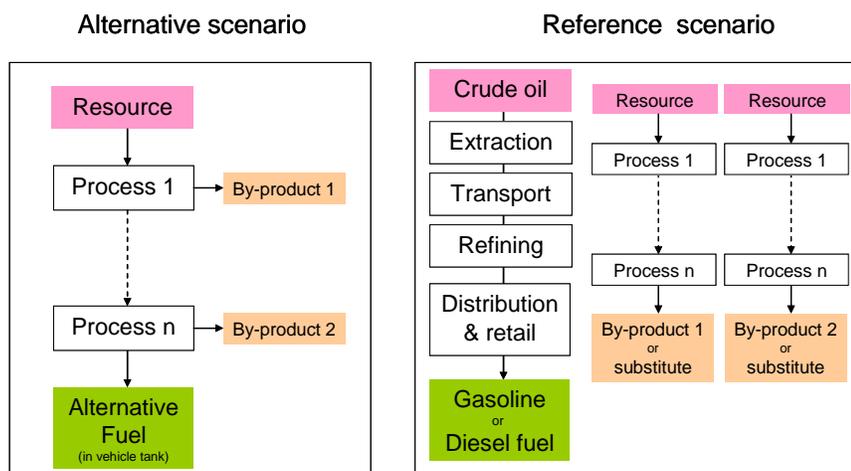
In most cases, by-products can conceivably be used in a variety of ways and we have included the more plausible ones. Different routes can have very different implications in terms of energy, GHG or cost and it must be realised that economics rather than energy use or GHG balance, are likely to dictate which routes are the most popular in real life.

2.1.5 Scale and availability

The scale at which a route might be developed is relevant to the selection of appropriate energy data but also to the attention that should be given to a particular option. Particularly for biofuels, scale issues can be important. A certain amount of biofuel can be produced in Europe, but if additional amounts are needed import pathways will need to be considered with potentially different GHG and energy balances.

The issue of availability is being widely debated in Europe and addressed by others. This section has not been updated in this version of our study. Considerations published in version 2b are still available for reference in *section 5 of the WTT report.*

2.1.6 Other factors of importance for biofuels

Biofuels present particular challenges to produce reliable GHG and energy balances, because the agricultural part of the equation is complex. In addition to the impact of fossil energy used in producing and processing the crop, GHG emissions are emitted over the growing period as nitrous oxide (N_2O), a gas with 296 times the greenhouse-gas potency of CO_2, as nitrogen from fertiliser and natural sources is broken down in the soil. N_2O emissions depend on soil type, fertiliser addition, the type of crop and also the weather, so they are difficult to estimate with accuracy. To determine the effect of growing the biofuel crop, we must also consider to what use the land would have been otherwise put – the emissions attributed to the biofuel are the difference between the two crops. Over a longer time period, carbon can be sequestered or released from the soil as CO_2, so converting, for example, pasture land to arable land for biofuels would add significantly to GHG emissions over a period of decades. In this study, we model only biofuels produced from land already under arable cultivation. These issues are discussed in *WTT Report Section 3.4.1.*

2.1.7 Data sources

The collaboration with LBST allowed us access to the comprehensive database compiled by the TES consortium and in the course of the study carried out by General Motors et al. in 2001-2002. With the

agreement of these two organisations we have used the information extensively. Over the years the existing data has been extensively reviewed and updated, and a number of new processes and a number of new pathways not hitherto considered have been added.

2.2 TTW approach

This part of the study accounts for the energy expended and the associated GHG emitted by the vehicle/fuel combinations in the reference NEDC driving cycle.

2.2.1 Vehicle data and performance

All simulations were based on a common model vehicle, representing a typical European compact size 5-seater sedan, comparable to e.g. a VW Golf (see reference vehicle characteristics in the *TTW report*). This model vehicle was used as a comparison tool for the various fuels and associated technologies. The fuel consumption figures are not deemed to be representative of the average European fleet. All required data for the baseline PISI gasoline model vehicle were collected from EUCAR member companies

In order to obtain a valid comparison between the various powertrain/fuel combinations, it was deemed essential that they should all comply with a minimum <u>set of performance criteria</u>, given in the following table.

Table 2.2.1   Minimum vehicle performance criteria

		Target
Time lag for 0-50 km/h	s	*<4*
Time lag for 0-100 km/h	s	*<13*
Time lag for 80-120 km/h in 4th gear	s	*<13*
Gradeability at 1 km/h	%	*>30*
Top speed	km/h	*>180*
Acceleration	m/s^2	*>4.0*
Range$^{(1)}$	km	*>600*

$^{(1)}$ *Where applicable 20 km ZEV range*

Technologies (engine, powertrain and after-treatment) required to comply with regulated pollutant emission regulations were assumed to be installed i.e.
- EURO 3 for 2002 vehicles,
- EURO 4 for 2010+ vehicles.

Powertrain configurations and components were selected accordingly. Compliance with EURO 5 and EURO 6 emissions standards, as mandated in EC Regulation No 715/2007 of 20 June 2007[4], is not yet included in the current revision of the WTW. The vehicle configurations required to achieve these performance criteria are detailed in the *TTW report*.

2.2.2 Vehicle simulations

ADVISOR, the open source vehicle simulation tool developed by the US-based National Renewable Energy Laboratory (NREL) was used and adapted to European conditions to comply with the study requirements. Conventional powertrains and fuels were simulated for the 2002 reference baseline. The 2010+ performance were derived by establishing percentage improvement over the 2002 level. 2010+ hybrids, fuel-cells and hydrogen applications were simulated directly.

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[4] See http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:171:0001:0016:EN:PDF

Simulations were carried out for each neat fuel separately (Gasoline, Diesel, CNG, LPG and hydrogen). For alternatives to gasoline (ethanol, MTBE/ETBE) and diesel (bio-diesel, synthetic diesel, DME) it was assumed that, whether used neat or in blends, the fuel consumption on energy basis would remain the same as for the base fuel. In other words these **alternatives fuels were deemed not to have any effect positive or negative on the energy efficiency of the engine**. The corresponding GHG emissions were then calculated from the compositional data.

The ADVISOR simulation model was adapted to the NEDC cycle. The main modifications were corrections to gear changes during the cycle, fuel cut-off during deceleration, and the energy management strategies for the hybrid and fuel cell vehicles.

The ADVISOR version we used presents some limitations to simulate transients. On the NEDC cycle (see *section 3.3* below), this is not limiting the comparative nature of the exercise. This was confirmed by a cross-check performed between measured results on a roller test bench and simulated results on ADVISOR, applied to the reference vehicle (Gasoline PISI 2002): the verification showed similar results. Furthermore, the validity of the simulation tool was checked against in-house simulation codes of a number of European manufacturers, showing comparable results.

The main vehicle simulation results delivered by ADVISOR are:
- **Fuel energy (MJ/km)** necessary to perform the NEDC cycle
- **GHG (g CO_{2eq}/km)** emitted during the cycle.

Note: total GHG emissions expressed in CO_{2eq} take N_2O and methane emissions into account, through estimates of their emissions, and using the appropriate IPCC factors (for details refer to the *TTW report section 3.2*).

A separate assessment of externally chargeable electric vehicles is presented in *WTW Appendix 2.*

2.2.3 Reference road cycle

The standard regulatory NEDC road driving cycle, as applied for measuring today's passenger car emissions and fuel consumption in Europe, was used for simulating the TTW emissions.

Figure 2.2.3   Reference NEDC driving cycle
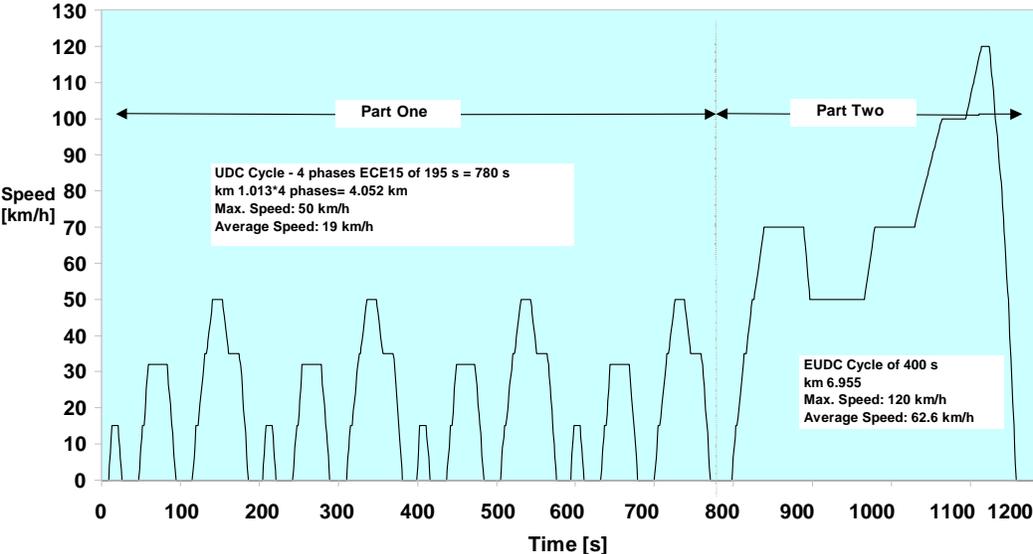
Cold start, as required by the standard certification tests, was included in the calculations. Experimental data from Volkswagen for a Golf with a PISI 1.6l engine were used to cross-check the simulation figures. Results were in close agreement: the simulated fuel consumption was 6.95 l/100 km, which is close to the measured result 7.0 l/100 km.

2.3 WTW integration

The results of the WTW integration are presented in the following sections. *Section 3 to 6* introduces the fuels, the characteristics of the relevant vehicles and presents the energy and GHG balances for the various pathways. *Section 7* deals with the cost aspects while potential fuel availability issues are discussed in *section 8*. Finally *section 9* briefly discusses the issue of optimum use of energy resources.

The WTW energy and GHG figures combine
  - The WTT **expended** energy (i.e. excluding the energy content of the fuel itself) per unit energy content of the fuel (LHV basis),
  - With the TTW energy consumed by the vehicle per unit of distance covered (on the NEDC cycle).

The energy figures are generally presented as **total** primary energy expended, regardless of its origin, to move the vehicle over 1 km on the NEDC cycle. These figures include both fossil and renewable energy. As such they describe the energy efficiency of the pathway.

Total WTW energy (MJ/100 km) = TTW energy (MJ_f/100 km) x (1 + WTT total expended energy (MJ_{xt}/MJ_f))

For fuels of renewable origin we have also evaluated the fossil energy expended in the pathway, illustrating the fossil energy saving potential of that pathway compared to conventional alternatives.

Fossil WTW energy (MJ_{fo}/100 km) = TTW energy (MJ_f/100 km) x (λ + WTT fossil expended energy (MJ_{xfo}/MJ_f))

λ = 1 for fossil fuels, 0 for renewable fuels
MJ_f refers to the energy contained in the fuel.
MJ_{xt} / MJ_{xfo} refer respectively to the total/fossil additional external energy needed to produce 1 MJ of fuel from the primary energy resource.

GHG figures represent the total grams of CO_2 equivalent emitted in the process of delivering 100 km of vehicle motion on the NEDC cycle.

WTW GHG (g CO_{2eq}/km) = TTW GHG (g CO_{2eq}/km) + TTW energy (MJ_f/100 km)/100 x WTT GHG (g CO_{2eq}/ MJ_f)

The uncertainty ranges from WTT and TTW have been combined as variances i.e. as the square root of the sum of squares.

Results for all pathways considered in the study are summarised in *WTW Appendix 1*.

3 Conventional Fuels and Powertrains 2002/2010[+]

3.1 Conventional gasoline and diesel fuel

Conventional road fuels are widely expected to provide the bulk of road transportation needs for many years to come and certainly within the time horizon of this study. Consequently, ICE engines fuelled by gasoline or diesel fuel from crude oil represent the reference against which all the alternatives were assessed.

The energy and GHG savings related to the replacement of gasoline and diesel by alternative fuels pertain therefore to marginal production up to say 10-15% of the total road fuels demand. Over the study time period, non-conventional crude sources are not expected to impact the European market and Middle East crude remains the appropriate marginal energy supply (see *WTT report, section 3.1*).

3.2 Fuels/vehicles combinations

The vehicles and powertrains already available today were simulated on the basis of available "real" 2002 data. Fuels, engine maps and vehicle characteristics, were precisely defined, constructed from a combination of existing and validated data. The 2002 conventional vehicle results are therefore considered as the starting reference for comparison.

Diversification of fuels and powertrains is expected from 2010 and beyond. For conventional vehicles the 2010 options essentially represent advances in conventional technologies including hybrids.

Table 3.2-1   Simulated combinations for conventional vehicles and fuels

Powertrains	PISI	DISI	DICI	Hybrid PISI	Hybrid DISI	Hybrid DICI
Fuels						
Gasoline	2002 2010+	2002 2010+		2010+	2010+	
Diesel fuel			2002 2010+			2010+

Fuel efficiency is expected to improve significantly over time. Achievable improvements were discussed and estimated among the EUCAR members on the basis of expected technological progress (e.g. friction reduction, engine control, combustion improvements etc). The 2010 Diesel vehicles are considered with and without particulate filter (DPF). The expected fuel consumption reductions for the various technologies are presented in the table below.

Table 3. 2-2   2002-2010 fuel efficiency improvements

Gasoline		LPG	Diesel	
PISI	DISI	PISI Bi-fuel	DICI no DPF[(1)]	DICI with DPF[(1)]
15%	10%	15%	12%	9.5%

For SI engines, the main contribution to fuel efficiency improvement comes from downsizing (minus 20%[5]) associated with supercharging. This contribution is reduced for DI engines as the "no-throttling" benefit is already included in the current 2002 engines.

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[5] The displacement of the gasoline engine was reduced from 1.6 litre down to 1.3 litre, the full torque being restored by a turbo charging at 1.2 : 1

Diesel engines are already non-throttled and turbo-charged in 2002, so that no additional benefits are expected through the "downsizing" route. Only standard technology improvement is accounted for (e.g. friction). The DPF option is assigned a fuel penalty of about 2.5% for the regeneration of the filter (reduced from 4% assumed in the first version of this study).

For hybrids, the additional fuel economy is a function of the 'hybrid control strategy' and of the power/mass ratio of the electric motor. The electric motor provides a high torque, available immediately upon start up and over a wide range of rotation speed. As a result, hybrid configurations deliver good acceleration performance, even though they tend to be heavier then conventional ones.

The hybrid configuration considered in the study is based on the following requirements:
- Capacity to run 20 km as ZEV on the battery,
- Top speed achieved without electrical assistance,
- Acceleration criteria achieved without electric motor peak power (for safety reasons).

Within these constraints the vehicle parameters have been set in order to obtain the best compromise between fuel economy and vehicle performance.

Hybrid configurations will benefit from all of the improvements applicable to conventional configurations for 2010+. In addition, it was considered that the hybrid architecture would allow further improvements from the 2002 engine efficiency maps, as shown in the following table.

Table 3.2-3   Additional fuel efficiency improvements for hybrids from 2002 engine maps

Gasoline	Diesel	
DISI	DICI no DPF[1]	DICI with DPF[1]
3%	3%	0.5%

[1] Diesel Particulate Filter

Although the large variety of vehicle hybridization options has not been investigated in the present version, the *TTW report* (*section 5.2.5*) includes a discussion of the upside potential of hybrids for higher fuel economy of about 6%. This potential has been represented by an increase of the uncertainty range towards higher efficiency.

3.3 Energy and GHG balances

The aggregated WTT and TTW energy and GHG figures for the 2002 and 2010 vehicles (including hybrids) are shown on the figure below. The WTT energy and GHG figures for conventional fuels are relatively low, so that the ranking of the different options is overwhelmingly determined by the performance of the powertrain.

As a result of the relative imbalance between gasoline and diesel fuel demand in Europe, the production of marginal diesel fuel is more energy-intensive than that of gasoline. On a WTW basis the impact is modest and more than compensated by the superior efficiency of the Diesel CIDI engine compared to the gasoline PISI. Over the NEDC cycle, the gasoline DISI engine has a lower fuel consumption than the PISI, due to its capacity to run in lean-burn mode.

The 2010 figures result from the relative fuel efficiency improvements indicated in *Table 3.2-2*. By then, gasoline PISI and DISI are predicted to come much closer together, PISI technologies taking a higher benefit from Downsizing /Turbo-charging applications.

PISI/DISI technologies are also closer to diesel, particularly when the latter is penalised by the addition of a DPF.

Figure 3.3-1a/b *WTW energy requirement and GHG emissions for conventional fuels ICE and hybrid powertrains*
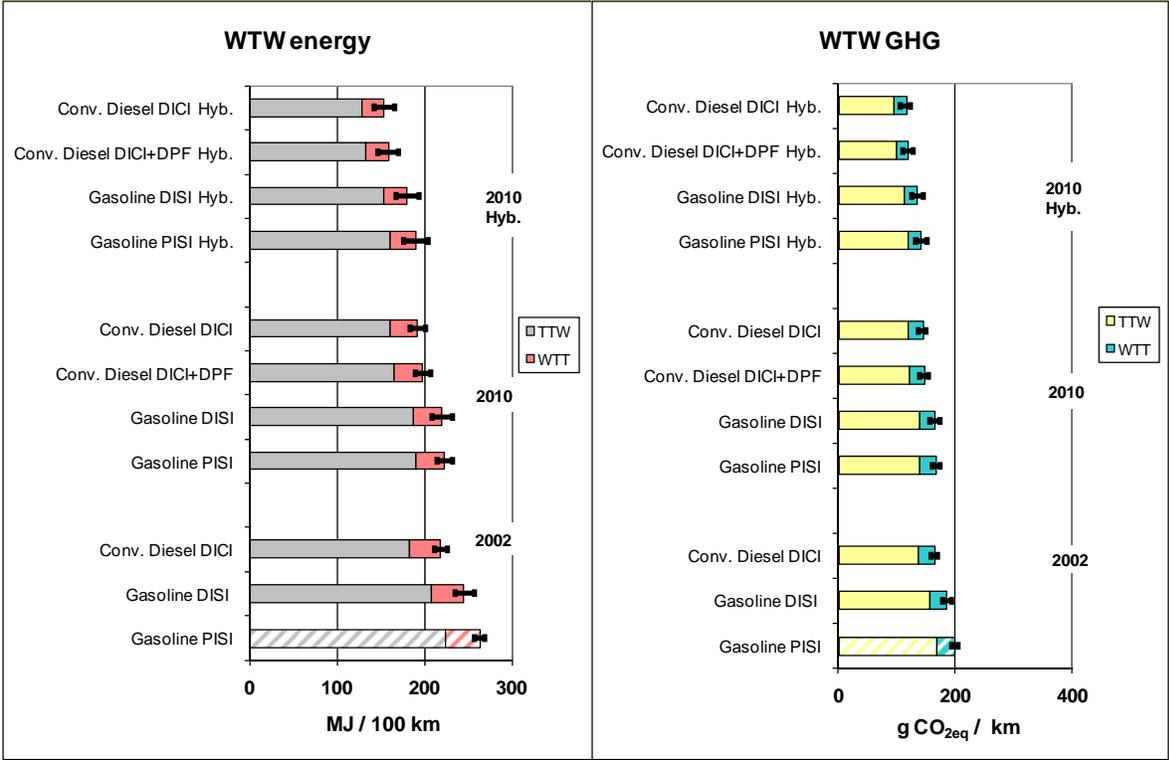
Figure 3.3-2 clearly illustrates the potential for improvement of conventional engines and fuels.

Figure 3.3-2 *WTW energy requirement and GHG emissions for conventional fuels ICE and hybrid powertrains*
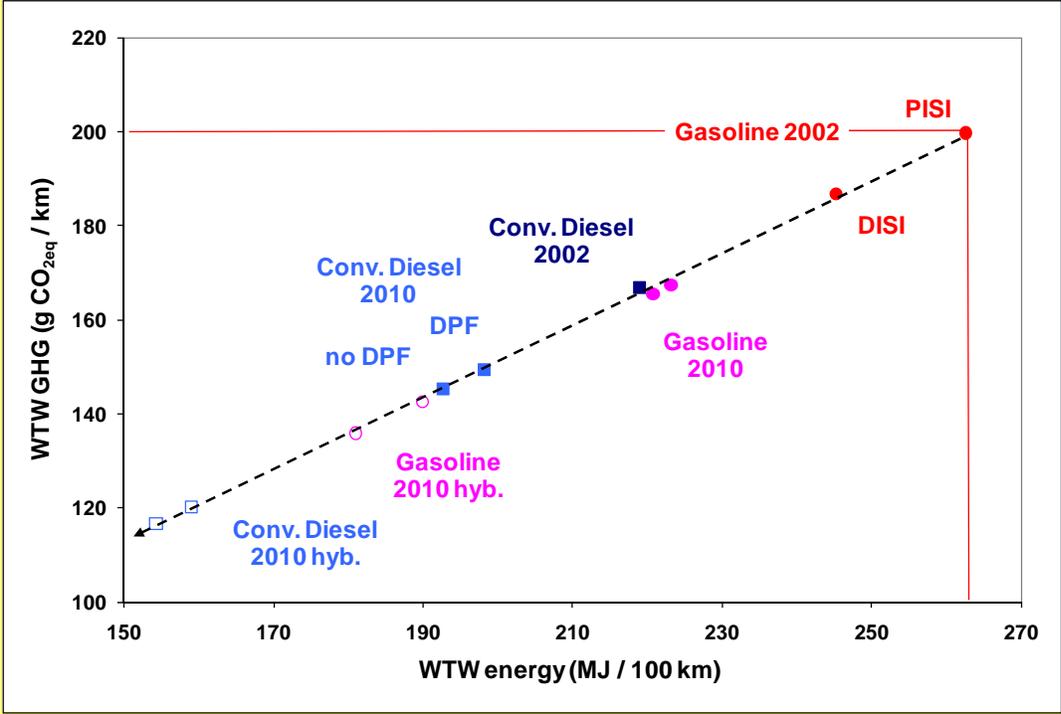
The efficiency gap between SI and CI vehicles is narrowing

The hybridization option investigated brings an additional energy reduction of about 15% for gasoline and 18% for diesel. Further optimisation of hybrid configurations may bring additional savings.

Developments in engine efficiency and vehicle technology options including hybrids will continue to contribute to CO_2 emissions reductions through reduced fuel consumption

4 Compressed Natural Gas (CNG), biogas (CBG), LPG

4.1 CNG production and availability

4.1.1 Natural gas sourcing

Natural gas is widely available in Europe, distributed through a dense network of pipelines to industrial, commercial and domestic consumers. The European production (mainly from the UK, the Netherlands and Norway) is complemented by sizeable imports from Algeria and mainly Russia. Demand is expected to grow strongly mainly to feed the increasing demand for electricity, particularly in view of the coal and nuclear phase-out in some countries.

World natural gas reserves are very large but European production is set to decline during the coming decade so that the share of imports in the European supply will steadily increase. Russia, other countries of the FSU and the Middle East are the most credible long-term major supply sources for Europe.

Additional natural gas for road transport would have to be sourced from marginal supplies. We have considered three sourcing scenarios:
- 7000 km pipeline (typically from western Siberia),
- 4000 km pipeline (typically from south-west Asia),
- LNG shipping over a distance of about 10,000 km (typically the Middle East[6]).

These future marginal gas supplies to Europe are far away and the associated transport energy represents an important fraction of the total energy and GHG balance of CNG.

On the other hand volumes that can reasonably be expected to find their way into road fuels within the timeframe of this study would only represent a small fraction of the total European natural gas consumption (a 5% share of the 2020 European road fuels market would represent about 2.5% extra gas demand) and would not require extensive addition to the gas distribution network (but will of course require refuelling equipment).

4.1.2 Distribution and refuelling infrastructure

Like all gaseous fuels, CNG requires a dedicated infrastructure for distribution and refuelling. The natural gas grid, developed in most areas of Europe to serve domestic, commercial and industrial customers can be used for supplying natural gas to refuelling stations. For a road fuel market penetration up to the 10% mark, it is generally accepted that sufficient capacity would be available in the existing grid. Some areas of Europe are not served by the grid and it is unlikely that transport demand alone would justify extensive additions to the existing networks. For such areas LNG, distributed by road and vaporised at the refuelling station, may be an option.

Infrastructure issues and costs are essentially related to refuelling stations. Assuming the existing conventional fuels sites are used, the investment and operating costs would be mostly associated with storage, compression and refuelling hardware. The safety issues related to the widespread use of a flammable gas at high pressure are real but well understood for CNG and not considered as a significant barrier to introduction.

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[6] Shipping distance between the Arabian gulf and Western European ports via the Suez canal

4.2 CNG vehicles

CNG vehicles have been in use for many years in Europe and in the rest of the world. The very limited refuelling infrastructure and the additional cost of the equipment required for the vehicle have so far limited their development to fleet vehicles or geographic niches, generally supported by a favourable tax regime for the fuel and/or the vehicles. In order to represent the real commercial options existing in 2002, a bi-fuel (gasoline-NG) and a dedicated vehicle were simulated.

4.2.1 2002 Bi-fuel and dedicated CNG vehicles

Bi-Fuel adapted vehicle

In such a vehicle, an additional CNG fuel system is fitted to the original gasoline engine. An additional CNG tank is also added, while the gasoline tank capacity is reduced.

No specific engine optimisation is possible, as gasoline operation must be preserved. As a consequence, the torque curve is shifted down by 12% over the engine speed range when operating on CNG. Top speed is not affected but the acceleration capability is slightly below target. As the performance criteria are met in gasoline mode this was considered acceptable.

Dedicated engine vehicle

This engine is based on the same level of technology as the gasoline engine (this is an area where we significantly differ from the GM study where only a downsized turbo-charged CNG engine was considered).

In this single fuel engine, the compression ratio can be optimised to get the benefit from the highest "knock resistance" (octane number) of natural gas. The CNG engine compression ratio was raised from 9.5:1 to 12.5:1 for an energy efficiency increase of 9% over the gasoline reference.

In order to fulfil all performance criteria and particularly acceleration a higher torque is required. This was achieved by increasing the engine displacement. In the second version of the study a somewhat more favourable CNG engine map was used (see *TTW report, section 4.1.3* for a detailed discussion). As a result the engine displacement increase could be limited to 0.3 litres (from 1.6 to 1.9 litres) compared to 0.4 litres in the previous version. This, together with the larger and heavier CNG tank accounts for a significant overweight compared to the base gasoline vehicle. The resulting fuel consumption penalty nearly compensates the advantage gained from optimisation so that the dedicated vehicle has only a slight advantage over the bi-fuel configuration in this respect.

Table 4.2-1   Characteristics of 2002 CNG vehicles

		PISI		
		Gasoline	CNG bi-fuel	CNG
Powertrain				
Displacement	l	1.6	1.6	1.9
Powertrain	kW	77	77/68	85
Engine mass	kg	120	120	150
Gearbox mass	kg	50	50	50
Storage System				
Tank pressure	MPa	0.1	25	25
Tank net capacity	kg	31.5	14/17.5	30
Tank mass empty	kg	15	12/61	103
Tank mass increase including 90% fuel	kg	0	59	87
Vehicle				
Reference mass	kg	1181	1181	1181
Vehicle mass	kg	1181	1240	1298
Cycle test mass	kg	1250	1360	1360
Performance mass	kg	1321	1380	1438

4.2.2 2010 improvements expected from CNG engines

Being spark ignited, CNG engines are expected to enjoy the same 15% fuel efficiency improvement as their gasoline homologues through downsizing and turbo-charging. An additional 1% improvement is thought to be achievable, due to the mixing ability of the gaseous fuel with air, allowing optimal aero-kinetics. The total improvement beyond 2010 was estimated at 16% compared to 2002.

4.2.3 2010 hybrids

For CNG hybrids, only the dedicated engine was considered. The availability of the electric motor allows the acceleration criteria to be met with the original 1.6 l engine displacement. As a result hybridisation is particularly beneficial to CNG with a potential improvement of 24% over the conventional 2010 PISI.

4.3   CNG pathways energy and GHG balances

The fuel economy performance of dedicated CNG vehicles compared to conventional ones is illustrated in *Figure 4.3-1* which also shows the changes from the first version of this study. Note that the 2002 dedicated vehicle is shown here for comparison but does not correspond to a real option today.

Figure 4.3-1   TTW fuel consumption for conventional and CNG vehicles
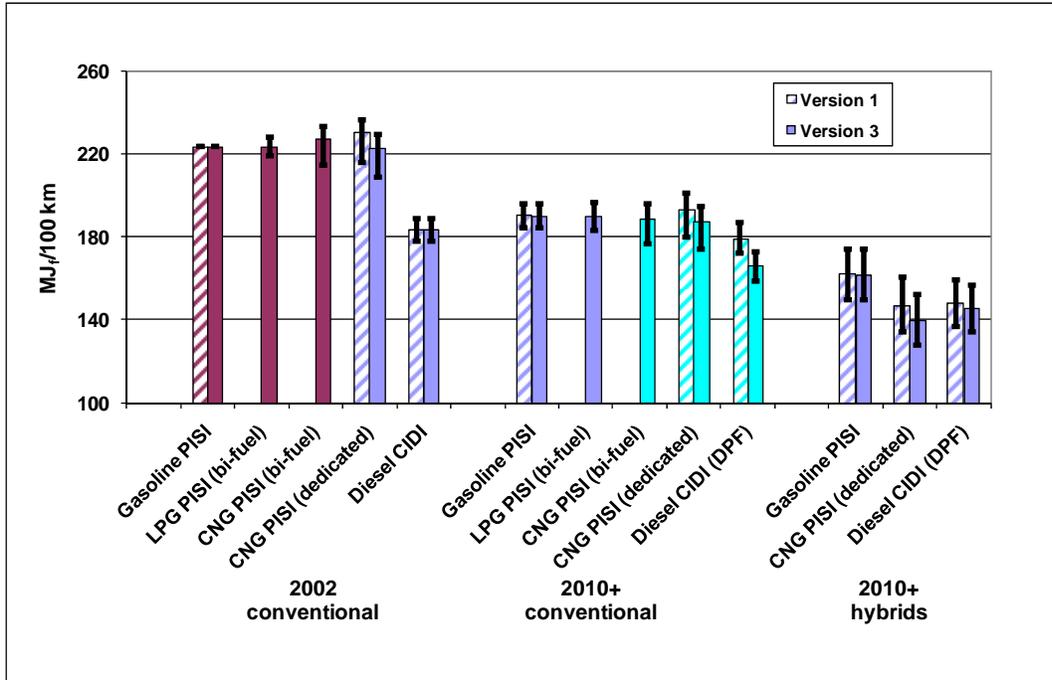
CNG vehicles are currently slightly less efficient than equivalent gasoline vehicles while diesel vehicles enjoy a net advantage. In the future, however, improvements in spark ignition engines will bring all technologies much closer together. Specific improvements in CNG engines will improve CNG beyond gasoline and bring it close to diesel. Hydridisation would be particularly favourable to CNG as it would resolve the issue of acceleration performance without having to revert to a larger engine, thereby delivering the full benefit of CNG's higher octane rating and associated higher compression ratio (see above, *section 4.2.1*).

Figure 4.3-2 shows the WTW figures, combining the impacts of vehicle technology and of the gas production route, particularly transport distance. The option of piped gas over 7000 km comes close to LNG and we have therefore not included it in these graphs for clarity. The higher hydrogen to carbon ratio gives natural gas an advantage over crude-based fuels in GHG terms but, on a WTW basis, this is compensated by extra energy requirement for fuel provision and somewhat lower vehicle fuel efficiency.

Figure 4.3-2a/b WTW energy requirement and GHG emissions for conventional and CNG pathways
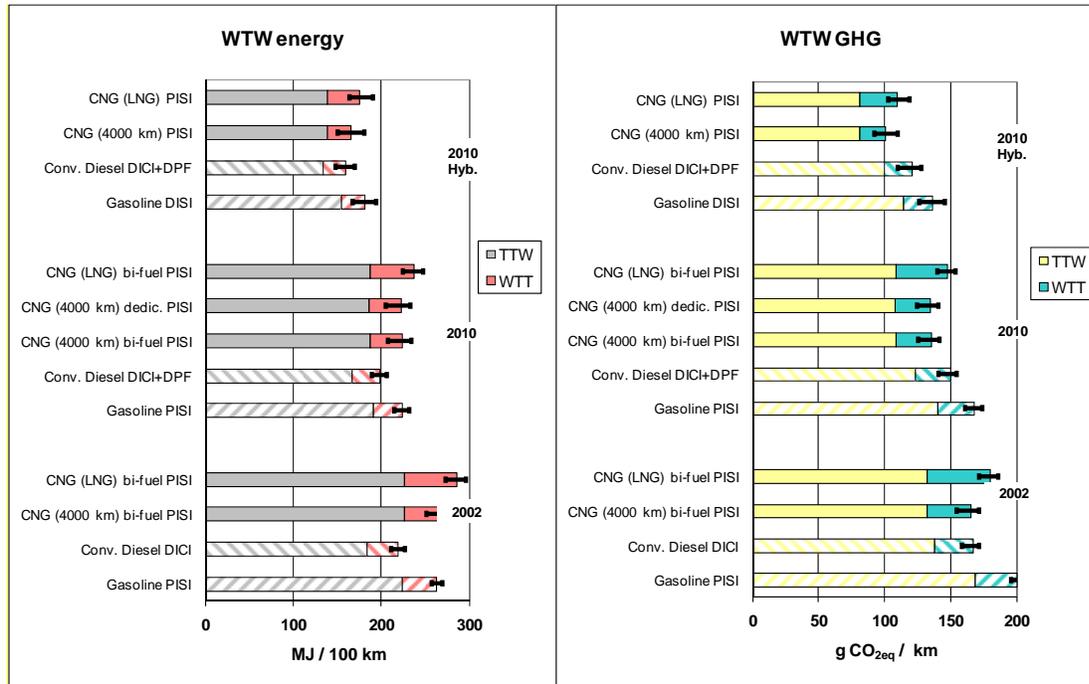
In the 2002 configurations the only available CNG vehicles are bi-fuel. These configurations are more energy intensive than both gasoline and diesel and between gasoline and diesel in GHG terms. By 2010 both bi-fuel and dedicated vehicles may become realistic options. The dedicated vehicle has a slight advantage over the bi-fuel version although it should be borne in mind that our bi-fuel configuration is a compromise and does not quite meet all performance criteria. The CNG engine efficiency improvement brings GHG emissions below those of diesel, although energy use is still higher. The effect is even stronger for hybrids as explained above.

Currently, the WTW GHG emissions for CNG lie between gasoline and diesel, approaching diesel in the best case.

Beyond 2010, greater engine efficiency gains are predicted for CNG vehicles, especially with hybridization:
o   *WTW GHG emissions becomes lower than those of diesel.*
o   *WTW energy use remains higher than for gasoline except in the case of hybrids for which it is lower than diesel.*

The gas transport distance and route is critical to the overall balance. The 4000 km pipeline route is considered as a reasonable representation of Europe's marginal supply for a number of years to come. Longer term, a larger share of LNG and possibly also longer pipeline routes can be expected. Pipeline technology is evolving and higher operating pressures are nowadays possible. This may result in new pipelines consuming less transport energy although other considerations such as initial pipeline costs, may limit this effect (see more details in *WTT report, section 3.2.2*).

The origin of the natural gas and the supply pathway are critical to the overall WTW energy and GHG balance.

4.4 Biogas

The anaerobic fermentation of organic matter produces a gaseous mixture, known as "biogas", consisting mainly of methane and CO_2. A suitable feedstock is biomass containing components such as carbohydrates (i.e. saccharides such as glucose), fatty acids and proteins. Anaerobic decomposition and formation of methane commonly occurs when manure, crop residues or municipal waste are

stockpiled or used as landfill, or when organic matter is immersed in water as occurs naturally in swamps, or is applied with liquid manure.

Although most biogas production installations have so far been at relatively small scale and geared to production of heat and power, concepts for larger plants have been developing with a view to produce a gas that can be used in combination with or as an alternative to natural gas as automotive fuel (Compressed Bio-Gas or CBG). This requires cleaning and upgrading of the gas to remove various impurities and the bulk of the CO_2. Some such plants already exist in Scandinavia.

We have considered five cases for upgraded biogas production. Three cases use waste material namely from municipal organic waste, dry manure and wet manure. In the last two cases it is assumed that farmed crops are used, namely wheat (as the whole plant) and a combination of corn and barley produced on the same land in a double cropping system. In all cases we have assumed that the upgraded gas joins an existing gas grid to reach the refuelling station.

The waste material used a feedstock is considered to be "GHG-free". Dedicated crops do carry a modest GHG footprint from farming activities (fossil carbon and N_2O emissions). In the production process, part of the biogas is used to fuel the process. As a result biogas has a generally favourable fossil energy and GHG emissions footprint. The total energy is relatively high but this is not very relevant for a process fuelled with a waste material that has no other uses. The overall GHG footprint is somewhat higher when dedicated crops are used. Biogas production occurs naturally with manure and particularly when diluted in water ("liquid" manure). Methane emissions can therefore be avoided by using that manure for dedicated biogas production. Note that the large resulting credit is the result of intensive livestock rearing rather than an intrinsic quality of biogas.

Figure 4.4a/b   WTW energy requirement and GHG emissions for biogas (as CBG) (2010+ vehicles, CBG vehicles as Bi-fuel PISI)
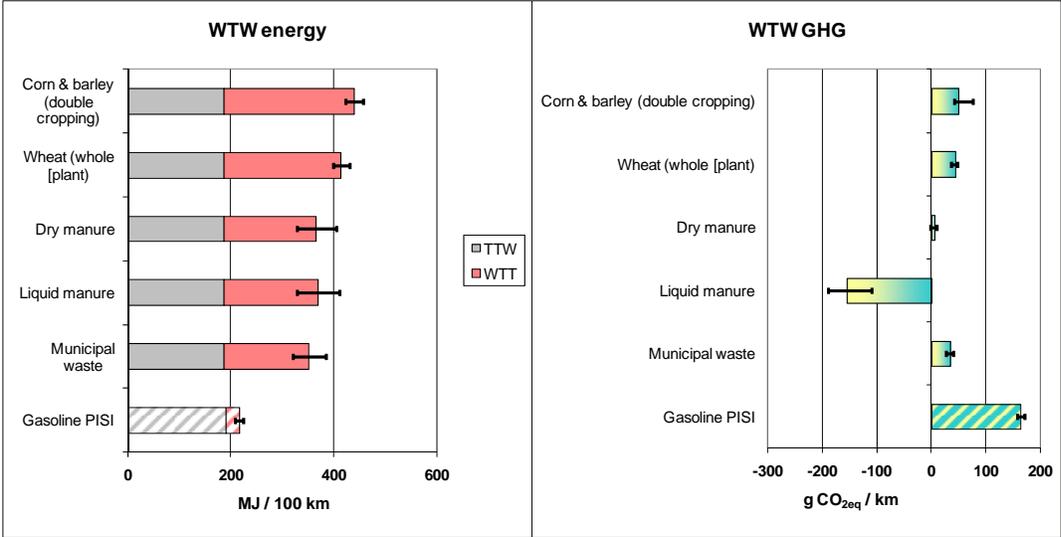
4.5 LPG

Liquefied Petroleum Gas (LPG) is a well-established niche automotive fuel in a number of EU countries. Although a large amount is produced by refineries, this production is entirely spoken for by existing markets such as domestic heating and cooking, various industrial applications and petrochemical feedstock. Indeed a large fraction of the LPG used in Europe today is imported, mostly originating from associated gases and liquids in crude oil and mainly natural gas production. The net effect of an increase in the use of LPG for automotive purposes would be to increase imports. Regardless of the physical source of supply, It is therefore the energy and GHG footprint of imported LPG that must be considered to gauge the impact on EU cost and global CO_2 emissions. We have therefore opted to represent the marginal case of LPG import into Europe from remote gas fields (Middle East).

The typical current LPG vehicle is bi-fuel (LPG/gasoline) PISI and this is not expected to change in the future. The engine efficiency remains the same on both fuels. Also we assumed liquid injection so that the torque characteristics and the associated acceleration performance remained the same. As a result the only change to the baseline gasoline PISI vehicle was the addition of an LPG tank, the extra mass being partly compensated by the smaller gasoline tank. Overall the mass increase was minimal and the same inertia class could be kept resulting in the same fuel economy for both vehicles.

The LPG WTW energy and GHG emissions balances are shown on the following figure, compared to the conventional and selected CNG figures. LPG's GHG emissions lie between diesel and CNG and energy between gasoline and diesel. Although not explicitly shown in the graph, transport distance has a significant impact, representing about 25% of the WTT energy in this case.

Figure 4.5a/b   WTW energy requirement and GHG emissions for LPG 2010+ vehicles
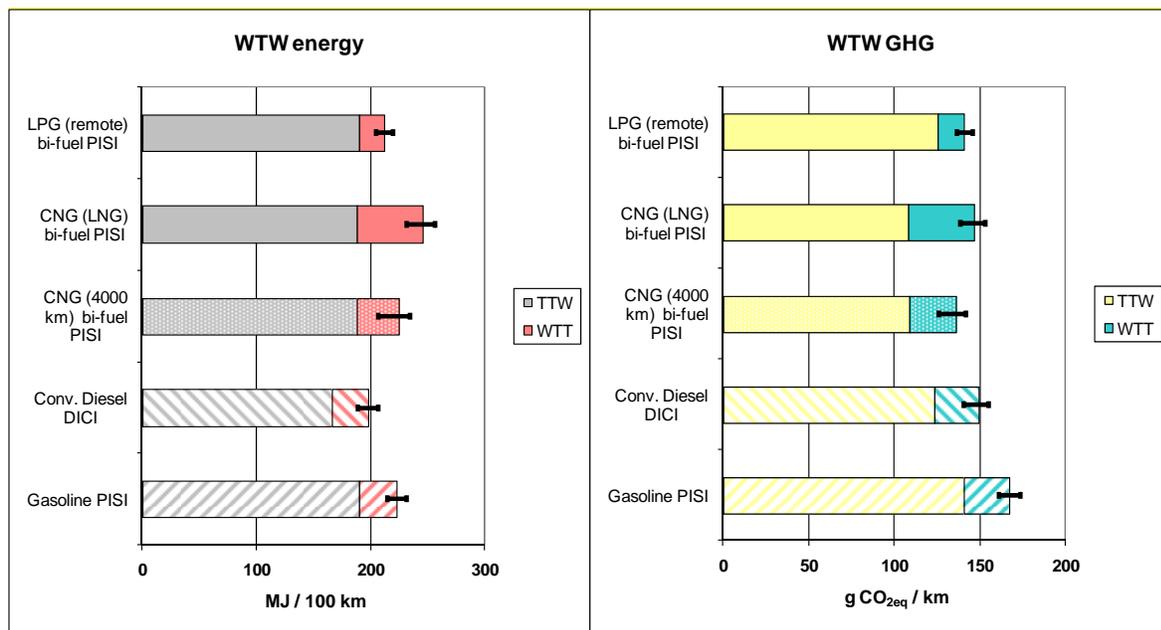
5   Alternative liquid fuels / components

This section deals with all the non-conventional liquid fuels produced in a variety of ways and which can be used either neat or in blends with conventional gasoline or diesel fuel. We have considered ethanol, bio-diesel and synthetic diesel fuel. For completeness we have also added ETBE, as an alternative way of using ethanol and MTBE for reference. Such fuels share three undeniable advantages over gaseous fuels.

Infrastructure

If used in blends with conventional fuels, these fuels do not require any special distribution infrastructure except what is necessary to transport them to existing refineries or fuel depots. If used neat, the required infrastructure is more extensive but still much simpler than what would be required for gaseous fuels.

Vehicles

Generally these fuels can be used in existing vehicles with little or no modification as long as they are in small percentage blends with conventional fuels. For high percentage blends or neat fuels specially adapted vehicles may be required although changes are much less drastic than for gaseous fuels.

Flexible usage

Being miscible with conventional fuels they can be used in various proportions in relation to their availability in a certain area and at a certain time, of course within the limits imposed by the vehicle population.

The special case of DME

Di-Methyl-Ether or DME does not share the above advantages but is also discussed in this section as it falls into the category of direct substitute for diesel fuel and can be produced in a very similar way to synthetic diesel fuel. DME is gaseous at ambient conditions but can be liquefied under moderate pressure. Its use would require a dedicated distribution infrastructure very similar to that of LPG as well as specially adapted vehicles (fuel storage and injection system).

Effect on engine efficiency

Generally these fuels, when used in low volume blends, have not demonstrated any material effect on the intrinsic efficiency of the engines. There are various claims in the literature that certain fuels such as ethanol or synthetic diesel may increase energy efficiency. We considered that, at least at this stage, such claims have been neither proven in practice nor scientifically explained and have stuck to the constant engine efficiency concept.

Where new fuels are used in higher concentrations, e.g. E85, it is possible that engines could be adapted to take advantage of the higher octane to increase efficiency. However, this is only possible for dedicated vehicles,

Our calculations are based on constant energy efficiency which represents the use of the alternative liquid fuels as low level blends in the existing fleet, or in vehicles essentially similar.

> A number of routes are available to produce alternative liquid fuels that can be used in blends with conventional fuels and, in some cases, neat, in the existing infrastructure and vehicles

In the WTT part of this study we have also included a number of pathways to produce methanol. The latter is not, however, envisaged as a fuel for ICE engines but as a vector for hydrogen (see further in *section 6*).

5.1 "Conventional" biofuels (ethanol and bio-diesel)

Ethanol is a well-established substitute for gasoline in spark-ignition engines. It has been used for many years in several parts of the world, occasionally neat, but more often in various blending ratios with conventional gasoline. It is generally accepted that engines developed and tuned for conventional gasoline can run with gasoline containing up to 5% ethanol without adverse short or long term effects. The European EN228 specification for gasoline allows blending of ethanol up to that level. Discussions are continuing on the potential to increase the ethanol level to 10%, and whether existing vehicles can use such fuels.

Bio-diesel is produced by reacting a vegetable oil with an alcohol, usually methanol to give a so-called Fatty Acid Methyl Ester (FAME). This process splits the tri-glyceride molecule, separating glycerine as a by-product and producing a fuel which boils at around 350°C and is a suitable diesel fuel. Pure vegetable oil is very viscous as well as unstable, and consequently unsuitable as a component in road diesel fuel. Bio-diesel can be used without problems in standard Diesel engines in blends up to 5% with conventional diesel fuel. Such blends are allowed by the EN590 diesel fuel specification

Although this has not been done in practice as yet, methanol can be substituted by ethanol to produce an Ethyl Ester (FAEE). Assuming ethanol is from bio origin, this has the advantage of boosting the "renewability" of the fuel. FAEE pathways have been included in this version of the study.

5.1.1 Sources and manufacturing processes of ethanol

Ethanol is traditionally produced by fermentation of sugars. Virtually any source of carbohydrates can be used. Sugars are readily converted whereas heavier compounds such as hemicellulose first need to be broken down in a hydrolysis step. For historical, economic and practical reasons, the main crops used for the industrial production of ethanol are sugar cane, corn (maize), wheat and sugar beet. The last two are currently, and for the foreseeable future the main sources of ethanol in Europe. Large scale ethanol production in Europe would rely mostly on wheat.

The fermentation process produces alcohol at a fairly low concentration in the water substrate. Purification of the ethanol by distillation is fundamentally energy-intensive.

In recent years there has been a lot of interest in processes to convert cellulose into ethanol via separation and breakdown of the cellulose into fermentable sugars. Such routes potentially make a much wider range of crops available including woody biomass in all shapes or form as well as by-products such as wheat straw or sugar beet pulp.

Amongst the vast number of possible options, we have elected to represent those that are the most relevant in Europe i.e. ethanol from sugar beet, wheat and woody biomass. For reference we have also added a pathway representing state-of-the-art production of ethanol from sugar cane in Brazil.

The basic processes for producing ethanol from sugar beet or wheat are well-established. One possible point of discussion is the energy associated to distillation. There have been significant advances in this respect and we have used data representing state-of-the-art plants. There are two essential elements that determine the final energy and GHG balances:
- The way the energy required for the production process is generated,
- The way the by-products are used.

One important point to remember is producers are likely to use energy and dispose of by-products in the most economic way, which is not necessarily the way that would maximise fossil energy saving and CO_2 avoidance. We have tried to represent the options that are most likely to "make sense" in practice but have also shown how currently less economic alternatives could alter the picture.

Sugar beet

We considered two options for utilising the pulp leftover after filtration of the diluted ethanol liquor:
- Animal feed,
- Fuel for the ethanol production process.

In practice only the first one is used today. The second option could be envisaged but, because of the cost, no-one would consider drying this by-product just to burn them. We considered instead the option of adding the pulp to the biogas digester (for cleaning the waste water), which gives almost the same energy balance and emissions as burning.

Wheat

Based on work done within the framework of the Low Carbon Vehicle Partnership in the UK, we have used the example of ethanol from wheat grain to illustrate the large impact of the process energy generation scheme on the overall energy and GHG balance. We have considered four options:

In the most basic (and low-capital) scheme, representative of many existing facilities (in Europe and elsewhere), a simple, usually gas-fired, boiler provides the steam while electricity is taken from the grid. Because heat is required at low temperature, ethanol plants offer, however, good opportunities for combined heat and power (CHP) schemes. Combining this with a natural gas fired gas turbine results in a very energy-efficient if capital-intensive process. In areas where coal or lignite is cheap and abundantly available, a simpler CHP scheme based on a coal-fired steam boiler combined with a backpressure steam turbine can also be envisaged. Finally surplus straw from the wheat itself can in principle be used as fuel through a similar CHP scheme. If this is likely to be a winner in terms of GHG emissions, this is also a very expensive and largely untested scheme to put on the ground and to operate.

Wheat grain processing leaves a protein-rich residue known as "distiller's dried grain with solubles" or DDGS which is traditionally used as animal feed because of its high protein content. DDGS has a high energy content and, after drying, could conceivably be used for energy generation e.g. through co-firing in a coal-fired power station.

Woody biomass and straw

The possibility of extending the range of feedstocks available for ethanol production from sugars and starch to cellulose is very attractive and a lot of research is being devoted to developing such routes.

Apart from the IOGEN straw conversion process (see below), we have represented all ligno-cellulose to ethanol routes under the single label of "wood". Accordingly, the underlying data represent a range of processes described in the literature although it must be realised that no such process has been proven at commercial scale. In such schemes the biomass input of the conversion plant includes non-cellulose material (e.g. the lignine of the wood) which is best used as an energy source. As the conversion energy represents most of the total energy requirement of the complete pathway, these pathways use very little external (fossil) energy.

As a separate option we have considered straw as a feedstock for ethanol production through the IOGEN process currently under development and which appears to be closer to commercial application. The conversion process is similar to the wood to ethanol process although the IOGEN data suggests higher efficiency than other sources.

5.1.2 Sources and manufacturing processes of bio-diesel

In Europe the main crops are rape (also known as colza) in the centre and north and, of less importance, sunflower in the south. Waste cooking oils are also used to a limited extent. Soy oil is the main crop in the Americas (mostly USA, Brazil and Argentina) while palm oil is produced in large quantities in South East Asia (Indonesia and Malaysia).

The processes to produce vegetable oil have been used for many years to produce food grade oil. The additional trans-esterification process is also well-established. The traditional alcohol used is methanol although (bio)ethanol can also be used. Oils from the crops mentioned above are all suitable for esterification although bio-diesels from some oils need to be blended with others (e.g. palm oil ester that has a high cloud point). There are a number of by-products the most important being the residue after pressing (or cake) and glycerine produced during the esterification step. The cake is a protein-rich animal feed used in substitution of otherwise imported soy meal. Glycerine could in principle be burned to fuel the process but, as it will command a much higher value as a chemical or as animal feed, this scenario is extremely unlikely. Glycerine itself is used in many food and cosmetics applications but the market is limited. In the future it could also be used as a substitute for alcohol and glycols in the manufacturing of e.g. paints, resins and antifreeze (see *WTT report, section 3.4.10* for details).

5.1.3 Hydrotreated vegetable oils (HVO)

The amount of FAME that can be added to conventional EN590 diesel fuel is limited to maintain acceptable fuel quality and compatibility with the vehicles in the market. In addition, the trans-esterification process leaves the basic backbone of the molecule unchanged, so the fuel properties depend to some extent on the type of oil or fat used in the process. Where the oil or fat contains many double bonds, stability may be a problem and conversely if the chains are long and saturated it may be difficult to meet cold flow requirements.

As an alternative to trans-esterification the pure oil can be hydrotreated. This removes double bonds and oxygen from the molecule, yielding a paraffinic fuel similar in properties to Fischer-Tropsch diesel (see *section 5.3*). This has all the advantages of such fuels, can either be used alone or blended with conventional diesel, and the final fuel properties are virtually independent of the original feedstock, so a wider range of feedstocks can be used.

The Neste Oil process (NexBTL®) was the first to be used in commercial production, and we have modelled this process using rapeseed, soy and palm oils. Similar processes are being developed by a number of other companies, and for comparison a process from UOP has been included, using rapeseed oil.

5.1.4 N_2O emissions from agriculture

The routes described above rely on traditional "food" crops, typically produced through intensive farming which is responsible for a large portion of the GHG emissions from these pathways. There are essentially two sources: nitrogen fertilizer production and emissions of nitrous oxide (N_2O) from the field. Because of the very powerful greenhouse effect of this gas (300 times that of CO_2), even relatively small emissions can have a significant impact on the overall GHG balance. N_2O emissions from different fields vary a by more than two orders of magnitude, depending on a complex combination of soil composition, climate, crop and farming practices.

LCA or WTT studies of biofuels have estimated N_2O emissions either from measurements on individual fields, or from calculations based on IPCC guidelines. The resulting error margins, if considered, are so enormous that it can be impossible to say for certain whether any pathway has a positive or negative GHG balance.

In this study we have exploited the expertise of the Soils and Waste Unit at the Institute for Environment and Sustainability at EC's Joint Research Centre at Ispra, and more particularly the results of a project for estimating greenhouse gas emissions from agricultural soils in Europe, in the context of GHG accounting for the Kyoto protocol. Emissions for the whole of the EU were calculated by combining GIS information on soil, daily climate and crop distribution with national data on fertilizer use and farm calendar. The emissions were then calculated day-by-day from the soils chemistry model and the data was segregated for different crops, to give EU-average N_2O emissions for each crop.

In this version of the study the data and tools available allowed us to carry out the simulations at a higher resolution level thereby minimising uncertainties due to uneven land quality. In v.1 we used soils and crop-distribution data available on a NUTS3 (1070 regions) level. This time we could make use of the LUCAS land-cover survey, which gives land cover at points on an 18km-grid, linked to soil parameters from the European Soil Bureau at JRC-Ispra. We also improved the model by adjusting the Nitrogen fertilizer rates according to recommendations for different soil types. We also used a reference-crop (see next paragraph).

Our method reduced the error margin to about 30%, mostly from the component of emissions from leached nitrogen, for which we still used the IPCC procedure. The improved values in this version are mostly slightly lower than those in the previous version, but still probably somewhat higher than those calculated using default IPCC values (depending on fertilizer assumptions). The IPCC procedure assumes that emissions are proportional to the nitrogen fertilizer rate. Interestingly, our results indicate that soil type, climate, and ground cover are more important than the fertilizer rate.

The soils model used in our calculations does not include short-rotation forestry in its crop-list. Therefore in this case only we used IPCC default factors. Fortunately the emissions are low anyway so that the additional uncertainty on emissions is moderate.

In spite of the thoroughness of these calculations, significant uncertainty remains, and some recent studies have suggested that field N_2O emissions may be significantly underestimated in such 'bottom-up' calculations.

(For more details see *WTT report, section 3.4.2).*

5.1.5 Reference scenario for crops

Growing crops for energy involves using land in a different way. How the land would be used otherwise is a question that needs to be addressed in order to determine what possible energy and/or emissions debits or credits are attached to this.

In version 1 of this study we argued that since most of the ethanol in EU would come from wheat diverted from export, we should not consider a reference crop. In this version, as in Version 2, we use as a baseline the updated 2005 projections of DG AGRI, which have a much smaller projected export, and much more set-aside area. As a result, most of the extra EU crops for biofuels would come from set-aside. We therefore had to consider as reference crop the use of the land on set-aside. We chose unfertilized, unharvested grass. This has negligible energy inputs, but a significant N_2O emission, which is subtracted from our calculation of N_2O from wheat and other crops.

Note that our reference scenario is for temporary grassland on land already brought into agriculture. Bringing permanent grassland or uncultivated land into arable use has longer term negative implications for GHG balances and is discussed in Section 5.1.6.

5.1.6 Energy and GHG balances

The figures in this section pertain to the **neat fuels** (ethanol and bio-diesel respectively). In practise they are most likely to be used in blend and the effects will be spread over a large number of vehicles.

Ethanol

Figure 5.1.6-1 shows the WTW fossil energy requirement and GHG emissions for a number of ethanol pathways. *Figure 5.1.6-2* shows the same information expressed as % savings compared to conventional gasoline.

Conventional production of ethanol from wheat as practiced in Europe gives modest fossil energy/GHG savings compared with gasoline. With a conventional energy production scheme and the currently most economic way of using DDGS (animal feed) the savings of fossil energy and GHG emissions are just over 30% compared to gasoline.

Figure 5.1.6-1a/b *WTW fossil energy requirement and GHG emissions for ethanol pathways (2010+ vehicles)*

(GHG bars represent the total WTT+TTW)
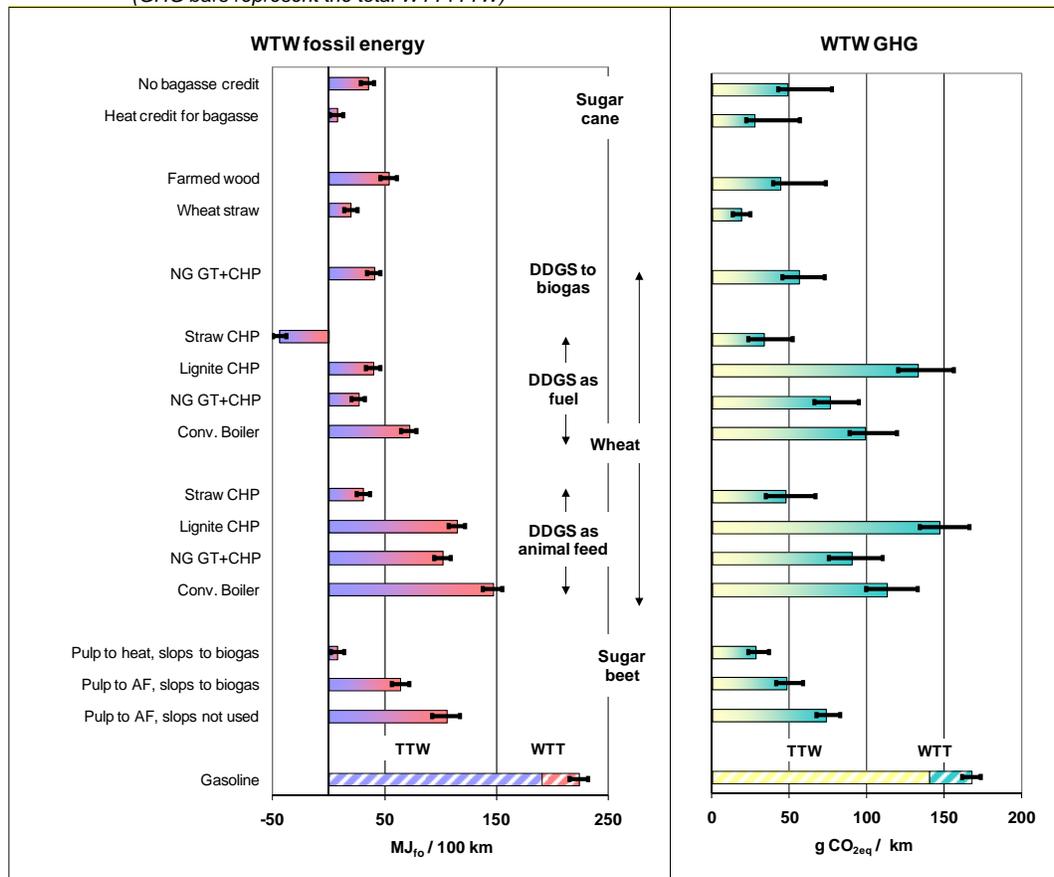
Figure 5.1.6-2 WTW fossil energy and GHG emissions savings for ethanol pathways compared to conventional gasoline- - (2010+ vehicles)
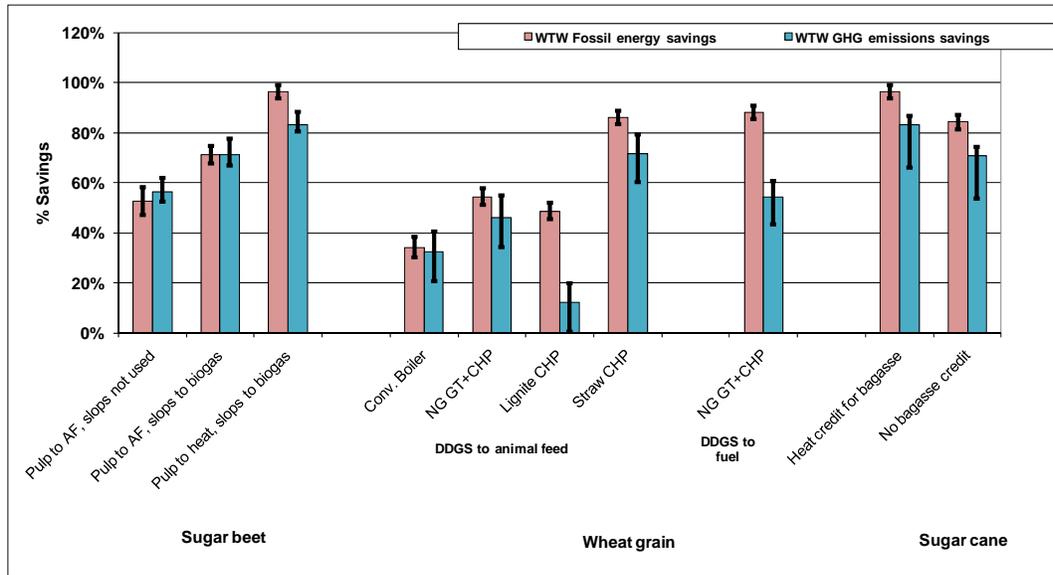
Use of co-generation particularly in combination with a gas-fired gas turbine can significantly improve these figures to 55% for fossil energy and 46% for GHG emissions. Even with the advantage of CHP, using coal wipes out most of these gains for GHG emissions. Straw burning is of course very favourable from this point of view but has other limitations as discussed below.

The sugar beet pathways are more favourable delivering between 53% fossil energy and between 56% GHG savings respectively in the base case where pulp is used for animal fodder and slops are discarded.

Using by-products for energy production rather than animal feed has a very large positive impact as more of the biomass is used towards energy production. Using DDGS to produce biogas improves the wheat-to-ethanol scheme savings to 82% fossil energy and 66% GHG emissions. In the sugar beet case, using slops to produce biogas significantly increases the savings. In principle pulp could also be used to produce biogas which would result in very high savings of 97% fossil energy and 83% GHG emissions. At the moment, and as long as the EU imports animal feed components such as soy meal, economics are, however, unlikely to favour use of co-products such as DDGS and sugar beet pulp as fuels.

For most pathways the error bars are noticeably larger for GHG than for energy because of the wide range of possible nitrous oxide emissions.

Advanced processes (from wood or straw) can also result in high savings, mostly because these processes use part of the biomass intake as fuel and therefore involve little fossil energy. The relatively large difference between the straw and wood case stem almost entirely from the process chemicals requirements indicated in the literature reference used. This is another indication that the actual processing scheme used is not indifferent to the final outcome in terms of energy and GHG.

For sugar cane "bagasse", the leftover after extraction of the sugar, is a convenient and abundant fuel for which there is no alternative use and which can meet all the needs of the processing plant. In the best cases surplus heat or electricity can be produced, further boosting the energy balance (we have accounted for a heat surplus displacing heating oil).

Bio-diesel

Figure 5.1.6-3 shows the WTW fossil energy requirement and GHG emissions for a number of bio-diesel pathways. *Figure 5.1.6-4* shows the same information expressed as % savings compared to conventional diesel fuel.

Bio-diesel is less energy-intensive than ethanol as the manufacturing process involves only relatively simple, low-temperature / low pressure steps. In GHG terms the picture is different because of the nitrous oxide emissions which account for an important fraction of the total and for most of the large variability ranges.

The impact of the fate of the glycerine by-product is discernable but much less marked than was the case for e.g. wheat DDGS. Note that the manufacture of the chemical products substituted by the glycerine is very energy-intensive, so that, in this case, economics are likely to accord with GHG saving. Animal feed is the next most economic route (more valuable than fuel), but gives the lowest GHG savings. Using the cake for producing energy (biogas) would indeed tremendously increase the GHG savings but, as mentioned above for DDGS, it is currently unlikely to be economically justified.

With cake used as animal fodder, RME (Rapeseed Methyl Ester) can save up to 70% of the fossil energy and 52% of the GHG emissions required for conventional diesel fuel. This could increase to 101% and 68% if cake was used for biogas production. As would have been expected the balance of REE (Rapeseed Ethyl Ester) is somewhat more favourable than that of RME because of the use of partly renewable ethanol. SME (Sunflower seed Methyl Ester) gives even more favourable results for a variety of reasons including a smaller requirement for fertilisers. Most of the intensive farming areas of Europe are, however, more favourable to rape and this crop provides virtually all the European bio-diesel production today.

Soy bean biodiesel is a particularly tricky pathway to treat using the substitution methodology, because of the high proportion of soy meal by-product compared to the oil. The choice of substitution for soy meal is especially difficult because soy meal is itself the main "swing-provider" of protein in animal feed. The net GHG savings depend very strongly on how the credit for the soy meal by-product is calculated. We have taken as the principal pathway soy bean farming in Brazil and crushing in Europe, with the meal replacing soy meal which would otherwise be imported from Brazil. In this way, the shipping to EU of the soy meal fraction of the soy beans is cancelled by the credit from avoided soy meal import. The resulting SYME pathway is more energy-intensive than RME and also potentially leads to more GHG emissions. The latter, however, have a very large uncertainty range mostly because of the uncertain field N2O emissions, compounded in this case by the large amount of meal co-product.

Palm oil methyl ester (POME) is less energy intensive than RME. The associated GHG emissions are much impacted by management of the plant effluent which is traditionally sent to an open pond where methane is released during the treatment process. Capturing this methane can tremendously reduce the overall footprint but this is not yet general practice.

It has also to be noted that there is much debate regarding the impact of increased Soy and Palm oil production on deforestation and, in the latter case, peatland drainage potentially leading to very large indirect GHG emissions. These effects are not included in the present figures.

Figure 5.1.6-3a/b   *WTW fossil energy requirement and GHG emissions for bio-diesel pathways (2010+ vehicles)*
(GHG bars represent the total WTT+TTW)
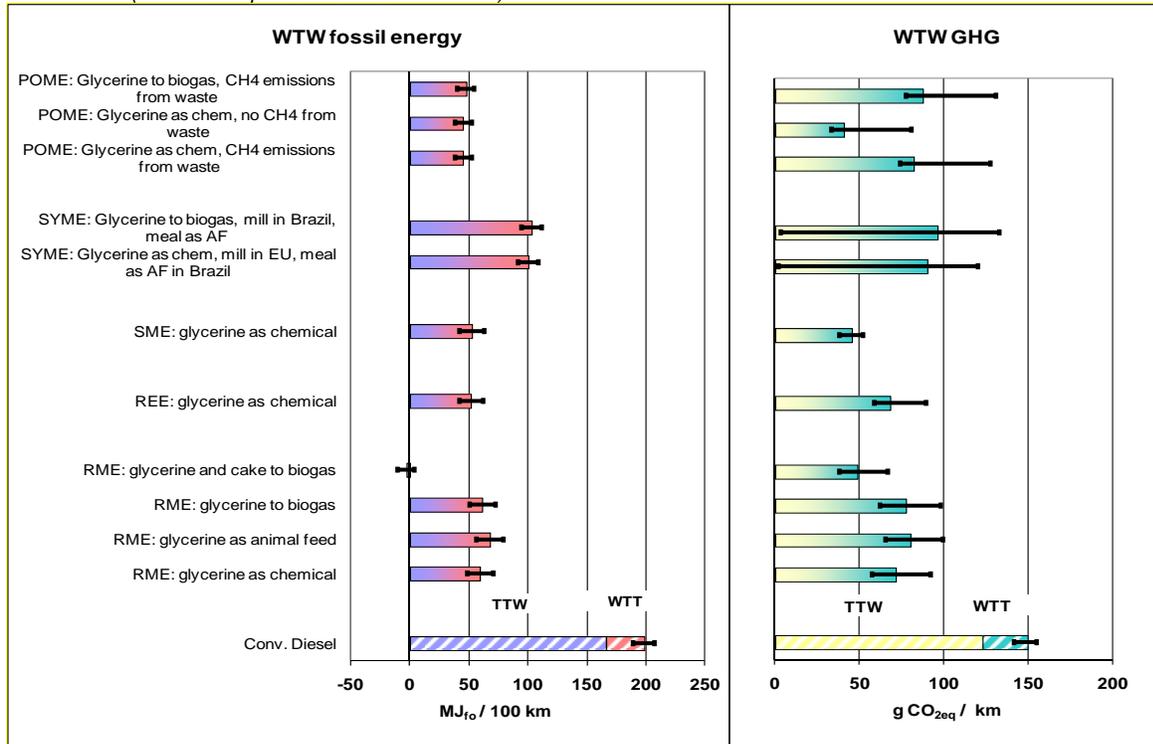
Figure 5.1.6-4   *WTW fossil energy and GHG emissions savings for bio-diesel pathways compared to conventional diesel fuel - (2010+ vehicles)*
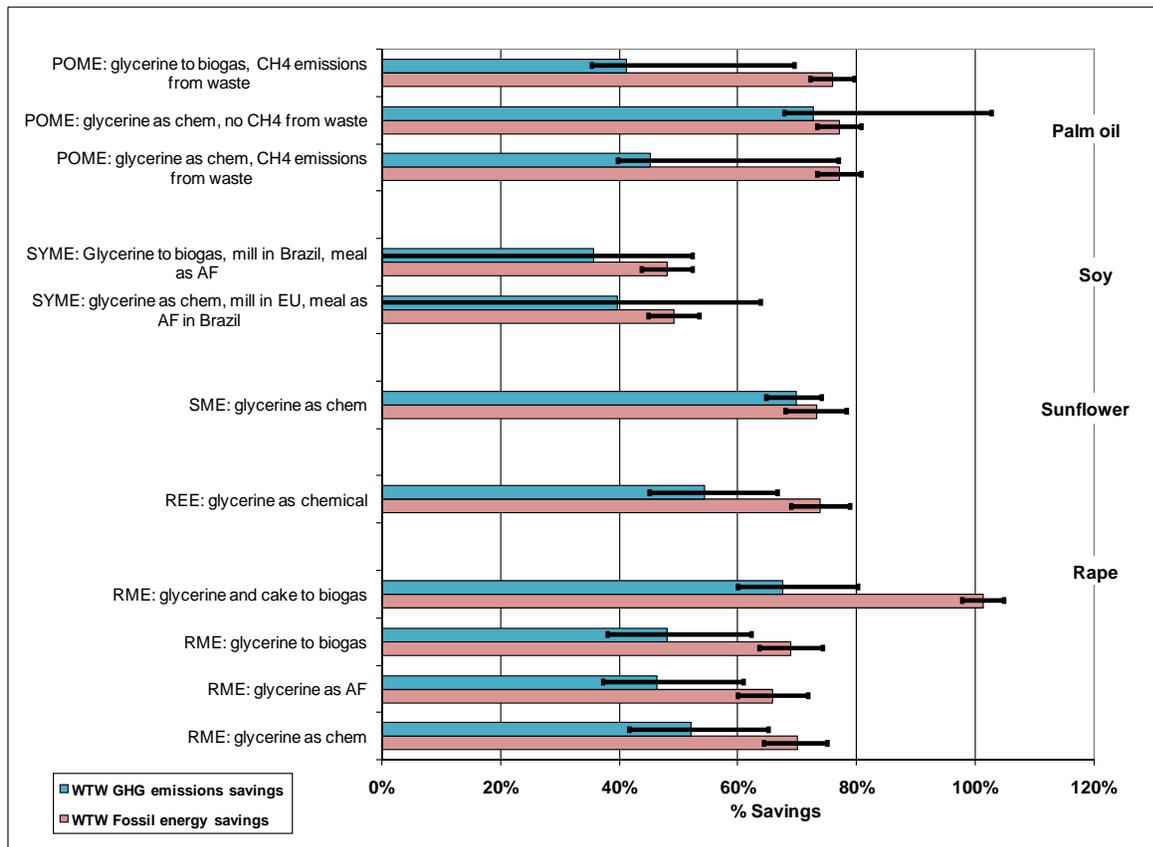
Hydrotreated vegetable oil

Figure 5.1.6-5 shows a selection of HVO pathways compared to the corresponding bio-diesel from the same oil. *Figure 5.1.6-6* shows the sae information expressed as % savings compared to conventional diesel fuel.

Although hydrogen manufacture is energy and GHG intensive (we have assumed it is made by steam reforming of natural gas), this is compensated by the higher energy content of the final product as compared to conventional bio-diesel. Overall HVO is slightly somewhat more energy-intensive than a bio-diesel from the same oil and very slightly more GHG-intensive, although the uncertainty ranges are overlapping. There is a small difference between the two technologies considered, although not significant for GHG emissions.

Figure 5.1.6-5a/b *WTW fossil energy requirement and GHG emissions for selected HVO and bio-diesel pathways - (2010+ vehicles)*

(GHG bars represent the total WTT+TTW)
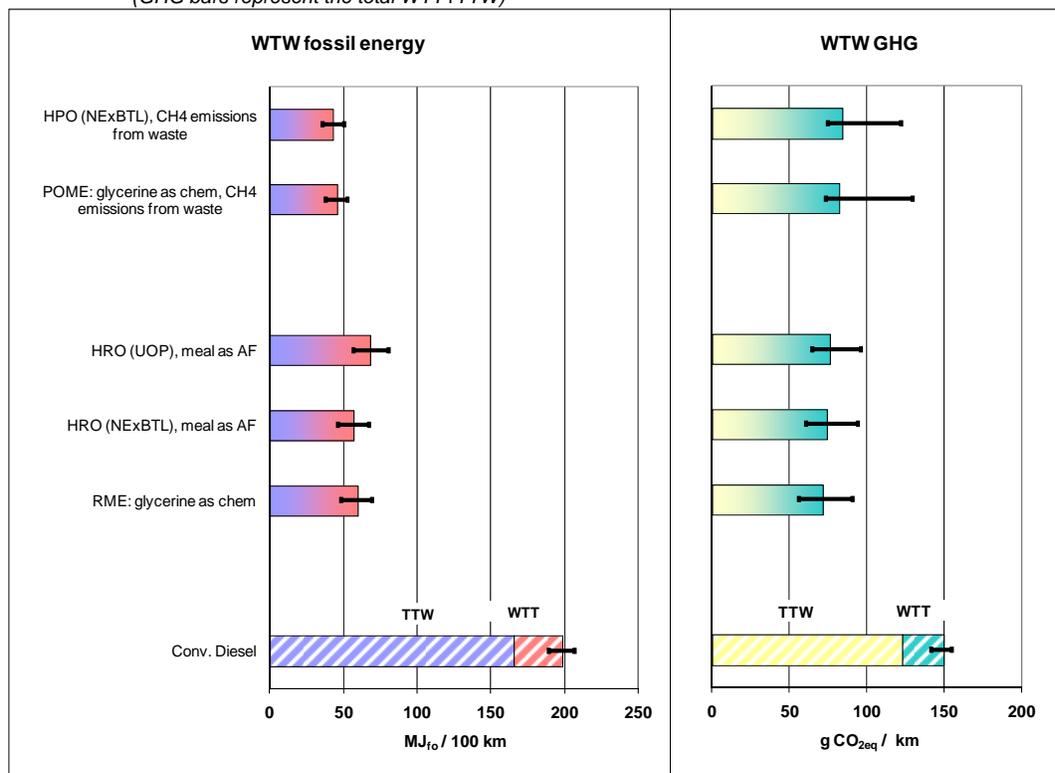
***Figure 5.1.6-6   WTW fossil energy and GHG emissions savings for selected bio-diesel and HVO
pathways compared to conventional diesel fuel - (2010+ vehicles)***
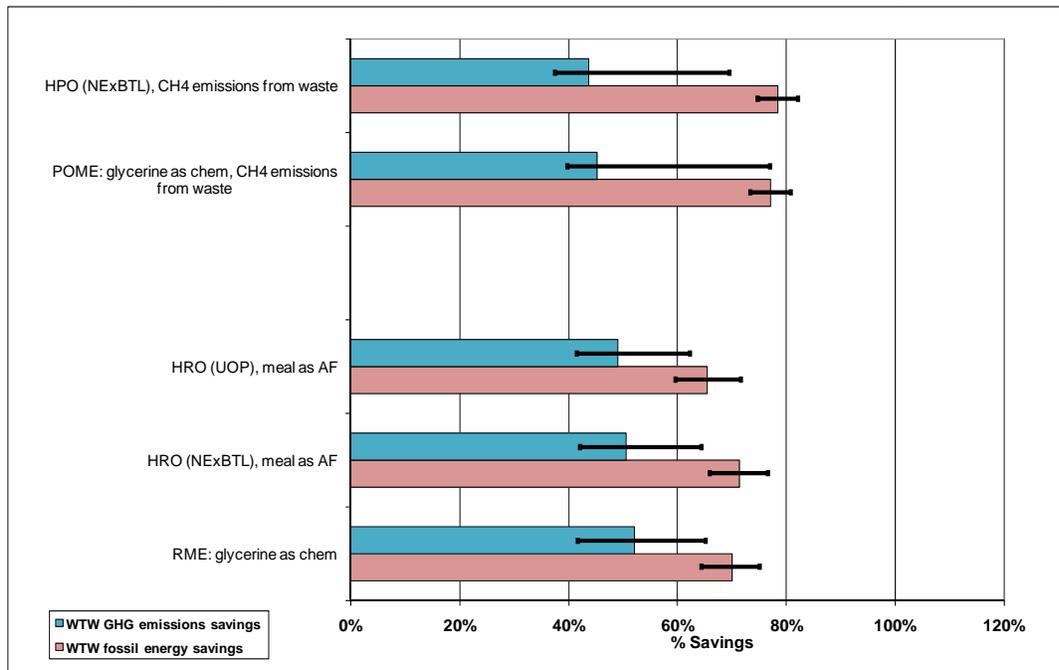
The fossil energy and GHG savings of conventionally produced bio-fuels such as ethanol and bio-diesel are critically dependent on manufacturing processes and the fate of by-products.

The GHG balance is particularly uncertain because of nitrous oxide emissions from agriculture.

When upgrading a vegetable oil to a road fuel, the esterification and hydrotreating routes are broadly equivalent in terms of GHG emissions.

The fossil energy savings discussed above should not lead to the conclusion that these pathways are energy-efficient. Taking into account the energy contained in the biomass resource one can calculate the total energy involved. ***Figure 5.1.6-4*** shows that this is several times higher than the fossil energy involved in the pathway itself and two to three times higher than the energy involved in making conventional fuels. These pathways are therefore fundamentally inefficient in the way they use biomass, a limited resource.

Figure 5.1.6-4a/b   *WTW total versus fossil energy*
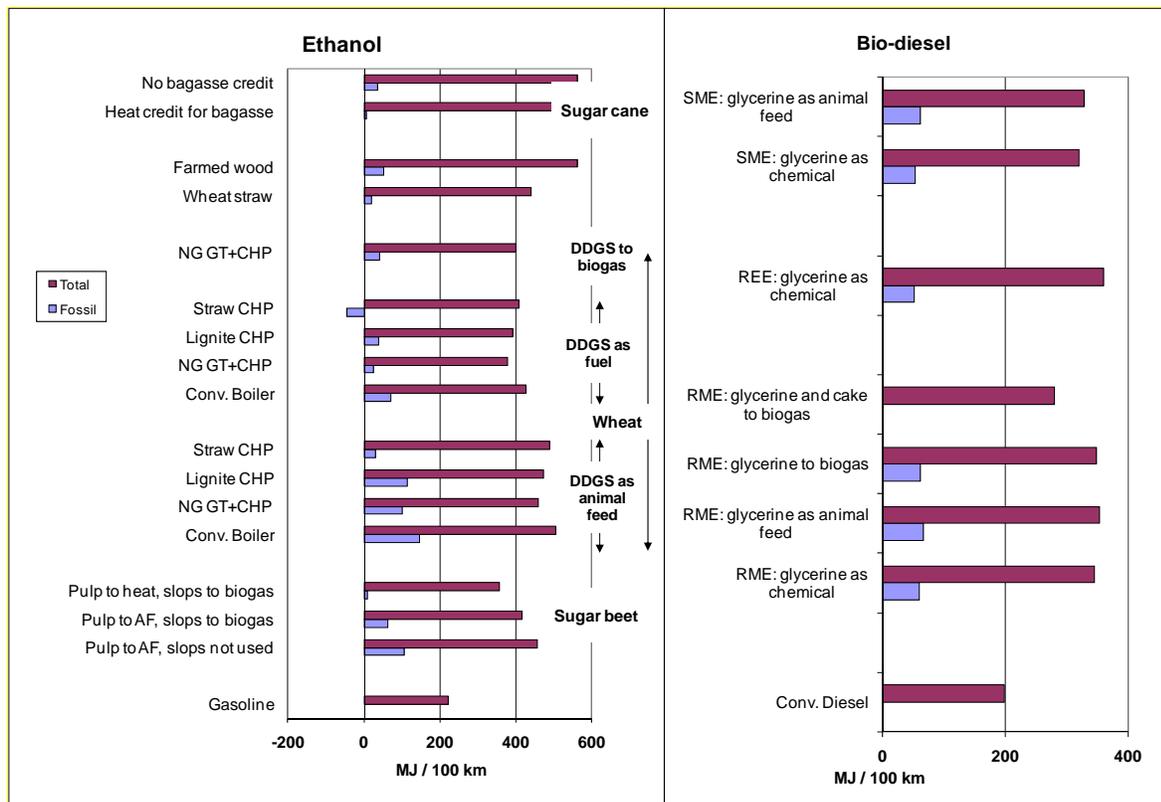
5.1.7 Impact of land use changes on GHG balances

The largest potential for expanding EU agricultural production for biofuels would be to increase the arable area at the expense of grazing land. However, there are very serious greenhouse-gas consequences to ploughing up grassland. The change in land-use results in a reduction in the organic carbon stored in the soil. Although this only happens once, the effect is very large and the carbon released would negate the GHG savings of biofuels for many decades. Similar considerations apply to use of forest land for short rotation forestry.

We conclude that **planting anything on grazing or forest land would be, in the short and medium term, counter-productive with regards to GHG reductions**.

Currently, government aspirations for biofuel production go beyond the levels that can be produced on existing arable land: the Renewable Energy Directive mandates 10% renewable energy in transport energy by 2020, and the US ethanol mandate calls for 36 million US gallons of ethanol by 2022, enough to replace about a quarter of US gasoline consumption. There is an on-going debate regarding the indirect impact of such policies on land utilisation in Europe, the USA and the rest of the world. This is a complex issue involving many parameters and variables and the outcome is highly uncertain. In this study we have purposely not taken into account such impacts which should therefore be added whenever a consensus is formed with regards to methodology and magnitude.

Land use changes are discussed in more depth in *WTT Report, Section 3.4.1*.

5.1.8 Other environmental impacts of biofuels production

Soil quality/erosion

Sugar beet can cause soil erosion, especially if grown on the light soils typical of southern Europe. New techniques of inter-sewing between cover crops can help. However, we do not expect that sugar

beet production would spread beyond areas of northern Europe with heavy soils. In wet areas, the heavy machinery used for harvesting sugar beet can cause soil compaction.

We already warned that increase of arable area would cause loss of soil organic carbon from grassland or forest: we assume it will not be allowed.

Continually removing straw instead of incorporating it in the soil will decrease the soil organic content, leading to poorer moisture retention. This should be a larger problem in light southern soils, but ironically this is where straw is most often removed, because its decomposition consumes nitrogen which has to be replaced. It is probably not a significant problem in the prime cereals-growing areas of Northern Europe where a high density of straw availability makes it most economic to site straw-to-biofuel conversion plants.

Eutrophication and acidification

Because intensive agriculture using fertilizers tends to cause eutrophication and acidification, increased crop production for biofuels would tend to exacerbate the problem. The driving force for intensification is crop price: hence meeting biofuels targets will probably cause more intensification of oilseed production than of cereals production. Sunflower, short rotation forest and other "advanced biofuels" crops generally use less fertilizer than the other crops, so have less impact.

Biodiversity

Growing energy crops instead of permanent crops and on "nature" land now in voluntary set-aside, would decrease biodiversity. A 2004 study by the European Environmental Agency concluded that the negative biodiversity impacts are high for rape, medium for sugar beet and low to medium for short rotation forestry. The use of wood residues was considered to have no impact.

Pesticide use affects biodiversity. Break-years encouraged by compulsory set-aside rules tend to reduce pests and diseases, so doing away with it would tend to increase pesticide use. Large increases of pesticide applications are needed if the frequency of sugar beet (and to a much lesser extent oilseed rape) crops in a rotation is increased beyond about one year in four. Sugar beet generally requires much more pesticide than other crops. Farmers might escape controls on pesticide levels if the crops are not for food.

Impact on water table

The increased growth of crops requiring extensive irrigation in arid areas will put pressure on water resources. For example sugar beet cultivation in Spain and Greece has a very high percentage of irrigated area (77 and 100% respectively). In Italy it is lower but still over a third of the area compared with 6% for Durum wheat and 7% for sunflower. Water use per tonne of dry matter is around 200 litres for sugar beet and 300 litres for wheat.

Increased cultivation of trees can also lead to a lowering of the water table. Lowering of the water table can have significant impact on the natural environment in the area concerned.

Introduction of non-native species and GMOs

There is some risk that non-native energy crops could spread in the wild, because they lack natural predators. Using sterile varieties (including GMOs) greatly reduce this risk. Some are concerned about GMOs in general, though.

5.2 MTBE and ETBE

Methyl-Tertiary-Butyl Ether or MTBE is a high octane blending component for gasoline. MTBE was widely used in US gasoline until water contamination issues led to it being withdrawn in some areas.

In Europe MTBE was introduced as one of the measures to recover octane after phasing out of lead in gasoline.

Figure 5.2a/b   WTW fossil energy requirement and GHG emissions for MTBE and ETBE pathways (2010+ vehicles)
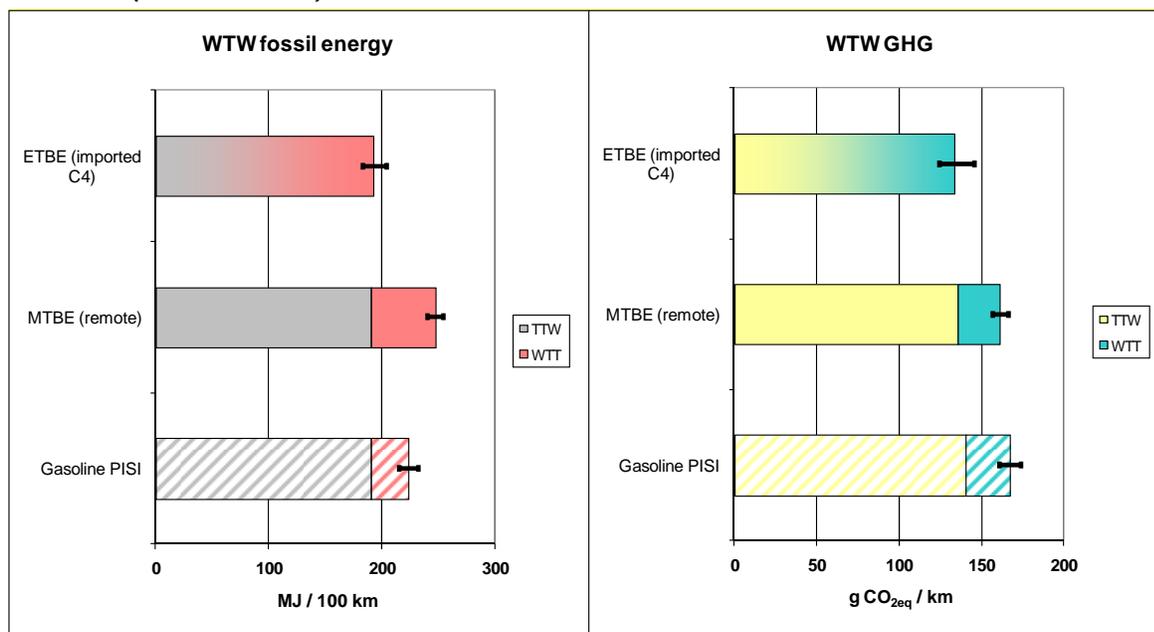
Note: Ethanol for ETBE assumed to be from wheat, NG gas turbine CHP, DDGS to animal feed (see *section 5.1*).

MTBE is synthesised by reacting isobutene with methanol. Some isobutene is produced by refineries and petrochemical plants as by-product of cracking processes. Large MTBE plants include, however, isobutene manufacture via isomerisation and dehydrogenation of normal butane often from gas fields, near which the plants are often located. The entire process is fairly energy-intensive. In that sense MTBE is a fuel derived from natural gas. Marginal MTBE available to Europe is from that source and this is the pathway that we have investigated.

Ethanol can be used as a substitute to methanol to produce ETBE (Ethyl-Tertiary-Butyl Ether) which has very similar properties to MTBE. The main advantage of ETBE over ethanol as a gasoline component is its low vapour pressure. MTBE plants only require minor changes to be able to produce ETBE.

ETBE is currently manufactured by some European oil refineries in plants that used to produce MTBE. The isobutene feed is not produced on purpose but is a by-product of the catalytic cracking process. It is only available in limited quantities. Whereas the energy required by the ETBE plant itself is known, the energy associated with the production of isobutene cannot be estimated in a rational way as isobutene is produced as one of many minor by-products of the cracking process. As a result this cannot be calculated as a discrete pathway. The way to approach the net impact of this route is to compare a base case where ethanol is used as such and MTBE is produced in refineries, to the alternative where ethanol is turned into ETBE in replacement of MTBE.

Should more ETBE be required it would have to be made from isobutene produced by isomerisation and dehydrogenation of normal butane. We have represented this pathway with the assumption that the marginal butane required is imported from gas fields.

MTBE requires more energy than gasoline although the GHG balances are more or less the same because MTBE manufacture uses essentially natural gas as energy source. ETBE has a lower fossil energy and GHG footprint as a result of the partial "renewability" of ethanol.

The case of "refinery" ETBE is described in the table below (see also *WTT report, section 4.7*).

Table 5.2 WTW fossil energy and GHG emissions balances for "refinery" ETBE

Use of ethanol	Fossil energy MJ_{xfo}/MJ_{EtOH}	GHG $g\ CO_{2eq} / MJ_{EtOH}$
As ethanol	0.53	45.8
As ETBE	0.28	41.0
Gasoline (for ref.)	*1.14*	*85.9*

Overall, using ethanol as ETBE, through replacing methanol in a refinery, results in lower fossil energy and consumption and marginally lower GHG emissions than would be the case when using ethanol as such. The reason is that it is equivalent to eliminating methanol and replacing it by extra gasoline which has a significantly lower energy footprint and marginally lower GHG emissions.

With more favourable blending properties than ethanol, ETBE can provide an alternative to direct ethanol blending into gasoline. Fossil energy and GHG gains are commensurate with the amount of ethanol used.

5.3 Synthetic diesel fuel and DME

5.3.1 Sources and manufacturing processes

Synthetic diesel fuel

By synthetic diesel fuel we mean the product made by Fischer-Tropsch (FT) synthesis from "syngas" the mixture of carbon monoxide and hydrogen obtained by partial oxidation of hydrocarbons (e.g. coal) or wood or by steam reforming of natural gas. The products of this process scheme are long-chain paraffins essentially free of sulphur and other impurities.

A hydrocracking unit is usually included in the FT process scheme to control the type of product being produced by splitting the chains appropriately. The main commercial products envisaged are diesel fuel (with or without the kerosene fraction), naphtha and some LPG. Most early plants are also likely to produce lubricant base oils and specialty products such as waxes but it anticipated that these markets will soon be saturated and future plants will concentrate on producing large volume products.

We have considered three routes i.e.
- From natural gas (known as Gas-to-Liquids of GTL),
- From coal (know as Coal-to-Liquids of CTL),
- From woody biomass (known as Biomass-to-Liquids or BTL).

GTL

The GTL process is technically well-established although the economics have, in the past, not been sufficiently favourable for large scale development to occur. This has been changing in recent years with a combination of technological advances and more favourable economics and a number of large scale plants are being built or are under design while more are being actively considered. All such plants will be built near a gas field usually at locations where the only alternative or bringing gas to market would be LNG.

There is a debate regarding the credits that should be allocated to GTL diesel compared to conventional diesel. Two studies by PriceWaterhouseCoopers (PWC) and one study by Nexant have

considered functionally equivalent hydrocarbon processing systems with and without GTL products, and calculated the energy and GHG balances for a portfolio of fuel products meeting the market demand. These calculations assume that availability of GTL can lead to less crude oil processing. In this situation, if lower availability of heavy fuel oil (HFO) were to result in a switch to natural gas in industrial heating and power generation, this would result in lower overall GHG emissions, thereby generating a credit for GTL diesel. In this way it is argued that the GHG emissions from the complete system are broadly equivalent for the scenarios with and without GTL fuels.

This study starts from the present situation with European oil refineries supplying the virtual entirety of the road fuels market. Within the timeframe considered all identified alternatives to refinery production (e.g. the availability of GTL diesel) could only replace a limited amount of either gasoline or diesel fuel. The impact on the refineries is therefore considered in this context and this forms the basis of the marginal analysis through which the energy and CO_2 emissions associated with a marginal change in either gasoline or diesel fuel production are estimated.

The key assumption made in the PWC and Nexant studies linking GTL diesel availability to HFO production and making the further assumption that a reduction of HFO production would be made up by natural gas may well be applicable in rapidly developing markets (such as China) where a clear choice would need to be made between additional crude oil processing capacity and new capacity for making synthetic diesel via a Fischer Tropsch (or other) route. We consider, however, that this is not an appropriate assumption in the European context. This is the key reason for the differences between the WTW results for GTL quoted in this study, as compared to the studies conducted by PWC and Nexant.

CTL

Coal gasification is a well understood process that can be coupled to Fischer-Tropsch synthesis to deliver products very similar to GTL. There are very few plants in operation today but these schemes are attracting a lot of interest especially in combination with CO_2 capture and storage (see *section 8*).

BTL

Wood gasification is of the same nature than coal gasification although using biomass creates specific issues related to, amongst others, the mineral content of certain biomass feedstocks, problems of slagging etc, each biomass feed creating different problems. Adaptation of the Fischer-Tropsch synthesis to syngas of different origins revolves around purity, cleanliness and CO/H_2 ratio of the gas.

Another challenge is the scale at which such processes could be practically used. Integrated gasification and FT plants are complex and expensive with any feedstock and benefit enormously from economies of scale. Biomass as a low energy density and relatively dispersed feedstock does not fit well within the traditional industrial model and novel ways have to be developed to find acceptable compromises.

The current search for alternative transport fuels has increased the level of interest for the BTL route and a number of pilot and demonstration projects are at various stages of development. These will always be complex engineering projects and will require many practical problems to be resolved before they become reliable and commercially viable. The major challenges for achieving this should not be underestimated. The potential rewards from these processes in terms of feed flexibility, quality of the products and very low GHG emissions justify further research and development.

The pulp and paper industry may provide a promising route for making significant amounts of synthetic fuels from woody material. This is the so-called "black liquor" route. Black liquor is a by-product of paper pulping that contains the lignin part of the wood. It is commonly used as internal fuel to power the paper mills. Through gasification of the black liquor rather than simple burning one can

generate syngas and therefore synthetic fuels. The energy balance of the paper mill must then be re-established by burning additional waste or low value wood. The net result is production of synthetic fuels from wood at a very high combined efficiency.

DME

DME is to diesel what LPG is to gasoline. It is gaseous at ambient conditions but can be liquefied at moderate pressure. As a fuel for compressed ignition engines it has very attractive characteristics, burning very cleanly and producing virtually no particulates (a dedicated DME vehicle would probably not require a particulate filter but would need a purpose-designed fuel handling and injection system).

DME is synthesised from syngas and can therefore be produced from a range of feedstocks. The synthesis process is very similar to that of methanol and has a similar efficiency, somewhat higher than the efficiency of the synthetic hydrocarbons processes. The most likely feedstock in the short term is natural gas but coal or wood can also be envisaged. The black liquor route mentioned above is eminently suitable for DME (or methanol) and is in fact more likely to be developed to produce these fuels rather than BTL, chiefly in Scandinavia.

A dedicated distribution network and dedicated vehicles would be required. The practical and commercial magnitude of the task of building such a network, building and marketing the vehicles as well as customer acceptance must not be underestimated. Use of this otherwise attractive fuel in fleets may be worth considering in certain cases, albeit with specially adapted vehicles.

5.3.2 Energy and GHG balances

The GTL, CTL and BTL processes can produce a variety of products. When focussing on the diesel fuel product from these processes, one is confronted with the issue of allocation of production energy. Although diesel fuel often is the main product in volume terms, its fraction in the total product will not, in practice, exceed 75% (higher yields may be achieved by recycling lighter products but at a considerable cost in energy). Naphtha takes the largest share of the balance and can hardly be considered as a by-product being of the same nature as diesel fuel and usable in applications where it also would displace petroleum products. There is no technical basis for arguing that more or less energy and emissions are associated to specific products so that, in this case, allocation on the basis of energy content is justified (i.e. that all products are produced with the same energy efficiency). We have taken this view which leads to consider that all products and their fate are independent of each other (see also *WTT report, section 3.2.5*).

The combined process of primary energy conversion and FT synthesis is energy-intensive, more so for coal and wood than for natural gas. This is mainly because the overall process is more straightforward and more energy efficient with gas. Also future GTL and CTL plants are expected to be very large and highly heat integrated. This is likely to be less so in smaller wood conversion plants where the size may be dictated by the raw material availability/collection and such complexity may not be economically justified.

The GTL scheme represented is for a plant sited near a remote gas field. The high energy requirement for the conversion process is partly compensated by the lower transportation energy. The GTL pathway is notably more energy-intensive than conventional diesel fuel. In GHG terms the difference is small because of the beneficial effect of using natural gas rather than crude oil as primary energy source.

Figure 5.3.2-1 shows a selection of HVO pathways compared to the corresponding bio-diesel from the same oil. *Figure 5.3.2-2* shows the same information expressed as % savings compared to conventional diesel fuel.

Figure 5.3.2-1a/b   *WTW energy requirement and GHG emissions for synthetic diesel and DME pathways (2010+ vehicles)*

(GHG bars represent the total WTT+TTW)
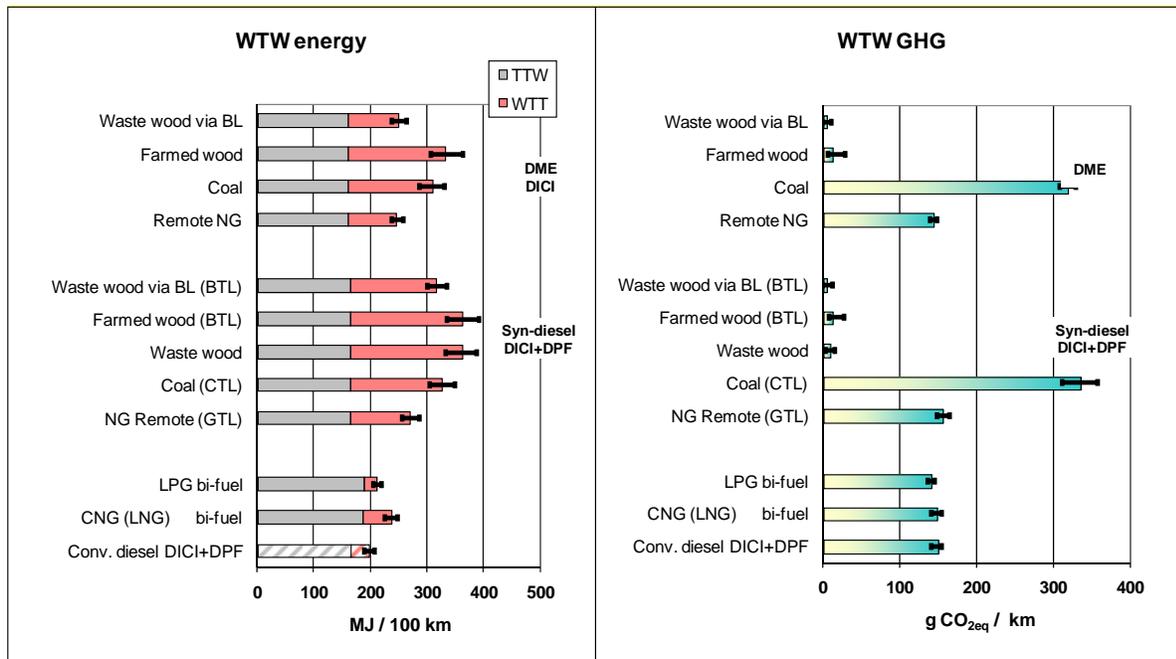
Figure 5.3.2-2 *WTW fossil energy and GHG emissions savings for pathways compared to conventional diesel fuel - (2010+ vehicles)*
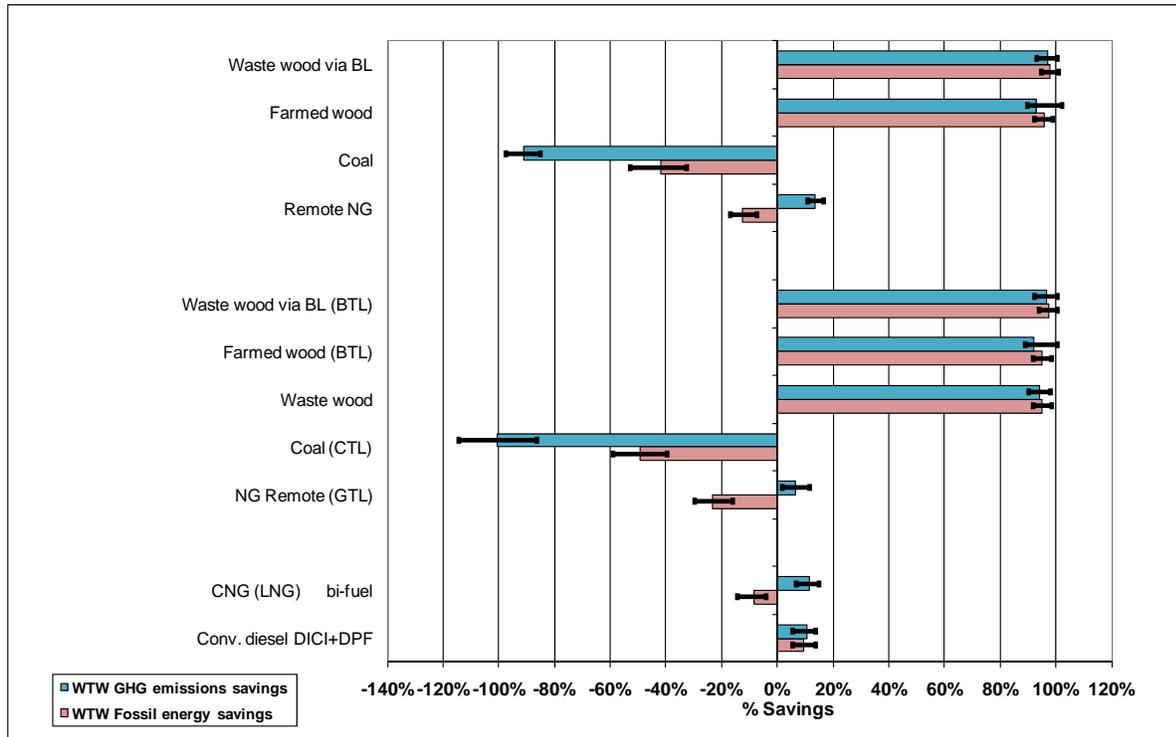
High quality diesel fuel can be produced from natural gas (GTL) and coal (CTL). GHG emissions from GTL diesel are slightly higher than those of conventional diesel, CTL diesel produces considerably more GHG.

The higher efficiency of the synthesis process gives DME a slight advantage on the synthetic diesel fuel from the same source. In the DME process, the sole product is DME which translates into high

yield of fuel for Diesel engines compared to FT diesel in the case of which other products (mostly naphtha) are also produced.

DME can be produced from natural gas or biomass with better energy and GHG results than other GTL or BTL fuels. DME being the sole product, the yield of fuel for use for Diesel engines is high.

CNG obtained with liquefied gas from the same remote location is still more advantageous than either GTL diesel or DME in WTW both energy and GHG terms.

Here again the wood pathways hardly produce any GHG because the main conversion process is fuelled by the wood itself although they are not particularly energy efficient. The black liquor route (BL) is even more favourable with lower energy consumption and very low GHG emissions.

New processes are being developed to produce synthetic diesel from biomass (BTL), offering lower overall GHG emissions, though still high energy use. Such advanced processes have the potential to save substantially more GHG emissions than current bio-fuel options.

6   Hydrogen

Hydrogen as a transportation fuel conjures up images of quiet, efficient, non-polluting vehicles and is therefore the focus of much attention. Reality is of course more complex and both the desirability to develop hydrogen as a road fuel and the way to get there need to be considered very carefully.

Although hydrogen can be used in an internal combustion engine, the real efficiency breakthrough comes from fuel cells, the commercial development of which is a crucial issue.

As the lightest of all gases, hydrogen has a low energy density and must be either compressed at very high pressures or liquefied at very low temperatures to be stored in any meaningful quantity. This presents significant challenges particularly for mobile applications.

Hydrogen is not a primary energy source but an energy vector. Although it is the most widespread element in the universe, free hydrogen does not occur in nature. It needs to be "extracted" from compounds such as hydrocarbons and of course water, at the cost of an energy input. This results in emissions of GHG to varying degrees depending on the source of that energy and the specific pathway chosen.

There are many possible routes to a "hydrogen alternative" leading to a very wide range of energy usage, GHG emissions and costs. If the WTW approach is required when considering any transport fuel, it is absolutely essential for hydrogen where a large part of the energy usage and all of the GHG emissions occur at the production stage.

In this section we first consider the "hydrogen users" i.e. the vehicles and powertrains that can use hydrogen as a fuel. Based on their requirements we then examine the routes to produce, transport and distribute hydrogen.

6.1   Hydrogen-fuelled powertrains and vehicles

6.1.1 Hydrogen Internal Combustion Engine
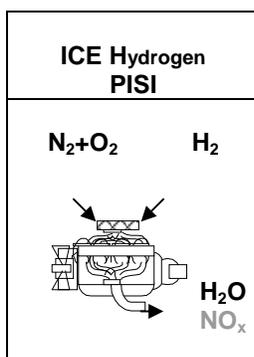
PISI internal combustion engines can be adapted to burn hydrogen. The high temperature combustion process results in the production of traces of NO_x (the N_2O part of which was accounted for as GHG in our calculations, even if practically insignificant). NOx emissions can be further reduced e.g. through a lean burn strategy. These vehicles are considered by California Air Resources Board as AT-PZEV regarding regulated pollutants. The maximum efficiency of these hydrogen ICEs is expected to be very close to the best 2010 Diesel engines. Although more advanced and efficient hydrogen engines can be envisaged, the same technologies can also be applied to gasoline and natural gas engines.

Hydrogen can be carried on board the vehicle either in compressed form at ambient temperature (C-H_2) in a high-pressure vessel, or in liquid form at atmospheric pressure (L-H_2) in a cryogenic tank. Although early prototypes have used pressures of 35 MPa, it is anticipated that 70 MPa will become the standard. This pressure level is necessary to store a sufficient quantity of hydrogen in a reasonable volume to provide a realistic vehicle range. For the same quantity of hydrogen, the C-H_2 tank is slightly heavier than the L-H_2 tank, slightly increasing the total mass of the vehicle. L-H_2 does, however, require some energy for vaporisation prior to use as well as additional equipment to reduce

boil-off so that, in practice there is no significant difference in energy efficiency terms between the two options. The use of liquid hydrogen also poses the problem of long term storage as heat ingress into a tank at some -253°C cannot be avoided, and there is a gradual loss of hydrogen from the tank if the vehicle is not used for some time. Compression or liquefaction account for a significant portion of the WTW energy requirement.

Table 6.1.1   2010 hydrogen ICE vehicles characteristics

| | | PISI | |
		C-H_2	L-H_2
Powertrain			
Displacement	l	1.3	1.3
Powertrain	kW	77	77
Engine mass	kg	120	120
Gearbox mass	kg	50	50
Storage System			
Tank pressure	MPa	35/70	Atmo.
Tank net capacity	kg	9	9
Tank mass empty	kg	120	109
Tank mass increase	kg	85	74
including 90% fuel			
Vehicle			
Reference mass	kg	1181	1181
Vehicle mass	kg	1266	1255
Cycle test mass	kg	1360	1360
Performance mass	kg	1406	1395

6.1.2 Fuel Cells

Fuel cells (FC) are chemical converters fed by gaseous hydrogen and ambient air, producing DC voltage/current, heat and water. Their principal attraction is their high energy conversion efficiency compared to thermal engines. If fuelled directly by hydrogen they emit no pollutants at the point of use, and so have true ZEV capability. The configurations of the two FC vehicle options considered in the study are schematically represented below.

Fig 6.1.2   2010 "direct" hydrogen FC powertrains
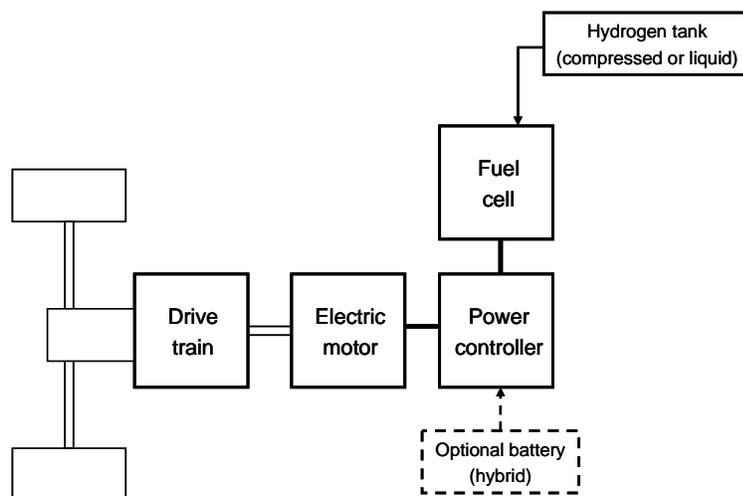
One of the many challenges facing FC developers is to reduce the heating up time to normal operation. The additional large battery pack in the hybrid FC offers the possibility to start on the battery without waiting for the FC heating delay, and also to benefit from braking energy recovery. The downside is of course the additional mass and cost.

With regard to on-board hydrogen storage the options are the same as for ICEs (i.e. compressed or liquid). Fuel cells being more efficient than ICEs, a smaller quantity of hydrogen is necessary to comply with the range criterion and the tank can therefore be smaller and lighter. No significant difference in overall fuel efficiency is expected between the two fuel storage options.

Table 6.1.2   Mass characteristics of 2010 hydrogen FC vehicles
(all figures in kg)

	Non Hybrid		Hybrid		Hybrid+reformer	
	C-H_2	L-H_2	C-H_2	L-H_2	Gasoline[1]	Methanol
Powertrain mass substitution						
Engine mass	-120	-120	-120	-120	-120	-120
Gearbox mass	-50	-50	-50	-50	-50	-50
Fuel Cell						
Fuel cell stack mass	150	150	150	150	150	150
Reformer mass	0	0	0	0	90	90
Cooling system additional mass	50	50	50	50	50	50
Electric parts						
Battery mass	0	0	20	20	40	40
Electric motor+electronics mass	73	73	73	73	73	73
Storage System						
Tank netto capacity	4.7	4.7	4.2	4.2	23	45
Tank mass empty	69	57	56	51	15	15
Tank mass increase including 90% fuel	30	18	16	11	-8	12
Vehicle						
Enlarged vehicle additional mass	50	50	50	50	50	50
Reference mass	1181	1181	1181	1181	1181	1181
Vehicle mass	1364	1352	1370	1365	1456	1476
Cycle test mass	1470	1470	1470	1470	1590	1590

[1] also valid for naphtha and diesel

6.1.3 Indirect hydrogen: on-board reformers

As an alternative to a hydrogen infrastructure and the range of issues and challenges it raises, hydrogen generation from a liquid fuel on-board the vehicle has been proposed.

Such vehicles would be equipped with small scale reformers, able to convert gasoline, methanol, naphtha or even diesel fuel into hydrogen which is then directly fed to the fuel cell. These vehicles represent a completely different approach combining on-board hydrogen production and usage. The advantages of avoiding the hydrogen distribution infrastructure and on-board storage are counterbalanced by the much greater complexity of the vehicle, the challenge of building a reformer that is small and efficient, the control system involving the reformer, the fuel cell and their interface, and the additional vehicle mass. Using "normal" liquid fuels, these vehicles also emit CO_2 and other pollutants. Here again the WTW approach is the only way to validly compare this option with others.

Fig 6.1.3   2010 Indirect FC vehicles
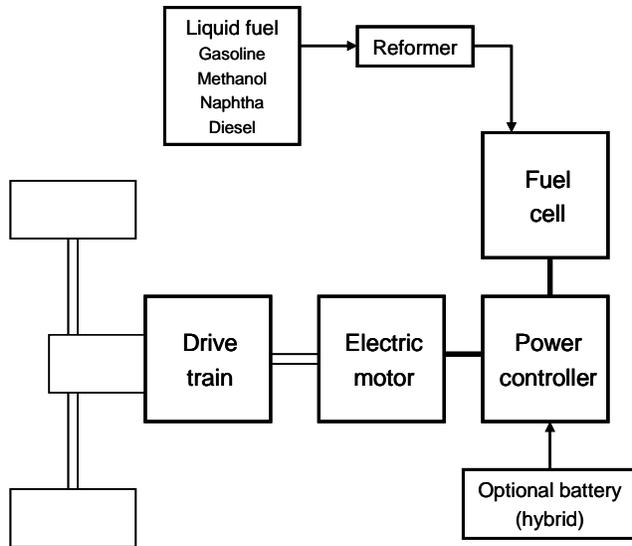
6.2 Hydrogen production routes and potential

One of the perceived merits of hydrogen is that it can in principle be produced from virtually any primary energy source. This can be done either via a chemical transformation process generally involving decarbonisation of a hydrocarbon or organic feedstock and splitting of water or through electricity via electrolysis of water.

Hydrogen is already produced in significant quantities today mostly for industrial applications. Oil refineries, in particular, are large hydrogen consumers for hydrodesulphurisation of various streams such as gasoils and heavy oil conversion processes.

The most widespread hydrogen production process is steam reforming of natural gas (essentially methane). The catalysed combination of methane and water at high temperature produces a mixture of carbon monoxide and hydrogen (known as "syngas"). The "CO-shift" reaction then combines CO with water to form CO_2 and hydrogen. The process is technically and commercially well-established and natural gas is a widely available and relatively cheap feedstock. Steam reforming of heavier hydrocarbons is also possible but little applied, if at all, in practice because the process equipment is more complex and the potential feedstocks such as LPG or naphtha have a higher alternative value. Existing reformers are mostly large industrial plants but small scale prototypes have been developed.

Partial oxidation of a carbonaceous feedstock in the presence of water also produces syngas and can be applied to a wide range of materials, in particular heavy feedstocks such as oil residues and coal, as well as biomass feeds such as wood. The front end of the process is essentially the same as for the manufacture of synthetic liquid fuels. The synthesis section is replaced by the CO-shift step. Small scale wood gasifiers for electricity production have been developed at the pilot plant stage and could conceivably be adapted for small scale hydrogen production.

In these processes and particularly for heavy feedstocks, the bulk of the hydrogen comes from water, the carbon in the feed providing the energy required for splitting the water molecule.

Reformers and gasifiers produce CO_2 at a single location and, when using oxygen rather than air, in a virtually pure form. Large scale installations may offer a viable platform for possible CO_2 capture and sequestration projects (see also *section 7*).

Electrolysis uses electricity to split the water molecule. This is a well-established technology both at large and small scale. Interest in large scale hydrogen production may result in improvements in terms of efficiency and costs. One particularly promising development route is high pressure electrolysers (higher production pressure means less compression energy for storage). The use of electricity as the energy vector to produce hydrogen opens the door to the use of a large variety of primary energy sources including fossil and biomass but also wind energy and of course nuclear.

Direct solar energy can also, in principle, be used to produce hydrogen either by thermal splitting of water or electrolysis through photovoltaic electricity. The development of the thermal splitting process is in its infancy while photovoltaic electricity is not expected to be viable at very large scale within the timeframe of this study. We have therefore not included these options.

For on-board hydrogen production, several options are in principle available. From a purely technical point of view, methanol is likely to be the most attractive as the reformer would operate at comparatively low temperatures and would be more tolerant to intermittent demand. Using methanol would once again open the issue of infrastructure and distribution. Gasoline may be the only practical one as it is already available on the forecourts and would enable these vehicles to be introduced even in very small numbers.

A lot of hydrogen can theoretically be produced. In practice though and in view of the availability of both feedstock and technology, only natural gas reforming provides a short term avenue for flexible large scale hydrogen production. The coal route requires large scale, costly plants with major financing and public acceptance issues and needs more research. Biomass is of course an option but of a limited nature particularly as they are many other potential uses for biomass (see *section 9*). The same constraint applies to wind energy which can be used directly as electricity. Only in "stranded wind" situations where electricity from wind could not practically be fed into the grid, would hydrogen production give more benefit than electricity generation. Nuclear energy is potentially a very large supplier of energy with currently low GHG emissions, and could contribute to the supply of hydrogen. However, its development opens societal, political as well as technical issues (*uranium ore availability & extraction process*), the discussion of which *is not considered* in this report.

6.3 Distribution and refuelling infrastructure

As mentioned in the previous section, hydrogen production can be envisaged either centrally in a large plant or, in a number of cases, locally in a small plant serving one or a few refuelling sites. This "on-site" option is plausible for natural gas reformers, wood gasifiers and electrolysers.

Although central plants tend to be more efficient, the downside is the need to transport hydrogen rather than e.g. natural gas or wood. Technologies are available for this and are in use in the industrial hydrogen transport networks in existence in Europe and other parts of the world. Hydrogen is commonly transported in gaseous form in pipelines and road pressurised cylinders or as a liquid in cryogenic tanks (mostly by road).

The development of a large scale hydrogen pipeline distribution network likely requires a European regulatory framework to ensure safety and public acceptance. Existing hydrogen pipelines in Europe link major industrial sites over relatively short distances and would be of limited use in this respect.

For small volumes, transport of gaseous hydrogen using tube trailers is feasible, but the mass of the containers is very high compared with the amount of hydrogen transported. It has been estimated that up to 19 trucks might be needed to deliver the same amount of energy delivered by one gasoline truck.

Even in liquid form, hydrogen remains a low-density energy carrier with implications on the options for road distribution channels (as an illustration supplying a hydrogen refuelling site might take five times as many trucks as is the case for conventional fuels).

This study includes options for pipeline distribution (over an area typical of a major urban community), road transport in pressurised cylinders or in liquid form in cryogenic tanks, as well as distributed hydrogen generation schemes that would reduce the transport problems.

For the refuelling stations, considerations similar to those applicable to CNG apply. Hydrogen dispensers operating at pressures of either 35 or 70MPa have been built and tested, demonstrating safe and reliable refuelling in a public environment.

6.4 Energy and GHG balances

We have considered a large number of alternatives hydrogen pathways and the reader may refer to *Appendix 1* of this report or to *the WTT and TTW reports* for details. In this section we only discuss some of the options to illustrate the most important findings.

The combination of the many routes available for hydrogen production with the choice of final converters makes the global picture rather complex as illustrated in *Figure 6.4*.

Figure 6.4 WTW energy requirement and GHG emissions for hydrogen pathways (2010+ vehicles)
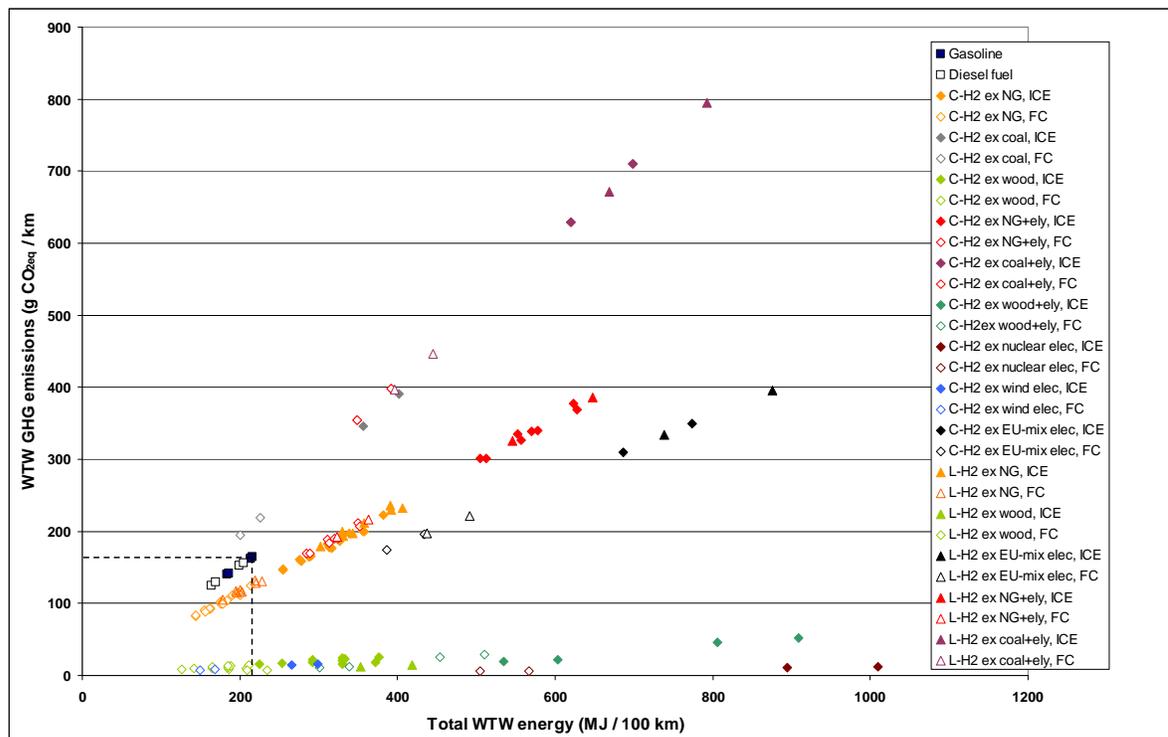
The WTW figures show a very large spread suggesting that, from an energy and GHG point of view, there are favourable and unfavourable ways of producing hydrogen. GHG reduction tends to be at the cost of extra energy although the high efficiency of the fuel cells can compensate for the high hydrogen production energy. Pathways based on electrolysis are very energy-intensive, reflecting the relatively low energy efficiency of electricity generation compared with chemical extraction of hydrogen.

Many potential hydrogen production routes exist and the energy and GHG balances are critically dependent on the pathway selected.

There is clearly a big difference between ICE and fuel cells with respect to energy use and GHG emissions. We first consider in more detail the effect of the final converter on the WTW performance by comparing various vehicles fed with hydrogen produced from natural gas. Focussing then on the fuel cell, we compare the different production routes available.

6.4.1 The impact of the vehicle technology

ICEs and direct fuel cells

Figures 6.4.1-1a/b compare the WTW performance of hydrogen ICE and FC vehicle options, for a common hydrogen source based on NG, to conventional fuel/vehicle and CNG pathways.

Figure 6.4.1-1a/b   WTW total energy requirement and GHG emissions for conventional, CNG and natural gas based hydrogen pathways (2010+ vehicles)

(NG source: pipeline 4000 km)
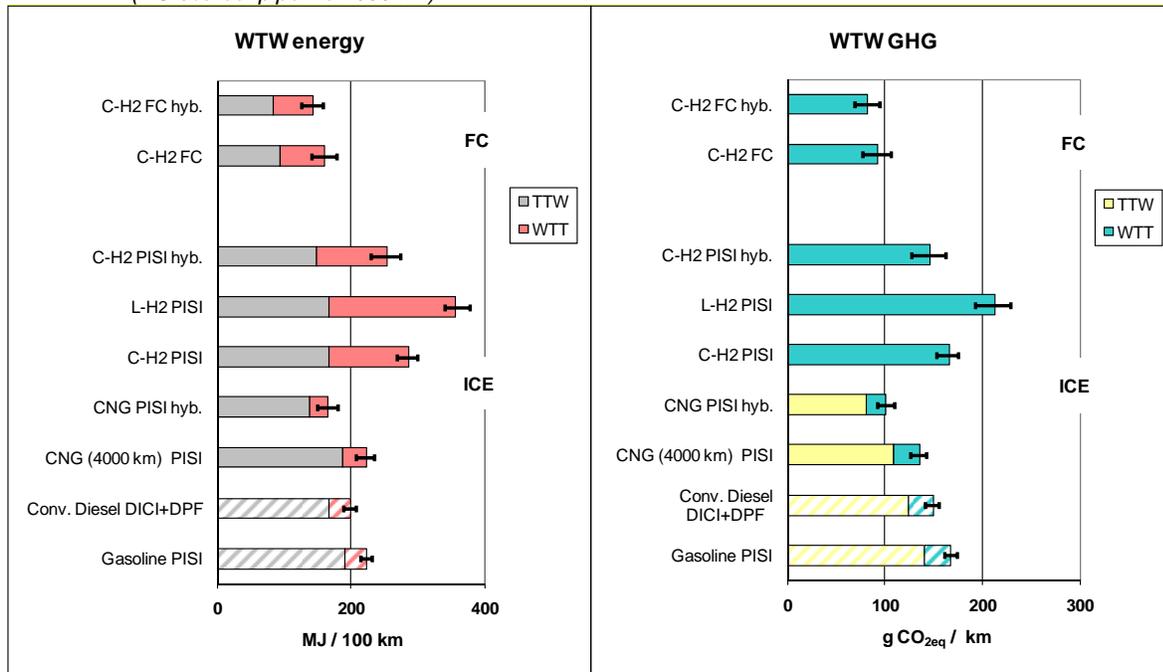
Although hydrogen ICEs have a good fuel efficiency, their WTW balance is unfavourable compared to direct use of NG as CNG. The vehicle cost increase is moderate and these vehicles could potentially be bi-fuel (gasoline-hydrogen). If used as a transition technology to support the development of a hydrogen infrastructure this would be at the cost of significant additional GHG emissions.

For ICE vehicles, direct use of NG as CNG is more energy/GHG efficient than hydrogen

This holds for C-H$_2$ and even more so for L-H$_2$ which requires noticeably more energy.

Liquid hydrogen is more energy intensive than compressed hydrogen

With fuel cells the hydrogen alternative becomes clearly better.

If hydrogen is produced from natural gas, WTW GHG emissions savings can only be achieved with fuel cell vehicles.

Note: in all these pathways the energy and GHG profiles are very similar as the bulk of the primary energy is expended in the form of natural gas.

Combined on-board reformers and fuel cells

Figure 6.4.1-2a/b ***WTW total energy requirement and GHG emissions for indirect hydrogen pathways (2010+ vehicles)***
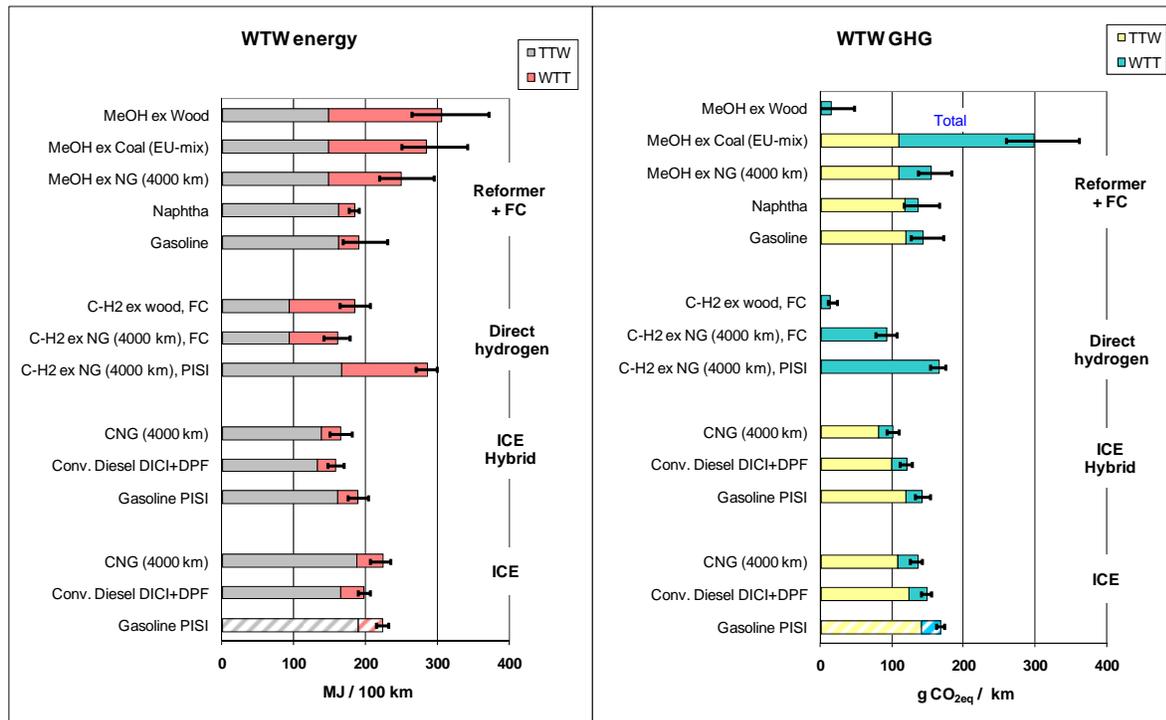
The combination of reforming of a hydrocarbon feedstock and of a fuel cell is less favourable than the direct route to hydrogen from NG combined with a fuel cell. The main reason for this is the lower expected efficiency of the on-board reformers because of their small size. Reforming of heavier feedstocks is also likely to be less efficient than is the case for natural gas while the GHG balance is further affected by the lower H/C ratio of heavier compounds.

With gasoline as the fuel, the on-board reformer option would do slightly better than the ICE but would be on a par with a hybrid version. Its main advantage would be as a transition technology to help growth of the fuel cell market.

> On-board hydrogen production associated to a fuel cell
> - Is more energy and GHG intensive than options using stationary hydrogen production,
> - Does not offer any GHG benefit compared to advanced ICEs / hybrids.

Methanol provides a vector to use natural gas and other non-liquid feeds for such vehicles but is penalised by the energy loss attached to the methanol synthesis. For natural gas this is partly compensated by the more favourable H/C ratio but there is still no advantage compared to more conventional solutions. Wood of course provides a low GHG route but there are other ways to use wood in a more efficient manner (*see section 9*).

6.4.2 The impact of the hydrogen production route

Direct hydrogen production

Figure 6.4.2-1a/b **WTW total energy requirement and GHG emissions for direct compressed hydrogen pathways (2010+ non-hybrid fuel cell vehicles)**
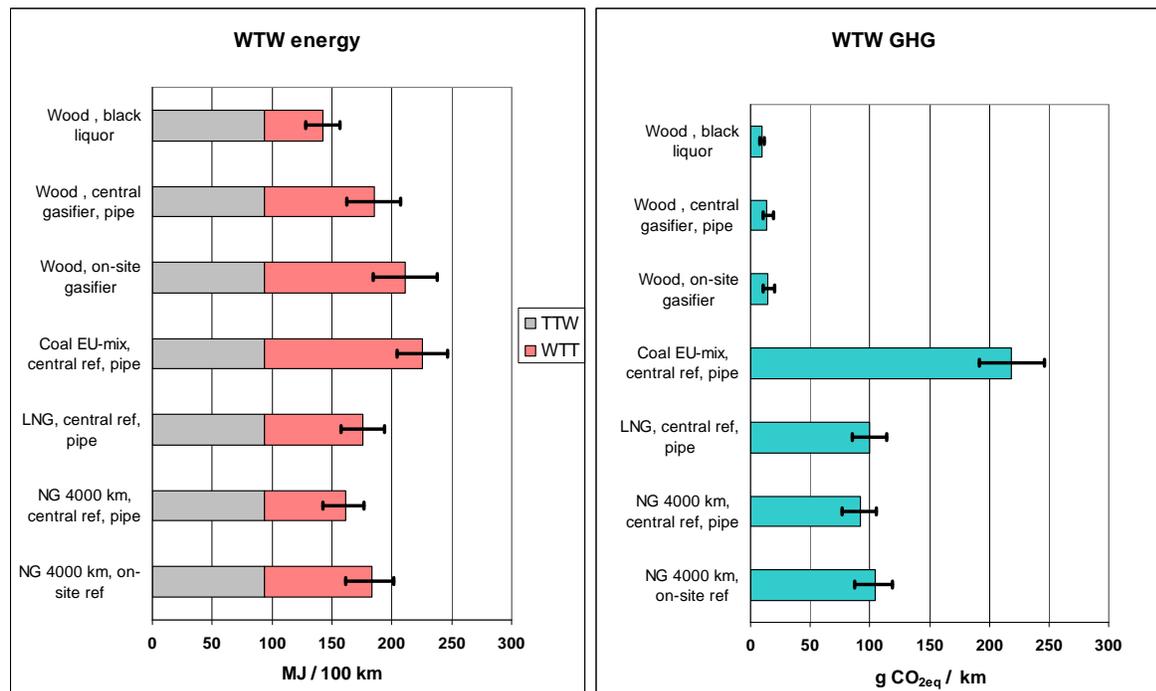
Natural gas reforming is more efficient when carried out centrally in a large plant, where waste energy can be recovered to produce electricity, rather than in a small local or on-site plant because, where this is not practical. In energy terms the contribution of hydrogen transport to the total is minor.

The source of natural gas plays a role through the transportation energy to deliver gas to Europe.

Gasification processes tend to be less energy-efficient than natural gas reforming because of the nature of the feedstock.

The GHG picture is very much consistent with the type of primary feedstock used.

Hydrogen via electrolysis

Turning primary energy into electricity and then electricity into hydrogen is not an energy-friendly route. Even when combined with the most efficient converter, the energy consumption remains higher than for conventional fuels and powertrains.

Note that the energy balance for wind and nuclear energy are somewhat arbitrary. In the case of wind, it is common practice to consider the electricity output of the wind turbine as primary which explains the seemingly low energy requirement. For nuclear, the balance is based on the energy released by the nuclear reaction.

Non-carbon routes obviously emit practically no GHG but here again the real issue for those is optimum use of limited resources (see *section 9*).

Figure 6.4.2-2a/b *WTW total energy requirement and GHG emissions for compressed hydrogen via electrolysis pathways and 2010+ fuel cell vehicles*
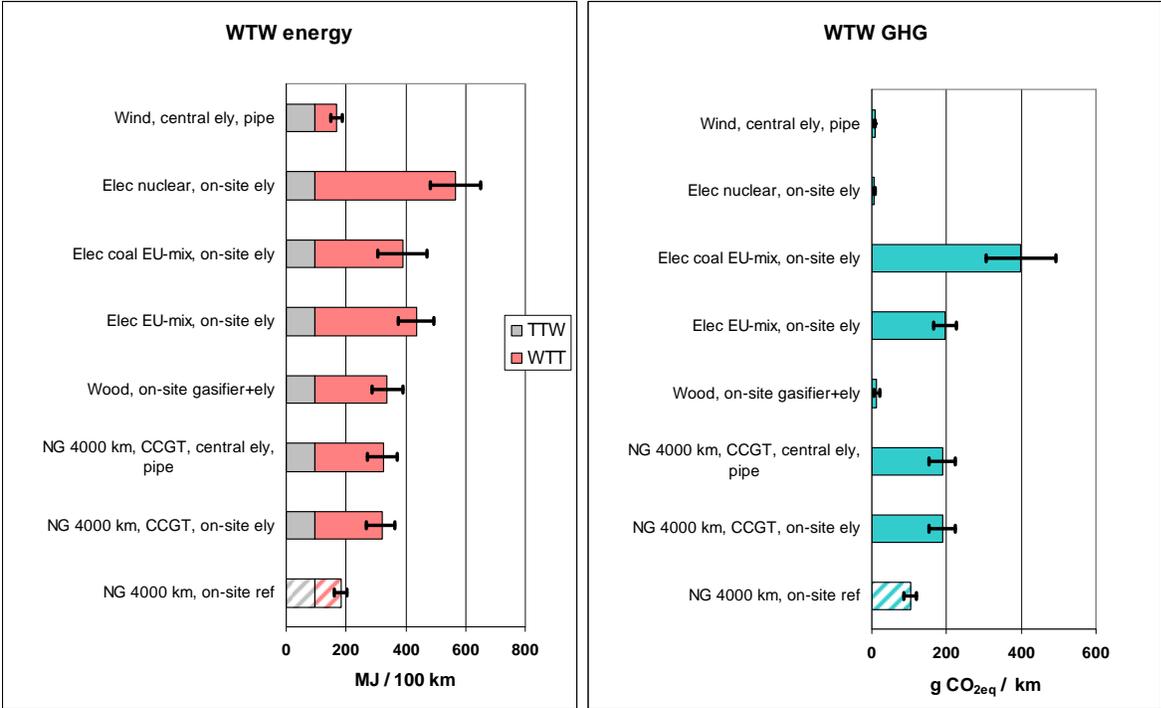
Ely = electrolysis

Electrolysis using EU-mix electricity results in higher GHG emissions than producing hydrogen directly from NG. Hydrogen from non-fossil sources (biomass, wind, nuclear) offers low overall GHG emissions.

7   CO$_2$ capture and storage (CCS)

The concept of isolating the CO$_2$ produced in combustion or conversion processes and injecting it into suitable geological formations has been gaining credibility in the last few years. There are many such structures available in most areas of the globe from depleted gas and oil fields to salt domes and aquifers. CO$_2$ injection can also be used to enhanced and prolonged production from ageing oil and gas fields. Pilot projects are already in operation in the oil and gas industry. The schemes include separation of CO$_2$ from other gases, compression and liquefaction, transport (by pipeline or ships) to the point of injection and injection under pressure.

Separation of CO$_2$ from other gases is a well-established process. In combustion applications using air, scrubbing CO$_2$ out of the flue gases is feasible although very large equipment is required because of the large gas volumes. Oxy-combustion is more favourable from this point of view as it delivers virtually pure CO$_2$, although additional energy needs to be expended in the air separation unit. Reforming and gasification processes deliver CO/hydrogen/CO$_2$ mixtures or mostly hydrogen/CO$_2$ after the shift reaction. In these cases CO$_2$ scrubbing is more straightforward. In some cases, for example before syngas is fed to a Fischer-Tropsch reactor, CO$_2$ scrubbing is required irrespective of the CCS option.

Following capture at the point of emission, CO$_2$ must be compressed and liquefied, transported to the point of storage and injected. Transport is usually envisaged via pipelines when distance between production and storage sites is relatively short. Long-distance transport by ship has also been considered. We have accounted for the energy required for compression to 15 MPa. No additional energy has been included under the assumption that this pressure level would be sufficient to transport CO$_2$ by pipeline over a reasonable distance (typically 100-150 km) and inject it into the geological storage.

In attempting to assess the CO$_2$ benefit and energy requirement of CCS in these different cases we found many literature references. In particular we were guided by a recent study by the IEA's Greenhouse gas R&D programme [*IEA 2005*]. As CCS has so far only been applied on a limited scale in very few locations worldwide, all references refer to theoretical studies. These do not always include details of the envisaged flow schemes and/or full comparative data between the case without CCS and the case with CCS. Many of the process schemes are complex, involving multiple sources of CO$_2$. In a GTL plant, for instance, CO$_2$ is emitted by the syngas production process, the Fischer-Tropsch process and the power plant. Each of these sources produces a different gas mixture which would require different systems to separate the CO$_2$. Generally therefore the degree of CO$_2$ recovery, the energy involved and the cost of the installations required will depend on which gas streams are being tackled.

Because of all these uncertainties and possible lack of consistency between the sources, we consider that the figures for the CCS schemes presented in this report should be regarded as preliminary and indicative of the potential of the technology. As more real-life applications develop, better estimates are expected to become available.

For the same reason we do not report cost figures as the data that can be inferred from the available literature did not seem consistent with the limited practical experience.

The concept can in principle be applied to many fuel production pathways. As illustration of its potential, we have included CCS in the following cases:
- Electricity from natural gas and coal (IGCC)
- LNG: CO$_2$ from the power plant associated to the liquefaction plant.

- Hydrogen from NG and coal: Process CO_2 after shift reaction
- GTL and CTL diesel: Process CO_2 after reforming / partial oxidation
- DME from NG: Process CO_2 after reforming

The compared energy and GHG balances of schemes with and without CCS are shown in the following figures.

Figure 7   ***WTW total energy and GHG balance of selected pathways with and without CCS (2010+ vehicles)***
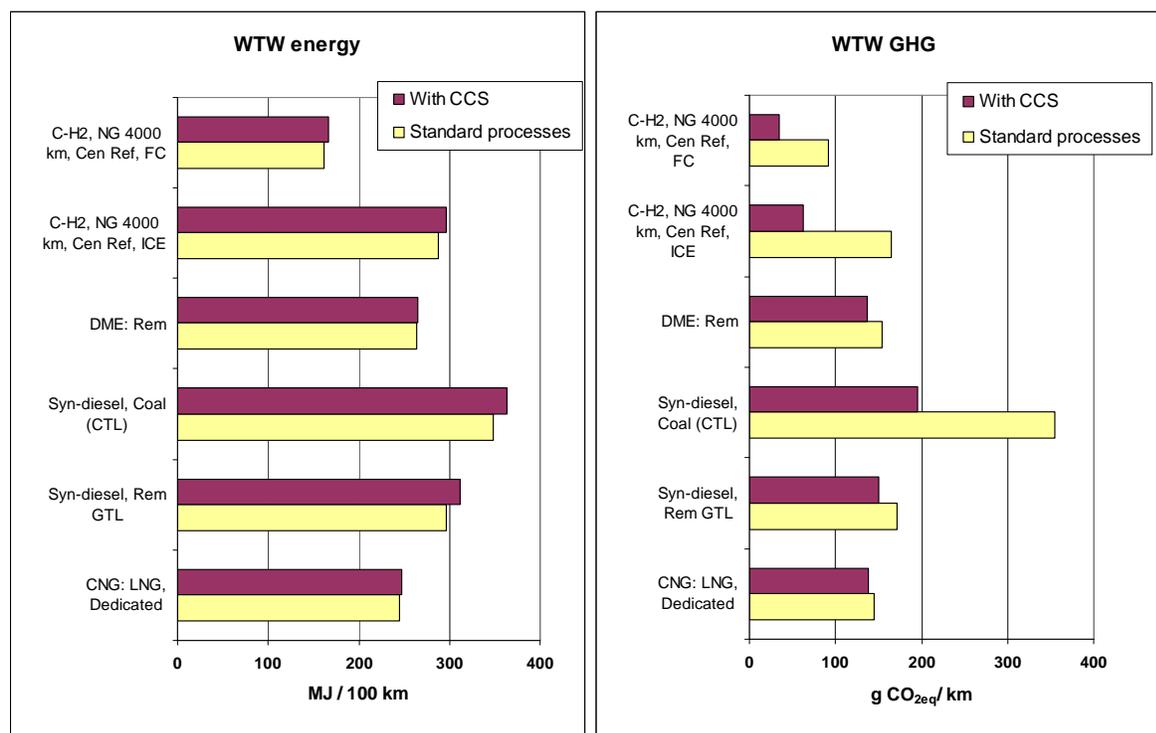
Clearly the potential benefits of CCS are much larger for certain pathways. Not surprisingly coal-based processes such as CTL stand to benefit the most as they involve low energy efficiency and high-carbon primary resource.

Hydrogen pathways involve complete decarbonisation of the feedstock and make therefore the majority of the original carbon available for capture. We have only represented a limited number of options but it stands to reason that pathways such as coal to hydrogen would show an even more favourable picture. It must also be pointed out that, in hydrogen pathways, CO_2 is already available in more or less pure form whether or not CCS is intended. As a result the extra energy requirement and cost are likely to be more limited than in other schemes.

Applying CCS to LNG or GTL schemes can also offer CO_2 reduction but of a more limited nature. The justification for such schemes comes from the fact that such plants would be located very near gas or oil fields where the CO_2 could be re-injected.

> Large scale production of synthetic fuels or hydrogen from coal or gas offers the potential for GHG emissions reduction via CO_2 capture and sequestration and this merits further study.

8 Costs and potential availability

This section has not been updated in this version 3. The figures computed in version 2b are considered obsolete and are not supported.

9   Alternative uses of primary energy resources

The previous sections cover the original scope and objectives of the study and the main key conclusions are summarised at the beginning of this report.

The present section 9 is extending the analysis, using the WTW data generated to highlight important aspects regarding primary energy resources. Indeed, their availability for transport fuels, in particular when assessing the biomass, merits considerations in a more general context of competing uses.

Figure 9 shows the relationship between total WTW energy usage and WTW GHG emissions for all non-hydrogen pathways. *Figure 6.4* gives the same information for hydrogen pathways. These figures clearly highlight the fact that, in general, a reduction of GHG emissions has to be paid for by more primary energy usage. Although GHG emissions are of prime concern today, energy conservation and efficient use of energy resources are also desirable goals.

Figure 9   WTW energy requirement and GHG emissions for non-hydrogen pathways (2010+ vehicles)
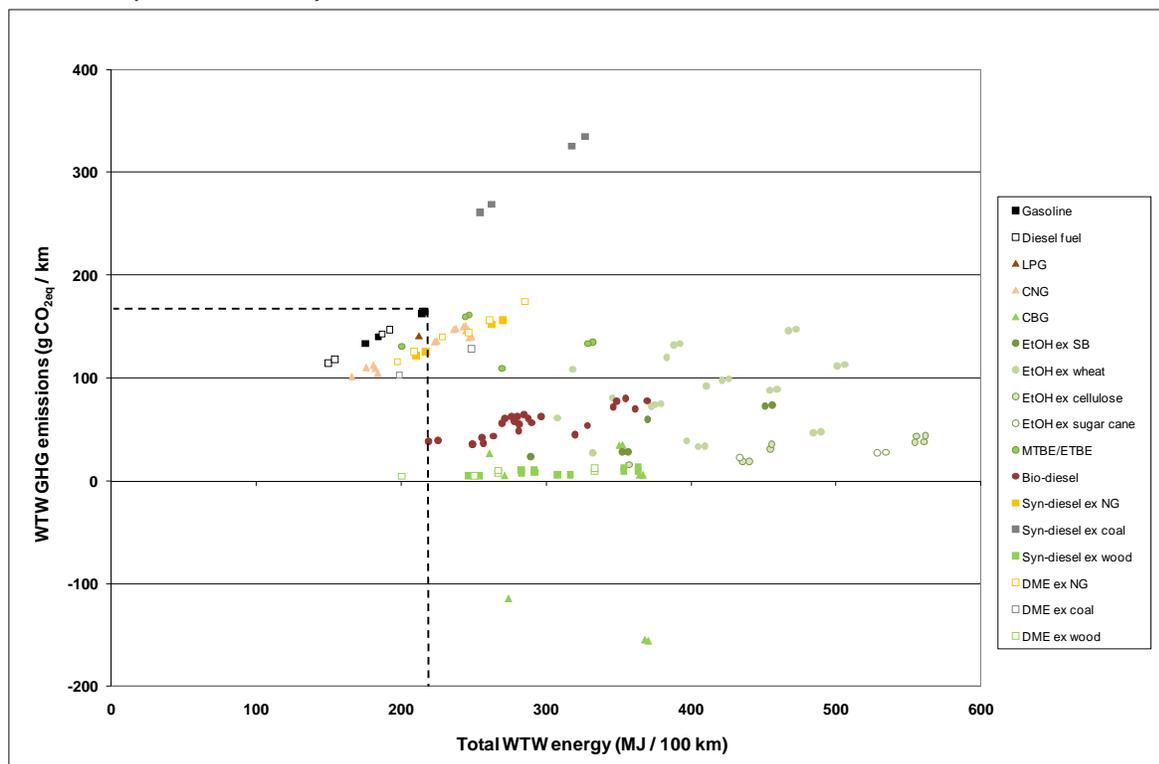
Virtually all primary energy resources are in practice available in limited quantities. For fossil fuels the limit is physical, expressed in barrels or m³ actually present in the ground and recoverable. For biomass the limit is total available land use. The planet is unlikely to run out of sun or out of wind in the foreseeable future but our capacity to harness these energies is very much limited by our ability to build enough converters at a reasonable cost and find acceptable sites to install them. In other words, access to primary energy is limited and it is therefore important to consider how GHG reductions could be achieved at minimum energy.

In the following sections we look at the various ways of using primary resources to produce road fuels and use electricity generation as a reference point. An exhaustive analysis would require consideration not only of road transport and electricity but of the whole energy sector.

9.1 Natural gas

Within the limited scope considered in this study for using natural gas as a source of transportation, availability of natural gas is not a real issue. There are, however, large differences in the amount of GHG that can be avoided with one MJ of natural gas.

To illustrate this point we have considered 5 possible substitution options:

- NG is commonly used to produce electricity and could replace coal, often considered as the marginal fuel for electricity production. Electricity from coal is GHG-intensive and this provides large GHG savings.
- CNG only provides small savings because its global GHG balance is close to that of the gasoline and diesel fuels it would replace.
- The opposite holds for FT diesel fuel which is slightly more GHG-intensive than conventional diesel fuel.
- Direct hydrogen production has the potential to save large amounts of GHG as long as the hydrogen is used in a fuel cell thereby reaping the energy efficiency benefit. The savings are, however, still much less than in the coal substitution case.

Figure 9.1 CO$_2$ avoidance from alternative uses of natural gas
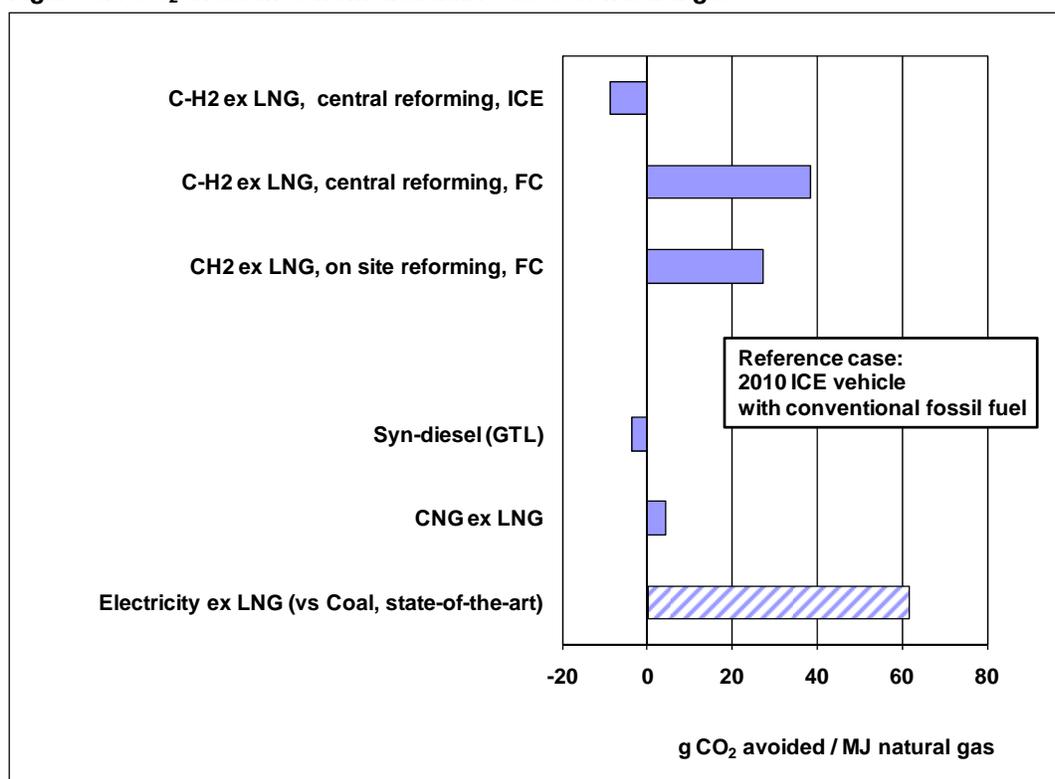
9.2 Biomass

Except for straw, which in suitable areas can be taken from food crops, and organic waste, land is the common biomass resource. It can be used in a myriad of ways some of which have been described in this study, but its availability for growing crops is essentially limited, particularly for energy crops that have to compete with food crops.

In the following figure we consider a hypothetical hectare of land and compare its "CO$_2$ avoidance potential" when used with different crops. The range shown for each option corresponds to the different pathways available.

Figure 9.2 CO$_2$ avoidance from alternative uses of land
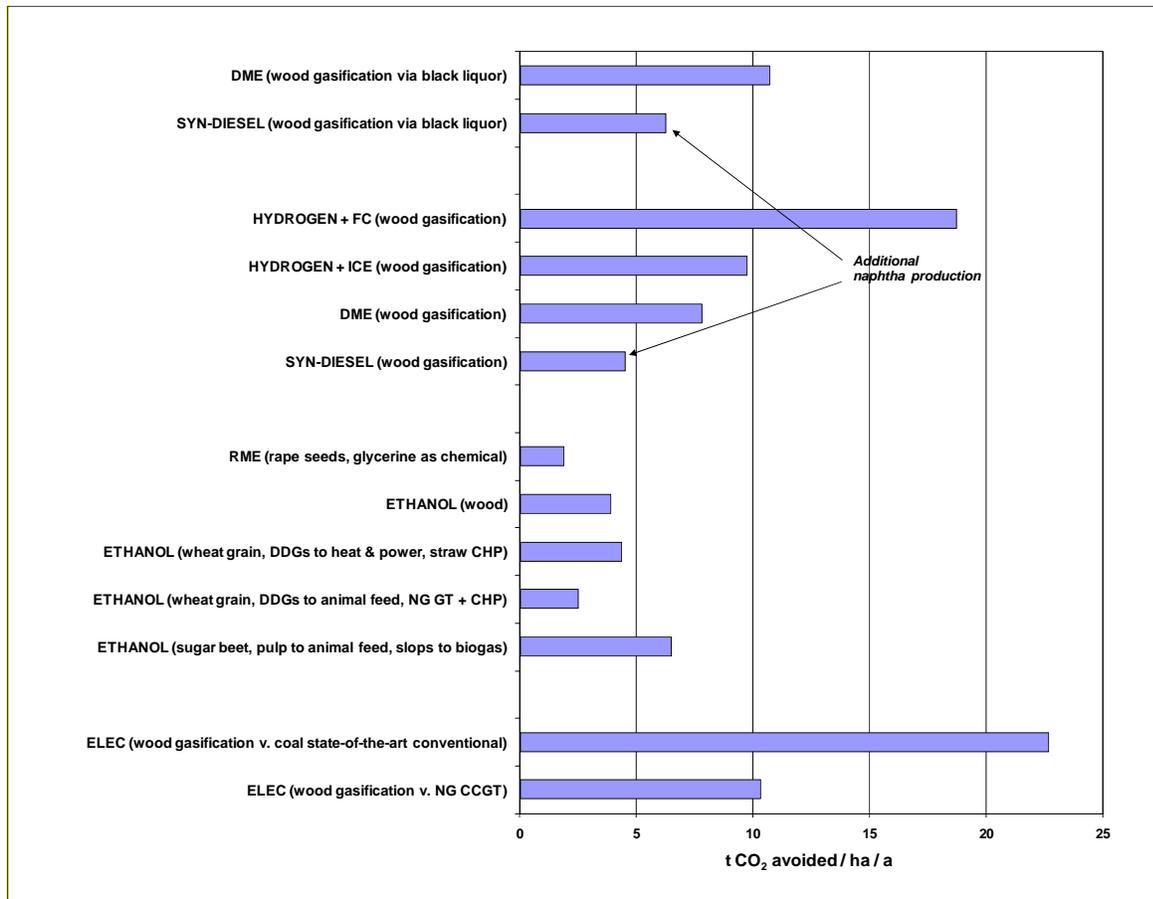
Electricity production is energy intensive and substitution by biomass results in large CO$_2$ savings, particularly when coal is being substituted. The technology used for biomass conversion can make a lot of difference, the IGCC concept (top end of the range) being far superior to a conventional boiler + steam turbine system (but also a lot more expensive). Note that wood is used here as a proxy for all high yield energy plants. Substitution of biomass for coal in electricity generation provides one of the best CO$_2$ savings.

Direct hydrogen production from wood is also attractive because of the reasonable efficiency of the conversion plants, particularly large ones. It can be better than substituting natural gas for electricity but only as long as the final converter is an efficient fuel cell. Even in the latter case, electrolysis (bottom of the range) is worse than the natural gas case. The high end of the range corresponds to wood conversion via the "black liquor" route, a particularly efficient option though limited in scope.

Ethanol and FAME are much less attractive partly because of yields but also because they do not allow a gain in efficiency on the vehicle side. Synthetic diesel fuel and DME are in the same range as natural gas electricity substitution.

This analysis is of course a little simplistic. Each hectare of land has its specific characteristics that make it most suitable for a certain kind of crop or crops (in rotation). Rape is for instance an attractive break crop on a land dedicated to cereals. One could obviously not grow wood for a year between two cereal cycles. Also yields can vary a great deal between areas and one should refrain from using the above figures to estimate the CO$_2$ that could be saved with a certain area of land.

The point is that there are significant overall differences between the options and one must look both at relative and absolute figures.

9.3 Wind

How much energy can be harnessed from wind can be a matter of endless debates. The main issue is first to find suitable sites, get the appropriate approvals and public acceptance and then to construct a suitable financial structure to make a project feasible. The rate of success in doing this, rather than the number of potential sites, will determine how much wind power is installed.

Technology is moving fast with increasingly large and more efficient turbines. The impact on wind farm on the environment is a big issue and one of the major stumbling blocks. People have generally nothing against wind farms as long as they can't see or hear them. Noise is indeed one of the problems although it is being addressed by manufacturers. In the long term, offshore installations are the most promising. They cause less environmental nuisance, can be very large and can benefit from much stronger and steadier winds.

In any case, there is no serious scenario suggesting that enough wind power could be installed to produce all of the European electricity demand. Because of its intermittent and partly unpredictable nature wind electricity can be difficult to integrate into the grid without risking major upsets. Figures of 10 to 20% have been mentioned as the maximum acceptable fraction of wind electricity in the total. Any surplus, either structural or occasional, could be used to produce e.g. hydrogen. Whether enough wind capacity is developed remains to be seen.

The following figure illustrates the CO_2 avoidance potential of wind electricity.

Figure 9.3 CO_2 avoidance potential of wind electricity
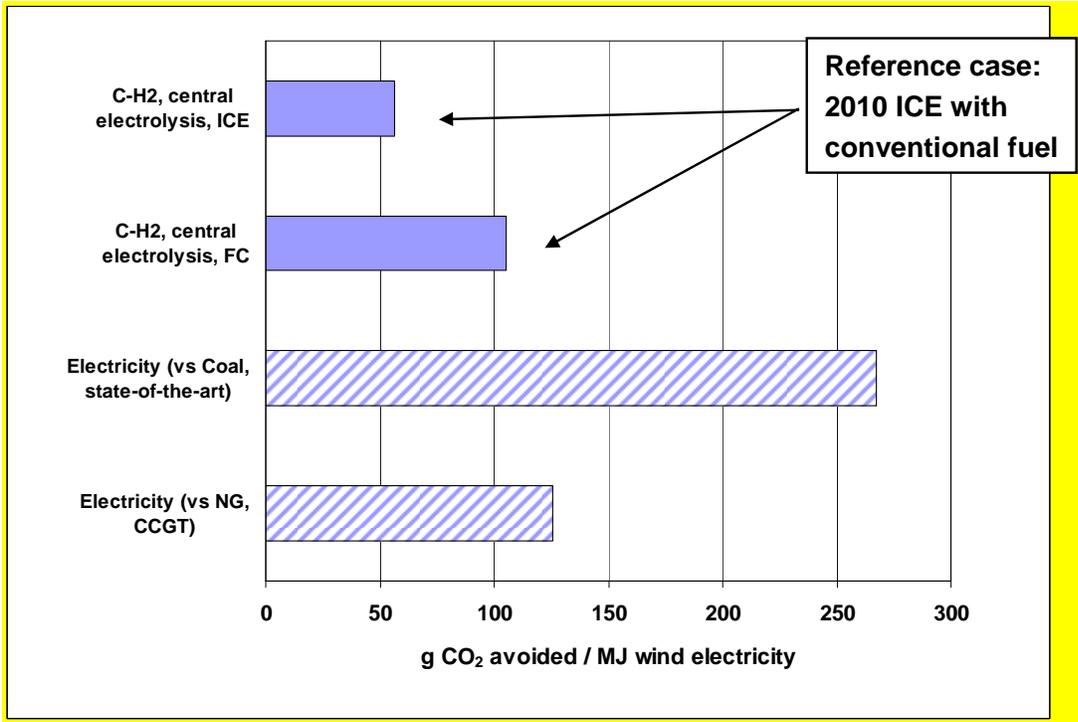
Substituting fossil electricity generally gives higher GHG reductions, even when the final converter is a fuel cell (this is because of the extra inefficiency introduced by the electrolyser).

Acronyms and abbreviations used in the WTW study

ADVISOR	A powertrain simulation model developed by the US-based National Renewable Energy Laboratory
BTL	Biomass-To-Liquids: denotes processes to convert biomass to synthetic liquid fuels, primarily diesel fuel
CAP	The EU's Common Agricultural Policy
CCGT	Combined Cycle Gas Turbine
CCS	CO_2 capture and storage
C-H_2	Compressed hydrogen
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO_2	Carbon dioxide: the principal greenhouse gas
CONCAWE	The oil companies' European association for environment, health and safety in refining and distribution
DDGS	Distiller's Dried Grain with Solubles: the residue left after production of ethanol from wheat grain
DG-AGRI	The EU Commission's General Directorate for Agriculture
DICI	An ICE using the Direct Injection Compression Ignition technology
DME	Di-Methyl-Ether
DPF	Diesel Particulate Filter
DISI	An ICE using the Direct Injection Spark Ignition technology
ETBE	Ethyl-Tertiary-Butyl Ether
EUCAR	European Council for Automotive Research and Development
EU-mix	The average composition of a certain resource or fuel in Europe. Applied to natural gas, coal and electricity
FAEE	Fatty Acid Ethyl Ester: Scientific name for bio-diesel made from vegetable oil and ethanol
FAME	Fatty Acid Methyl Ester: Scientific name for bio-diesel made from vegetable oil and methanol
FAPRI	Food and Agriculture Policy Research Institute (USA)
FC	Fuel Cell
FSU	Former Soviet Union
FT	Fischer-Tropsch: the process named after its original inventors that converts syngas to hydrocarbon chains
GDP	Gross Domestic Product
GHG	Greenhouse gas
GTL	Gas-To-Liquids: denotes processes to convert natural gas to liquid fuels
HC	Hydrocarbons (as a regulated pollutant)
HRSG	Heat Recovery Steam Generator
ICE	Internal Combustion Engine
IEA	International Energy Agency
IES	Institute for Environment and Sustainability
IFP	Institut Français du Pétrole
IGCC	Integrated Gasification and Combined Cycle
IPCC	Intergovernmental Panel for Climate Change
JRC	Joint Research Centre of the EU Commission
LBST	L-B-Systemtechnik GmbH
LCA	Life Cycle Analysis
L-H_2	Liquid hydrogen
LHV	Lower Heating Value ('Lower" indicates that the heat of condensation of water is not included)
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gases
MDEA	Methyl Di-Ethanol Amine
ME	The Middle East
MTBE	Methyl-Tertiary-Butyl Ether
MPa	Mega Pascal, unit of pressure (1 MPa = 10 bar). Unless otherwise

	stated pressure figures are expressed as "gauge" i.e. over and above atmospheric pressure
Mtoe	Million tonnes oil equivalent. The "oil equivalent" is a notional fuel with a LHV of 42 GJ/t
N_2O	Nitrous oxide: a very potent greenhouse gas
NEDC	New European Drive Cycle
NG	Natural Gas
NOx	A mixture of various nitrogen oxides as emitted by combustion sources
OCF	Oil Cost Factor
OGP	Oil & Gas Producers
PEM fuel cell	Proton Exchange Membrane fuel cell
PISI	An ICE using the Port Injection Spark Ignition technology
PSA	Pressure Swing Absorption unit
RME	Rapeseed Methyl Ester: biodiesel derived from rapeseed oil (colza)
SMDS	The Shell Middle Distillate Synthesis process
SME	Sunflower Methyl Ester: biodiesel derived from sunflower oil
SOC	State Of Charge (of a battery)
SRF	Short Rotation Forestry
SSCF	Simultaneous Saccharification and Co-Fermentation: a process for converting cellulosic material to ethanol
SUV	Sport-Utility Vehicle
Syngas	A mixture of CO and hydrogen produced by gasification or steam reforming of various feedstocks and used for the manufacture of synthetic fuels and hydrogen
TES	Transport Energy Strategy. A German consortium that worked on alternative fuels, in particular on hydrogen
TTW	Tank-To-Wheels: description of the burning of a fuel in a vehicle
ULCC	Ultra Large Crude Carrier
VLCC	Very Large Crude Carrier
WTT	Well-To-Tank: the cascade of steps required to produce and distribute a fuel (starting from the primary energy resource), including vehicle refuelling
WTW	Well-To-Wheels: the integration of all steps required to produce and distribute a fuel (starting from the primary energy resource) and use it in a vehicle
ZEV	Zero Emission Vehicle

European Commission

Abstract

WELL-TO-WHEELS ANALYSIS OF FUTURE AUTOMOTIVE FUELS AND POWERTRAINS IN THE
EUROPEAN CONTEXT

The JEC research partners [Joint Research Centre of the European Commission, EUCAR and CONCAWE]
have updated their joint evaluation of the well-to-wheels energy use and greenhouse gas emissions for a wide
range of potential future fuel and powertrain options.

This document reports on the third release of this study replacing Version 2c published in March 2007.

The original version was published in December 2003.

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