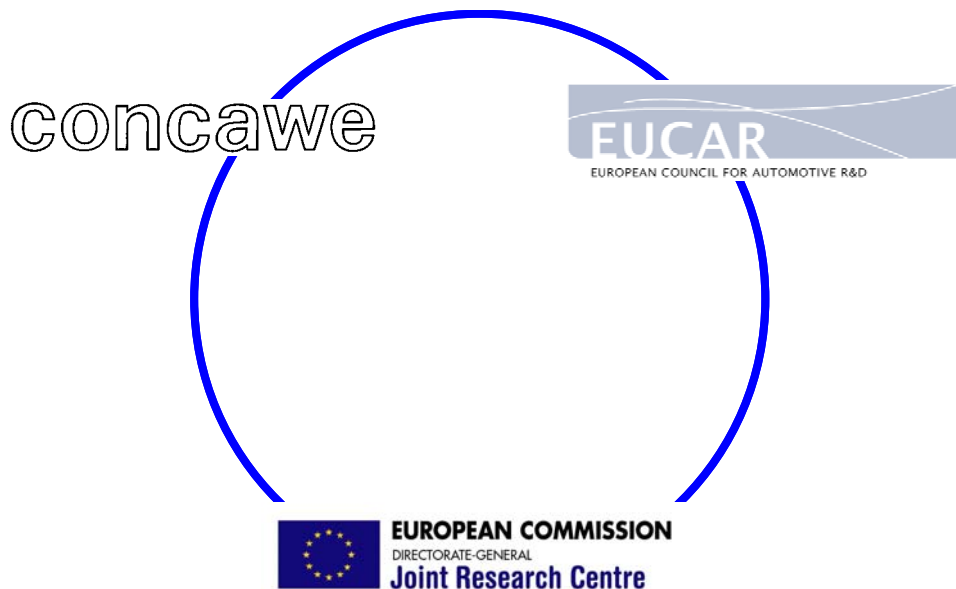


**WELL-TO-WHEELS ANALYSIS OF
FUTURE AUTOMOTIVE FUELS AND
POWERTRAINS
IN THE EUROPEAN CONTEXT**



WELL-to-WHEELS Report

Version 2b, May 2006

This report is available as an ADOBE pdf file on the JRC/IES website at:

<http://ies.jrc.ec.europa.eu/WTW>

Questions and remarks may be sent to:

infoWTW@jrc.it

Notes on version number:

This document reports on the second release of this study replacing version 2a published in December 2005. The original version 1b was published in December 2003.

There have been extensive modifications to the 2003 report including addition on new pathways, review of certain pathway basic data, review and update of cost and availability as well as correction of some errors pointed out by our readers.

Compared to version 2a, the modifications are limited to cost and availability figures:

- Minor adjustments to biomass availability figures
- Significant review of vehicles costs affecting primarily hybrids and fuel cells

Key Findings

EUCAR, CONCAWE and JRC (the Joint Research Centre of the EU 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 energy. The specific pathway is critical.
- Results must further be evaluated in the context of volume potential, feasibility, practicability, costs and customer acceptance of the pathways investigated.
- *A shift to renewable/low carbon sources is currently expensive.*
 - *GHG emission reductions always entail costs but high cost does not always result in large GHG reductions*
- *No single fuel pathway offers a short term route to high volumes of "low carbon" fuel*
 - *Contributions from a number of technologies/routes will be needed*
 - *A wider variety of fuels may be expected in the market*
 - *Blends with conventional fuels and niche applications should be considered if they can produce significant GHG reductions at reasonable cost.*
- Large scale production of synthetic fuels or hydrogen from coal or gas offers the potential for GHG emissions reduction via CO₂ 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 CO₂ saving potential coupled with refuelling infrastructure and vehicle costs lead to a fairly high cost per tonne of CO₂ 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.
- 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.
- *Potential volumes of ethanol and bio-diesel are limited. The cost/benefit, including cost of CO₂ avoidance and cost of fossil fuel substitution crucially depend on the specific pathway, by-product usage and N₂O emissions. Ethanol from cellulose could significantly increase the production potential at a cost comparable with more traditional options or lower when using low value feedstocks such as straw.*
- 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 and cheapest 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 and are at present expensive.*
- *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.*
- *The technical challenges in distribution, storage and use of hydrogen lead to high costs. Also the cost, availability, complexity and customer acceptance of vehicle technology utilizing hydrogen technology should not be underestimated.*
- ❑ For hydrogen as a transportation fuel virtually all GHG emissions occur in the WTT portion, making it particularly attractive for CO₂ 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/IES (the Institute for Environment and Sustainability of the EU Commission's Joint Research Centre), assisted by personnel from L-B-Systemtechnik GmbH (LBST) and the Institut Français de Pétrole (IFP).

Main authors

R. Edwards (WTT)	JRC/IES
J-F. Larivé (WTT/WTW)	CONCAWE
V. Mahieu (WTW)	JRC/IES
P. Rouveïrolles (TTW)	Renault

Scientific Advisory Board

H. Hass	Ford
V. Mahieu	JRC/IES
D. Rickeard	ExxonMobil
G. De Santi	JRC/IES
N. Thompson	CONCAWE
A. van Zyl	EUCAR

CONCAWE task force

J. Baro	Repsol
R. Cracknell	Shell
J. Dartoy	Total
J-F. Larivé	CONCAWE
J. Nikkonen	Neste Oil
D. Rickeard	ExxonMobil
N. Thompson	CONCAWE
C. Wilks	BP

EUCAR task force

H. Hass	Ford
A. Jungk	BMW
S. Keppeler	DaimlerChrysler
E. Leber / T. Becker	Opel
B. Maurer	PSA
G. Migliaccio	Fiat
H. Richter	Porsche
P. Rouveïrolles	Renault
A. Røj	Volvo
R. Wegener	VW

LBST (Well-to-Tank consultant)

J. Schindler
W. Weindorf

IFP (Tank-to-Wheel consultant)

J-C Dabadie
S. His

Table of contents

1	Study objectives and organisational structure	10
2	Scope and methodology	12
2.1	WTT approach	14
2.1.1	Pathways and processes	15
2.1.2	Costing basis	15
2.1.3	Incremental approach	15
2.1.4	By-product credits	16
2.1.5	Scale and availability	17
2.1.6	Data sources	17
2.2	TTW approach	17
2.2.1	Vehicle data and performance	17
2.2.2	Vehicle simulations	18
2.2.3	Reference road cycle	19
2.3	WTW integration	19
3	Conventional Fuels and Powertrains 2002/2010⁺	21
3.1	Conventional gasoline and diesel fuel	21
3.2	Fuels/vehicles combinations	21
3.3	Energy and GHG balances	22
4	Compressed Natural Gas (CNG), biogas (CBG), LPG	25
4.1	CNG production and availability	25
4.1.1	Natural gas sourcing	25
4.1.2	Distribution and refuelling infrastructure	25
4.2	CNG vehicles	25
4.2.1	2002 Bi-fuel and dedicated CNG vehicles	26
4.2.2	2010 improvements expected from CNG engines	27
4.2.3	2010 hybrids	27
4.3	CNG pathways energy and GHG balances	27
4.4	Biogas	29
4.5	LPG	30
5	Alternative liquid fuels / components	31
5.1	"Conventional" biofuels (ethanol and bio-diesel)	31
5.1.1	Sources and manufacturing processes of ethanol	32
5.1.2	Sources and manufacturing processes of bio-diesel	33
5.1.3	N ₂ O emissions from agriculture	34
5.1.4	Reference scenario for crops	34
5.1.5	Energy and GHG balances	35
5.1.6	Other environmental impacts of biofuels production	37
5.2	MTBE and ETBE	39
5.3	Synthetic diesel fuel and DME	40
5.3.1	Sources and manufacturing processes	40
5.3.2	Energy and GHG balances	42

6	Hydrogen	44
6.1	Hydrogen-fuelled powertrains and vehicles	44
6.1.1	Hydrogen Internal Combustion Engine	44
6.1.2	Fuel Cells	45
6.1.3	Indirect hydrogen: on-board reformers	46
6.2	Hydrogen production routes and potential	47
6.3	Distribution and refuelling infrastructure	48
6.4	Energy and GHG balances	49
6.4.1	The impact of the vehicle technology	50
6.4.2	The impact of the hydrogen production route	52
7	CO₂ capture and storage (CC&S)	54
8	Costs and potential availability	56
8.1	WTT costs	56
8.1.1	Fossil fuels and raw materials	56
8.1.2	Investment and operating costs	57
8.1.3	Conventional fuels	58
8.1.4	CNG	58
8.1.5	(Compressed) Biogas	58
8.1.6	LPG	59
8.1.7	Biomass resources	59
8.1.8	Liquid fuels and DME	60
8.1.9	Hydrogen	61
8.2	TTW costs: Vehicle retail price estimation	61
8.3	Road fuels demand forecasts	63
8.4	Cost estimates	63
8.4.1	CNG/CBG/LPG, liquid fuels and DME	64
8.4.2	Hydrogen	71
8.5	Availability of fossil resources and fuels	74
8.6	Availability of biomass-based fuels	76
8.6.1	Conventional ethanol and bio-diesel	77
8.6.2	"Advanced" biofuels	78
8.6.3	Biogas	80
8.6.4	Overview of biomass potential	81
9	Alternative uses of primary energy resources	83
9.1	Natural gas	84
9.2	Biomass	84
9.3	Wind	86
	Acronyms and abbreviations used in the WTW study	87

1 Study objectives and organisational structure

EUCAR, CONCAWE and JRC (the Joint Research Centre of the EU 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 remain the same:

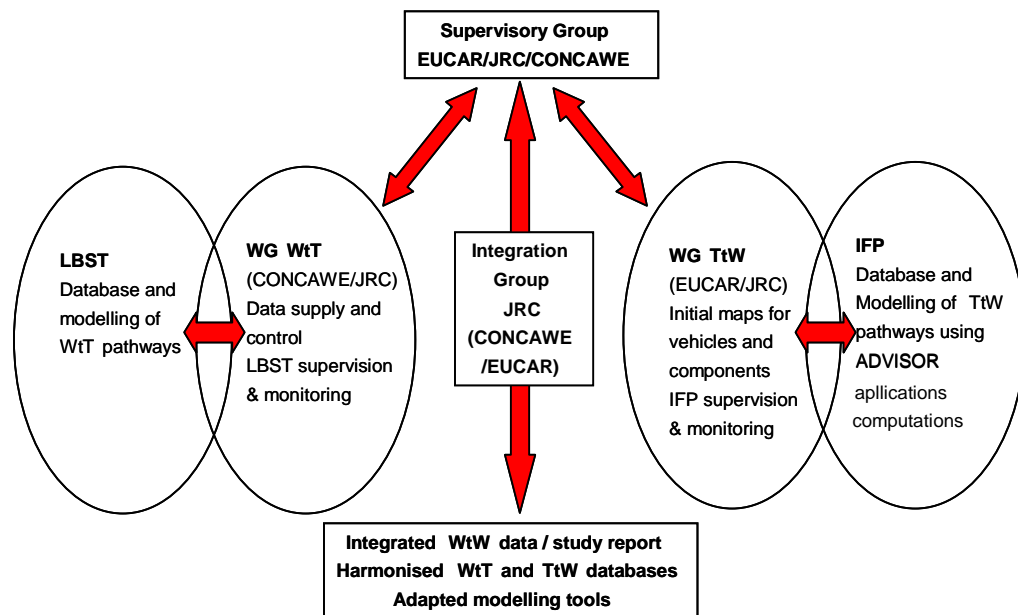
- Establish, in a transparent and objective manner, a consensual well-to-wheels energy use and GHG emissions assessment of a wide range of automotive fuels and powertrains relevant to Europe in 2010 and beyond.
- Consider the viability of each fuel pathway and estimate the associated macro-economic costs.
- Have the outcome accepted as a reference by all relevant stakeholders.

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 Joint Research Centre of the EU 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 LBST¹, a consultancy firm with a proven track record in WTW assessment and which had a major involvement in previous work by General Motors² and the TES consortium³. JRC IES⁴ 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 IES contributed to the initial ADVISOR code assessment and its adaptation to European market conditions.

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

¹ E² 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

⁴ Institute for Environment and Sustainability

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 CO₂ 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 CO₂ capture and storage. *Section 8* gives an overview of the costs of substitution and CO₂ 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. In terms of cost, however, we have focussed on Europe as a macro-economic entity, taking into account, in particular, the commodity markets that govern the prices of a number of raw materials and products. We have only considered the "direct" costs related e.g. to purchasing feedstocks, building plants, infrastructure and vehicles. We have not considered other possible sources of costs (or benefits) related to e.g. employment opportunities, regional development and the like.

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

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

⁽¹⁾ with/without CO₂ capture and sequestration

⁽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

The best options from an energy or GHG point of view are only likely to raise interest if they can be developed at a reasonable cost. Cost estimation is a difficult discipline and one must endeavour to define clearly what is intended. In this case we have attempted to estimate the "macro-economic" costs to the EU as an entity of producing a certain fuel in a certain way at a certain scale.

For those resources that are also internationally traded commodities (such as oil products, natural gas or wheat grain), the market price represents the minimum cost as it corresponds to the amount either required to purchase that commodity or not realised by using that resource elsewhere (for instance the cost of crude oil to the EU is not its production cost but its price on the international market). Production at a higher cost within the EU is only likely to occur if some form of subsidy is available. Since costs and not customer prices are presented, subsidies and taxes are not included in the calculation. The figures represent the full cost to the EU, regardless of how this is shared out. For other resources (e.g. wood) we have estimated the production cost from the various processes involved.

We have considered two separate cost scenarios for crude oil prices of 25 and 50 €/bbl. In time most economic actors are affected by a major change of crude oil price and we have attached an "Oil Cost Factor" (OCF) to most cost items.

2.1.3 Incremental approach

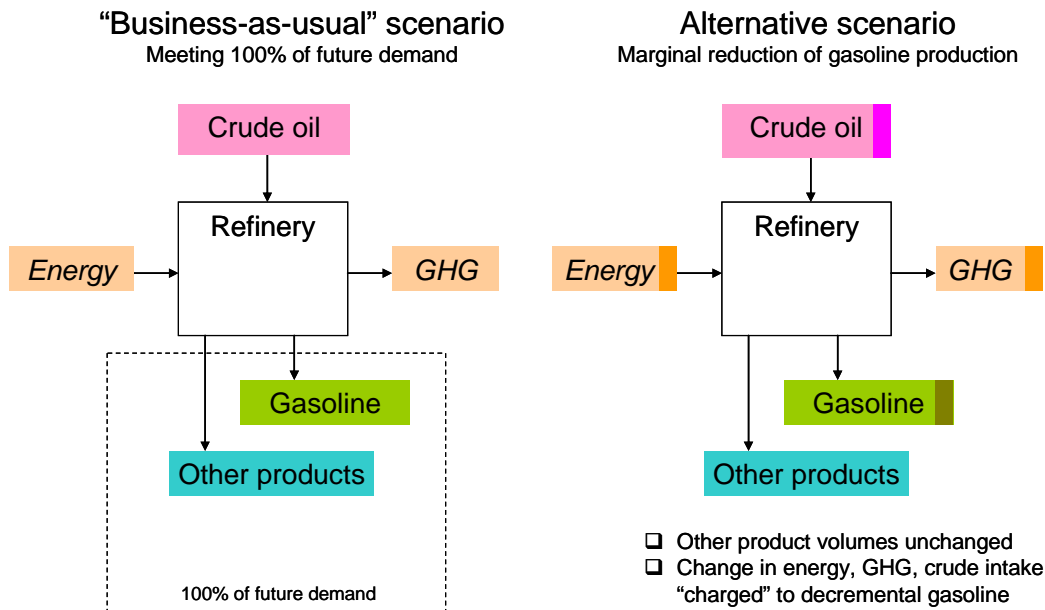
The ultimate purpose of this study is to guide those who have to make a judgement on the potential benefits of substituting conventional fuels by alternatives. It is clear that these benefits depend on the *incremental* resources required for alternative fuels and the *incremental* savings from conventional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



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.

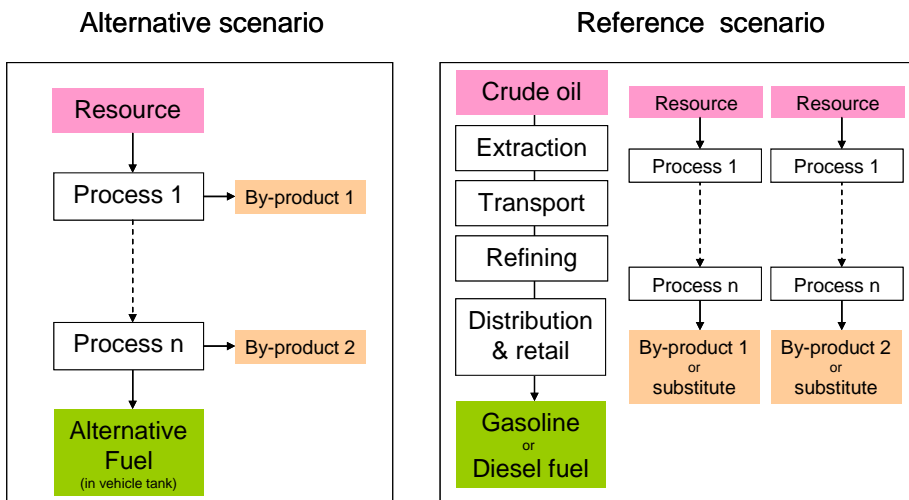
The implication of this logic is the following methodology (**Figure 2.1.4**):

- 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. We have therefore endeavoured to assess the future “availability” of the different fuels and associated resources. A full discussion of availability data is included in the *WTT report, section 5*. The most important points are also discussed in the relevant sections of this report for each fuel type. In preparing these estimates we have tried to be realistic taking into account economical as well as practical constraints.

2.1.6 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. Our contribution has been to review and update the existing data and add a number of new processes and a number of new pathways not hitherto considered.

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 PISl 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 set of performance criteria, given in the following table.

Table 2.2.1 Minimum vehicle performance criteria

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 4 th gear	s	<13
Time lag for 80-120 km/h in 5 th gear	s	-
Gradability 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

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 i.e.

- EURO III for 2002 vehicles,
- EURO IV for 2010+ vehicles.

Powertrain configurations and components were selected accordingly. 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.

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:

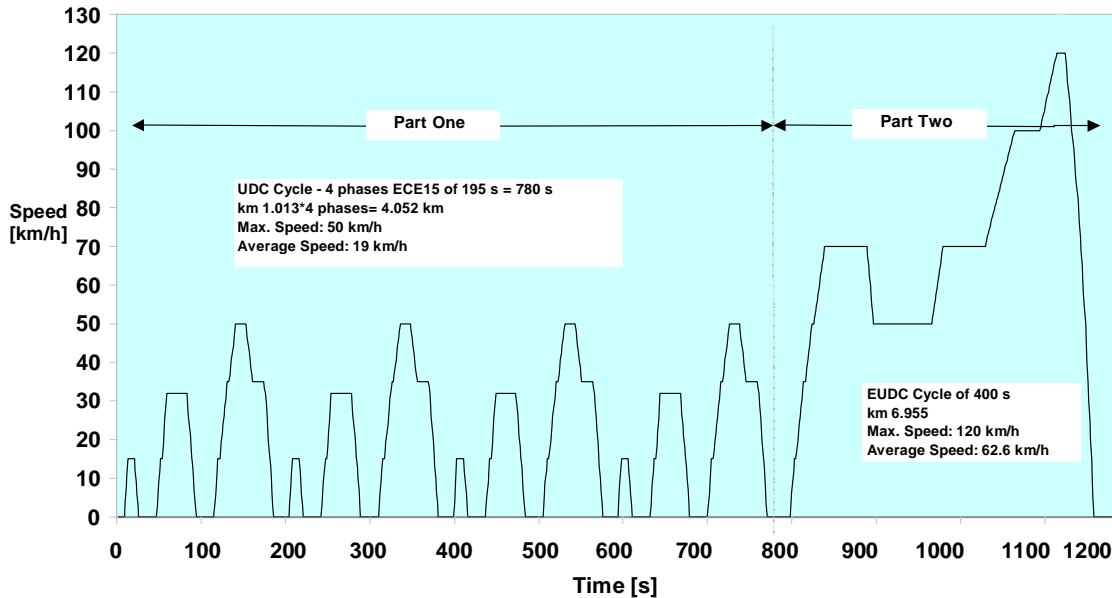
- **Fuel energy (MJ/km)** necessary to perform the NEDC cycle
- **GHG (g CO_{2eq}/km)** emitted during the cycle.

Note: total GHG emissions expressed in CO_{2eq} take N₂O 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*).

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.

$$\text{Total WTW energy (MJ/100 km)} = \text{TTW energy (MJ/100 km)} \times (1 + \text{WTT total expended energy (MJ}_x\text{/MJ}_f\text{)})$$

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_f/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 CO₂ 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. The energy and GHG savings related to their replacement by alternative fuels pertain therefore to marginal production up to say 10-15% of the total road fuels demand.

Consequently, ICE engines fuelled by gasoline or diesel fuel from crude oil represent the reference against which all the alternatives were assessed.

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		Diesel	
PISI	DISI	DICI no DPF ⁽¹⁾	DICI with DPF ⁽¹⁾
15%	10%	6%	3.5%

⁽¹⁾ Diesel Particulate Filter

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.

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

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

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 than 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 from 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

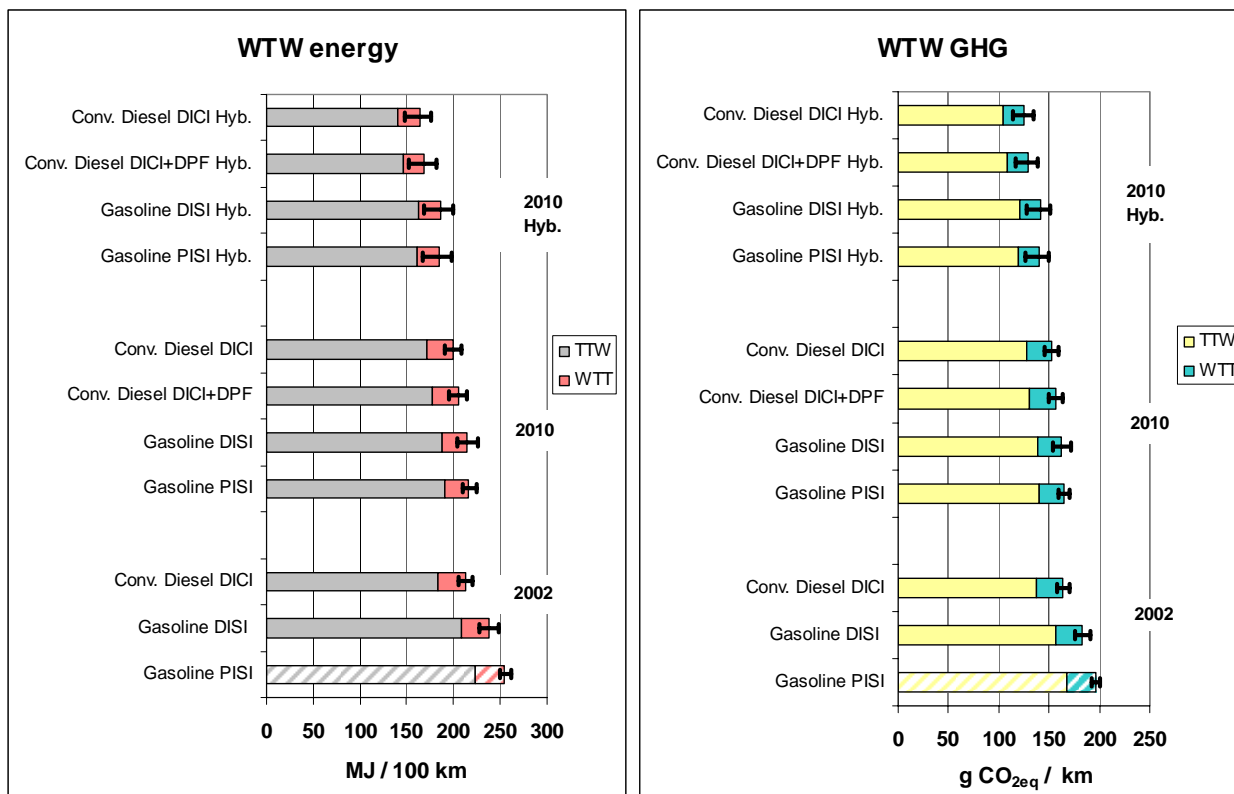
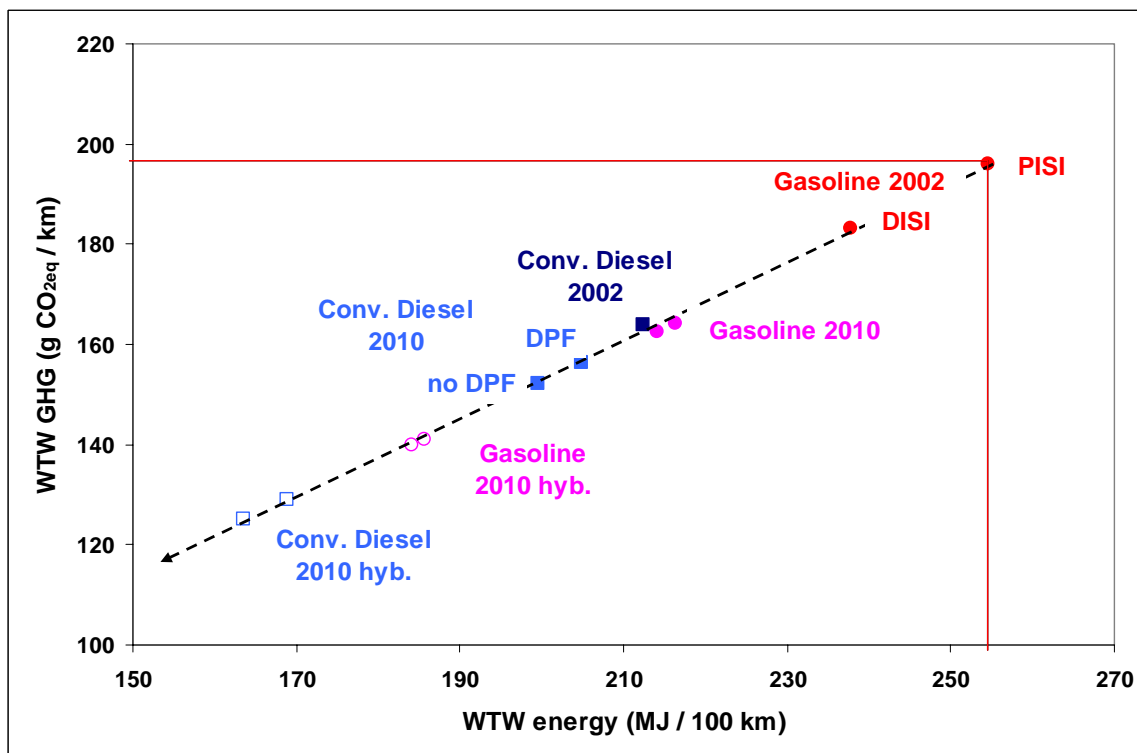


Figure 3.3-2 clearly illustrates the potential for improvement of conventional engines and fuels.

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 CO₂ 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 from around the end of this 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 East⁶).

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). We took this into account in the estimation of distribution costs.

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.

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

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

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 this 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.

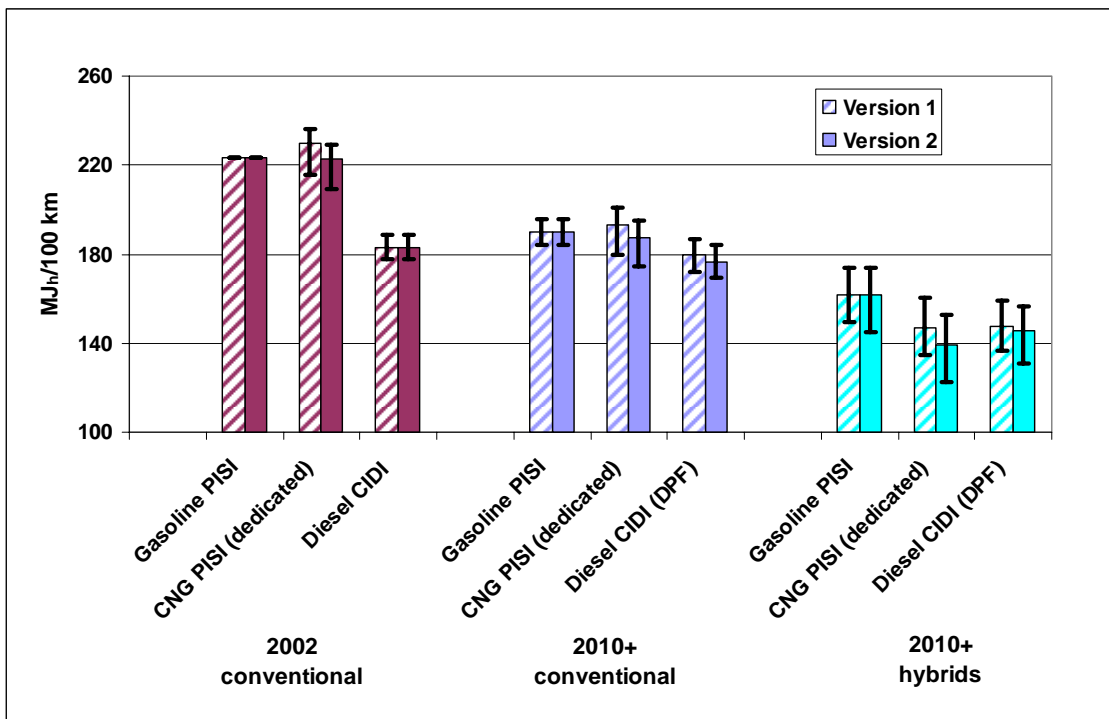
4.2.3 2010 hybrids

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

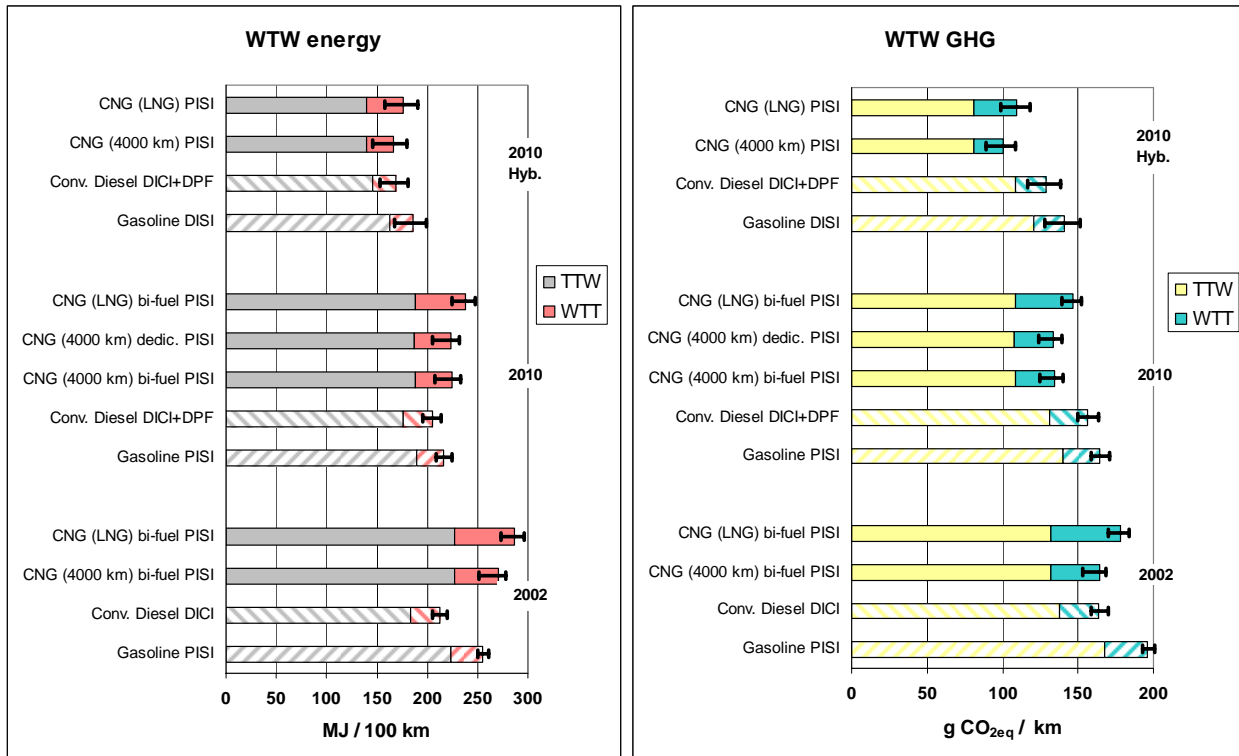


CNG vehicles are currently slightly less efficient than equivalent gasoline vehicles while diesel vehicles enjoy a net advantage. In the future, however, improvements in spark ignition engines will bring all technologies much closer together. Specific improvements in CNG engines will improve CNG beyond gasoline and bring it close to diesel. Hybridisation 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.
 WTW GHG emissions becomes lower than those of diesel.
 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

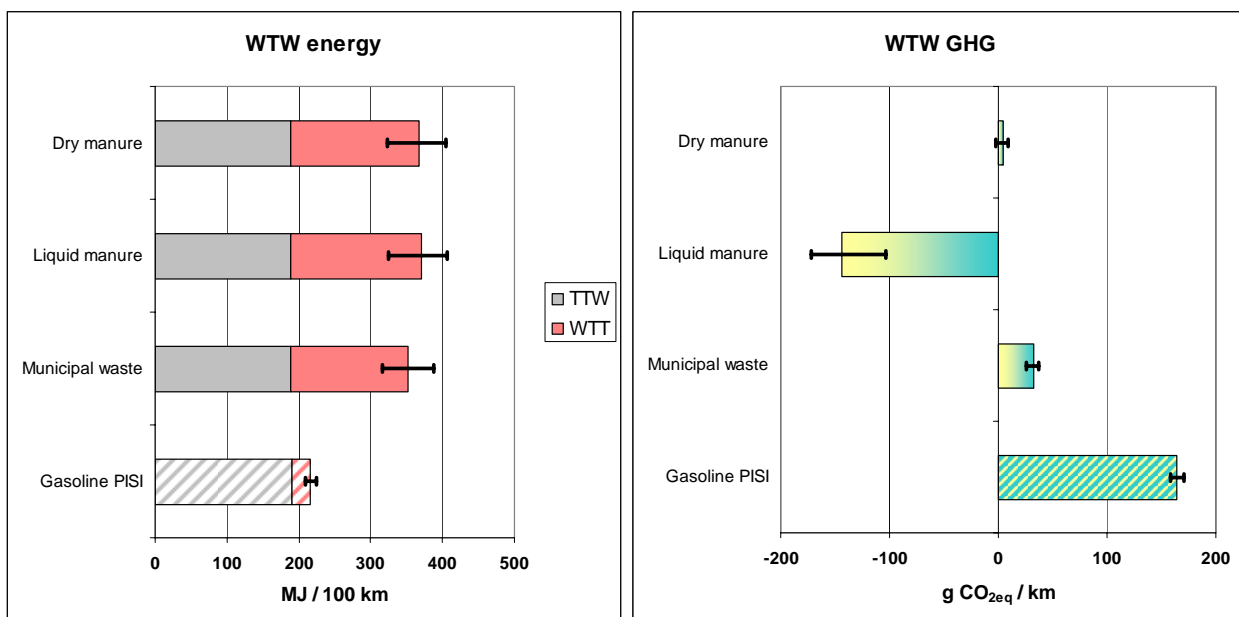
The anaerobic fermentation of organic matter produces a gaseous mixture, known as "biogas", consisting mainly of methane and CO₂. A suitable feedstock is biomass containing components such as carbohydrates (i.e. saccharides such as glucose), fatty acids and proteins. Anaerobic decomposition and formation 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 CO₂. Some such plants already exist in Scandinavia.

We have considered three cases for upgraded biogas production from municipal waste, dry manure and wet manure. In all cases we have assumed that the upgraded gas joins an existing gas grid to reach the refuelling station. It is also possible to produce biogas from farmed crops. However, feedstock costs would make it rather unattractive at least in the foreseeable future and we have not included it (see also *section 8.6.3*).

Biogas production starts from a fossil-carbon-free biomass waste product and uses part of the biogas to fuel the process. As a result biogas has a 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 energy requirement for the process varies slightly for the different feedstocks but the main difference stems from the avoidance of methane emissions. Indeed the biogas production process 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)



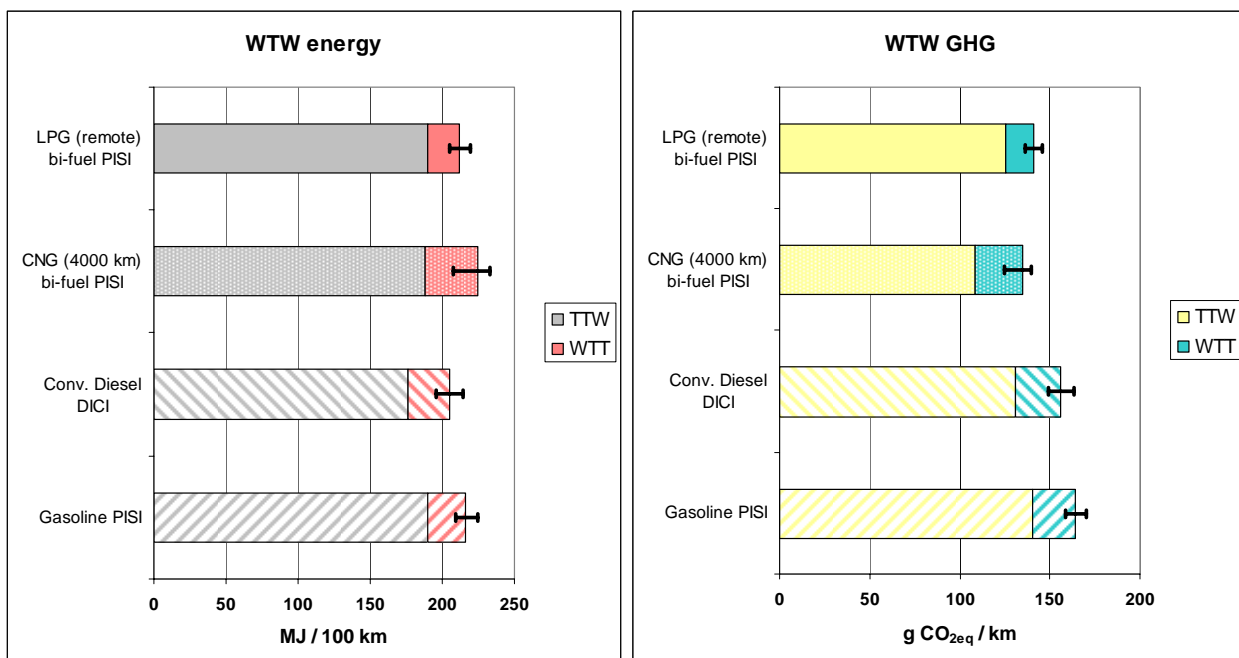
4.5 LPG

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 CO₂ 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 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.

- *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.

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 CO₂ 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 logen 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 logen 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 logen 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.

The processes to produce vegetable oil have been used for many years to produce food grade oil. The additional esterification process is also well-established (with methanol). 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 3.4.5* for details).

5.1.3 N₂O 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 (N₂O) from the field. Because of the very powerful greenhouse effect of this gas (300 times that of CO₂), even relatively small emissions can have a significant impact on the overall GHG balance. N₂O 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 N₂O 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 N₂O 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.

For more details see *WTT report, section 3.4.1*.

5.1.4 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.

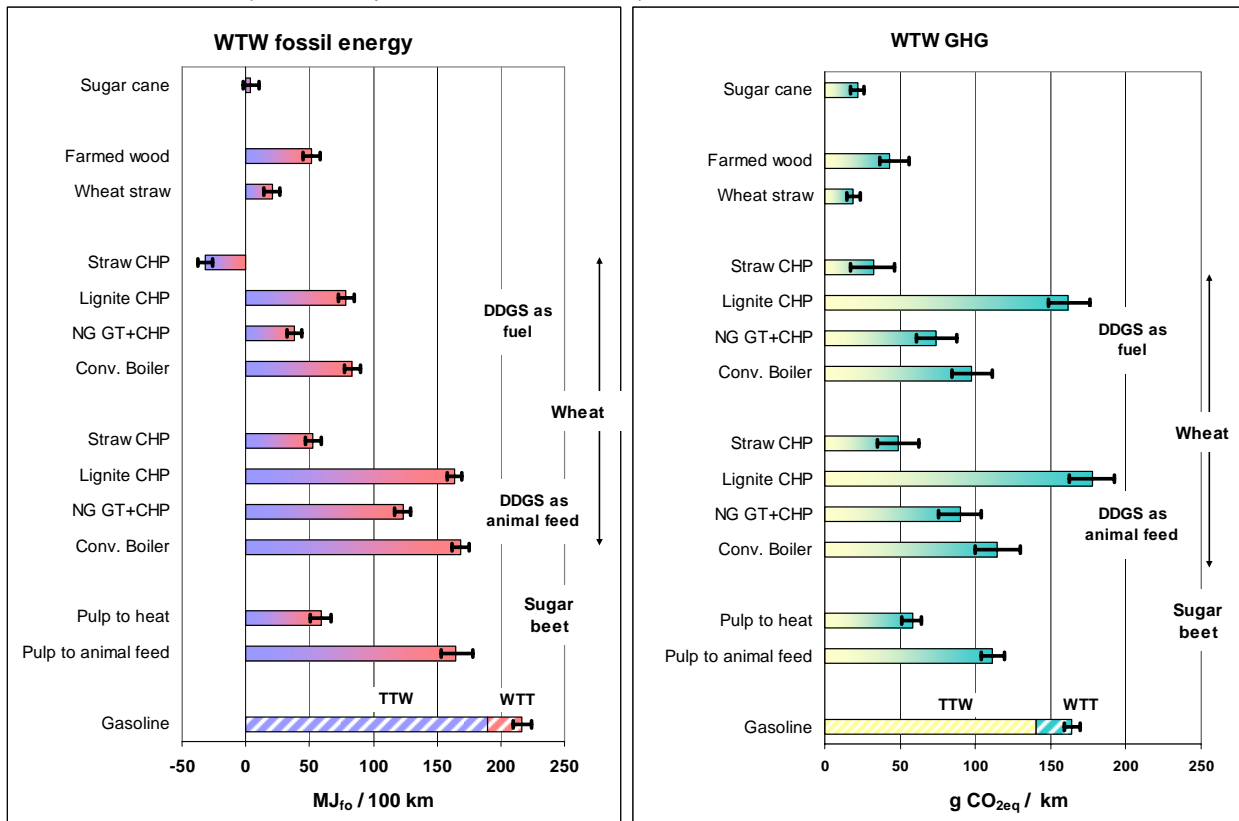
In version 1 of this study we argued that since most of the ethanol in EU would come from wheat diverted from export, we should not consider a reference crop. In this version, we use as a baseline the updated 2005 projections of DG AGRI, which have a much smaller projected export, and much more set-aside 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 N₂O emission, which is subtracted from our calculation of N₂O from wheat and other crops.

5.1.5 Energy and GHG balances

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

Figure 5.1.5-1 WTW fossil energy requirement and GHG emissions for ethanol pathways (2010+ vehicles)
 (GHG bars represent the total WTT+TTW)



Conventional production of ethanol as practiced in Europe gives modest fossil energy/GHG savings compared with gasoline. For sugar beet and wheat, with conventional energy production scheme and the currently most economic way of using by-products the schemes save about 23% of the fossil energy required for gasoline and just over 30% of the GHG emissions.

Use of co-generation particularly in combination with a gas-fired gas turbine can significantly improve these figures to 43% for energy and 45% for GHG emissions. Even with the advantage of CHP, using coal wipes out most of these gains and can even result in increased GHG emissions. Straw burning is of course very favourable from this point of view but has other limitations as discussed below.

Using by-products for energy production rather than animal feed has a very large impact. With pulp to heat, the sugar beet pathway can deliver savings of 73% for energy and 65% for GHG emissions. Similar reduction can be achieved with wheat DDGS. 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 these by-products as fuels.

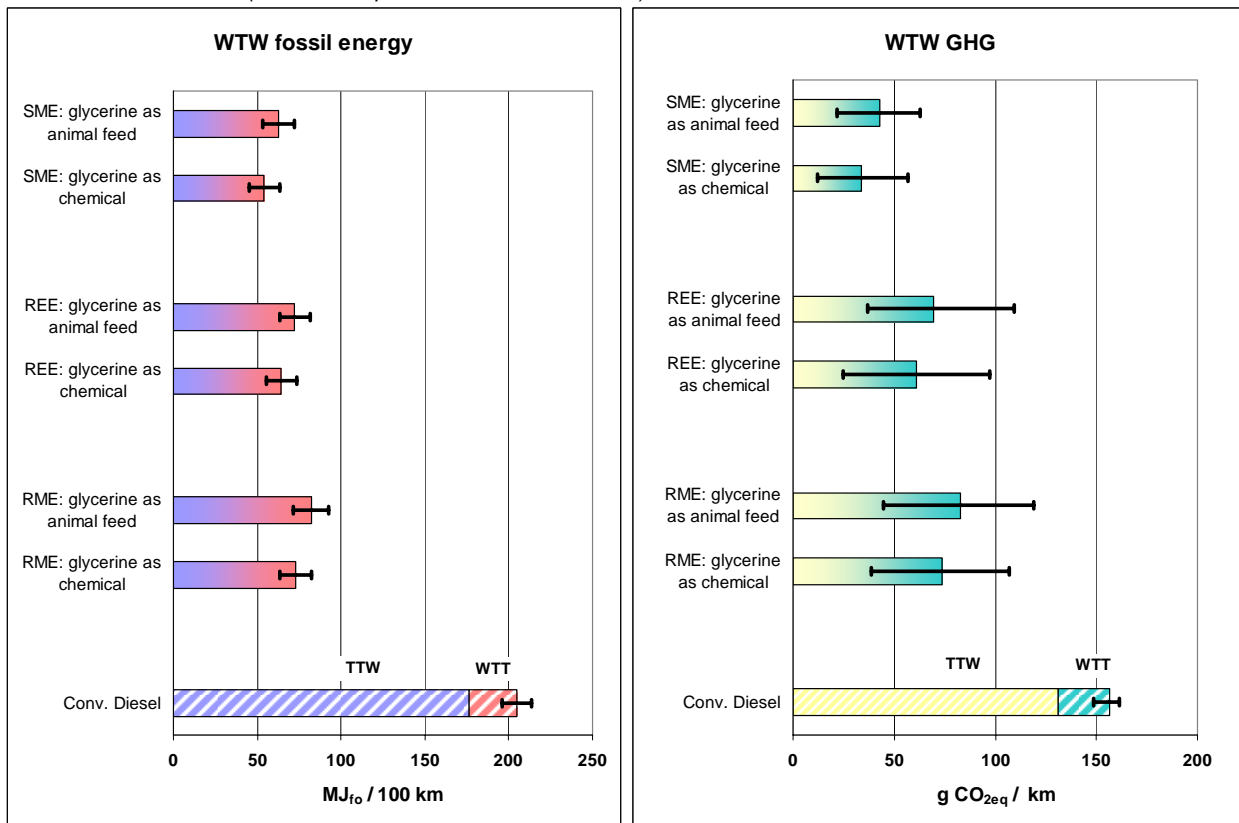
For most pathways the error bars are noticeably larger for GHG than for energy because of the wide range of possible nitrous oxide emissions.

Advanced processes (from wood or straw) can give higher savings still, 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).

Figure 5.1.5-2a/b WTW fossil energy requirement and GHG emissions for bio-diesel pathways (2010+ vehicles)

(GHG bars represent the total WTT+TTW)



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.

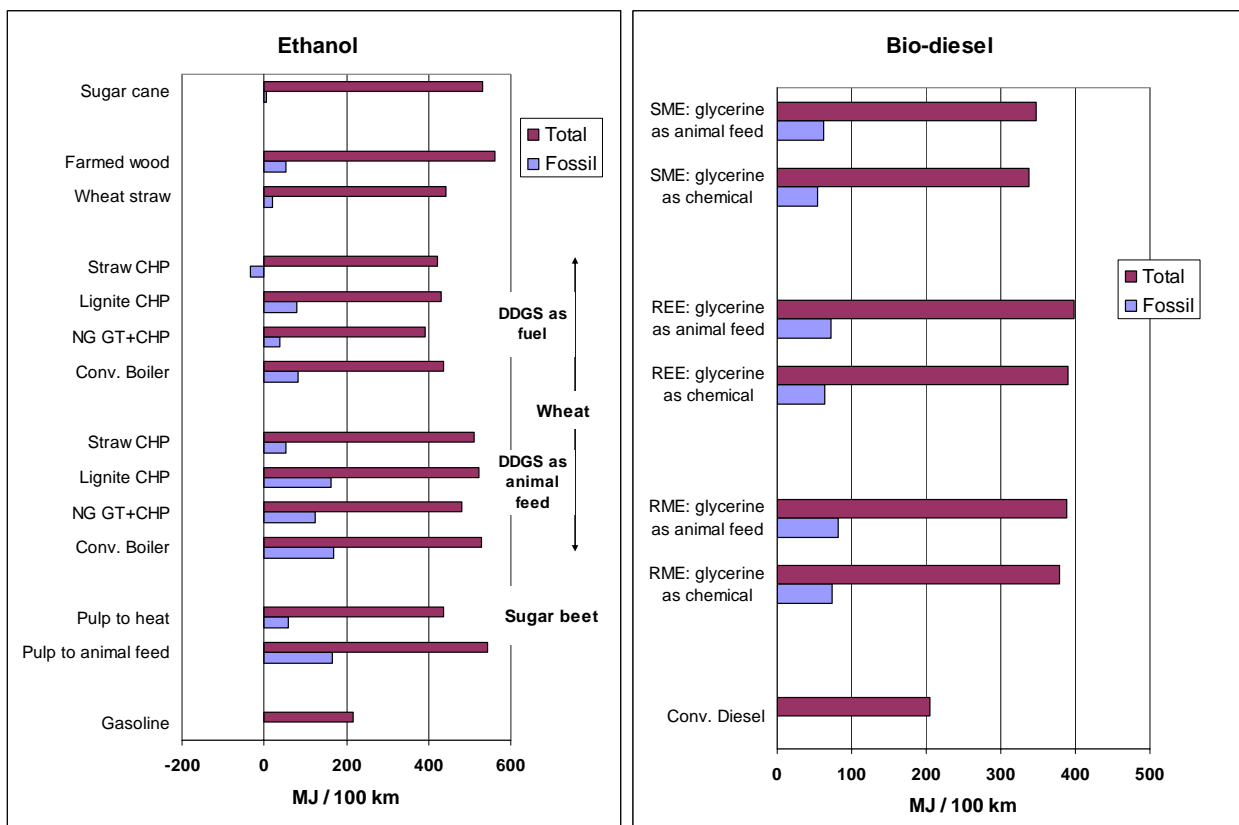
In the most favourable case RME (Rapeseed Methyl Ester) can save 64% of the fossil energy and 53% of the GHG emissions required for conventional diesel fuel. As would have been

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.

- 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.

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 5.1.5-3** 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. In *section 9* we further develop this theme by looking at alternative uses of biomass resources.

Figure 5.1.5-3a/b WTW total versus fossil energy



5.1.6 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.

Conclusion

Few of these potential impacts are inevitable: they can be controlled by appropriate regulations and effective enforcement. The pressure to push the limits of regulations varies from crop to crop: in general sugar beet is the most environmentally suspect crop and short rotation forestry the least.

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.

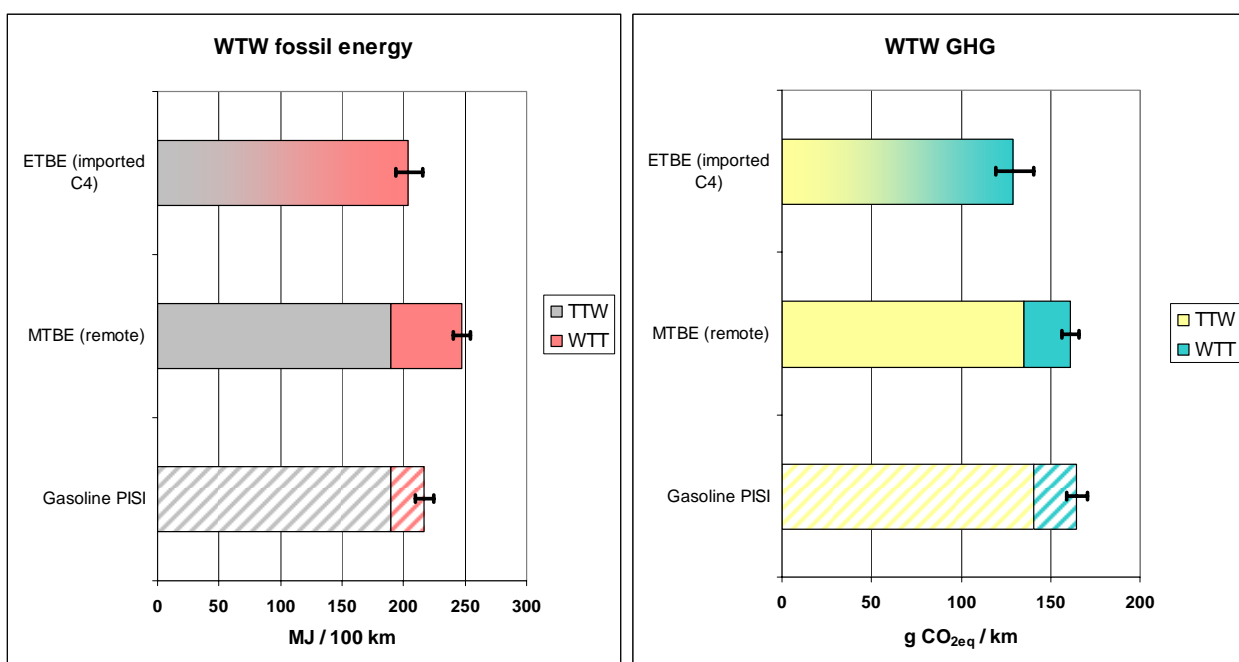
MTBE is synthesised by reacting isobutene with methanol. Some isobutene is produced by refineries and petrochemical plants as by-product of cracking processes. Large MTBE plants include, however, isobutene manufacture via isomerisation and dehydrogenation of normal butane often from gas fields, near 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.

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 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 _{xf0} /MJ _{EtOH}	GHG g CO _{2eq} / MJ _{EtOH}
As ethanol	0.65	46.6
As ETBE	0.39	42.0
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 this 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 CO₂ 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 CO₂ 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/H₂ 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.

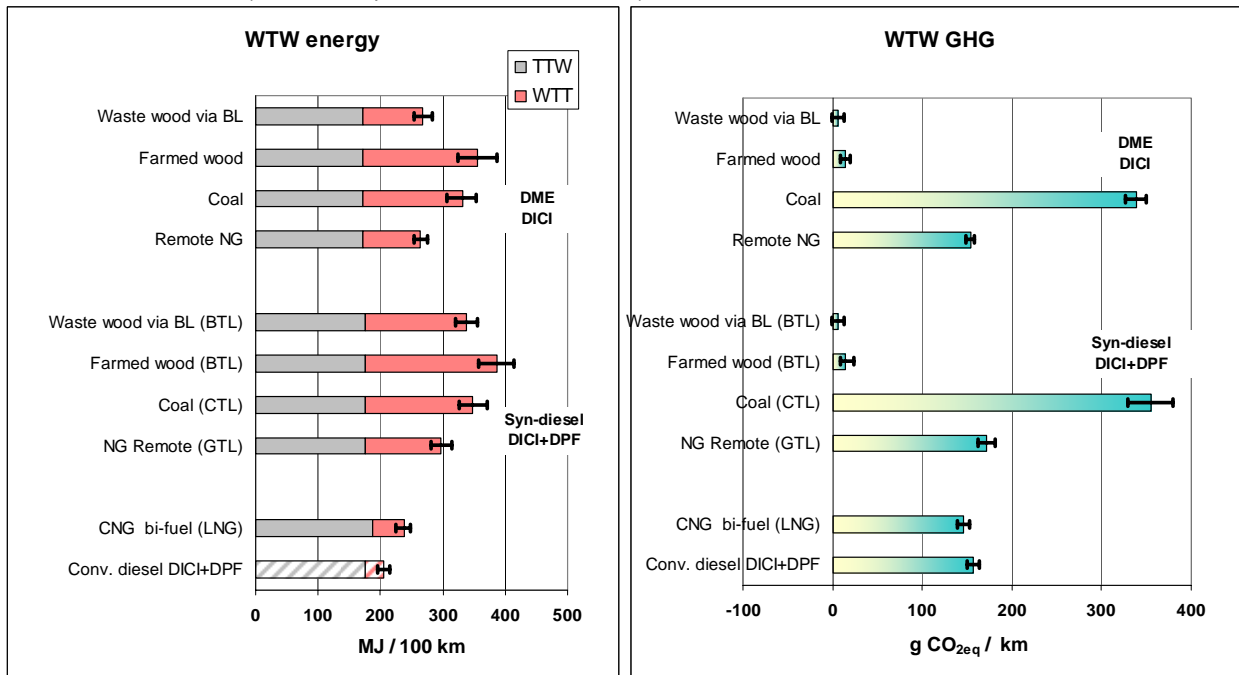
5.3.2 Energy and GHG balances

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 5.3.2a/b **WTW energy requirement and GHG emissions for synthetic diesel fuel and DME pathways (2010+ vehicles)**
 (GHG bars represent the total WTT+TTW)



- 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.

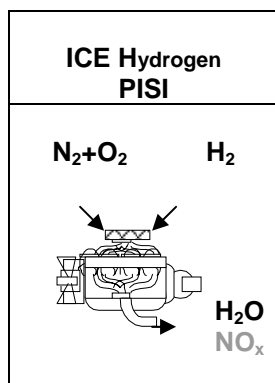
Hydrogen is not a primary energy source but an energy vector. Although it is the most widespread element in the universe, free hydrogen does not occur in nature. It needs to be “extracted” from compounds such as hydrocarbons and of course water, at the cost of an energy input. This results in emissions 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 N₂O part of which was accounted for as GHG in our calculations, even if practically insignificant). NO_x 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-H₂) in a high-pressure vessel, or in liquid form at atmospheric pressure (L-H₂) 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-H₂ tank is slightly heavier than the L-H₂ tank, slightly increasing the total mass of the vehicle. L-H₂ does, however, require some energy for vaporisation prior to use 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.

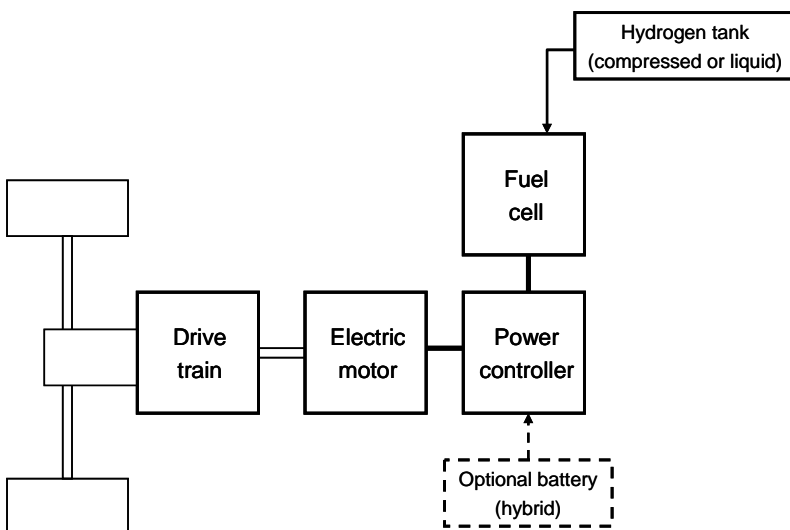
Table 6.1.1 2010 hydrogen ICE vehicles characteristics

		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 including 90% fuel	kg	85	74
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

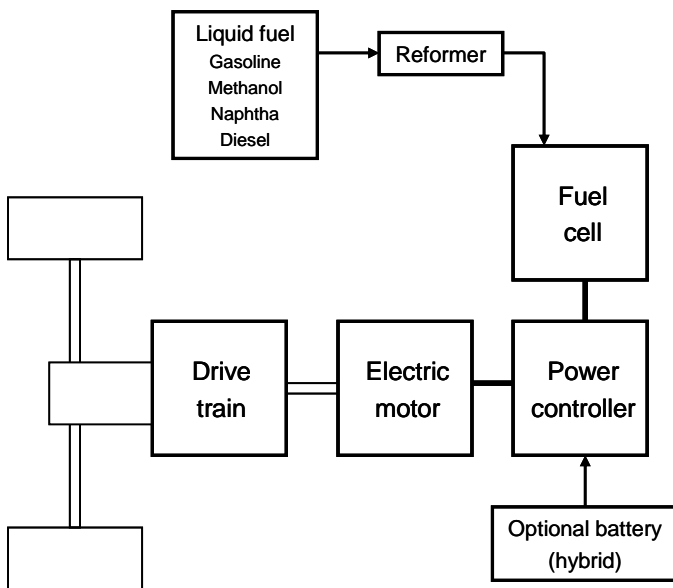
⁽¹⁾ also valid for naphtha and diesel

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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 electrolyzers (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 there 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 electrolyzers.

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 would be costly and would also require a European regulatory framework to ensure safety and public acceptance. Those hydrogen pipelines that already exist in Europe cover relatively short distances to link major industrial sites 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.

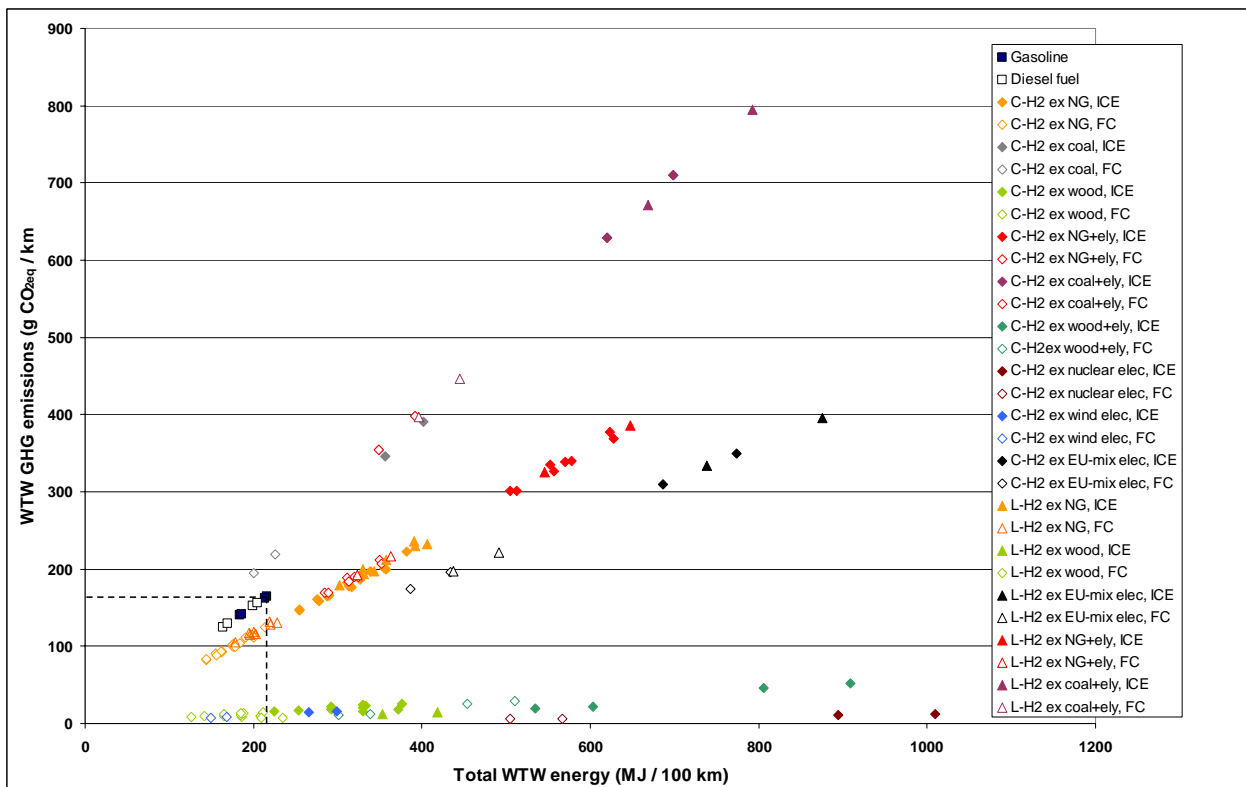
For the refuelling stations, considerations similar to those applicable to CNG apply but with much more challenging engineering constraints, particularly in relation to safety. Several prototypes of hydrogen dispensers have been built and tested. There is a level of confidence that these can be made to operate safely and reliably in a public environment although considerable development work is needed to get to that stage. Ensuring reliably fast and safe refuelling, at pressures as high as 70 MPa, is a challenge.

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.

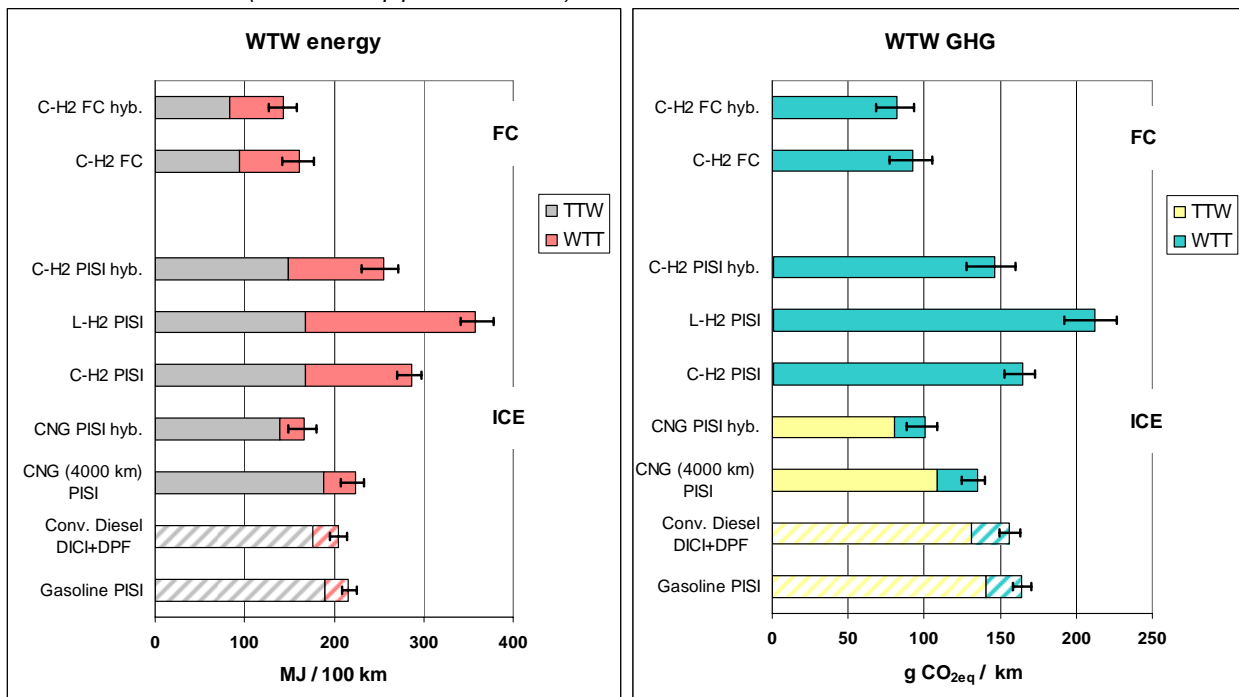
6.4.1 The impact of the vehicle technology

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-H₂ and even more so for L-H₂ which requires noticeably more energy.

- *Liquid hydrogen is more energy intensive than compressed hydrogen*

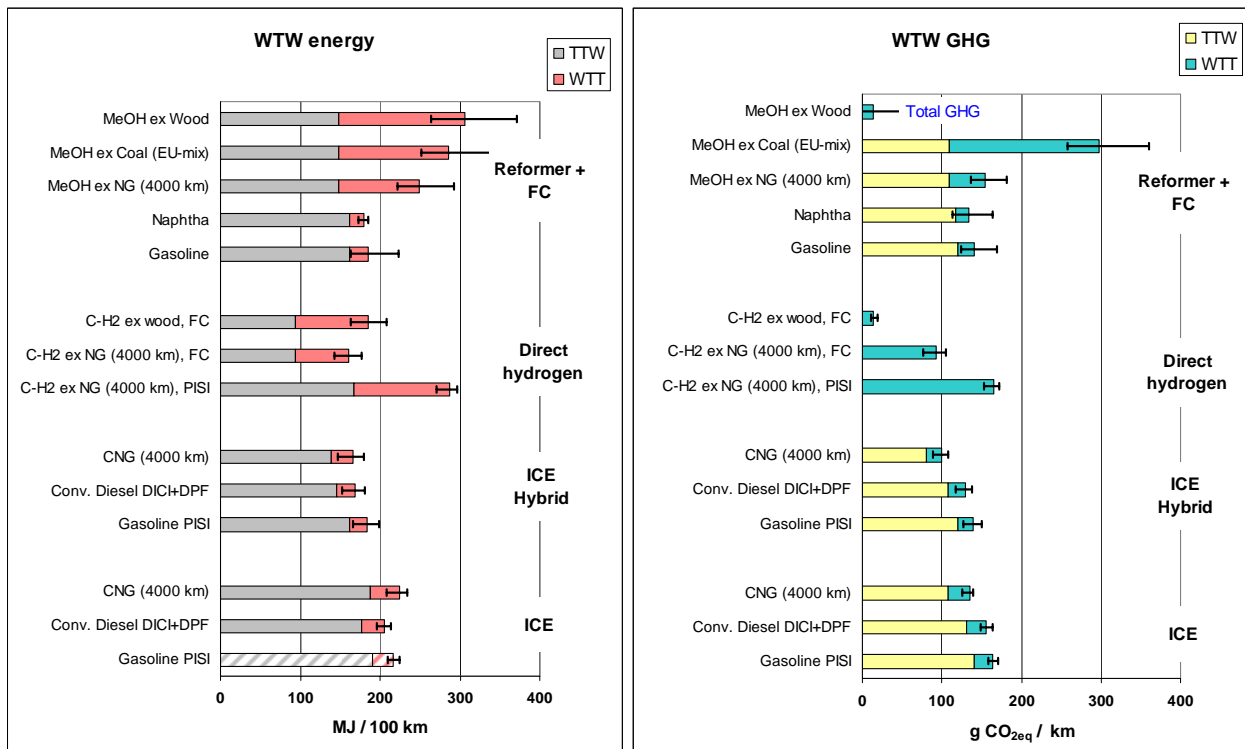
With fuel cells the hydrogen alternative becomes clearly better.

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

Note that 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.

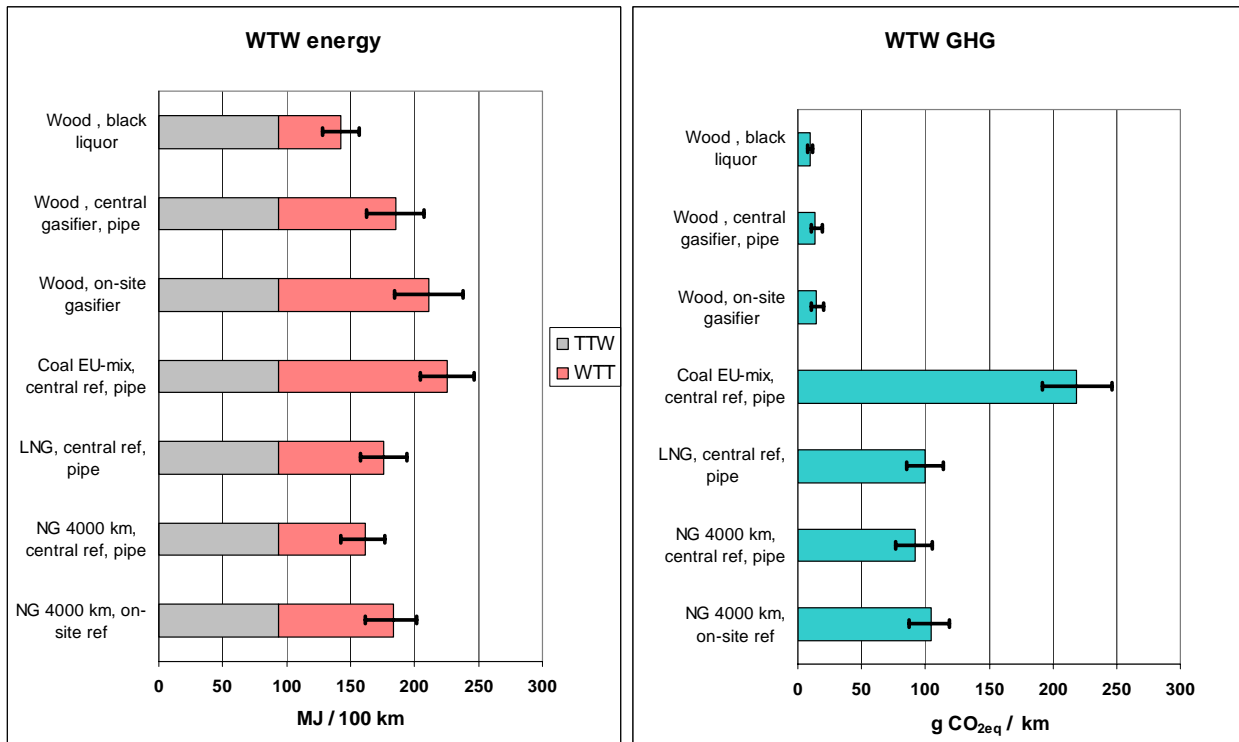
- On-board hydrogen production associated to a fuel cell
 - Is more energy and GHG intensive than options using stationary hydrogen production,
 - Does not offer any GHG benefit compared to advanced ICEs / hybrids.

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.

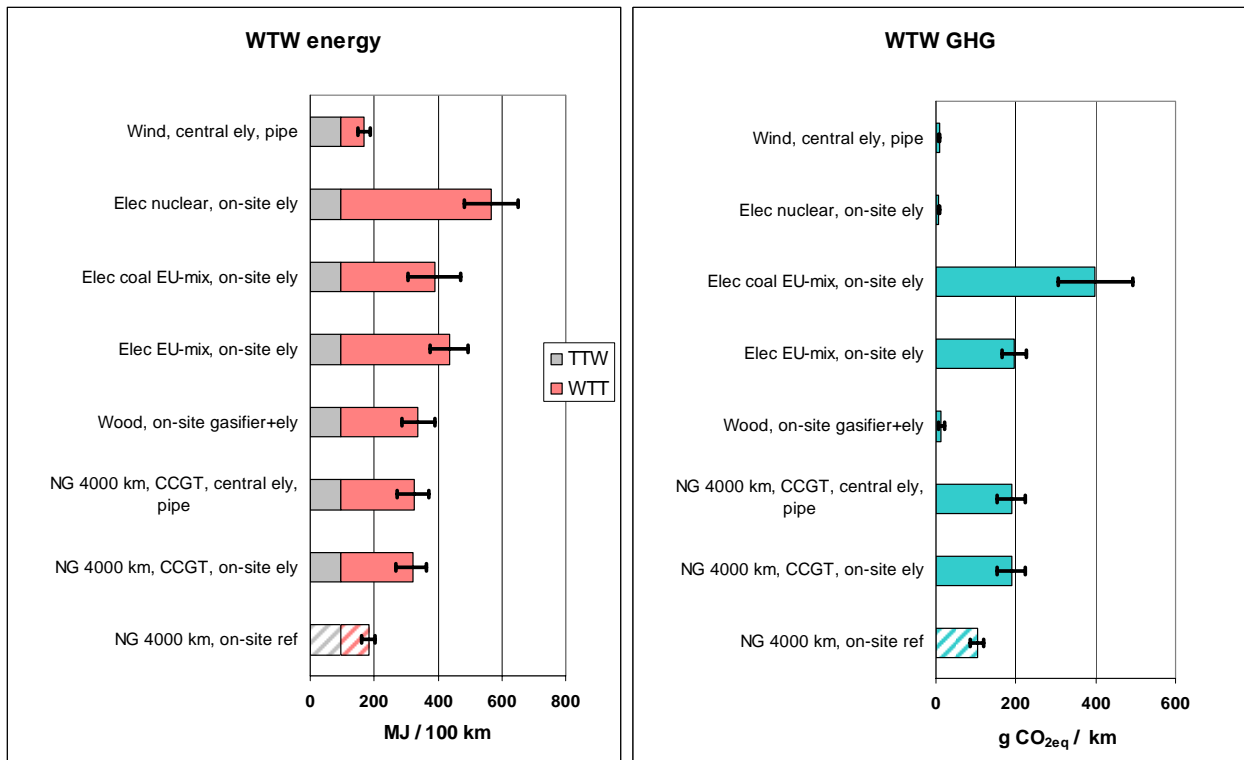
Hydrogen via electrolysis

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 no 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 CO₂ capture and storage (CC&S)

The concept of isolating the CO₂ 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. CO₂ 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 includes separation of CO₂ from other gases, compression and liquefaction, transport (by pipeline or ships) to the point of injection and injection under pressure.

Separation of CO₂ from other gases is a well established process. In combustion applications using air, scrubbing CO₂ 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 CO₂, although additional energy needs to be expended in the air separation unit. Reforming and gasification processes deliver CO/hydrogen/CO₂ mixtures or mostly hydrogen/CO₂ after the shift reaction. In these cases CO₂ scrubbing is more straightforward. In some cases, for example before syngas is fed to a Fischer-Tropsch reactor, CO₂ scrubbing is required irrespective of the CC&S option.

Following capture at the point of emission, CO₂ 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 CO₂ by pipeline over a reasonable distance (typically 100-150 km) and inject it into the geological storage.

In attempting to assess the CO₂ benefit and energy requirement of CC&S 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 CC&S 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 CC&S and the case with CC&S. Many of the process schemes are complex, involving multiple sources of CO₂. In a GTL plant, for instance, CO₂ 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 CO₂. Generally therefore the degree of CO₂ 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 CC&S 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.

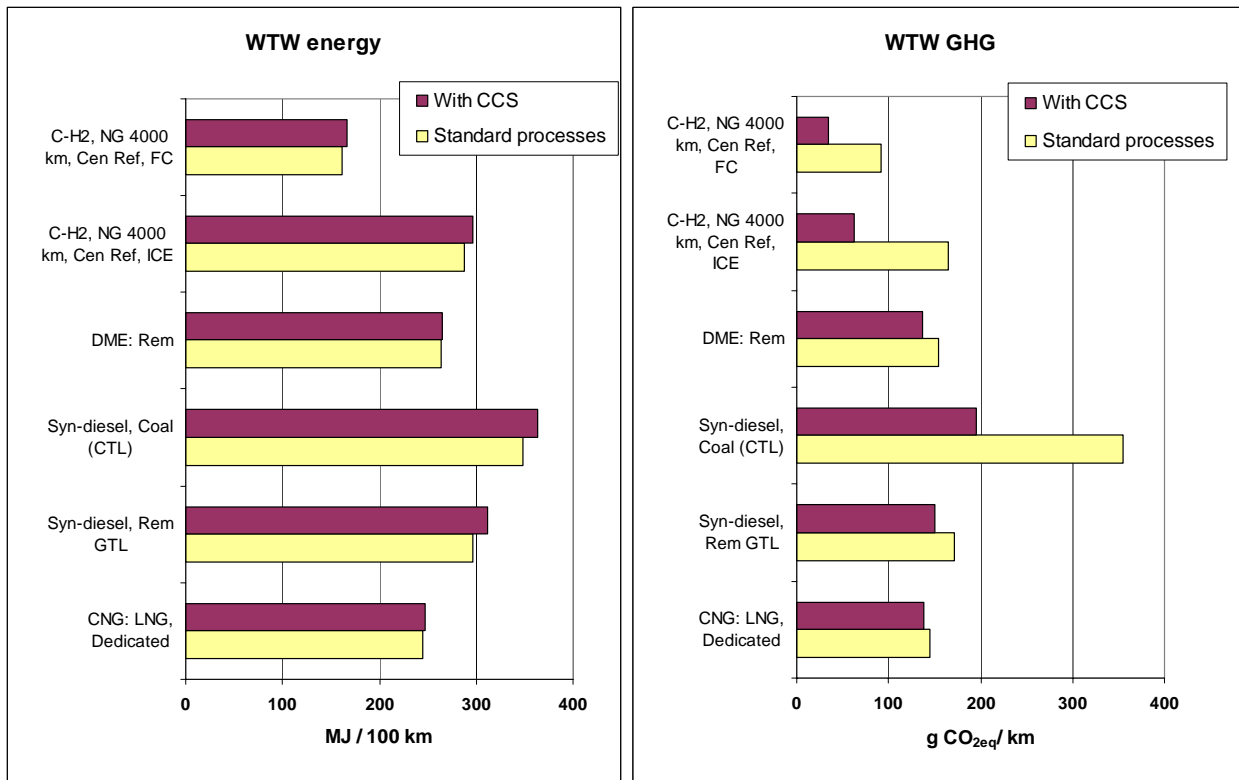
For the same reason we do not report cost figures as the data that can be inferred from the available literature did not seem consistent with the limited practical experience.

The concept can in principle be applied to many fuel production pathways. As illustration of its potential, we have included CC&S in the following cases:

- Electricity from natural gas and coal (IGCC)
- LNG: CO₂ from the power plant associated to the liquefaction plant.
- Hydrogen from NG and coal: Process CO₂ after shift reaction
- GTL and CTL diesel: Process CO₂ after reforming / partial oxidation
- DME from NG: Process CO₂ after reforming

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

Figure 7 **WTW total energy and GHG balance of selected pathways with and without CC&S (2010+ vehicles)**



Clearly the potential benefits of CC&S 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, CO₂ is already available in more or less pure form whether or not CC&S is intended. As a result the extra energy requirement and cost are likely to be more limited than in other schemes.

Applying CC&S to LNG or GTL schemes can also offer CO₂ 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 CO₂ could be re-injected.

- *Large scale production of synthetic fuels or hydrogen from coal or gas offers the potential for GHG emissions reduction via CO₂ capture and sequestration and this merits further study.*

8 Costs and potential availability

The question of how much of a certain fuel could conceivably be made from a given feedstock and at what cost is, of course, central to an analysis of competing fuel pathways. It is, however, arguably the most difficult part.

The potential availability of a feedstock or resource to produce a certain fuel depends on many factors. There may be physical limitations (e.g. land) and/or practical ones (e.g. number of sites for wind turbines). There may also be issues of competing uses of resources, social and political choices etc.

Cost evaluations and forecasts are always fraught with difficulties, particularly so when it comes to processes or systems that do not yet exist at any notable scale. The future cost of feedstocks or of access to resources will depend on more or less the same factors as availability and both aspects are to an extent interdependent.

Although a definitive analysis is clearly not possible we believe the available data can provide a valuable insight into the various options.

In order to estimate the costs associated with a pathway, we considered:

- The "WTT" cost of producing or procuring the fuel and making it available to the vehicle. This includes feedstock, manufacturing and distribution infrastructure.
- The "TTW" cost associated with any required changes to the vehicle fleet.

As already alluded to in *section 2.1* we attempted to estimate the costs to Europe (EU-25) as a whole of using particular fuel/vehicle combinations compared to the business-as-usual case of conventional vehicles and fossil fuels. The logic of such an approach is that the cost of a product is based on its alternative value in other applications. It implies in particular, that the minimum cost of an international commodity is its market price in Europe. This holds true when the commodity is imported but also when it is produced within Europe as any amount used internally denies Europe a revenue based on that market price. A production cost below the market price, represents a competitive advantage for the producer but does not change the cost to Europe (as long as the volumes involved are insufficient to have a notable influence on the market). Attempting to forecast future commodity prices is, of course, futile. The only course of action available is to consider a set of scenarios, clearly explaining what the assumptions are and analyse the consequences.

Only direct costs were included. We did not make any allowance for more subjective costs or benefits related to such issues as employment, rural development etc.

All costs are expressed in EUROS. Whenever the literature source indicated cost in US Dollars we have assume €/ \$ parity.

The main rationales for cost assumptions and calculations are discussed below. A more detailed discussion, complete with references, can be found in the *WTT (section 5) and TTW (section 7) reports*. In addition all basic data, calculation tables and results are assembled in **WTW Appendix 2**.

8.1 WTT costs

8.1.1 Fossil fuels and raw materials

A number of fossil raw materials and fuels are used in the study. They are all internationally traded commodities, the macro-economic cost of which is equal to its price on the international market as it is a disposal route that is always open to the producer. Our basic assumption has

been that the price of crude oil would determine the pricing level of all other fossil raw materials and products. Each of these was therefore assigned a price related to crude oil.

In order to represent the fluctuations of the oil price we made the calculations for 25 and 50 €/bbl (i.e. around 30 and 60 \$/bbl respectively at current exchange rate). A major change in oil price, if sustained over a long period, would undoubtedly have an effect on prices of other commodities, resources and services. We have taken this into account by applying an "oil cost factor" (OCF) to all major cost items, expressed as a fraction of the change in crude price (with an OCF of 1 the price would track that of crude oil; with an OCF of 0.5 a doubling of crude price would result in a 50% increase). For energy commodities the OCF reflects the linkage of the particular form of energy to crude oil. For goods and services, it reflects the fraction of the cost that originates from energy and the energy mix used.

Table 8.1.1-1 Cost of fossil raw materials and fuels

Crude oil	Density	LHV	Reference price		Sensitivity	
	t/m ³	GJ/t	€/bbl	€/GJ	€/bbl	€/GJ
	0.820	42.0	25	4.6	50	9.1
Natural gas		Ratio to crude		€/GJ	OCF	€/GJ
At EU border		0.8		3.7	1.00	7.3
Remote				2.0		4.0
Coal				€/GJ	OCF	€/GJ
Hard				1.5	0.65	2.5
Brown (Lignite)				1.2		2.0
Nuclear fuel				€/GJ	OCF	€/GJ
				1.1	0.20	1.3
Road fuels of fossil origin				€/GJ	OCF	€/GJ
Gasoline and diesel fuel		Ratio to crude				
		1.3		5.9	1.00	11.9
LPG		Ratio to crude				
		1.2		5.5	1.00	11.0
Marine fuel oil		Ratio to Crude				
		0.8		3.7	1.00	7.3
Synthetic diesel		Ratio to diesel				
		1.2		7.1	1.00	14.2
Methanol		Ratio to crude (t/t)				
		1.0		9.6	0.40	13.5

Purchasing and selling electricity also generates costs or revenues streams in a number of pathways. We have assumed that the same price applies to both sale and purchase (at a given voltage level) and used the following figures.

Table 8.1.1-2 Cost of electricity

EU-mix electricity	Low oil price		High oil price	
	€/MWh		OCF	€/MWh Cumulative
		Cum.		
Production	38	38	0.50	57
MV dist.	20	58		77
LV dist.	7	65		84

8.1.2 Investment and operating costs

For those fuels manufactured in Europe we estimated production costs on the basis of published literature. We used a capital charge of 12% representing a rate of return on investment of about 8% without accounting for a profit tax (which can be considered as an internal money stream within Europe). Capital investment figures were assumed to pertain to

the low oil price scenario and an OCF of 0.1 was used. Uncertainty ranges of $\pm 20\%$ and $\pm 40\%$ were applied for established and new technologies respectively.

Operating costs were assumed to be 3% of capital investment for established technologies and 4.5% for new technologies or high-tech plants. A higher rate of 8% was used for refuelling stations.

Variable costs, mostly related to energy, resulted from the prices considered for the relevant fossil and renewable energy carriers.

8.1.3 Conventional fuels

In this study, conventional fuels represent the "business-as-usual" case to which other options are compared. The marginal costs associated with their provision are therefore "avoided" when implementing alternative fuel and powertrain options and must be deducted from the costs of such alternatives.

Within the timeframe of the study only a limited substitution of conventional fuels can be reasonably envisaged so that the fixed costs associated with refining and distributing conventional fuels are unlikely to be notably affected.

Distribution costs must be added to the market price. On a marginal basis, only the variable costs (essentially associated with transport energy) are relevant.

8.1.4 CNG

The total WTT cost of CNG implementation includes:

- Gas purchase cost
- Distribution and refuelling infrastructure costs (operating and investment)
- Extra cost for the vehicles

Natural gas is an internationally traded commodity so that the cost of gas is equal to its price on the international market. This of course fluctuates a great deal particularly short term. Over long periods gas price is expected to broadly follow oil price. In relation to crude oil we have used a ratio of 80% on an energy basis, which is consistent with the historical level. There is a small additional cost associated with the use of the existing natural gas distribution grid.

As mentioned in *section 4.1.2* the main infrastructural costs are related to refuelling station equipment for which we estimate an average annual cost of around 80 k€ per station (capital and operating costs, not including the cost of electricity for compression which are accounted for separately). It must be noted that this cost implies that use is made of the existing road fuel retail infrastructure. Creating a completely new network would involve costs several times larger, without mentioning the challenges attached to such an endeavour in terms of land acquisition, permitting etc. In the 5% penetration scenario presented later in this report the total infrastructure cost would be in the order of 1.5 G€/a.

In the 2010-2020 scenario of a limited penetration of CNG, no savings beyond the variable operating costs can be expected from the reduced conventional fuel volumes. Indeed the distribution and retail network would essentially remain the same.

8.1.5 (Compressed) Biogas

The cost of biogas is mostly related to the cost of production as the organic waste feedstock is essentially free (except for a small transport charge). Biogas plants are not very complex but they still tend to be expensive when compared to their gas production. The cost per unit of gas produced is also a function of the type of waste used, animal waste for instance coming out cheaper than liquid manure because of a higher gas yield. For the most plausible scenario of a mixture of the two feeds we have estimated a biogas cost of around 16 €/GJ. Other costs incurred to turn biogas into a road fuel available at the pump are the same as for CNG.

8.1.6 LPG

LPG is an internationally traded commodity. Based on historical data we have adopted a price ratio of 1.2 between LPG and crude oil on an energy content basis. In addition the cost evaluation includes elements for land transport, intermediate storage and retail facilities within the EU.

8.1.7 Biomass resources

Most agricultural crops and even animal-feed by-products are internationally traded and have therefore an intrinsic value in international markets. The market prices represent the cost to Europe of using these crops for energy purposes as they could otherwise be traded for that amount.

The only by-products without an internationally traded price are sugar beet pulp and DDGS, the by-product of ethanol distillation. Their price was worked out from the animal feeds they substitute (taking also into account the quality difference).

We based our food commodity prices on 2012 projections by FAPRI, the Food and Agriculture Policy Research Institute, set up by US government to provide it with forecasts of international agricultural commodity markets. The forecasts are reviewed by US and international experts and used by DG-AGRI in their own European projections.

Reaching the biofuels Directive target of 5.75% replacement with bio-diesel would represent an additional demand of 9% of 2012 world oilseeds supply. We estimated from market flexibility indications that the world price would then increase by between 6 and 16%. As a middle course, we incremented the FAPRI price by 10%. If the EU imposed import tariffs to maximise domestic oilseed production, the price increase inside EU would be much greater. The extra cereals needed to produce the bio-ethanol target would only represent 1.5% of the projected world cereals production in 2012. The cereals market would therefore only be marginally affected.

The extra supply of by-products from biofuels production would depress the world price for protein animal feed. The combined production of oilseed cake and DDGS from 5.75% EU road-fuel replacement would substitute about 9% of the oilseed meal market. Our estimate from the demand elasticity is a price fall of 30% (with a 20% error margin!). This is a higher figure than that for oilseeds because the market flexibility is different, perhaps because these products are more difficult to transport.

The glycerine price is very volatile. Fortunately it is not an important element of the cost of bio-diesel. Most glycerine at present is a by-product of fat and oils processing and its supply would hardly change if more was produced from bio-diesel. Therefore a large increase in supply could only be accommodated by finding other uses, at a lower price. At present the price has collapsed due to the fast expansion of bio-diesel (some producers have to pay to dispose of it), but we can expect industry to find uses for it as a chemical feedstock which could lift the price to about 130 €/t in the long term,

For sugar beet, we calculated the price which would make it competitive with wheat grain for ethanol production. This turned out to be the same as the sugar beet price suggested in the current European Commission proposal for the reform of the sugar policy.

The cost of straw was taken from the price paid for straw delivered to the large straw-burning power station at Ely, in the UK. There is no subsidy on straw.

We calculated the "cost to EU" of farmed wood by stripping out the subsidies from the commercial price. Forest residuals price was estimated from newly-published cost-supply curves for some EU countries. Sufficient forest residuals to replace all the black-liquor gasified to produce transport fuels would be available at pulp mills for 2.8 €/GJ. This would be principally in Scandinavia. To collect most of the forest residuals in other places one would need to pay about 4.1 €/GJ, the same price as farmed wood.

Table 8.1.7 Cost of biomass resources
(delivered to processing plant)

	Moisture content	LHV GJ/t	Low oil price (oil at 25 €/bbl)		Own variability	High oil price (oil at 50 €/bbl)		
			€/t	€/GJ		OCF		
							€/t	€/GJ
Wheat grain	13%	14.8	95	6.4	16%	0.05	100	6.7
Sugar beet	77%	3.8	25	6.5	16%	0.05	26	6.8
Rapeseed	10%	23.8	237	9.9	14%	0.05	248	10.4
Sunflower seed	10%	23.8	265	11.1	14%	0.05	278	11.7
Wheat straw	16%	14.4	35	2.4	13%	0.05	37	2.5
Waste wood	0%	18.0	50	2.8	13%	0.05	53	2.9
Farmed wood	0%	18.0	77	4.3	5%	0.05	81	4.5
By-products substitutes								
Animal feed substitute		14.4	95	6.6	20%	0.10	105	7.3
Glycerine substitute		20.0	130	6.5	16%	0.68	218	

8.1.8 Liquid fuels and DME

Alternative liquid fuels are expected to be used mostly in low concentration blends with gasoline or diesel fuel and distributed via the existing infrastructure. Under these circumstances existing vehicles can be used without modifications and the costs are thus only related to production and transportation to the point of blending with the mainstream fuel.

The main cost items for production of these fuels are:

- The cost of feedstocks (either fossil hydrocarbons or biomass),
- The investment for the production plants and their operating costs (including purchase and sale of energy),
- The credits associated to by-products.

As we are considering the "cost to Europe", any imported fuel that could be considered as an international commodity was costed at its international market price. That same international market price provided a backstop for the cost of fuels manufactured within Europe.

The production plant investment costs were obtained from relevant literature sources. Operating costs were estimated as a yearly percentage of investment.

Synthetic diesel fuel will be offered on world markets and mostly used as a high quality blending component to help meet diesel fuel specifications. It is therefore likely to trade at diesel fuel price plus a certain quality premium. We have used a 20% premium over the standard EN590 diesel fuel corresponding to about 100 €/t in the 50 €/bbl crude scenario. As this price is assumed to be available at major European trading locations (e.g. Rotterdam or Sicily) there are virtually no other costs associated with the use of GTL diesel fuel (assuming it is used in blend with conventional diesel fuel). It should be noted, however, that there may be competition from other areas of the world for available GTL stocks. The cost of transporting fuel from the Middle East to Europe is higher than, for instance, to South East Asia.

We have not considered the option of producing GTL diesel in Europe from imported natural gas as it does not make economic sense.

The above price will be valid for synthetic diesel fuel imported into Europe from remote GTL or CTL plants. It will also provide a backstop (outside any subsidy) for any similar material produced internally from biomass or coal. Although this is not a very likely scenario, we made a separate calculation for CTL diesel as if produced in Europe based on imported coal price.

DME is thus far not a commodity. Its production route is, however, very similar to that of methanol both in terms of feedstock and in terms of hardware to the extent that plants producing DME could feasibly also produce methanol. The latter is a very widely traded commodity and it is plausible that DME would trade at a price corresponding to the methanol

equivalent. We have nevertheless ignored this potential link and have reported DME production costs.

As a liquefied gas, DME would face broadly the same fuel distribution issues as LPG (which is marketed today as a road fuel) and cost information can be inferred from the LPG case. Also in the case of DME, dedicated vehicles would be needed. The additional cost would be partly compensated by less complex and therefore less costly production plants.

8.1.9 Hydrogen

Similar calculations were carried out for the main hydrogen production pathways based on feedstock cost, and investments in manufacturing plants, distribution and refuelling systems. This included thermal processes, electricity generation and electrolyzers.

8.2 TTW costs: Vehicle retail price estimation

The economical assessment of future technologies, in a trade competitive domain, is probably among the most risky challenge ever proposed to a crystal ball.

The methodology we selected intended to estimate the retail price increment expectable at the 2010+ horizons for the various technologies under consideration. Maintenance costs were not considered.

Inspired by the MIT study "On the road in 2020"⁷, the exercise delivered orders of magnitude in a simple and transparent way. The retail price was obtained by subtracting the price impact of the original internal combustion engine and adding the impact of the new powertrain components. Specific price increment for special tanks (hydrogen or natural gas), or electric components (batteries, electric motors) was also added where relevant.

The majority of the reference sources are public, and the list is given in the *TTW Appendix 1*.

From **Table 8.2** a detailed assessment of each considered powertrain was made using 2010 as a baseline. These data on incremental retail price estimations need to be interpreted in a relative rather than absolute way as no assumptions were made with respect to market share.

Figure 8.2 shows the percent retail price increase for the 2010 vehicles, compared to the PISI ICE Gasoline 2010 vehicle (assumed retail price **19,560 €**). These figures are deemed to represent fair price differentials based on commercial realities or reflecting the lack of reliable consolidated data. They are one of the components in the economic assessment of the alternative pathways in the Well-to-Wheels integration.

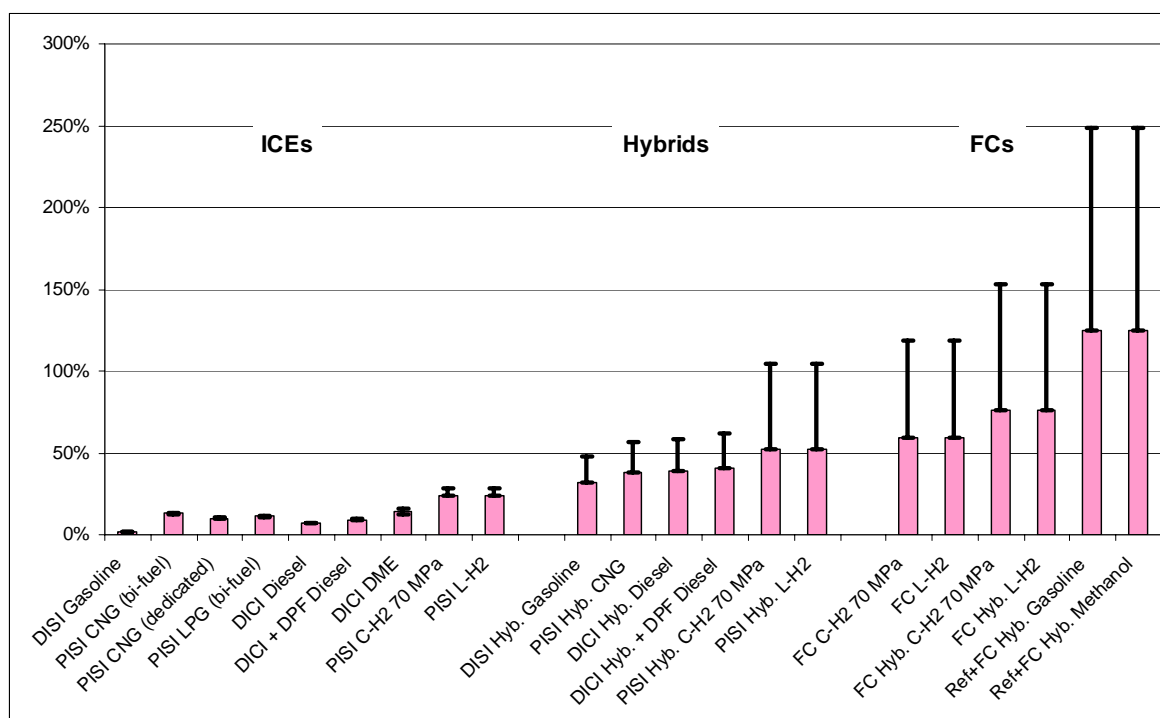
The figure also shows the estimated uncertainty ranges. The range is fairly narrow for established technologies but widens slightly when it comes to less developed options such as hybrids. For fuel cell technology we have applied a 100% upwards range reflecting the many uncertainties attached to these technologies.

⁷ "On the road in 2020", Malcolm A. Weiss, John B. Heywood, Elisabeth M. Drake, Andreas Schafer and Felix F. Au Yeung, October 2000.

Table 8.2 Technology impact on vehicle retail price

Component or system		Price	Reference
ICE			
Engine + transmission	€/kW	30	a
DICI	€	1500	b
DISI	€	500	b
Turbo	€	180	c
Friction improvement	€	60	j
20% downsizing SI		220	j
Stop & go system SI	€	200	a
Stop & go system CI	€	300	a
Double inj. system for CNG or LPG Bi-fuel	€	700	c
EURO IV SI	€	300	a
EURO IV Diesel	€	300	a
EURO IV Diesel with DPF	€	700	c
Credit for three way catalyst	€	430	b
Fuel tank			
Gasoline	€	125	a
CNG	€	1838	d
DME or LPG	€	1500	a
Comp. Hydrogen @70 MPa ⁽¹⁾	€/kg H ₂	575	e
Liquid hydrogen ⁽¹⁾	€/kg H ₂	575	e,f
Electric motor			
Electric motor	€/kW	8	c
Motor controller	€/kW	19	j
Total electric motor + controller	€/kW	27	j
Hybrid electric powertrains			
Powertrain and vehicle components upgrade ⁽²⁾	€	2630	j
Credit for standard alternator + starter	€	-300	j
Li-Ion battery⁽³⁾			
	€/kWh	600	g
Fuel cells			
FC system ⁽⁴⁾	€/kWnet	105	h
FC system + reformer	€/kWnet	251	h

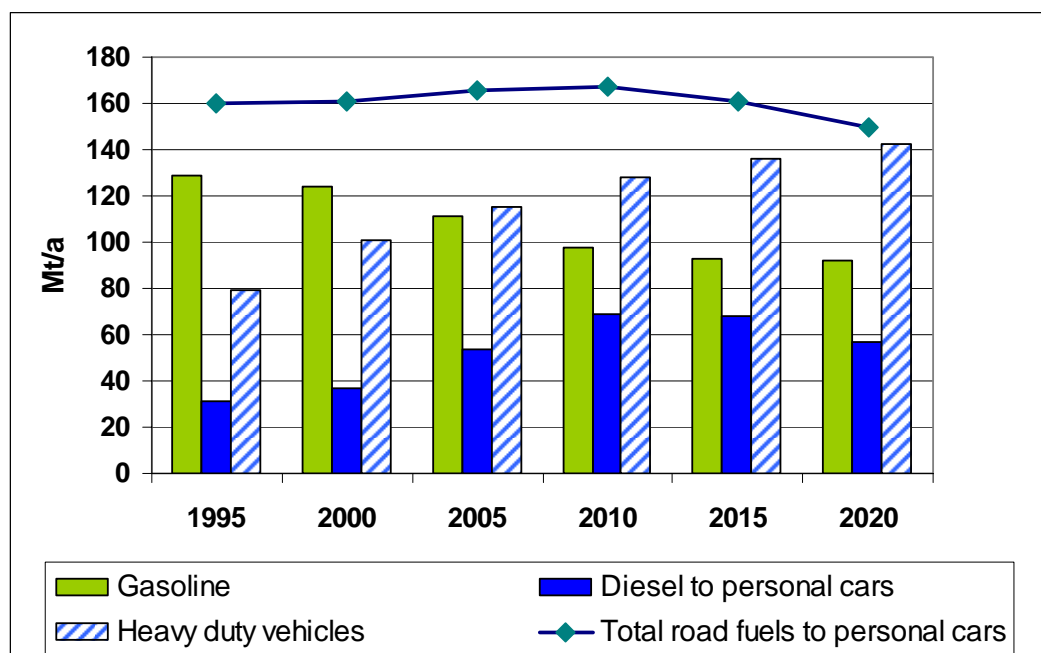
Figure 8.2 Estimated incremental vehicle retail price
(Expressed in percentage relative to a 2010 gasoline PISI vehicle)



8.3 Road fuels demand forecasts

We have used figures proposed by Wood Mackenzie in a recent multi-client study. The historical and forecast demand for road fuels in EU-25 is summarised in the figure below.

Figure 8.3 Historical and forecast EU-25 road fuels demand



There are three major trends to note:

- The total demand for passenger cars is close to static with only a slight short term increase followed by a slow decline in later years.
- The share of diesel in that demand grows steadily until the first half of the next decade after which some rebalancing is forecast.
- Diesel fuel demand for heavy duty vehicles grows steadily, tracking growth of the economy. In 1995 it represented 50% of the total personal car fuel market, by 2020 it will nearly reach parity.

8.4 Cost estimates

For most pathways or combinations of pathways we calculated the costs and savings in terms of fossil energy, CO₂ emissions and conventional fuel associated with introduction of the fuel under consideration to a level corresponding to 5% of the estimated distance driven in Europe in 2015. Because our TTW data only pertain to personal cars, we have limited the scope of the calculation to this segment of the market, i.e. excluding the diesel fuel consumed by heavy duty vehicles.

Note: the total amount of conventional fuel substituted depended on the alternative fuel under consideration. For instance introduction of ethanol would only affect the gasoline vehicle market and that of DME only the diesel market, whereas we considered that CNG or hydrogen would replace a combination of gasoline and diesel vehicles.

Many cost elements are a function of the scale at which an activity is deemed to be carried out. This is the case for instance for distribution infrastructure costs which tend to become lower as a particular option gains market share. The use of the common "5% scenario" ensured that the non-linearity of some cost elements was taken into account in a consistent manner. This 5% substitution level may be achievable for a number of the options considered but, in a number of cases, practical and technical limitations make this level of penetration unlikely within the

timeframe of the study. It is used here simply as a consistent calculation basis and does not constitute a forecast or imply feasibility. Our estimate of the fossil fuel substitution potential of the different options is discussed in the next section.

The costs were calculated as incremental to the reference scenario in which the demand is covered by conventional fuels and powertrains (gasoline and diesel).

The vehicle cost calculation assumed “steady-state” i.e. that the required share of the fleet had already been achieved and was being maintained by a constant percentage of the new vehicle sales.

The reference data, applicable to all fuels and pathways, are shown in **Table 8-4**.

The results of the calculations are presented and discussed in the two following sections for the two crude oil price scenarios of 25 and 50 €/bbl. We first discuss CNG/CBG/LPG, liquid fuels and DME followed by hydrogen in a separate section.

Table 8.4 Main cost scenario reference data

		Total	Gasoline	Diesel
Fuels market 2015⁽¹⁾				
Total	Mt/a		93	204
	Mtoe/a	305	95	209
	PJ/a	12790	3996	8794
Fuel to passenger cars			100%	33%
	PJ/a	6898	3996	2902
Vehicle population				
Passenger car population ⁽¹⁾	M	247	156	91
Specific fuel consumption	GJ/car/a		25.7	31.8
Vehicle lifetime	Years		13	15
New vehicle sales	M/a	18.1	12.0	6.1
Energy and GHG of model vehicle		2010+ ICE		
		Average	PISI	CIDI/DPF
TTW energy	MJ/km	1.84	1.90	1.77
WTW energy	MJ/km	2.12	2.16	2.05
WTW GHG	g/km	161	164	156
Distance driven				
Per vehicle	km/a		13517	17972
Total	Tm/a	3746	2103	1642
Refuelling stations	k	100		
Substitution scenario		5% of distance driven		
		Total	Gasoline	Diesel
Distance driven	Tm/a	187	105	82
Conventional fuels substituted	PJ/a	345	200	145
Alternative vehicle sales	M/a	0.90	0.60	0.30
Required ref. stations coverage	k	20.0		
Base GHG emissions	Mt/a	30.1	17.3	12.8

⁽¹⁾ Source: [Wood MacKenzie 2005]

8.4.1 CNG/CBG/LPG, liquid fuels and DME

Table 8.4.1a/b gives an overview of the costs and benefits associated with the major pathways.

Table 8.4.1a/b **Costs and benefits of major pathways compared to conventional road fuels**

Fuel	Powertrain	Alt. fuel consumed	Fuel substituted		Base case GHG Mt CO _{2eq} /a	WTW savings ^(1,2)				Incremental cost over ref. scenario			Cost of substitution		Cost of CO ₂ avoided €/t CO _{2eq}	
			Gasoline	Diesel		Energy (PJ/a)	GHG		G€/a			€/t fossil fuel	€/100 km			
							Total	Fossil	WTT	Vehicles	Total					
Oil price @25 €/bbl																
Conventional	Hybrids	291	200	145	30.1	62	62	4.7	16%	-0.3	5.6	5.3			2.82	1131
CNG (pipeline 4000 km / LNG)			200	145	30.1											
	PISI (BF)	353				-36	-36	4.3	14%	0.7	1.7	2.5	310	1.32		579
	PISI (ded.)	351				-33	-33	4.4	15%	0.7	1.2	1.9	243	1.04		437
	Hybrid	261				76	76	10.9	36%	0.3	6.1	6.5	808	3.45		593
CBG (mixed sources)	PISI (BF)	353				-291	376	50.4	167%	4.9	1.7	6.6	832	3.55		132
LPG (remote)	PISI (BF)	356	356		30.1	-1	-1	3.8	12%	1.1	1.4	2.5	316	1.35		672
Ethanol																
	PISI	200	200		17.3											
Sugar beet																
Pulp to fodder						-343	54	5.6	32%	1.9		1.9	413	1.82		342
Pulp to heat						-231	166	11.1	65%	2.2		2.2	478	2.10		198
Ex wheat																
DDGS to animal feed																
Conv. Boiler						-328	50	5.3	30%	1.9		1.9	407	1.79		358
NG GT + CHP						-278	98	7.8	45%	1.5		1.5	325	1.43		193
Lignite CHP						-321	55	-1.4	-8%	2.0		2.0	425	1.87		
Straw CHP						-310	172	12.1	70%	2.2		2.2	466	2.05		178
DDGS to energy																
Conv. Boiler						-233	140	7.0	40%	2.3		2.3	499	2.20		331
NG CCGT						-184	187	9.5	55%	1.9		1.9	417	1.83		203
Lignite CHP						-226	145	0.3	2%	2.4		2.4	517	2.27		7856
Straw CHP						-216	261	13.8	80%	2.6		2.6	558	2.45		186
Ex straw						-236	206	15.3	89%	1.0		1.0	220	0.97		67
Ex wood						-361	173	12.9	75%	3.0		3.0	650	2.86		233
Bio-diesel																
	CIDI+DPF	145		145	12.8											
Glycerine as chemical																
RME						-143	108	6.8	53%	1.5		1.5	438	1.80		217
REE						-152	115	7.8	61%	1.5		1.5	442	1.81		190
SME						-110	124	10.0	78%	1.6		1.6	469	1.92		157
Glycerine as animal feed																
RME						-150	101	6.0	47%	1.5		1.5	436	1.79		243
REE						-159	109	7.1	56%	1.5		1.5	440	1.80		208
SME						-117	117	9.3	72%	1.6		1.6	467	1.91		169
Synthetic diesel fuels																
Syn-diesel ex NG (remote)	CIDI+DPF	145		145	12.8	-75	-75	-1.2	-9%	0.2		0.2	51	0.21		
Syn-diesel ex coal	CIDI+DPF					-118	-118	-16.3	-127%	0.6		0.6	170	0.70		
Syn-diesel ex wood	CIDI+DPF					-150	159	11.7	91%	2.8		2.8	824	3.38		237
Syn-diesel ex wood via BL	CIDI+DPF					-109	163	12.3	96%	1.2		1.2	355	1.46		97
DME ex NG (remote)	CIDI					-48	-48	0.2	2%	0.8	0.3	1.1	332	1.36		
DME ex coal	CIDI					-104	-104	-15.0	-117%	1.0	0.3	1.3	390	1.60		
DME ex wood	CIDI					-124	160	11.8	92%	2.2	0.3	2.5	750	3.07		215
DME wood via BL	CIDI					-51	164	12.4	96%	0.8	0.3	1.1	330	1.35		90
Oil price @50 €/bbl																
Conventional	Hybrids	291	200	145	30.1	62	62	4.7	16%	-0.7	5.6	5.0			2.65	1062
CNG (pipeline 4000 km / LNG)			200	145	30.1											
	PISI (BF)	353				-36	-36	4.3	14%	0.2	1.7	1.9	238	1.01		444
	PISI (ded.)	351				-33	-33	4.4	15%	0.1	1.2	1.4	169	0.72		305
	Hybrid	261				76	76	10.9	36%	-0.6	6.1	5.5	692	2.95		508
CBG (mixed sources)	PISI (BF)	353				-291	376	50.4	167%	3.5	1.7	5.2	655	2.79		104
LPG (remote)	PISI (BF)	356	356		30.1	-1	-1	3.8	12%	1.1	1.4	2.6	322	1.37		684
Ethanol																
	PISI	200	200		17.3											
Sugar beet																
Pulp to fodder						-343	54	5.6	32%	1.2		1.2	250	1.10		207
Pulp to heat						-231	166	11.1	65%	1.1		1.1	234	1.03		97
Ex wheat																
DDGS to animal feed																
Conv. Boiler						-328	50	5.3	30%	1.3		1.3	272	1.19		239
NG GT + CHP						-278	98	7.8	45%	0.8		0.8	182	0.80		108
Lignite CHP						-321	55	-1.4	-8%	1.1		1.1	234	1.03		
Straw CHP						-310	172	12.1	70%	1.2		1.2	253	1.11		97
DDGS to energy																
Conv. Boiler						-233	140	7.0	40%	1.6		1.6	349	1.53		231
NG CCGT						-184	187	9.5	55%	1.2		1.2	259	1.14		126
Lignite CHP						-226	145	0.3	2%	1.4		1.4	311	1.37		4734
Straw CHP						-216	261	13.8	80%	1.5		1.5	330	1.45		110
Ex straw						-236	206	15.3	89%	-0.2		-0.2	-44	-0.20		-13
Ex wood						-361	173	12.9	75%	2.1		2.1	445	1.96		160
Bio-diesel																
	CIDI+DPF	145		145	12.8											
Glycerine as chemical																
RME						-143	108	6.8	53%	0.8		0.8	241	0.99		119
REE						-152	115	7.8	61%	0.8		0.8	246	1.01		106
SME						-110	124	10.0	78%	0.9		0.9	273	1.12		92
Glycerine as animal feed																
RME						-150	101	6.0	47%	0.8		0.8	229	0.94		127
REE						-159	109	7.1	56%	0.8		0.8	234	0.96		110
SME						-117	117	9.3	72%	0.9		0.9	260	1.07		94
Synthetic diesel fuels																
Syn-diesel ex NG (remote)	CIDI+DPF	145		145	12.8	-75	-75	-1.2	-9%	0.3		0.3	102	0.42		
Syn-diesel ex coal	CIDI+DPF					-118	-118	-16.3	-127%	0.1		0.1	20	0.08		
Syn-diesel ex wood	CIDI+DPF					-150	159	11.7	91%	2.2		2.2	654	2.68		188
Syn-diesel ex wood via BL	CIDI+DPF					-109	163	12.3	96%	0.6		0.6	187	0.77		51
DME ex NG (remote)	CIDI					-48	-48	0.2	2%	0.5	0.3	0.8	230	0.94		
DME ex coal	CIDI					-104	-104	-15.0	-117%	0.5	0.3	0.8	250	1.02		
DME ex wood	CIDI					-124	160	11.8	92%	1.6	0.3	1.9	568	2.33		162
DME wood via BL	CIDI					-51	164	12.4	96%	0.1	0.3	0.4	116	0.48		32

⁽¹⁾ i.e. a negative number denotes an increase

⁽²⁾ Relative to the "business-as-usual" scenario: gasoline PISI for ethanol, diesel CIDI for diesel fuels and combined scenario for other fuels

These tables contain a lot of information and maybe difficult to interpret correctly. Taking the example of the CNG PISI bi-fuel vehicle in the 50 €/bbl scenario, the data should be understood as follows:

- 353 PJ/a of CNG (assumed here to be from a 70/30 combination of natural gas from a 4000 km pipeline and LNG) would replace 200 PJ/a of gasoline plus 145 PJ/a of diesel (through substitution of a combination of gasoline and diesel vehicles). The combined amounts of conventional fuels would have caused 30.1 Mt/a of CO₂ equivalent to be emitted.
- The CNG pathways use more energy than conventional fuels (negative saving of -36 PJ/a, in this case total and fossil energy are the same), but produce somewhat less CO₂ (saving of 4.3 Mt/a representing 14% of the 30.1 Mt/a that would have been emitted by fossil fuels).
- Compared to the conventional fuel pathways, the extra costs are 0.2 G€/a for making CNG available (WTT) and 1.7 G€/a for the specialised vehicles for a total of 1.9 G€/a. This corresponds to a cost of substitution of 229 €/t of conventional fuel substituted (i.e. 238 €/t more than the cost of conventional fuels) or 1.01 €/100 km. In terms of CO₂ avoidance the cost is 444 €/t CO₂ avoided.

The same data is further presented in graphical form below in three sets of graphs.

Figure 8.4.1-1a/b shows the cost of CO₂ avoidance compared to the potential for eliminating the CO₂ emitted by the corresponding fossil fuels. In this representation the best options are in the top left hand quadrant. This potential should not be confused with a measure of the potential availability of the alternative fuels. It is simply a representation of the fraction of fossil energy involved in the total energy used in the pathway.

**Figure 8.4.1-1a Cost and potential for CO₂ avoidance
 Oil @ 25 €/bbl**

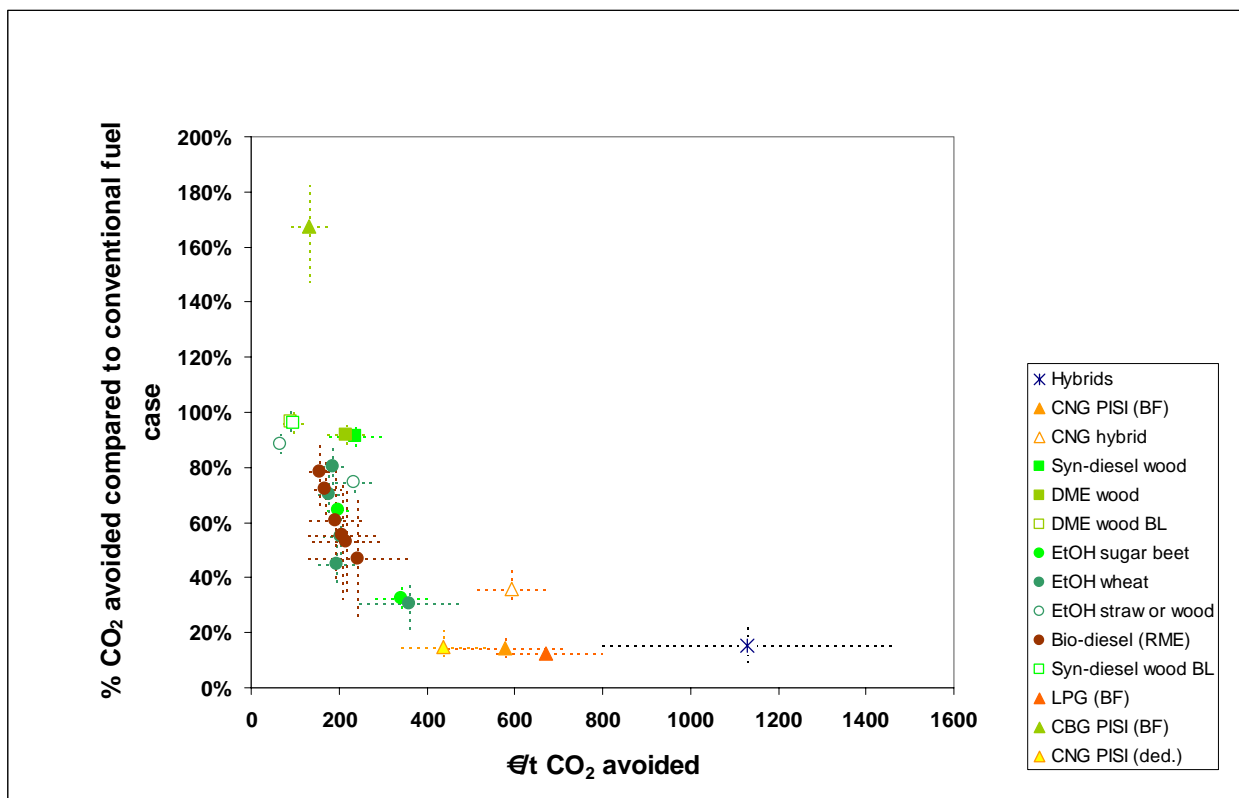
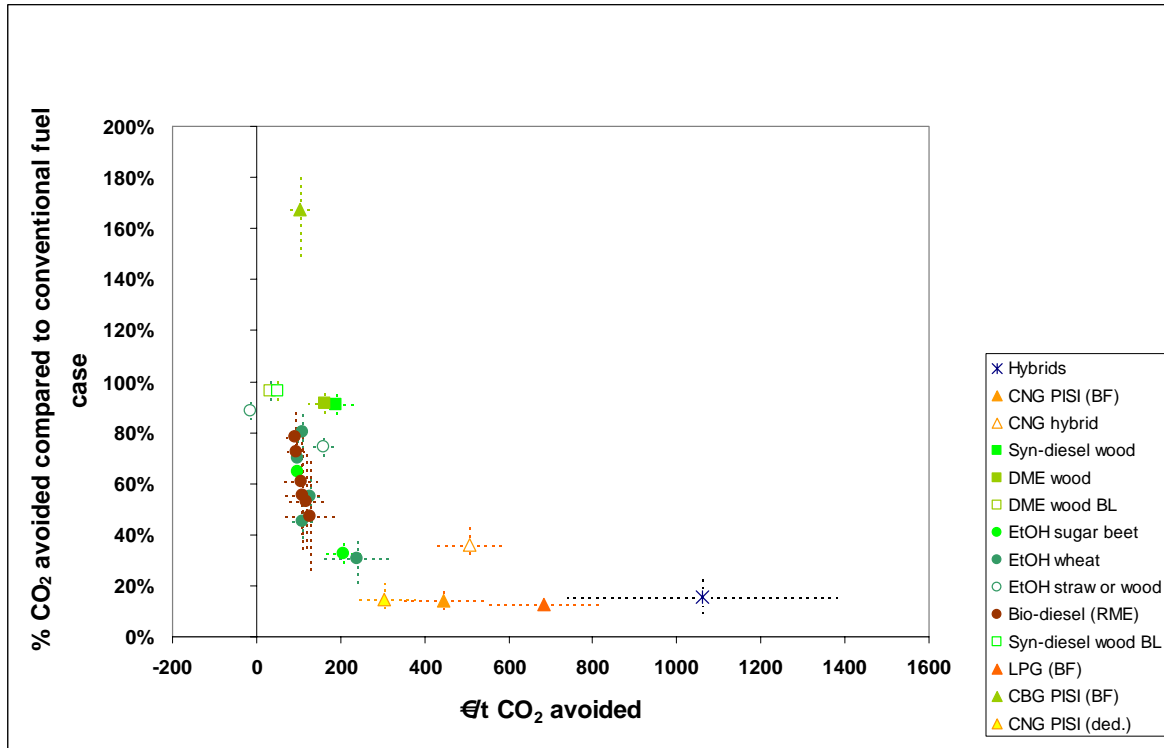


Figure 8.4.1-1b Cost and potential for CO₂ avoidance
Oil @ 50 €/bbl



Being incremental to conventional fuels, costs generally decrease with increasing oil price because a number of elements increase more slowly than the price of oil ($OCF < 1$). Even in the high oil price scenario, few options are under the 100 €/t CO₂ mark, still much higher than the current value of CO₂ of 20-30 €/t.

Hybridisation is included as a possible alternative with potential for GHG reduction. It is only shown for conventional fuels but could of course also be used in combination with alternative liquid fuels where it would provide a similar improvement. The large incremental cost to the vehicles is only partly counterbalanced by the higher efficiency and resulting lower fuel cost. Note that the incremental cost of hybrids has been significantly increased compared to previous versions of this study as additional technical information has become available and relevant pre-industrial experience has been gained.

At one extreme LPG and CNG stand out with high cost of CO₂ avoided as a result of the combination of relatively small savings with additional costs for infrastructure and vehicles.

With a relatively limited GHG saving potential and the burden of the infrastructure and vehicle adaptation costs, the CNG option has a fairly high cost per tonne CO₂ avoided. The hybrid version suffers from the high incremental cost. The CNG vehicle incremental cost compared to the gasoline PISI is around 13% for the CNG PISI bi-fuel, 10% for the dedicated version and 38% for the hybrid. For the assumed 900,000 vehicles per year required in the scenario, this translates to a net vehicle cost of around 1.7, 1.2 and 6.1 G€/a respectively. The main WTT cost goes to the 20,000 refuelling stations with 1.5 G€/a, partly compensated by the cheaper fuel. From this point of view, application of CNG to captive fleet with a limited territorial scope may be more attractive. It considerably reduces the refuelling infrastructure requirements both in terms of number of sites and complexity of the installations (for instance refuelling times can often be longer if programmed during idle periods of the vehicles). It also addresses vehicles with a high utilisation rate and large fuel consumption thereby increasing the effectiveness of the vehicle investments.

The final WTW number for CNG is of course very sensitive to the assumed natural gas to oil price ratio. It must also be noted that these costs have the potential to decrease by about 20% in a 10% market penetration scenario because of a better utilisation of the refuelling infrastructure.

The same applies to LPG with extra costs of 1.4 G€/a for vehicles and 0.5 G€/a for refuelling stations.

Biogas fares quite well on the scale of CO₂ avoidance cost but possibly less well than could have been expected in view of the "free" feedstock and very large CO₂ avoidance. Although they are relatively simple technologically, biogas plants tend to be capital-intensive because they have to handle a lot of biomass to produce comparatively small amounts of biogas. Based on a number of literature sources we have used a figure of 2000 €/kW of biogas produced.

- *Limited CO₂ saving potential coupled with refuelling infrastructure and vehicle costs lead to a fairly high cost per tonne of CO₂ avoided for CNG and LPG.*
- *When made from waste material CBG provides high and relatively low cost GHG savings.*

Conventional biofuels are in the range of 150-300 €/t with oil at 25 €/bbl and 100-200 €/t at 50 €/bbl. Advanced biofuels are in the same ballpark but can save a greater proportion of CO₂, the black liquor route showing its efficiency and cost advantages. The two points depicting ethanol from cellulosic material ("wood" and "straw") are quite far apart, illustrating the uncertainty on the potential performance of these processes..

Syn-diesel from wood provides CO₂ savings in the region of 200 €/t decreasing to around 50-100 €/t (depending on oil price) when using the black liquor route. The figures are about 20 €/t lower for DME.

All these figures must also be considered in the light of other considerations, particularly availability, where all options are far from equivalent. Biogas and straw can only be available economically in limited quantities which limits the attractiveness of these options for road fuels.

Figures 8.4.1-2a/b show the cost of CO₂ avoidance now versus the extra cost of the pathway per t of conventional fuel substituted which is a measure of the cost of diversification of road fuel supplies. In this representation the best options are near the bottom left hand quadrant.

The substitution costs have to be compared to the base cost of the conventional fuels assumed to be 255 and 510 €/t in the 25 and 50 €/bbl scenario respectively. Even in the high oil price scenario the general level of 250 €/t applicable to a number of schemes represents a 50% increase in the cost of procuring fuels.

Although it does not perform so well in terms of cost of CO₂ avoidance, CNG and to a lesser extent LPG are relatively cheap options for diversifying supplies. Biogas can save a lot of CO₂ but has a high cost per unit of conventional fuel substituted.

Conventional biofuels perform reasonably well on both counts but have limited availability.

Ethanol from straw fares very well as it can save a large proportion of the CO₂ at an attractive cost. BTL (syn-diesel from wood) can save a lot of CO₂ but has a high cost per unit of conventional fuel substituted. Manufacturing costs must clearly come down if the other benefits of this route in terms of flexibility and potential volumes (see *section 9*) are to be fully realised.

Figure 8.4.1-2a Cost of CO₂ avoidance versus cost of substitution
 Oil @ 25 €/bbl

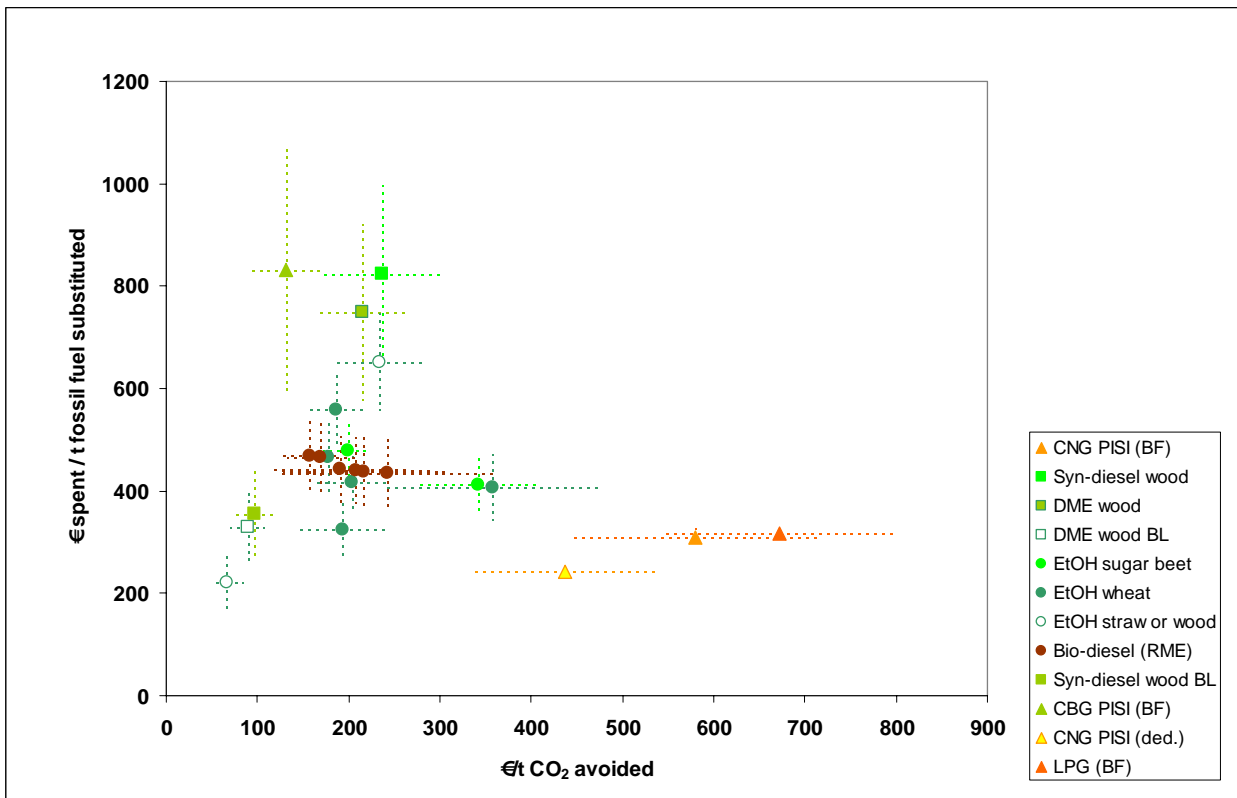


Figure 8.4.1-2b Cost of CO₂ avoidance versus cost of substitution
 Oil @ 50 €/bbl

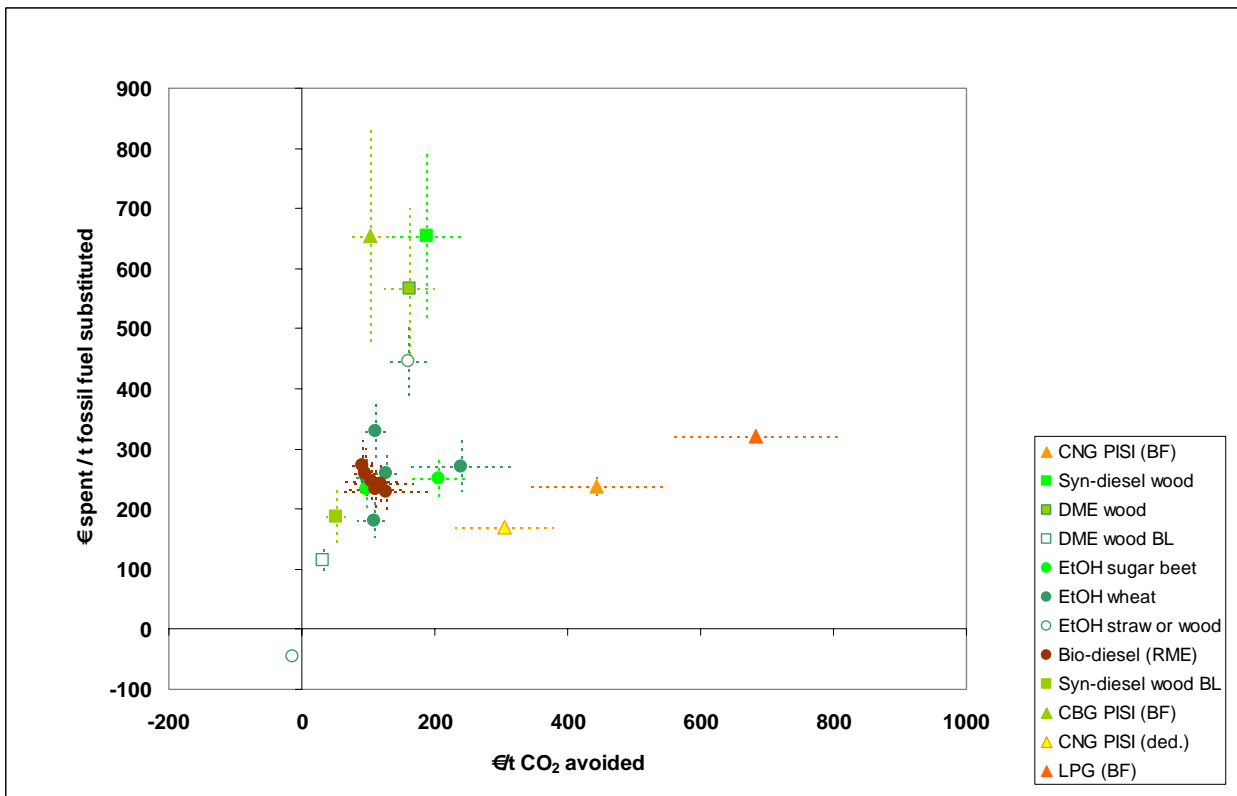


Figure 8.4.1-3a % CO₂ avoided versus cost of substitution
 Oil @ 25 €/bbl

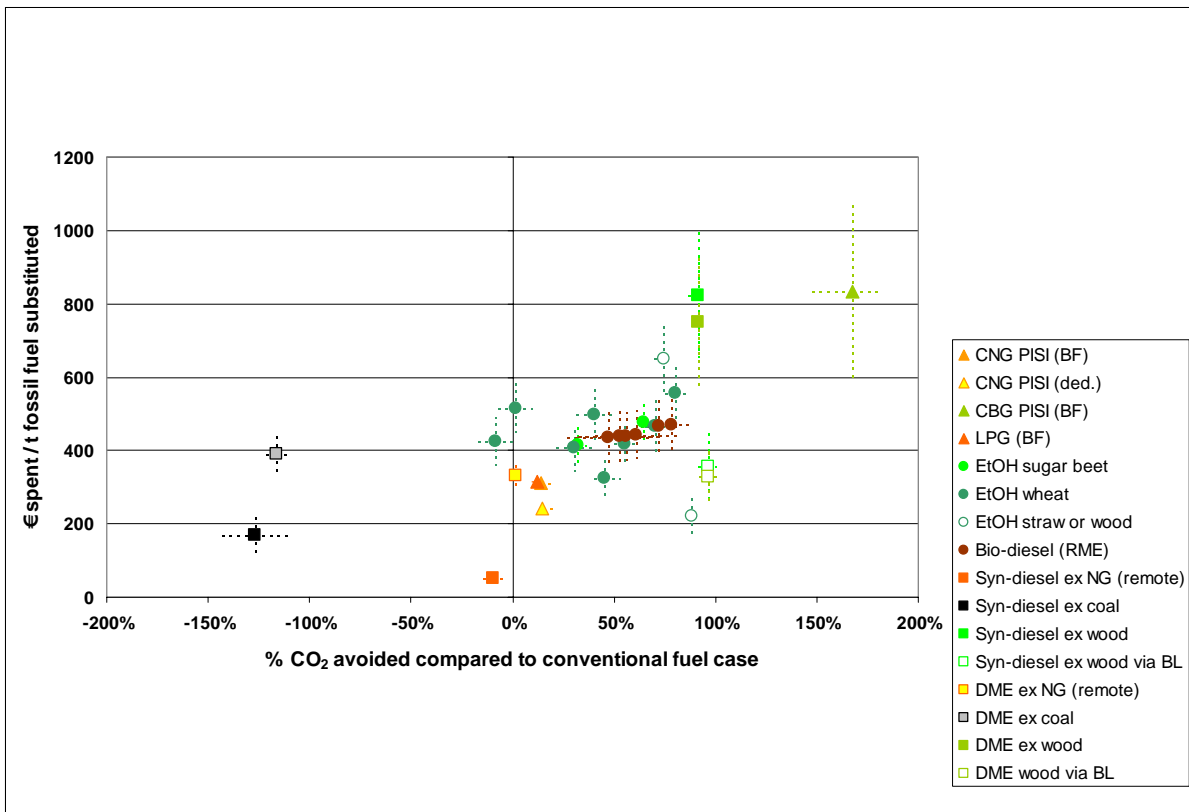
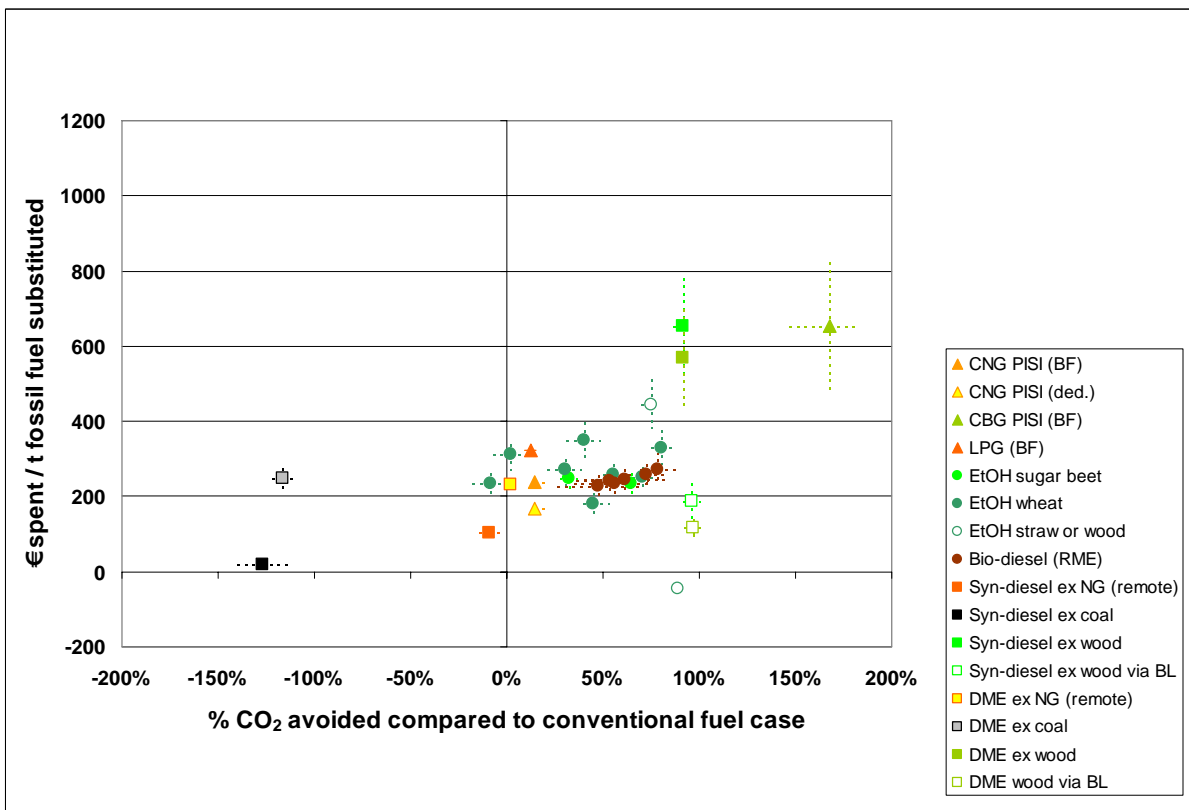


Figure 8.4.1-3b % CO₂ avoided versus cost of substitution
 Oil @ 50 €/bbl



In the two previous representations, only those options that do save CO₂ appear. In **Figures 8.4.1-3a/b** we have plotted the percentage (positive or negative) of CO₂ avoided compared to the conventional fuel reference versus the cost of substitution.

GTL and CTL routes are by far the cheapest routes for diversifying supplies (in the case of GTL we must remember that this is premised on a fixed premium of GTL above conventional diesel and availability of cheap "stranded" gas. It also highlights the fact that GTL is nearly CO₂ neutral compared to conventional diesel. For CTL the CC&S option is clearly very attractive as long as it does not induce a prohibitive cost increase.

8.4.2 Hydrogen

The tables and figures presented in *section 8.4.1* are repeated in this section for hydrogen pathways. Because the economics are dominated by the cost of infrastructure and vehicles, the influence of crude oil price is low in relative terms so that the figures are shown for the 50 €/bbl oil price only.

They illustrate the generally high potential of hydrogen for CO₂ avoidance but also its high cost both in terms of CO₂ avoidance and of conventional fuels substitution. The former is particularly high for hydrogen from natural gas whereas the latter is also shown to be high for a number of schemes that produce a lot more CO₂ than conventional fuels.

Natural gas is not only the most practical but also likely to be the cheapest source of hydrogen, and when produced in a large central plant the cost per MJ may approach that of conventional fuels, particularly in a high oil price scenario. Use of small scale on-site reformers could increase the cost significantly. In addition, hydrogen distribution adds considerably to the total cost, with pipelines incurring a large investment cost. Although it requires more energy than gaseous distribution, liquid hydrogen has some advantages in terms of distribution cost.

Even with mass production the price premium over the basic gasoline PISI vehicle is estimated to be 25% for hydrogen ICE vehicles and at least 50% for fuel cells, considerably adding to the cost.

- *In the short term, natural gas is the only potential source of large-scale hydrogen (and the cheapest).*
- *The need for a specific and technically challenging infrastructure for distribution, storage and use of hydrogen leads to high costs.*

For the on-board reformer options virtually all costs are shifted onto the vehicles. As a "reverse economy of scale" effect this is likely to result in high costs.

Table 8.4.2a/b Costs and benefits of major pathways compared to conventional road fuels

Fuel	Powertrain	Alt. fuel consumed PJ/a	Fuel substituted		Base case GHG Mt CO _{2eq} /a	WTW savings ^(1,2)				Incremental cost over ref. scenario			Cost of substitution		Cost of CO ₂ avoided €/t CO _{2eq}
			Gasoline	Diesel		Energy (PJ/a)		GHG		G€/a			€/t fossil fuel	€/100 km	
			PJ/a	PJ/a		Total	Fossil	Mt CO _{2eq} /a	% of base	WTT	Vehicles	Total			
Oil price @25 €/bbl															
Hydrogen from thermal processes															
Ex NG reforming	ICE PISI	314	200	145	30.1	-232	-232	-6.2	-21%	5.7	3.7	9.4	1180	5.03	
	ICE hybrid	278				-154	-154	-1.7	-6%	5.1	8.7	13.8	1728	7.37	
	FC	176				44	44	9.8	33%	3.9	10.0	13.9	1735	7.40	1415
	FC hybrid	157				82	82	12.0	40%	3.6	12.9	16.6	2072	8.84	1377
Ex coal gasification	ICE PISI	314				-422	-421	-29.4	-98%	6.9	3.7	10.6	1332	5.68	
	ICE hybrid	278				-329	-328	-22.7	-76%	6.2	8.7	14.9	1861	7.94	
	FC	176				-63	-62	-13.3	-44%	4.2	10.0	14.1	1768	7.54	
	FC hybrid	157				-12	-12	-8.6	-28%	3.8	12.9	16.7	2095	8.94	
Ex wood gasification	ICE PISI	314				-288	346	26.6	88%	6.9	3.7	10.6	1332	5.69	400
	ICE hybrid	278				-198	352	27.0	90%	6.2	8.7	14.9	1866	7.96	552
	FC	176				12	368	28.2	94%	4.3	10.0	14.3	1785	7.62	506
	FC hybrid	157				55	371	28.4	94%	3.9	12.9	16.9	2114	9.02	595
Hydrogen from electrolysis															
Electricity ex			200	145	30.1										
NG	ICE PISI	314				-644	-644	-31.4	-104%	9.0	3.7	12.7	1594	6.80	
	ICE hybrid	278				-514	-514	-23.7	-79%	8.1	8.7	16.8	2098	8.95	
	FC	176				-252	-252	-8.1	-27%	5.5	10.0	15.4	1932	8.25	
	FC hybrid	157				-181	-181	-3.9	-13%	5.0	12.9	17.9	2245	9.58	
Coal	ICE PISI	314				-974	-974	-108.4	-360%	8.6	3.7	12.3	1543	6.58	
	ICE hybrid	278				-796	-796	-90.5	-300%	7.7	8.7	16.4	2053	8.76	
	FC	176				-373	-373	-47.6	-158%	5.3	10.0	15.2	1903	8.12	
	FC hybrid	157				-288	-288	-39.0	-130%	4.8	12.9	17.7	2219	9.47	
Nuclear	ICE PISI	314				-945	-944	26.8	89%	11.5	3.7	15.2	1902	8.12	566
	ICE hybrid	278				-796	-795	27.2	90%	10.3	8.7	18.9	2371	10.12	696
	FC	176				-696	-695	27.2	90%	6.9	10.0	16.8	2105	8.98	619
	FC hybrid	157				-576	-576	27.5	91%	6.2	12.9	19.2	2399	10.24	697
Wind	ICE PISI	314				-24	349	26.5	88%	11.3	3.7	15.1	1886	8.05	568
	ICE hybrid	278				23	355	26.9	89%	10.2	8.7	18.8	2356	10.05	700
	FC	176				50	357	26.9	89%	6.8	10.0	16.7	2096	8.94	622
	FC hybrid	157				88	362	27.3	91%	6.2	12.9	19.1	2391	10.20	700
Indirect hydrogen															
Ref + FC		304	200	145	30.1										
Gasoline						50	50	3.8	13%	-0.3	21.4	21.2	2650	11.31	5552
Naphtha						59	59	5.1	17%	-0.3	21.4	21.2	2650	11.31	4189
Diesel						44	44	3.1	10%	-0.3	21.4	21.2	2650	11.31	6858
Methanol ex NG		277													
Remote/import						-50	-50	3.0	10%	1.4	21.4	22.8	2851	12.16	7610
4000 km NG						-71	-71	1.3	4%	1.4	21.4	22.8	2851	12.16	17387
Methanol ex coal						-139	-139	-25.5	-85%	1.4	21.4	22.8	2851	12.16	
Methanol ex wood						-177	-177	26.9	89%	2.2	21.4	23.7	3054	12.63	879
Methanol ex wood via BL						-44	-44	28.1	93%	0.9	21.4	22.4	2973	11.93	795
Oil price @50 €/bbl															
Hydrogen from thermal processes															
Ex NG reforming	ICE PISI	314	200	145	30.1	-232	-232	-6.2	-21%	5.9	3.7	9.6	1206	5.14	
	ICE hybrid	278				-154	-154	-1.7	-6%	5.1	8.7	13.8	1725	7.36	
	FC	176				44	44	9.8	33%	3.3	10.0	13.2	1657	7.07	1351
	FC hybrid	157				82	82	12.0	40%	2.9	12.9	15.8	1978	8.44	1315
Ex coal gasification	ICE PISI	314				-422	-421	-29.4	-98%	6.3	3.7	10.1	1259	5.37	
	ICE hybrid	278				-329	-328	-22.7	-76%	5.5	8.7	14.2	1771	7.56	
	FC	176				-63	-62	-13.3	-44%	3.1	10.0	13.0	1629	6.95	
	FC hybrid	157				-12	-12	-8.6	-28%	2.6	12.9	15.6	1947	8.31	
Ex wood gasification	ICE PISI	314				-288	346	26.6	88%	5.7	3.7	9.4	1181	5.04	355
	ICE hybrid	278				-198	352	27.0	90%	5.0	8.7	13.6	1707	7.28	505
	FC	176				12	368	28.2	94%	2.9	10.0	12.8	1604	6.85	455
	FC hybrid	157				55	371	28.4	94%	2.5	12.9	15.4	1929	8.23	543
Hydrogen from electrolysis															
Electricity ex			200	145	30.1										
NG	ICE PISI	314				-644	-644	-31.4	-104%	9.6	3.7	13.4	1672	7.13	
	ICE hybrid	278				-514	-514	-23.7	-79%	8.4	8.7	17.1	2142	9.14	
	FC	176				-252	-252	-8.1	-27%	5.1	10.0	15.0	1880	8.02	
	FC hybrid	157				-181	-181	-3.9	-13%	4.4	12.9	17.4	2174	9.28	
Coal	ICE PISI	314				-974	-974	-108.4	-360%	7.7	3.7	11.4	1431	6.11	
	ICE hybrid	278				-796	-796	-90.5	-300%	6.7	8.7	15.4	1929	8.23	
	FC	176				-373	-373	-47.6	-158%	4.0	10.0	13.9	1745	7.44	
	FC hybrid	157				-288	-288	-39.0	-130%	3.5	12.9	16.4	2054	8.76	
Nuclear	ICE PISI	314				-945	-944	26.8	89%	10.4	3.7	14.2	1776	7.58	529
	ICE hybrid	278				-796	-795	27.2	90%	9.2	8.7	17.9	2234	9.53	656
	FC	176				-696	-695	27.2	90%	5.5	10.0	15.5	1938	8.27	570
	FC hybrid	157				-576	-576	27.5	91%	4.8	12.9	17.8	2226	9.50	647
Wind	ICE PISI	314				-24	349	26.5	88%	10.2	3.7	14.0	1750	7.47	527
	ICE hybrid	278				23	355	26.9	89%	9.0	8.7	17.7	2211	9.43	656
	FC	176				50	357	26.9	89%	5.4	10.0	15.4	1923	8.21	571
	FC hybrid	157				88	362	27.3	91%	4.7	12.9	17.7	2213	9.44	648
Indirect hydrogen															
Ref + FC		304	200	145	30.1										
Gasoline						50	50	3.8	13%	-0.5	21.4	20.9	2619	11.18	5488
Naphtha						59	59	5.1	17%	-0.5	21.4	20.9	2619	11.18	4141
Diesel						44	44	3.1	10%	-0.5	21.4	20.9	2619	11.18	6779
Methanol ex NG		277													
Remote/import						-50	-50	3.0	10%	0.5	21.4	21.9	2739	11.69	7313
4000 km NG						-71	-71	1.3	4%	0.6	21.4	22.1	2760	11.78	16834
Methanol ex coal						-139	-139	-25.5	-85%	0.5	21.4	21.9	2739	11.69	
Methanol ex wood						-177	-177	26.9	89%	1.6	21.4	23.0	2846	12.30	856
Methanol ex wood via BL						-44	-44	28.1	93%	0.0	21.4	21.4	2761	11.44	762

⁽¹⁾ i.e. a negative number denotes an increase

⁽²⁾ Relative to the "business-as-usual" scenario: gasoline PISI for ethanol, diesel CIDI for diesel fuels and combined scenario for other fuels

Figure 8.4.2-1 Cost and potential for CO₂ avoidance
Oil @ 50 €/bbl

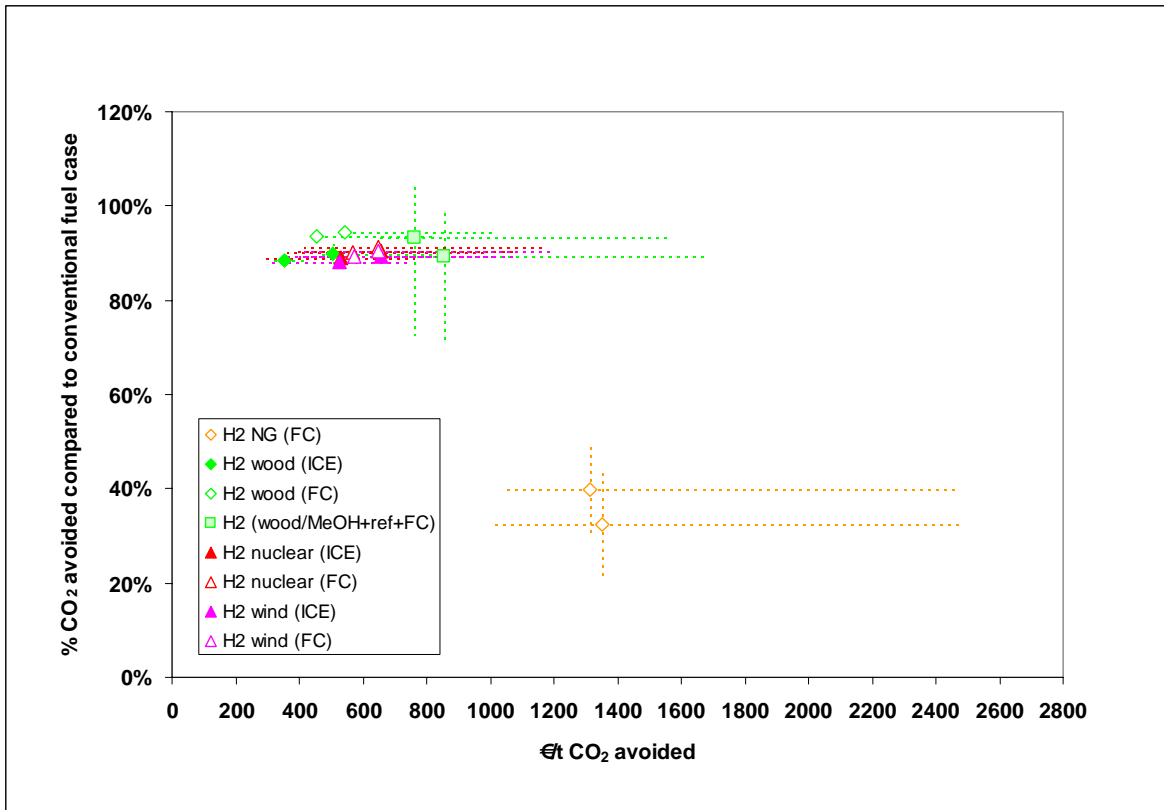
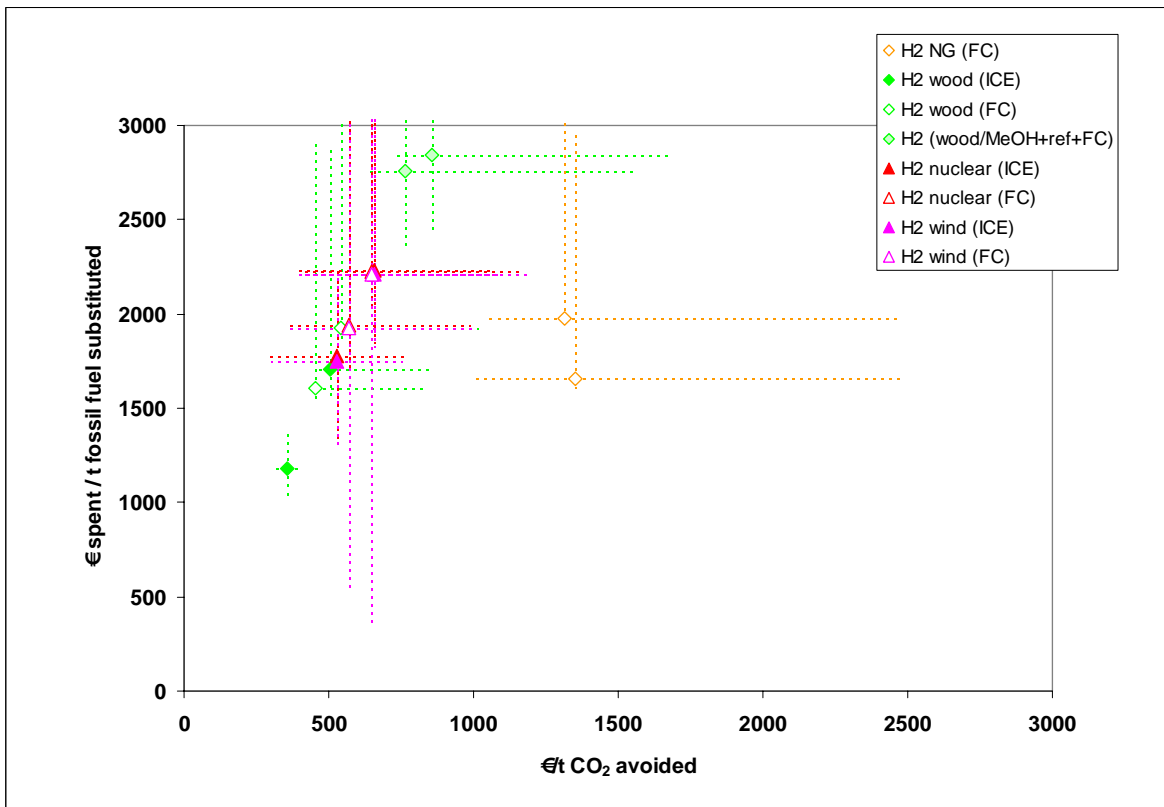
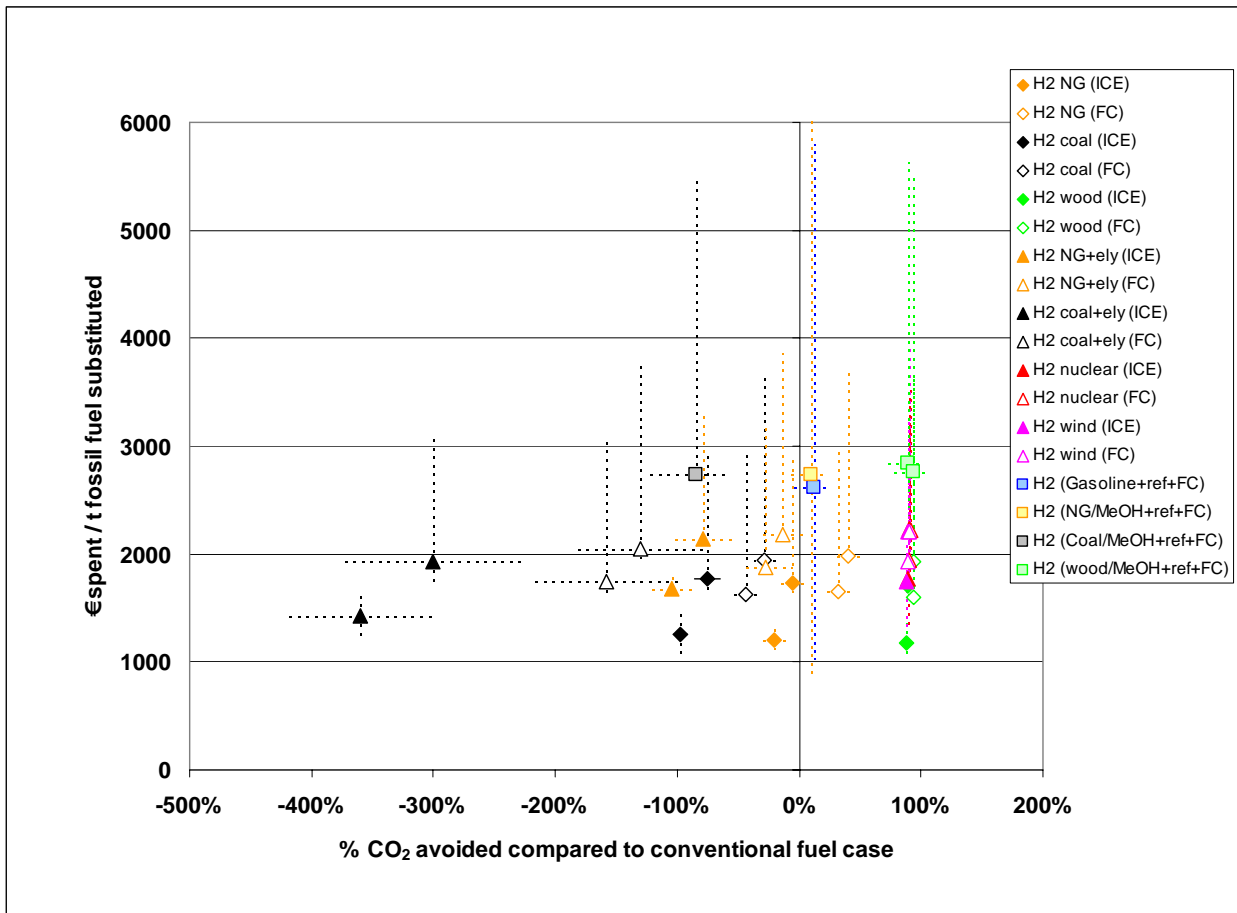


Figure 8.4.2-2 Cost of CO₂ avoidance versus cost of substitution
Oil @ 50 €/bbl



**Figure 8.4.2-3 % CO₂ avoided versus cost of substitution
 Oil @ 50 €/bbl**



8.5 Availability of fossil resources and fuels

The long-term adequacy of oil resources to cover world demand is currently a matter of debate. It is, however, not the purpose of this study to enter that debate. In any case, there is no serious threat to European supplies of crude oil and products within the timeframe of this study. The "business-as-usual" case where the whole road fuel demand is met with conventional fossil fuels is therefore considered entirely plausible.

Natural gas demand in the EU has increased at a steady 4% per annum over the past 10 years and is expected to increase strongly over the coming years as more power stations as well as industrial users switch to gas under the pressure of environmental legislation. A gas industry projection foresees that EU natural gas demand will have increased by more than 50% by the end of the next decade. In comparison, a 5% share of the 2020 European road fuel market would represent 12-15 Mtoe/a, i.e. only some 2.5% extra demand.

Europe (including Norway) already imports more than one third of its gas demand and this is set to increase to more than two thirds by 2020. This justifies our view that any gas used for road transport should be considered as incremental import.

Worldwide NG reserves are vast and in many parts of the world, untapped. A number of existing and potential producing regions are located such that Europe would be one of their most natural markets from a logistic and therefore cost point of view (North and West Africa, Middle East and of course Russia and other FSU States). Reserves are sufficient to cover any realistic demand scenario for a number of decades to come. Bringing the gas to market may, however, be an

issue. Natural gas projects are large, costly and involve a complex network of interest that has to include the investors, the producing country but also the consuming countries and, in case of pipelines, the countries through which the pipelines travels. Because of the weight of the infrastructure these are long-term projects. The large investments required are only likely to be realised if the economic and political conditions are right.

In spite of these reservations it is generally considered that natural gas supply to Europe will not be a serious issue, at least within the timeframe of this study. Limitations to the development of CNG are more likely to come from other constraints such as infrastructure issues and customer acceptance.

- *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.*

Natural gas will reach Europe mainly via pipelines but also increasingly as LNG from remote locations. GTL plants will also be sited near a remote gas field to take advantage of the low value of such remote gas reserves so that it will be in competition with LNG.

GTL plants are complex and need to be large to be economically viable. A typical state-of-the-art plant would be designed to produce 2-3 Mt/a of total products, about two thirds of which would be diesel fuel. The investment is expected to be in the region of 2 G€. Many conditions have to be fulfilled for such large and expensive projects to be developed successfully.

Four large GTL plants are now in various stages of planning design and construction in Qatar, bringing the total announced global GTL production to 700,000 bbl/d by 2015 (corresponding to around 20 Mt/a of diesel (plus other co-products). Although gas reserves are available and many other potential sites exist, it is generally considered that there will not be more than about 10 worldscale plants in the world by 2020. The 30 to 50 Mt/a of GTL diesel fuel thus produced would represent only a few percent of global road fuel demand. If used as a pure fuel it will therefore remain a niche product and may prove more valuable as a diesel fuel blending component.

The CTL route has in principle a large potential in view of the plentiful and widely distributed world coal reserves. There is great interest for this technology mainly in countries that have large coal reserves such as the USA, China or South Africa. From an environmental point of view the main drawback of this route is the very large associated CO₂ emissions. It is therefore likely that the technology will be mostly developed in combination with CO₂ capture and storage (see *section 7*) in these regions. The complexity of the technology and the large capital investment required will, however, limit its development although we have noted from **Figure 8.4.1-3b** that it appears to be close to being competitive with conventional oil at current prices. Europe has few economic coal reserves and it is unlikely that this technology could be widespread within the EU. CTL diesel fuel is therefore more likely to supplement the supply of GTL diesel on world market rather than become a mainstream product.

- *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.*

DME can also be produced in large quantities from either natural gas or coal. One advantage is a simpler and cheaper conversion plant. Some DME may actually be produced as an alternative to LNG as a way to transport natural gas to power stations, particularly in the Japanese market. As a road transport fuel it is likely to face the same limitations as CNG.

- *While large quantities of DME could be produced from either natural gas or coal, infrastructure and market barriers are likely to be the main factors constraining the development of DME as a road fuel.*

In this study methanol is only considered as a fuel for on-board reformers. Methanol is an international commodity, large quantities of which are produced from coal and mostly natural gas, for use in the chemical industry. The technology is fully commercial and sourcing additional methanol for road applications is unlikely to be an issue especially for limited quantities.

Hydrogen can also be produced from natural gas or coal using well proven technologies. In fact natural gas is already today the source of most of the great majority of hydrogen produced across the world and would be the most readily available and economic source for additional supplies.

8.6 Availability of biomass-based fuels

Biomass for energy needs land and is therefore in competition with other crops, particularly food crops. As a baseline we used a DG-AGRI projection for agricultural production and markets up to 2012, assuming biofuels production remaining at 2005 levels as well as a constant demand for food crops (with the exception of sugar, see below). We then considered the possibilities and consequences of increasing biofuels production at the 2012 horizon.

For most crops, production and consumption of agricultural products are today roughly in balance in EU-25 (with the exception of oilseeds, almost half of which is imported), The additional sources of agricultural capacity for growing energy crops are as follows:

- The reduction of sugar subsidies is expected to reduce sugar beet production, thereby releasing land currently used for sugar beet but where yields are poor. In high yield areas, however, some land is still expected to be used for sugar production if there is a market for ethanol.
- A steady improvement of agricultural yields has been achieved over the last decades and this trend is expected to continue.
- Set-asides can in principle be used for non-food production although it is difficult to make an accurate estimate of land quality and therefore of yields.
- There is a certain potential for collection and use of waste woody biomass as well as straw for advanced biofuels.
- Finally some organic waste (domestic waste, manure, dairies, fish farms, slaughterhouses etc) is available for the production of biogas.

Considering land as the primary resource leads to difficulties because of the large variations in land quality and therefore potential yields. Instead we used cereal production as a proxy for yield postulating a constant ratio between the yield of cereal and the yield of other crops.

We deliberately did not consider the expansion of arable area onto other land, notably pasture and forest. Apart from the societal resistance, such change in land use would be likely to release large amounts of carbon from the soil, negating any benefit of the energy crops for decades to come.

A very important point, which has often been overlooked in past studies, is that **the availability of waste biomass for energy is much higher than that for conversion to road fuels**. This is because of the economic scale of the plants: heat and combined-heat-and power applications are economic on a small scale, and can exploit dispersed resources. In contrast, plants for converting waste to biofuels are complex and expensive: to be economic, they must be large to benefit from the economies of scale (100-200MWth at the least). That means there are considerable logistical problems (trucks-per hour) and transport costs associated with bringing enough biomass to the plant. Therefore, only the wastes which are available with a high area-density can only be used for biofuels.

As a result our estimates are less optimistic than what other studies have reported.

8.6.1 Conventional ethanol and bio-diesel

The scenario for maximum possible production in the EU of conventionally produced ethanol and bio-diesel is summarised in the table below.

The scenario assumes a production of 230 PJ/a of ethanol corresponding to 5.75% of the gasoline demand on an energy content basis (the EU Commission's target for 2010). This can be achieved with the sugar beet surplus (8.0 Mt/a) plus just under half of the surplus cereal production potential (22.4 Mt/a) and an additional 1.5 Mt/a already used for this purpose today (**Table 8.6.1**).

The remaining notional cereal surplus of 24.7 Mt/a from the balance of the set-asides, the net land released by the sugar reform and yield improvements, is available for bio-diesel production. If the land corresponding to this cereal surplus were used for oil seeds production, 12.5 Mt/a of rape seeds and 3.4 Mt/a sunflower seeds could be produced (assuming a 80/20 land use ratio). The total oil seeds potential, including the 5.6 Mt/a of oil seeds already used today for bio-diesel production, corresponds to 302 PJ/a of bio-diesel equivalent to 3.4% of the total diesel fuel market including personal cars, commercial and heavy duty vehicles. It must be realised that this estimate assumes no change in the amount of oilseeds imported for food use.

Overall, around 4.2% of the road fuels market can be covered by these conventional bio-fuels (in energy terms), equivalent to the substitution of 12.3 Mt/a of fossil fuels. Note that the net fossil energy saved is only 2.2% and the GHG savings only 2.0% because these fuels are only partly renewable.

The estimated cost for replacing fossil fuels with biofuels with the realistic grain/oilseed trading scenario is 408 and 231 €/t and the cost of CO₂ avoided is 228 and 130 €/t for the low and high oil price scenario respectively. This is the additional cost above that of the fossil fuel in the base-case.

This scenario is, however, unlikely to happen. Firstly, it would require new import barriers to prevent imports undercutting EU-produced oilseeds and these are probably not compatible with existing trade agreements. Secondly, it would be cheaper for the EU to import oilseeds in exchange for cereals exports. The reason is that Europe is climatically better suited to cereals production than oilseeds (that is why EU already imports almost half its present oilseed requirements). Very large increases in oilseed price would be needed to induce oilseed production on unsuitable EU land, or too frequently in crop rotations for optimum results.

Table 8.6.1 Potential for production of conventional ethanol and bio-diesel in EU-25

	Crop		Ethanol PJ/a	Bio- diesel PJ/a	Fossil fuels replaced		WTW avoidance				Cost @25 €/bbl			Cost @50 €/bbl		
	Mt/a	PJ/a			PJ/a	PJ/a	Mt/a	WTW Fossil energy		WTW CO _{2eq}		€/t conv	G€/a	€/t CO ₂ av	€/t conv fuel	G€/a
			MJ/MJ	PJ/a				g/MJ	Mt/a							
Surplus sugar beet ("C" sugar)	8.0	31	16		0.4	0.27	4	28.4	0.5	413	0.16	342	250	0.09	207	
Surplus grain (as food grade wheat)																
From set-asides	22.9															
From and released by sugar reform	9.3															
From improved yields	14.9															
Total	47.1															
To ethanol	22.4	376	202		4.7	0.46	94	36.4	7.3	359	1.68	243	216	1.01	148	
To oil seeds	24.7															
Equivalent oil seeds ⁽¹⁾	↓															
Rape	12.5	298		174	4.0	0.72	125	45.1	7.8	437	1.76	230	235	0.95	123	
Sunflower	3.4	80		50	1.2	0.83	42	67.4	3.4	467	0.54	169	260	0.30	94	
Existing crops for energy																
Rape	5.6	133		78	1.8	0.72	56	45.1	3.5	437	0.79	230	235	0.42	123	
Cereals	1.5	22	12		0.3	0.46	6	36.4	0.4	366	0.10	276	227	0.06	174	
Total			230	302	532	12.3		326	23.0	408	5.03	228	231	2.84	130	
Gasoline/diesel market coverage			5.75%	3.4%												
Total road fuel market coverage			4.2%													
WTW avoidance, % of fossil fuels base case									2.2%						2.0%	

(1) Assumes 80/20 rape/sunflower

Several studies have quoted the percentage of arable land which would be needed to reach the biofuels Directive targets. The vast difference in yields between different types of land makes a "% of land" meaningless. According to our figures, the extra crops required to bring about the required increase in biofuel production (assuming 5.75% replacement of diesel by bio-diesel

and 5.75% of gasoline by ethanol on an energy basis) would replace 27% of projected EU 2012 cereals production, or roughly 22% of total arable capacity (not including set-asides) or roughly 19% of arable capacity including set-asides.

The EU does not have enough arable capacity on the existing arable land area + set-asides to reach this target in 2012 without increasing food imports (elimination of potential cereals exports is already included in our figures). Possible reasons that other studies reach different conclusions are:

- They did not account for the fact that the effective yields from set-aside yields are much lower than the EU average (our figure is already the *maximum* which could be expected),
- They used more optimistic yield increases than those foreseen by DG-AGRI,
- They did imply an increase in food imports.

Imported ethanol

Using sugar cane and relatively cheap local labour, countries such as Brazil can produce ethanol with a better greenhouse balance and at a considerably lower cost than is possible in Europe (even when factoring sea transport in). The production cost is competitive with gasoline at current oil prices. There is no GHG objection to increasing sugar cane area onto existing grazing land in Brazil, because this would actually increase soil carbon stocks. It is claimed that sugar cane is only grown on 1% of the suitable land in Brazil: this may be an exaggeration, but anyway it is clear that there is a lot more room to expand ethanol production than is the case in Europe.

At the moment there is a high tariff for ethanol imports to EU. A sudden tariff reduction could lead to Brazilian exports substituting use in Brazil, which would be counter-productive in GHG terms. However, a programmed increase in imports could be met by production increases. Brazilian ethanol production is already now expanding by 10% a year, driven by the high oil price: a study is needed to show how fast it can realistically expand in future.

It must be noted that the cost-to-Europe of imported ethanol is unlikely to be related to the production cost. The price paid by EU importers would rather align itself with the cost of the cheapest EU producer.

Imported oilseeds or vegetable oils

So far the trade pattern has been to import the raw materials (oil seeds) rather than finished biodiesel. Perhaps this is because until now there has been a ready and profitable market for the animal-feed by-products in the EU.

The import of oilseeds or vegetable oils for biodiesel production (or for replacing domestic oilseeds which are diverted to oilseed manufacture) raises major questions about sustainability. One source with a potential for expansion are soybeans in Brazil, but these are typically grown close to the rainforest and the existing high demand for soybeans is already suspected of accelerating the destruction of the rainforest. Another major source is palm oils from Malaysia and Indonesia: a rapid increase in demand could be met by unsustainable production on rainforest land. Sustainable certification could be considered as a solution, the EU importing only certified sustainable products. However, unless the scheme was adopted worldwide, sustainable exports to EU would simply be replaced by unsustainable production for other markets.

8.6.2 "Advanced" biofuels

Under this generic term we include ethanol from cellulosic material and synthetic fuels produced by biomass gasification and syngas-based synthesis processes. "Wood" is considered here as a proxy for a range of materials, the largest potential sources being farmed wood, perennial grasses and wood waste from forestry.

The potential for farmed wood (short rotation forestry or SRF) was estimated on the basis of the cereal surplus discussed above, assuming a substitution mass ratio of 1.57 t of wood per t of

cereal (**Table 8.6.2-1**). The land producing the estimated 47.1 Mt/a surplus cereals could potentially produce 83.9 Mt/a of wood instead, with an additional 19.7 Mt/a from substitution of oil seeds and cereals currently used for biofuels.

Wood waste availability was estimated on the basis of a recent detailed study of wood (mostly forest residuals) for energy. About one quarter of the total would be available cheaply (2.8 €/GJ) at pulp mills suitable for using the black-liquor biofuels route. Of the rest, we estimated that only 1/3 would be logistically available to other plants for making biofuels, and then the price would rise to that of farmed wood: 4.1€/GJ. That means a total of about half the energy-wood is available for making biofuels: about 26 Mt/a. This brings the total wood availability to just under 130 Mt/a.

Wheat straw is the most concentrated source of cellulosic material. We used a GIS-based study which considered regional straw yields, alternative uses and the logistics of bringing straw to large electricity plants. Although the total unused straw in EU is about 820 PJ/a, the amount which can logistically be brought to plants of 120 MW_{th} capacity is only 230 PJ/a.

Table 8.6.2-1 Potential for production of advanced biofuels in EU-25

Resource	Mt/a	PJ/a	Ethanol PJ/a	Syn-diesel PJ/a	(Naphtha) PJ/a	DME PJ/a	Hydrogen PJ/a
Surplus sugar beet	8.0	31	16				
Wheat straw	15.9	230	97				
Surplus grain (as food grade wheat)							
Set-asides	22.9						
From net land released by sugar reform	9.3						
Improved yields	14.9						
	↓						
As farmed wood	83.9	1511	518	472	157	771	942
Existing oil seeds and cereals for energy	7.1						
	↓						
As farmed wood	19.7	355	122	111	37	181	221
Waste wood	26.2	471	162	167	56	274	332

Assumptions for all scenarios:

Marginal sugar beet still grown

Straw only used for ethanol production

50% of waste wood used though black liquor route

Different scenarios were then considered, using the total wood resource for producing ethanol, synthetic diesel (and naphtha), DME or hydrogen (**Table 8.6.2-2**). In the latter case two cases were considered according to the powertrain in which the hydrogen would be used, ICE or fuel cell.

In all scenarios the non-food sugar beet was assumed to be unaffected and used to produce a baseline amount of ethanol. The rationale for this is that sugar beet is grown on high quality soils on which switching to other crops, particularly SRF wood, would be unlikely. Straw was also affected to ethanol production in all scenarios. Where relevant, 50% of the available waste wood would be used through the "black liquor" route (mostly in Scandinavian paper mills).

Table 8.6.2-2 Fossil energy and GHG emissions avoidance potential from advanced biofuels and hydrogen in EU-25

Scenario	Total Alt fuels PJ/a	Road fuels market coverage			Fossil fuels replaced		WTW avoidance						Cost					
		Gasoline	Diesel	Total	PJ/a	Mt/a	WTW fossil energy			WTW CO ₂ eq			Oil @ 25 €/bbl			Oil @ 50 €/bbl		
							MJ/MJ	PJ/a	% of total for fossil fuels	g/MJ	Mt/a	% of total for fossil fuels	€/t fossil fuel	G€/a	€/t CO ₂ av	€/t fossil fuel	G€/a	€/t CO ₂ av
"Max ethanol" total	914			7.1%	914	21.2	0.87	798	5.4%	66	60	5.3%	601	12.7	218	390	8.3	143
Ethanol	914	22.9%																
"Max syn-diesel" total	863	2.8%	8.5%	6.8%	863	20.0	1.07	928	6.3%	79	69	6.1%	711	14.2	209	532	10.6	156
Ethanol	113	2.8%			113	2.6		104	0.7%	8	8	0.7%						
Syn-diesel	750		8.5%		750	17.4		824	5.6%	61	61	5.4%						
Naphtha	250							262	1.8%	21	21	1.9%						
"Max DME" total	1339	2.8%	14.3%	10.7%	1372	31.8	1.12	1494	10.1%	82	110	9.8%	673	21.4	196	483	15.4	140
Ethanol	113	2.8%			113	2.6		104	0.7%	8	8	0.7%						
DME	1226		14.3%		1259	29.2		1390	9.4%	103	103	9.1%						
"Max hydrogen" total	1608																	
Ethanol	113	2.8%		0.9%	113	2.6		104	0.7%	8	8	0.7%						
Hyd used in ICE	1495	26.7%	7.9%	13.7%	1756	40.7	1.05	1681	11.4%	82	131	11.7%	1699	69.1	520	1000	40.7	312
Hydrogen	1495	23.8%	7.9%	12.8%	1643	38.1		1577	10.7%	123	123	11.0%						
Hyd used in FC	1495	45.3%	14.0%	23.8%	3042	70.5	1.97	3170	21.5%	152	244	21.7%	2047	144.3	586	1527	107.6	441
Hydrogen	1495	42.5%	14.0%	22.9%	2929	67.9		3066	20.8%	236	236	21.0%						

The maximum ethanol potential represents a saving of 21.2 Mt/a of gasoline (22.9% of the EU gasoline market or 7.1% of the total road fuels market). It would save a net 5.4% of the fossil energy used by fossil fuels and 60 Mt/a of CO₂ equivalent emissions.

The syn-diesel and DME scenarios make a small contribution to gasoline savings through ethanol, the balance addressing the diesel market. DME can save substantially more conventional diesel than syn-diesel (BTL) partly because the production process is more efficient, the DME vehicles are somewhat more fuel efficient than the diesel ones and mostly because the BTL process also produces other products, mainly naphtha. The latter would be used as chemical feedstock rather than road fuel but would still attract fossil energy and GHG savings by substituting refinery naphtha. In total the "max syn-diesel" scenario would produce a saving of around 20 Mt/a of fossil diesel fuel and 90 Mt/a of CO₂, while the "max DME" scenario would achieve nearly 32 Mt/a of fossil diesel fuel substitution and 110 Mt/a of CO₂.

When used in ICEs hydrogen has somewhat more potential because the manufacturing process uses the biomass more efficiently. The improvement is much bigger with fuel cells the much higher efficiency of which allows larger fossil fuel savings for a given transport demand.

8.6.3 Biogas

In order to arrive at a realistic potential for biogas many factors must be considered. Although there is a lot suitable biomass feed around, the problem is to estimate what proportion of the total available could be used, and at what cost. Although municipal waste or sewage can play some role, the main potential feedstock is manure. Again, the availability for making transport fuel is much less than the availability for energy use.

Biogas plants are capital-intensive relative to their output, particularly when upgraded gas is required e.g. for use as CBG. These plants cannot support high feedstock costs such as may be associated with long-distance transport. In Denmark, the EU country where the biogas industry is the most developed and where intensive agriculture and short distances provide a favourable environment, even fairly large scale plants can only be economic when co-processing waste from fisheries, slaughterhouses and dairies, for which they actually get paid.

We have chosen the most economic example of biogas production for our availability scenario, on the basis that this would be how the industry is most likely to develop in the next 10-20 years. This requires co-feeding of slurry and organic waste (either food industry waste or municipal waste). The potential road fuel production from this type of plant is limited to less than 200 PJ/a in EU-25 by the simultaneous availability of organic waste and large quantities of animal slurry.

Farmed crops can also potentially be used to produce biogas. However the high cost of such feedstocks is likely to make this option uneconomic compared to other alternatives. We have therefore elected not to consider it.

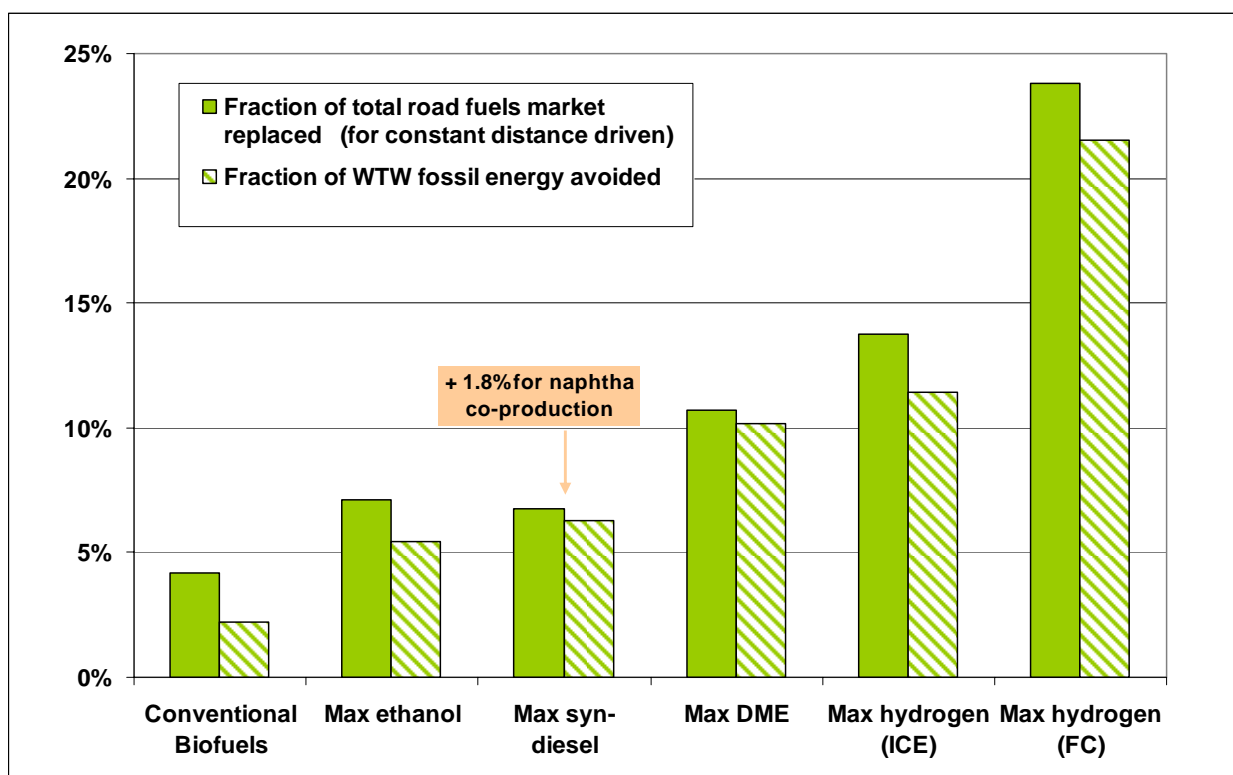
Table 8.6.3 Fossil energy and GHG emissions avoidance potential from biogas in EU-25

Scenario	Total Alt fuels PJ/a	Road fuels market coverage			Fossil fuels replaced		WTW avoidance						Cost					
		Gasoline	Diesel	Total	PJ/a	Mt/a	WTW fossil energy			WTW CO _{2eq}			Oil @ 25 €/bbl		Oil @ 50 €/bbl			
							MJ/MJ	PJ/a	% of total for fossil fuels	g/MJ	Mt/a	% of total for fossil fuels	€/t fossil fuel	G€/a	€/t CO ₂ av	€/t fossil fuel	G€/a	€/t CO ₂ av
Biogas	200	2.8%	0.9%	1.5%	196	4.5	0.99	198	1.3%	140	28	2.5%	832	3.8	132	655	3.0	104

8.6.4 Overview of biomass potential

Figure 8.6.4 shows, for the different scenarios considered from "conventional biofuels" only scenario to "max hydrogen, the percentage of fossil road fuels that can be substituted (in effect a "TTW" figure) as well as the percentage of WTW fossil energy that can be saved.

Figure 8.6.4 Potential of biomass for fossil fuel substitution



It must be kept in mind that, generally, the routes that save more fossil fuel are also more expensive to put in place. Once again this illustrates the need for further R&D in the "advanced" biomass conversion options in order to reduce costs.

Each of these scenarios, concentrating on a single fuel, represents an extreme case. Reality is of course more likely to see a combination, resulting from the complex interplay of economics, government policies and practical constraints. In particular one should not underestimate the fundamental changes to agricultural practices and to the countryside as well as the logistical infrastructure that would be required for the "all wood" scenarios. Over 100 Mt/a of farmed wood would require an area of between 7 and 15 Mha (depending on the soil quality) hitherto dedicated to crops such as cereals, representing between half and the total UK arable land. Harvesting and transporting wood to the plants would require a vast logistic system and so would the collection and transport of waste wood. The need to feed the plant in a practical and economic manner is likely to call for fairly small plants with capacities in the region of 100,000 to 200,000 t/a of total liquid product equivalent to 0.5 to 1 Mt/a of wood. Between 100 and 200 such plants would be required across Europe. By comparison there are currently less than 100 oil refineries in Europe to cover the whole of the road transport and other energy markets. All

these figures illustrate the complexity of the task and the magnitude of the challenge facing those who may wish to develop this route.

Road fuels from biomass will also be in direct competition with fuels for stationary applications, mostly heat and electricity generation. The important issue of optimal use of land and other sources of renewable energy to maximise CO₂ avoidance is discussed in *section 9*.

- *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.*

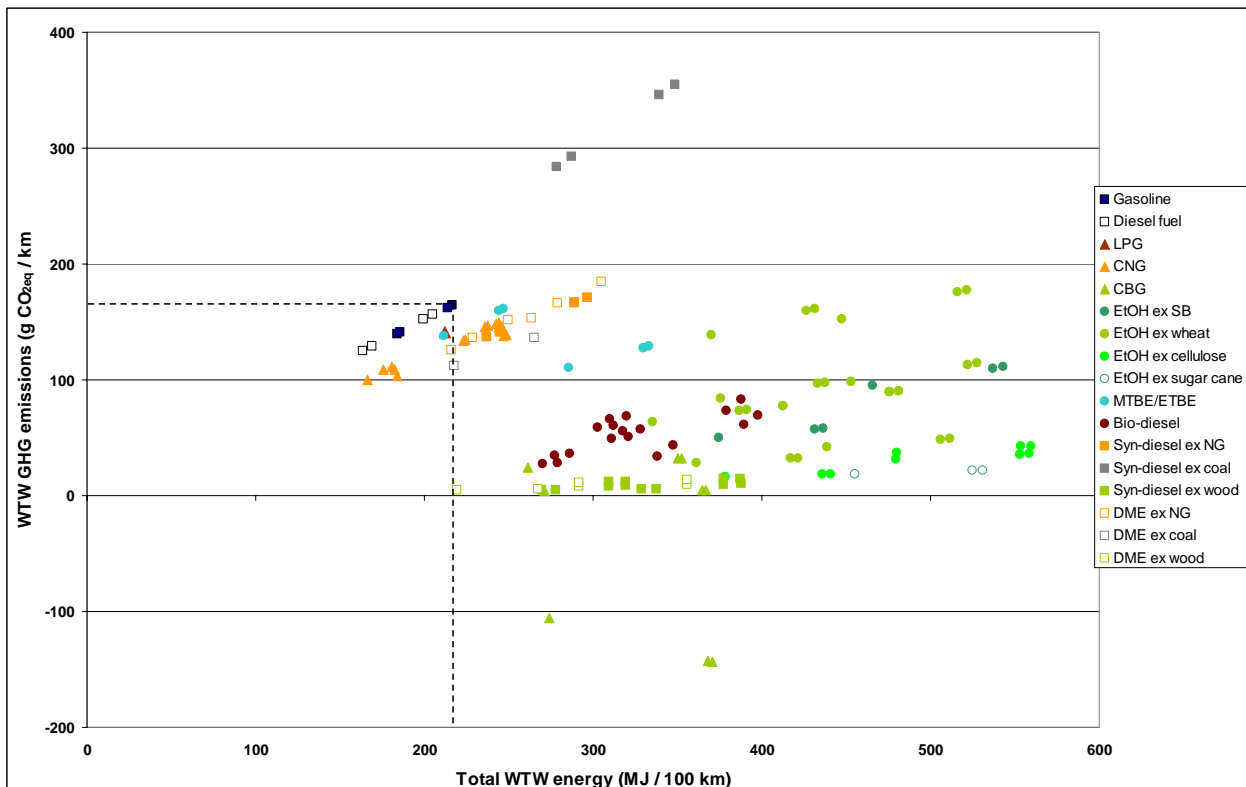
9 Alternative uses of primary energy resources

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 highlighted 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.

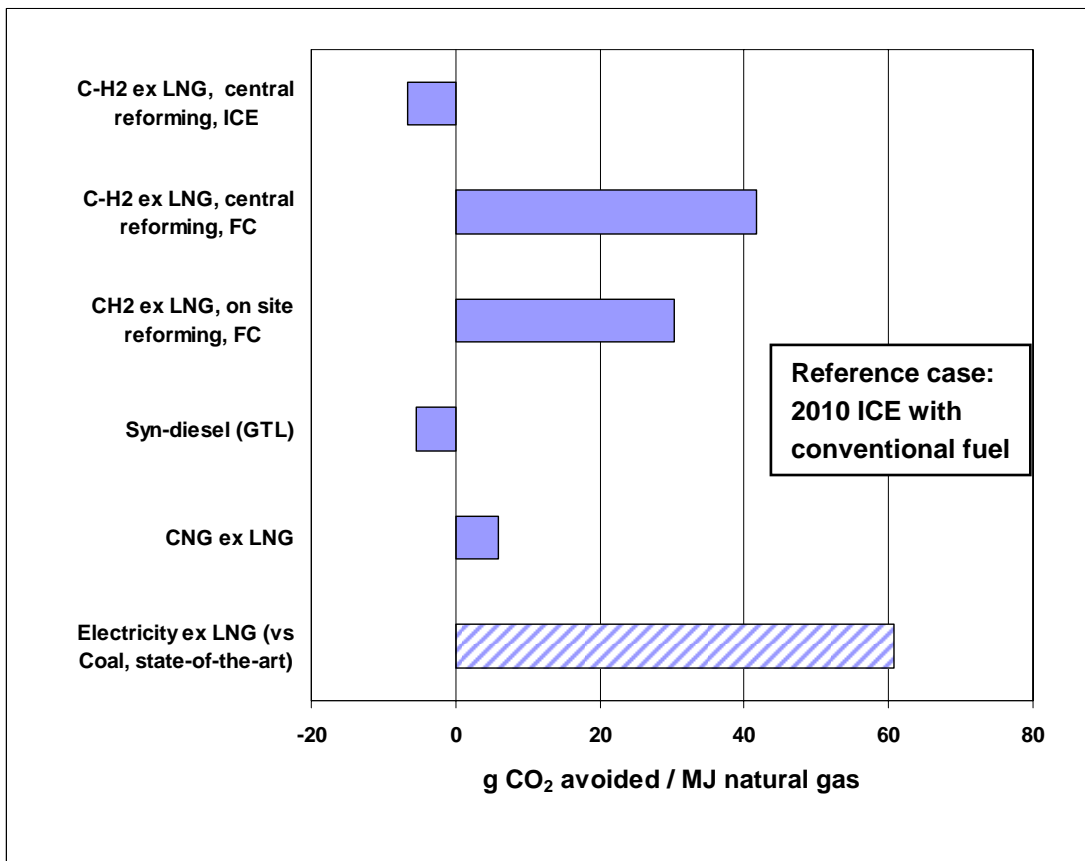
9.1 Natural gas

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 *CO₂ avoidance from alternative uses of natural gas*

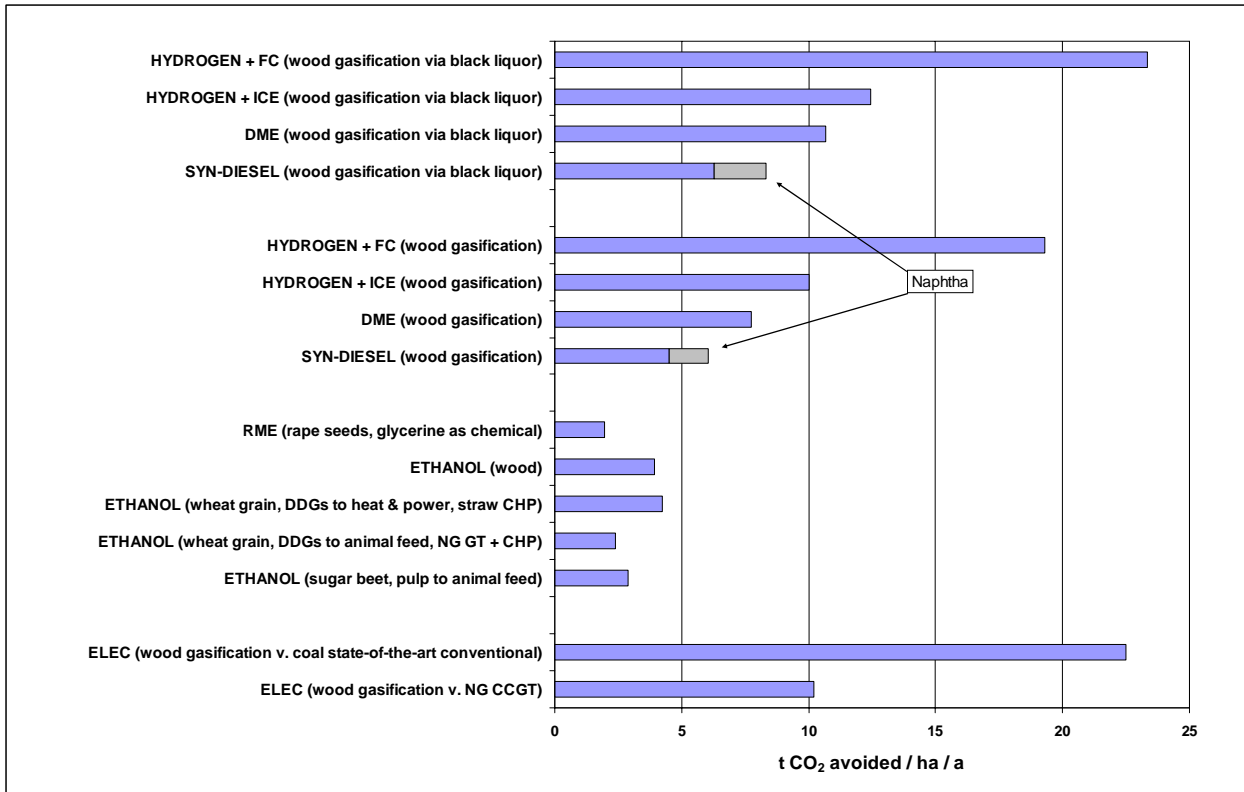


9.2 Biomass

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 “CO₂ avoidance potential” when used with different crops. The range shown for each option corresponds to the different pathways available.

Figure 9.2 CO₂ avoidance from alternative uses of land



Electricity production is energy intensive and substitution by biomass results in large CO₂ 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 CO₂ 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 correspond 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 CO₂ 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

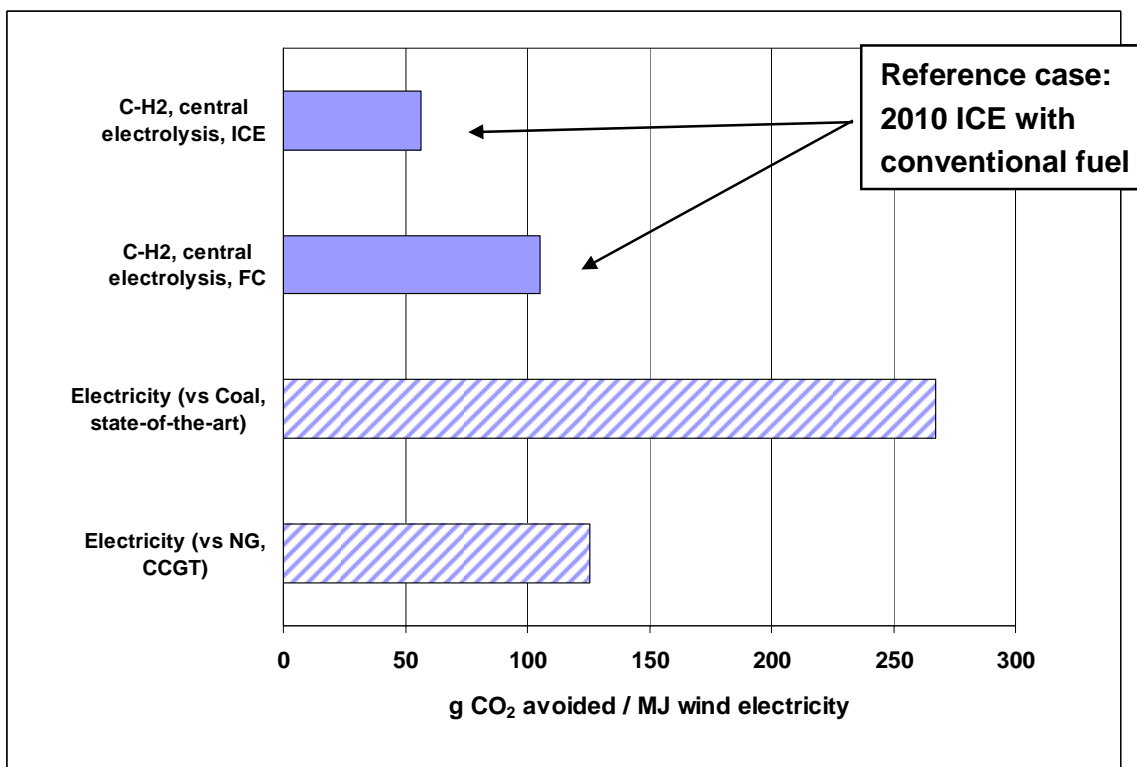
How much energy can be harnessed from wind can be a matter of endless debates. The main issue is first to find suitable sites, get the appropriate approvals and public acceptance and then to construct a suitable financial structure to make a project feasible. The rate of success in doing this, rather 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 CO₂ avoidance potential of wind electricity.

Figure 9.3 CO₂ 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
CC&S	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 ₂ O	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

Energy requirement and GHG emissions for marginal gasoline and diesel fuel production

This study is about alternative road fuels and their potential to replace conventional gasoline and diesel fuels. When we evaluate these alternatives we need to consider their potential to save energy and GHG. At the 2010-2020 horizon, alternative fuels can only be reasonably expected to supply say 10% to 20% of the road fuel demand. As far as the conventional fuels are concerned, the issue is therefore how much can be saved by not producing the marginal 10 or 20% of the 2010-2020 expected demand.

Oil refineries produce a number of different products simultaneously from a single feedstock. Whereas the total amount of energy (and other resources) used by refineries is well documented, there is no simple, non-controversial way to allocate energy, emissions or cost to a specific product. Distributing the resources used in refining amongst the various products invariably involves the use of arbitrary allocation keys that can have a major influence on the results.

For example energy content is a popular allocation key; there is, however, no physical reason why a product with higher energy content should systematically attract more production energy. Another example is provided by naphtha reforming, a ubiquitous refinery process that dehydrogenates virgin naphthas into a high octane gasoline component; a superficial analysis would call for allocating most of the energy requirement of this process to gasoline production; however the bulk of that energy is chemical energy related to the simultaneous production of hydrogen which, in turns, is used for the desulphurisation of diesel components.

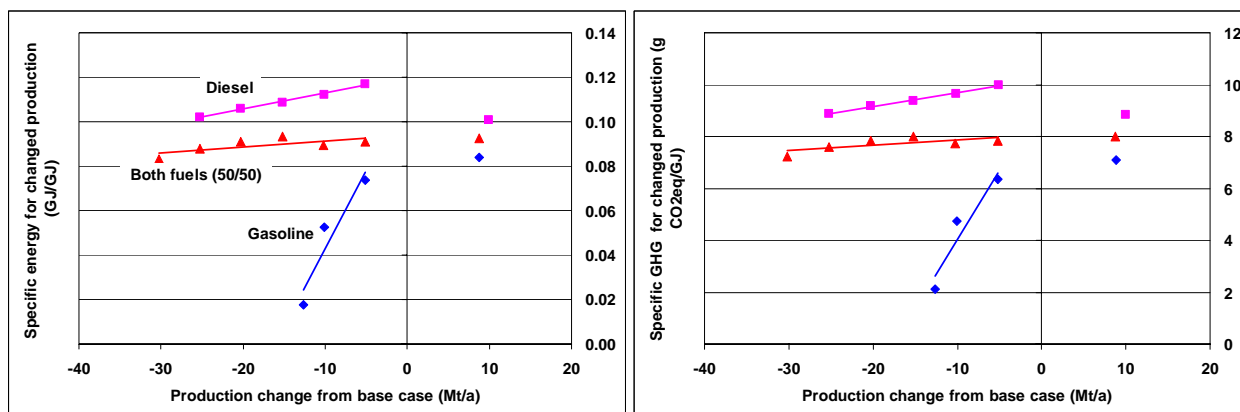
More to the point, such a simplistic allocation method ignores the complex interactions, constraints, synergies within a refinery and also between the different refineries in a certain region and is likely to lead to misleading conclusions. From an energy and GHG emissions point of view, this is also likely to give an incomplete picture as it ignores overall changes in energy/carbon content of feeds and products.

To approach the problem we performed a marginal analysis of the European refining system using the CONCAWE EU refining model. In a "business-as-usual" base case no alternative fuels are involved and the EU refineries have to substantially meet the total 2010 demand with minimum adaptation of the refining configuration. In the alternative cases conventional gasoline and/or diesel demand is reduced by a certain amount assumed to be substituted by other fuels. Demands for other oil products are fixed to the values expected to prevail in 2010. The crude oil supply is also fixed, with the exception of a balancing crude (heavy Middle Eastern considered as the marginal crude). Gasoline and diesel maximum sulphur content are assumed to be 10 ppm. All other fuel specifications are assumed to remain at the currently legislated levels i.e. maximum 35%v/v aromatics in gasoline from 2005 and other specifications remaining at current values.

The difference in energy consumption and GHG emissions between the base case and an alternative can be credibly attributed to the single change in gasoline or diesel fuel production

The CONCAWE model is fully carbon and energy balanced so that the differentials between two cases take into account small changes in energy and carbon content of all products.

The outcome of this work is shown in the figure below where the energy and CO₂ emissions associated to a certain marginal production of either diesel or gasoline are plotted as a function of that production. The data points represent the average value per MJ for the total amount produced.



Note: data points show the average saving at a given reduction level

The first striking point is that more energy/CO₂ can be saved through substituting diesel rather than gasoline. This goes somewhat against “conventional wisdom” according to which gasoline production is more energy-intensive than diesel’s. Whereas this assertion can be challenged for any modern refinery, this is particularly incorrect in Europe where the demand pattern is such that refineries struggle to produce the large middle distillate demand while having to export substantial quantities of gasoline.

The pattern is somewhat different when looking at either an increase or a decrease in production from the base case. The latter represents the point that was “planned for” i.e. for which the refineries invested.

Reducing production from the base case represents a situation where refineries would have over-invested. Diesel is in high demand in Europe and the marginal production routes are likely to be rather inefficient. At a lower production spare capacity becomes available and the system sheds first the least efficient production routes, thus the downward slope of the curve. Gasoline is in surplus and any reduction of production will increase the imbalance and therefore result in a low energy saving, the more so as the production is further decreased.

Increasing production from the base case represents a situation where refineries have correctly anticipated the level of demand for conventional fuels. The figures thus pertain to the additional “cost” that would have been incurred by having to produce more. The somewhat lower figure for diesel reflects the fact that additional new processes are likely to be efficient.

As refineries tend to adapt to the market as it develops rather than over-invest, we believe these latter figures are the most relevant. Accordingly we have proposed to use 0.08 and 0.10 MJ_{ex}/MJ_f and 6.5 and 8.6 g CO₂/MJ_f for gasoline and diesel fuel respectively.

It must be realised that the outcome of such an analysis is still dependent on a number of assumptions particularly with regard to the base case and the actual level of demand compared to the production capacity. Clearly a reduction of gasoline demand below general expectations could lead to very small energy savings.

Our base case includes a certain amount of diesel imports and it could be argued that these will be the first one to be substituted. Reality is likely to be more complex and some imports will undoubtedly still take place with or without alternative diesel sources. In any case, imported diesel will be made in non-European refineries, the level of complexity and conversion of which will have to be similar to the European ones inasmuch as the demand for residual products relative to lighter ones is globally decreasing. The energy and GHG emissions figures associated to this production would be at most similar to European figures or more likely lower as such refineries would produce a more balanced product basket. By using the European figures we therefore err on the conservative side.

There are further sources of uncertainty that may materially affect our results:

WTT APPENDIX 3

- Although our model includes a number of safeguards to avoid over-optimisation, there is a real possibility that actual refinery operations will be sub-optimum. As this would affect both the base case and the alternative cases in a similar way it does not materially affect the differential numbers.
- Historically, European refineries have improved their energy efficiency by about 1% per year. We have assumed this trend will continue a/o under pressure of site CO₂ emissions limitations. The effect of a change to this assumption would be small compared to the variability of the figures shown in the figures above.
- Refineries traditionally use part of their crude intake as fuel, in the form of gases produced in various process units, coke produced internally in the FCC supplemented by liquid (mainly residual) fuel. Some refineries have replaced part or all their liquid fuel by imported natural gas usually to meet local SO₂ emissions regulations. This trend has the potential to increase somewhat in the future either because of increased pressure on SO₂ emissions or actions to reduce site CO₂ emissions. Such a change would not impact energy efficiency figures, but would slightly reduce CO₂ emissions. Again the effect is small compared to other sources of variability.

Summary of WTW Energy and GHG balances

This appendix gives, for each WTW pathway, i.e. a combination of a fuel production route and a powertrain, the energy and GHG figures including uncertainty ranges for WTT, TTW and WTW.

New pathways in this version are highlighted in **yellow**.

Note that fossil energy is only indicated where lower than total energy (i.e. for partly renewable pathways).

Table of contents

1	Crude oil based fuels	2
2	CNG / CBG	3
3	Ethanol	4
4	Ethers	6
5	Bio-diesel	7
6	Synthetic diesel fuel	8
7	Methanol and DME	9
8	Compressed hydrogen (C-H₂)	10
	8.1 C-H ₂ from natural gas reforming and coal gasification	10
	8.2 C-H ₂ from biomass processing	11
	8.3 C-H ₂ from electrolysis (all electricity sources)	12
9	Liquid hydrogen (L-H₂)	13
10	Summary of pathways with CC&S	14

1 Crude oil based fuels

WTT Code	Powertrain	Energy MJ / 100 km												GHG g CO _{2eq} / km								
		Total									Fossil			TTW			WTT			WTW		
		TTW (MJ/100 km)			WTT (MJ/100 km)			WTW (MJ/100km)			WTW (MJ/100km)			Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Conventional fuels pathways																						
COG1	Conventional gasoline																					
	PISI 2002	224	0	0	3	4	6	255	4	6												
	DISI 2002	209	8	8	26	4	6	238	10	11												
	PISI 2010	190	6	6	26	4	5	216	7	8												
	DISI 2010	188	9	9	26	4	5	214	11	12												
	PISI hybrid	162	17	12	22	3	5	184	18	14												
	DISI hybrid	163	17	13	23	3	5	186	18	14												
	Reformer + FC	162	21	37	23	3	5	185	22	38												
COD1	Conventional diesel																					
	DICI 2002	183	5	5	29	4	4	212	7	7												
	DICI 2010 no DPF	172	7	7	27	4	4	200	9	9												
	DICI 2010 DPF	177	7	7	26	4	4	205	9	9												
	DICI hybrid n DPF	141	15	11	23	3	3	164	16	12												
	DICI hybrid DPF	146	15	11	23	3	3	169	16	12												
	Reformer + FC	162	28	41	26	4	4	188	29	43												
CON1	Conventional naphtha																					
	Reformer + FC	162	7	4	18	2	3	180	8	5												
LRLP1	LPG: imports from remote gas field																					
	PISI 2002	224	4	4	26	0	2	250	4	5												
	PISI 2010	190	7	7	22	0	2	212	7	7												

2 CNG / CBG

WTT Code	Powertrain	Energy MJ / 100 km												GHG g CO _{2eq} / km																				
		Total						Fossil						TTW						WTT														
		TTW (MJ/100 km)			WTT (MJ/100 km)			WTW (MJ/100km)			WTW (MJ/100km)			Mean			Min			Max			Mean			Min			Max					
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max				
CNG pathways																																		
GMCG1	CNG: EU-mix																																	
	PISI bi-fuel 2002	227	12	6	27	5	6	254	14	9				132	7	4	19	2	3	151	8	5												
	PISI dedicated 2002	223	14	6	27	5	6	249	15	9				130	8	4	19	2	3	149	9	5												
	PISI bi-fuel 2010	188	12	8	22	4	5	211	13	10				108	7	4	16	2	3	124	7	5												
	PISI dedicated 2010	187	13	8	22	4	5	209	14	10				108	7	4	16	2	3	123	8	5												
	PISI hybrid	139	17	13	17	3	4	156	17	14				81	10	8	12	1	2	92	10	8												
GPCG1a	CNG: Pipeline 7000 km																																	
	PISI bi-fuel 2002	227	12	6	67	24	1	294	30	7				132	7	4	49	13	1	181	18	4												
	PISI dedicated 2002	223	14	6	66	23	1	289	31	7				130	8	4	48	13	1	178	18	4												
	PISI bi-fuel 2010	188	12	8	56	20	1	244	26	9				108	7	4	41	11	1	149	15	5												
	PISI dedicated 2010	187	13	8	56	20	1	243	27	8				108	7	4	41	11	1	148	16	5												
	PISI hybrid	139	17	13	41	15	1	181	26	14				81	10	8	30	6	1	111	15	8												
GPCG1b	CNG: Pipeline 4000 km																																	
	PISI bi-fuel 2002	227	12	6	43	12	4	270	19	8				132	7	4	32	7	2	164	11	5												
	PISI dedicated 2002	223	14	6	43	12	4	265	20	8				130	8	4	31	6	2	161	12	5												
	PISI bi-fuel 2010	188	12	8	36	10	3	224	17	9				108	7	4	26	5	2	135	10	5												
	PISI dedicated 2010	187	13	8	36	10	3	223	18	9				108	7	4	26	5	2	134	10	5												
	PISI hybrid	139	17	13	27	7	2	166	20	14				81	10	8	20	4	1	100	12	8												
GRCG1	CNG: LNG, Vap, Pipe																																	
	PISI bi-fuel 2002	227	12	6	69	5	6	296	15	10				132	7	4	45	3	3	177	9	6												
	PISI dedicated 2002	223	14	6	68	5	6	291	17	10				130	8	4	44	3	3	174	10	6												
	PISI bi-fuel 2010	188	12	8	58	4	5	246	14	11				108	7	4	38	2	3	146	8	6												
	PISI dedicated 2010	187	13	8	57	4	5	244	15	11				108	7	4	37	2	3	145	9	6												
	PISI hybrid	139	17	13	43	3	4	182	19	15				81	10	8	28	2	2	109	11	9												
GRCG1C	CNG: LNG, Vap, Pipe, CCS																																	
	PISI bi-fuel 2002	227	12	6	77	5	6	299	15	10				132	7	4	37	3	3	169	8	6												
	PISI dedicated 2002	223	14	6	77	5	6	294	17	10				130	8	4	36	3	3	166	9	5												
	PISI bi-fuel 2010	188	12	8	60	5	5	248	14	11				108	7	4	31	2	2	139	8	6												
	PISI dedicated 2010	187	13	8	60	5	5	247	15	11				108	7	4	31	2	2	138	9	6												
	PISI hybrid	139	17	13	44	3	3	184	19	15				81	10	8	23	2	2	104	11	9												
GRCG2	CNG: LNG, Road, Vap																																	
	PISI bi-fuel 2002	227	12	6	59	3	6	286	13	10				132	7	4	46	1	3	178	8	6												
	PISI dedicated 2002	223	14	6	58	2	5	281	15	9				130	8	4	45	1	3	175	9	6												
	PISI bi-fuel 2010	188	12	8	49	2	5	238	13	10				108	7	4	38	1	2	147	8	6												
	PISI dedicated 2010	187	13	8	49	2	5	236	14	10				108	7	4	38	1	2	146	8	6												
	PISI hybrid	139	17	13	36	2	3	176	18	15				81	10	8	28	1	2	109	11	9												
CBG pathways																																		
OWCG1	CBG: municipal waste																																	
	PISI bi-fuel 2002	227	12	6	198	29	33	425	42	39	39	15	10	132	7	4	-92	7	7	41	7	6												
	PISI dedicated 2002	223	14	6	198	29	33	417	43	39	38	16	10	130	8	4	-90	7	7	40	8	5												
	PISI bi-fuel 2010	188	12	8	164	24	28	353	36	35	32	13	10	108	7	4	-76	6	6	32	7	5												
	PISI dedicated 2010	187	13	8	163	24	27	351	38	35	32	15	10	108	7	4	-76	6	5	32	7	5												
	PISI hybrid	139	17	13	122	18	20	261	37	34	24	18	14	81	10	8	-56	4	4	24	10	8												
OWCG2	CBG: liquid manure																																	
	PISI bi-fuel 2002	227	12	6	219	40	34	446	53	41	7	12	7	132	7	4	-304	5	61	-171	36	52												
	PISI dedicated 2002	223	14	6	216	39	33	438	55	40	7	14	6	130	8	4	-298	5	60	-168	33	51												
	PISI bi-fuel 2010	188	12	8	182	33	28	370	46	37	6	12	8	108	7	4	-252	4	50	-144	28	40												
	PISI dedicated 2010	187	13	8	181	33	28	368	47	36	6	13	8	108	7	4	-250	4	50	-143	26	40												
	PISI hybrid	139	17	13	136	25	21	274	44	36	4	17	13	81	10	8	-186	3	37	-106	13	21												
OWCG3	CBG: dry manure																																	
	PISI bi-fuel 2002	227	12	6	215	38	36	442	51	43	2	12	6	132	7	4	-125	7	6	7	7	5												
	PISI dedicated 2002	223	14	6	211	38	35	434	52	42	2	14	6	130	8	4	-123	7	6	7	8	4												
	PISI bi-fuel 2010	188	12	8	179	32	30	367	44	38	2	12	8	108	7	4	-104	6	5	5	7	5												
	PISI dedicated 2010	187	13	8	177	32	30	365	46	38	2	13	8	108	7	4	-103	6	5	5	8	5												
	PISI hybrid	139	17	13	132	24	22	272	43	37	1	17	13	81	10	8	-77	4	4	4	11	8												

3 Ethanol

WTT Code	Powertrain	Energy MJ / 100 km												GHG g CO _{2eq} / km											
		Total						Fossil						TTW				WTT							
		TTW (MJ/100 km)		WTT (MJ/100 km)		WTW (MJ/100km)		TTW (MJ/100km)		WTT (MJ/100km)		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max		
Ethanol pathways, as blended fuels																									
SBET1	EtOH: Sugar beet, pulp to fodder	224	2	2	50	31	31	274	31	32	252			168	2	2	25	3	5	193	4	5			
	PISI 2002 95/5	209	9	9	47	29	29	256	32	32	235			157	6	6	23	3	4	180	8	8			
	PISI 2010 95/5	190	6	6	43	26	26	233	28	28	214			140	4	4	21	3	4	162	6	7			
	PISI 2010 95/5	188	10	10	42	26	26	230	30	30	212			139	7	7	21	3	4	160	8	9			
	DISI hybrid 95/5	163	17	13	37	22	23	200	31	28	183			120	13	9	18	2	4	139	13	11			
SBET3	EtOH: Sugar beet, pulp to heat	224	2	2	44	8	8	268	8	9	245			168	2	2	22	3	5	190	4	5			
	PISI 2002 95/5	209	9	9	41	7	7	250	12	12	229			157	6	6	21	3	4	177	8	8			
	PISI 2010 95/5	190	6	6	37	6	7	227	10	10	209			140	4	4	19	3	4	159	6	6			
	PISI 2010 95/5	188	10	10	37	6	7	225	13	13	206			139	7	7	18	3	4	157	8	9			
	DISI hybrid 95/5	163	17	13	37	6	6	199	19	15	179			120	13	9	16	2	3	136	13	10			
WTET1a	EtOH: Wheat, conv NG boiler, DDGS as AF	224	2	2	49	14	9	273	15	9	252			168	2	2	25	4	5	193	4	6			
	PISI 2002 95/5	209	9	9	46	13	8	255	17	13	235			157	6	6	24	4	5	180	8	9			
	PISI 2010 95/5	190	6	6	42	12	7	232	15	11	214			140	4	4	21	3	5	162	6	7			
	PISI 2010 95/5	188	10	10	42	12	7	229	17	13	212			139	7	7	21	3	4	160	8	9			
	DISI hybrid 95/5	163	17	13	36	10	6	199	22	16	184			120	13	9	18	3	4	139	13	11			
WTET1b	EtOH: Wheat, conv NG boiler, DDGS as fuel	224	2	2	44	9	9	268	10	9	247			168	2	2	24	4	5	192	4	6			
	PISI 2002 95/5	209	9	9	41	8	8	250	13	13	231			157	6	6	23	4	5	180	8	9			
	PISI 2010 95/5	190	6	6	37	8	7	227	11	10	210			140	4	4	21	3	4	161	6	7			
	PISI 2010 95/5	188	10	10	37	8	7	225	13	13	207			139	7	7	20	3	4	159	8	9			
	DISI hybrid 95/5	163	17	13	37	7	6	199	20	15	180			120	13	9	18	3	4	138	13	11			
WTET2a	EtOH: Wheat, NG GT+CHP, DDGS as AF	224	2	2	41	11	9	270	12	9	249			168	2	2	24	4	5	192	4	6			
	PISI 2002 95/5	209	9	9	44	11	8	252	15	13	235			157	6	6	22	4	5	179	8	9			
	PISI 2010 95/5	190	6	6	40	10	7	230	12	11	212			140	4	4	20	3	4	160	6	7			
	PISI 2010 95/5	188	10	10	39	10	7	227	15	13	209			139	7	7	20	3	4	159	8	9			
	DISI hybrid 95/5	163	17	13	34	8	6	197	21	15	182			120	13	9	17	3	4	138	13	11			
WTET2b	EtOH: Wheat, NG GT+CHP, DDGS as fuel	224	2	2	41	6	9	265	7	9	244			168	2	2	23	4	5	191	4	6			
	PISI 2002 95/5	209	9	9	39	6	8	247	11	13	228			157	6	6	21	3	5	178	8	9			
	PISI 2010 95/5	190	6	6	35	5	7	225	9	10	207			140	4	4	19	3	4	160	6	7			
	PISI 2010 95/5	188	10	10	35	5	7	223	12	13	205			139	7	7	19	3	4	158	8	9			
	DISI hybrid 95/5	163	17	13	30	5	6	193	19	15	178			120	13	9	17	3	4	137	13	11			
WTET3a	EtOH: Wheat, Lignite CHP, DDGS as AF	224	2	2	49	14	9	273	14	9	251			168	2	2	29	4	5	197	5	6			
	PISI 2002 95/5	209	9	9	46	13	8	255	17	13	235			157	6	6	27	4	5	184	8	9			
	PISI 2010 95/5	190	6	6	42	12	7	232	14	11	214			140	4	4	25	3	4	165	6	7			
	PISI 2010 95/5	188	10	10	41	12	7	229	17	13	211			139	7	7	24	3	4	163	8	9			
	DISI hybrid 95/5	163	17	13	36	10	6	199	22	16	183			120	13	9	21	3	4	142	13	11			
WTET3b	EtOH: Wheat, Lignite CHP, DDGS as fuel	224	2	2	44	9	9	267	9	9	246			168	2	2	28	4	5	196	4	6			
	PISI 2002 95/5	209	9	9	41	8	8	250	13	13	230			157	6	6	26	3	5	183	8	9			
	PISI 2010 95/5	190	6	6	37	7	7	227	11	10	209			140	4	4	24	3	4	164	6	7			
	PISI 2010 95/5	188	10	10	37	7	7	225	13	13	207			139	7	7	24	3	4	162	8	9			
	DISI hybrid 95/5	163	17	13	32	6	6	195	20	15	180			120	13	9	20	3	4	141	13	11			
WTET4a	EtOH: Wheat, Straw CHP, DDGS as AF	224	2	2	48	7	9	272	8	9	245			168	2	2	21	4	5	189	4	6			
	PISI 2002 95/5	209	9	9	45	7	8	254	12	13	229			157	6	6	20	4	5	177	8	9			
	PISI 2010 95/5	190	6	6	41	6	7	231	10	11	208			140	4	4	18	3	4	158	6	7			
	PISI 2010 95/5	188	10	10	41	6	7	229	13	13	206			139	7	7	18	3	4	157	8	9			
	DISI hybrid 95/5	163	17	13	35	5	6	198	19	16	179			120	13	9	16	3	4	136	13	11			
WTET4b	EtOH: Wheat, Straw CHP, DDGS as fuel	224	2	2	40	2	9	267	3	9	240			168	2	2	20	4	5	188	4	6			
	PISI 2002 95/5	209	9	9	40	2	8	249	9	13	224			157	6	6	19	4	5	176	8	9			
	PISI 2010 95/5	190	6	6	37	2	7	227	7	10	204			140	4	4	17	3	4	158	6	7			
	PISI 2010 95/5	188	10	10	36	2	7	224	10	13	202			139	7	7	17	3	4	156	8	9			
	DISI hybrid 95/5	163	17	13	31	2	6	194	18	15	175			120	13	9	15	3	4	135	13	11			
WWET1	EtOH: W Wood	224	2	2	51	7	7	275	8	8	245			168	2	2	21	3	4	188	4	5			
	PISI 2002 95/5	209	9	9	48	7	6	257	12	12	229			157	6	6	19	3	4	176	7	8			
	PISI 2010 95/5	190	6	6	44	6	6	234	10	9	208			140	4	4	18	3	4	158	5	6			
	PISI 2010 95/5	188	10	10	43	6	6	231	13	12	206			139	7	7	17	3	4	156	8	8			
	DISI hybrid 95/5	163	17	13	37	5	5	200	19	15	179			120	13	9	15	2	3	136	13	10			
WFET1	EtOH: F wood	224	2	2	51	7	7	275	8	8	245			168	2	2	21	3	5	189	4	6			
	PISI 2002 95/5	209	9	9	48	7	7	257	12	12	229			157	6	6	20	3	5	177	8	9			
	PISI 2010 95/5	190	6	6	44	6	6	234	10	10	208			140	4	4	18	3	4	158	6	7			
	PISI 2010 95/5	188	10	10	43	6	6	231	13	13	206			139	7	7	18	3	4	156	8	9			
	DISI hybrid 95/5	163	17	13	37	5	5	200	19	15	179			120	13	9	15	2	4	136	13	11			
STET1	EtOH: Wheat straw	224	2	2	44	5	7	268	6	7	243			168	2	2	20	3	4	187	4	5			
	PISI 2002 95/5	209	9	9	41	5	6	250	11	12	227			157	6	6	18	3	4	175	7	8			
	PISI 2010 95/5	190	6	6	38	5	6	228	8	9	207			140	4	4	17	3	4	157	5	6			
	PISI 2010 95/5	188	10	10	37	4	6	225	12	12	204			139	7	7	17	3	4	155	8	8			
	DISI hybrid 95/5	163	17	13	32	4	5	195	18	15	177			120	13	9	14	2	3	135	13	10			
SCET1	EtOH: Sugar cane (Brazil)	224	2	2	50	4	7	273	5	8	242			168	2	2	20	3	4	188	4	5			
	PISI 2002 95/5	209	9	9	46	4	6	255	10	12	226			157	6	6	19	3	4	175	7	8			
	PISI 2010 95/5	190	6	6	42	4	6	232	8	9	206			140	4	4	17	3	4	157	5	6			
	PISI 2010 95/5	188	10	10	42	4	6	230	11	12	204			139	7	7	17	3	4	155	8	8			
	DISI hybrid 95/5	163	17	13	36	3	5	199	18	15	177			120	13	9	14	2	3	135	13	10			

WTW APPENDIX 1

WTT Code	Powertrain	Energy MJ / 100 km												GHG g CO _{2eq} / km								
		Total						Fossil						TTW			WTT			WTW		
		TTW (MJ/100 km)		WTT (MJ/100 km)		WTW (MJ/100km)		TTW (MJ/100km)		WTT (MJ/100km)		WTW (MJ/100km)		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
EtOH pathways contribution based on neat fuel (netback calculation)																						
SBET1	EtOH: Sugar beet, pulp to fodder																					
	PISI 2002	224	2	2	415	26	30	639	30	34	194	14	16	161	2	2	-31	7	8	130	7	8
	DISI 2002	209	9	9	388	24	28	597	41	45	181	21	22	151	6	6	-29	7	7	122	8	9
	PISI 2010	190	6	6	353	22	25	543	34	37	165	17	18	137	4	4	-26	6	7	111	7	7
	DISI 2010	188	10	10	349	22	25	537	41	44	163	21	22	136	7	7	-26	6	7	110	8	9
SBET3	EtOH: Sugar beet, pulp to heat																					
	PISI 2002	224	2	2	290	26	27	513	29	30	69	7	8	161	2	2	-93	6	4	68	5	4
	DISI 2002	209	9	9	271	24	26	480	36	38	65	12	12	151	6	6	-87	6	4	64	7	6
	PISI 2010	190	6	6	246	22	23	436	30	32	59	9	10	137	4	4	-79	5	4	58	5	5
	DISI 2010	188	10	10	244	22	23	432	36	37	58	13	13	136	7	7	-78	5	4	58	7	7
WTET1a	EtOH: Wheat, conv NG boiler, DDGS as AF																					
	PISI 2002	224	2	2	397	4	5	621	8	9	198	5	5	161	2	2	-27	16	18	134	16	18
	DISI 2002	209	9	9	371	4	5	580	21	22	185	13	13	151	6	6	-26	15	17	125	16	17
	PISI 2010	190	6	6	338	4	4	528	15	16	168	9	10	137	4	4	-23	14	15	114	14	15
	DISI 2010	188	10	10	334	4	4	522	23	23	167	14	14	136	7	7	-23	14	15	113	15	16
WTET1b	EtOH: Wheat, conv NG boiler, DDGS as fuel																					
	PISI 2002	224	2	2	292	5	5	515	9	8	98	4	3	161	2	2	-47	15	15	115	15	15
	DISI 2002	209	9	9	272	5	4	481	18	18	92	10	10	151	6	6	-44	14	14	107	14	14
	PISI 2010	190	6	6	246	5	4	438	14	13	84	7	7	137	4	4	-40	13	13	98	13	12
	DISI 2010	188	10	10	245	5	4	433	20	19	83	11	11	136	7	7	-39	13	13	97	13	13
WTET2a	EtOH: Wheat, NG GT+CHP, DDGS as AF																					
	PISI 2002	224	2	2	342	4	5	566	8	8	145	4	4	161	2	2	-55	16	15	106	16	14
	DISI 2002	209	9	9	320	4	4	529	19	20	135	11	11	151	6	6	-52	15	14	99	15	13
	PISI 2010	190	6	6	291	4	4	481	14	15	123	8	8	137	4	4	-47	14	13	90	13	12
	DISI 2010	188	10	10	288	4	4	476	21	21	122	12	12	136	7	7	-47	14	13	89	13	12
WTET2b	EtOH: Wheat, NG GT+CHP, DDGS as fuel																					
	PISI 2002	224	2	2	236	5	5	460	7	7	45	3	3	161	2	2	-75	14	15	87	13	15
	DISI 2002	209	9	9	221	4	4	430	16	16	42	9	9	151	6	6	-70	13	14	81	12	13
	PISI 2010	190	6	6	201	4	4	391	12	12	38	6	6	137	4	4	-64	12	13	74	11	12
	DISI 2010	188	10	10	199	4	4	387	17	17	38	10	10	136	7	7	-63	12	13	73	11	12
WTET3a	EtOH: Wheat, Lignite CHP, DDGS as AF																					
	PISI 2002	224	2	2	390	1	1	613	5	5	193	3	3	161	2	2	47	17	17	209	18	17
	DISI 2002	209	9	9	364	1	1	573	18	18	180	12	12	151	6	6	44	16	15	195	19	18
	PISI 2010	190	6	6	331	1	1	521	13	13	164	8	8	137	4	4	40	15	14	178	17	16
	DISI 2010	188	10	10	328	1	1	516	20	20	162	13	13	136	7	7	40	15	14	176	18	17
WTET3b	EtOH: Wheat, Lignite CHP, DDGS as fuel																					
	PISI 2002	224	2	2	284	1	1	508	4	4	93	3	3	161	2	2	28	14	17	189	14	17
	DISI 2002	209	9	9	265	1	1	474	15	15	87	9	9	151	6	6	26	13	16	177	16	18
	PISI 2010	190	6	6	241	1	1	431	10	10	79	7	7	137	4	4	24	12	14	161	13	16
	DISI 2010	188	10	10	239	1	1	427	16	16	78	10	10	136	7	7	24	12	14	160	15	17
WTET4a	EtOH: Wheat, Straw CHP, DDGS as AF																					
	PISI 2002	224	2	2	378	1	1	602	5	5	62	2	2	161	2	2	-104	16	15	57	15	14
	DISI 2002	209	9	9	359	1	1	562	18	18	58	9	9	151	6	6	-97	15	14	54	13	12
	PISI 2010	190	6	6	321	1	1	511	12	12	53	6	6	137	4	4	-88	14	13	49	12	11
	DISI 2010	188	10	10	316	1	1	506	19	19	52	10	10	136	7	7	-88	14	13	48	11	11
WTET4b	EtOH: Wheat, Straw CHP, DDGS as fuel																					
	PISI 2002	224	2	2	272	1	1	496	4	4	-38	2	2	161	2	2	-123	17	15	38	16	14
	DISI 2002	209	9	9	254	1	1	463	14	14	-35	9	9	151	6	6	-115	16	14	36	13	11
	PISI 2010	190	6	6	231	1	1	421	10	10	-32	6	6	137	4	4	-105	15	13	33	12	10
	DISI 2010	188	10	10	229	1	1	417	16	16	-32	10	10	136	7	7	-104	14	13	32	12	10
WWET1	EtOH: W Wood																					
	PISI 2002	224	2	2	434	23	23	657	28	28	60	4	4	161	2	2	-119	0	0	42	2	2
	DISI 2002	209	9	9	405	22	22	614	40	39	56	10	10	151	6	6	-112	0	0	39	8	8
	PISI 2010	190	6	6	369	20	20	559	32	32	51	7	7	137	4	4	-101	0	0	36	5	5
	DISI 2010	188	10	10	365	20	20	553	39	39	50	11	11	136	7	7	-100	0	0	36	9	9
WFET1	EtOH: F wood																					
	PISI 2002	224	2	2	430	24	23	659	28	27	61	5	4	161	2	2	-111	6	15	50	5	14
	DISI 2002	209	9	9	407	22	21	615	40	39	57	10	10	151	6	6	-104	6	14	47	7	11
	PISI 2010	190	6	6	370	20	19	560	32	32	52	7	7	137	4	4	-94	5	12	43	5	10
	DISI 2010	188	10	10	366	20	19	554	40	39	51	11	11	136	7	7	-93	5	12	43	7	10
STET1	EtOH: Wheat straw																					
	PISI 2002	224	2	2	295	0	0	519	4	4	24	2	2	161	2	2	-140	0	0	22	2	2
	DISI 2002	209	9	9	276	0	0	485	14	14	22	9	9	151	6	6	-130	0	0	20	8	8
	PISI 2010	190	6	6	251	0	0	441	10	10	20	6	6	137	4	4	-119	0	0	19	6	6
	DISI 2010	188	10	10	248	0	0	436	16	16	20	10	10	136	7	7	-117	0	0	19	9	9
SCET1	EtOH: Sugar cane (Brazil)																					
	PISI 2002	224	2	2	401	1	1	625	5	5	5	2	2	161	2	2	-136	1	1	25	2	2
	DISI 2002	209	9	9	375	1	1	583	18	18	5	9	9	151	6	6	-127	0	1	24	8	8
	PISI 2010	190	6	6	341	1	1	531	13	13	4	6	6	137	4	4	-116	0	1	22	5	5
	DISI 2010	188	10	10	337	1	1	525	20	20	4	10	10	136	7	7	-115	0	0	21	9	9
DISI hybrid	163	17	13	292	0	0	455	35	26	4	17	13	118	13	9	-99	0	0	19	16	12	

4 Ethers

WTT Code	Powertrain	Energy MJ / 100 km												GHG g CO _{2eq} / km									
		Total						Fossil						TTW			WTT			WTW			
		TTW (MJ/100 km)			WTT (MJ/100 km)			WTW (MJ/100km)			WTW (MJ/100km)			Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Ethers (as neat fuels)																							
GRMB1	MTBE: remote plant																						
	PISI 2002	224	2	2	67	1	3	290	3	4				159	2	2	30	0	2	189	2	3	
	DISI 2002	209	9	9	63	1	3	271	9	10				149	6	6	28	0	2	177	7	7	
	PISI 2010	190	6	6	57	1	3	247	6	7				135	4	4	26	0	2	161	5	5	
	DISI 2010	188	10	10	56	1	3	244	10	11				134	7	7	25	0	2	159	7	8	
	DISI hybrid	163	17	13	49	0	2	212	18	14				116	12	9	22	0	1	138	13	10	
LREB1	ETBE: imported C4 and wheat ethanol																						
	PISI 2002	224	2	2	169	1	3	392	4	5	240	5	7	160	2	2	-8	6	6	152	6	6	
	DISI 2002	209	9	9	157	1	3	366	12	13	224	14	16	149	6	6	-7	5	6	142	8	8	
	PISI 2010	190	6	6	143	1	2	333	8	9	204	10	12	136	4	4	-6	5	5	129	6	7	
	DISI 2010	188	10	10	142	1	2	330	13	14	202	15	17	134	7	7	-6	5	5	128	8	9	
	DISI hybrid	163	17	13	123	1	2	286	22	17	175	26	21	116	12	9	-6	4	5	111	13	10	

5 Bio-diesel

WTT Code	Powertrain	Energy MJ / 100 km												GHG g CO _{2eq} / km												
		Total						Fossil						TTW						WTT						
		TTW (MJ/100 km)			WTT (MJ/100 km)			WTT (MJ/100km)			WTT (MJ/100km)			TTW			WTT			WTT						
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max		
Bio-diesel pathways, as blended fuels	ROFA1	RME: Gly as chemical																								
		DICI 2002 95/5	183	6	6	36	8	7	221	11	10	205				138	4	4	21	5	5	160	7	7		
		DICI 2010 no DPF 95/5	172	8	8	36	7	6	208	12	11	193				128	6	6	20	4	5	148	8	8		
		DICI 2010 DPF 95/5	177	8	8	37	7	7	214	12	11	198				132	6	6	21	4	5	152	8	8		
		DICI hybrid n DPF 95/5	141	15	11	29	6	5	171	17	13	158				106	11	8	16	4	4	121	12	10		
	DICI hybrid DPF 95/5	146	15	11	30	6	5	176	18	14	163				109	11	8	16	4	4	125	13	10			
ROFA2		RME: Gly as animal feed																								
		DICI 2002 95/5	183	6	6	36	8	7	222	11	10	206				138	4	4	22	5	5	160	7	7		
		DICI 2010 no DPF 95/5	172	8	8	36	8	6	209	12	11	193				128	6	6	20	5	5	149	8	8		
		DICI 2010 DPF 95/5	177	8	8	37	8	7	214	12	11	199				132	6	6	21	5	5	153	8	8		
		DICI hybrid n DPF 95/5	141	15	11	30	6	5	171	17	13	159				106	11	8	16	4	4	122	12	10		
	DICI hybrid DPF 95/5	146	15	11	31	7	5	176	18	14	164				109	11	8	17	4	4	126	13	10			
ROFE1		REE: Gly as chemical																								
		DICI 2002 95/5	183	6	6	36	7	7	222	10	10	205				138	4	4	21	5	5	159	7	7		
		DICI 2010 no DPF 95/5	172	8	8	36	7	6	209	11	11	193				128	6	6	19	4	5	148	8	8		
		DICI 2010 DPF 95/5	177	8	8	37	6	6	214	12	11	198				132	6	6	20	5	5	152	8	8		
		DICI hybrid n DPF 95/5	141	15	11	30	6	5	171	17	13	158				106	11	8	15	4	4	121	12	10		
	DICI hybrid DPF 95/5	146	15	11	31	6	5	176	18	14	163				109	11	8	16	4	4	125	13	10			
ROFE2		REE: Gly as animal feed																								
		DICI 2002 95/5	183	6	6	36	8	7	222	11	10	205				138	4	4	21	4	5	159	7	7		
		DICI 2010 no DPF 95/5	172	8	8	37	7	6	209	12	11	193				128	6	6	20	4	5	148	8	8		
		DICI 2010 DPF 95/5	177	8	8	37	6	6	215	12	11	198				132	6	6	20	4	5	152	8	8		
		DICI hybrid n DPF 95/5	141	15	11	30	6	5	171	17	13	158				106	11	8	16	4	4	121	12	10		
	DICI hybrid DPF 95/5	146	15	11	31	6	5	176	18	14	163				109	11	8	16	4	5	125	13	10			
SOFA1		SME: Gly as chemical																								
		DICI 2002 95/5	183	6	6	36	7	6	219	10	9	206				138	4	4	19	4	4	158	6	7		
		DICI 2010 no DPF 95/5	172	8	8	36	6	5	206	11	10	192				128	6	6	18	4	4	146	7	7		
		DICI 2010 DPF 95/5	177	8	8	36	7	5	212	11	10	197				132	6	6	19	4	4	150	7	8		
		DICI hybrid n DPF 95/5	141	15	11	28	5	4	169	17	13	157				106	11	8	14	3	4	119	12	9		
	DICI hybrid DPF 95/5	146	15	11	29	5	5	174	17	13	162				109	11	8	14	3	4	123	12	10			
SOFA2		SME: Gly as animal feed																								
		DICI 2002 95/5	183	6	6	37	7	6	220	10	9	205				138	4	4	20	4	4	158	6	6		
		DICI 2010 no DPF 95/5	172	8	8	34	7	5	207	11	10	192				128	6	6	18	4	4	147	7	7		
		DICI 2010 DPF 95/5	177	8	8	35	7	5	212	11	10	198				132	6	6	19	4	4	151	7	8		
		DICI hybrid n DPF 95/5	141	15	11	28	6	4	169	17	13	158				106	11	8	14	3	3	120	12	9		
	DICI hybrid DPF 95/5	146	15	11	29	6	5	175	17	13	163				109	11	8	15	3	3	124	12	10			
Bio-diesel pathways contribution based on neat fuel (netback calculation)																										
ROFA1		RME: Gly as chemical																								
		DICI 2002	183	5	5	210	18	16	393	25	23	76	10	10	143	4	4	-65	35	34	78	34	33			
		DICI 2010 no DPF	172	7	7	197	17	15	369	26	24	71	12	11	133	6	6	-61	33	32	72	31	30			
		DICI 2010 DPF	177	7	7	202	17	15	379	27	25	73	12	11	136	6	6	-63	34	33	73	32	31			
		DICI hybrid n DPF	141	15	11	16	14	12	303	34	27	58	18	14	109	11	8	-50	27	27	59	25	24			
	DICI hybrid DPF	146	15	11	16	14	13	312	35	28	60	19	14	113	12	9	-52	26	27	61	26	25				
ROFA2		RME: Gly as animal feed																								
		DICI 2002	183	5	5	219	20	20	402	27	28	85	12	12	143	4	4	-56	39	37	87	37	36			
		DICI 2010 no DPF	172	7	7	206	18	19	378	28	29	80	13	13	133	6	6	-52	36	35	81	35	33			
		DICI 2010 DPF	177	7	7	211	19	20	388	29	30	82	13	13	136	6	6	-54	37	36	83	35	34			
		DICI hybrid n DPF	141	15	11	169	15	16	310	36	31	66	19	16	109	11	8	-43	30	29	66	28	27			
	DICI hybrid DPF	146	15	11	174	16	16	320	37	32	68	20	16	113	12	9	-44	31	30	68	29	28				
ROFE1		REE: Gly as chemical																								
		DICI 2002	183	5	5	221	17	18	404	24	25	67	9	9	143	4	4	-78	37	37	65	35	35			
		DICI 2010 no DPF	172	7	7	207	16	17	380	26	27	63	10	11	133	6	6	-73	35	35	59	32	32			
		DICI 2010 DPF	177	7	7	213	16	17	390	26	27	64	11	11	136	6	6	-75	36	36	61	33	33			
		DICI hybrid n DPF	141	15	11	170	13	14	311	34	29	51	17	14	109	11	8	-60	29	29	49	25	26			
	DICI hybrid DPF	146	15	11	175	13	14	321	35	30	53	18	14	113	12	9	-62	29	30	51	26	26				
ROFE2		REE: Gly as animal feed																								
		DICI 2002	183	5	5	229	15	20	412	22	27	75	9	10	143	4	4	-69	33	41	73	31	39			
		DICI 2010 no DPF	172	7	7	216	14	18	388	24	29	70	10	12	133	6	6	-65	31	38	68	29	36			
		DICI 2010 DPF	177	7	7	221	14	19	398	25	29	72	11	12	136	6	6	-67	32	39	69	30	37			
		DICI hybrid n DPF	141	15	11	177	11	15	318	33	31	58	17	14	109	11	8	-54	25	31	56	23	29			
	DICI hybrid DPF	146	15	11	182	12	16	328	34	32	60	18	15	113	12	9	-55	26	32	57	24	29				
SOFA1		SME: Gly as chemical																								
		DICI 2002	183	5	5	160	15	17	351	21	23	56	9	9	143	4	4	-106	22	23	37	19	20			
		DICI 2010 no DPF	172	7	7	157	14	16	330	22	24	52	10	11	133	6	6	-100	20	22	33	17	18			
		DICI 2010 DPF	177	7	7	162	15	17	338	23	25	54	10	11	136	6	6	-102	21	22	34	17	19			
		DICI hybrid n DPF	141	15	11	129	12	13	270	29	26	43	17	13	109	11	8	-82	17	18	27	14	14			
	DICI hybrid DPF	146	15	11	133	12	14	279	30	26	44	17	14	113	12	9	-84	17	18	28	14	15				
SOFA2		SME: Gly as animal feed																								
		DICI 2002	183	5	5	177	15	17	360	22	23	65	9	10	143	4	4	-97	21	19	46	19	17			
		DICI 2010 no DPF	172	7	7	166	15	16	339	23	24	61	11	11	133	6	6	-91	20	18	42	17	15			
		DICI 2010 DPF	177	7	7	171	15	16	348	23	25	63	11	11	136	6	6	-93	20	19	43	18	16			
		DICI hybrid n DPF	141	15	11	136	12	13	278	30	26	50	17	14	109	11	8	-74	16	15	35	14	12			
	DICI hybrid DPF	146																								

6 Synthetic diesel fuel

WTT Code	Powertrain	Energy MJ / 100 km												GHG g CO _{2eq} / km								
		Total						Fossil						TTW			WTT			WTW		
		TTW (MJ/100 km)			WTT (MJ/100 km)			WTW (MJ/100km)			TTW (MJ/100km)			WTT			WTW					
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	
SD pathways, as blended fuels																						
GRSD1	Syn-diesel: Rem GTL, Sea, Diesel mix																					
	DICI 2002	183	5	5	34	4	5	217	8	8			138	4	4	27	3	4	165	6	6	
	DICI 2010 no DPF	172	7	7	34	4	4	204	9	9			128	6	6	25	3	3	153	7	7	
	DICI 2010 DPF	177	7	7	33	4	4	209	9	10			131	6	6	26	3	3	157	7	7	
	DICI hybrid n DPF	141	15	11	26	3	4	167	16	12			105	11	8	21	2	3	126	12	9	
	DICI hybrid DPF	146	15	11	27	3	4	173	16	13			108	11	8	21	2	3	130	12	10	
WWSD1	Syn-diesel: W Wood, diesel mix																					
	DICI 2002	183	5	5	39	5	5	222	8	8	202		138	4	4	19	3	3	156	6	6	
	DICI 2010 no DPF	172	7	7	36	5	5	208	10	10	190		128	6	6	18	3	3	145	7	7	
	DICI 2010 DPF	177	7	7	37	5	5	214	10	10	195		131	6	6	18	3	3	149	7	7	
	DICI hybrid n DPF	141	15	11	30	4	4	171	16	12	156		104	11	8	14	2	2	119	12	9	
	DICI hybrid DPF	146	15	11	31	4	4	176	17	13	161		108	11	8	15	2	3	123	12	9	
WFSD1	Syn-diesel: F wood, diesel mix																					
	DICI 2002	183	5	5	39	5	5	222	8	8	202		138	4	4	19	3	4	157	6	6	
	DICI 2010 no DPF	172	7	7	36	5	5	208	10	10	190		128	6	6	18	3	4	145	7	7	
	DICI 2010 DPF	177	7	7	37	5	5	214	10	10	195		131	6	6	18	3	4	149	7	7	
	DICI hybrid n DPF	141	15	11	30	4	4	171	16	12	156		105	11	8	15	2	3	119	12	9	
	DICI hybrid DPF	146	15	11	31	4	4	176	17	13	161		108	11	8	15	2	3	123	12	9	
BLSD1																						
	Syn-diesel: W Wood, Black liquor																					
	DICI 2002	183	5	5	36	4	5	219	8	8	202		138	4	4	18	3	3	156	6	6	
	DICI 2010 no DPF	172	7	7	34	4	4	206	9	9	190		128	6	6	17	3	3	145	7	7	
	DICI 2010 DPF	177	7	7	34	4	4	212	9	10	195		131	6	6	18	3	3	149	7	7	
	DICI hybrid n DPF	141	15	11	28	3	3	169	16	12	156		105	11	8	14	2	2	119	12	9	
	DICI hybrid DPF	146	15	11	29	4	4	174	16	13	160		108	11	8	15	2	3	123	12	9	
SD pathways as neat fuel																						
GRSD1	Syn-diesel: Rem GTL, Sea, Diesel mix																					
	DICI 2002	183	5	5	124	8	13	307	13	17			133	4	4	46	5	7	179	7	9	
	DICI 2010 no DPF	172	7	7	117	8	12	289	15	18			124	5	5	43	4	7	167	8	10	
	DICI 2010 DPF	177	7	7	120	8	12	297	15	19			127	5	5	44	5	7	171	8	10	
	DICI hybrid n DPF	141	15	15	96	6	10	237	22	25			102	11	11	35	4	6	137	13	14	
	DICI hybrid DPF	146	15	15	99	7	10	244	23	25			105	11	11	36	4	6	141	13	14	
GRSD2	Syn-diesel: Rem GTL, Sea, Rail/Road																					
	DICI 2002	183	5	5	125	9	11	308	14	16			133	4	4	46	5	6	179	7	9	
	DICI 2010 no DPF	172	7	7	117	8	11	289	15	17			124	5	5	43	5	6	167	8	9	
	DICI 2010 DPF	177	7	7	120	8	11	297	15	18			127	5	5	44	5	6	171	8	10	
	DICI hybrid n DPF	141	15	11	96	7	9	237	22	19			102	11	8	35	4	5	137	13	11	
	DICI hybrid DPF	146	15	11	99	7	9	245	23	20			105	11	8	36	4	5	141	13	11	
GRSD2C	Syn-diesel: Rem GTL, Sea, Rail/Road, CC&S																					
	DICI 2002	183	5	5	139	9	11	323	15	16			133	4	4	24	5	6	157	7	8	
	DICI 2010 no DPF	172	7	7	131	9	10	303	16	17			124	5	5	22	5	6	146	8	9	
	DICI 2010 DPF	177	7	7	133	9	10	311	17	18			127	5	5	23	5	6	150	8	9	
	DICI hybrid n DPF	141	15	11	107	7	8	249	23	20			102	11	8	18	4	5	120	12	10	
	DICI hybrid DPF	146	15	11	111	7	9	257	24	20			105	11	8	19	4	5	124	12	10	
KOSD1	Syn-diesel: CTL, Diesel mix																					
	DICI 2002	183	5	5	178	15	15	361	21	21			133	4	4	236	15	15	369	23	23	
	DICI 2010 no DPF	172	7	7	167	14	14	339	23	22			124	5	5	222	14	14	346	24	24	
	DICI 2010 DPF	177	7	7	172	15	14	348	23	23			127	5	5	228	15	15	355	25	25	
	DICI hybrid n DPF	141	15	11	137	12	11	278	30	25			102	11	8	182	12	12	284	32	27	
	DICI hybrid DPF	146	15	11	142	12	12	287	31	25			105	11	8	188	12	12	293	33	28	
KOSD1C	Syn-diesel: CTL, CC&S, Diesel mix																					
	DICI 2002	183	5	5	194	14	15	377	21	22			133	4	4	71	14	15	204	17	18	
	DICI 2010 no DPF	172	7	7	182	13	14	354	22	23			124	5	5	67	14	14	191	17	18	
	DICI 2010 DPF	177	7	7	187	14	14	363	23	24			127	5	5	69	14	15	196	18	18	
	DICI hybrid n DPF	141	15	11	149	11	12	290	30	25			102	11	8	55	11	12	157	20	18	
	DICI hybrid DPF	146	15	11	154	11	12	299	31	26			105	11	8	57	12	12	162	20	18	
WWSD1	Syn-diesel: W Wood, diesel mix																					
	DICI 2002	183	5	5	219	21	19	402	28	26	12	6	6	133	4	4	-121	0	0	12	5	5
	DICI 2010 no DPF	172	7	7	205	20	18	378	30	28	11	7	7	124	5	5	-114	0	0	10	7	7
	DICI 2010 DPF	177	7	7	211	20	19	388	30	29	12	8	8	127	5	5	-117	0	0	10	7	7
	DICI hybrid n DPF	141	15	11	168	16	15	310	37	30	9	15	11	102	11	8	-93	0	0	8	14	10
	DICI hybrid DPF	146	15	11	174	17	15	319	38	31	9	15	11	105	11	8	-96	0	0	9	14	11
WFSD1	Syn-diesel: F wood, diesel mix																					
	DICI 2002	183	5	5	219	21	17	402	28	24	12	6	6	133	4	4	-116	5	12	17	4	9
	DICI 2010 no DPF	172	7	7	205	20	16	378	29	26	11	7	7	124	5	5	-109	5	11	14	5	8
	DICI 2010 DPF	177	7	7	211	20	17	388	30	27	11	8	8	127	5	5	-112	5	11	15	5	9
	DICI hybrid n DPF	141	15	11	168	16	13	309	36	28	9	15	11	102	11	8	-90	4	9	12	12	8
	DICI hybrid DPF	146	15	11	174	17	14	319	38	29	9	15	11	105	11	8	-92	4	9	12	12	8
BLSD1	Syn-diesel: W Wood, Black liquor																					
	DICI 2002	183	5	5	167	10	10	350	16	16	7	6	6	133	4	4	-125	0	0	8	5	5
	DICI 2010 no DPF	172	7	7	157	9	10	329	17	18	6	7	7	124	5	5	-118	0	0	6	7	7
	DICI 2010 DPF	177	7	7	161	9	10	338	18	18	6	8	8	127	5	5	-121	0	0	6	7	7
	DICI hybrid n DPF	141	15	11	126	8	8	270	25	21	5	15	11	102	11	8	-97	0	0	5	14	11
	DICI hybrid DPF	146	15	11	133	8	8	278	26	21	5	15	11	105	11	8	-100	0	0	5	15	11

7 Methanol and DME

WTT Code	Powertrain	Energy MJ / 100 km												GHG g CO _{2eq} / km												
		Total						Fossil						TTW			WTT			WTW						
		TTW (MJ/100 km)			WTT (MJ/100 km)			WTW (MJ/100km)			WTW (MJ _{fossil} /100km)			Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	
Methanol pathways																										
GPME1a	MeOH: NG 7000 km, Syn, Rail/Road Reformer + FC	148	18	34	125	2	1	273	25	45								109	13	25	61	12	2	170	23	30
GPME1b	MeOH: NG 4000 km, Syn, Rail/Road Reformer + FC	148	18	34	102	9	2	250	28	43								109	13	25	44	5	1	154	17	28
GRME1	MeOH: Rem Syn, Sea, Rail/Road Reformer + FC	148	18	34	90	3	4	238	23	42								109	13	25	35	2	3	145	15	27
KOME1	MeOH: Coal EU-mix, Cen, Rail/Road Reformer + FC	148	18	34	138	13	15	286	35	58								109	13	25	188	13	15	297	39	64
WWME1	MeOH: W Wood, Road Reformer + FC	148	18	34	158	19	20	306	42	65	9	18	34					109	13	25	-95	0	0	14	18	33
WFME1	MeOH: F Wood, Road Reformer + FC	148	18	34	150	20	18	306	43	64	9	18	34					109	13	25	-92	3	6	18	16	29
BLME1	MeOH: W Wood, Black liquor Reformer + FC	148	18	34	87	7	7	235	25	43	5	18	34					109	13	25	-99	0	0	11	18	34
DME pathways																										
GPDE1a	DME: NG 7000 km, Syn, Rail/Road DICI 2002	183	5	5	14	26	3	324	31	9								127	4	4	71	15	2	198	17	6
	DICI 2010 no DPF	172	7	7	130	25	3	305	31	11								118	5	5	67	14	2	185	17	7
	DICI hybrid n DPF	141	15	11	109	20	3	250	35	15								97	10	7	55	11	1	152	20	9
GPDE1b	DME: NG 4000 km, Syn, Rail/Road DICI 2002	183	5	5	114	12	4	297	16	9								127	4	4	51	7	2	178	9	5
	DICI 2010 no DPF	172	7	7	107	11	3	279	17	11								118	5	5	48	6	2	166	10	6
	DICI hybrid n DPF	141	15	11	88	9	3	229	23	14								97	10	7	40	5	2	136	14	9
GRDE1	DME: Rem Syn, Sea, Rail/Road DICI 2002	183	5	5	97	3	6	280	8	10								127	4	4	38	0	0	165	4	4
	DICI 2010 no DPF	172	7	7	97	3	6	264	10	12								118	5	5	36	0	0	154	5	5
	DICI hybrid n DPF	141	15	11	75	3	5	216	18	15								97	10	7	29	0	0	126	11	8
KODE1	DME: Coal EU-mix, Cen, Rail/Road DICI 2002	183	5	5	170	18	15	353	24	21								127	4	4	235	18	0	361	8	8
	DICI 2010 no DPF	172	7	7	160	17	14	332	25	22								118	5	5	221	1	1	338	11	11
	DICI hybrid n DPF	141	15	11	131	14	12	272	31	24								97	10	7	181	7	1	278	23	17
GRDE1C	DME: Rem Syn, Sea, Rail/Road, CCS DICI 2002	183	5	5	99	0	13	282	6	17								127	4	4	20	0	0	146	4	4
	DICI 2010 no DPF	172	7	7	93	0	12	265	8	18								118	5	5	19	0	0	136	5	5
	DICI hybrid n DPF	141	15	11	76	0	10	217	17	19								97	10	7	15	0	0	112	10	8
WWDE1	DME: W Wood, Road DICI 2002	183	5	5	196	22	27	379	29	34	11	6	6					127	4	4	-115	0	0	12	5	5
	DICI 2010 no DPF	172	7	7	184	21	26	356	30	34	10	7	8					118	5	5	-108	0	0	10	7	7
	DICI hybrid n DPF	141	15	11	151	17	21	292	36	34	9	15	11					97	10	7	-89	0	0	8	13	10
WFDE1	DME: F Wood, Road DICI 2002	183	5	5	198	24	24	379	31	30	11	6	6					127	4	4	-110	3	9	16	4	7
	DICI 2010 no DPF	172	7	7	184	23	22	356	31	31	10	8	7					118	5	5	-104	3	8	14	5	6
	DICI hybrid n DPF	141	15	11	151	19	18	292	37	32	8	15	11					97	10	7	-85	3	7	12	12	7
BLDE1	DME: W Wood, Black liquor DICI 2002	183	5	5	101	8	10	284	12	14	6	6	6					127	4	4	-119	0	0	7	5	5
	DICI 2010 no DPF	172	7	7	95	7	9	267	14	15	5	7	7					118	5	5	-112	0	0	6	7	7
	DICI hybrid n DPF	141	15	11	78	6	7	219	20	17	4	15	11					97	10	7	-92	0	0	5	14	10

8 Compressed hydrogen (C-H₂)

8.1 C-H₂ from natural gas reforming and coal gasification

WTT Code	Powertrain	Energy MJ / 100 km												GHG g CO _{2eq} / km										
		Total						Fossil						TTW			WTT			WTW				
		TTW (MJ/100 km)		WTT (MJ/100 km)		WTW (MJ/100km)		WTW (MJ/100km)		TTW		WTT		WTW		TTW		WTT		WTW				
Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	
C-H₂ pathways																								
GMCH1	C-H ₂ , EU-mix, O/S Ref	180	0	0	152	6	10	332	6	10					0	0	0	189	3	5	189	3	5	
	PISI 2002	168	5	5	141	6	9	309	11	14					0	0	0	175	3	5	176	8	10	
	PISI 2010	149	13	11	125	5	8	274	20	21					0	0	0	155	3	4	156	16	16	
	PISI hybrid	94	12	12	79	3	5	173	17	19					0	0	0	98	2	3	98	14	15	
	FC	84	10	10	71	3	4	154	15	17					0	0	0	88	2	2	88	12	13	
	FC hybrid	84	10	10	71	3	4	154	15	17					0	0	0	88	2	2	88	12	13	
GPCH1a	C-H ₂ , NG 7000 km, O/S Ref	180	0	0	199	28	4	379	28	4					0	0	0	220	15	3	220	15	3	
	PISI 2002	168	5	5	185	26	4	353	32	10					0	0	0	205	14	2	205	20	8	
	PISI 2010	149	13	11	164	23	3	313	39	19					0	0	0	181	13	2	182	28	16	
	PISI hybrid	94	12	12	104	14	2	198	29	19					0	0	0	115	8	1	115	22	15	
	FC	84	10	10	93	13	2	176	26	17					0	0	0	102	7	1	102	20	14	
	FC hybrid	84	10	10	93	13	2	176	26	17					0	0	0	102	7	1	102	20	14	
GPCH1b	C-H ₂ , NG 4000 km, O/S Ref	180	0	0	171	14	6	351	14	6					0	0	0	200	8	3	200	8	3	
	PISI 2002	168	5	5	159	13	5	327	19	11					0	0	0	186	8	3	186	13	8	
	PISI 2010	149	13	11	141	12	5	290	27	19					0	0	0	165	7	2	165	21	15	
	PISI hybrid	94	12	12	89	7	3	183	22	18					0	0	0	104	4	2	104	17	14	
	FC	84	10	10	80	7	3	163	19	16					0	0	0	93	4	1	93	15	13	
	FC hybrid	84	10	10	80	7	3	163	19	16					0	0	0	93	4	1	93	15	13	
GPCH2a	C-H ₂ , NG 7000 km, Cen ref, Pipe	180	0	0	154	26	5	334	26	5					0	0	0	195	15	3	195	15	3	
	PISI 2002	168	5	5	144	24	4	311	29	10					0	0	0	182	14	2	182	19	8	
	PISI 2010	149	13	11	127	22	4	276	35	18					0	0	0	161	12	2	161	26	14	
	PISI hybrid	94	12	12	81	14	2	179	26	17					0	0	0	102	6	1	102	20	14	
	FC	84	10	10	72	12	2	155	23	15					0	0	0	91	7	1	91	18	12	
	FC hybrid	84	10	10	72	12	2	155	23	15					0	0	0	91	7	1	91	18	12	
GPCH2b	C-H ₂ , NG 4000 km, Cen Ref, Pipe	180	0	0	129	13	5	309	13	5					0	0	0	177	7	3	177	7	3	
	PISI 2002	168	5	5	120	12	5	287	16	10					0	0	0	164	7	3	165	12	8	
	PISI 2010	149	13	11	106	11	4	255	24	17					0	0	0	146	6	2	146	19	13	
	PISI hybrid	94	12	12	67	7	3	161	19	16					0	0	0	92	4	1	92	15	13	
	FC	84	10	10	60	6	2	144	17	14					0	0	0	82	3	1	82	13	11	
	FC hybrid	84	10	10	60	6	2	144	17	14					0	0	0	82	3	1	82	13	11	
GPCH2bC	C-H ₂ , NG 4000 km, Cen Ref, Pipe, CCS	180	0	0	139	14	6	319	14	6					0	0	0	67	8	3	67	8	3	
	PISI 2002	168	5	5	129	13	5	297	17	11					0	0	0	62	7	3	63	9	5	
	PISI 2010	149	13	11	115	11	5	263	25	18					0	0	0	55	6	2	56	11	7	
	PISI hybrid	94	12	12	73	7	3	167	20	17					0	0	0	35	4	2	35	8	6	
	FC	84	10	10	65	6	3	148	18	15					0	0	0	31	4	1	31	7	5	
	FC hybrid	84	10	10	65	6	3	148	18	15					0	0	0	31	4	1	31	7	5	
GPCH3b	C-H ₂ , NG 4000 km, Cen Ref, Road	180	0	0	124	12	4	309	12	4					0	0	0	178	7	2	178	7	2	
	PISI 2002	168	5	5	120	11	4	288	15	9					0	0	0	166	6	2	166	11	7	
	PISI 2010	149	13	11	107	10	3	255	23	16					0	0	0	147	6	2	148	18	13	
	PISI hybrid	94	12	12	67	6	2	161	18	16					0	0	0	93	4	1	93	15	13	
	FC	84	10	10	60	5	2	144	16	14					0	0	0	83	3	1	83	13	11	
	FC hybrid	84	10	10	60	5	2	144	16	14					0	0	0	83	3	1	83	13	11	
GPLCHb	C-H ₂ , NG 4000 km, Cen Ref, Liq, Road, Vap/comp.	180	0	0	230	25	14	410	25	14					0	0	0	239	15	8	239	15	8	
	PISI 2002	168	5	5	214	24	13	382	30	20					0	0	0	222	14	8	223	21	14	
	PISI 2010	149	13	11	190	21	11	338	39	28					0	0	0	197	12	7	198	29	22	
	PISI hybrid	94	12	12	120	13	7	214	30	25					0	0	0	125	8	4	125	23	20	
	FC	84	10	10	107	12	6	191	27	22					0	0	0	111	7	4	111	21	17	
	FC hybrid	84	10	10	107	12	6	191	27	22					0	0	0	111	7	4	111	21	17	
GRCH1	C-H ₂ , LNG, O/S Ref	180	0	0	202	6	11	382	6	11					0	0	0	215	4	6	215	4	6	
	PISI 2002	168	5	5	186	6	10	355	12	16					0	0	0	200	3	5	201	9	11	
	PISI 2010	149	13	11	166	5	9	315	23	24					0	0	0	177	3	5	178	18	18	
	PISI hybrid	94	12	12	105	3	6	199	20	22					0	0	0	112	2	3	112	16	17	
	FC	84	10	10	94	3	5	177	18	19					0	0	0	100	2	3	100	14	15	
	FC hybrid	84	10	10	94	3	5	177	18	19					0	0	0	100	2	3	100	14	15	
GRCH2	C-H ₂ , LNG, Cen Ref, Pipe	180	0	0	157	7	9	337	7	9					0	0	0	191	3	5	191	3	5	
	PISI 2002	168	5	5	146	6	8	313	12	14					0	0	0	178	3	5	178	9	10	
	PISI 2010	149	13	11	129	5	7	278	21	21					0	0	0	157	3	4	158	16	16	
	PISI hybrid	94	12	12	82	3	5	176	18	19					0	0	0	100	2	3	100	14	15	
	FC	84	10	10	73	3	4	156	16	17					0	0	0	89	2	2	89	12	13	
	FC hybrid	84	10	10	73	3	4	156	16	17					0	0	0	89	2	2	89	12	13	
GRCH3	C-H ₂ , Rem NG, methanol, O/S Ref	180	0	0	204	4	8	384	4	8					0	0	0	214	2	4	214	2	4	
	PISI 2002	168	5	5	190																			

8.2 C-H₂ from biomass processing

WTT Code	Powertrain	Energy MJ / 100 km												GHG g CO _{2eq} / km									
		Total						Fossil						TTW			WTT			WTW			
		TTW (MJ/100 km)			WTT (MJ _d /100 km)			WTW (MJ/100km)			WTW (MJ _d /100km)			Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
WWCH1	C-H2: Wood W, O/S gasif	180	0	0	220	18	18	400	18	18	34	3	3	0	0	0	0	0	0	1	19	1	1
	PISI 2002	168	5	5	204	17	17	372	24	24	32	6	6	0	0	0	0	0	18	1	18	2	2
	PISI 2010	149	13	11	181	15	15	330	33	31	28	14	12	0	0	0	0	0	16	1	16	3	2
	PISI hybrid	94	12	12	115	10	10	209	26	26	18	12	12	0	0	0	0	0	10	1	10	2	2
	FC	84	10	10	102	9	9	186	23	23	16	11	11	0	0	0	0	0	9	1	9	2	2
WWCH2	C-H2: Wood W, Cen gasif, Pipe	180	0	0	175	15	14	355	15	14	41	3	3	0	0	0	0	22	1	22	1	1	
	PISI 2002	168	5	5	162	14	13	330	19	18	38	7	7	0	0	0	0	20	1	21	2	2	
	PISI 2010	149	13	11	144	12	11	293	28	25	34	14	12	0	0	0	0	18	1	18	3	3	
	PISI hybrid	94	12	12	91	8	7	185	22	22	22	12	12	0	0	0	0	11	1	11	2	2	
	FC	84	10	10	81	7	6	165	20	19	19	11	11	0	0	0	0	10	1	10	2	2	
WFCH1	C-H2: Wood F, O/S gasif	180	0	0	224	19	18	404	19	18	39	3	3	0	0	0	0	27	4	27	4	8	
	PISI 2002	168	5	5	208	17	17	376	24	24	36	6	6	0	0	0	0	25	4	26	4	8	
	PISI 2010	149	13	11	185	15	15	333	34	31	32	14	12	0	0	0	0	23	3	23	5	8	
	PISI hybrid	94	12	12	117	10	10	211	27	27	20	12	12	0	0	0	0	14	2	14	4	6	
	FC	84	10	10	104	9	9	188	24	24	18	11	11	0	0	0	0	13	2	13	3	5	
WFCH2	C-H2: Wood F, Cen gasif, pipe	180	0	0	175	15	15	355	15	15	41	4	4	0	0	0	0	26	2	26	2	7	
	PISI 2002	168	5	5	162	14	14	330	20	20	36	7	7	0	0	0	0	24	2	24	3	7	
	PISI 2010	149	13	11	144	12	13	292	28	26	34	14	13	0	0	0	0	21	2	22	4	8	
	PISI hybrid	94	12	12	91	8	8	185	22	22	22	12	12	0	0	0	0	13	1	13	3	5	
	FC	84	10	10	81	7	7	165	20	20	19	11	11	0	0	0	0	12	1	12	3	5	
BLCH1	C-H2: Wood W, Black liquor	180	0	0	92	5	7	272	5	7	37	2	3	0	0	0	0	18	1	18	1	1	
	PISI 2002	168	5	5	86	5	7	253	9	11	34	6	6	0	0	0	0	17	1	17	2	2	
	PISI 2010	149	13	11	76	4	6	224	17	16	30	13	12	0	0	0	0	15	1	15	2	2	
	PISI hybrid	94	12	12	48	3	4	142	14	15	19	12	12	0	0	0	0	9	1	9	2	2	
	FC	84	10	10	43	2	3	126	13	13	17	11	11	0	0	0	0	8	1	8	2	2	

8.3 C-H₂ from electrolysis (all electricity sources)

WTT Code	Powertrain	Energy MJ / 100 km									GHG g CO _{2eq} / km								
		Total			Fossil			TTW			WTT			WTW					
		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max			
GPEL1a/CH1	C-H2: NG 7000 km, CCGT, O/S Ely	180	0	0	490	75	21	670	75	21	0	0	0	406	45	13	406	45	13
	PISI 2002	168	5	5	456	70	19	623	84	33	0	0	0	377	41	12	378	53	23
	PISI 2010	149	13	11	406	62	17	552	98	49	0	0	0	335	37	11	335	65	36
	PISI hybrid	94	12	12	256	39	11	350	72	44	0	0	0	212	23	7	212	49	33
	FC	84	10	10	226	35	10	311	64	39	0	0	0	189	21	6	189	44	29
GPEL1b/CH1	C-H2: NG 4000 km, CCGT, O/S Ely	180	0	0	433	43	29	613	43	29	0	0	0	364	25	17	364	25	17
	PISI 2002	168	5	5	402	40	27	570	52	40	0	0	0	339	24	16	339	34	26
	PISI 2010	149	13	11	357	35	24	505	67	52	0	0	0	300	21	14	301	47	37
	PISI hybrid	94	12	12	226	22	15	320	51	44	0	0	0	190	13	9	190	37	32
	FC	84	10	10	201	20	14	285	46	40	0	0	0	169	12	8	169	33	29
GPEL1b/CH2	C-H2: NG 4000 km, CCGT, Cen Ely, Pipe	180	0	0	442	47	34	622	47	34	0	0	0	364	28	20	364	28	20
	PISI 2002	168	5	5	411	44	32	578	56	44	0	0	0	339	26	19	339	36	29
	PISI 2010	149	13	11	364	39	28	513	71	57	0	0	0	300	23	17	300	49	39
	PISI hybrid	94	12	12	231	24	18	325	54	47	0	0	0	190	15	10	190	38	34
	FC	84	10	10	206	22	16	289	48	42	0	0	0	169	13	9	169	34	30
GREL1/CH1	C-H2: LNG, O/S Ely	180	0	0	490	43	45	675	43	45	0	0	0	396	25	26	396	25	26
	PISI 2002	168	5	5	460	40	42	628	54	56	0	0	0	368	23	24	369	34	36
	PISI 2010	149	13	11	406	36	37	557	72	69	0	0	0	327	21	22	327	49	47
	PISI hybrid	94	12	12	256	23	24	352	55	56	0	0	0	207	13	14	207	38	39
	FC	84	10	10	230	20	21	314	49	50	0	0	0	184	12	12	184	34	35
WFEL2/CH1	C-H2: F Wood, 200 MW gasif, CCGT, O/S Ely	180	0	0	469	38	39	649	38	39	14	1	1	0	0	0	23	6	16
	PISI 2002	168	5	5	436	35	37	603	48	50	13	5	5	0	0	0	21	5	15
	PISI 2010	149	13	11	386	31	32	535	66	63	11	13	11	0	0	0	19	5	13
	PISI hybrid	94	12	12	245	20	21	339	51	52	7	12	12	0	0	0	12	3	9
	FC	84	10	10	218	18	18	301	45	46	6	10	10	0	0	0	11	3	8
WFEL3/CH1	C-H2: F Wood, Conv power, O/S Ely	180	0	0	797	68	52	977	68	52	20	2	1	0	0	0	56	9	24
	PISI 2002	168	5	5	741	64	49	909	86	71	19	5	5	0	0	0	52	8	22
	PISI 2010	149	13	11	657	56	43	806	114	94	17	13	12	0	0	0	46	7	20
	PISI hybrid	94	12	12	416	36	27	510	87	79	11	12	12	0	0	0	29	5	12
	FC	84	10	10	370	32	24	454	78	70	9	10	10	0	0	0	26	4	11
EMEL1/CH1	C-H2: Elec EU-mix, O/S Ely	180	0	0	652	31	31	833	31	31	0	0	0	375	14	14	375	14	14
	PISI 2002	168	5	5	607	29	29	774	47	47	0	0	0	349	13	13	349	23	23
	PISI 2010	149	13	11	536	26	25	686	73	67	0	0	0	309	11	11	310	38	35
	PISI hybrid	94	12	12	340	16	16	434	59	59	0	0	0	196	7	7	196	31	31
	FC	84	10	10	303	14	14	387	53	52	0	0	0	174	6	6	174	28	28
KOEL1/CH1	C-H2: Elec coal EU-mix, O/S Ely	180	0	0	571	96	76	751	96	76	0	0	0	763	85	90	763	85	90
	PISI 2002	168	5	5	531	89	71	699	105	87	0	0	0	709	79	84	710	101	105
	PISI 2010	149	13	11	471	79	63	619	120	99	0	0	0	629	70	74	629	124	122
	PISI hybrid	94	12	12	298	50	40	392	87	77	0	0	0	398	44	47	398	93	96
	FC	84	10	10	265	45	36	349	78	69	0	0	0	354	40	42	354	83	85
KOEL1/CH2	C-H2: Elec coal EU-mix, Cen eLy, Pipe	180	0	0	571	96	76	751	96	76	0	0	0	763	85	90	763	85	90
	PISI 2002	168	5	5	531	89	71	699	105	87	0	0	0	709	79	84	710	101	105
	PISI 2010	149	13	11	471	79	63	619	120	99	0	0	0	629	70	74	629	124	122
	PISI hybrid	94	12	12	298	50	40	392	87	77	0	0	0	398	44	47	398	93	96
	FC	84	10	10	265	45	36	349	78	69	0	0	0	354	40	42	354	83	85
NUEL1/CH1	C-H2: Elec nuclear, O/S Ely	180	0	0	905	48	48	1085	48	48	0	0	0	13	1	1	13	1	1
	PISI 2002	168	5	5	842	45	45	1010	70	70	0	0	0	12	1	1	12	1	1
	PISI 2010	149	13	11	746	40	40	895	105	97	0	0	0	10	1	1	11	1	1
	PISI hybrid	94	12	12	472	25	25	566	84	84	0	0	0	7	0	0	7	1	1
	FC	84	10	10	421	22	22	504	75	75	0	0	0	6	0	0	6	1	1
WDEL1/CH2	C-H2: Wind, Cen Ely, Pipe	180	0	0	142	11	10	322	11	10	35	3	2	0	0	0	16	1	1
	PISI 2002	168	5	5	132	10	9	299	15	14	32	6	6	0	0	0	15	1	1
	PISI 2010	149	13	11	117	9	8	265	23	21	29	14	12	0	0	0	14	1	1
	PISI hybrid	94	12	12	74	6	5	168	19	18	16	12	12	0	0	0	9	1	1
	FC	84	10	10	66	5	5	150	17	16	16	11	11	0	0	0	8	1	1

9 Liquid hydrogen (L-H₂)

WTT Code	Powertrain	Energy MJ / 100 km												GHG g CO _{2eq} / km											
		Total						Fossil						TTW			WTT			WTW					
		TTW (MJ/100 km)			WTT (MJ _w /100 km)			WTW (MJ/100km)			WTW (MJ _w /100km)			Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
L-H₂ pathways																									
GPLH1a	L-H ₂ :NG 7000 km, Cen Ref, Liq, Road	180	0	0	240	40	6	420	40	6	0	0	0	253	23	4	253	23	4	253	23	4	253	23	4
	PISI 2002	168	5	5	220	37	6	391	44	14	0	0	0	236	21	4	236	21	4	236	21	4	236	21	4
	PISI 2010	141	11	12	188	31	5	330	47	24	0	0	0	199	18	3	199	18	3	199	18	3	199	18	3
	FC	94	12	12	125	21	3	219	38	22	0	0	0	132	12	2	132	12	2	132	12	2	132	12	2
	FC hybrid	84	10	10	111	18	3	195	34	20	0	0	0	118	11	2	118	11	2	118	11	2	118	11	2
GPLH1b	L-H ₂ : NG 4000 km, Cen Ref, Liq, Road	180	0	0	204	25	15	384	25	15	0	0	0	227	15	9	227	15	9	227	15	9	227	15	9
	PISI 2002	168	5	5	190	23	14	357	29	20	0	0	0	212	14	8	212	14	8	212	14	8	212	14	8
	PISI 2010	141	11	12	160	19	12	302	33	28	0	0	0	179	11	7	179	11	7	179	11	7	179	11	7
	FC	94	12	12	107	13	8	201	28	24	0	0	0	119	8	5	119	8	5	119	8	5	119	8	5
	FC hybrid	84	10	10	95	11	7	179	25	21	0	0	0	106	7	4	106	7	4	106	7	4	106	7	4
GRLH1	L-H ₂ : Rem Ref, Liq, Sea, Road	180	0	0	256	22	27	437	22	27	0	0	0	250	13	15	250	13	15	250	13	15	250	13	15
	PISI 2002	168	5	5	236	21	25	406	28	32	0	0	0	232	12	14	232	12	14	232	12	14	232	12	14
	PISI 2010	141	11	12	201	18	21	343	35	40	0	0	0	196	10	12	196	10	12	196	10	12	196	10	12
	FC	94	12	12	134	12	14	228	30	32	0	0	0	130	7	8	130	7	8	130	7	8	130	7	8
	FC hybrid	84	10	10	119	10	12	203	27	29	0	0	0	116	6	7	116	6	7	116	6	7	116	6	7
GRLH2	L-H ₂ : LNG, Cen Ref, Liq, Road	180	0	0	241	21	23	421	21	23	0	0	0	247	12	13	247	12	13	247	12	13	247	12	13
	PISI 2002	168	5	5	224	19	21	392	26	28	0	0	0	229	11	12	230	18	19	230	18	19	230	18	19
	PISI 2010	141	11	12	189	16	18	331	32	36	0	0	0	194	9	10	194	9	10	194	9	10	194	9	10
	FC	94	12	12	126	11	12	220	29	30	0	0	0	129	6	7	129	6	7	129	6	7	129	6	7
	FC hybrid	84	10	10	112	10	11	196	25	26	0	0	0	115	6	6	115	6	6	115	6	6	115	6	6
WFLH1	L-H ₂ : Wood F, Cen gasif, Liq, Road	180	0	0	270	30	24	450	30	24	12	1	1	0	0	0	15	3	9	15	3	9	15	3	9
	PISI 2002	168	5	5	251	28	22	418	36	30	11	5	5	0	0	0	14	2	8	14	2	8	14	2	8
	PISI 2010	141	11	12	212	24	19	353	41	39	9	11	12	0	0	0	11	2	7	12	3	8	12	3	8
	FC	94	12	12	141	16	13	235	35	32	6	12	12	0	0	0	8	1	5	8	2	5	8	2	5
	FC hybrid	84	10	10	125	14	11	209	31	28	5	10	10	0	0	0	7	1	4	7	2	5	7	2	5
GPEL1b/LH1	L-H ₂ : NG 4000 km, CCGT, Cen Ely, Liq, Road	180	0	0	516	53	30	696	53	30	0	0	0	415	33	18	415	33	18	415	33	18	415	33	18
	PISI 2002	168	5	5	480	49	28	647	64	43	0	0	0	386	29	17	386	29	17	386	29	17	386	29	17
	PISI 2010	141	11	12	405	41	24	546	73	60	0	0	0	325	24	14	326	49	42	326	49	42	326	49	42
	FC	94	12	12	269	28	16	363	62	50	0	0	0	216	16	9	216	16	9	216	16	9	216	16	9
	FC hybrid	84	10	10	240	25	14	323	55	45	0	0	0	193	14	8	193	14	8	193	14	8	193	14	8
EMEL1/LH1	L-H ₂ : Elec EU-mix, Cen Ely, Liq, Road	180	0	0	761	38	36	941	38	36	0	0	0	425	17	16	425	17	16	425	17	16	425	17	16
	PISI 2002	168	5	5	708	35	33	875	56	55	0	0	0	395	16	15	396	28	27	396	28	27	396	28	27
	PISI 2010	141	11	12	597	30	28	739	76	80	0	0	0	334	13	13	334	39	41	334	39	41	334	39	41
	FC	94	12	12	397	20	19	491	69	68	0	0	0	222	9	8	222	36	36	222	36	36	222	36	36
	FC hybrid	84	10	10	354	17	17	437	62	61	0	0	0	197	6	7	197	32	32	197	32	32	197	32	32
KOEL1/LH1	L-H ₂ : Elec coal EU-mix, Cen Ely, Liq, Road	180	0	0	672	99	77	852	99	77	0	0	0	854	79	101	854	79	101	854	79	101	854	79	101
	PISI 2002	168	5	5	626	93	72	793	111	91	0	0	0	795	73	94	795	97	118	795	97	118	795	97	118
	PISI 2010	141	11	12	526	78	61	669	119	107	0	0	0	671	62	80	671	113	137	671	113	137	671	113	137
	FC	94	12	12	351	52	40	445	96	84	0	0	0	446	41	53	446	96	108	446	96	108	446	96	108
	FC hybrid	84	10	10	312	46	36	396	85	75	0	0	0	397	37	47	397	85	96	397	85	96	397	85	96

10 Summary of pathways with CC&S

WTT Code	Powertrain	Energy MJ / 100 km												GHG g CO _{2eq} / km											
		Total									Fossil			TTW			WTT			WTW					
		TTW (MJ/100 km)			WTT (MJ/100 km)			WTW (MJ/100km)			WTW (MJ/100km)			Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
CCS pathways																									
GRCG1C	CNG: LNG, Vap, Pipe, CC&S																								
	PISI bi-fuel 2002	227	12	6	72	5	6	299	15	10				132	7	4	37	3	3	169	8	6			
	PISI dedicated 2002	223	14	6	71	5	6	294	17	10				130	8	4	36	3	3	166	9	5			
	PISI bi-fuel 2010	188	12	8	60	5	5	248	14	11				108	7	4	31	2	2	139	8	6			
	PISI dedicated 2010	187	13	8	60	5	5	247	15	11				108	7	4	31	2	2	138	9	6			
	PISI hybrid	139	17	13	44	3	3	184	19	15				81	10	8	23	2	2	104	11	9			
GPCH2bC	C-H2: NG 4000 km, Cen Ref, Pipe, CC&S																								
	PISI 2002	180	0	0	139	14	6	319	14	6				0	0	0	67	8	3	67	8	3			
	PISI 2010	168	5	5	129	13	5	297	17	11				0	0	0	62	7	3	63	9	5			
	PISI hybrid	149	13	11	115	11	5	263	25	18				0	0	0	55	6	2	56	11	7			
	FC	94	12	12	73	7	3	167	20	17				0	0	0	35	4	2	35	8	6			
	FC hybrid	84	10	10	65	6	3	148	18	15				0	0	0	31	4	1	31	7	5			
KOCH1C	C-H2: Coal EU-mix, cen Ref, Pipe, CC&S																								
	PISI 2002	180	0	0	319	3	3	499	3	3				0	0	0	92	1	1	92	1	1			
	PISI 2010	168	5	5	297	3	3	464	13	13				0	0	0	85	1	1	86	4	4			
	PISI hybrid	149	13	11	263	2	2	412	28	25				0	0	0	76	1	1	76	8	7			
	FC	94	12	12	167	2	2	261	25	25				0	0	0	48	1	1	48	7	7			
	FC hybrid	84	10	10	148	1	1	232	22	22				0	0	0	43	1	1	43	6	6			
GRSD2C	Syn-diesel: Rem GTL, Sea, Rail/Road, CC&S																								
	DICI 2002	183	5	5	139	9	11	323	15	16				133	4	4	24	5	6	157	7	8			
	DICI 2010 no DPF	172	7	7	131	9	10	303	16	17				124	5	5	22	5	6	146	8	9			
	DICI 2010 DPF	177	7	7	135	9	10	311	17	18				127	5	5	23	5	6	150	8	9			
	DICI hybrid n DPF	141	15	11	107	7	8	249	23	20				102	11	8	18	4	5	120	12	10			
	DICI hybrid DPF	146	15	11	111	7	9	257	24	20				105	11	8	19	4	5	124	12	10			
KOSD1C	Syn-diesel: CTL, CC&S, Diesel mix																								
	DICI 2002	183	5	5	194	14	15	377	21	22				135	4	4	71	14	15	204	17	18			
	DICI 2010 no DPF	172	7	7	182	13	14	354	22	23				124	5	5	67	14	14	191	17	18			
	DICI 2010 DPF	177	7	7	187	14	14	363	23	24				127	5	5	69	14	15	196	18	18			
	DICI hybrid n DPF	141	15	11	149	11	12	290	30	25				102	11	8	55	11	12	157	20	18			
	DICI hybrid DPF	146	15	11	154	11	12	299	31	26				105	11	8	57	12	12	162	20	18			
GRDE1C	DME: Rem Syn, Sea, Rail/Road, CC&S																								
	DICI 2002	183	5	5	99	0	13	282	6	17				127	4	4	20	0	0	146	4	4			
	DICI 2010 no DPF	172	7	7	93	0	12	265	8	18				118	5	5	19	0	0	136	5	5			
	DICI hybrid n DPF	141	15	11	76	0	10	217	17	19				97	10	7	15	0	0	112	10	8			