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Biofuels Versus Diesel and Gasoline in the JEC-WTW report version 2c

An Extract from the 'Well-to-Wheels Analysis of Future Automotive
Fuels and Powertrains in the European Context', ver. 2c March 2007

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This report is an extract, made by Marinka Vignali (JRC/IES), from the original report 'Well-to Wheels analysis of future automotive fuels and powertrains in the European context' 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).

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The extract is available on the JRC/IES/RE Unit website at:
http://re.jrc.ec.europa.eu/biof/html/documents_publications.htm

Both reports are available as ADOBE pdf files.

ABSTRACT

An extract of the JRC-EUCAR-CONCAWE (JEC) Well-to-Wheels Report (WTW) Version 2c, March 2007 has been made to form an easily readable reference for people interested only in biofuels.

Thus, among all alternative fuels analysed in the WTW study, only the biofuels have been extracted. Conventional fuels, namely standard gasoline and diesel, have been incorporated for comparison.

In particular, the following biomass types are considered:

- Sugar beet, sugar cane, wheat and straw (to ethanol and further conversion from ethanol to ETBE (Ethyl-Tertiary-Butyl Ether))
- Oil seeds -rapeseed, sunflower- (to bio-diesel)
- Wood (to ethanol and to synthetic liquid fuels)
- Organic wastes (to compressed biogas)

The extract incorporates the complete pathway of the biofuel, from the production of the raw material to the final biofuel use in the car.

It means to have listed in the report for each biofuel:

- availability in EU at given cost
- costs involved in the processing, transportation, infrastructures
- GHG emissions and energetic balance.

Natural gas sources, hydrogen, fossil fuels and uses to electricity are not part of this report.

KEY FINDINGS OF THE WTW STUDY

EUCAR, CONCAWE and JRC (the Joint Research Centre of the European Commission) have jointly evaluated the **Well-to-Wheels (WTW) energy use and greenhouse gas (GHG) emissions** for a wide range of potential future fuel and powertrain options. The specific objectives of the WTW study have been:

- 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.

All the main **conclusions and observations** of the WTW study are copied below to give to the reader a complete overview of the arguments covered by the original report (the points pertaining to energy and GHG balance are in normal font, additional points involving feasibility, availability and costs are 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 CO_2 capture and storage and this merits further study.

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

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

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

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

CONVENTIONAL FUELS / VEHICLE TECHNOLOGIES

- Developments in engine and vehicle technologies will continue to contribute to the reduction of energy use and GHG emissions:
  - Within the timeframe considered in this study, higher energy efficiency improvements are predicted for the gasoline and CNG engine technology (PISI) than for the Diesel engine technology.
  - Hybridization of the conventional engine technologies can provide further energy and GHG emission benefits.

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

COMPRESSED NATURAL GAS, BIOGAS, LPG

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

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

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

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

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

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

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

ALTERNATIVE LIQUID FUELS

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

- The fossil energy and GHG savings of conventionally produced bio-fuels such as ethanol and bio-diesel are critically dependent on manufacturing processes and the fate of by-products.
  - The GHG balance is particularly uncertain because of nitrous oxide emissions from agriculture.

- 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 CO_2 avoidance and cost of fossil fuel substitution crucially depend on the specific pathway, by-product usage and N_2O 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.*

CONTENTS

LIST OF ABBREVIATIONS

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
CBG	Compressed Biogas
CCGT	Combined Cycle Gas Turbine
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)
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
LHV	Lower Heating Value ('Lower" indicates that the heat of condensation of water is not included)
LPG	Liquefied Petroleum Gases
MDEA	Methyl Di-Ethanol Amine
ME	The Middle East
MPa	Mega Pascal, unit of pressure (1 MPa = 10 bar). Unless otherwise stated pressure figures are expressed as "gauge" i.e. over and above atmospheric pressure
Mtoe	Million tonnes oil equivalent. The "oil equivalent" is a notional fuel with a LHV of 42 GJ/t
N_2O	Nitrous oxide, a very potent greenhouse gas

NEDC	New European Drive Cycle
NG	Natural Gas
NOx	A mixture of various nitrogen oxides as emitted by combustion sources
OCF	Oil Cost Factor
OGP	Oil & Gas Producers
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
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
TES	Transport Energy Strategy. A German consortium that worked on alternative fuels, in particular on hydrogen
TOE	Ton of oil equivalent
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

CONVERSION FACTORS

1 kWh = 3.6 MJ = 3412 Btu
1 MW = 1 MJ/s = 28.8 TJ/y (1 year ~ 8000 h)
1 toe = 41.868 GJ
1 Nm^3 EU-mix NG ~ 0.8 kg → ~ 40 MJ (almost the same energy content as 1 kg of crude oil)

Green house gases (GHG) coefficients and calculations

CO_2-equivalence coefficients

Greenhouse gas	t CO_2eq / t
CO_2	1
Methane (CH_4)	23
Nitrous oxide (N_2O)	296

The CO_2 equivalence is applied to the non-CO_2 greenhouse gases according to the conversion coefficients recommended by the third assessment report of the Inter-governmental Panel for Climate Change [*IPCC*].

Other GHGs are not emitted in significant quantities in any of the processes considered.

CO_2 emissions from combustion (assuming total combustion)

- 1 kg of a fuel with C% carbon emits:

$$1[\mathrm{kg_{fuel}}]\cdot\frac{C\%}{100}\left[\frac{\mathrm{kg_C}}{\mathrm{kg_{fuel}}}\right]\cdot\frac{44}{12}\left[\frac{\mathrm{kg_{CO_2}}}{\mathrm{kg_C}}\right]=0.0367\cdot C\%[\mathrm{kg_{CO_2}}]$$

- 1 MJ of a fuel with λ MJ/kg (LHV) and C% carbon emits:

$$\frac{1[\mathrm{MJ_{fuel}}]}{\lambda\left[\frac{\mathrm{MJ_{fuel}}}{\mathrm{kg_{fuel}}}\right]}\cdot 0.0367\cdot C\%[\mathrm{kg_{CO_2}}]=0.0367\cdot\frac{C\%}{\lambda}\left[\frac{\mathrm{kg_{CO_2}}}{\mathrm{kg_{fuel}}}\right]$$

1 Introduction

❒ Scope and methodology of the WTW study

The aim of the WTW study 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.

The 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.

In terms of cost, Europe has been treated 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. Only "direct" costs related e.g. to purchasing feedstocks, building plants, infrastructure and vehicles have been considered. No other possible sources of costs (or benefits) related to e.g. employment opportunities, regional development and the like have been analysed.

The energy or GHG emissions associated with construction or decommissioning of plants and vehicles are not considered because available data are often sketchy and uncertain. Furthermore, the impact of these additional energy requirements on the total pathway balance is generally small and within the range of uncertainty of the total estimates. This may, however, not always be the case and this should be checked when looking at a particular route in more details.

Among the available data only what was judged to be the most appropriate sources has been chosen as starting point for the WTW study. 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. Finally, 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.

In summary, the WTW study tried to answer to the following questions relative to the fuels potential for the next decade:

- 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?

❒ Structure of the extract compared to the WTW report

The original WTW report (simply recalled in this extract as 'WTW') was devided in three parts:

- Well to Tank (WTT): the cascade of steps required to produce and distribute a fuel (starting from the primary energy resource), including vehicle refuelling
- Tank to Wheels (TTW): the fuel/vehicle combinations to describe the burning of a fuel in a vehicle
- Well to Wheels (WTW): the integration of all steps required to produce and distribute a fuel (starting from the primary energy resource) and use it in a vehicle.

This means each step of the WTW chain was presented for all fuels simultaneously.

This extract has been structured in a different way: single chapters for each fuel have been made by extracting all information on the entire pathway from the primary energy resource to the use in the vehicle, from the three original parts of the WTW report.

An introduction on the methodology constituting the base of the WTW study is followed by 'conventional gasoline and diesel fuels' and 'biofuels'.

These fuel-chapters have the same structure:

- Description of the use of the fuel and its primary resources
- Analysis of the costs and availability. For the biofuel-chapter a deeper discussion is added at the end of the chapter, where the potential volumes that could be produced via the different routes have been considered and the methodology, figures and assumptions used for cost estimates have been presented.

- Description of the complete pathway of the fuel step by step, followed by the required costs in terms of energy and GHG emissions.

Furthermore, the biofuel-chapter covers alternative uses of energy resources.

The various contribution to the costs (energy or GHG emissions) are still identified as WTT, TTW and WTW costs. To facilitate the reader to find the same information in the original report to be compared with other fuels not present in this extract (e.g. hydrogen), table and figure titles and process codes are maintained as in the original report.

❒ Units and convertions

The energy figures are presented as total primary energy expended (MJ_{xt}), regardless of its origin, to produce 1 MJ of the finished fuel under study (LHV basis)[1] (recalled as MJ_f in the WTW figures and MJ_{prod} in the WTT figures). The figures exclude the heat content of the fuel itself (i.e. 1 MJ_{xt}/MJ_f means that as much energy is required to produce the fuel as is available to the final user) but include both fossil and renewable energy. As such they describe the energy efficiency of the pathway. For fuels of renewable origin the fossil energy expended in the pathway (MJ_{xf}) has also been evaluated, illustrating the fossil energy saving potential of that pathway compared to conventional alternatives.

GHG figures represent the total grams of CO_2 equivalent emitted in the process of obtaining 1 MJ_f of the finished fuel. For fuels of biomass origin, an additional credit is allocated, equal to the amount of CO_2 generated by complete combustion of the fuel. In this way the TTW CO_2 emissions do not need to take account of the origin of the fuel but only of its composition.

To show how the input data of a process are taken from the tables and then used to calculate the energy expended and the associated GHG emissions, a new section (D.1) has been added (where are also recalled the definitions of the parameters of a process).

❒ References

All references, including those relevant to the appendices are listed at the end of this document.

1.1 Overview of the complete pathway for a generic fuel

1.1.1 From the primary energy resource to the fuel (Well to Tank)

This part of the extract 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.

The notional time horizon for the study has been the next decade 2010-2020. The technologies considered are those that are expected to become commercially available in that time frame. The same applies to supply/demand, availability and potential for substitution of conventional fuels.

1.1.1.1 Incremental approach

The ultimate purpose of the WTW study has been 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, the *difference* between two realistic future scenarios has been calculated: 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. 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 have then been derived.

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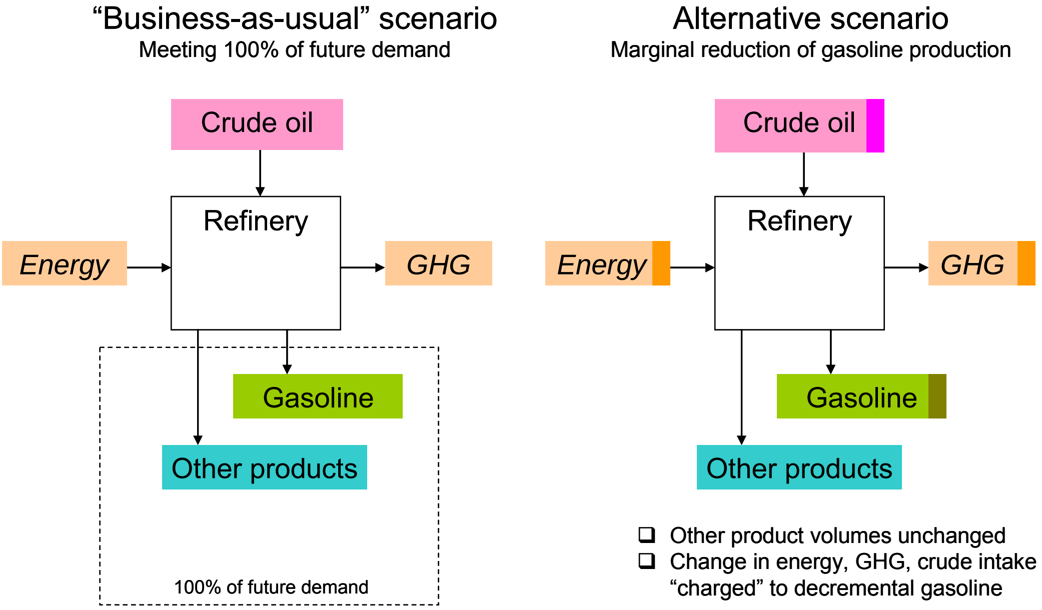
[1] In Appendix E, which shows the WTT detailed input data, the figures shown relate to a MJ of the output of each individual process.

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.

The question to consider to estimate the savings from conventional fuels has been **what could be saved** by using less of these **rather than how much** energy, GHG emissions and costs are involved in absolute terms. The energy and GHG emissions associated with production and use of conventional fuels have thus been considered to pertain to the marginal rather than the average volumes. Marginal production figures representative of the European situation have been obtained through modelling of the EU-wide refining system (Figure 1.1; more details in *WTT Appendix F*).

Figure 1.1: Impact of a marginal reduction of conventional gasoline demand



- ☐ Other product volumes unchanged
- ☐ Change in energy, GHG, crude intake "charged" to decremental gasoline

Distribution energy has been taken as proportional to volumes. 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, 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 and therefore only variable distribution costs have been taken into account. They become significant for fuels that are not fungible with conventional ones (e.g. gaseous fuels), since they critically depend on the scale envisaged.

For the most significant fuel options, a production and distribution cost scenario based on satisfying 5% of the future passenger car transport demand has been chosen to compare the various options.

1.1.1.2 Pathways and processes

The primary focus has been to establish the **energy and greenhouse gas (GHG) balance** for the different routes to make the final fuel available to the vehicles. The methodology used has been based on the description of individual processes, which are discreet steps in a total pathway.

A number of existing and potential road transport **fuels** have been identified, in association with existing and/or future powertrains. Each fuel can be produced from a single or several **resources** as the source of primary energy

The calculations of the total energy and GHG associated with a given pathway have been carried by a software program developed by LBST[2] which takes into account the main input and output, secondary inputs, by-products as well as closed loops included in some pathways that have to be solved by iteration.

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[2] E^3 database by L-B-Systemtechnik, Germany

Each pathway is described to a suitable level of detail including itemised contributions of the different processes. To facilitate comparison between sometimes very different pathways the results are also presented according to 5 generic stages:

- **Production and conditioning at source** includes all operations required to extract, capture or cultivate the primary energy source. In most cases, the extracted or harvested energy carrier requires some form of treatment or conditioning before it can be conveniently, economically and safely transported.
- **Transformation at source** is used for those cases where a major industrial process is carried out at or near the production site of the primary energy (e.g. gas-to-liquids plant).
- **Transportation to EU** is relevant to energy carriers which are produced outside the EU and need to be transported over long distances.
- **Transformation in EU** includes the processing and transformation that takes place near the market place in order to produce a final fuel according to an agreed specification (e.g. oil refineries).
- **Conditioning and distribution** relates to the final stages required to distribute the finished fuels from the point of import or production to the individual refuelling points (e.g. road transport) and available to the vehicle tank (e.g. compression in the case of biogas).

The table below (Table 1.1) summarises the pathways considered in this extract.

Table 1.1 Primary energy resources and automotive fuel

Resource / **Fuel**		**Gasoline, Diesel (2010 quality)**	**CBG**	**Synthetic diesel (Fischer-Tropsch)**	**DME**	**Ethanol**	**ETBE**	**FAME/FAEE**
Crude oil		x						
Biomass	Sugar beet					x	⇳	
	Wheat					x	x	
	Wheat straw					x		
	Sugar cane					x		
	Rapeseed							x
	Sunflower							x
	Woody waste			x	x	x		
	Farmed wood			x	x	x		
	Organic waste		x					
	Black liquor			x	x			

The energy source from which a fuel originates 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 the WTW study, all fuels and primary energy sources that appear relevant for the foreseeable future have been included. Since the number of conceivable fuels and fuel production routes is very large, certain combinations considered less relevant have been left out at this stage of the WTW study. The following matrix summarises the main combinations that have been included.

Whenever major contributions were at stake, different pathways have been created to directly show the effect of a particular option or view. This approach would, however, be impractical to deal with all sources of variability.

Industry generally uses a range of processes which, at least historically, have not been selected based solely on their energy efficiency but mainly on economic grounds. So established production paths display a range of variability.

Considering that new processes or improved existing ones have been mainly addressed, their future performance is necessarily somewhat speculative. As a result, each step in a pathway carries a certain variability range representing the combination of the range of performance of the future installations and the uncertainty attached to the expected technical developments. On the basis of the quality of the data available, the degree of development of the process and any other relevant parameter, a judgement has been made as to the level of uncertainty attached to each figure as well as the probability distribution within the range. A Gaussian distribution has been used as default but also a so-called “double-triangle” for asymmetrical ranges and an equal-probability or “square” distribution when there is reason to believe that all values in the range are equally probable.

To combine all uncertainties in a pathway and arrive at a plausible range of variation for the total pathway, the traditional Monte Carlo approach has been used. Subsequent calculations have been carried out with the median figure.

1.1.1.3 Costing basis

A detailed analysis of each pathway is essential but by no means sufficient to capture the potential value and relevance of a particular route. Indeed issues of availability, feasibility of certain processes, costs, acceptability by the general public on a large scale, all play an important role to assess the practical potential of a certain route. However, the best options from an energy or GHG point of view are thus only likely to raise interest if they can be developed at a reasonable cost.

The future availability of the different fuels and associated resources has been therefore assessed. In preparing these estimates economical as well as practical constraints have been taken into account. Within the timeframe of the study availability is not a major issue for fossil fuels, but the potential of primary renewable resources certainly needs to be carefully considered. The issues to consider have been either physical limitations, or those related to competing use (e.g. use of arable land for food versus energy crops), or achievability.

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. (For example the size of the plants and of the ships, the distance between producer and customer are all affected to a degree (when it comes to investment in plants and infrastructure, costs are critically dependent on scale)).

Costs have been evaluated on a macro-economics basis for Europe (EU-25) as a whole.

The logic of using particular fuel/vehicle combinations compared to the business-as-usual case of conventional vehicles and fossil fuels 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 (such as oil products or wheat grain) 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 (for instance the cost of crude oil to the EU is not its production cost but its price on the international market), 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. For crop prices in 2012 a respected forecast has been used, upon which the market effects of increasing biofuels use has been estimated. 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) the production cost has been estimated from the various processes involved.

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

All costs are expressed in EUROS. Whenever the literature source indicated cost in US Dollars, €/$ parity has been assumed. However, forecasts of agricultural commodity prices follow [*DG-AGRI 2005*] in converting 2012 prices from dollars at a rate of 1.15 $/€.

When it comes to cost of new facilities (production, distribution etc) one has to rely mainly on literature sources which, even when carefully selected, often cannot be independently checked. Because they mostly refer to facilities which exist either at a limited scale or not at all, cost figures are often only rough estimates with both upwards (unforeseen items) and downwards (experience, scale) potential.

Although a definitive analysis is clearly not possible, the available data could provide a valuable insight into the various options.

To estimate the costs associated with a pathway, the following costs-contributions have been considered:

- to produce or procure the fuel and making it available to the vehicle. This includes feedstock, manufacturing and distribution infrastructure (WTT costs).

- to make any required changes to the vehicle fleet (TTW costs).

❒ Reference scenario for road fuels demand

An underlying scenario is therefore required to arrive at reasonable and consistent volume figures. A demand scenario for road transport is the starting point.

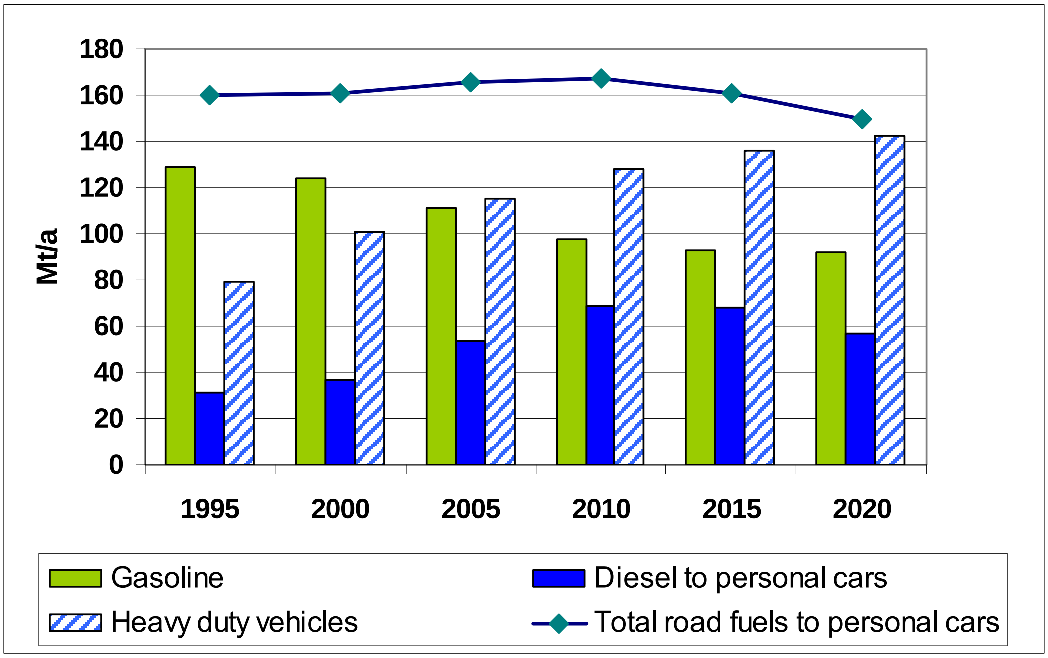
European road fuel demand is characterised by a slow decrease in gasoline more than compensated by an increase in diesel fuel. This is the combined result of the increasing shift to diesel passenger cars (encouraged by the drive to reduce CO_2 emissions) and of the increasing road haulage activities. In spite of the already achieved and expected further improvements in efficiency, road haulage should be responsible for a continued increase in diesel fuel consumption as it follows economic growth.

These trends are somewhat less marked when incorporating Eastern European countries where gasoline demand is still expected to grow for some time.

Figures proposed by Wood Mackenzie in a recent multi-client study have been used. The historical and forecast demand for road fuels in EU-25 is summarised in Figure 1.2, where three major trends could be noted:

- 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.

Figure 1.2 Historical and forecast EU-25 road fuels demand (Mt/a)



Source: Wood McKenzie (unpublished Industry study)

These figures represent total demand for road transportation i.e. including what might be supplied by alternative fuels. They can be used as guidance when judging the potential of certain pathways for substitution of a portion of the road fuel market.

Other sources may somewhat deviate from these but this would not have a material effect on the conclusions. Indeed the figures are used to provide orders of magnitude and to ensure consistency between the various options.

1.1.1.4 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 the “incremental” impact of these by-products has been represented. 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.

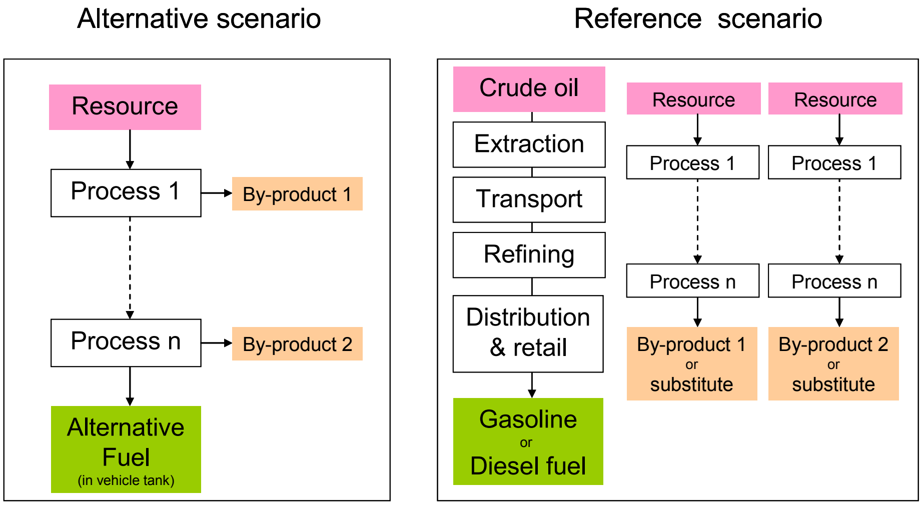
The logic is reflected in the following methodology (Figure 1.3):

- 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).

The "substitution" method attempts to model reality by tracking the likely fate of by-products.

It has the advantage to take into account that any benefit from a by-product must *depend on what the by-product substitutes.* Many other studies based on "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 could give flawed results. (The following example shows how allocation methods can bear little relation to reality. The manufacture of FAME (biodiesel) makes glycerine as a by-product. Amongst other options, the glycerine could be used instead of synthetic (pharmaceutical) glycerine or as animal feed, instead of wheat grain. Making 1 MJ synthetic glycerine requires about 18 MJ of fossil energy. Making 1 MJ of wheat takes about 0.13 MJ. Clearly much more fossil carbon emissions will be saved in the first option than in the second. Yet the “allocation” approaches based on energy or mass predict that the savings will be exactly the same!)

Figure 1.3 By-product credit methodology



Only the more plausible uses of by-products have been included. In fact, economics rather than energy use or GHG balance, are likely to dictate which routes are the most popular in real life.

Many processes have more than one energy product: for example, many wood and straw processing pathways include a significant electricity export. The procedure above deals with how to find the greenhouse gas and fossil energy savings for the process, but it does not specify how much of the savings are due to making biofuels and how much is due to making bioelectricity. If one attributes all the GHG/energy credits to the biofuel, one comes to the conclusion that the smaller the fraction of biofuels produced compared to electricity, the better the GHG balance. That quantity of bio-electricity could have been produced by a free-standing bioelectricity generator: its existence does not depend on the biofuels process. It is clear that to get a balance which pertains only to the biofuel output, the bioelectricity part of the process must be subtracted. This is done by using a dedicated biomass-to-electricity process in the reference scenario; then the difference between the alternative and reference scenarios is only the production of biofuel.

1.1.1.5 Miscellaneous assumptions

A number of processes in the pathways make use of common assumptions listed below:

- Energy content : all energy contents referred to are on LHV basis i.e. excluding the heat generated after the combustion process by the condensation of water vapour.
- Shipping: many pathways include long-distance shipping of gases or liquids. In all such case published data for a type of ship consistent with the length of the envisaged trip and the material being carried have been used. Such ships normally return empty and the corresponding fuel consumption has been taken into account through the so-called “Admiralty formula” according to which the fuel consumption of a ship is proportional to the cubic root of the water displacement.

1.1.2 Fuel/Vehicle combination costs (TTW costs)

For most pathways or combinations of pathways the costs and savings have been calculated in terms of fossil energy, CO_2 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 (see chapter 4 for a description on the used methodology).

Because the available data only relate to compact passenger car applications, the scope of the calculation has been limited to this segment of the market and should not be generalized to other segments such as Heavy Duty or SUVs. Furthermore, the model vehicle is merely a comparison tool and is not deemed to represent the European average, a/o in terms of fuel consumption.

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.

Table 1.2 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*]

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 1.2**,** where the costs have been calculated as incremental to the reference scenario in which the demand is covered by conventional fuels and powertrains (gasoline and diesel).

Conventional biofuels (ethanol and biodiesel) are assumed to be blended into fossil fuels. For up to 5% blend, this means there is no change needed in the cars. Then the TTW costs are the same for biofuels and gasoline or diesel. Therefore when calculating the cost-of-substitution, the WTT costs cancels out. The same is true for synthetic diesel and ETBE. Only DME and compressed biogas have different WTT costs compared to the fossil reference case.

1.1.3 From the primary energy resource to the vehicle (Well to wheels integration)

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),
- The TTW energy consumed by the vehicle per unit of distance covered (on the standard road driving cycle, NEDC (sec. 4.1.5, pag. 101)).

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

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

where:

MJ_f refers to the energy contained in the finished fuel.

MJ_{xt} refers to the total additional external energy needed to produce 1 MJ of fuel from the primary energy resource.

(For example a figure of 0.5 means that making the fuel requires 50% of the energy that it can produce when burned)

This total energy figure gives a truly comparable picture of the various pathways in terms of their ability to use energy efficiently.

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

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

where:

λ = 1 for fossil fuels, 0 for renewable fuels.

MJ_{xfo} refers to the fossil additional external energy needed to produce 1 MJ of fuel from the primary energy resource.

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

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

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

1.2 Reporting formats

Biofuels are compared with gasoline and diesel as reference. So, conventional fuels are introduced as first (chapter 2), followed by all biofuels (chapter 3) described in the WTW report.

The processes necessary to convert a certain primary resource into a final fuel have been described through the stepwise description of the pathways together with the detailed input data (further detailed comments and remarks on individual processes are given in *Appendix D)*.

The detailed energy and GHG balance have been reported for each pathway. In order to illustrate the relative importance of the different stages of the pathway, detailed results have been given according to the 5 standard steps defined in sec. 1.1.1.2. The actual figures with additional details for each pathway are listed in Appendix E.

The reported WTT GHG figures exclude CO_2 emissions associated with the combustion of the final fuel. For the WTW analysis, carbon-containing fuels of renewable origin are, however, given a credit for an amount of CO_2 equivalent to that released during combustion. In the TTW study, all fuels have then been treated in the same way and allocated CO_2 emissions corresponding to their carbon content regardless of its origin (a specific section, 3.6, has been made to compare the cost of CO_2 avoidance for all fuels options described in the original WTW study).

The gasoline or diesel balance has also been included in many graphs: for total energy, it provides a valid reference as long as vehicle efficiency is expected to be essentially the same for fossil and biofuel. To make the same comparison for fossil energy or total GHG emissions, the combustion energy and CO_2 emissions for the fossil fuels have been added.

2 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 the WTW 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, 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. Therefore ICE engines fuelled by gasoline or diesel fuel from crude oil represent the reference against which all the alternatives have been assessed.

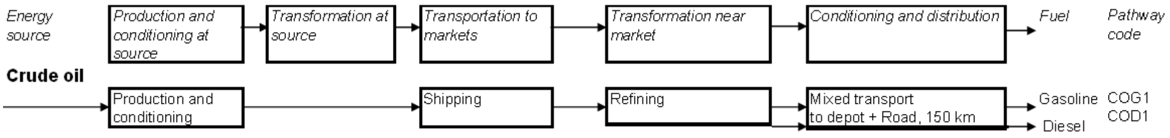
Within the timeframe of the WTW study only a limited substitution of conventional fuels can be reasonably envisaged so that the fixed costs associated with refining and distributing conventional fuels are unlikely to be notably affected.

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

2.1 Crude oil pathways

The pathways from crude oil to road fuels are straightforward, as illustrated in the following figure.

Figure 2.1 Conventional fuels pathways



2.1.1 Energy source: crude oil supply and cost to Europe

Crude oil is an internationally traded commodity, 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. The basic assumption has been that the price of crude oil would determine the pricing level of all other products. Each of these was therefore assigned a price related to crude oil. Although most grades are traded on a wide geographical basis, consuming regions tend, for logistic and geopolitical reasons, to have preferred supply sources. In Europe the main sources are:

- North Sea: this is indigenous production for which Western Europe has a clear logistic advantage. Although some North Sea crude finds its way to the US, the bulk is consumed in Europe.
- Africa: North African crudes (Algeria, Lybia, Egypt) are naturally part of Southern Europe’s “captive” production. West African crudes can profitably go either to North America or to Europe and the market is divided between these two destinations.
- Middle East: The region is an important supplier, mainly of heavy, high-sulphur grades, typically used for the manufacture of bitumen or base oils for lubricant production and by refineries with appropriate desulphurisation and residue conversion facilities.
- FSU: Russia is a steady supplier to Europe, partly through an extensive inland pipeline system extending to most former East European block countries. The Caspian basin is poised to become a major producer with Europe as a preferred customer because of favourable logistics.

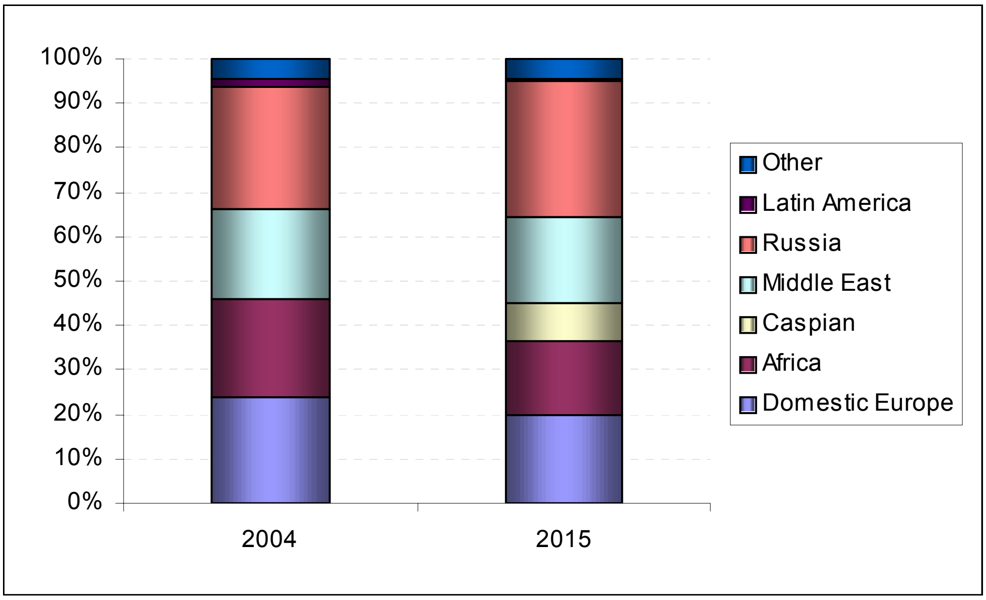
Concerning crude oil availability, the long-term adequacy of oil resources to cover world demand is currently a matter of debate (debate not treated in the WTW study). In any case, there is no serious threat to European supplies of crude oil and products within the timeframe of the WTW study. The "business-as-usual"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

In order to represent the fluctuations of the oil price the calculations for 25 and 50 €/bbl have been made (i.e. around 30 and 60 \$/bbl respectively, March 2007). 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. This has been taken 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.

EU-25 will consume about 650 Mt of crude oil in 2005 (plus some 85 Mt of various feedstocks). This is set to grow slightly up to around 665 Mt in 2015 with a subsequent slight decrease at the 2020 horizon. Although it is considered that supply should be adequate within this timeframe, the sources of supply for Europe will change. North Sea production will decline but other regions such as West Africa and the Caspian basin will take over. These changes in the origin of the crude oil will not significantly affect the average quality and the current proportion of around 48% of sweet (i.e. low sulphur) crudes should remain essentially constant over the next decade.

The current and forecast European supply is shown in the following figure.

Figure 2.2 **Current and future EU crude oil supply**



(Source Wood MacKenzie)

As discussed earlier, the marginal substitution of conventional fuels has been considered. The relevant cost figure is therefore not the cost of providing these marginal fuels but rather the savings that would be realised by not producing them.

When faced with a decrease in demand refiners can either reduce production or trade i.e. seek to export more if the product is globally in surplus in the region or reduce imports if the product is in deficit. The most economically attractive route will depend on the interplay between the international markets of crude and products. In a “short” market, typical of diesel fuel in Europe, the price will be driven towards that of imports, most likely to be above the domestic costs of production. The most likely outcome of a reduction of demand will be a sustained domestic production and a reduction of imports. In a “long” market, typical of gasoline in Europe, the price will be dragged down towards that of the marginal available export market. Export will only make sense if a net profit can be made on the marginal volumes which may or may not be the case. So far in Europe export markets have been available for gasoline while diesel fuel prices have encouraged maximum domestic production. For the purpose of the WTW study this situation has been assumed to remain.

The “saving” to Europe of not consuming a fuel is therefore equal to its international market price in a European port. Refined product and crude prices are loosely linked but the ratios fluctuate considerably. Gasoline and diesel fuels typically trade at 1.2 to 1.4 times crude price on a mass basis. At the 25 €/bbl crude price level the typical road fuel price would then be in the 225-260 €/t bracket. A ratio of 1.3 has been used for both fuels, irrespective of crude price.

Table 2.1 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
Road fuels of fossil origin				€ /GJ	OCF	€ /GJ
Gasoline and diesel fuel	Ratio to crude 1.3			5.9	1.00	11.9

❒ Investment and operating costs

For those fuels manufactured in Europe production costs on the basis of published literature have been estimated. 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) has been used. Capital investment figures have been assumed to pertain to the low oil price scenario and an OCF of 0.1 has been used. Uncertainty ranges of ± 20% and ± 40% have been applied for established and new technologies respectively.

Operating costs have been 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.

2.1.2 Crude oil production and conditioning at source

Crude oil is generally extracted under the natural pressure of the underground reservoir. In some, mostly older fields, it may be necessary to boost the reservoir pressure by gas injection. In most cases oil is associated with gases and needs to be stabilised before shipment. Water separation is also sometimes required. The associated gases used to be commonly flared but are now generally either conditioned and shipped separately (e.g. LPG) or re-injected into the reservoirs.

Production conditions vary considerably between producing regions, fields and even between individual wells and it is only meaningful to give typical or average energy consumption and GHG emission figures for the range of crudes under consideration. A value of 0.025 MJ/MJ (0.01-0.04) and 3.3 g CO_2eq/MJ (2.8-3.9) have been used, representing the combined estimates of a number of CONCAWE member companies.

The marginal crude available to Europe is likely to originate from the Middle East where production energy tends to be at the low end of the range. From this point of view the use of the above average figures can be considered as conservative.

2.1.3 Crude oil transportation to markets

Crude needs to be transported from the production areas to refineries in Europe. Crude oil is mostly transported by sea. The type of ship used depends on the distance to be covered. The bulk of the Arab Gulf crude is shipped in large ships (VLCC or even ULCC Very/Ultra Large Crude Carrier) that can carry between 200 and 500 kt and travel via the Cape of Good Hope to destinations in Western Europe and America or directly to the Far East. North Sea or African crudes travel shorter distances for which smaller ships (100 kt typically) are used.

Pipelines are also extensively used from the production fields to a shipping terminal. Some Middle Eastern crudes are piped to a Mediterranean port. The developing regions of the Caspian basin will rely on one or several new pipelines to be built to the Black Sea. Crude from central Russia is piped to the Black Sea as well as directly to eastern European refineries through an extensive pipeline network. Although the majority of refineries tend to be at coastal locations, a number of them are inland. Within Western Europe, there are several inland pipelines from the Mediterranean to North Eastern France and Germany as well as from the Rotterdam area to Germany.

Here again, there is a wide diversity of practical situations. Considering mainly marginal crude originating from the Middle East an energy figure of 1% (10 MJ/MJ) has been used, corresponding to 0.8 g CO_2eq/MJ assuming a ship fuelled by heavy fuel oil.

2.1.4 Crude oil refining

Traditionally, crude oil is transported as such and refined near the markets. The advent, from the early 80's, of large "export" refineries in the Middle East provided another model of refining at source and long-haul product transportation. However, the number of such refineries remains limited and so does their impact, specifically on Europe where the overwhelming majority of finished products are produced by local refineries importing crude oil. Although Europe imports some blending components and finished products, the bulk of the fuels sold in Europe is manufactured in European refineries. The WTW study therefore assumes that crude oil based fuels are manufactured from crude oil in European refineries.

An oil refinery is a complex combination of process plants, the objective of which is to turn crude oil into marketable products of the right quality and in the right quantities. This entails

- Physical separation of the crude components
- Treating to remove such compounds as sulphur
- Conversion of mainly heavy molecules into lighter ones to match the production slate to the market demand

European refineries consume about 6% of their own intake as processing energy. Some energy is exchanged with the outside (e.g. electricity import/export, natural gas import). Although European refineries are global importers of energy/fuels other than crude oil, the bulk of the energy used by refineries comes from their crude oil intake. The refineries burn gas (mainly generated in the refinery processes) as well as liquid and solid fuels.

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. 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.

In the context of the WTW study, the energy and GHG emissions associated with production and use of conventional fuels should be representative of how the EU refineries would have to adapt to a marginal reduction of demand. Such figures were obtained through modelling of the EU-wide refining system (see Figure 1.1, pag. 15***)*** and more details in Appendix F).

In Europe, marginal diesel fuel is more energy-intensive than marginal gasoline. In recent years Europe has seen an unprecedented growth in diesel fuel demand while gasoline has been stagnating or even dropping. According to all forecasts, this trend will continue in future years, driven by increased dieselisation of the personal car and the growth of freight transport in line with GDP. At the same time, jet fuel demand also steadily increases as air transport develops. The ratio of an ever increasing call for "middle distillates" and a call for gasoline that is at best constant goes beyond the "natural" capabilities of a refining system that was by and large designed with a focus on gasoline production. Reducing diesel fuel demand therefore "de-constrains" the system whereas decreasing gasoline demand makes the imbalance worse.

Based on the obtained results, the following figures (in the table) have been adopted.

		Gasoline	**Diesel fuel**
Energy	MJ/MJ	0.08	0.10
GHG	g CO_2eq/MJ	6.5	8.6

The calculations have been carried out on the basis of a 2010 base case including all foreseen fuel specifications including sulphur-free road fuels. Although the additional quality requirements will result in a higher absolute level of energy consumption in the refineries in 2010 compared to the current situation, the effect on the marginal value are of a second order of magnitude. The above figures can therefore be considered as representative of the whole time period.

Note: In principle the same marginal analysis should apply to the other stages of the elaboration and distribution of conventional fuels. However, these figures are small compared to those for refining and it can reasonably be assumed that energy and GHG emissions associated with crude production and transportation as well as product distribution are proportional to the volumes concerned.

2.1.5 Gasoline and diesel fuel distribution

Finished products from the refinery are transported either by road tanker directly to a retail station or, for the larger part, to a depot by pipeline, train or barge. For the calculation a mix of the different transportation modes has been used according to the actual share of each mode in

Europe. Depots and service stations also account for a small energy consumption, essentially in the form of electricity.

The total average figure for Europe is estimated at 20 kJ and just over 1 g CO_2eq per MJ of delivered fuel. These figures can reasonably be assumed to be independent of the volumes concerned.

2.2 Energy and GHG balances

The **WTT** total energy and GHG balance are shown in Figure 2.3 and Figure 2.4 respectively.

Figure 2.3 WTT total energy balance for crude oil based fuels

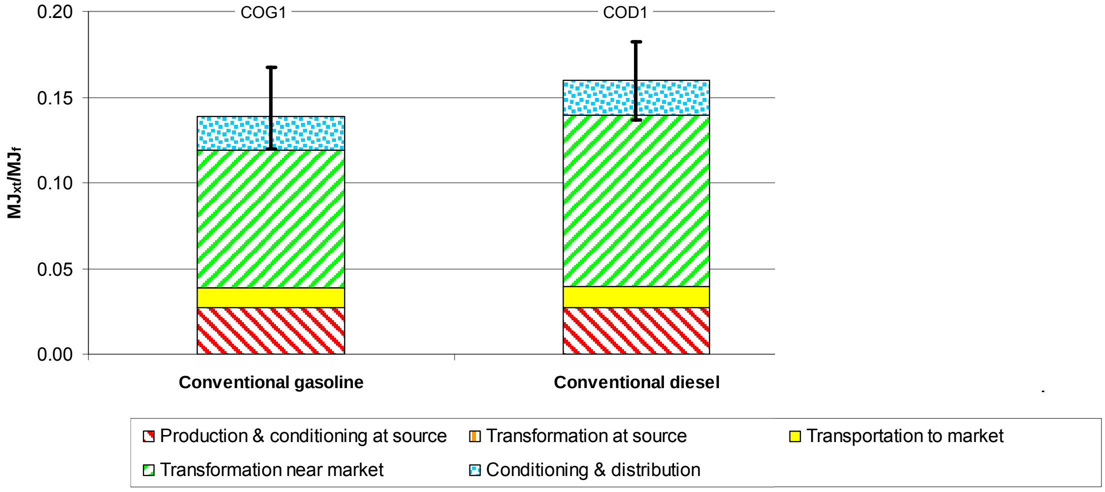
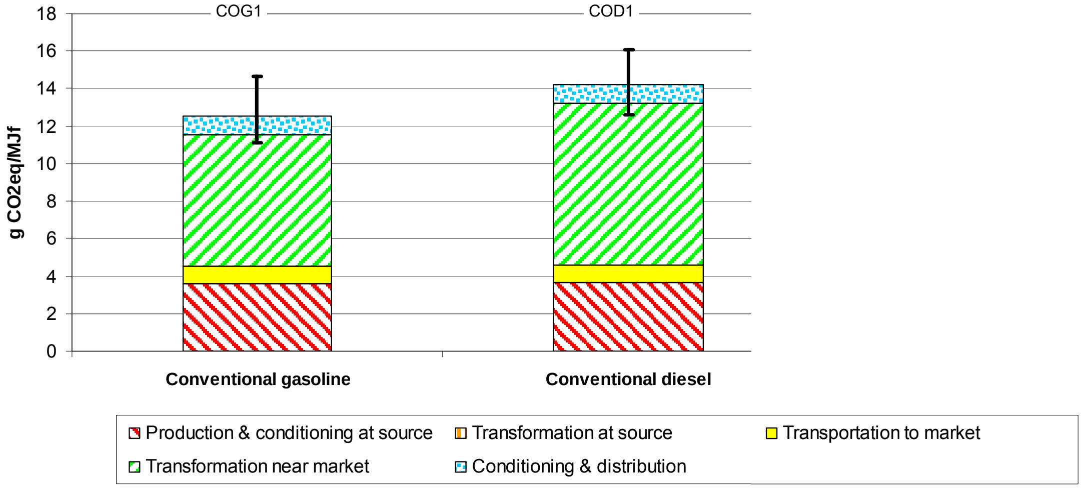


Figure 2.4 WTT GHG balance for crude oil based fuels



Refining is the most energy-consuming step followed by crude production. 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 (as discussed in sec. 2.1.4).

Note: these figures apply to Europe as a result of the specific situation prevailing in the region. The situation will be different in other parts of the world and a similar assessment would have to be made taking into account the local parameters and leading to different figures and conclusions.

The **aggregated WTT and TTW** energy and GHG figures for the 2002 and 2010 vehicles are shown on the figure below, illustrating the potential for improvement of conventional engines and fuels (Figure 2.5) and also that *the efficiency gap between Spark Ignition and Compression Ignition is narrowing (*Figure 2.6*).*

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.

On a WTW basis the impact of marginal diesel production versus gasoline is modest and more than compensated by the superior efficiency of the Diesel DICI 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 4.6. 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 2.5 **WTW energy requirement and GHG emissions for conventional fuels ICE powertrains**

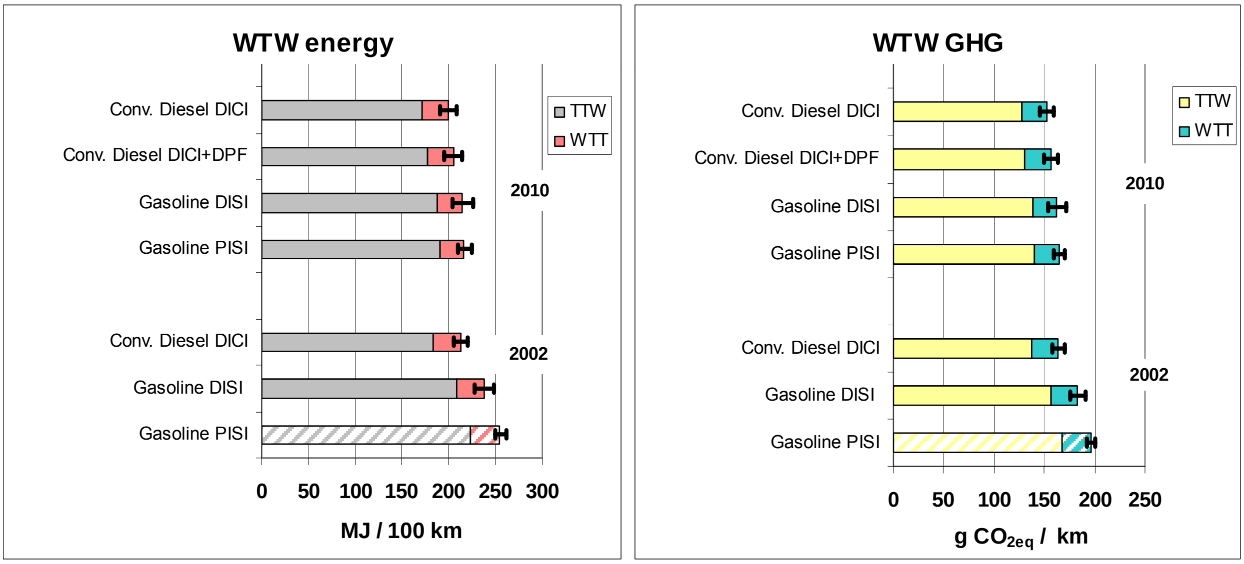
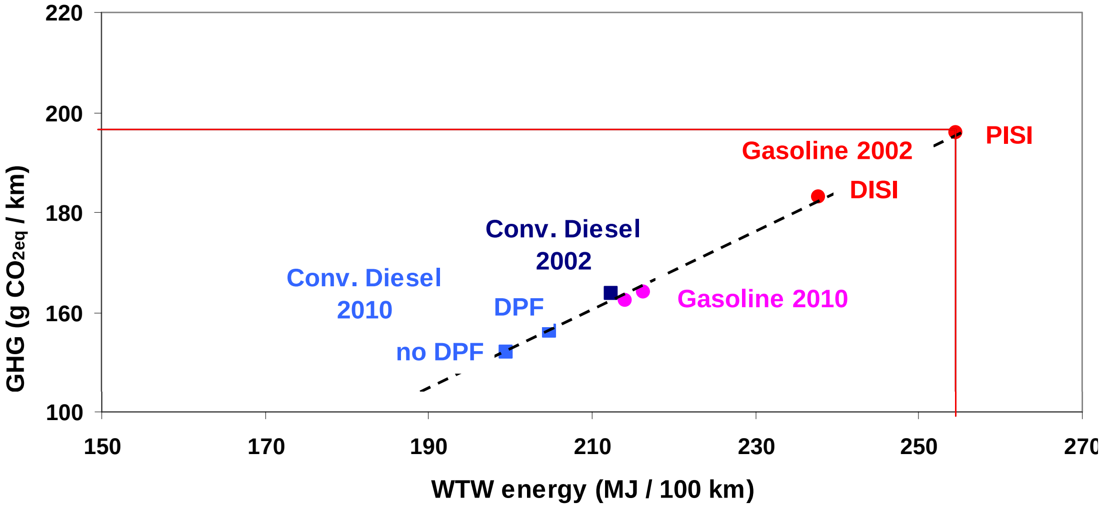


Figure 2.6 **WTW energy requirement and GHG emissions for conventional fuels ICE powertrains**



3 Biofuels

3.1 Introduction

All sources of biomass which have the potential to substitute a significant amount of transport fuel in the EU have been included, i.e. farmed crops such as sugar beet, wheat and oil seeds and woody biomass either in the form of waste or purpose-grown. “Wood farming” incorporates also perennial grasses such as miscanthus or switch grass.

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 a product known as “distiller’s dried grain with solubles” (DDGS), the by-product of ethanol distillation. Their price has been worked out from the animal feeds they substitute (taking also into account the quality difference).

The food commodity prices has been based 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. From market flexibility indications it has been estimated that the world price would then increase by between 6 and 16%. As a middle course, the FAPRI price has been incremented 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. The WTW 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.

Table 3.1 **Cost of biomass resources** (delivered to processing plant)

	Moisture content	LHV	Low oil price (oil at 25 €/bbl)		Own	High oil price		
						OCF	(oil at 50 €/bbl)	
		GJ/t	€ /t	€ /GJ	variability		€ /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	

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 industry can be expected 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, the price which would make it competitive with wheat grain for ethanol production has been calculated. 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 (sec. 3.7).

The cost of straw has been 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.

The "cost to EU" of farmed wood has been calculated by stripping out the subsidies from the commercial price. Forest residuals price has been 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.

Availability and costs are strongly independent and have been combined in a more detailed discussion, reported in section 3.7.

3.2 Common issues

3.2.1 Nitrous oxide emissions

The biofuels pathways on traditional "food" crops, typically include intensive farming which is responsible for a large portion of the GHG emissions essentially from two sources: nitrogen fertilizer production and emissions of nitrous oxide (N_2O) from the field. Because of the very powerful greenhouse effect of this gas (300 times that of CO_2), even relatively small emissions can have a significant impact on the overall GHG balance. N_2O emissions from different fields vary a by more than two orders of magnitude, depending on a complex combination of soil type, climate, tillage, fertilizer rates and crop (in approximate descending order of importance). Therefore it is worthwhile putting a large effort into improving the accuracy of the soils-emissions estimates.

Other biofuels studies have adopted two approaches to estimating nitrous oxide emissions from soils but 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. One is to extrapolate from measurements on individual fields; the other is to use the IPCC guidelines. The revised 1996 IPCC guidelines [*IPCC 1996/2*] only give the possibility to consider nitrogen fertilizer and manure use, and whether or not the crop is nitrogen-fixing. To account for other variables, IPCC specifies a wide error range: the max/min ratio varies from 9 (for direct emissions) to 60 (for indirect emissions from leached nitrogen). But even this range is by far not sufficient to cover the range of values which have been measured on individual fields. (For example, emissions ten times the *maximum* value from IPCC guidelines have been measured for fields with wet, peaty, soil).

For the WTW study 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 have been exploited. Emissions for the whole of the EU have been calculated by combining GIS information on soil, daily climate and crop distribution with national data on fertilizer use and farm calendar. The emissions have then been calculated day-by-day from the soils chemistry model and the data has been segregated for different crops, to give EU-average N_2O emissions for each crop.

A recent version of a well-validated soils chemistry model, DNDC (version 82N) [*UNH 2003*], is used to calculate daily nitrous oxide emissions from fields, as well as the amount of nitrogen leached off into the groundwater. The model has been applied to points from the LUCAS land-cover survey [*Eurostat 2003*], which reports land use for clusters of ten measurement points on an 18-km grid covering EU-15, in the year 2000. The other main inputs have been:

- The soil properties for each measurement point: from the soils database maintained by the European Soils Bureau at JRC-EIS, which attempts 1 km resolution by a disaggregating process based on GIS land-cover data.
- Daily weather for the year 2000, obtained from the 50 km meteo-grid of the MARS project at JRC-IHCP institute.
- Manure rates, per country and crop, derived from the CAPRI model at the University of Bonn.
- Fertilizer rates: the crop and soils characteristics at each grid point have been used to derive the recommended nitrogen fertilizer rate, according to [*DEFRA 2000*]. Then a separate correction factor has been applied to the nitrogen rates for each country and

crop, in order to make the averages coincide with the actual usage published by the International Fertilizer Association [*IFA 2002*].

The indirect nitrous oxide emissions has been calculated from the amount of nitrogen leached from the field, using the default IPCC N_2O-emission-factors for indirect emissions. The error range of these factors is the largest uncertainty in the WTW estimate, even though the indirect emissions are smaller than the direct ones, while the IPCC procedure assumes that emissions are proportional to the nitrogen fertilizer rate. Interestingly, the WTW results indicate that soil type, climate, and ground cover are more important than the fertilizer rate.

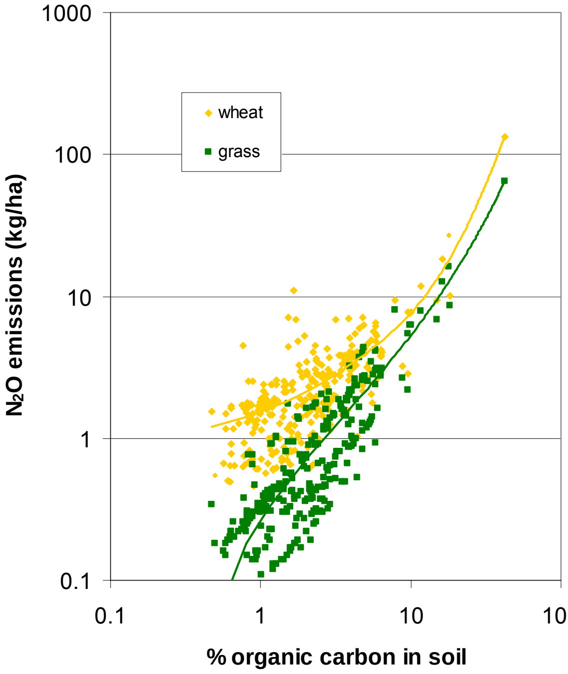
Per-hectare nitrous oxide emissions were averaged for all points sharing a common crop, and divided by the average year-2000 yields from EUROSTAT. In this way emissions for fields where the crop is actually grown have been averaged.

Figure 3.1 shows, for points from the LUCAS survey, the calculated N_2O emissions per hectare when growing wheat or unfertilized grass. The difference between the two represents the incremental N_2O emissions from growing wheat on set-aside. The same calculation was carried out for the other crops: in each case the emissions from fields actually growing the crops were compared to what the emissions *would* have been if they grew grass (unfertilized except for a small amount of manure: see below).

The most sensitive parameter influencing agricultural N_2O emissions is the soil organic content (usually described by the soil organic carbon (SOC) concentration), as indicated in Figure 3.1. Much of the emissions, especially from high-organic fields, would occur even if the field was not ploughed, and this effect is taken into account through the "grass" reference case. However, the *extra* N_2O emissions from arable farming also increase with SOC, and very rapidly when the SOC is over 10% (the scale is logarithmic). In fact this effect is so strong that the results from a few fields with over 10% SOC significantly affect the whole average.

These unlikely combinations of soil type and crop arise because of a difference in the nature of the soils-database and the LUCAS database. The soils database assesses the *typical* soil for the grid-square centred on a grid point, whereas the LUCAS dataset gives the “spot” ground cover observed on the ground at each measurement-point[3]. Therefore it sometimes happens that an arable field at a LUCAS measurement point falls in a square of the soils database which is predominantly peat-bog, for example. The soils properties for the peat-bog would then falsely be associated with an arable field.

Figure 3.1 Nitrous oxide emissions from 3459 EU fields growing either wheat or grass - Year 2000



In reality arable crops would not be grown on such high-organic soils likely to be too waterlogged and acid. Before averaging the N_2O emissions calculated for a particular crop, therefore the points which showed an unlikely combination of soil and crop have been eliminated: arable crops would not be grown on soils with more than 10% organic-carbon (in the top 30 cm).

To obtain the emissions-per-tonne-of-crop, the average per-ha emissions for each crop (calculated for the year 2000) has been divided by the average EU-15 yields for the same year (from EUROSTAT). The year 2000 has been chosen for the emission calculations because yields in 2000 were typical for recent years.

The results are shown in the Table 3.2 for the main crops considered in the WTW study.

Rapeseed has the highest emissions because it is grown in the Northern half of Europe, where soils generally have a higher organic content. Conversely, sunflower, grown in the South, has the lowest emissions per ha, but also a low yield. The high yield of sugar beet brings its emissions-per-GJ-crop below that of the others.

Most of the uncertainty comes from the

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[3] The soils database starts with a list of principal soil types in each region (“soil polygon”), and then assigns one of these soil types to each grid point according to the *typical* land cover around that point (using pseudo-transfer rules). The typical land cover is taken as the most common land cover reported for the surrounding 100m “pixels” of the CORINE land-use database, based on satellite data.

estimate of indirect emissions from leached nitrogen (because the full IPCC range of emission factors had to be used). Uncertainty is lower for sugar beet because this crop cannot be grown in waterlogged soil, where run-off is worst and indirect emissions highest.

Table 3.2 Average nitrous oxide (N_2O) emissions from biofuels crops grown in the EU

EU-15 average emissions (kg/ha)	*Wheat*		*Sugar Beet*	*Rapeseed*	*Sunflower*
N_2O soil emissions	1.65		2.52	2.70	1.01
N_2O from leached N	0.58		0.27	0.42	0.10
Total N_2O	**2.23**		**2.79**	**3.12**	**1.11**
range+/-	**1.49**		**0.88**	**1.23**	**0.33**
	Soft wheat	*Feed-wheat*			
EU-15 av. yield in 2000 (moist t/ha)	**7.07**	**8.02**	**61.2**	**3.03**	**1.78**
g N_2O/t moist crop					
N_2O soil emissions		0.206	0.041	0.892	0.568
N_2O from leached N		0.072	0.004	0.138	0.056
TOTAL N_2O		0.278	0.046	1.030	0.625
range+/-		0.185	0.014	0.407	0.186

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

3.2.2 Carbon release from changes in land-use

❒ Use of grassland

The largest potential for expanding EU agricultural production for biofuels would be to increase the arable area at the expense of grazing land. However, there are very serious greenhouse-gas consequences to ploughing up grassland. The change in land-use results in a reduction in the organic carbon stored in the soil. Although this only happens once, the effect is very large and long-lasting. The soil reaches a new (lower) carbon content at a decaying-exponential rate, characterized by about a 20-year time-constant and an annual CO_2 emission (representative of EU-15) of the order of 3.7 t/ha, although the uncertainty range is more than 50% ([*Vleeshouwers 2002*], quoted by [*DG-ENV 2003*]). That makes a total of roughly 73 t/ha CO_2 (±>50%) emitted due to the change in land use. This figure is also congruent with the difference between grassland and arable soil-carbon stocks according to the default IPCC figures for temperate climates [*IPCC 1996/2*].

Note: *Table 5.10 of [IPCC 1996/2] indicates a soil C stock of 50 t/ha for grassland and improved pasture in cold temperate climate. The table 5.11 indicates the same figure for "native vegetation" in cold temperate conditions on "active" soils (the most likely soil type to be converted to arable cropping), rising to 110 t/ha for moist warm temperate climate. So 50 t carbon/ha (in top 30cm) are taken as a conservative figure for carbon stocks in EU grassland/pasture/native ground cover.*
IPCC recommends calculating the change in carbon stocks by the change in the "base factor" for different types of land use. For improved pasture (and therefore also grassland) the base factor is 1.1 (table 5.12). For continuous arable crops the base factor is 0.7. The difference, 0.4, represents the fraction of the nominal C lost due to the land use change from grassland to arable. Thus the expected carbon loss is 0.4x50 = 20 tonnes of C per hectare. This loss is equivalent to 20x44/12 = ***73 tonnes of CO2 emitted per hectare.***

Every year biofuels produced on the land give a GHG saving, gradually compensating the emissions due to the change in land-use. Table 3.3 gives a very rough estimate of the GHG payback time, using GHG balances for the basic pathways for various crops from the WTW study. These should only be taken as an order-of-magnitude guide, because no account is taken of the variation in soil carbon levels in different areas (for example, soil carbon is generally lower in the South, where sunflower is grown than in climates suitable for rapeseed). There is also a huge uncertainty in the soil carbon data.

Note: *For simplicity, EU average yields for arable crops (incremented by 13.5% for feed-quality wheat) have been taken: this is higher than the yield one would expect on the sort of land converted from grassland, so the WTW break-even times are probably too short. To allow comparison between crops, the yield of* *farmed wood which one could expect on average wheat fields has been estimated from the WTW yield ratios.*

Table 3.3 Rough estimate of GHG payback time for biofuels crops on grassland

Crop	FeedWheat	Sugar Beet	Rapeseed	Sunflower	Farmed wood
Example pathway	WTET1	SBET1	ROFA1	SOFA1	WFSD1
EU av. yield (t/ha)	8.0	61.2	3.0	1.8	11.1
Biofuel (GJ/ha/a)	73	124	42	27	76
GHG saved per GJ biofuel (kg CO_{2eq}/GJ)	9	36	36	58	64
GHG saved (kg CO_{2eq}/ha/a	660	4429	1505	1545	4806
Total C stock change (t CO_2/ha) +/-50%	-73	-73	-73	-73	0 to -73
Years for GHG to breakeven +/-50%	111	17	49	47	0 to 15

Planting biofuels crops on grazing land would probably not pay off in GHG terms for decades.

Reviews of carbon sequestration (e.g. [*Vleeshouwers 2002*]) generally assume soil carbon levels for Short Rotation Forestry (SRF) to be equivalent to forest and grassland. Until now, no-one has measured what happens to soil carbon stocks when SRF is planted on former grazing or forest. A newly published study on a 40-year-old poplar plantation [*Ferré 2005*] shows that total soil carbon had declined 25% compared to the original natural forest: a loss equivalent to 42 tonnes/ha of CO_2. It is well known that soil disturbance releases soil carbon, and the ground is usually ploughed before SRF is planted (although one could develop techniques to avoid this). Thus one expects some reduction in soil carbon, but less than from converting grassland to arable. That is why in the table a range for the soil carbon change for grazing-land to SRF has been given between zero and that for changing to arable.

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

❐ Carbon release resulting from reduced cereal exports

Making biofuels from cereals which would otherwise be exported by EU would cause an expansion in cereals production outside Europe, compared to the reference scenario where more biofuels are not made. This would tend to increase pressure to bring grazing or forest land into cultivation, probably leading to GHG emissions from soil carbon and deforestation. However the effect is difficult to quantify. Like every other LCA or WTW study, it has not been taken into account.

3.2.3 Reference crop

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.

An updated version of the DG-AGRI's "*Prospects for agricultural markets and income in the EU*" which projects more set-aside (see box pag. 75 for set-aside definition) and less cereals exports has been used as baseline agricultural scenario. Therefore the most common scenario for growing extra biofuels crops consists in growing on set-aside land. The alternative use of the land under set-aside is thus taken as reference crop.

Apart from the area already used for energy crops, set-aside is either left fallow, or sown with a green cover crop (there were no statistics on the most common uses). To estimate nitrous oxide emissions the DNDS soil chemistry model has been used which offers a restricted set of options: another arable crop, fallow or grass.

Fallow is perhaps the most common land-use for set-aside, but unfortunately in the DNDS soils model selecting "fallow" as a crop suppresses all vegetative growth. In practice even a fallow field would not stay uncovered for long, especially on land good enough for arable crops. Even weeds are partially effective as a cover crop, reducing the loss of nitrogen from the soil by incorporating it until ploughed under for planting the next crop, so the assumption of *no* vegetation is worse than assuming that grass or another crop is present, even for "fallow" land.

Secondly, there is a question of manure use in the reference scenario. The amount of manure used in EU depends on how much is available rather than on which crop is grown. So the manure used in the "biofuels crop" scenario does not disappear if the field is in set-aside instead: even if used on another field, it would cause some N_2O emissions. Therefore, it is better to assume that the same amount of manure is used on the set-aside field, than to assume none is used. It is quite conceivable that manure would be applied on a field of unfertilized grass (for example, directly by grazing animals), but no-one would put manure on a fallow field. Furthermore, the absence of plant cover on a fallow field would change the amount of N_2O released by manure decomposition.

Grass seems therefore to be the best choice of reference crop. Since grass has to represent all types of set-aside use including fallow, farming inputs have not been attributed to the maintenance of the field in set-aside.

For biofuels crops grown on voluntary set-aside land, [*Kaltschmitt 1997*] considered as reference crop a field under set-aside planted with unfertilized rye grass. This was effectively the same as no reference crop because the N_2O emissions were assumed proportional to the extra nitrogen applied. [*LBST 2002*] considered both this scenario and one in which clover (a nitrogen-fixing plant) was sown on the reference field. In this case, there was a reduction of between 1 and 2.5% in farming energy inputs (due to a small saving on nitrogen fertilizer for the next crop). This is well within the range of overall uncertainties in the farming emissions, and can be neglected. LBST calculated a negligible effect of the choice reference crop on soil emissions because the saving on N_2O emissions caused by the fertilizer was compensated by soils emissions from the clover.

The WTW study does not assume N_2O emissions tobe proportional to the nitrogen fertilizer rate, and emissions have been found significant also from unfertilized land. Therefore the emissions must be subctracted in the reference scenario.

3.2.4 Yields and farming inputs

There are huge variations in yield for different land areas. For example the EU-15 national averages for soft wheat yields vary by a factor 6. The spread between individual farms would be even greater. The situation is similar for other crops, including wood. Therefore *extreme caution must be used in using “average” or “typical” yields:* they must correspond to the land being considered. In particular, EU land which is not already being used for arable farming is likely to give lower than average yields.

Different yields are needed for different purposes. The WTW availability calculations have been based on the 2012 yields for EU-25 projected by DG-AGRI [*DG-AGRI 2005*]. However, the wheat yield has been increased per hectare because the low-protein feed wheat suitable for making ethanol has a higher yield than the EU-mix of 43% bread-making and 57% feed-wheat. With the introduction of new varieties of feed-wheat with higher yields and lower protein content, experts expect the spread between bread-making and feed-wheat yield to increase to 30%. Thus the wheat-for-ethanol yield has been increased by 13.5%.

For calculating energy balance, GHG balance and cost, the yields which corresponded to the data had on farming inputs have been needed. For all crops except wheat, data from [*FfE 1998*] have been taken which estimates all significant farming inputs (for fertilizers only EU- average data is available). The FfE study indicates higher Nitrogen rates than EU-25 average, but also higher yields. These effects cancel each other out, so the values of kg N/MJ crop are almost identical to the production-weighted averages for EU-25.

The potassium and phosphorous fertilizer rates vary greatly according to geography, but do not correlate with yield. However, they are only of minor importance in the calculation. The FfE diesel use per tonne of crop has also been taken as typical. This may lead to a slight underestimate because with a high yield one would expect fewer tractor-km per tonne of crop: on the other hand German farming may be more mechanized than average.

[*DG AGRI 2005*] expect EU yields to continue their slower rate of increase of recent years, (averaging 0.89% per year for EU-25 cereals between now and 2012. These increases are generally achieved by breeding and technical improvements which allow the crops to make use of more nitrogen. But this extra nitrogen must be provided (as fertilizer) to achieve the higher yield. Therefore the amount of nitrogen fertilizer applied per tonne of crop will not change much, and the WTW values from [*FfE 1998*] have been considered to remain valid. The average soil emissions per MJ crop will also be little affected by yield increases, because, *for a given field*, N_2O emissions due to farming are very roughly proportional to nitrogen fertilizer rate.

An exception to the constant-farming-input-per-tonne rule must be made the new low-protein feed wheat varieties referred to above. They increase yields by decreasing the content of (nitrogen-rich) protein, *without* an increase in nitrogen fertilizer. Therefore, in this update, the previous per-hectare wheat-farming inputs have been kept in spite of the yield increase, thereby reducing the specific inputs (per tonne of crop). The corresponding yield has been increased by 13.5% to 7.9 dry t/ha (9 t/ha at 15% moisture). The reference farming inputs and yields have been based on UK average figures [*ETSU 1996*] because [*FfE 1998*] does not include wheat farming. The farming inputs data have been peer-reviewed by experts from the food industry and elsewhere for the UK Low Carbon Vehicle Partnership Report [*LowCVP 2004*].

Where straw is collected, fertilizers should be added to compensate for the lost minerals; figures from [*Kaltschmitt 2001*] have been used. However, the effect of this on the calculations for straw pathways is hardly significant. It has not been assumed that more nitrogen must be added to compensate for the nitrogen removed in the straw, because the decomposition of the straw consumes nitrogen from the soil. One could indeed argue for a nitrogen *credit* for straw removal. However, in Southern Europe, where decomposition is fastest, the straw is often removed from the soil (even if it is just piled at the field perimeter) just to prevent this effect.

No correction (in the other direction) has been made for any long-term reduction in yields due to reducing the organic content of the soil (degradation of soil texture) by repeated straw removal. This would be the result of the soils losing some capacity for water retention, which would be important in times of water-stress. However, the effects depend extremely on local soil conditions, weather and hydrology: farmers will not sell their straw if it could be damaging to their soil.

The diesel used for baling and collecting straw has been taken from [*GEMIS 4.2*]

The WTW agricultural inputs per MJ are generally slightly lower than those in [*ADEME 2002*] although their reported diesel fuel use for rapeseed is, strangely, much higher than for wheat. The main reason that ADEME ends up with different results for energy balance is that they arbitrarily allocate energy inputs and emissions to by-products on a mass basis rather than calculating credits for the materials the by-products replace (see *section 1.1.1.4* on by-product methodology). The WTW inputs are also broadly in line with those of other studies.

3.2.5 Agro-chemicals production

The energy and GHG input associated with agro-chemicals (mainly fertilizers) is sizable and represents a small but significant share of the total pathway energy.

The WTW figures for agro-chemicals production are derived from [*Kaltschmitt 1997*]. They are not much different from those in other studies, such as [*ADEME 2002*]. Fertilizer transport is included, but is negligible.

3.2.6 Other environmental effects of biofuels

❒ Soil quality/erosion

Sugar beet can cause soil erosion, especially if grown on the light soils typical of southern Europe. New techniques of inter-sowing between cover crops can help. However, it is not expected that sugar beet production would spread beyond areas of northern Europe with heavier soils. In wet areas, the heavy machinery used for harvesting sugar beet can cause soil compaction.

It is important to underline that increase of arable area would cause loss of soil organic carbon from grassland or forest: in the WTW study, it is assumed 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 plant.

❒ 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 biofuel crops instead of permanent crops, and on “nature” land now in voluntary set-aside, would decrease biodiversity. [*EEA 2004*] 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 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.

❒ Conclusions

Few of these environmental impacts are inevitable. However, most of them 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.

3.3 Biomass transportation

Even if 'transportation' is not the first of the pathway-steps from the resource to the final fuel, it has been introduced at this point, being a common aspect for all biomass.

The energy and GHG emissions for biomass transportation to the processing plants are a very minor part of all pathways. However, the cost is very significant especially for materials such as forest residuals and straw (see sec. 3.7). For describing the emissions and cost-per-tonne, data for Germany estimated by LBST have been used. Independent estimates of transport distances have been made (see Appendix *D, section 1-9*). For farmed crops an average distance of 50 km is considered sufficient to feed a 200 MW plant (such a plant would e.g. consume some 350 kt/a of wood requiring 35,000 ha or about 4% of the area comprised within a 50 km circle). This distance would be reduced to 10 km for a 10 MW plant. Wood residuals are more scattered and would require sea transport over longer distances (400 km, typical of the Baltic Sea) when fed to a large plant. Transport distance for straw is only 25 km for 200 MW because processing plants would only be economic where there is a concentrated resource.

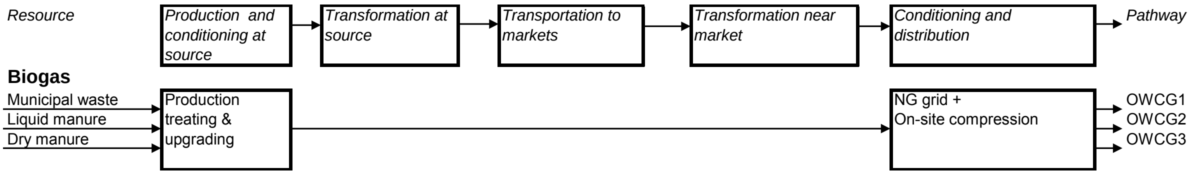
3.4 Biogas

3.4.1 Waste organic material pathways

In the WTW study, biogas is obtained from a waste organic material. Three possible feedstocks have been considered in the following pathways:

- Organic municipal waste (sec. 3.4.1.1)
- Liquid manure (sec. 3.4.1.2)
- Dry manure (mixed with straw) (sec. 3.4.1.3)

Figure 3.2 CBG pathways



In all cases the upgraded gas has been supposed to join 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 (not included, see also sec. 3.7.10.1).

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 anaerobic fermentation of organic matter produces a gaseous mixture, known as "biogas", consisting mainly of methane and CO_2 (typically 60/40 % v/v although the actual composition varies significantly depending on the type of organic matter). Biogas also contains small amounts of other substances, such as H_2 (0-1%), N_2 (0-7%), H_2S (0-1%) and traces of NH_3 as well as water vapour (in case of landfill gas also small amounts of halogenated compounds can occur).

The process consists of a hydrolysis step, formation of organic acids and of methane. In case of glucose (a saccharide) the methane formation reaction is:

$$C_6H_{12}O_6 \Rightarrow 3\ CH_4 + 3\ CO_2$$

A **suitable feedstock** is biomass which contains components such as carbohydrates (i.e. saccharides such as glucose), fatty acids and proteins. Cellulose and hemicellulose are converted to saccharides via hydrolysis. Lignin cannot be decomposed via anaerobic fermentation but only via aerobic processes which do not generate methane.

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 as liquid manure. It is particularly suitable for wet feedstocks, since drying is not required.

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.

The WTW study has been primarily focused on pathways representing biogas use as a motor fuel, which include supply of the feedstock, biogas production, biogas treatment and upgrading, biogas distribution and finally compression to 25 MPa to refuel a vehicle.

Although most biogas production installations have so far been at relatively small scale and geared to production of heat and power (in a dedicated gas engine), 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, CBG) or to connect with the local natural gas grid. This requires **cleaning and upgrading** of the gas to remove various impurities, particularly H_2S, and upgraded to a higher heating value or Wobbe index by removing the bulk of the CO_2. Certain feedstocks (e.g. sewage) need to be "hygienised" by heat treatment prior to biogas production to avoid propagation of harmful bacteria or by operating the fermenter at 50 to 55°C (suitable for thermophilic bacteria). Some such plants already exist in Scandinavia, driven both by environmental concerns and, in the case of municipal waste, increasing disposal constraints.

3.4.1.1 Municipal waste to automotive biogas pathway (OWCG1)

❒ Feedstock supply

Municipal waste needs to be collected to a central point in any case so no energy/GHG debit applies to this stage.

❒ Raw biogas production

The feedstock is processed in a "digester" in a batch process that can take several days. The gas produced is collected and sent to the treating section. The required heat and electricity are produced within the plant by a dedicated gas engine running on the raw biogas itself. The conversion level of the organic matter is typically 70%. The unconverted material is a good quality fertiliser for which a credit needs to be calculated (based on the traditional fertiliser substituted). In fact, the nitrogen in digested fertilizer is more quickly available to plants than that in manure, so that its use is more like that of synthetic nitrogen fertilizer. By applying digested fertilizer at the start of the growing season, a greater proportion of the nitrogen can be taken up than is the case with manure. Accordingly, a credit to the biogas pathways corresponding to the equivalent quantity of synthetic nitrogen fertilizer has been given.

❒ Biogas treatment and upgrading

H_2S can be removed by several methods. A common method consists in adding small amounts of air into the fermenter (3 to 5% of the total amount of biogas). Bacteria (sulfobakter oxydans) convert the H_2S into solid sulphur which is collected on the surface of the fermented substrate (biological desulphurization). Reaction with metal oxides or adsorption on active carbon can also be used. Reaction with metal oxides generally is carried out downstream the biological desulphurization to achieve very low sulphur contents (<1 ppm).

In small to medium scale plants, CO_2 removal is normally carried out with a pressurised water wash for which the gas needs to be compressed to typically 1 MPa. The electricity required for compressing the gas and pumping the water is also supplied by the "in-house" power plant. Typical water consumption is 10-20 m^3 per 100 Nm^3 of gas. Waste water from the municipal treatment plant can be used for this purpose. If water availability is a problem it can be recycled after desorption at reduced pressure. In the process some methane emissions are inevitable (0.2 g CH_4/MJ treated biogas).

❒ Heat and power plant

The concomitant requirement of power and low temperature heat is a favourable situation leading to a high efficiency of the gas engine (nearly 90%). It has been assumed that the operation of the gas engine is adjusted to produce the heat requirement of the plant, leading to a surplus of electricity. Exported to the grid, this surplus commands a credit for substitution based on the EU-mix. Minor CH_4 losses are also taken into account.

❒ Distribution and compression

The treated biogas is available at around 0.9 MPa at the plant outlet which is considered adequate for joining the grid without any further energy requirement. Compression energy is as assumed for natural gas i.e. 0.4 MPa suction and 25 MPa discharge.

3.4.1.2 Liquid manure to automotive biogas pathway (OWCG2)

This pathway is similar to the previous one with a few notable differences:

- Under the assumption of a medium size biogas plant, the manure has to be collected from individual farms and transported to the plant (a distance of 10 km has been assumed).
- The biogas production step requires different amounts of heat and electricity due to the different nature of the feedstock.
- The residue left after biogas production still contains all the minerals and nitrogen of the original material and can be used as fertiliser. The credit for this is slightly different from the one considered in OWCG1.
- The largest difference though is due to the large GHG credit related to the avoidance of methane emissions from the manure when used in the traditional way. This is estimated to typically amount to some 15% of the biogas produced.

3.4.1.3 Dry manure + straw to automotive biogas pathway (OWCG3)

Again in this case the general setup is the same with a minor change in the transport energy due to the different nature of the feed. The main difference with OWCG2, however, is the much smaller credit for avoided methane emissions. Indeed with dry manure, these are only estimated to be about 1/10th of those with wet manure.

Liquid manure is mainly produced by intensive pig farms, while dry manure results from more environmentally-aware farming practices. It can therefore be argued that the large credit registered for liquid manure is mostly a compensating mechanism for inappropriate farming practices.

3.4.2 Final fuels: Energy and GHG balance

Figure 3.3 shows a relatively high total **WTT energy**, mostly related to the limited conversion rate of the biomass used (assumed 70%). However, it is the only practical way of using such wastes for energy purposes. The fossil energy share of this is very small indeed ranging from 0.17 MJ_{xf}/MJ_f for municipal waste to 0.01 for dry manure.

Note: the higher fossil energy for municipal waste results from the WTW authors decision to limit the on-site energy generation to the process heat requirement, which in this case demands some electricity import (compared to export in the manure cases.

The GHG emissions balance is very favourable (WTT GHG, Figure 3.4), the more so in the case of liquid manure because large emissions of methane from the raw manure are avoided in the process (the credit has been given at the collection stage). Collecting liquid manure and using it for biogas production in itself prevents some GHG emissions to the atmosphere. Note that this is essentially the result of bad farming practices which should be avoided in any case.

All in all, using organic waste to produce biogas is a good option from an energy and GHG viewpoint. Whether and under which circumstances it can make practical and economic sense to produce biogas and use it as automotive fuel is another matter that is discussed in sec. 3.7 together with the related issue of potential.

Figure 3.3 WTT total energy balance

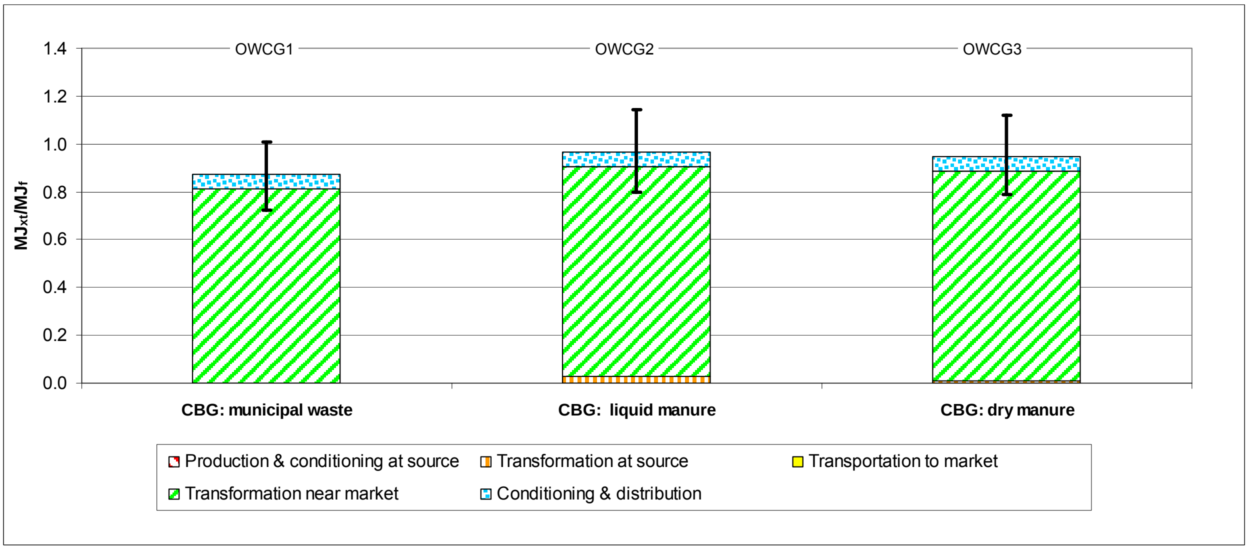


Figure 3.4 WTT GHG balance

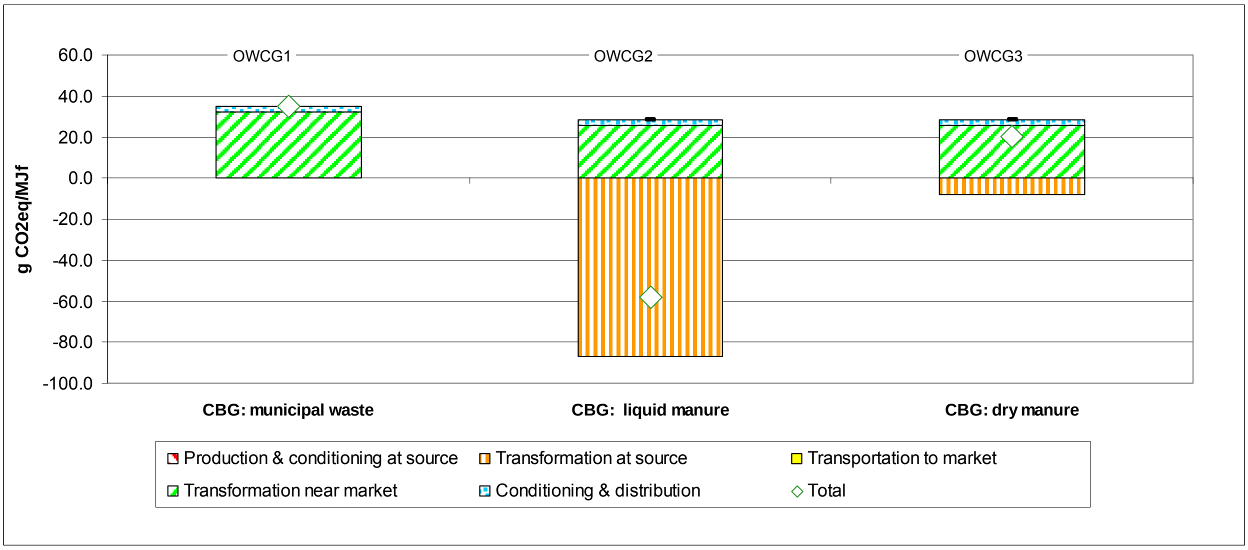


Table 3.4 (**TTW costs**) contains a lot of information and maybe difficult to interpret correctly. Taking the example of the CBG PISI bi-fuel vehicle in the 50 €/bbl scenario, the data should be understood as follows:

- 353 PJ/a of CBG 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 CO_2 equivalent to be emitted.
- The CBG pathways use more energy than conventional fuels (negative saving of -291 PJ/a for total energy and 376 PJ/a for fossil energy), but produce less CO_2 (saving of

50.4 Mt/a representing 167% of the 30.1 Mt/a that would have been emitted by fossil fuels).

Compared to the conventional fuel pathways, the extra costs are 3.5 G€/a for making CBG available (WTT) and 1.7 G€/a for the specialised vehicles for a total of 5.2 G€/a. This corresponds to a cost of substitution of 655 €/t of conventional fuel substituted (i.e. 655 €/t more than the cost of conventional fuels) or 2.79 €/100 km. In terms of CO_2 avoidance the cost is 104 €/t CO_2 avoided.

Table 3.4 TTW costs and benefits of CBG pathway compared to conventional road fuels at 25 and 50 €/bbl

Fuel	*Powertrain*	Alt. fuel consumed	Fuel substituted		Base case	WTW savings[1,2]				Incremental cost over ref. scenario			Cost of substitution		Cost of CO_2 avoided
			Gasoline	Diesel	GHG	Energy (PJ/a)		GHG		G€/a			€/t fossil fuel	€/100 km	
Oil price @25 €/bbl		PJ/a	PJ/a		Mt CO_{2eq}/a	Total	Fossil	Mt CO_{2eq}/a	% of base	WTT	Vehicles	Total			€/t CO_{2eq}
CBG (mixed sources)	PISI (BF)	353	200	145	30.1	-291	**376**	**50.4**	**167%**	4.9	1.7	6.6	832	3.55	**132**

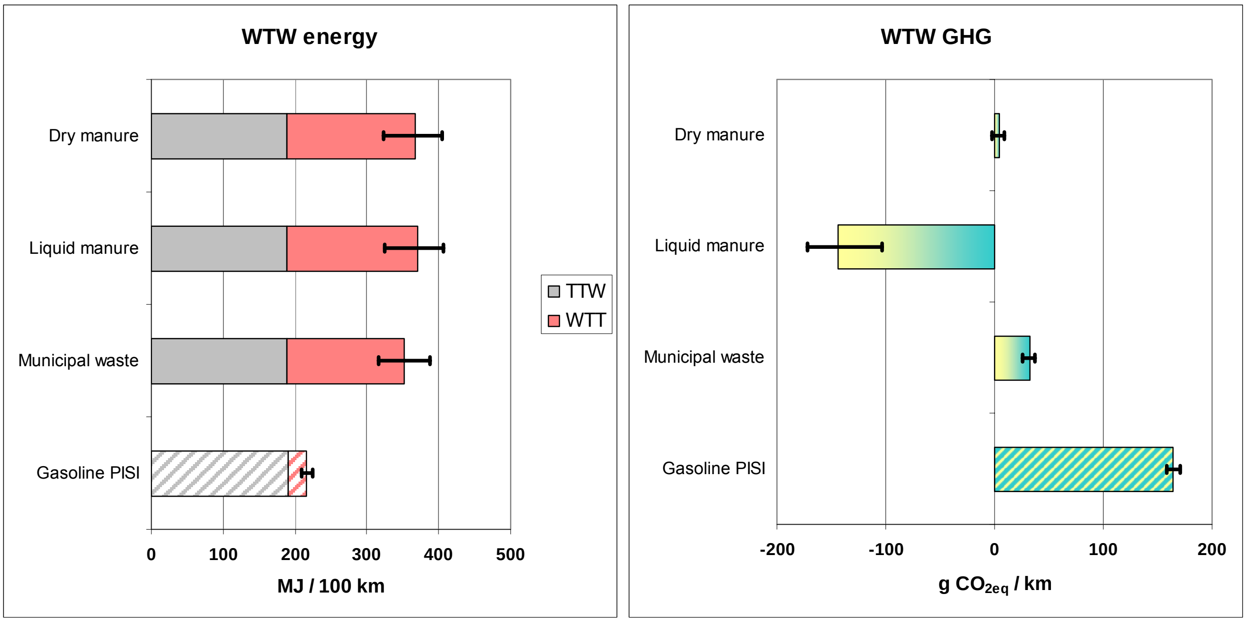
Fuel	*Powertrain*	Alt. fuel consumed	Fuel substituted		Base case	WTW savings[1,2]				Incremental cost over ref. scenario			Cost of substitution		Cost of CO_2 avoided
			Gasoline	Diesel	GHG	Energy (PJ/a)		GHG		G€/a			€/t fossil fuel	€/100 km	
Oil price @50 €/bbl		PJ/a	PJ/a		Mt CO_{2eq}/a	Total	Fossil	Mt CO_{2eq}/a	% of base	WTT	Vehicles	Total			€/t CO_{2eq}
CBG (mixed sources)	PISI (BF)	353	200	145	30.1	-291	**376**	**50.4**	**167%**	3.5	1.7	5.2	655	2.79	**104**

(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

To conclude, 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 a biogas cost of around 16 €/GJ has been estimated. Other costs incurred to turn biogas into a road fuel available at the pump are the same as for CNG.

Figure 3.5 WTW energy requirement and GHG emissions for compressed biogas (as CBG) (2010+ vehicles, CBG vehicles as Bi-fuel PISI)



3.5 Liquid fuels

3.5.1 Introduction

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: ethanol, bio-diesel (both considered as 'conventional biofuels'), synthetic diesel fuel (also DME) and ETBE, as an alternative way of using ethanol. The main advantages over gaseous fuels are the following:

❒ 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 (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 Liquid Petroleum Gas (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. At this stage of the WTW study, such claims have been neither proven in practice nor scientifically explained and have stuck to the constant engine efficiency concept.

❒ Costs

Considering all these aspects, the costs are thus only related to production and transportation to the point of blending with the mainstream fuel:

- 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 the "cost to Europe" have been considered, any imported fuel that could be considered as an international commodity has been 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. A 20% premium has been used 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.

The above price provide a backstop (outside any subsidy) for any material similar to synthetic diesel produced internally from biomass.

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. This potential link have nevertheless been ignored and DME production costs have been reported.

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 (see original WTW report). 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.

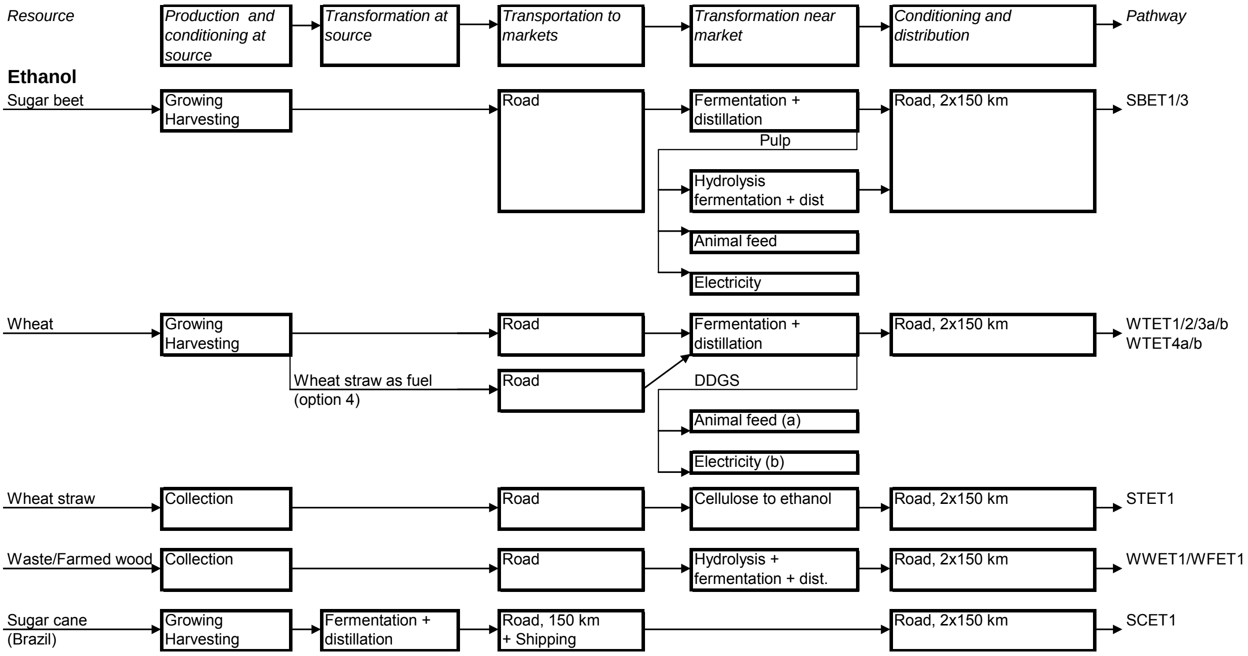
3.5.2 Ethanol

3.5.2.1 Pathways

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.

Ethanol can be produced from a variety of crops; traditionally it is 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.

Figure 3.6 Ethanol pathways



The fermentation process produces alcohol at a fairly low concentration in the water substrate. Purification of the ethanol by distillation is fundamentally energy-intensive (the associated energy constitutes a point of debate; however, there have been significant advances in this respect and data representing state-of-the-art plants have been used).

Amongst the vast number of possible options, only the most common in Europe have been represented i.e. sugar beet and wheat. For each of these crops a number of options are available depending on the use of by-products and the way the energy for the manufacturing process is generated. Also included are two more advanced pathways for the hydrolysis of the cellulose into fermentable sugars, one with wheat straw (Iogen process), the second with wood representing the more general group of cellulose feeds. 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. For comparison purposes ethanol produced in Brazil from sugar cane and imported to Europe has also been included.

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

3.5.2.1.1 Sugar beet

Sugar beet is a high yield crop. It produces carbohydrate already in the form of sugar and is easily crushed and mashed for fermentation which makes the processing into alcohol rather cheap. The economics of its cultivation are highly distorted by the CAP, as discussed in sec. 3.7.

Sugar beet continues to respire in storage causing a material loss. In order to limit the energy loss, the processing “campaigns” average 90 days. But since the syrup extracted from the sliced beets is pasteurised, one supposes that it could be stored to keep the fermentation and distillation parts of the plant running all year. By-products of the conversion process are sugar beet pulp and dried slop (everything insoluble produced by fermentation), which together are the beet equivalent of DDGS from wheat, but with a lower protein content; about the same as wheat grain. Thus a credit as a low-protein animal feed has been done, based on the wheat-growing process and tables of digestible energy content.

Two options for utilising the pulp leftover after filtration of the diluted ethanol liquor have been considered:

- 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. The option of adding the pulp to the biogas digester (for cleaning the waste water) has been instead considered, which gives almost the same energy balance and emissions as burning.To improve the yield of ethanol, the pulp could, in principle, be treated by a SSCF-type process (Simultaneous Saccharification and Co-Fermentation) to break down the cellulose and hemicellulose. No such process actually exists and this route has not been further considered.

3.5.2.1.2 Wheat grain

Ethanol can be produced from wheat grain by hydrolysis and fermentation. The process is more complex and therefore more expensive than with sugar beet. Milling and distilling are the most energetically expensive parts of the wheat-to-ethanol pathway. These processes require some electricity but mostly heat albeit at a low temperature level. This makes the scheme well suited for combined heat and power schemes (CHP). The figures used in the WTW study for the wheat grain to ethanol plants are essentially the same as in a study carried out in 2004 under the UK's Low Carbon Vehicle Partnership [*LowCVP 2004*], where the example of ethanol from wheat grain has been used to illustrate the large impact of the process energy generation scheme on the overall energy and GHG balance.

Four options have been considered, where the energy can be provided by a variety of sources: 3 scenarios have been based on fossil fuels representing plants actually on the ground or planned in Europe. A fourth scenario uses straw as energy source. Although this is in principle feasible there are no concrete examples of this either existing or considered.

There are 4 energy supply options:

❒ Conventional natural gas boiler (WTET1)

In the most basic (and low-capital) scheme, heat is supplied by a conventional natural gas fired boiler and electricity is imported. This can be considered as representative of the vast majority of existing installations and is also by far the cheapest solution.

❒ Combined cycle gas turbine (WTET2)

A natural gas fired gas turbine with a heat recovery steam generator (HRSG) provides both heat and electricity. As more heat than electricity is required supplementary firing is applied in the HRSG. As the heat is required only as low pressure steam, a back pressure turbo-generator is also installed behind the HRSG. The plant is assumed to be sized and operated to produce the heat required for ethanol manufacture. There is, however, a surplus of electricity which is exported into the grid, thereby generating an energy and GHG credit.

This solution is considerably more energy efficient but also significantly more complex and expensive to build and operate.

❒ Lignite boiler CHP (WTET3)

In certain parts of Europe where lignite is cheap and abundantly available (actual plants are either operating or under construction in Eastern Germany), a simpler CHP scheme can be envisaged. High pressure steam is produced in a lignite boiler. A back pressure turbo-generator produces electricity and low pressure steam for the process. Here again the plant is assumed to be sized and operated to produce the heat required for ethanol manufacture but it nevertheless generates an electricity surplus.

❒ Straw boiler CHP (WTET4)

Wheat cultivation produces large amounts of straw. Some LCA studies have considered straw as a by-product but this is not necessarily the case. In most of the EU it should be ploughed back to maintain the water-retention properties of the soil (see straw availability, sec. 3.7.3). Where it may be removed from the field it is partly already used for litter and other applications. Therefore it is misleading to systematically assume that straw can be used to fuel the ethanol production process. In practice this should only be proposed where there is little water stress, a high density of cereals production and a low density of livestock. These conditions would apply to concentrated wheat-producing areas in Northern Europe excluding the Low Countries and Denmark. In any case removing straw will reduce soil nutrients, which needs to be compensated by an additional fertiliser input.

This scheme is similar to the previous case but straw in used instead of lignite. The main advantage of this scheme is to use a renewable source of energy to drive the process (and thus the best option in terms of GHG emissions). It must be realised, however, that handling and burning of solids is considerably more complex and costly than with liquids or gases, particularly in the case of a low energy density material such as straw. This will therefore be the most expensive option.

NOTE: All CHP schemes produce a surplus of electricity which is assumed to be exported to the grid and must therefore generate a credit (energy and GHG). An ethanol plant with a CHP scheme in effect co-produces ethanol and electricity. If a straightforward credit is applied (e.g. based on substitution of EU-mix electricity) and the whole balance expressed relative only to the ethanol produced, ethanol is given a credit resulting from generation of electricity from straw. One would conclude that the higher the electricity generation compared to the ethanol yield, the better the fossil energy balance of ethanol! In the case of a natural gas CHP, this could be taken quite far as there is no physical limit to the size of the power plant that can be built.

The real contribution of ethanol to electricity generation is to provide and opportunity for CHP so that the credit should be based on the same fuel producing electricity only in a stand alone power plant. Although the energy and GHG saved by the bio-electricity itself is not credited to ethanol, the ethanol pathway does benefit from the extra energy efficiency resulting from the use of CHP.

3.5.2.1.3 Wheat straw

Straw has been considered as a feedstock for ethanol production through the Iogen process currently under development and which appears to be closer to commercial application. The conversion process is similar to the wood to ethanol process although the Iogen data suggests higher efficiency than other sources.

In the above section the conversion of wheat grain to ethanol has been described, with optional use of straw as fuel for the process. The possibility also exists to use the straw as ethanol feedstock through an SSCF-type process (Simultaneous Saccharification and Co-Fermentation) that turns cellulose into sugars and can in principle be applied to all cellulosic biomass materials.

On the basis of experience with their pilot plant, Iogen corp. (Ontario, Canada) provided energy and emissions data for a projected 140 MW_{th} plant straw-to-ethanol plant [*Iogen 2003*].

Straw has a more suitable composition for SSCF than wood, and the Iogen plant claims a slightly higher energy efficiency than the projected SSCF wood-to-ethanol plant from NREL.

3.5.2.1.4 Wood

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.

There are no commercial wood-to-ethanol plants operating at present. NREL have made detailed studies of an SSCF process for converting wood and other biomass to ethanol. Their “base case” has been selected as the WTW “worst case”: it is the design for a plant using the state-of the art technology available in 1999. For the WTW “best cast” their “best of industry” plant has been selected, which already anticipates advances which are still at the laboratory stage. Their projections have not been considered further into the future to be appropriate for a 2010 timeframe.

Most of the wood processing schemes quoted in the literature produce some surplus electricity (and therefore consume some additional wood to that effect). This may make good economic sense in practice and, in some cases exploit genuine synergies. If this electricity is deemed to replace fossil electricity or even EU-mix electricity, this can generate a very large credit which considerably distorts the result while it is simply a reflection of the fact that two notionally independent processes are conducted side-by-side.

To arrive at a meaningful comparison and in accordance with the WTW philosophy that the reference scenario should differ from the biofuels scenario only in the production of biofuels, all the wood conversion processes have been made electricity-neutral by adding or subtracting an appropriate proportion of a wood-to-electricity process. For each case a power station has been chosen which closely matched the one in the process: for example, processes making fuels using the BCL gasifier were made electricity-neutral using the efficiency of a wood power station based on BCL. To compare the efficiency of the processes, which now all had about zero emissions, the “primary energy efficiency” has been compared defined as (all primary energy in)/(fuel out). The WTW efficiency values for pure fuel processes do not correspond to the overall process efficiencies quoted in some references such as [*Tijmensen 2002*]: which are for mixed electricity + fuel processes, with the electrical and fuel energies of the products simply added.

All ligno-cellulose to ethanol routes,apart from the Iogen straw conversion process described below, have been represented 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.

Wood waste is often presented as a vast untapped source of energy. Upon closer investigation, it appears that industrial wastes or used wood are already used as much as is possible (some problems with contamination) [*SBH 2000*] and agricultural prunings are mostly uneconomic to collect. The only type of wood waste which could make a significant impact on the energy sector with realistic economics is forest residuals from commercial forestry. The main producer countries already have plans to use more forest residuals for electricity and heat, but one could think to convert them to liquid fuels instead. Their use is essentially linked to pulp-mills.

The most efficient way to make biofuels from forest residuals is to use them inside a pulp mill, to substitute the burning of black liquor for process heat (see sec 3.5.5.1.1.1). This leads to a separate pathway for the “black liquor route”, which is essentially limited to the forest residuals associated with pulp-wood (see specific section below).

Although mature forests continue to sequester carbon by gradually increasing the thickness of their organic soil, harvested forests absorb carbon dioxide much faster when they re-grow, so harvesting them for energy definitely increases their CO_2 uptake. The commercial forests in EU grow more than is harvested each year, so there is potential to increase the sustainable supply of stem-wood in EU, for energy purposes. The pulp, paper and woodworking industry is understandably concerned about subsidized competition for their feedstock, both stem-wood and wood chips. This is not to be ignored, because life cycle analyses almost all agree that wood saves more greenhouse gas when made into durable products than when burnt for energy.

The other potential source of wood for energy is “wood farming” i.e. short rotation forestry (SRF) using fast-growing species to maximise biomass generation. This can be complemented by perennial grasses such as miscanthus and switchgrass. Miscanthus has yields in the same range as SRF without risking the expense of removing tree-roots if the land-use needs to go back to arable. Switchgrass has lower yields but also lower water requirements, an important consideration when agriculture has been considered limited by water availability in a large part of the EU. As a fuel perennial grasses are similar to straw: although the lignin/cellulose ratio and dry-matter energy content are similar to wood, they have a higher salt content (which can cause ash agglomeration and corrosion in the burners) and lower bulk density. This makes them less attractive as a fuel, and perennial grasses command a similar market price to straw. Therefore SRF is usually the more profitable crop.

The drive to plant SRF on arable land in EU is motivated by three considerations: limiting food surpluses, providing renewable energy and sequestering carbon in the soil (see sec. 3.2).

Perennial crops and forests are thought to have a higher potential biomass yield than annual crops because the root system is already established at the start of the season. However, the very high yield expectations of the ‘80s have given way to more realism: in practice commercial SRF plantations give only slightly higher biomass yields than wheat on the same land, less if the straw is also harvested (see also sec. 3.7.2). On soils too poor to support arable crops, SRF is likely to fail altogether, rather than produce the “8-10 tonnes/ha/a” figure often quoted.

On the other hand, wood requires less fertilizer, labour and other inputs, and can therefore be grown more cheaply. SRF is also more eco-friendly and wood is generally a better fuel than straw and perennial grasses, having a lower salt content. Furthermore, perennial crops may keep more carbon in the soil than arable crops, so that one might be able to plant them on grassland without causing unacceptable reduction in soil carbon stock. However, in this case one should be prepared for very much lower yields, as explained above.

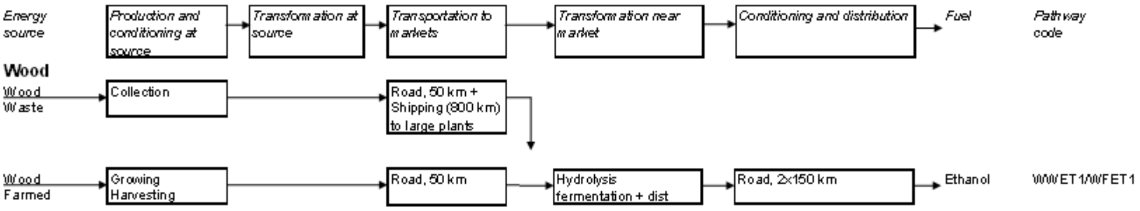
Wheat + straw as a bio-energy crop

Taking straw with the wheat would give a total (moist) biomass yield of at least 1.65 times the grain yield. If in addition the wheat variety is a high-yield low protein variety, the collectable (moist) biomass yield will be at least 1.78 times the average wheat yield. This corresponds to 1.56 dry biomass / conventional wheat yield. So feed-wheat + straw is actually a high-yielding biomass crop, but it requires more inputs (fertilizer, diesel, labour…) than SRF.

SRF wood can be burned directly to supply heat and possibly electricity via steam-raising. However, a more sophisticated route, which is now attracting a lot of attention, is gasification. The process is rather similar to coal gasification, producing syngas, which can be either used to fuel a gas turbine or further processed to a synthetic liquid fuel such as DME or synthetic diesel fuel.

Gasification can be envisioned at either small or large scale. The former would only be suitable for electricity or possibly hydrogen production because of the high cost of investment and plant maintenance for more sophisticated processes.

Figure 3.7 Wood pathway



3.5.2.1.5 *Sugar cane (Brazil)*

Sugar cane is an excellent biomass crop from almost every point of view, except that it will not grow in Europe. It resembles more a permanent biomass crop like miscanthus than it does an arable crop. There are usually 5 harvests, with very high annualized yields of about 68 t/ha/a (moist). Each tonne yields 86 litres (1.83 GJ) anhydrous ethanol at a conservative estimate.

Brazil is the by far the world’s largest producer, and has the greatest potential to expand production. The main growing area is in the South of the country, around Sao Paulo province.

Expansion of sugar cane growth would occur in this and neighbouring regions, at the expense of rough grazing land. This is a very long way from any surviving rainforest. There is a small amount of sugar cane production in the coastal areas of the NE, nearer some patches of Atlantic rainforest, but this is not viable without subsidies, and is unlikely to expand.

Unlike arable crops in Europe, planting sugar cane on grazing land is believed to actually increase the soil carbon stocks. The risk of soil erosion (a major concern in Brazil) is only heightened in the first year of establishment. The plant has low fertilizer and water requirements and has low levels of minerals in the foliage.

A major benefit of the sugar cane to ethanol process is that the process heat is entirely provided by the bagasse; in fact there is even a small surplus of bagasse which can provides fuel for neighbouring food-processing plant (for example, orange juice production), generating a credit for saved fuel oil. The plant is self-sufficient for electricity. The vinasse from the fermentation vats is nowadays recycled to the fields. The emissions calculation takes into account the typical practice of burning the foliage to allow easier harvesting, although this is sometimes banned near populous areas.

Input data have been taken from a very thorough analysis by prof. Macedo et al. [*Macedo 2004*]. The balances include a credit for additional saving of fuel oil from the excess bagasse.

3.5.2.1.6 DDGS as by-product

DDGS is the solid residue after digestion of the carbohydrates of the ethanol production. DDGS is a protein-rich material and is therefore a useful animal feed component. Its nearest equivalent is corn gluten feed, a by-product of maize milling, the supply of which is fixed by the amount of maize. In the EU the balance of animal feed demand is met by soy meal (the *main* product of soybeans) which is, in the end, what DDGS substitutes. The equivalent quantity of soy bean meal is calculated on the basis of the protein content using data from [*NRC 1998*]. The energy and emissions for the soy meal is calculated according to a scenario of soy beans grown in the US, and crushed in EU, following [*UBA 1999*].

One should consider *how much* DDGS could be used as animal feed. Cattle and pigs can take an average of more than 25% corn DDGS in their diets [*Shurson 2005*]. For wheat DDGS, with its higher protein content, this should conservatively be reducec to 20%. EU animal feed consumption is around 300 Mt/a. 60 Mt per year of DDGS corresponds to 350 PJ ethanol, or about 6% of EU-2010 gasoline. But at this level, not all DDGS would directly replace soy meal. EU soy meal consumption is about 25 Mt. That is equivalent to 30 Mt dry DDGS, and an ethanol supply of 160 PJ, or 2.8% of 2010 gasoline consumption. There would be some indirect replacement of soy meal by replacing other imported feeds (such as 4.4 Mt of maize gluten). Then one comes into conflict with rapeseed cake (see sec. 3.7.1).

Animal feed is by far the most lucrative usage and therefore the most likely; but it has been seen that the animal feed market will saturate within EU if the 5.75% target of gasoline replacement is reached. At this point DDGS might be used as fuel, for instance in solid-burning (i.e. coal) power plants that need to meet their renewable energy obligations. The calorific energy content of DDGS is considerably greater than the energy required to produce the equivalent animal feed, so burning DDGS gives a higher energy credit (e.g. through co-firing in a coal-fired power station). These two options have been illustrated in sub-pathways:

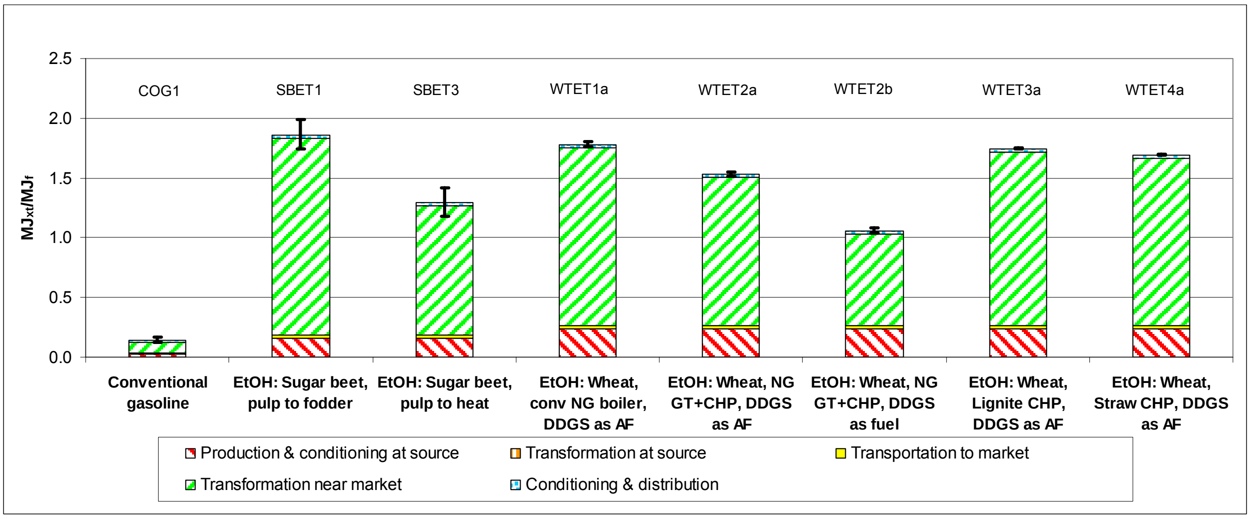
- WTET2/3/4a: DDGS as animal feed
- WTET2/3/4b: DDGS as fuel

3.5.2.2 Energy and GHG balance

Figure 3.8 shows the **WTT total energy** build-up along the different stages of the more conventional pathways to bio-ethanol.

The gasoline balance is also included as reference (gasoline and ethanol are used in the same vehicles delivering the same energy efficiency). In this case "total" energy includes the energy content of the bio-feedstock used (e.g. wheat grain) as well as the energy content of any biomass used as a fuel at any stage of the pathway (this is the energy "expended" i.e. it excludes the energy content of the ethanol produced, which is of course 1 MJ/MJ in all cases).

Figure 3.8 **WTT total energy balance of ethanol pathways (sugar beet and wheat)**



All pathways require several times more energy than is the case for gasoline although there are large differences between the various options. Most of this energy is expended during ethanol manufacturing and to a lesser extent for growing the crop (a large portion of the latter energy stemming from fertilisers).

The energy balance is critically dependent on the specific pathway, particularly with regards to the fate of by-products. As a result of the energy credits generated, the more by-products are used for energy purposes, the better the energy balance (compare e.g. SBET1 to SBET3 and WTET2a to WTET2b).

The way energy for the manufacturing process is produced has also an impact on the energy balance: in WTET2a the use of a CHP scheme reduces the energy requirement by about 15% compared to the more conventional scheme used in WTET1a.

For WTET3/4, although CHP is also used the relatively low efficiency of solids burning compared to gas reduces the energy gain to insignificance.

Figure 3.9 shows the **WTT total energy** balance for more advanced biomass-to-ethanol pathways (WTET2a is repeated for comparison).

Clearly these pathways do not offer much from a total energy point of view. Their interest resides in their potential to save fossil energy and therefore to reduce GHG emissions (see below).

Figure 3.9 **WTT total energy balance of ethanol pathways (various feedstocks)**

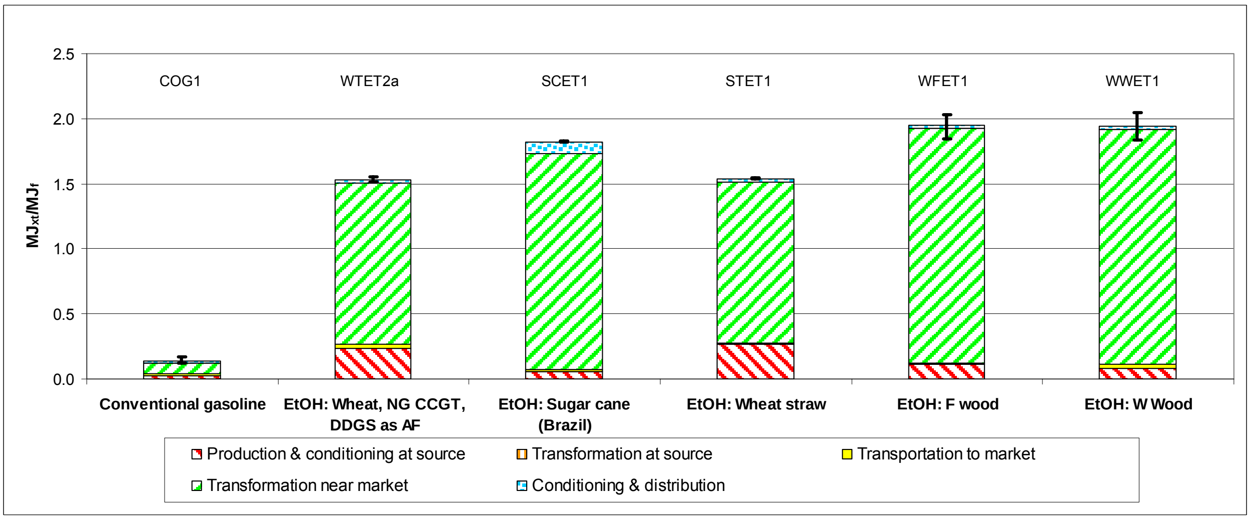
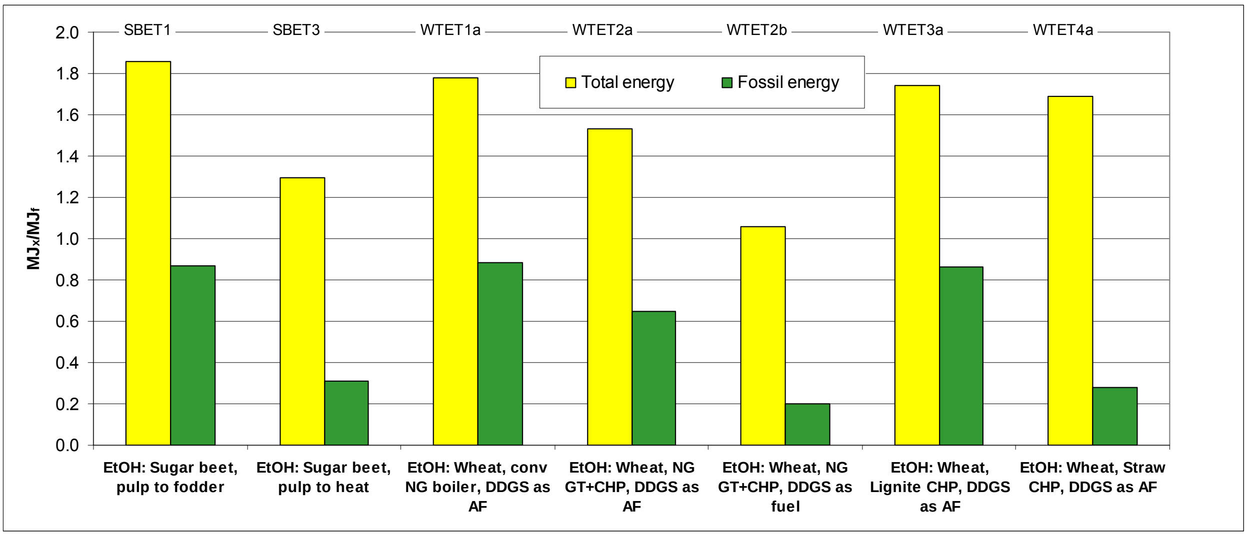


Figure 3.10 and Figure 3.11 compares **WTT total and fossil energy** as a measure of the "renewability" of the pathways.

Figure 3.10 WTT fossil energy balance of ethanol pathways (sugar beet and wheat)



In order to compare the *fossil* energy or GHG balances of renewable and non-renewable pathways one has to take into account the fossil energy and non-renewable carbon content of the fuels produced through the different routes (i.e. for energy, 1 MJ/MJ for fossil fuels and 0 MJ/MJ for renewable fuels). For ethanol, this is in effect the WTW fossil energy (as no additional fossil energy is expended in the vehicle).

The impact of using by-products for energy purposes and/or using bio-energy for fuelling the production process appears very clearly in this case. For the more conventional pathways, this does not, however, generally correspond to either common practice or economic optimum. The advanced pathways use a lot less fossil energy because the processes used allow usage of biomass for the major energy requirements. Using bagasse to fuel the sugar cane ethanol manufacturing plant is a well established practice (a credit for additional fuel oil saving further reduce the net fossil energy used in SCET1). In pathways using wood or straw a significant proportion of the energy used is also of renewable origin. Note that using wheat straw induces a small penalty as additional fertilisers have to be used in order to replace the nutrient contained in the straw.

Figure 3.11 WTT fossil energy balance of ethanol pathways (various feedstocks)

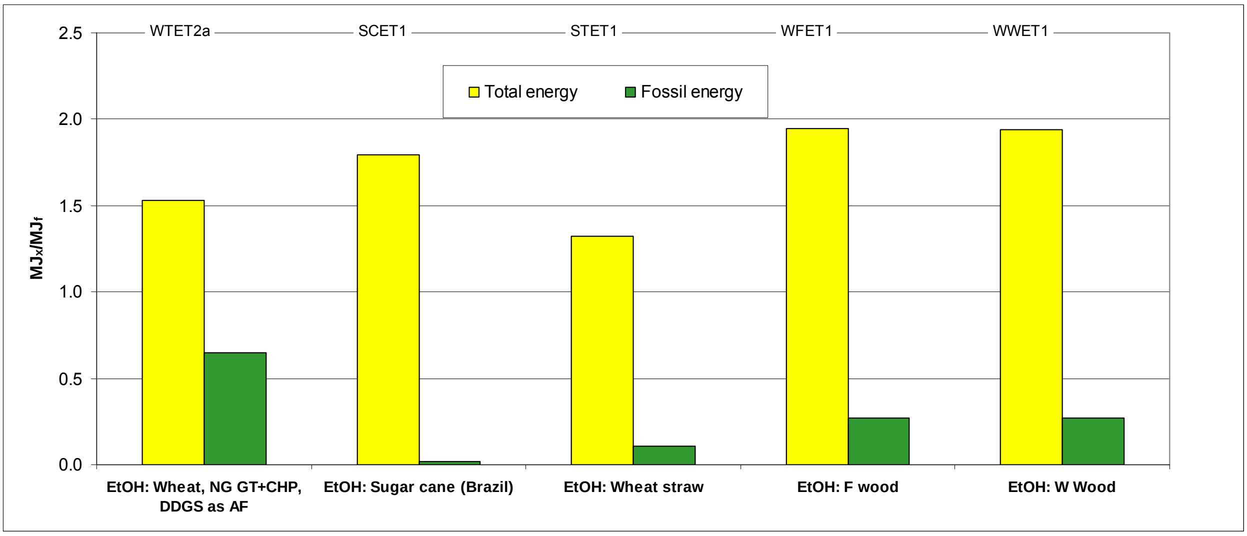
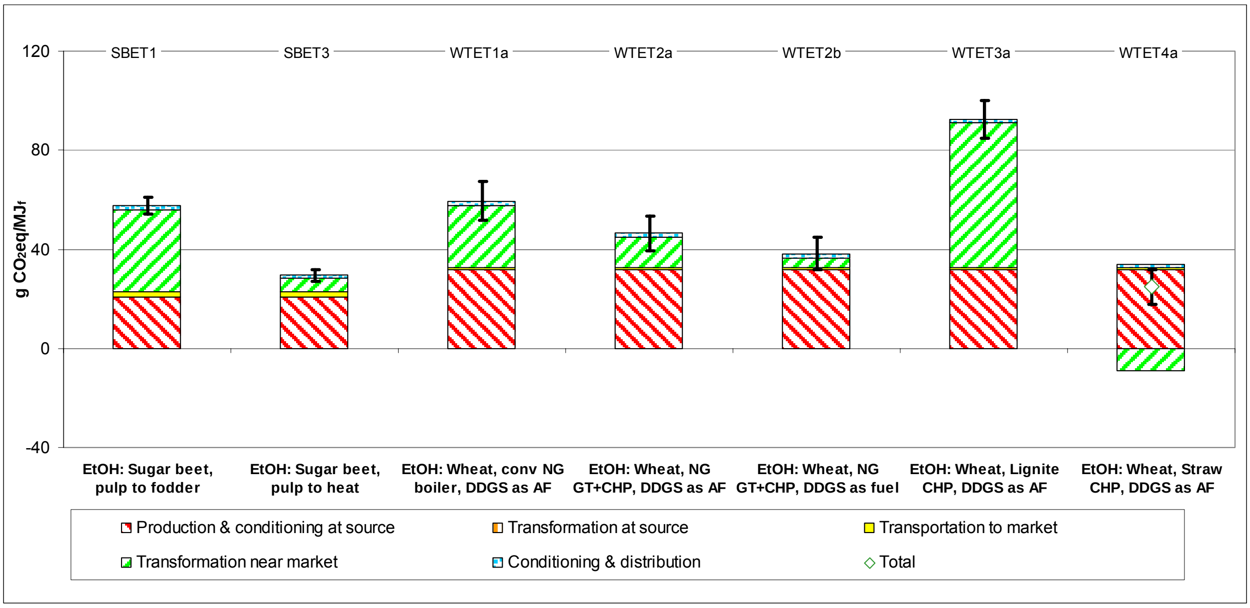


Figure 3.12 and Figure 3.13 show the **WTT total GHG** build-up along the different stages of the pathways. The gasoline balance is also included as reference (as for the fossil energy figures above, the gasoline combustion CO_2 has been added to make the GHG figures comparable).

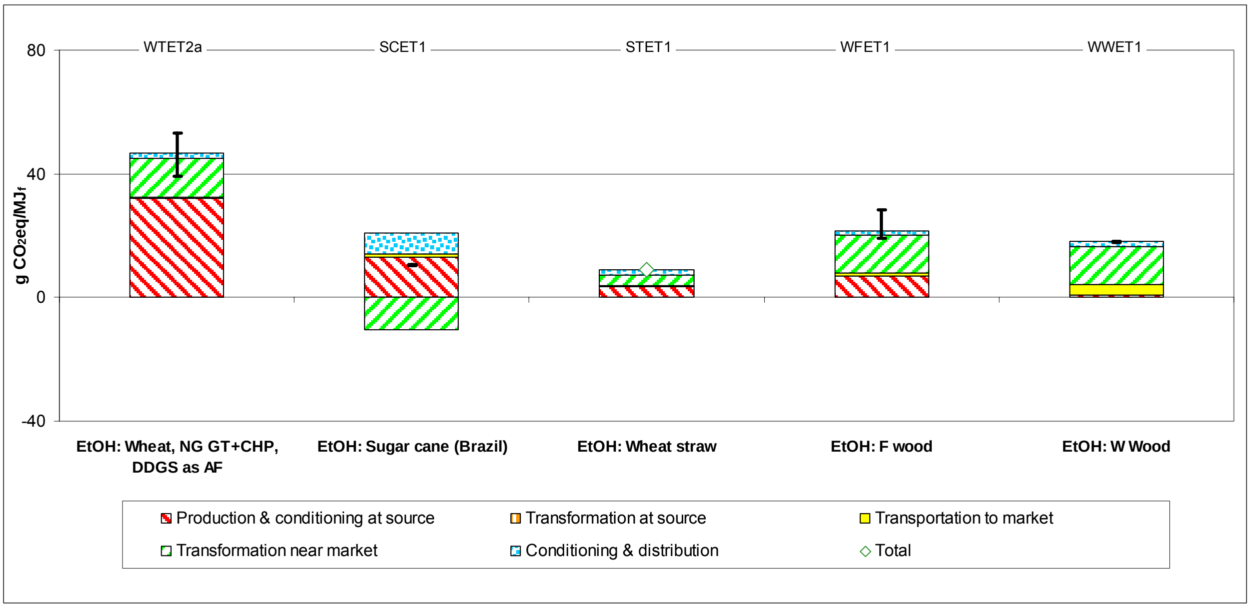
Figure 3.12 GHG balance of ethanol pathways (sugar beet and wheat)



The impact of by-product use and production energy generation scheme is again apparent here. The picture is similar to that of fossil energy above although there are additional impacts related to field N_2O emissions and to the type of fossil fuel used. Wheat production requires more nitrogen than sugar beet resulting in higher field emissions. Sugar cane and farmed wood require much less still. Uncertainties attached to N_2O emissions are also responsible for the relatively large error bars, particularly for wheat. Switching from natural gas to lignite for fuelling the ethanol plant has a dramatic effect, resulting in an increase of GHG emissions for ethanol compared to gasoline. For sugar cane, the CO_2 credit attached to additional fuel oil saving from surplus bagasse results in a negative figure for the "transformation" step.

The wood-based pathways yield a very favourable GHG balance as very little fossil energy is involved in the process. The straw option is less favourable because of the increased farming inputs required to compensate for removing the straw from the land (additional energy for fertiliser production and additional N_2O emissions from the fields).

Figure 3.13 GHG balance of ethanol pathways (various feedstocks)



In Table 3.5 are reported the TTW costs for the pathways to ethanol (see the correspondent Table 3.4 for data interpretation).

Table 3.5 Costs and benefits of major pathways compared to conventional road fuels

Fuel	*Powertrain*	Alt. fuel consumed	Fuel substituted		Base case	WTW savings(1,2)				Incremental cost over ref. scenario			Cost of substitution		Cost of CO_2 avoided
			Gasoline	Diesel	GHG	Energy (PJ/a)		GHG		G€ /a			€ /t fossil fuel	€ / 100 km	
Oil price @25 €/bbl		PJ/a	PJ/a		Mt CO_{2eq}/a	Total	Fossil	Mt CO_{2eq}/a	% of base	WTT	Vehicles	Total			€ /t CO_{2eq}
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	**8481**
Straw CHP						-216	**261**	**13.8**	**80%**	2.6		2.6	558	2.45	**186**
Ex straw						-236	**206**	**15.3**	**89%**	2.9		2.9	634	2.79	**192**
Ex wood						-361	**173**	**12.9**	**75%**	3.6		3.6	776	3.41	**279**

Fuel	*Powertrain*	Alt. fuel consumed	Fuel substituted		Base case	WTW savings(1,2)				Incremental cost over ref. scenario			Cost of substitution		Cost of CO_2 avoided
			Gasoline	Diesel	GHG	Energy (PJ/a)		GHG		G€ /a			€ /t fossil fuel	€ / 100 km	
Oil price @50 €/bbl		PJ/a	PJ/a		Mt CO_{2eq}/a	Total	Fossil	Mt CO_{2eq}/a	% of base	WTT	Vehicles	Total			€ /t CO_{2eq}
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	**5110**
Straw CHP						-216	**261**	**13.8**	**80%**	1.5		1.5	330	1.45	**110**
Ex straw						-236	**206**	**15.3**	**89%**	2.0		2.0	431	1.89	**130**
Ex wood						-361	**173**	**12.9**	**75%**	2.9		2.9	621	2.73	**223**

(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

The **WTW** figures (Figure 3.14, Figure 3.15 and Figure 3.16) 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.

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 (a heat surplus displacing heating oil has been accounted for).

Figure 3.14 **WTW fossil energy requirement and GHG emissions for ethanol pathways (2010+ vehicles)** ***(GHG bars represent the total WTT+TTW)***

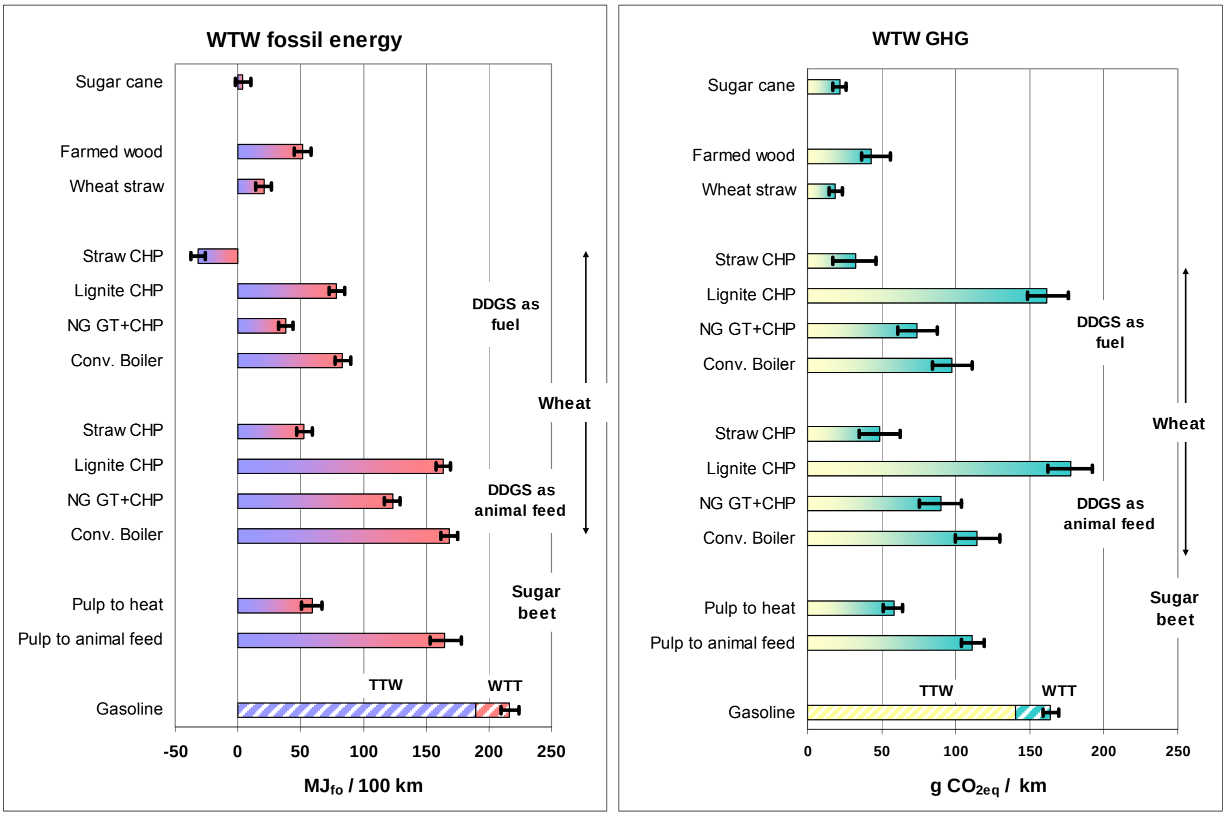
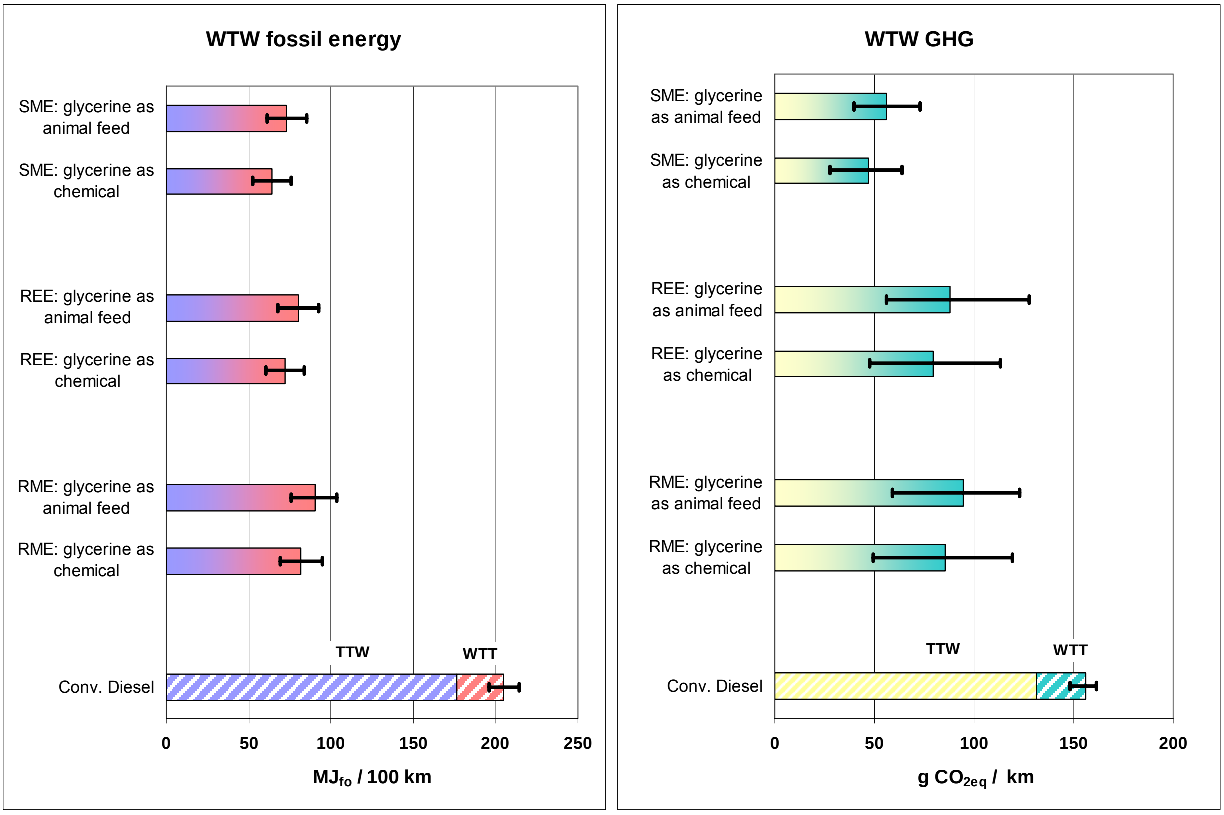


Figure 3.15 **WTW fossil energy requirement and GHG emissions for bio-diesel pathways (2010+ vehicles)** ***(GHG bars represent the total WTT+TTW)***



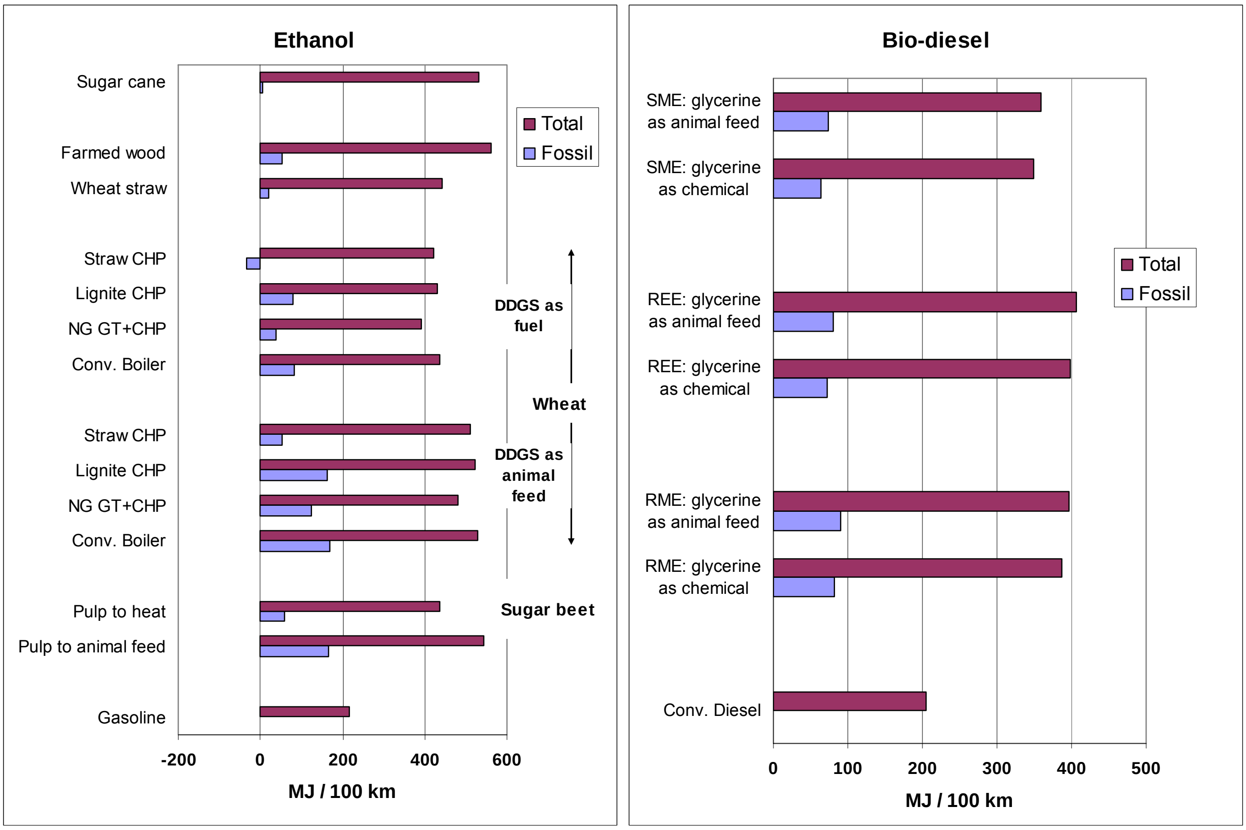
Bio-diesel is less energy-intensive than ethanol as the manufacturing process involves only relatively simple, low-temperature/low pressure steps. In GHG terms the picture is different because of the nitrous oxide emissions which account for an important fraction of the total and for most of the large 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 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 3.16 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 sec. 3.8 this theme has been further developed by looking at alternative uses of biomass resources.

Figure 3.16 WTW total versus fossil energy

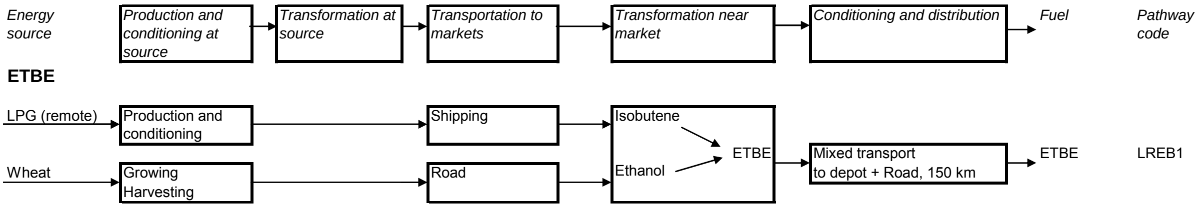


3.5.3 Ethanol to ETBE

As an alternative to using ethanol as such as a gasoline blending component, it can be converted to ETBE (Ethyl-Tertiary-Butyl Ether). ETBE is a high octane component with very similar properties to Methyl-Tertiary-Butyl Ether (MTBE) but with a lower solubility in water. The main advantage of ETBE over ethanol as a gasoline component is its low vapour pressure.

ETBE is synthesised by reacting isobutene with ethanol in a so similar process to MTBE process that MTBE plants only require minor changes to be able to produce ETBE.

Figure 3.17 Wheat-ethanol to ETBE pathway



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 (the MTBE process is described in the original WTW report, WTT part, section 4.7).

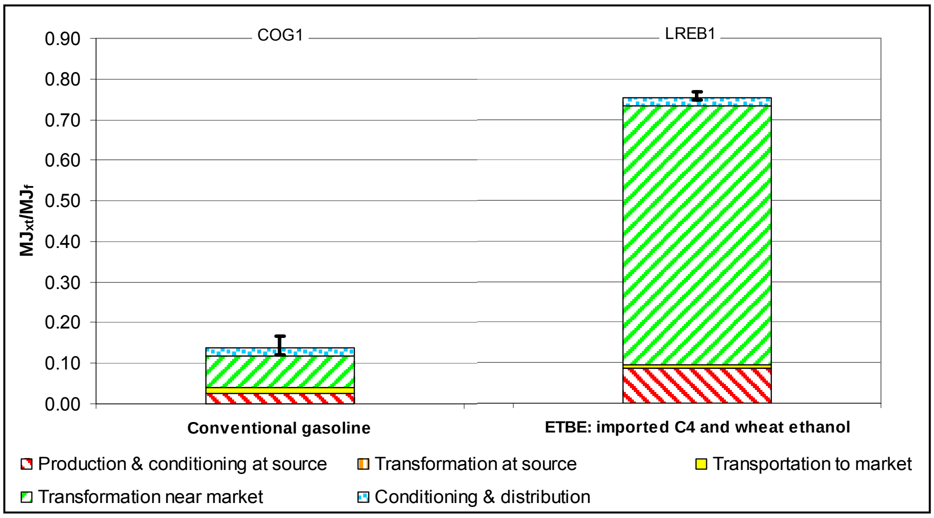
Should more ETBE be required it would have to be made from isobutene produced by isomerisation and dehydrogenation of normal butane. This pathway has been represented with the assumption that the marginal butane required is imported from gas fields.

3.5.3.1 Energy and GHG balance

Pathway LREB1 represents a case where ETBE would be produced in Europe from imported butane and bio-ethanol (from wheat according to pathway WTET2a).

ETBE's energy footprint is much higher than gasoline, partly because of the high energy demand for bio-ethanol. Part of that energy is renewable though and this is taken into account when calculating GHG emissions. ETBE is itself partly renewable so that, to compare GHG emissions with purely fossil pathways, only the non-renewable part of the CO_2 combustion emissions (2/3) has to be factored in.

Figure 3.18 WTT total energy balance of ETBE pathway



Pathway LREB1 is thus far a hypothetical case inasmuch as ETBE is currently made by substituting methanol by ethanol in existing refinery MTBE plants. In order to assess the impact of this route it has been looked at the differential between a base case where MTBE is made in the refinery and an alternative where ETBE is made instead. The calculations are summarised in Table 3.6.

Concerning **total energy**, 1 MJ of MTBE requires 0.82 MJ of isobutene. That same amount can produce 1.2 MJ of ETBE by replacing 0.21 MJ of methanol by 0.40 MJ of ethanol (this is simply the result of the chemical balance). Thus in the base case 1 MJ of MTBE is available along with 0.40 MJ of ethanol that can both be used as gasoline. When making ETBE a total of only 1.2 MJ is available to the gasoline pool while 0.21 MJ of methanol have been "saved". In order to bring both cases to the same basis one has to add to the ETBE case the amounts related to production of additional gasoline (1.40-1.20 = 0.20 MJ).

Figure 3.19 WTT GHG balance of ETBE pathway

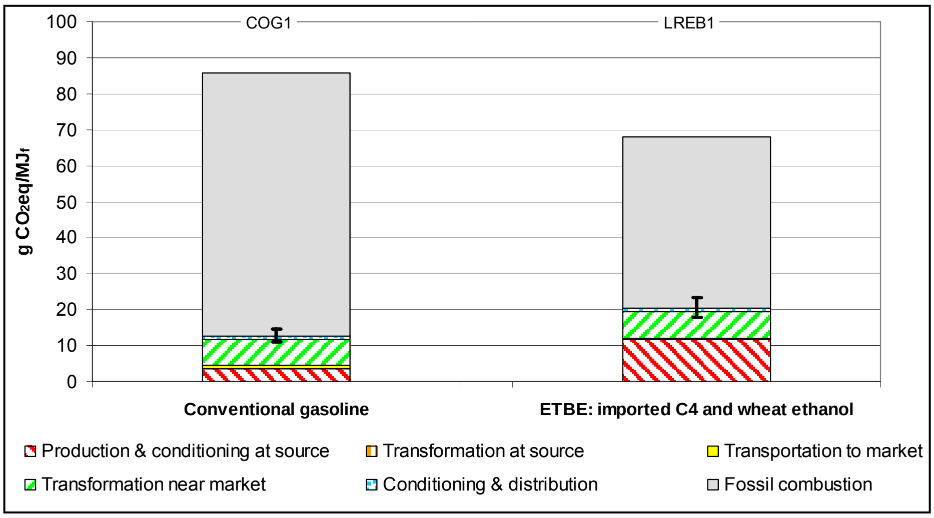
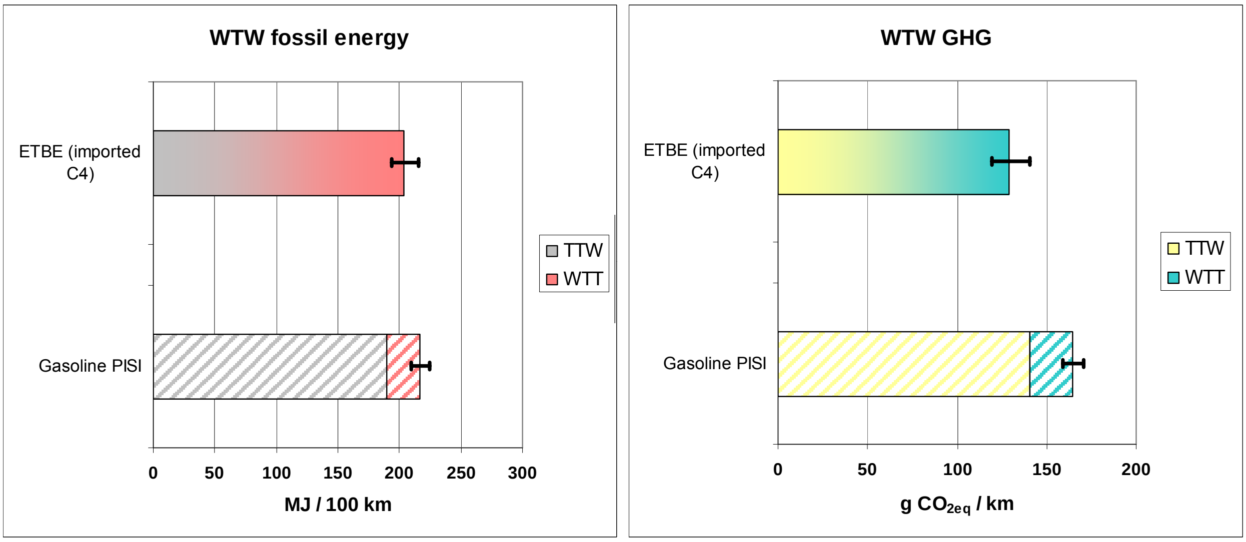


Table 3.6 Substitution of methanol by bio-ethanol for ETBE manufacture in refineries

		Gasoline components available				Additional	Feedstocks used			Balance		**Balance**	
		MTBE	ETBE	Ethanol	Total	gasoline	Isobutene	Methanol	Ethanol	/MJ MTBE	/MJ ETBE	/MJ EtOH	
Use of ethanol as such													
Used or produced	MJ_f	1.00		0.40	1.40		0.82	0.21					
Total energy	MJ_{xt}			1.01						1.01		**2.53**	
Fossil energy	MJ_{xf}			0.26						0.26		**0.65**	
GHG	g CO_2eq			18.58						18.58		**46.6**	
ETBE instead of MTBE													Net
Used or produced	MJ_f		1.20		1.20	0.20	0.82	-0.21	0.40				
Total energy	MJ_{xt}					0.230		-0.33	1.01	0.91	0.76	**2.28**	**-0.26**
Fossil energy	MJ_{xf}					0.23		-0.33	0.26	0.16	0.13	**0.39**	**-0.26**
GHG	g CO_2eq					17.3		-19.2	18.6	16.75	13.99	**42.0**	**-4.6**

The ETBE route is slightly more favourable from a **GHG** point of view, i.e. using ethanol to make ETBE as a substitute to refinery MTBE saves more GHG than using that ethanol as such. The reason for this is that making ETBE saves in part methanol instead of gasoline, the former having a larger GHG footprint.

Figure 3.20 WTW fossil energy requirement and GHG emissions for ETBE pathway (2010+ vehicles)



Note: Ethanol for ETBE assumed to be from wheat, DDGS to animal feed.

Table 3.7 WTW fossil energy and GHG emissions balances for "refinery" ETBE

Use of ethanol	Fossil energy MJ_{xfo}/MJ_{EtOH}	GHG $g\ CO_{2eq}\ /\ MJ_{EtOH}$
As ethanol	0.65	46.6
As ETBE	0.39	42.0
Gasoline (for ref.)	*1.14*	*85.9*

The case of "refinery" ETBE is described in Table 3.7.

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.

3.5.4 Bio-diesel: FAME and FAEE

3.5.4.1 Pathways

In Europe the two most used oil seed crops are rape (also known as colza) and sunflowers. Agricultural yields are much lower than for wheat or sugar beet. A certain proportion of oil seeds in crop rotation with cereals produces a synergistic improvement of cereal yields. Rape grows better in the North (at less extent also at the centre) of EU and is more intensive. Sunflower is more suited to southern Europe. Processing of the oil seeds from either source is practically identical. Waste cooking oils are also used to a limited extent.

Pure vegetable oil can be thought of as three fatty acid “ribs” attached to glycerol (=propan1,2,3-triol) “backbone”. This large molecule is viscous and thermally unstable, forming the yellow deposit familiar on frying utensils, and consequently it is unsuitable as an internal combustion engine fuel. The "trans-esterification" process consists of replacing its organic acid functions with three methanol molecules, so that three separate Fatty Acid Methyl Ester (FAME) molecules are formed from each molecule of plant oil. The processing is relatively straightforward, cheap and does not require a lot of energy.

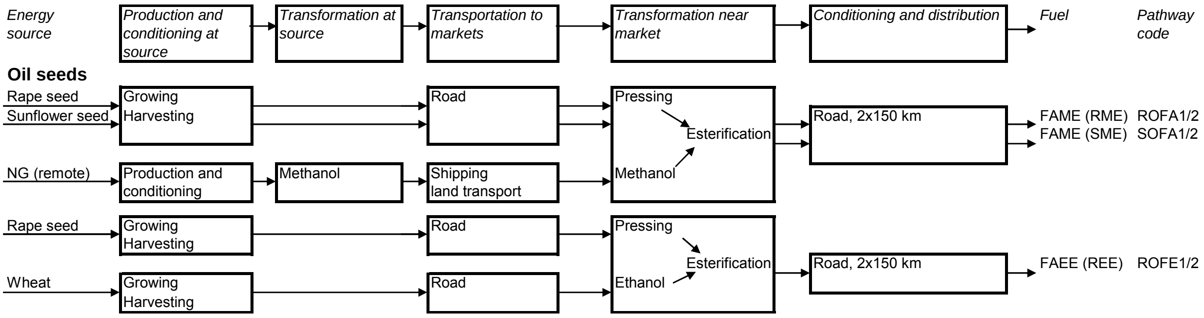
The process produces a fuel which boils at around 350°C and is a suitable diesel fuel and, as the most important by’products, the residue after pressing (or cake) and glycerine. The cake is a protein-rich animal feed used in substitution of otherwise imported soy meal. Glycerine could in principle be 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.

Both rape (biodiesel produced as RME) and sunflower seeds have been included with two options for the disposal of glycerine.

Today methanol is used as it is abundantly available and cheap. Other alcohols, particularly (bio)-ethanol can be used, in principle. Although there are no such processes in actual operation, this option has been included in combination with rapeseed to show the impact of using bio-ethanol on the overall energy and GHG balance to produce a fatty acid ETHYL ester (FAEE) (since ethanol is from bio origin, this has the advantage of boosting the "renewability" of the fuel). Actual process data could not be sourced and, in representing this option, the same energy input has been assumed as for FAME for the esterification process, the benefit coming from the use of a partially renewable alcohol.

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.

Figure 3.21 Oil seeds to bio-diesel pathways



3.5.4.1.1 Rapeseed

In the oil mill, the rapeseed is crushed, and oil extracted by steam and hexane. The described process is very similar to others in the literature. The by-product is rapeseed cake, a high-protein animal feed, replacing soy bean cake as described for DDGS from wheat. It is interesting that the production of soy bean cake also makes a by-product: soy oil, which receives a credit based on the main pathway for rapeseed oil (this creates a calculation loop). Rapeseed cake could also in principle be used as a fuel, much in the same way as DDGS. This is at this stage an unlikely option because of its high value as animal feed and a pathway to cover this has not been developed.

The next step is purification, in which acidity is neutralized and the oil clarified. The trans-esterification reaction mentioned above often takes place in a separate plant inasmuch as it is the only step which is specific to bio-diesel compared to vegetable oil for food.

The raw glycerine stream contains only 80% pure glycerine but could be refined and sold as distilled pharmaceutical-quality synthetic glycerol. Several studies (including [*LBST 2002*]) have used this to calculate a by-product credit. This is very good for the energy ratio, because synthetic glycerol production uses about 18 times its heating value in fossil fuel. However, the scenario is not very realistic if the size of the market is condidered. Total EU glycerol consumption is about 275 kt/a [*NRC 2004*] and the only remaining synthetic glycerol plant in EU has an output of 36 kt/a. By comparison 5% replacement of EU diesel fuel would pour an extra 1.15 *million* tonnes of glycerine onto the EU market (about 2.5kg per person per year), more than thirty times the EU production of synthetic glycerol. Therefore this substitution option has not been considered.

Most of the glycerine produced today is a by-product of soap-making from fats and oils and the supply will hardly change if more is produced from bio-diesel. Therefore a large increase in supply can only be accommodated by finding other uses, at a lower price. In fact in 2005 the effect of expanding bio-diesel production was already felt on the glycerol market: the crude 80% glycerine from bio-diesel fetched 130-200 €/t on the EU commodities markets. This price reflects the cost of purifying it to the standard vegetable-grade specification the EU price for which declined from 550 to as low as 300 €/t during 2005.

In a scenario of continuing rapid expansion of bio-diesel production in the EU, the glycerol price will be depressed further in the short term (indeed in the UK there are already reports of bio-diesel producers paying to dispose of glycerine as a waste). However, [*DOE 2004*] states that glycerine will be attractive as a chemical feedstock if the price remains between 80 and 200 €/t (0.2 to 0.5 $/lb). Therefore, in the long term industry is expected to develop processes using glycerine which will stabilize the price at the bottom of its current range. On this basis the WTW best-estimate medium term glycerine price is 130 €/tonne.

To get an idea of the potential size of this market it has been considered that synthetic propylene glycol and ethylene glycol are chemically similar to glycerol. They have a combined market about 14 times greater than synthetic glycerol [*DOE 2003*] and still fetch around 1100 €/tonne and 680 €/t in 2005. So even this market could still only absorb about half the potential glycerine glut.

Since an estimate of the fossil energy content of propylene glycol has been had from [*GEMIS 4.1*], this has been taken as the upper limit of the energy and emissions credit. On the other hand, only a slight fall from the 2005 price would make glycerine attractive as animal feed. This gives a much lower energy and emissions credit. If glycerine is used as fuel (at a value of only 20€/t according to [*DOE 2003*]), the energy and emissions credit would lie between half-way these two extremes. So the average credit for glycerine would be between these values.

3.5.4.1.2 Sunflower

Sunflower processing differs from rapeseed only inasmuch as the pressing yield is slightly higher, and the sunflower cake by-product has a lower protein content, replacing 0.61 kg pure soy-meal per kg, instead of 0.80 kg/kg for rapeseed cake.

3.5.4.2 Availability

Europe is short of oil seeds. So far the trade pattern has been to import the raw materials (oil seeds) rather than finished bio-diesel. 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 bio-diesel 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 oil 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.

3.5.4.3 Energy and GHG balance

Figure 3.22 shows the **WTT total energy** build-up along the different stages of the pathways. The fossil diesel balance is also included as reference (conventional and bio-diesel are used in the same vehicles delivering the same energy efficiency). In this case "total" energy includes the energy content of the oil seeds as well as the energy content of any biomass used as a fuel at any stage of the pathway (as said before, this is the energy "expended" i.e. it excludes the energy content of the bio-diesel produced).

Bio-diesel requires up to 5 times more total energy than fossil diesel. Sunflower is somewhat more favourable than rape in this respect. Using ethanol instead of methanol for esterification further increases the required energy. Use of glycerine as a chemical or animal feed has only a marginal impact.

Figure 3.22 WTT total energy balance of bio-diesel pathways

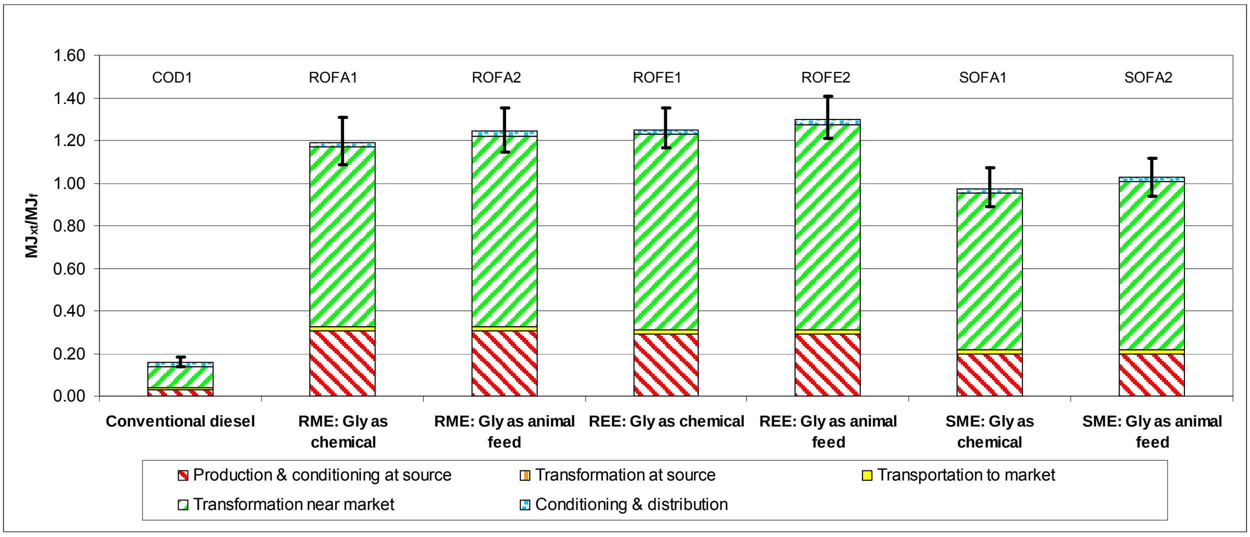


Figure 3.23 compares **total and fossil energy** as a measure of the "renewability" of the pathways. For bio-diesel, this is in effect the WTW fossil energy (as no additional fossil energy is expended in the vehicle).

When focussing on fossil energy, the ratio to fossil diesel is in the region of 0.4 for rape, i.e. a net fossil energy saving of about 60% compared to fossil diesel. Again sunflower is slightly more favourable than rape. Obviously the use of bio-ethanol instead of fossil-based methanol results in a small decrease of the total fossil energy requirement.

Figure 3.24 shows the **WTT total GHG** build-up along the different stages of the pathways. The fossil diesel balance is also included as reference (as for the fossil energy figures above, the fossil diesel combustion CO_2 has been added to make the GHG figures comparable).

The GHG emissions are dominated by the seed production step, mostly through N_2O emissions. This is largely due to the fact that oil seed crops, and particularly rape, require a lot of nitrogen fertiliser. The uncertainty attached to these emissions is also responsible for the large error bars.

The negative numbers shown for the "transformation" stage are the result of fossil energy credits for by-products including the residue from pressing the oil seeds and the glycerine produced by the esterification process.

Figure 3.23 WTT fossil energy balance of bio-diesel pathways

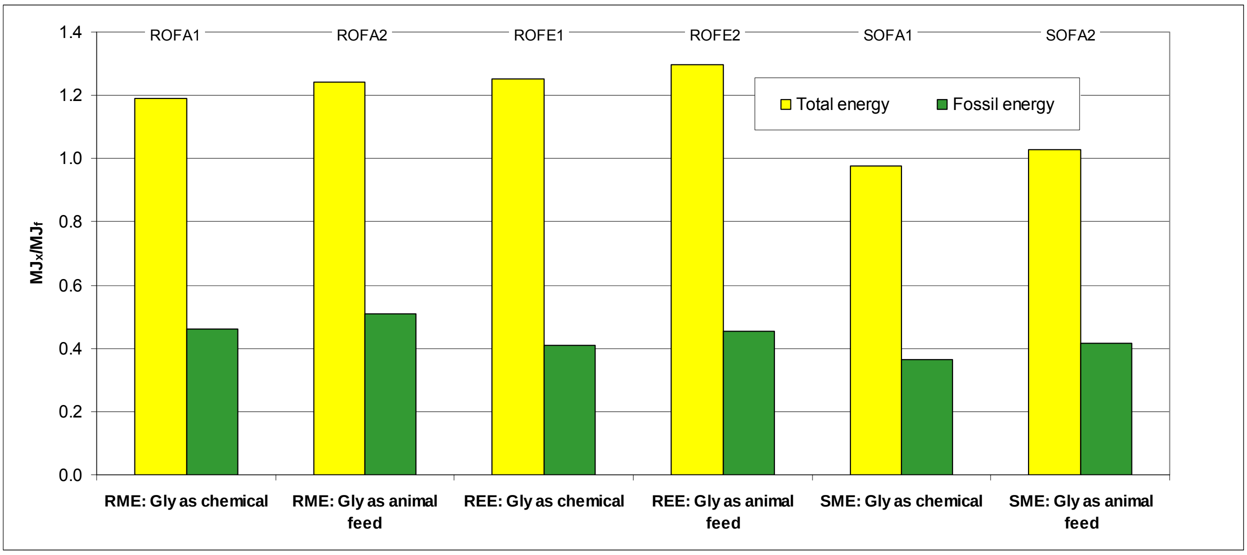


Figure 3.24 WTT GHG balance of bio-diesel pathways

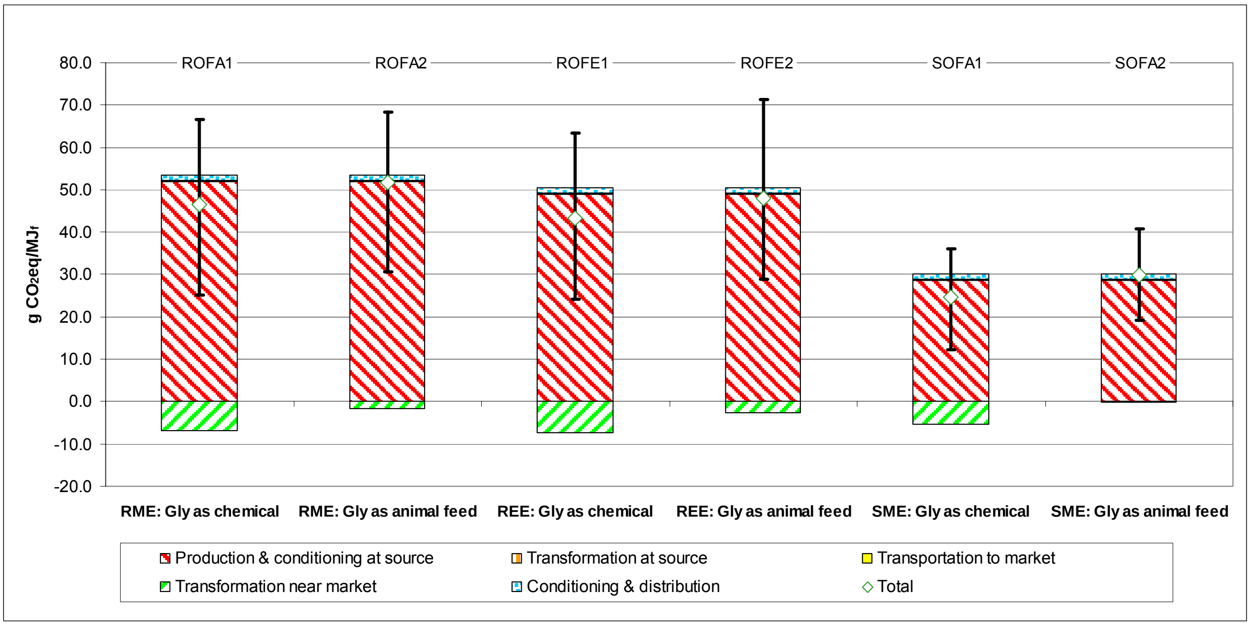


Table 3.8 gives an overview of the **TTW costs** and benefits associated with the major pathways.

Table 3.8 Costs and benefits of major pathways compared to conventional road fuels

Fuel	*Powertrain*	Alt. fuel consumed	Fuel substituted		Base case	WTW savings$^{(1,2)}$				Incremental cost over ref. scenario			Cost of substitution		Cost of CO_2 avoided
			Gasoline	Diesel	GHG	Energy (PJ/a)		GHG		G€ /a			€ /t fossil fuel	€ / 100 km	
Oil price @25 €/bbl		PJ/a	PJ/a		Mt CO_{2eq}/a	Total	Fossil	Mt CO_{2eq}/a	% of base	WTT	Vehicles	Total			€ /t CO_{2eq}
Bio-diesel	CIDI+DPF	145		145	12.8										
Glycerine as chemical															
RME						-150	**102**	**5.8**	**45%**	1.5		1.5	438	1.80	**254**
REE						-158	**109**	**6.3**	**49%**	1.5		1.5	442	1.81	**237**
SME						-118	**115**	**9.0**	**70%**	1.6		1.6	469	1.92	**176**
Glycerine as animal feed															
RME						-157	**94**	**5.1**	**39%**	1.5		1.5	436	1.79	**290**
REE						-165	**102**	**5.6**	**44%**	1.5		1.5	440	1.80	**264**
SME						-126	**108**	**8.2**	**64%**	1.6		1.6	467	1.91	**191**

Fuel	*Powertrain*	Alt. fuel consumed	Fuel substituted		Base case	WTW savings[(1,2)]				Incremental cost over ref. scenario			Cost of substitution		Cost of CO_2 avoided
			Gasoline	Diesel	GHG	Energy (PJ/a)		GHG		G€ /a			€ /t fossil fuel	€ / 100 km	
Oil price @50 €/bbl		PJ/a	PJ/a		Mt CO_{2eq}/a	Total	Fossil	Mt CO_{2eq}/a	% of base	WTT	Vehicles	Total			€ /t CO_{2eq}
Bio-diesel	CIDI+DPF	145		145	12.8										
Glycerine as chemical															
RME						-150	**102**	**5.8**	**45%**	0.8		0.8	241	0.99	**140**
REE						-158	**109**	**6.3**	**49%**	0.8		0.8	246	1.01	**131**
SME						-118	**115**	**9.0**	**70%**	0.9		0.9	273	1.12	**102**
Glycerine as animal feed															
RME						-157	**94**	**5.1**	**39%**	0.8		0.8	229	0.94	**152**
REE						-165	**102**	**5.6**	**44%**	0.8		0.8	234	0.96	**141**
SME						-126	**108**	**8.2**	**64%**	0.9		0.9	260	1.07	**107**

(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

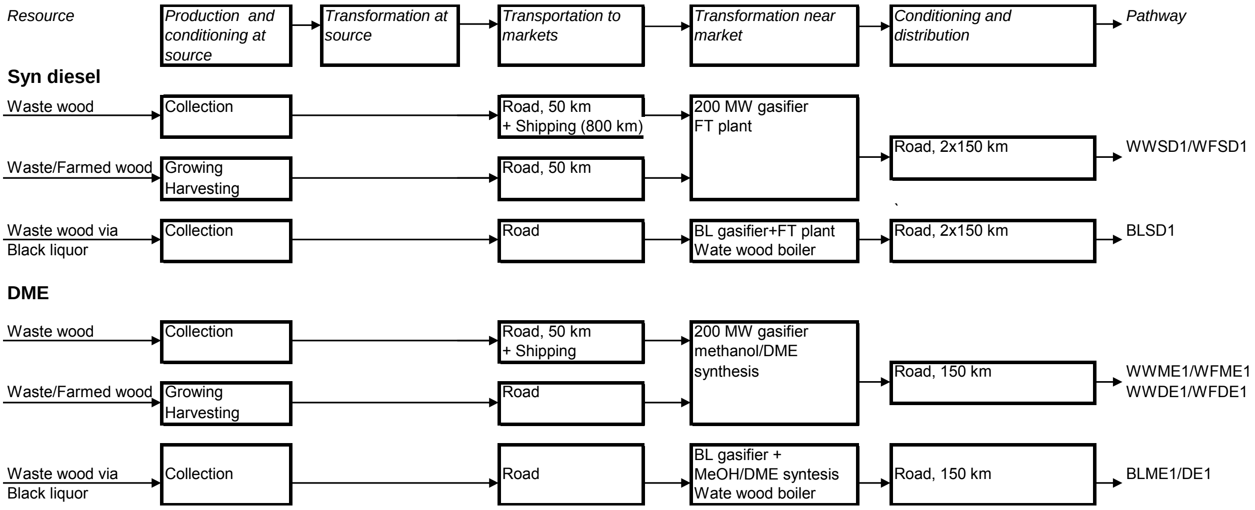
3.5.5 Synthetic fuels

Two synthetic fuels namely Fischer-Tropsch or syn-diesel and DME have been considered. DME has attractive characteristics as a fuel for diesel engines although the fact that it is gaseous at ambient conditions reduces its appeal.

The manufacturing of such fuels relies on steam reforming or partial oxidation of a fossil hydrocarbon or organic feedstock to produce syngas which is, in turn, converted into the desired fuel using the appropriate process.

Biomass, most likely in the form of wood or perennial grasses, is also being actively considered as a source of such fuels. The WTW generic wood pathways represent this group of feedstocks. This includes farmed wood (based on poplar) and waste wood. One particularly attractive option for using waste wood would be the so-called Black Liquor route.

Figure 3.25 Synthetic fuels pathways



3.5.5.1 *Synthetic diesel fuel*

By synthetic diesel fuel it is meant the product made by Fischer-Tropsch (FT) synthesis from “syngas” the mixture of carbon monoxide and hydrogen obtained by partial oxidation of wood. The products of this process scheme are long-chain paraffins essentially free of sulphur and other impurities.

3.5.5.1.1 *Processes*

A hydrocracking unit is usually included in the FT process scheme to control the type of product being produced by splitting the chains appropriately. Among the main commercial products envisaged diesel fuel from woody biomass (known as **Biomass-to-Liquids or BTL**) is considered. 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.

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

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

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

The pulp and paper industry may provide a promising route for making significant amounts of synthetic fuels from woody material.

For biomass-to-liquid (Fischer-Tropsch) fuels, a **process analysis based on the BCL gasifier** has also been used. The efficiency of this process depends strongly on the performance of the FT catalyst. For the WTW "best estimate" the middle value of chain growth probability (0.85) quoted by [*Tijmensen 2002*] has been used.

The "best case" is the Choren process under development based on a DM2-type gasifier. They claim an efficiency of 51% combined with an output of pure diesel fuel (kerosene and gasoil), which others believe is not achievable, even assuming the best performing catalyst. Note that to produce only diesel fuel, the lighter FT products have to be recycled all the way back to the gasifier, an operation which is bound to require additional energy. The lowest efficiency limit is the BCL-based process again, but with the most pessimistic assumption for catalyst performance.

Apart from Choren, biomass-to-FT plants all produce 2 fuels simultaneously: naphtha and diesel fuel. The simple approach has been adopted as considering the two equally valid products, and quoting the efficiency for the sum of both fuel products.

Other processes for conversion of wood to liquids are described in the literature such as fast pyrolysis or the HTU process. These options have not been included. Fast-pyrolysis of wood produces products that cannot be used directly as road fuels, but can be fed to a gasifer in the same way as black liquor. Thus fast pyrolysis is a sort of pre-treatment step as far a road-fuel production is concerned. It may be a viable process for making other chemical products, but the capital cost of two processing plants in series is likely to present a major hurdle.

The HTU process has been under bench-scale development for some time. It converts the feedstock to a mix of solid and liquid products in superheated water. It is hoped that the liquid fraction can be upgraded to hydrocarbon fuel by hydrogenation. Clearly it is more attractive for wet feeds like organic waste or wet crops than wood. However, processing sewage is not likely to be economic because its low heat content means low throughput, which would not repay the high investment cost of the pressurized tank. So HTU is best thought of as an alternative to anaerobic digestion to produce biogas. The proposed process has changed greatly since it was included in [*LBST 2002*] and the new process configuration has not yet been costed in detail, so it could not be included.

Most of the wood processing schemes quoted in the literature produce some surplus electricity (and therefore consume some additional wood to that effect). To arrive at a meaningful comparison and in accordance with the WTW philosophy that the reference scenario should differ from the biofuels scenario only in the production of biofuels, all the wood conversion processes have been made electricity-neutral by adding or subtracting an appropriate proportion of a wood-to-electricity process. For each case a power station has been chosen which closely matched the one in the process: for example, processes making fuels using the BCL gasifier were made electricity-neutral using the efficiency of a wood power station based on BCL. To compare the efficiency of the processes, which now all had about zero emissions, the "primary energy efficiency" has been compared defined as (all primary energy in)/(fuel out). The WTW efficiency values for pure fuel processes do not correspond to the overall process efficiencies quoted in some references such as [*Tijmensen 2002*]: which are for mixed electricity + fuel processes, with the electrical and fuel energies of the products simply added.

3.5.5.1.1.1 Waste wood in combination with black liquor gasification

Paper pulp manufacture involves separation of wood cellulose from the lignin which forms an important proportion of the wood matter and energy content. The residue from this process, known as black liquor, is a water-based slurry, 70 to 80% of which consists of lignin and spent pulping chemicals.

In conventional pulp mills the black liquor is burned in a so-called "recovery boiler". The non-combustible components leave the recovery boiler as the so-called "smelt" mainly consisting of molten sodium sulfide (Na_2S) and sodium carbonate (Na_2CO_3) which are recycled to the pulping process. The corrosive nature of the smelt limits the recovery boiler efficiency to about 65%.

The recovery boiler provides heat and electricity for the pulp mill. Including the combustion of the bark and the use of the sludge from the effluent treatment a modern pulp mill is self-sufficient in energy.

Replacement of the recovery boiler by a gasifier has been considered by the pulp and paper industry for some time. The original drive for such a scheme was increased energy efficiency which would allow combined production of process heat and surplus electricity for export. As the product of the gasifier is syngas, production of synthetic fuels can also be envisaged. However, the energy used for producing the synthetic fuels must be compensated for by another energy source, conveniently supplied in the form of additional (waste) wood intake into the "hog fuel" boiler already present to burn the bark and other residues. The net result is to turn waste (or low value) wood into synthetic fuels at a very high combined efficiency.

Taking the original pulp mill as reference and for the same pulp production and electricity balance, one can calculate the net efficiency of synthetic fuels production, which turns out to be appreciably higher than that of the direct wood conversion processes. The reason is that the additional burning of forest residuals increases the thermal capacity of the plant, whilst the stack losses are reduced because the hog-fuel boiler has higher efficiency than the replaced recovery boiler. Almost all the heat from the syngas is recovered.

Of course this efficiency improvement can only come about through a substantial investment in a black liquor gasifier and fuel synthesis plant. The gasifier is expensive because of the need to resist corrosion by the very high sulphur and salt content of the syngas (the results of the first industrial trials have not been yet provided).

In [*Ekbom 2003*] the generation of methanol and DME from black liquor has been investigated within the BLGMF (Black Liquor Gasification to Motor Fuels) project. These pathways have been included as well as pathways to synthetic diesel inferred from the DME data. The electricity pathway has also been included as it will be the reference against which mill operators will judge the attractiveness of fuel manufacture.

The following table summarises the “wood efficiency” of the various wood processes after correction for electricity production as discussed above.

Table 3.9 Wood efficiency of various wood conversion routes

MJ wood/ MJ final fuel	10 MW			200 MW			Black liquor route		
(corrected for electridity production)	Mean	min	Max	Mean	min	Max	Mean	min	Max
Electricity	2.8	2.7	3.0	2.1	2.0	2.2	1.1		
Synthetic diesel (200 MW)				2.1	2.0	2.2	1.8	1.7	1.9
Mehanol/DME (200 MW)				2.0	1.7	2.2	1.5	1.4	1.6
Hydrogen	1.9	1.8	2.0	1.5	1.4	1.5	1.2	1.2	1.3
Ethanol	2.9	2.8	3.1						

3.5.5.1.2 Energy and GHG emissions

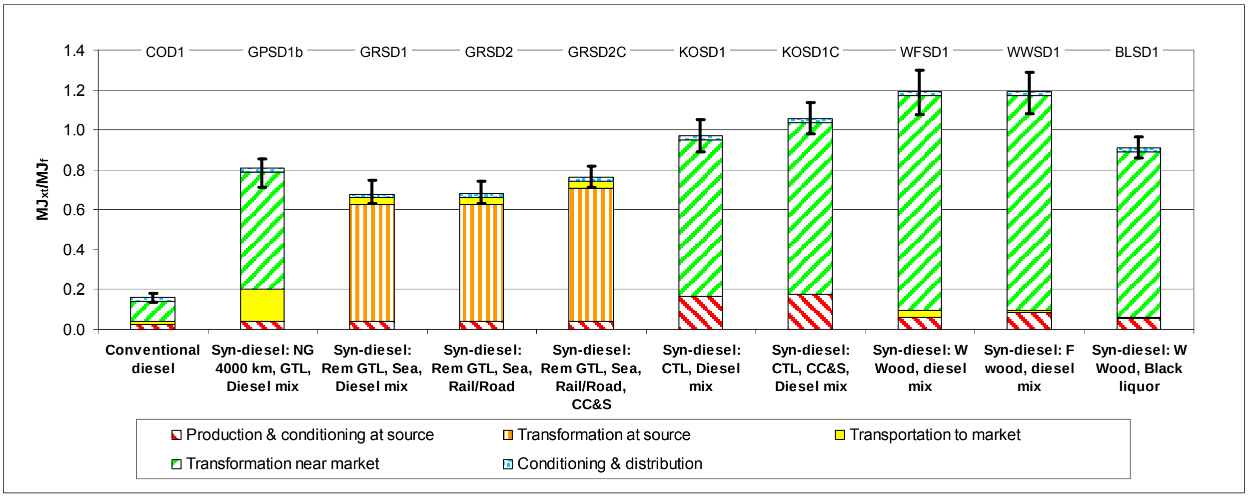
Making synthetic diesel is an energy-intensive endeavour. The combination of steam reforming, partial oxidation and Fischer-Tropsch synthesis result in overall efficiencies within a broad range of 45 to 65% depending mostly of the feedstock and to a lesser extent the process scheme.

The wood-based processes are expected to be efficient up to 50% because of the inherent complexity of wood processing compared to gas and also because the plants are likely to be much smaller and less optimised in energy terms. This is also the main reason why wood processes are less favourable than CTL from this point of view. Future developments may improve the performance of these processes. In the black liquor case there is a potential for up to 55% efficiency. Wood waste is, as expected, slightly less energy-intensive than farmed wood, the difference being larger for GHG emissions mainly as a result of N_2O emissions related to wood farming.

In the best case syn-diesel fuel production still requires about 4 times as much energy as conventional diesel fuel (GRSD1/COD1).

The **WTT** total energy graph (Figure 3.26) represents the *expended* energy (i.e. excluding the energy content of the fuel itself).

Figure 3.26 WTT total energy balance of syn-diesel pathways



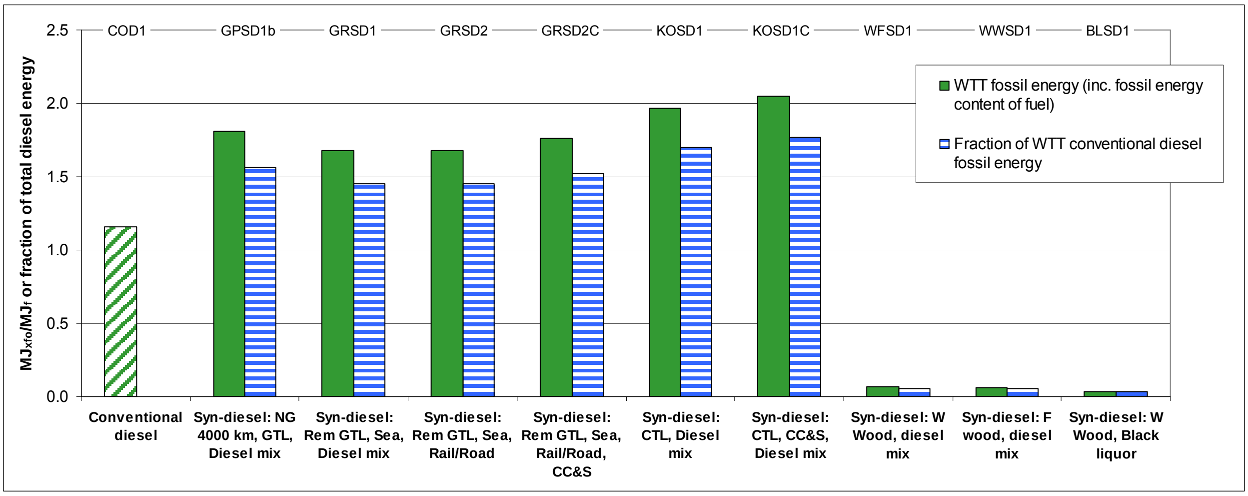
The **fossil energy balance** for the different routes to synthetic diesel is shown in Figure 3.27.

In this case all options produce a diesel fuel that will result in the same efficiency when burned in a given vehicle (see Table 3.10) and the figures calculated in that way are in fact the same as the WTW figures expressed per MJ_f rather than per km.

Figure 3.27 reveals ratios of 1.5 to 2 between conventional diesel and the different fossil-based syn-diesel options.

Wood-based options hardly use any fossil energy as these processes are mostly fuelled by their own feedstock (note, however, that this increases the specific rate of biomass usage and therefore the potential of such fuels for a given biomass availability, see also sec. 3.7).

Figure 3.27 WTT fossil energy balance of syn-diesel pathways (including fossil energy content of the final fuel)



For wood, **WTT GHG emissions** (Figure 3.28 and Figure 3.29) are mainly incurred for wood growing and collection/transport.

Figure 3.28 WTT GHG balance of syn-diesel pathways (including fossil CO_2content of final fuels)

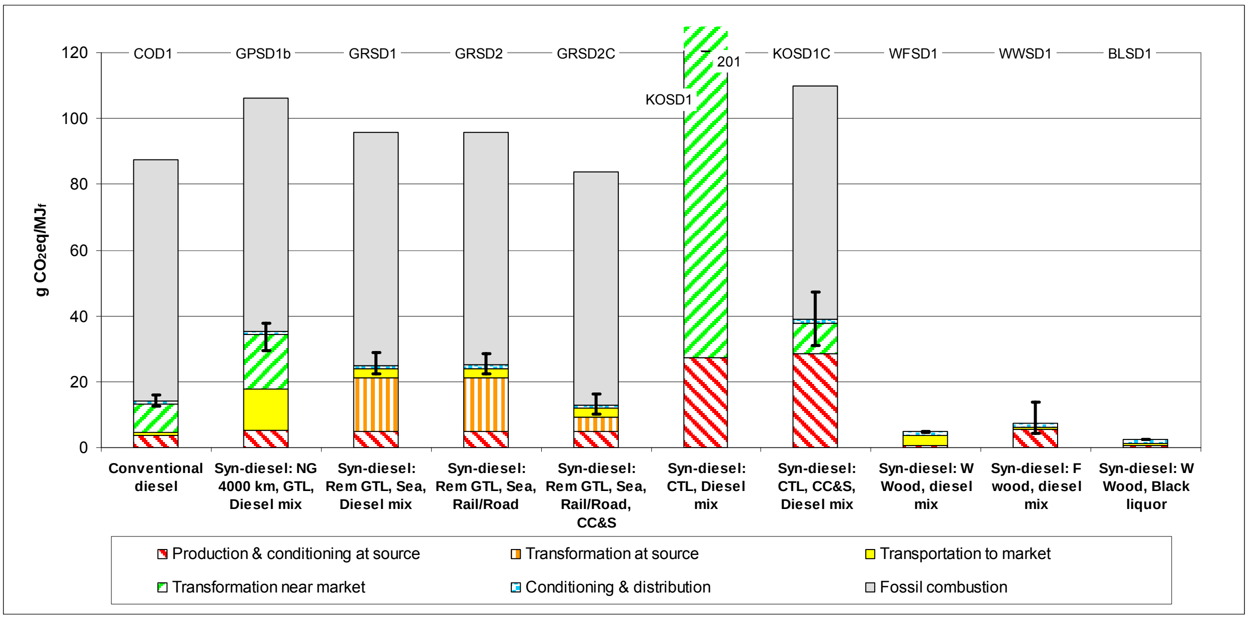
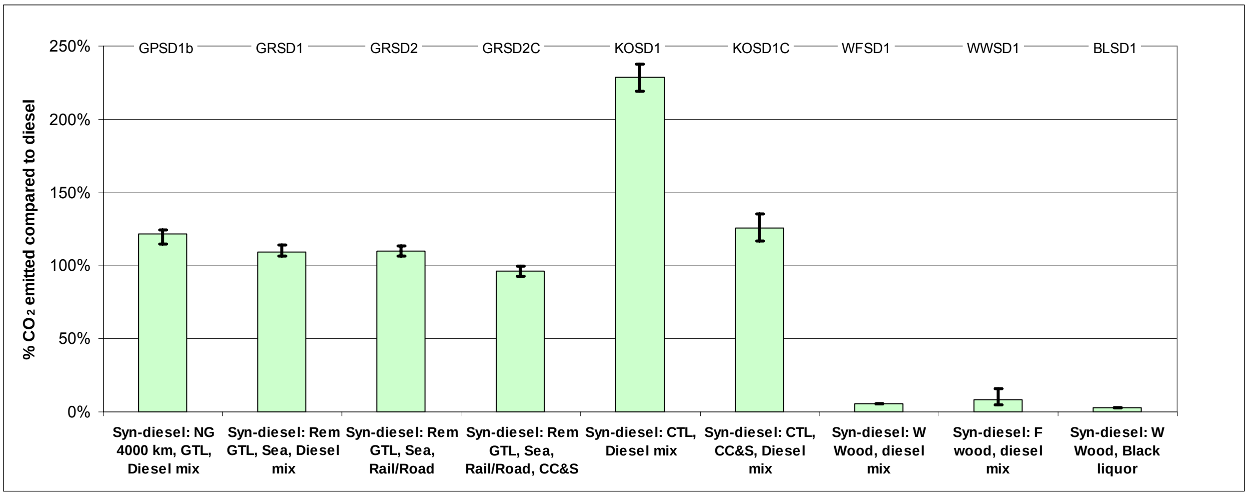


Figure 3.29 WTT GHG balance of syn-diesel pathways compared to conventional fossil diesel (including fossil CO_2 content of final fuels)



In Table 3.10 are reported the **TTW costs** for the pathways to synthetic diesel (WTW costs in Figure 3.34).

Table 3.10 Costs and benefits of major pathways compared to conventional road fuels

Fuel	*Powertrain*	Alt. fuel consumed	Fuel substituted		Base case	WTW savings(1,2)				Incremental cost over ref. scenario			Cost of substitution		Cost of CO_2 avoided
			Gasoline	Diesel	GHG	Energy (PJ/a)		GHG		G€ /a			€ /t fossil fuel	€ / 100 km	
Oil price @25 €/bbl		PJ/a	PJ/a		Mt CO_{2eq}/a	Total	Fossil	Mt CO_{2eq}/a	% of base	WTT	Vehicles	Total			€ /t CO_{2eq}
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**

Fuel	*Powertrain*	Alt. fuel consumed	Fuel substituted		Base case	WTW savings(1,2)				Incremental cost over ref. scenario			Cost of substitution		Cost of CO_2 avoided
			Gasoline	Diesel	GHG	Energy (PJ/a)		GHG		G€ /a			€ /t fossil fuel	€ / 100 km	
Oil price @50 €/bbl		PJ/a	PJ/a		Mt CO_{2eq}/a	Total	Fossil	Mt CO_{2eq}/a	% of base	WTT	Vehicles	Total			€ /t CO_{2eq}
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**

(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

3.5.5.2 DME

DME 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 and is in fact more likely to be developed to produce these fuels rather than BTL, chiefly in Scandinavia. DME is produced by the same process: the only difference is the nature of the final catalyst. In the literature two analyses have been found: one based on the BCL gasifier [*Katofsky 1993*], which becomes the “best case”, and a “worst case” based on the simpler Värnamo auto-thermal pressurized fluidized-bed gasifier, used with oxygen blowing [*Atrax 1999*].

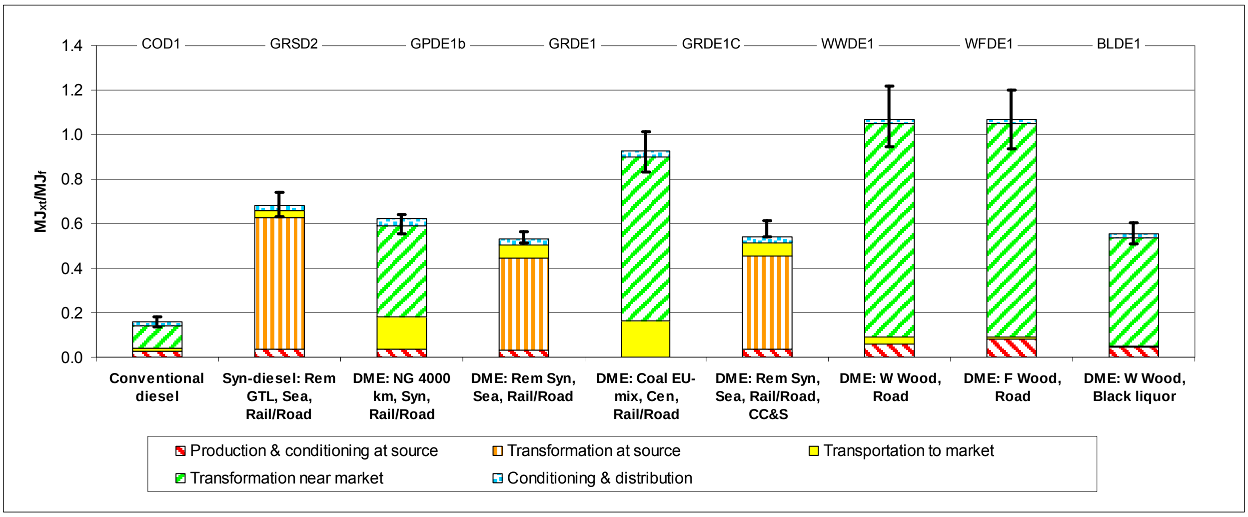
Note that no data have been had for process for DME based on the Choren DM2 gasifier. To compare efficiency between production of FT and DME, one should compare the “best-case” FT process with the “best-estimate” process for DME.

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.

3.5.5.2.1 Energy and GHG emissions

The synthesis of DME is a more efficient than that of FT diesel, resulting is a more favourable energy balance (compare GRSD2 and GRDE1 in Figure 3.30).

Figure 3.30 WTT total energy balance of DME pathways



DME from wood is much less energy-efficient but virtually all the energy used comes from the wood itself, resulting in a very favourable fossil energy balance (Figure 3.31).

The black liquor route offers a substantial energy efficiency improvement when using wood. In terms of fossil energy or GHG balance the difference is of course small in absolute terms (because all figures are small). The main benefit resides in the better utilisation of a limited resource allowing substitution of more fossil energy with the same quantity of wood.

Note: when comparing DME with liquid diesel fuels, the WTT fossil energy figures including the fuel fossil energy content are not quite equivalent to the WTW figures because DME burns with a somewhat higher efficiency in the vehicle

Figure 3.31 WTT fossil energy balance of DME pathways (including fossil energy content of the final fuel)

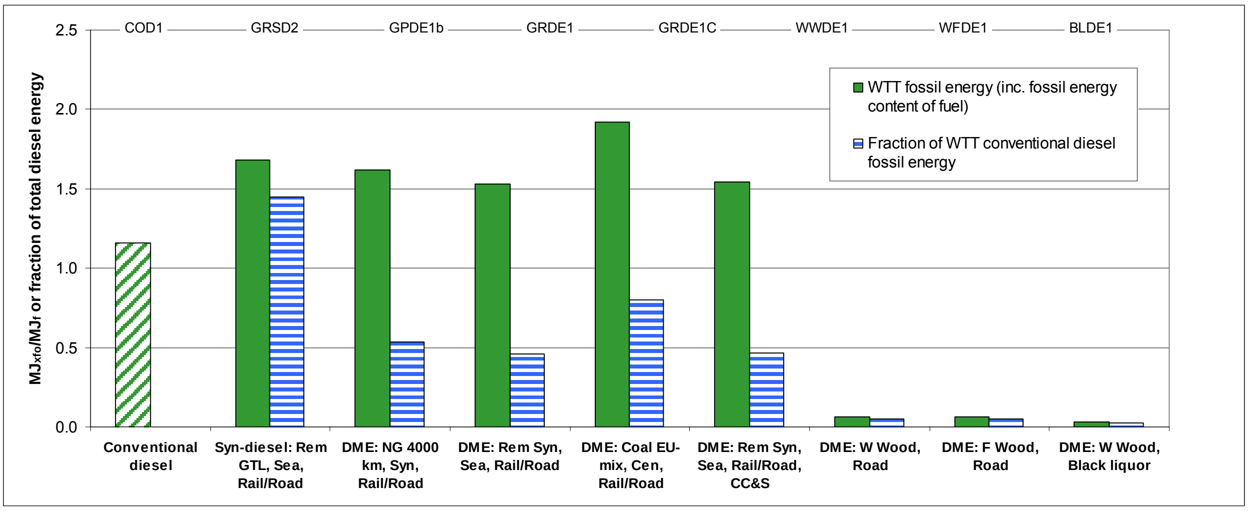


Figure 3.32 WTT GHG balance of DME pathways (including fossil CO_2 content of final fuels)

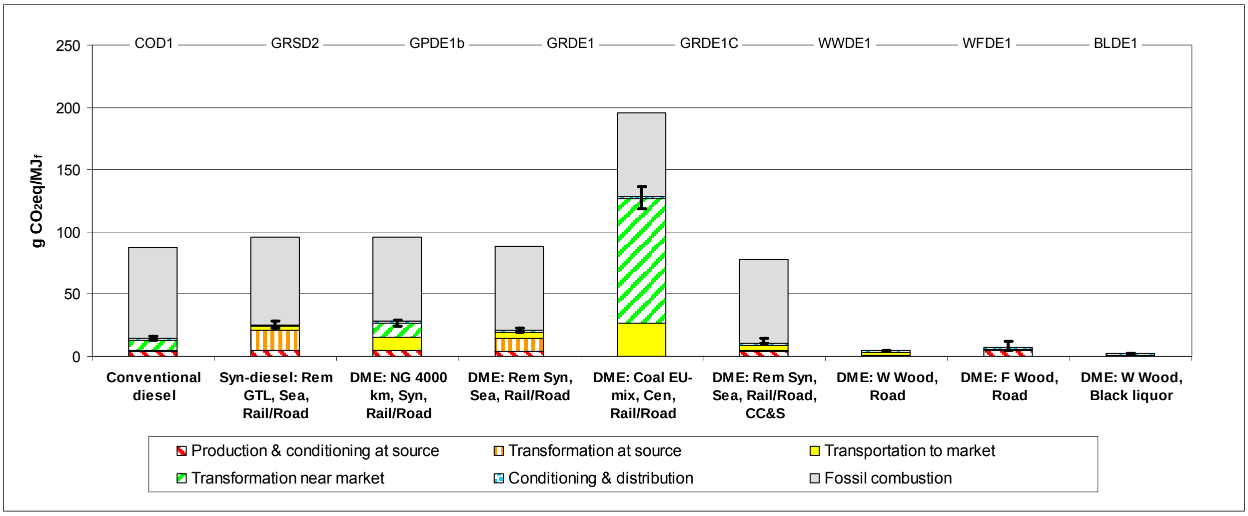


Figure 3.33 WTT GHG balance of DME pathways compared to conventional fossil diesel (including fossil CO_2 content of final fuels)

In Table 3.11 are reported the **TTW costs** for the pathways to DME.

Table 3.11 Costs and benefits of major pathways compared to conventional road fuels

Fuel	*Powertrain*	Alt. fuel consumed	Fuel substituted		Base case	WTW savings$^{(1,2)}$				Incremental cost over ref. scenario			Cost of substitution		Cost of CO_2 avoided
			Gasoline	Diesel	GHG	Energy (PJ/a)		GHG		G€ /a			€ /t fossil fuel	€ / 100 km	
Oil price @25 €/bbl		PJ/a	PJ/a		Mt CO_{2eq}/a	Total	Fossil	Mt CO_{2eq}/a	% of base	WTT	Vehicles	Total			€ /t CO_{2eq}
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**

Fuel	*Powertrain*	Alt. fuel consumed	Fuel substituted		Base case	WTW savings$^{(1,2)}$				Incremental cost over ref. scenario			Cost of substitution		Cost of CO_2 avoided
			Gasoline	Diesel	GHG	Energy (PJ/a)		GHG		G€ /a			€ /t fossil fuel	€ / 100 km	
Oil price @50 €/bbl		PJ/a	PJ/a		Mt CO_{2eq}/a	Total	Fossil	Mt CO_{2eq}/a	% of base	WTT	Vehicles	Total			€ /t CO_{2eq}
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

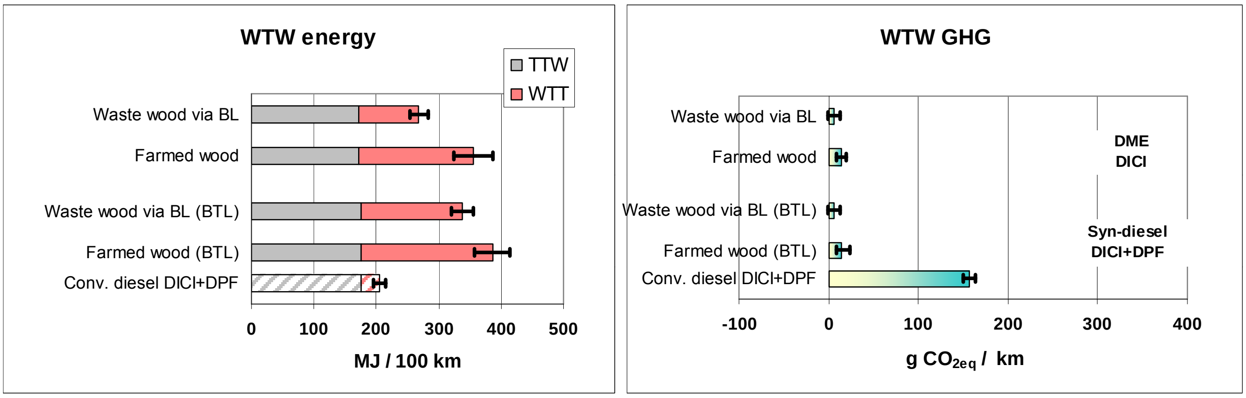
(2) Relative to the "business-as-usual" scenario: gasoline PISI for ethanol, diesel CIDI for diesel fuels and combined scenario for other fuels

The **WTW costs** are reported for synthetic diesel and DME in Figure 3.34.

The 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). 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). This view leads to consider that all products and their fate are independent of each other.

The combined process of primary energy conversion and FT synthesis is energy-intensive. This is mainly because the overall process is more straightforward and more energy efficient with gas. Very large and highly heat integrated plants are not expected for wood conversion plants where the size may be dictated by the raw material availability/collection and such complexity may not be economically justified.

Figure 3.34 WTW energy requirement and GHG emissions for synthetic diesel fuel and DME pathways (2010+ vehicles) ***(GHG bars represent the total WTT+TTW)***



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.

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.

3.6 Vehicle/fuel combination costs of CO_2 avoidance

To show the cost of CO_2 avoidance compared to the potential for eliminating the CO_2 emitted by the corresponding fossil fuels, **all the possible fuels options** analysed in the original WTW study are reported in Figure 3.35 and Figure 3.36. In these representations 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.

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 CO_2 mark, still much higher than the current value of CO_2 of 20-30 €/t.

Biogas fares quite well on the scale of CO_2 avoidance cost but possibly less well than could have been expected in view of the "free" feedstock and very large CO_2 avoidance. Although they are relatively simple technologically, biogas plants tend to be capital-intensive because the have to handle a lot of biomass to produce comparatively small amounts of biogas. Based on a number of literature sources a figure of 2000 €/kW of biogas produced has been used.

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 CO_2, the black liquor route showing its efficiency and cost advantages. The two points depicting ethanol from cellulosic material ("wood" and "straw") are quire far apart, illustrating the uncertainty on the potential performance of these processes..

Syn-diesel from wood provides CO_2 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.

Figure 3.35 Cost and potential for CO_2 avoidance (Oil @ 25 €/bbl)

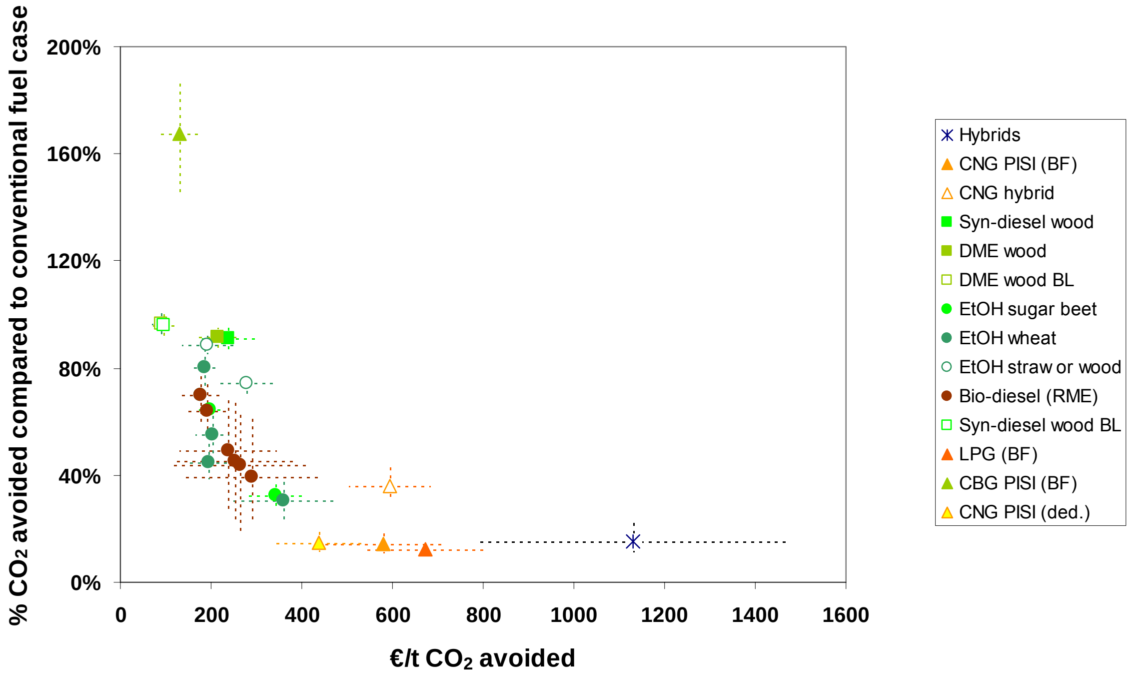


Figure 3.36 Cost and potential for CO_2 avoidance (Oil @ 50 €/bbl)

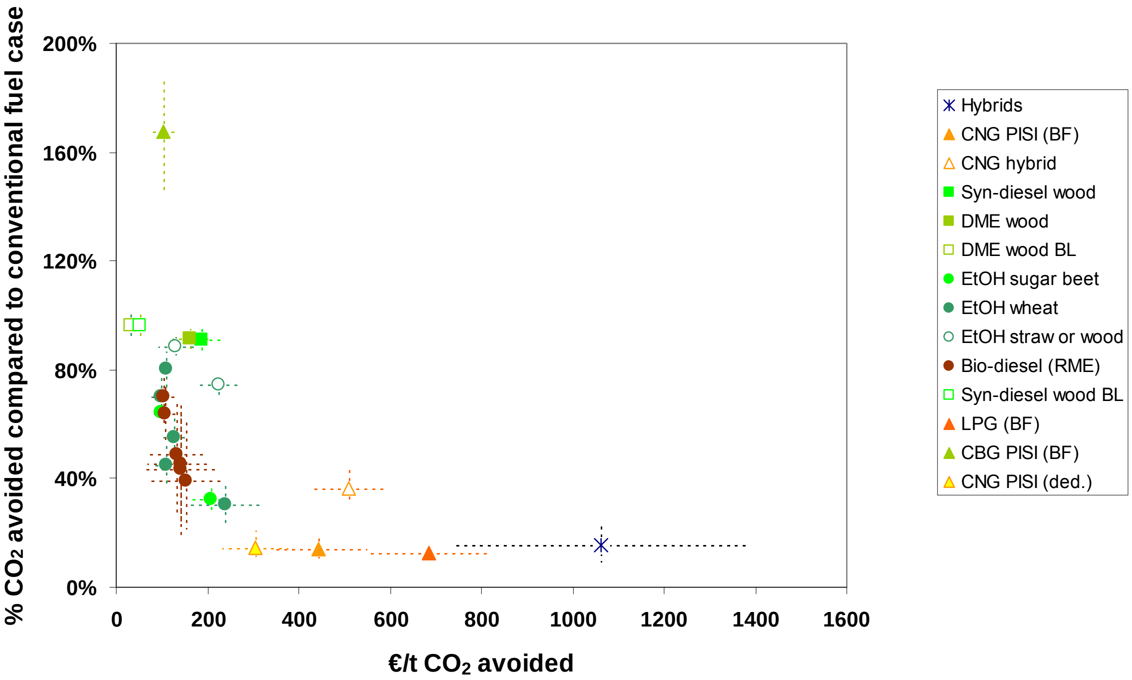
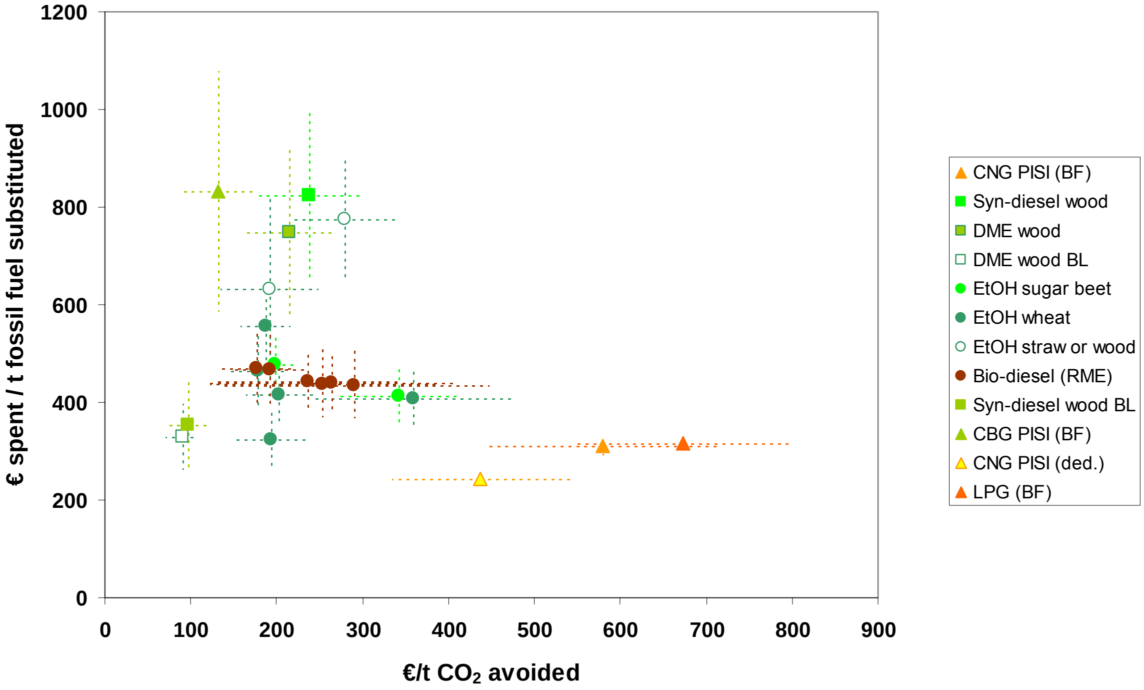


Figure 3.37 and Figure 3.38 show the cost of CO_2 avoidance now versus the extra cost of the pathway per t of conventional fuel substituted which is a measure of the cost of diversification of road fuel supplies. In this representation the best options are near the bottom left hand quadrant.

Figure 3.37 Cost of CO_2 avoidance versus cost of substitution (Oil @ 25 €/bbl)



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.

Biogas can save a lot of CO_2 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 CO_2 at an attractive cost. BTL (syn-diesel from wood) can save a lot of CO_2 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 3.8) are to be fully realised.

Figure 3.38 **Cost of CO_2 avoidance versus cost of substitution (Oil @ 50 €/bbl)**

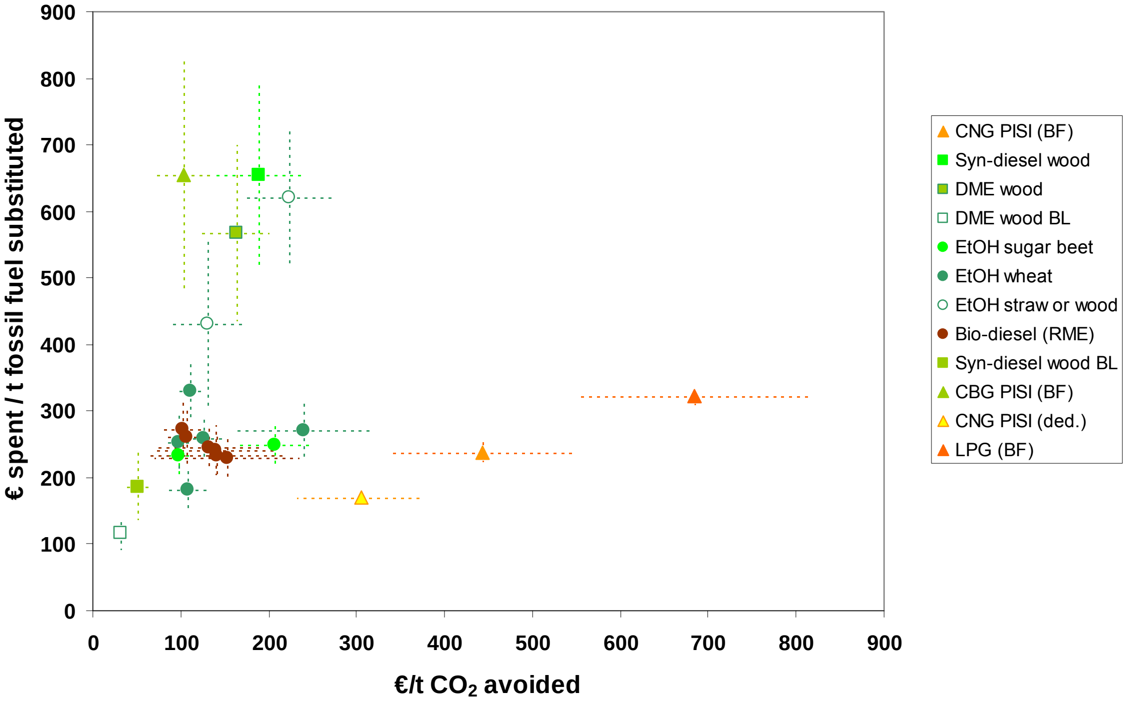


Figure 3.39 **% CO_2 avoided versus cost of substitution (Oil @ 25 €/bbl)**

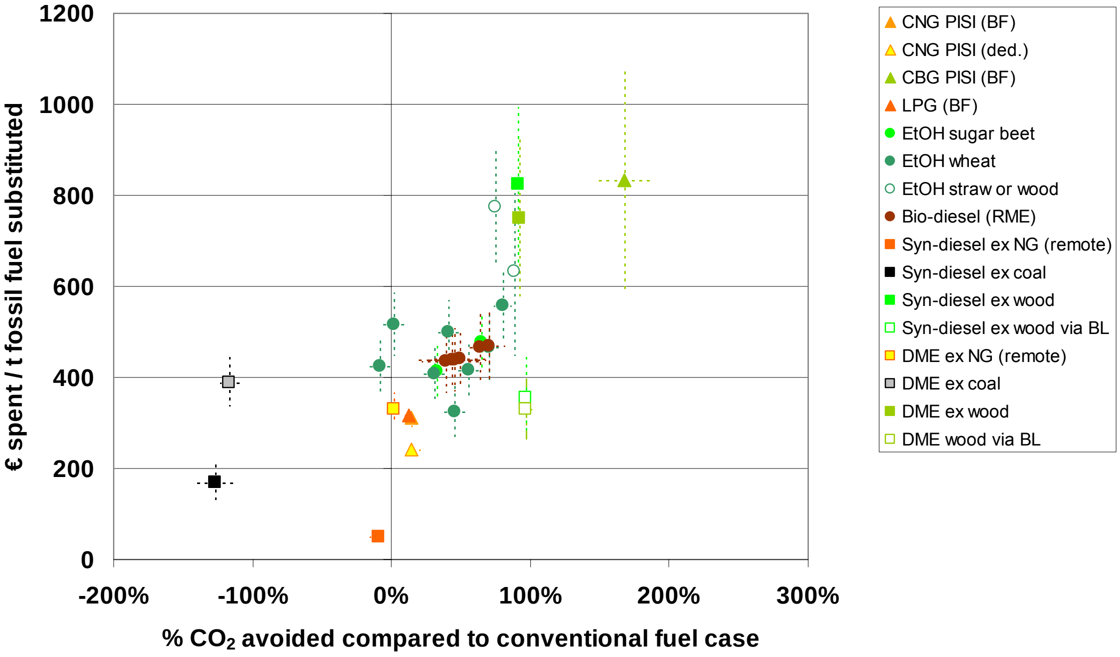
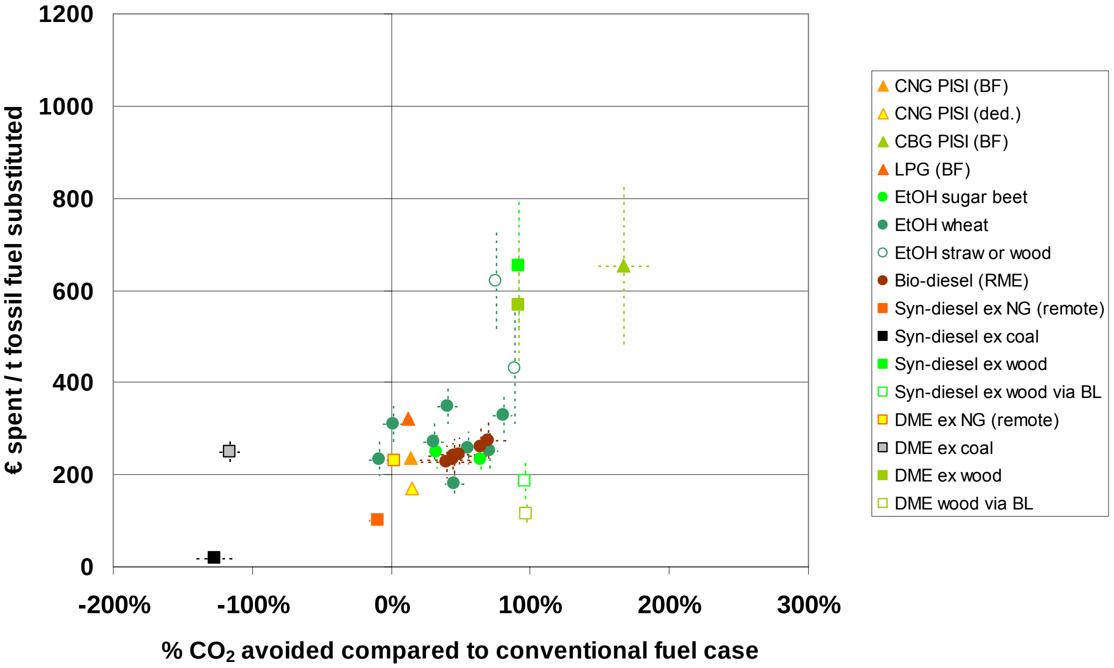


Figure 3.40 % CO_2 avoided versus cost of substitution (Oil @ 50 €/bbl)



In the two previous representations, only those options that do save CO_2 appear. In Figure 3.39 and Figure 3.40 the percentage (positive or negative) of CO_2 avoided compared to the conventional fuel reference has been plotted versus the cost of substitution.

3.7 Availability and costs of biomass-based fuels

The potential supply for all crops (and other biomass resources) is a strong function of the price one is prepared to pay. While there is a tendency in the literature to report the costs from the cheapest supply scenario while choosing the maximum availability limit regardless of cost, availability and cost should be assessed *together*: In fact it should be known how much biofuel can be produced for the cost one is considering (ideally, one would like to generate a cost-supply curve for each resource).

The expansion of arable area onto other land, notably pasture and forest has not been deliberately considered. 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.

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

3.7.1 Methodology for agricultural availability calculations

Learning curves for future yields and costs

Biomass for energy needs land and is therefore in competition with other crops, particularly food crops. As a baseline a DG-AGRI projection for agricultural production and markets up to 2012 has been used (with future agricultural yield improvements of 0.8% per year in EU15 and higher in the new Member States for conventional crops -including oilseeds and cereals- and the addition of new data on newly-developed high-yield varieties of feed wheat), assuming biofuels production remaining at 2005 levels as well as a constant demand for food crops (with the exception of sugar, see below). The possibilities and consequences of increasing biofuels production at the 2012 horizon have then been considered.

Some studies have proposed strong learning curves, which reduce the cost estimates for future biomass supplies. This makes sense for long-term estimates of relatively undeveloped processes (e.g. energy crops such as short rotation forestry). However, for the relatively short time horizon of the WTW study, it has been assumed that the best current commercial practice of short-rotation forestry will be typical by 2012. 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. For these reasons, there is a little opportunity for future cost reductions, so present-day costs have been used.

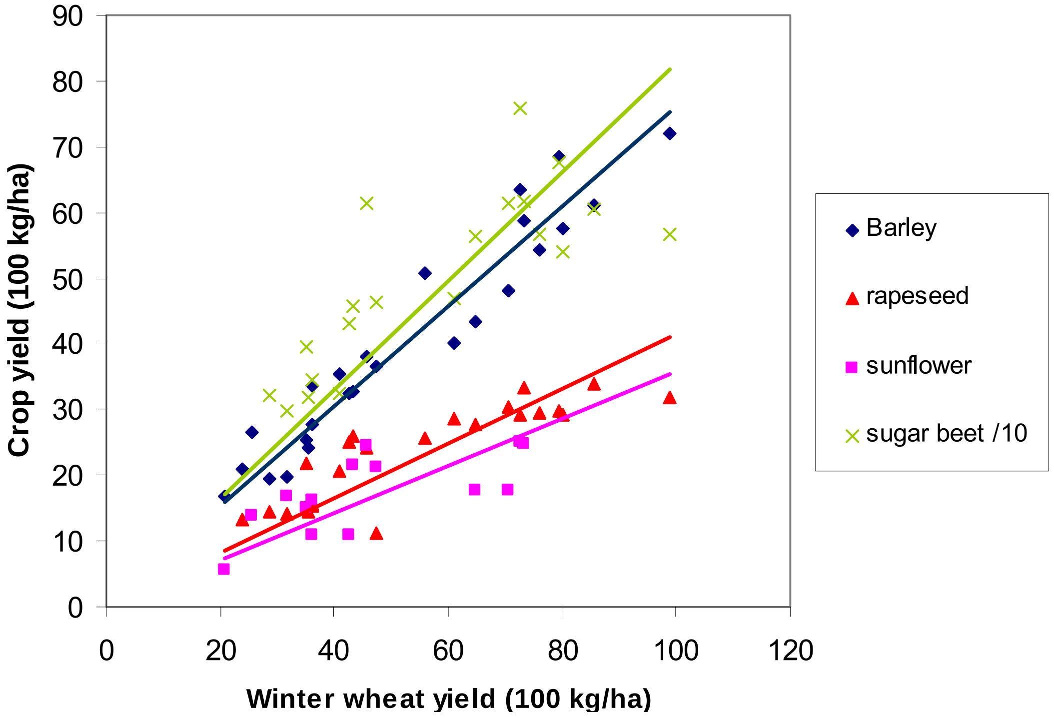
Using yield ratios is much more accurate than "average yield" calculations

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. Even within the area presently planted with wheat, some EU-15 land yields seven times less than the best. If more marginal land was planted in order to increase total production even worse yields could be encountered. However, there is a relatively good correlation between the yield of different crops on the same land (see Figure 3.41).

Figure 3.41 Correlation between yields of different crops in EU-25 (National averages, excluding irrigated crops)



Instead cereal production has been used as a proxy for yield postulating a constant ratio between the yield of cereal and the yield of other crops. Cereals are grown on 86% of EU arable land. Since it grows on most areas, the agricultural resources of EU has been expressed in terms of how much cereals could be grown on the available land, rather than on the number of hectares available. The agricultural capacity has been measured in "Mt **A**verage **C**ereals **E**quivalent". 1 Mt feed wheat has an average cereals equivalent (ACE) of 1.135 Mt, because the new varieties of feed wheat now coming into use show 30% better yield than soft bread-wheat, and 13.5% better yield than the weighted average of the present mix of wheat types.

Such approach automatically takes into account the limitations on agricultural potential imposed by water resources, which is the dominating constraint in many of the drier parts of Europe.

Impact of geographical distribution and break-crop effect on yield ratios

According to [*Christen 1999*], the yield of wheat after a crop of rapeseed is 10% higher than after another wheat crop. An increase in EU oilseed production would be met principally by increasing the frequency of oilseeds in a cereals rotation. If a typical rotation of wheat-wheat-barley-rapeseed is taken, it would shorten to wheat-rapeseed-wheat-rapeseed. Then for each extra rapeseed crop, one barley crop is lost and one wheat crop grown after wheat is replaced by one wheat crop grown after rapeseed. The net loss of cereals is about 85% of the average yield on that land.

Using EUROSTAT crop distribution and yield data, the average cereals yield has been calculated in the area where rapeseed is grown: 5.76 t/ha. On the basis of an average rapeseed yield of 3 t/ha (= EU15 average yield), growing an extra 1 Mt rapeseed by increasing the frequency of rapeseed-years in a cereal rotation leads to the loss of (only) 1.58 Mt average cereals, much less than the simple yield difference would indicate. So 1 Mt rapeseed has an Average Cereals Equivalent (ACE) of 1.58. The same calculation for sunflower indicates 1.47 Mt cereals lost per Mt sunflower seed. So 1 Mt sunflower seed is 1.47 Mt ACE.

3.7.2 Defining the baseline scenario

The WTW "business as usual" baseline adds sugar-reform to an existing DG-AGRI agricultural market projection, which assumes no expansion of biofuels.

In July 2005 DG-AGRI released a projection for EU agricultural markets up to 2012 in EU-25 [*DG-AGRI 2005*]. This assumes the implementation of planned CAP reforms and the transitional measures for the new Member States. Also taken into account are the Uruguay Round Agreement on Agriculture (URAA) commitments on subsidized exports and import barriers.

A qualitative discussion has been included of a scenario where the Biofuels Directive is implemented by subsidizing biofuels consumption, under the current CAP and trade regimes (see box in sec.3.7.4). However, the quantitative projections are for biofuels production at expected 2005 levels. This constitutes a baseline onto which the foreseeable effects of expanded biofuels production can be built.

Table 3.12 2012 total cereals and oilseeds production and prices according to [DG-AGRI 2005]

		Cereals	Oilseeds
World production (FAPRI)	Mt/a	1602.4	334.4
EU-25			
Production	Mt/a	270.9	19.9
Consumption	Mt/a	256.0	37.8
Exports-imports	Mt/a	14.9	-17.9
Consumption for biofuels	Mt/a	1.5	5.6
Commodity price (FAPRI)(1)	€/t	150 (2)	215 (2) (3)

(1)Converted at 1.15 $/€ (DG-AGRI's assumed exchange rate)

(2)For US hard red wheat. Equivalent price for feed wheat 85 €/t

(3)FAPRI rapeseed price (FOB Hamburg)

In 2012 [*DG-AGRI 2005*] projects that the arable area would remain practically unchanged from the 2005 level: 58 Mha of which 50 Mha are devoted to cereals. Out of a total EU-25 cereals production of 271 Mt in 2012, there would be a surplus of 14.9 Mt (equal to exports–imports if stocks are constant). Other crops would be roughly in balance except for oilseeds: if bio-diesel remained at the present level of production the EU would continue to import almost half its total oilseed requirements: 17.9 out of 37.8 Mt in 2012.

The area of set-aside is expected to increase to 8.3 Mha, because of the extension of compulsory set-aside in the new Member States and the extension of voluntary set-aside due to declining profitability there. This accounts for a large proportion of the present "land reserve" of abandoned or under-utilized agricultural land in Eastern and Central Europe.

However the DG-AGRI projection does not include the effects of the proposed reform of the sugar regime, which would have a significant effect on EU arable potential. Since these reforms do not depend on biofuels production, they have been added in to the WTW baseline projection.

Reform of the EU sugar policy will probably release about 9 Mt cereals capacity.

In [*EC 2005*] the EC describes its proposals to reduce EU sugar production by reducing the support price. Some type of reform is forced by international trade agreements, but it was not yet considered in [*DG-AGRI 2005*].

The present support regime for sugar beet leads to its cultivation in many regions of the EU that are not agronomically very suitable. However, the proposed reduction in price will, by 2012, confine its growth to the lowest cost regions: France, Belgium, Denmark, and a few parts of the Netherlands, Germany and UK. A price reduction from the present 41 €/tonne to 25 €/tonne is expected to reduce sugar beet production by 76 Mt, from the present total of 182 to 106 Mt (22.7 Mt to 13.2 Mt sugar equivalent), assuming the option of buying an extra 1 Mt “C sugar" quota under the reform is taken up [*EC 2005*].

The WTW calculations confirm that the total anticipated sugar beet production in [*EC 2005*] corresponds to growing one crop of sugar beet for every four crops of wheat in the most suitable areas: this is the maximum frequency recommended to avoid the survival of pests in the soil from one sugar beet crop to the next (sugar beet can be grown more frequently only by intensive use of pesticides to disinfest the soil).

For simplicity, all the land released have been assumed to make cereals in the baseline scenario. To estimate how much extra cereals would be produced, a suitable ratio of sugar beet to cereals yield needs to be found. Sugar beet requires good soil and plenty of water, so one expects winter wheat to be the preferred replacement crop, and to show a better-than-average wheat yield. On the other hand, the locations where sugar beet production will be abandoned will be where yields are poorest. Assuming these effects roughly cancel each other out, the simple ratio of EU-average sugar beet to winter-wheat yield has been used. According to EUROSTAT data for the year 2000 (an average year) the average EU-25 yield for sugar beet at 76% moisture was 56.24 t/ha and for winter wheat at 13% moisture 6.49 t/ha: a ratio of 8.66 to 1 (not quite the same value as the slope of Figure 3.41, because that is a line through un-weighted national yields). The ratio for EU-15 is the same because both yields are 9% higher.

Thus, at 2005 yields, an extra 8.8 Mt/a cereals could be produced on the land released from the sugar reform. [*DG AGRI 2005*] assume 0.8% per year improvement in cereals yields, which would raise the **cereals production on ex-sugar-beet land to 9.3 Mt/a (ACE) in 2012. This raises the cereals surplus from 14.9 Mt/a in [*DG-AGRI 2005*] to 24.2 Mt/a in the WTW baseline scenario.**

EU imports almost half its oilseed requirements, both now and in the 2012 projection. To estimate the maximum bio-diesel which can be made in the EU, the absolute level of imports has been assumed to be the same as in the baseline.

Table 3.13 Calculation of baseline total cereals and oilseeds production

		Cereals	Oilseeds
Production	Mt/a	270.9	19.9
+ from land released by sugar reform	Mt/a	9.3	0.0
= total production in baseline	Mt/a	**280.2**	**19.9**
EU consumption	Mt/a	256.0	37.8
Baseline exports-imports	Mt/a	24.2	-17.9
Baseline biofuel feedstock price (1)	€/t	85 (2)	215 (3)

(1)Converted at 1.15 $/€ (DG-AGRI’s assumed exchange rate)

(2)For low-protein wheat. Corresponding FAPRI price for US hard bread-wheat is commodity price is 140 €/t

(3)FAPRI rapeseed price (FOB Hamburg)

Table 3.14 shows the amount of biofuels which would be produced from EU sources in the WTW baseline scenario for 2012. The amounts of cereals and rapeseed for biofuels are those in the [*DG-AGRI 2005*] 2012 projection, based on conservative estimates of the EU biofuels production figures for 2005.

Table 3.14 Biofuels in the 2012 baseline scenario: fixed at 2004/5 levels

	Crop		Ethanol	Bio-diesel
	Mt/a	PJ/a	PJ/a	PJ/a
Rapeseed	5.6	133		78
Cereals	1.7	25	13	
Gasoline/diesel market coverage			**0.3%**	**0.9%**
Total road fuel market coverage			**0.7%**	

Organisation of section 3.7

In *section 3.7.3* conventional biofuels have been analysed: first it has been considered how much could be grown in EU regardless of cost and concluded that it is not possible to reach the targets in the biofuels Directive from EU production only. To allow the fulfilment of the Directive's targets, scenarios allowing imports have then been considered. In these cases the targets have been assumed as exactly achieved and it has been looked at the effect on agricultural prices and on how much of the crops required would be produced in the EU. The first scenario is the simplest: set-aside rules would be kept unchanged. The second scenario looks at what would happen if set-aside was abolished: agricultural prices have been used in the scenario for the WTW calculations of total biofuels costs. Both import scenarios assume that the present agreements on agricultural trade are respected.

Using alternative biofuels one can think to exceed the biofuels Directive targets for 2010 using domestic production. *Section 3.7.7* looks at the cost and supply of crop residuals, wood waste and farmed wood, transported to biofuels conversion plants. Finally, *section 3.7.8* examines how much compressed biogas could be produced in EU at the present cost.

3.7.3 Conventional biofuels production in the EU

In this first section it has been estimated in a transparent way how much bio-ethanol (from cereals and sugar beet) and bio-diesel could possibly be produced from EU domestic sources in 2012, regardless of how this would affect prices.

What has been assumed:

- Same food consumption and food imports as in the reference "business-as-usual" scenario. This includes continuing to import about half the EU's food-oilseed requirements.
- 5.75% of diesel should be replaced by bio-diesel and 5.75% of gasoline by bio-ethanol (the biofuels Directive target of 5.75% replacement of road fuels by 2010 does not specify how this should be split between gasoline and diesel)
- The diversion of EU exports to biofuel production has been allowed in the WTW study.

What has been excluded:

- The expansion of arable area by ploughing up pasture or forest land, to avoid loss of historical soil carbon stocks (see sec. 3.2).
- Biofuels from EU-grown animal feed crops. These latters could be diverted to increase biofuel production, but these would have to be replaced by imported animal feed. In other words biofuels from this source would be made from indirectly-imported crops.

There are three sources for increased EU production of biofuels crops in 2012

I_Diversion of the baseline cereals exports (including land from sugar reform)

Although the present EU cereals production is roughly balanced with consumption, Table 3.12 and Table 3.13 show that the WTW 2012 baseline scenario projects 23.7 Mt ACE surplus cereals for export. This comprises 14.9 Mt ACE in [*DG AGRI 2005*] (due to improved yields) and an additional 8.8 Mt ACE on land released by the sugar reform. To maximize EU-produced biofuels all this arable capacity has been assumed to make biofuels.

II_Additional production on ex-set-aside land

The extra production from set-aside cannot be calculated simply from the average EU wheat yield

Production of oilseed and cereals for biofuels is already permitted on set-aside land, but only if the farmer has a contract with a biofuel producer. The effect is to confine production on set-aside to farms in the region of biofuels factories. However, if set-aside rules were abolished there would be a general increase in cereals output, which could translate directly and indirectly into increased EU production for biofuels. First the general increase in cereals output has been estimated.

Rotational set-aside is already part of cereal rotations and the effect of removing these compulsory break-years is offset by the need for break-years anyway and by the benefit of break-crops to subsequent cereals yields. Voluntary set-aside land would also give lower-than average yields because it is relatively poor land where cereal farming is hardly profitable. Much of the land would not be good enough for wheat production: a mix of cereal types would be produced. Statistical analysis of data from the 1990s, when set-aside rates were changed several times, indicated that set-aside at 14% reduced cereals production by 10% [*DEFRA 2000*].

Looking at the variation in cereals area as compulsory set-aside was reduced from 10% to 5% in 2004 and then increased again to 10% in 2005 suggests that the effect on cereals production is now significantly lower than this, implying that farmers have learnt how better to integrate set-aside years in their crop rotations (but the set-aside increase for 2004 was announced too late to allow planting of winter fcwheat, so one should not take these data alone). Another reason why the DEFRA ratio will give an overestimate of set-aside production is that, in 2012, there would be a substantial increase in voluntary set-aside on poorly-yielding marginal land in the new Member States. Nevertheless, the DEFRA ratio shall be used for giving the **upper limit** of EU production.

The overall rate of set-aside projected for 2012 in the WTW baseline [*DG-AGRI 2005*] is 13.6%, that could reduce the potential cereals output by a maximum of 10%. The projected 2012 cereals production is 270.9 Mt, so the maximum on set-aside would be about 27 Mt. About 19 Mt of this would be from compulsory set-aside. To find how much *extra* biofuels could be grown on set-aside, the baseline production of biofuels crops has to be subtracted on set-aside, which amounted to 2.4 Mt rapeseed [*DG-AGRI 2005*] (equivalent to 3.8 Mt average-cereals), plus roughly 0.3 Mt cereals-for-ethanol. So the *extra* production on set-aside would be equivalent to 23 Mt average-cereals at maximum. The extra production on only *compulsary* set-aside would be 15 Mt ACE.

What is a set-aside?

There are two types of set-aside at present in EU-15: compulsory (or “rotational”) and voluntary (or “permanent”) set-aside. Compulsory set-aside forbids cereals farmers growing food on part of their land. The “default” area of obligatory set-aside is 10% of the area of all farms growing a significant amount of cereals, but the reference rate is adjusted according to the level of EU cereals stocks.

However, farmers are allowed to grow non-food crops on set-side land without further subsidy: these are generally part of a crop rotation with cereals. At present about 20-30% of set-aside in EU-15 is planted with “industrial” oilseeds (mostly rape for bio-diesel production) as part of cereals rotations, producing about 2.2-2.4 Mt/a of seeds designated as “industrial” [*FEDIOL 2002*][*DG-AGRI 2005*]. Set-aside rules will come into force in the new Member States in 2009: they will set-aside about 1.25 Mha arable land.

If planted year-after-year, cereals decline in yield because of disease build-up and soil degradation. This applies especially to soft wheat, which has the highest yield. As a result, most wheat in Europe is grown in rotation with a lower-yielding “break” crop. The farmer can declare a field to be in rotational set-aside and still use it for a break-crop, such as grass, clover or rapeseed. So the effect of set-aside is to encourage more frequent break-crops, and the reduction in EU cereals output is less than would be predicted by the % area in set-aside (a phenomenon known as “slippage”).

Although small farms are exempted from set-aside obligation, the overall set-aside rate in EU-15 is well above 10% (14% in 1999/2000 [*DEFRA 2000*]) of the eligible area, because of the operation of permanent set-aside: farmers are rewarded for turning up to 50% of their land over to “nature” for at least five years. According to current CAP rules, permanent set-aside cannot be used to grow arable biofuels crops, but can be used for wood farming.

Not much sugar beet would be grown on set-aside

Sugar beet is grown in rotation with other crops, especially wheat. In areas where sugar beet production at 25 €/t is more profitable than wheat, sugar beet will already be planted as frequently as possible in the rotation. That means roughly once in 4 years if large pesticide applications are to be avoided. Where sugar beet is the most profitable crop, farmers time set-aside years to be in the part of the rotation where sugar beet is not grown. So eliminating set-aside would not increase sugar beet production significantly: it would mostly increase the other crops in the rotation, most likely wheat. The land in voluntary set-aside is not good enough to produce sugar beet at all.

A significant amount of extra sugar beet might be produced at a competitive price if the wheat price increased significantly, for example if total ethanol production was pushed beyond 5.75% gasoline replacement.

III Use of “C” sugar beet

“C sugar” is sugar produced in excess of the food-quota. It cannot be sold for food in the EU but can be exported (assumed in the baseline) or sold for ethanol production. The sugar reform proposal allows up to 1 Mt of “C sugar” production (equivalent to 8 Mt sugar beet).

[*EC 2005*] estimates that the price of sugar beet should be 25 €/t to reach the planned levels of production. The WTW processing-cost calculations show that ethanol production from sugar beet at 25 €/t is just competitive with ethanol from wheat. So the production cannot anyway be increased much above this level without making ethanol from sugar beet uncompetitive.

The EU cannot produce enough crops to meet the 2010 biofuels Directive target using conventional biofuels, even if set-aside is abolished.

Table 3.15 sums the maximum extra production of arable crops from sources I and II above, expressed in terms of Average-Cereals-Equivalent. Sufficient cereals have been assigned to provide exactly 5.75% gasoline replacement with bio-ethanol (see also forecast road fuels demand in Table 2.7) taking into account:

- The existing (2005) production for biofuels, and the higher yield of cereals varieties suitable for bio-ethanol production expected in 2012,
- The 13.5% better yield produced by distillation-quality wheat varieties compared to average cereals,
- The additional ethanol available from 8 Mt “C” sugar beet as a result of the sugar reform.

The **rest** of the arable capacity was assigned to oilseed production, assuming 80% of it would go to rapeseed and 20% to sunflower seed production.

Table 3.15 Upper limit of conventional biofuels production from EU crops in 2012, with set-aside abolished.

	ACE(1)	Crop		Ethanol	Biodiesel
	Mt/a	Mt/a	PJ/a	PJ/a	PJ/a
I Diverted baseline cereal exports:					
From land released by sugar reform	9.3				
Fom improved yields	14.9				
II Maximum extra cereal from set-asides(2)	22.9				
Total spare cereals	47.1				
To feed-wheat for ethanol	22.4	25.4	376	202	
To oil seeds	24.7				
Equivalent oil seeds(3)	⇩				
Rapeseed	19.8	12.5	298		174
Sunflower	4.9	3.4	80		50
III Ethanol from"C" sugar beet		8.0	31	16	
Existing crops for energy in baseline(4)					
Rapeseed		5.6	133		78
Cereals		1.5	22	12	
Total				**230**	**302**
Gasoline/diesel market coverage				**5.75%**	**3.4%**
Total road fuel market coverage				**4.2%**	

(1) Average Cereals Equivalent (our measure of arable capacity)

(2) Excluding biofuels already grown on set-asides

(3) Assumes 80/20 rape/sunflower

(4) i.e. in the baseline scenario, including those grown on set-aside

The existing arable area, even including set-asides**, is not sufficient to attain the biofuels targets through domestic production in 2012. An upper limit of 4.2% of conventional road-fuels can be substituted, which is 72% of the biofuels Directive target**. Some fossil energy is used in making biofuels. Taking a mix of the most likely biofuels processes, the net fossil energy avoided has been estimated to be about 3.2% of the total used for making road-fuels in 2012.

Without more biofuels from set-aside only 2.5% road-fuels can be replaced by domestic production

The same procedure could be performed without assuming an increase in arable production on set-aside compared to the baseline (i.e. no source II). After satisfying the cereals-for ethanol demand, there is not much capacity left over for bio-diesel. In reality, the proportion of resources going to oilseeds would be somewhat higher than indicated, but this hardly affects the overall replacement of road-fuel: about 2.5% from EU crops.

Table 3.16 Limit of conventional biofuels production from EU crops in 2012 with no increase in production on set-aside

	ACE(1)	Crop		Ethanol	Biodiesel
	Mt/a	Mt/a	PJ/a	PJ/a	PJ/a
I Diverted baseline cereal exports:					
From land released by sugar reform	9.3				
Fom improved yields	14.9				
II Maximum extra cereal from set-asides(2)	0.0				
Total spare cereals	24.2				
To feed-wheat for ethanol	22.4	25.4	376	202	
To oil seeds	1.8				
Equivalent oil seeds(3)	⇩				
Rapeseed	1.4	0.9	22		13
Sunflower	0.4	0.2	6		4
III Ethanol from"C" sugar beet		8.0	31	16	
Existing crops for energy in baseline(4)					
Rapeseed		5.6	133		78
Cereals		1.5	22	12	
Total				**230**	**94**
Gasoline/diesel market coverage				**5.75%**	**1.1%**
Total road fuel market coverage				**2.5%**	

for notes see table 5.2.3-1

Maximizing production of biofuel from EU crops would cause a large rise in oilseed price

Still assuming oilseeds are not diverted from food-use, the maximum EU production scenario above requires an extra 15.7 Mt oilseeds from EU production, raising it to 178% of the 2012 baseline production of 19.9 Mt (see Table 3.12). However, the release of set-aside land would increase the EU arable capacity by up to about 10% compared to baseline 2012. Therefore the *fraction* of arable capacity used for oilseeds would rise to about 163% of the fraction in the baseline scenario.

The long-term EU oilseed-sector area response flexibility on price was estimated to be 0.84 in [*Meilke 1998*] (that means that a price increase of 1% causes a supply increase of 0.84% at constant yield). This implies that the price increase associated with a 63% increase in production would be about 63/0.84 = 75%! Other estimates for the flexibility are lower, implying even higher price rises. More details of the WTW method of price-change calculation are given in sec.3.7.4

Crop rotations limit maximum rapeseed production

Flexibility calculations are not really valid for such large changes. The large oilseed price increases found to accompany this maximum EU production scenario indicate that it is probably beyond what is agronomically reasonable. To quote [*DG-AGRI 2005*]: “under an extreme scenario with substantial price increases, the rise in domestic production of cereal and oilseed could meet 50% of the additional demand from the biofuels Directive" (although the assumptions behind this calculation are not clear). The WTW maximum EU production amounts to 68% of the additional demand from the biofuels Directive.

At the moment almost all bio-diesel grown in EU is from rapeseed, because it is the cheapest and most suitable vegetable oil grown in EU. Soil and climate limitations mean that rapeseed is usually rotated with common wheat. Common wheat production would be about 140 Mt in 2012 [*DG-AGRI-2005*], whereas the WTW upper limit of oilseed (rapeseed + sunflower in Table 3.15) cultivation is 24.7 Mt. The unadjusted yield ratio of wheat/rapeseed is about 2.3, so, if all extra production is rapeseed, there would be only about 2.5 wheat crops to each rapeseed crop. Bearing in mind that less land is suitable for rapeseed than common wheat, this is an extreme scenario. It means that rapeseed would have to be grown in 3 or even 2-year rotations (which reduces the benefit of the break-crop and may allow survival of pests between crops), and/or on land for which it is not very suited, probably rotating with coarse cereals.

One expects that the lower yields and dilution of the break-crop benefit would increase the marginal cost of rapeseed production substantially. The increasing price of rapeseed oil would drive biofuels producers to mix in other oils such as sunflower oil, which can be grown in EU areas unsuitable for rapeseed. 20% of the oil demand has been assumed to come from sunflower oil, but the proportion is not critical to the calculation of the overall biofuels production potential.

The contribution of animal fats and used cooking oil is small and uncertain

EU-15 used to use about 1 Mt animal fats per year in animal feed. That is no longer permitted because of the BSE problem, so turning it into useful bio-diesel is a very attractive idea. One could also possibly divert some of the 2 Mt animal fat used for other purposes in the EU. Argent energy are building a plant to convert most of the material available in the UK to a form of bio-diesel. Animal fats give a more viscous quality of FAME with a high cloud point, so there may be problems to reach road fuel specification.

About 6 Mt/a vegetable oils are consumed in EU-15, but the proportion that can be recovered separately and economically is highly speculative.

These sources have not been included in the WTW availability scenarios for conventional biofuels.

3.7.4 Estimate of bio-fuel crop prices

Market prices rather than bottom-up costs

Many LCA studies attempt to calculate costs of agricultural products by bottom-up estimates of farming cost. In such difficult way to approach the subject, it is almost impossible to represent an average "cost to EU" and it is very easy to lose touch with farming reality. The reforms of the CAP have largely brought internal EU prices in line with world prices (with the exception, until now, of sugar beet). In any case, since biofuels crops are internationally traded commodities, the cost to EU is the price which EU gets for exporting them or pays for importing them. Not only are these world prices known, but there are sophisticated projections available about how they may develop in the future.

In this section only the implications of meeting the targets for road-fuels replacement in the biofuels Directive (in 2012) have been estimated (the effects on domestic production, imports, exports and cost are considered).

Ligno-cellulosic resources (wood waste, short rotation forestry and crop residuals) are treated separately, since their production is not confined to arable land.

Key assumptions are:

- *5.75% (energy content) of the 2012 gasoline and diesel fuel demand* is replaced by bio-ethanol and bio-diesel respectively,
- *There is no expansion of arable area onto forest or grazing land*, to avoid loss of historical soil carbon stocks (see sec.3.2),
- *Existing trade agreements are maintained.*
- The EU is committed to various trade treaties, and probably cannot erect new tariff barriers even if it was desirable to restrict imports of feedstock for biofuels.
- *Cereals are treated as a single market*
- Even though not all types of cereals are equally suited for making ethanol, there is plenty of flexibility in competing uses, especially animal feed. Furthermore some farmers will change the

cereals crop they grow, if one or other becomes relatively more expensive. Therefore when estimating the effect on prices of demand changes, cereals have been considered as a single market (thought more appropriate than to consider wheat only). There is an argument for including also alternative carbohydrate animal feeds, such as manioc, but the effect on the results would be marginal.

- *Oilseeds are treated as a single world market*
- At present, quality standards restrict EU bio-diesel production effectively to rapeseed. In the future technology and legislation may be expected to evolve to permit use of a wider range of oilseeds. But even if this does not happen, rapeseed oil is easily substituted by other oils in the food market. Thus at the moment most EU bio-diesel is made from domestically grown rapeseed, but this is partly substituted by importing other oilseeds to satisfy the food demand.
- *The single farm payment is not included in the costs*
- In line with other costs, the cost considered is the direct cost-to-EU. However, the cost does not include the single farm payment. This incorporates the former “direct area payment” of 63 €/t nominal historic cereal production on the land, including rotational set-asides, no matter what crop the farmer produces. This payment would remain the same whatever use is made of the crops so that it does not have to be taken into account in the biofuels cost assessment.
- *Food and feed demand are the same as in the baseline 2012 scenario*
- This means the only supply elasticity has been considered. Although in theory the demand elasticity should also be considered, the demand elasticities in the literature are caused by people switching from one type of cereal or oilseed for another. If the whole cereal or oilseed market is considered, the demand elasticities will be very low: people and cows will not eat much less in total even if the price rises.

WTW study started from DG-AGRI’s prices projection for 2012 without extra biofuels

[*DG-AGRI 2005*] forecasts EU prices on the basis of the interaction of the CAP and other EU agronomic and trade rules. The introduction of the single farm payment, combined with the progressive lowering of trade barriers in agriculture according to obligations under trade treaties, means that the price of agricultural products in the EU is tied to the world market price. Thus [*DG-AGRI 2005*] bases its agricultural prices for 2012 on two independent forecasts of the world market, from FAPRI and OECD, which predict the price of agricultural commodities at EU ports. For the products of interest, the two forecasts are very similar: they differ by much less than the uncertainty from fluctuations in the $/€ exchange rate (which is assumed to stabilize at 1.15 $/€ in [*DG-AGRI 2005*]). The price forecast has been used from [*FAPRI 2005*] because it differentiates between different oilseeds.

The prices in [*FAPRI 2005*] and [*DG-AGRI 2005*] assume that biofuel production stays at 2005 levels (0.6% road fuel replacement, mostly by bio-diesel). Thus they could serve for calculating the cost of biofuels *where there is only a marginal increase in biofuels production*. But as it is shown below, attaining 5.75% road fuels substitution will have a large effect not only on EU agricultural markets, but even on the world market.

Distillation-quality wheat costs 95 €/t in the baseline scenario

[*DG-AGRI 2005*] quote the [*FAPRI 2005*] price projection of 159 $/t for the standard commodity “hard red US wheat FOB Gulf”. EU soft wheat trades at about 40$/t less than this, and experts expect further improvements in yields of distillation-quality very-low-protein feed wheat to reduce the production cost by a further 10$/t by 2012, bringing the price to 109$/t, or **95€/t**. At this price it could be competitive with imported feed-barley, even without an import tariff barrier. This type of wheat requires adequate water, so is especially suitable for growing in the highly-intensive wheat-growing regions of Northern Europe.

In the WTW baseline scenario, the extra cereals production on land released by the sugar reform would decrease world cereals prices by a negligible 1% or so.

Effect of meeting the biofuels Directive targets on trade, food and feedstocks prices:

DG-AGRI's analysis

[*DG-AGRI 2005*] warns that achieving the biofuels directive’s target of 5.75% road-fuels substitution by biofuels in 2010 would have a “major impact” on cereal and oilseed prices.

The effect on ethanol production cost would be partially offset by an increase in the value of by-products as animal feed, due to ethanol production competing for the supply of feed-wheat. On the other hand, the EU would end up paying substantially more not only for the crops used for biofuels, **but also for the crops used for food and animal feed.** This would be reflected in sharply improved farm incomes and higher food prices for consumers.

Effect of biofuels targets on imports

On the assumption that the trade regime follows current obligations (import tariffs and quotas), [*DG-AGRI 2005*] discusses the effect on the market and on production of achieving 5.75% replacement of gasoline and diesel by bioethanol and FAME respectively.

The report states that "under an extreme scenario with substantial price increases, the rise in domestic production of cereal and oilseed could meet 50% of the additional demand from the biofuels directive".

Of the remaining demand, 25% would be met through direct imports and 25% by diverting wheat, maize and rapeseed from animal feed and food use. The supplies of animal feed and food would then be made up by imports, so in the end at least 50% of the extra biofuel supplies would come directly or indirectly from imported crops.

Thus DG-AGRI contends that the EU would become a net importer of cereals, despite the substitution of feed-wheat by other (partly imported) animal feeds, and the existence of import barriers. The EU already imports half its oilseed requirements and the production of oilseeds is constrained by crop rotations, climate, and the Blair House agreement. Therefore, under the current trading regime, **more than half of the extra vegetable oils needed to reach 5.75% diesel substitution by FAME would come from imported oilseeds or vegetable oil.**

3.7.5 Meeting the Biofuels Directive with imported crops: impact on prices and EU production

No change in trade barriers

It has been seen that attempting to maximize EU-produced biofuels can give large price increases and lead to a shortage of oilseeds. EU imports about half its present oilseed requirements, and they attract no import tariff. Furthermore, it would be legally difficult to erect new trade barriers against imports of oilseeds. Therefore, trade has been considered to be an essential part of a realistic scenario for biofuels pricing. EU has a 90€/t tariff on imports of cereals, but this has limited impact because the EU is expected to have a net cereals surplus.

5.75% EU ethanol in gasoline would increase world cereals prices slightly

The rate at which cereals supply varies with price is called the supply flexibility. Estimates vary widely, partly because of geographical variations and (often unspecified) statistical uncertainty, but also because different effects may be included. Values for individual cereals types reflect the flexibility of farmers to switch between different cereals crops, but the flexibility for the cereals sector is needed as a whole. Furthermore, the inertia for change from one growing season to the next should not be included, because in the WTW case the change happens over a number of years. An analysis which produced a sensitivity measure suitable for the WTW purposes is described in [*DEFRA 2000*] (p.132). Separating out the inertia for change in a separate coefficient, they find the EU-15 cereals sectorial supply flexibility to be 0.62 +/- 0.26.

Although there would be no increase in EU *production cost* due to the extra demand from biofuels, there will be a small increase in cereals *market price* compared to baseline, because expanding biofuels production would deprive the world market of the baseline EU exports. These total 24.2 Mt ACE (see Table 3.15) or 1.5% of the projected world 2012 cereals production of 1600 Mt. If production on set-aside was unchanged, this would cause a 2.3% increase in world price (± 1.2 %). But the baseline price should anyway be 1% below the DG-AGRI/FAPRI projection due to the effects of the sugar reform: the net price change is insignificant.

This is a simplified analysis: the effects of making biofuels on local prices may be more significant due to the isolating effects of transport and shipping costs. Here we are talking of differences in the region of 10-20 €/t: still less than the annual variation due to weather.

5.75% EU bio-diesel would increase world oilseed prices significantly

Replacing 5.75% of EU 2012 diesel with bio-diesel from rapeseed would require 36 Mt of oilseed. Subtracting the oilseeds already used for EU bio-diesel in the baseline scenario, the demand *increase* would be 30.8 Mt, 9% of the projected world oilseed supply in 2012 (or 160% of projected 2012 EU production in the baseline scenario).

The world supply flexibility of the oilseed sector is needed as a block. The nearest which could be found was long-term area response flexibilities for the oilseed block in different countries. These may be used as a proxy for supply flexibility, because yields hardly change with price [*DEFRA 2000*]. According to [*Meilke 1998*], the flexibilities range from 0.2 to 1.03 for different countries. If an average figure of 0.8 ± 0.3 is taken, the conclusion is that a 9% increase in oilseed supply would require a **rise in world price between 8% and 18%.** If set-aside is liberated, the price rise should be lower because of the increase in arable area. However, the effect on the price estimate is insignificant. The oilseeds prices for the WTW biofuels cost calculations are set at **10% above the 2012 FAPRI-projection prices** quoted in [*DG-AGRI 2005*]. That brings them to **237 €/t for rapeseed and 265 €/t for sunflower.**

EU cereals production for biofuels should increase more than oilseed production

The WTW cost analyses show that bio-ethanol from cereals and bio-diesel are approximately cost-competitive. At the time of writing, bio-diesel production is expanding more rapidly than ethanol, but that is probably because of the shorter lead-time and lower capital cost for bio-diesel production plants; furthermore EU oilseed production is not keeping pace with the increase in bio-diesel processing capacity. In the longer term, the EU oilseed price can be expected to increase much faster than that of cereals (for comparable increases in FAME and ethanol production) because the EU oilseed supply potential is much smaller (being limited by rotations, climate and soils). If bio-diesel and bio-ethanol are given equal incentives, bio-diesel would use more imported feedstock than bio-ethanol processed in EU.

Since the EU is projected to produce more cereals than it consumes for food and feed, its use for ethanol production inside the EU also avoids the costs associated with exporting it. This does not apply to oilseeds which would not be exported anyway, because the EU has a deficit in supply.

So one may expect most of the spare EU arable capacity to go towards satisfying the cereals-for-ethanol demand until that market is saturated (in Table 3.15 it is assumed that it happened at 5.75% gasoline replacement). After that, using EU arable capacity for oilseeds becomes more interesting because any *more* cereals produced would then have to be exported, with associated costs.

The effect of liberating or freezing production on set-aside

There is presumably no legal barrier to EU relaxing its set-aside rules in order to reduce imports. Even if the present set-aside rules are not changed, some expansion of production on set-aside could be expected. But the extra production will be limited by logistics, because according to the present CAP rules, crops from set-aside must be contracted to go directly to a processor, rather than joining the larger food/feed market. Furthermore, production of oilseeds on set-aside is partially constrained by the Blair House agreement (see box).

The Blair House agreement

The Blair House agreement, extended in 2002, limits the effect on US soy bean exports of the oilseed-meal by-products from subsidized “industrial” oilseeds grown on EU set-aside land. In practice it limits oilseed production on EU-15 set-aside land to about 2.4 Mt, grown on approximatively 0.95 Mha. [*DG-AGRI 1997*]. Current production of rapeseed on set-aside runs at close to this level.

But biofuels manufacturers are already using almost three times this amount of oilseeds: they have to buy unsubsidized "food" rapeseed at the world market price.

Blair House would not seem to prevent set-aside areas being used to grow food crops in replacement of crops grown for biofuels on non-set-aside, or simply doing away with set-aside altogether. Anyway, Blair House only applies to *subsidized* oilseed farming: it is not applicable if bio-diesel production is encouraged by fuel tax exemptions rather than by direct farming subsidies. So in practice Blair House need not limit bio-diesel production, even if set-aside land is used.

If the EU wishes to increase oilseed production for biofuel, it appears that Blair House disallows the use of more subsidized oilseeds but allows subsidies on biofuels production.

To cover the range of outcomes for different set-aside policies, two extremes have been considered. In one case production on set-aside has been frozen at the 2004/5 levels assumed for 2012 in [*DG-AGRI 2005*]. In the second case set-asides has been assumed to be liberalized, so farmers could choose which crops to grow on that land, and that the produce could be sold freely on the market. The maximum possible production on set-asides was already estimated in sec. 3.7.3. The problem now is to analyse how much oilseeds and how much cereals would actually be produced in the EU.

Only production on voluntary set-aside would cost more than baseline

The supply calculated for a given market price would not be valid if that price was exceeded by the production cost. The extra sources of arable potential for expanded biofuels, compared to baseline scenario, are production on set-asides and diverted exports. The cost of crop production on compulsory (rotational) set-aside is about the same as on the same land not in set-aside [*DEFRA 2000*]. Exported cereals (from increased yields and the good farmland liberated by the sugar reform) could be diverted to biofuel production even with a cost saving, because no shipping is needed. Only the marginal land typically volunteered for voluntary set-aside would have higher crop production costs. Arable farming on most of this land would probably not be profitable even with the price rises due to biofuels. Furthermore, although there may be little historical accumulation of soil carbon to lose on voluntary set-aside land, ploughing it up would prevent any *increase* of soil carbon uptake.

If the potential production from voluntary set-aside is not taken into account, the EU cereals potential is get at the baseline production cost. Voluntary set-aside contributed about 30% to the WTW total EU 2012 set-aside production potential, leaving a contribution of about 16 Mt average-cereals from rotational set-aside. This is included in Table 3.17.

Table 3.17 Achieving the biofuels Directive targets with trade Set-aside frozen at baseline production (2004/5)

	ACE(1)	Crop		Ethanol	Biodiesel
	Mt/a	Mt/a	PJ/a	PJ/a	PJ/a
I Diverted baseline cereal exports:					
From land released by sugar reform	9.3				
Fom improved yields	14.9				
II Maximum extra cereal from set-asides(2	0.0				
Total spare cereals	24.2				
To feed-wheat for ethanol	22.4	25.4	376	202	
To rape seeds(3)	1.8	1.1	27		16
Oil seeds imports		**29.6**	704		**412**
III Ethanol from"C" sugar beet		8.0	31	16	
Existing crops for energy in baseline(4)					
Rapeseed		5.6	133		78
Cereals		1.5	22	12	
Total				**230**	**505**
Gasoline/diesel market coverage				**5.75%**	**5.75%**
Total road fuel market coverage				**5.75%**	

(1)Average Cereals Equivalent (our measure of arable capacity)

(2)Excluding biofuels already grown on set-asides

(3)Small extra production, most cheaply from rapeseed

(4)i.e. in the baseline scenario, including those grown on set-aside

The market would favour exporting cereals and importing most oilseeds

Having estimated the effect of the biofuels Directive on the world price, it is now possible to see how this would affect EU oilseed output. For the WTW cost calculations in the "biofuels" scenario (see sec.3.7.5), an oilseed price of 10% above the business-as-usual price has been chosen, although the calculation showed the increase could be in the range 8 to 18%.

[*Meilke 1998*] states that the long-term area response flexibility for oilseeds sector in EU is 0.87. Therefore a price increase of 10% results in a production increase of about 8.7% (assuming constant yield). The WTW baseline EU oilseed production is 19.9 Mt/a. So, on the same arable area one would expect to get an additional 1.7 Mt oilseeds. However the sugar reform increases arable capacity by 4% and the possible liberation of compulsory set-aside by a further 7%, so the total **increase in EU oilseeds supply would be about 2 Mt/a** according to the WTW reference price increase, with a range is between 1.5 and 3.4 Mt/a. This is only a small part of the extra 31 Mt/a oilseeds needed to reach the 5.75% bio-diesel target.

Note: Shipping costs tend to favour local production. However, the calculation is based on changes from the baseline scenario, where oilseeds already compete with EU production in spite of shipping costs, so this effect should cancel out. Furthermore the cereals are exported also in the baseline scenario, so shipping costs should make no difference there either. Anyway, adding 10% costs for shipping would not change the main conclusion.

The main point is that it would be more profitable for EU farmers to use most their increased arable capacity in 2012 for cereals exports rather than growing oilseeds, and it would be cheaper for biofuels producers to import (directly or indirectly) most of their feedstock. This reflects the reality that, compared to the rest of the world, EU is more suited to growing cereals than oilseeds. In practice, rapeseed is preferred for bio-diesel production, whereas soy, sunflower and maize oils (mostly imported) are preferred for food. Therefore EU rapeseed oil would be diverted from food-use to bio-diesel, to be replaced by imported food oils. Thus the feedstock for bio-diesel would largely come *indirectly* from imports.

Table 3.18 Achieving the biofuels Directive targets with trade Set-aside abolished

	ACE(1)	Crop		Ethanol	Biodiesel
	Mt/a	Mt/a	PJ/a	PJ/a	PJ/a
I Diverted baseline cereal exports:					
From land released by sugar reform	9.3				
Fom improved yields	14.9				
II Maximum extra cereal from set-asides(2	16.0				
Total spare cereals	40.2				
To feed-wheat for ethanol	22.4	25.4	376	202	
To rape seeds(3)	3.0	1.9	46		27
To cereal exports	14.8				
Oil seeds imports		**28.8**	687		**401**
III Ethanol from"C" sugar beet		8.0	31	16	
Existing crops for energy in baseline(4)					
Rapeseed		5.6	133		78
Cereals		1.5	22	12	
Total				**230**	**506**
Gasoline/diesel market coverage				**5.75%**	**5.75%**
Total road fuel market coverage				**5.75%**	

for notes see table 5.2.5-1

So, without increasing production on rotational set-aside, there is only just enough arable capacity in the EU to produce 5.75% ethanol in gasoline; very little left over for oilseeds or exports.

Comparing the two scenarios, the main effect of liberating rotational set-aside would be to increase cereals exports. In either case nearly 30 Mt of oilseeds (rapeseed equivalent) would be imported in a free agricultural market. Of course this could also be in the form of vegetable oil or processed bio-diesel. Importing processed bio-ethanol would lead to a little more oilseed production if set-asides are frozen, but mostly to more cereals exports in a free agricultural market.

Of course, EU could intervene in the market in various ways to promote use of EU-produced oilseeds for bio-diesel at the expense of cereals exports, but this would be at additional cost.

By-product markets

Large additional production of protein animal feed by-products would cause a price decrease

Both ethanol and bio-diesel lead to the production of protein animal feed by-products namely DDGS and oil-cake respectively. They are produced in the EU if the processing is done there, regardless of whether the feedstock is imported or not. For the energy and emissions balance, a credit representing the present main source of animal protein in the EU is given: soy meal made from imported beans. Forecasts of the by-products themselves have been used.

It is important to know the amount of animal-feed by-product in order to check that the market can absorb it all. An extra 218 PJ of ethanol is needed to replace 5.75% of EU gasoline consumption (above baseline). The DDGS by-product is most valuable as animal feed, replacing 7 Mt soybean meal. Replacing 5.75% diesel with bio-diesel would produce enough extra rapeseed and sunflower cake (compared to baseline) to replace a further 14 Mt soybean meal. The combined total of 21 Mt soybean meal equivalent compares to EU 2012 imports of 24.8 Mt (FAPRI forecast).

If biofuels are imported as fuels or vegetable oil, then of course a portion of these by-products will be produced outside EU, but they still impact on the world market price. At the moment the pattern is to import oilseeds rather than bio-diesel, so the by-products are still produced in EU, but by 2012 one may anticipate a shift to the use of palm oil and other oils not pressed in EU.

FAPRI quoted in [*DG-AGRI 2005*] project a 2012 world oilseed meal supply of 212 Mt. In [*Meilke 2005*] the average supply flexibility for the major world producers is about 0.3. On this basis one expects the extra biofuels needed to meet the biofuels Directive to depress the price of oilseed cake by about **30%,** although the margin for error is wide, because of many unforeseeable factors in the market and the scarcity of clear statistical data on which to base the estimates of the market flexibility. This makes the WTW **best-estimate prices 76 €/t for rapeseed cake and 66€/t for sunflower cake** (both at conventional 10% moisture). Both have an error margin of +/-20%.

DDGS prices

The market for DDGS is not sufficiently developed for world market prices to be quoted. Therefore a price based on the protein-replacement ratio with soybean meal had to be used (see Appendix *D*). Like oilseed cake, DDGS is considered a poorer quality feed than soy meal. Therefore both DDGS price and oilseed prices have been linked, via their protein-replacement ratios, to a "virtual soy meal price", which is lower than the expected soy meal price to take account of the quality differences. This virtual price (labelled "animal feed substitute" in the price table) is set to give the prices of oilseed cakes already estimated in the last paragraph. The resulting **price estimate for DDGS is 74 €/tonne**.

Rapeseed cake, sunflower cake and DDGS are not as easily digested as soybean meal, so that they cannot replace it entirely. This would suggest that some of the output would have to be exported. Bearing in mind the cost of sterilization, packaging and shipping, the fall in price at the factory gate could be even more dramatic. Of course the figure given is very uncertain, but it warns that the glut of protein-animal feed from biofuels by-products is likely to severely impact protein-feed prices, which will increase the costs of biofuels production.

The market outlook for glycerine affects the choice of substitution (see sec.3.5.4.1).

3.7.6 Potential production of 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 (Table 3.19).

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 3.19).

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 CO_2 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 3.19 Potential for production of conventional ethanol and bio-diesel in EU-25

	Crop		Ethanol	Bio-diesel	Fossil fuels replaced		WTW avoidance				Cost @25 €/bbl			Cost @50 €/bbl		
							WTW Fossil energy		WTW CO_{2eq}		€/ t conv	G€/a	€/ t CO2 av	€/ t conv fuel	G€/a	€/ t CO2 av
	Mt/a	PJ/a	PJ/a	PJ/a	PJ/a	Mt/a	MJ/MJ	PJ/a	g/MJ	Mt/a						
Surplus sugar beet ("C" sug	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	0.67	117	38.3	6.7	437	1.76	272	235	0.95	146
Sunflower	3.4	80		50		1.2	0.77	39	60.1	3.0	467	0.54	191	260	0.30	107
Existing crops for energy																
Rape	5.6	133		78		1.8	0.67	53	38.3	3.0	437	0.79	272	235	0.42	146
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**		**312**		**20.9**	**408**	**5.03**	**252**	**231**	**2.84**	**143**
Gasoline/diesel market coverage			**5.75%**	**3.4%**												
Total road fuel market coverage			**4.2%**													
WTW avoidance, % of fossil fuels base case								**2.1%**		**1.9%**						

(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 the WTW 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 the WTW 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 (the WTW 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 bio-diesel. 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.

3.7.7 Advanced biofuels scenario

Farmed wood availability

-Farmed wood price

The highest yield from forestry on an annualized basis comes from short-rotation forestry (SRF). The best-yielding varieties are willow and poplar in north of Europe and eucalyptus in the south. Willow is more suited to wet conditions. It is harvested (“coppiced”) every 2-4 years by cutting the shoots which grow up from the trunk. The remaining root system allows trees to re-grow biomass quicker than annual crops. After about five cuts, the whole tree is harvested. Poplar stems are cut after 8-15 years. The cost for establishing SRF and returning the land to arable again is very high, so there should be a long-term policy. Wood is the preferred type of biomass fuel: it has lower salt content and higher bulk density than other energy crops.

There is a huge range of farming costs for SRF in the literature: from about 39 €/dry tonne [*Bauen 2001*] up to 153 €/dry tonne [*FfE 1998*].

The cost-to-EU of SRF wood has been directly calculated from the commercial price paid to UK willow farmers by power utilities, who buy it to meet their renewable energy obligation by co-firing in coal-burning power stations. These prices and the prevailing subsidy regime are sufficient to persuade some farmers to grow willow, without causing a rush to cover the countryside with willow plantations. So they seem a good basis for the WTW cost estimate.

Industry sources told that utilities pay about £38 (≈55 €) per dry tonne of delivered willow chips. This is broadly confirmed by the Renewable Energy Farmers’ Association website, which quotes £30. However growers also get subsidies of £1000/ha (≈1450 €/ha) establishment grant from UK government and 45€/ha energy crop subsidy from CAP. The establishment subsidy can be treated like a plant investment, which also has a 15-20 year lifetime: the WTW standard capital charge of 12% (equivalent to 8% discount rate) has been applied. For a typical UK yield of 10 dry tonnes/ha, the **unsubsidized cost** including delivery works out at **77 €/dry tonne**[4]**.**

The UK is generally very suited to growing willow and the first plantings are likely to be in the lower cost locations, so one could argue that the cost of SRF for large-scale planting of SRF elsewhere in the EU has been underestimated. On the other hand one expects costs to fall as farmers get more experience with the new crop. The WTW costs are towards the higher end of the range assumed in the VIEWLS project, but the first ones are for 2015; the latters are for 2030 (see text box).

-Best current practice gives SRF yields only 1.57 times cereals yield

In the 1980s people were very optimistic about the potential yields from SRF on the basis of trials by various research institutes. Experience in the 1990s with real plantations brought down yield expectations: [*Mitchell 1999*] wrote “realism is creeping in, lower yields than anticipated are being accepted, matched by lower costs”.

[*Unseld 1998*] reported trials of short-rotation forestry on various sites in Germany. Annualized yields varied from 1 to 29 dry tonnes per year, depending mostly on the water availability. Thus it will be difficult to establish an average EU yield. The concept of average yield can anyway be misleading when considering establishment of SRF on former arable land, because the productivity of arable land varies enormously itself. The best approach is to estimate the ratio between the yield of crops and SRF wood, because yield variations for different crops are strongly correlated: land which is good for one crop is usually good for another. The problem is that few trials of SRF state the cereals yield on the same land.

In the UK willow farming was established for the ARBRE project. Most SRF production goes now to co-firing in coal-burning power stations. Industry sources say that “grade 3” ex-cereals land yields 10-12 dry tonnes per ha, but that results on “grade 4” arable land are poor. On grade

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[4] 55 + (1450 * 0.12 + 45) / 10 = 77.

3 agricultural land in the area wheat yield was estimated to be about 7 t/ha, also giving a yield ratio of 1.57.

On the other hand, an association of energy farmers told that, as a rule of thumb, the yield of SRF is about equal to the winter wheat yield on the same field. This may be based on information from the earliest cuts, but [*Mitchell 1999*] states that the anticipated increases in yield on subsequent cuts did not materialise on commercial plantations; implying the yield ratio would stay at only 1.

Comparing returns from SRF to those from arable crops, [*Mitchell 1999*] implies that 10 dry t/ha SRF yield is to be expected from land with 8 t/ha winter wheat yield (a ratio of 1.25).

[*LWF 2000*] also states that previous average yield estimates were too optimistic for SRF in Bavaria. Their careful assessment of SRF potential in Bavaria gives an average yield of 8-10 dry t/ha. This could be compared to an average wheat yield in Bavaria of about 6 t/ha (yield ratio 1.57).

For 2012**, it has been assumed a yield ratio of 1.57** dry tonnes of annualized SRF production per tonne of winter wheat production (mix of bread-making and feed varieties) at the standard 13% moisture. This implies wood farmers adopt current best practice.

So the resource potential for farmed wood is higher than “conventional” biofuels. The question marks are the costs, the time to develop the technology, infrastructure and plantations, and whether it is better to use the wood for electricity and heating.

SRF: The view from VIEWLS

[*VIEWLS 2005*] includes a sophisticated analysis of cost and availability of biofuels that could be produced in the EU by 2030. Basically, the study assumes maximum biofuels production by re-assigning the use of all land (not just agricultural land) not already built on or foreseen for urban development.

The land available for biofuel crops is assessed by subtracting from this total:

- the land needed for food crops to feed each country’s population
- the forest area needed to grow the estimated wood requirements
- the land needed to grow fodder for animals (no grazing).

ALL the remaining land (predominantly grazing and unharvested forest) is assigned to a biofuel crop: either rapeseed, sugar beet, miscanthus or willow. The cost of growing the biofuels crops is then calculated on the basis of various agro-economic scenarios, bearing in mind the varying yields on different types of land. Curves of average production cost against availability for each crop and scenario are then derived.

The VIEWLS availabilities of sugar beet and rapeseed do not apparently take into account the limits imposed by crop rotations or the negative effect on soil carbon of the proposed land use changes from forest and grassland to arable. Therefore it is pointless to compare the arable crops results with the WTW figures. But the rotation limits do not apply to the permanent crops, and the size of the soil carbon reduction by planting SRF or miscanthus on forest or grazing land is much less certain (although probably detrimental to some extent), so one may tentatively consider the VIEWLS estimate for these crops.

Willow gives the highest forecast availability at a given cost. To attain an availability figure for willow to compare with the WTW figures, VIEWLS agro-economic scenario closest to DG-AGRI forecasts (“scenario 3”) has been chosen. The availability–cost curve shows a broad plateau up to **8000 PJ** followed by a steep cost increase. This forecast 2030 availability would be at an estimated production cost of 3.2 €/GJ (HHV), or 62 €/ dry tonne. The reasons the availability is much higher than ours for EU25-2012 are as follows:

- SRF expands onto grazing, forest and other land, whereas only arable land has been considered.
- VIEWLS assumes much improved SRF yields by 2030.

For another VIEWLS scenario (V5), where CEEC costs matched EU-15 costs, the corresponding plateau cost was about 4.2 €/GJ (HHV), or 82 €/dry tonne. In this scenario, the production cost on second-grade “suitable” land in Poland is 3.2 €/GJ (HHV) = 62 €/ dry tonne. These values compare with the WTW delivered unsubsidized cost for willow chips of 77 €/dry tonne, or about 70 €/t at the farm gate. So the costs seem to be in the same ballpark.

The costs do not look much different, until one compares the corresponding wheat yields. VIEWLS propose SRF yields on their second-category “suitable” land in Poland to average about 11.2 t/ha. The record 2004 winter wheat yield in Poland averaged 4.28 t/ha and that was presumably mostly on “very suitable” land. So VIEWLS is expecting SRF yields to be at least 2.5 times higher than winter wheat yields. Comparing this with the present yield ratio of 1.57 at most, implies VIEWLS anticipates an increase in SRF yield of more than 60% from now to

2030. Although the tendency until now has been for SRF yield expectations to fall, it is not unreasonable to expect that from now on there will be rapid improvements in varieties and commercial farming techniques for this new crop.

Availability of agricultural and forestry wastes

-Far more waste is available for energy than for biofuels production

Lignocellulosic materials can be converted to ethanol by the wet SSCF process or to other fuels via gasification. Both these are complex processes with economics dominated by the high plant investment costs: to make them viable it is important to use economies of scale. The straw-to-ethanol pilot plant of Iogen Corporation has a capacity of 140 MW_{th}, and gasifiers in general should be larger still for good economics. By contrast, reasonably efficient and clean biomass boilers are available at much smaller scales, for heating commercial buildings or small industrial processes, and the size of combined-heat-and power electricity generating plants is anyway limited by the demand for heat. Even straight biomass power stations are less complex and capital-intensive than a biofuel plant.

Thus, when estimating the availability of feedstock, one should consider not only how much is there in the field or forest and how much can technically environmentally and economically collected, but also how much can logistically be brought to large processing plants.

-Straw and other agricultural residues

[*Edwards 2005*] reports on a GIS-based study on the availability of straw in EU for feeding power stations. Taking into account competing uses, they estimated that EU produced 820 PJ straw in excess of existing requirements, but that a maximum of only **230 PJ** (28%) would be logistically available to plants of 120 MW_{th} or larger. This is because of the dispersed nature of the resource and the need for spare resource capacity around a plant to account for annual variations in supply etc. This figures have been used in the WTW study, even though some of the conversion plants in the WTW study would be larger, and no account was taken of areas where straw-taking could degrade soils (although this is not as great a limitation as might be expected, because the areas with a concentrated supply are also areas where the soil conditions permit it to be taken). Therefore the figure is optimistic, when applied to biofuels.

The price of straw depends strongly on local conditions and the quantities involved; there is a great spread of cost data in EUROSTAT. However, a good basis for the WTW purpose is the price paid at Ely straw-burning power station in the UK (the world’s largest). Straw is sourced from within 50 km of the plant and average transport distance is 35-40 km. The delivered price is 23-25 £/t at 15% water (≈33-36 €/t) on a fixed contract. Spot price delivered to power stations for co-firing is 28 £/t (41 €/t). There is no subsidy on the straw. On this basis a **straw price of 35 +/-5 €/t** has been adopted.

[*Edwards 2005*] dealt with straw from cereals which occupy 86% of the EU arable land. Of course many other crops produce prunings and residues, but these are far more dispersed, all have different processing characteristics, and many are already used for animal feed (a point overlooked in some surveys!). Therefore their possible contribution to making renewable transport fuels would be less than the uncertainty in the WTW straw estimate. Again, they could contribute more to bio-energy resources than biofuels.

Waste wood

-Sources of waste wood

There are several types of wood wastes:

- “Forest residuals”: branches, tops, undersize thinnings and, with latest forestry technology, roots.
- “Mill residues” bark and other wastes produced at the pulp mill.
- “Secondary wastes”: from the wood industry (sawdust, shavings etc)
- “Used wood” from building demolition, pallets etc
- “Agricultural residues” from woody plants such as fruit trees and vines
- Forest litter: dead wood removed from old stands or natural forest to reduce fire risk

There is no industrial-scale production of transport fuels from wood waste at present. Current EU total wood waste now used for energy production (heat/electricity) is 50 dry Mt/a [*EUREC 2002*]. This represents 48% of total wood used for energy, the rest being non-industrial trees cut for firewood. It subdivides into 40% residues, 39% secondary residues and 21% used wood.

Apart from straw, very little woody agricultural residues are currently used to produce energy in EU commercial plant. Generally residues occur at a very low density over a wide geographical area and are only available once a year. The cost of transport makes waste wood cogeneration only marginally economic even in the middle of a forested region, where the density of production is high and the wood can be transported all year round. With the exception of cereal straw (see above), therefore there is no possibility to economically collect a significant part of the agricultural woody residues for energy use. The special situation of straw is considered above.

Secondary waste is the most consistent in quality and easy to obtain. It has been used in many pilot studies of gasification etc. However, it is already almost completely recycled within the wood industry (40% for products, 60% for heat and electricity). Life cycle analysis studies almost all agree that use in products is better for greenhouse gas than use as energy.

Used wood is the driest and therefore convenient for small pilot plant studies. At present it has near-zero or negative cost at source. But the source is extremely dispersed. Furthermore, there is a problem of contamination: only a fraction of the potential supply can be used within health regulations. Detoxification is under study by the wood industry, who would like to recycle more of it.

Mill waste is completely used within the pulp/paper mills (for process heat and electricity export) and so is not available for conversion to road fuel.

It is sometimes claimed that forest litter could be a useful woody biomass resource: the high cost of collection might be justified by the external credits from avoiding forest fires. This calculation has not been done. However, the resource would certainly be very dispersed, making it suitable for energy use in local heating, for example, but probably not for transporting to large centralized plants for conversion to biofuels.

Summarising, it appears that **forest residuals are the only significant potential source of more woody waste for transport fuel**.

-Availability of forest residuals

When harvesting trees in commercial forestry, the branches and tops are stripped from the trunk at the harvest site and forwarded to a baler or a roadside chipper. The bales or chips are carried to the mill by adapted log-trucks. Recently, integral harvesters have been developed. These remove the roots as well, but cannot be used in difficult terrain. An advantage of taking the roots is that they are better fuel: drier, and with a lower mineral content than branches; the disadvantage is that the disruption of the soil could lead to loss of soil carbon and soil erosion at sensitive sites.

As with many other sources of biomass for energy, studies conducted ten years ago were far more optimistic about availability than the latest studies. For example, estimates in six successive studies of the possible availability of Swedish forest residues have declined by a factor five from around 380 PJ in 1995 to 75 PJ in 2005 (of which 32 PJ already used) [*Lundmark 2005*].

[*METLA 2004*] used broadly the same approach to estimate the technically and economically available forest residuals in EU-25: they started from the statistics on fellings and then estimated extension factors to find the amount of residuals associated with these. However, the METLA study is more detailed and includes cost-supply curves for various countries. Therefore their results have been adopted for the present study.

[*METLA 2004*] also considers using the excess roundwood for energy purposes (i.e. the annual excess of commercial forest growth over actual fellings). METLA assume 25% of the excess growth could be used. At present, some countries such as Portugal have no excess growth whereas others, for example Finland, have a large excess growth but are reluctant to cut it for energy use.

Forest residuals for replacement of gasified black liquor

Black liquor is the by-product of pulp-making containing the lignin fraction of the wood, mixed with process chemical in a slurry. In existing pulp mills, it is burnt in a recovery boiler for process heat. Instead, one can gasify the black liquor and make up the missing process heat using a boiler fired by forest residuals. The syngas from the gasifier can be used to produce either electricity or transport fuels.

The amount of fuels that can be made in pulp mills using the efficient black liquor route depends on how many mills have large enough boilers to make black liquor gasification economic. This is the case for about 80% of EU plants and they could be converted gradually as their recovery boilers come up for renewal over the next 20 years.

According to [*Ekbom 2003*], EU-15 produced 395 PJ black liquor in the year 2000. First it has been added 11% to this figure to account for pulp production in the new Member States (proportional to the pulp production figures from EUROSTAT). The growth rates projected by [*Ekbom 2003*] have then been used to calculate an EU-25 black liquor production of 527 PJ in 2012. However, only about 80% of this would come from plants large enough for economic conversion to black liquor gasification so the amount available for gasification would be 422 PJ. Again according to [*Ekbom 2003*] 408 GJ forest residuals would replace 487 GJ of gasified black liquor in their model black liquor gasification plant. This results in a potential demand of 353 PJ forest residuals to fully exploit the possibilities of black liquor gasification in EU-25 in 2012.

[*METLA 2004*] estimated the technical availability of forest residuals and roundwood balance country-by-country. Comparison of the results of [*METLA 2004*] with the black liquor potentials of [*Ekbom 2003*] gasification study shows that each pulp-producing country in EU-15 can supply just enough forest residuals to fully exploit its potential of black liquor gasification.

The cost-supply curves for Finland in [*METLA 2004*] and for Sweden in [*Lundmark 2005*] indicate that these two principal producers could provide just sufficient forest residuals at a price of 2.8 €/GJ. The cost-supply curve for Poland in [*METLA 2004*] indicates that new Member States could supply it for even less. The cost-supply curve for France indicates that almost no forest residuals would be available at 2.8 €/GJ, and the same is probably true of other small EU-15 pulp producers. But France, Austria and Spain could possibly supply the biomass at that price by exploiting some of their roundwood balance. Portugal has no roundwood balance to exploit, and Germany and the UK have no pulp industry. In all EU-25, it has been estimated **325PJ woody biomass would be available to pulp mills at 2.8 €/GJ**: 92% of that required for full exploitation of black liquor gasification.

A larger constraint is techno-political: even if the maximum number of EU pulp-mills were converted for black liquor gasification, some might prefer to produce electricity (or methanol rather than transport fuels) either for economic reasons or more likely as a result of renewable policies in certain countries. Even though black liquor gasification is a very efficient way of producing transport fuel from biomass, making electricity could save more GHG from the same biomass and for less money. In particular there is little enthusiasm for producing transport fuels in Finland, after some disappointing tests in the 1970s. And of course, the whole concept is still at the pilot plant stage: it is not yet known how long gasifiers will withstand the severe sulphidation conditions. Accordingly, it has been assumed that a maximum of **2/3 of the black liquor gasification capacity could realistically be exploited to produce transport fuels. This would consume 238 PJ woody biomass, mostly forest residuals.**

Forest residuals for other conversion routes

In the WTW advanced biofuels scenario, the cheapest sources of forest residuals have mostly been exploited for the black liquor at pulp plants, because collecting residues is a large-scale operation combined with clear-fell harvesting and can make use of the same transport infrastructure to bring the residuals to the pulp mills.

[*METLA 2004*] estimated the maximum technical availability of forest residuals and roundwood balance in EU-25 at 1008 PJ/a. If the 325 PJ available at pulp mills for processing by the black-liquor gasification route is subtracted, 683 PJ remain for other uses. However, this resource is far more dispersed than the residuals at pulp mills: it could be brought to saw-mills (typically much smaller than pulp-mills) or supplied along with traditional fire-wood. A larger proportion is from forest thinnings. This is a comparable situation to straw availability: it is logistically difficult to get the resource to large plants of the type needed to convert it to transport fuel. It could much more easily be exploited for energy in the form of local heating and CHP plant. A detailed GIS study is needed for a proper estimate. Since none is available, the WTW estimate has been made congruent with the situation of straw supply and assumed that at most 1/3 of the supply could be brought to a plant with a capacity greater than 130 MW_{th}. That means about 230 PJ, similar to the maximum amount that could be processed into transport fuels via the black liquor route.

In [*METLA 2004*] the cost-supply curve for France shows that to collect most of the available residues here one would need to increase the price to around 4.1 €/GJ which is the WTW price for SRF wood. Prices in other EU-15 countries, notably Germany and Austria, have been supposed to be comparable.

Conservatively the WTW cost calculations have been done using the lower price of 2.8 €/GJ for the entire waste wood supply.

3.7.8 Organic waste for compressed biogas

The potential for biogas is much higher for energy than for transport fuel

As with other energy-from-waste schemes, the availability of compressed biogas as a transport fuel is much less than that of biogas as an energy source for heating and small-scale electricity generation. Heat and electricity can be made even on simple farm-size plants, but *compressed* biogas for transportation requires a purification plant, a compressor, consistent quality and preferably an output sufficient for at least one filling station. Because of all these factors compressed biogas for transport needs to be produced in large centralized plants of the scale presently seen in Denmark to be economically viable.

Animal manure from intensive livestock farms is the biggest resource for transport-biogas at the WTW production price

[*FfE 1998*] and [*Holm-Nielsen 1997*] have estimated how much potentially-digestible waste is produced in EU-15. The largest resource is animal manure, and by far the largest contribution is from cattle ([*FfE 1998*] use 18 t/a for the average amount of manure produced by cattle, a very high figure compared to other studies which report between 8.5 and 15 t/a. Average figures of 11 t/a per head of cattle and 1.7 t/a for pigs have been favoured). This size of plant is only possible in areas of intensive livestock farming, where animals are kept indoors and manure is collected as slurry.

Sewage is more dilute and more dispersed than animal manure, giving higher biogas production costs. Agricultural wastes could be made into biogas, but many of the suitable ones are more valuable as animal feed. There is also a problem of year-round availability.

Organic wastes from separated municipal waste and from the food industry are very suitable for biogas production: they produce much more biogas per tonne than does manure, and they cost money to dispose of by other routes. Furthermore, there are synergistic advantages in mixing manure and organic wastes: the temperature of the fermentation and the C:N ratio can be kept nearer the optimum. The problem is that there is much less of it than animal manure, and it is difficult to get enough together in one place to make a biogas plant large enough to make compressed biogas at the WTW price.

Purpose-grown crops, or grass collected from surplus grassland can also be digested, but the cost is far higher than using wastes. Since the WTW cost results show that compressed biogas from waste already has trouble to compete on price with conventional biofuels in EU, this option is unlikely to be developed in the WTW time horizon. It could possibly be considered competing with more expensive advanced-biofuels concepts in the more distant future.

Capital costs dominate

Biogas production is highly capital intensive: the typical feedstock of manure has a low specific energy content, and the residence time in the reactor is much longer than for thermal conversion processes. This makes the plant very large for a specific energy output, so that capital servicing is the main component of the total gas cost.

Large Danish plants process 300 tonnes biomass a day and would produce 6000 m^3/day (1.6 MW) raw biogas if they were fed only from animal slurry. This is the amount of manure produced by about 8000 cattle or 50,000 pigs. In Denmark these plants typically collect manure from about 50 farms within a radius of less than 10 km.

Adding organic waste makes the process viable at 15.5 €/GJ

Usually manure slurry is not paid for. It is collected from the farm and the processed fertilizer returned without charge to the farmer (but farmers often own a share of the biogas plant). Danish plants are only economically viable because of co-feeding with organic wastes from the food industry (slaughterhouse waste, fisheries processing waste, dairy waste etc.), both because these boost the biogas yield and because, being expensive to dispose of by other safe routes (incineration etc.) the biogas producer actually gets paid to process them.

One tonne of a typical mix of 20% organic waste with 80% slurry produces a net 30 Nm^3 biogas (“net”, because some of the total biogas production is used to warm the fermentor), whereas animal slurry alone produces only about 20 Nm^3/t. So the same size and cost of plant produces 50% more gas. Already biomass plants are competing for the supply of organic wastes, so that most are operating at the edge of profitability [*Hjort-Greersen 1999*].

The WTW best-estimate biogas price of 15.5 €/GJ corresponds to this model of biogas production, but with no gate fee for the organic waste. Thus such price does not take into account the cost of alternative treatments for the slurry and organic wastes. According to [*AEA 1998*] these are higher than for anaerobic digestion (beyond the scope of the WTW study to evaluate them). Note that this price does not include the considerable costs of compressed-gas distribution and vehicle modifications.

A typical mix is 80% animal slurry / 20% organic waste. It is cheaper to transport the organic waste than the animal slurry, so the plants would be located in areas of intensive indoor livestock farming, producing manure as slurry. EUROSTAT statistics show that 30% of EU cattle live on farms of more than 200 head, and 36% pigs live on farms of more than 2000 head. This may give a rough indication of the availability of slurry from intensive farms. The conclusion is that the biogas production at this price is limited by the availability of organic waste.

The availability of organic waste limits the EU supply of compressed biogas to 200 PJ at a maximum price of 15.5 €/GJ

Total municipal organic waste in EU-15 is estimated at 57 Mt/a [*Fazoino 2005*]. The figure is close to the estimate in [*FfE 1998*] and [*Barth 2000*]. The fraction collectable is difficult to estimate for the whole of the EU: at present it ranges from 0% in Greece to 78% in Germany. A figure of 62% has been taken: the present performance in Flanders. The estimate of food industry waste was from [*FfE 1998*].

If it is assumed that ALL the organic waste could be brought to a biogas plant at a site where there is a sufficient local slurry to supply a plant of the WTW size, it is found that AT MAXIMUM about **200 PJ/a** purified biogas, suitable for compression, could be available at a price of **15.5 €/GJ.**

The problem is that intensive animal farming tends to be concentrated in a few regions of the EU: Western Denmark, Po Valley, etc. So even though one could afford to transport organic waste as far as 200 km, much of it could still be produced in areas far from where there is a sufficiently concentrated source of slurry. However, sufficient data on how slurry sources are distributed in EU could not be found, so the WTW estimate could not be further refined.

Table 3.20 Biogas potential from animal slurry and organic waste at 15.5 €/GJ

		EU-15	EU-25*
Total digestible fraction of MSW	*Mt/a*	*57*	*69*
Realistically collectable as separate waste	Mt/a	34	41
PLUS food industry waste	Mt/a	12	14
Total digestible organic waste	Mt/a	46	56
Biogas potential from organic waste	PJ/a	76	92
Animal slurry for 4:1 mixture	Mt/a	185	223
Biogas potential from slurry + organic waste	PJ/a	164	197

* scaled by population

Of course, more biogas would be available if the *price* was increased to allow production from pure slurry (the WTW estimate is 21.3 €/GJ), or the use of specially-grown crops. However, the most economic production of compressed biogas for transport is all that one could hope to develop within the next 10-20 years. It is important to underline that much more biogas could be available for small-scale *energy* use (heat or small-scale electricity generation).

3.7.9 Overview of biomass feedstock costs

Based on the foregoing the following cost data have been used. Note that the costs arrived at above have been assumed to pertain to a 25 €/bbl oil price scenario. An "oil cost factor" has been added (representing a notional fraction of the cost related to energy) so that these costs are higher when the cost of oil increases.

Table 3.21 Cost of biomass resources (delivered to processing plant)

	Moisture content	LHV	Low oil price (oil at 25 €/bbl)		Own variability	High oil price		
						OCF	(oil at 50 €/bbl)	
		GJ/t	€ /t	€ /GJ			€ /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	

3.7.10 Potential production of advanced biofuels

Under this generic term ethanol from cellulosic material and synthetic fuels produced by biomass gasification and syngas-based synthesis processes have been included. “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.

Using the availability figures discussed above a number of extreme scenarios have been built illustrating the potential of a number of single options for using the available biomass. It must be noted that these scenarios are mutually exclusive inasmuch as they represent alternative ways of using the same resource. The numbers are shown in Table 3.22.

The second and third columns show the availability of the different types of biomass. In all scenarios it is assumed that surplus sugar beet is still grown and is turned to ethanol, and so is straw which accounts for a base ethanol production of 117 PJ/a. All surplus cereals as well as the area currently used for oilseeds are converted to SRF or equivalent to produce woody biomass. This "wood" is then converted, together with waste wood to either ethanol, syndiesel or DME.

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 3.22). 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, 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. A GIS-based study has been used 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 3.22 Potential for production of advanced biofuels in EU-25

Resource	Mt/a	PJ/a	Ethanol PJ/a	Syn-diesel PJ/a	DME 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	771
Existing oil seeds and cereals for energy	*7.1*				
	⇩				
As farmed wood	19.7	355	122	111	181
Waste wood	26.2	471	162	167	274
Scenarios					
Max ethanol			914		
Max syn-diesel			113		
Max DME			113	1226	

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 or DME (Table 3.23).

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 3.23 Fossil energy and GHG emissions avoidance potential from advanced biofuels in EU-25

Scenario	Total Alt fuels	Road fuels market coverage			Fossil fuels replaced		WTW avoidance						Cost					
							WTW fossil energy			WTW CO_{2eq}			Oil @ 25 €/bbl			Oil @ 50 €/bbl		
	PJ/a	Gasoline	Diesel	Total	PJ/a	Mt/a	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%**	**754**	**16.0**	**271**	**595**	**12.6**	**214**
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%**	**757**	**15.2**	**223**	**585**	**11.7**	**172**
Ethanol	113	2.8%			113	2.6		104	0.7%		8	0.7%						
Syn-diesel	750		8.5%		750	17.4		824	5.6%		61	5.4%						
"Max DME" total	**1339**	**2.8%**	**14.3%**	**10.7%**	**1372**	**31.8**	**1.12**	**1494**	**10.1%**	**82**	**110**	**9.8%**	**702**	**22.3**	**204**	**516**	**16.4**	**150**
Ethanol	113	2.8%			113	2.6		104	0.7%		8	0.7%						
DME	1226		14.3%		1259	29.2		1390	9.4%		103	9.1%						

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 CO_2 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. 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 CO_2, while the "max DME" scenario would achieve nearly 32 Mt/a of fossil diesel fuel substitution and 110 Mt/a of CO_2.

3.7.10.1 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.

The most economic example of biogas production has been chosen for the WTW 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 and thus it has not been considered.

Table 3.24 Fossil energy and GHG emissions avoidance potential from biogas in EU-25

Scenario	Total Alt fuels	Road fuels market coverage			Fossil fuels replaced		WTW avoidance						Cost					
							WTW fossil energy			WTW CO_{2eq}			Oil @ 25 €/bbl			Oil @ 50 €/bbl		
	PJ/a	Gasoline	Diesel	Total	PJ/a	Mt/a	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**

3.7.11 Fuel production and distribution costs

For all fuels produced in Europe and for those, such as DME which cannot be linked to a commodity price, a cost of production has been estimated based on published literature.

Unless there was clear evidence to support other numbers it has been considered that a processing plant would have annual operating costs of 3% of the initial capital investment for established technologies and 4.5% for new technologies or high-tech plants. This included personnel and maintenance but not energy which was accounted for separately according to its source. For processes that already exist today, a range of ±20% for investment costs has been used. For new or future processes it has been used ±30%.

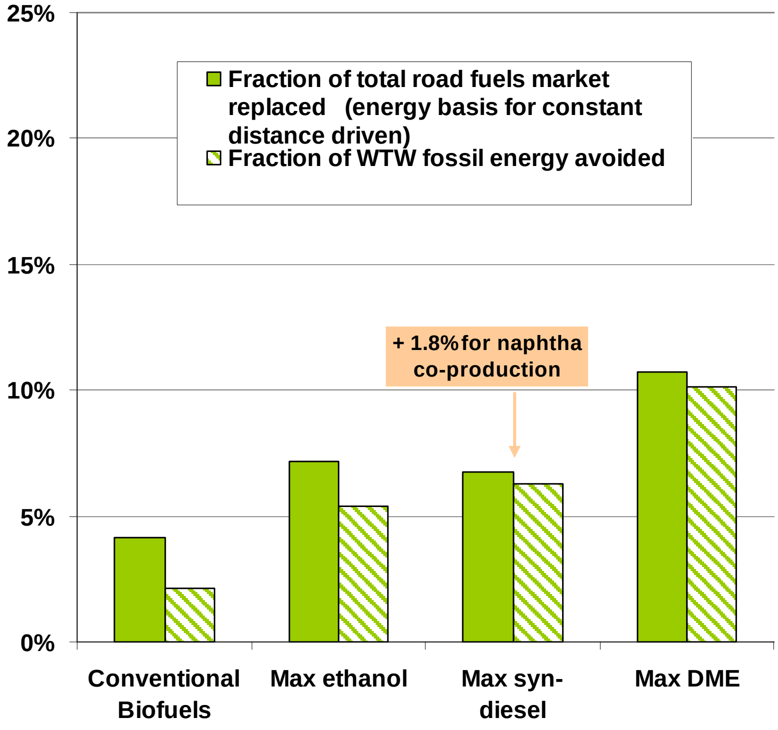
In order to express all costs on a common basis, capital investments need to be turned into a cost item expressed e.g. per annum or per MJ of product. The concept of capital charge has been used which is the revenue that a facility must produce every year of the project life (in addition to operating costs) for the investment to be repaid and to produce a desired rate of return. The capital charge is a function of a number of factors such as lifetime of the project, building time, expected revenue profile, inflation and also tax on profits. As cost for Europe as a whole have been looked at, the tax element has been considered as an internal issue rather than an external cost. It would of course be taken into account by individual investors wishing to undertake a project. A commonly accepted rate of return for capital investment is 8% (real terms) being the long term return of stocks and shares. For a typical industrial project with a lifetime of 15-20 years and 2-3 years building time, this corresponds to a capital charge of about 12% which is the figure that has been used.

Distribution and retail costs include energy cost (transport, compression, dispensing etc), cost of incremental distribution infrastructure and cost of specific refuelling infrastructure. In line with the WTW incremental approach, it has been taken the view that the existing infrastructure for conventional fuels would not be significantly affected by a limited introduction of alternative fuels. As a consequence the savings from "not distributing" marginal conventional fuels were limited to variable costs (essentially energy-related). Conversely, however, the extra cost for refuelling infrastructure when required only related to the cost of the additional equipment and did not include any contribution to fixed costs e.g. for establishment and maintenance of a site and the like.

3.7.12 Overview of biomass potential

Figure 3.42 shows for the different scenarios from "conventional biofuels" only scenario to "max biofuel", the percentage of fossil road fuels that can be substituted (in effect a "TTW" figure) as well as the percentage of the WTW fossil energy that can be saved.

Figure 3.42 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.

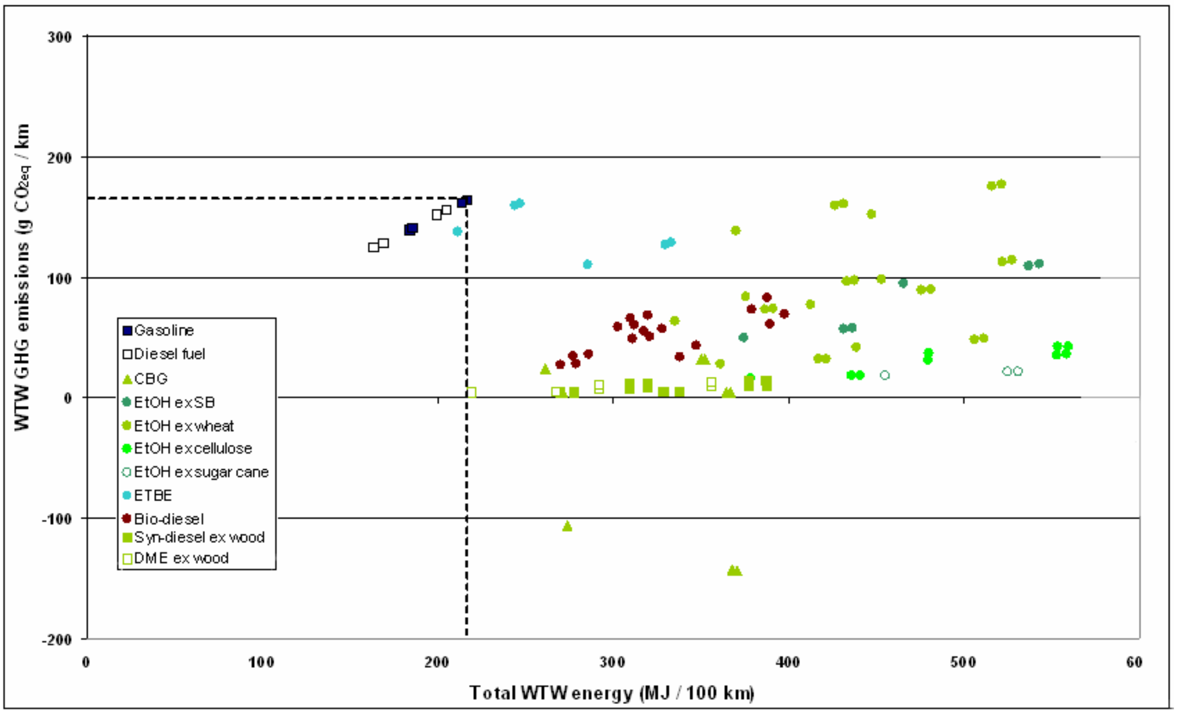
Road fuels from biomass will also be in direct competition with fuels for stationary applications, mostly heat and electricity generation. The important issue of optimal use of land and other sources of renewable energy to maximise CO_2 avoidance is discussed in sec.3.8.

3.8 Alternative uses of primary energy resources

In the present section, using the WTW data generated, are highlighted 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 3.43 shows the relationship between total WTW energy usage and WTW GHG emissions, highlighting 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 3.43 WTW energy requirement and GHG emissions (2010+ vehicles)



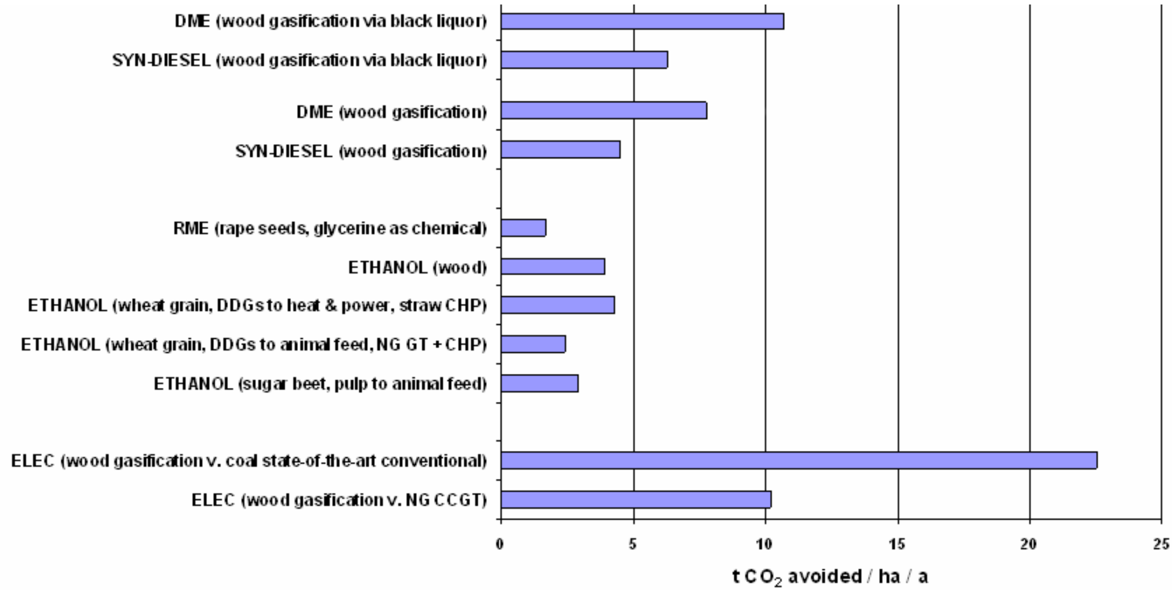
Virtually all primary energy resources are in practice available in limited quantities. For fossil fuels the limit is physical, expressed in barrels or m^3 actually present in the ground and recoverable. For biomass the limit is total available land use. The planet is unlikely to run out of sun or out of wind in the foreseeable future but the WTW capacity to harness these energies is very much limited by the WTW 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.

3.8.1 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 the WTW 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 a hypothetical hectare of land is considered to compare its "CO_2 avoidance potential" when used with different crops. The range shown for each option corresponds to the different pathways available.

Figure 9.2 CO_2 avoidance from alternative uses of land



Electricity production is energy intensive and substitution by biomass results in large CO_2 savings, particularly when coal is being substituted. The technology used for biomass conversion can make a lot of difference, the IGCC concept (top end of the range) being far superior to a conventional boiler + steam turbine system (but also a lot more expensive). Note that wood is used here as a proxy for all high yield energy plants. Substitution of biomass for coal in electricity generation provides one of the best CO_2 savings.

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

This analysis is of course a little simplistic. Each hectare of land has its specific characteristics that make it most suitable for a certain kind of crop or crops (in rotation). Rape is for instance an attractive break crop on a land dedicated to cereals. One could obviously not grow wood for a year between two cereal cycles. Also yields can vary a great deal between areas and one should refrain from using the above figures to estimate the CO_2 that could be saved with a certain area of land.

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

4 Vehicle/fuel combination

4.1.1 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. This model vehicle was used as a comparison tool for the various fuels and associated technologies. The fuel consumption figures are not deemed to be representative of the average European fleet. All required data for the baseline PISI gasoline model vehicle were collected from EUCAR member companies. The reference is a 2002 Port Injected Spark Ignition gasoline (PISI) powertrain (Table 4.1).

Table 4.1 Characteristics of the 2002 gasoline PISI reference vehicle

Curb weight	kg	1181
Weight class	kg	1250
Drag coefficient	-	0.321
Vehicle front area	m²	2.1
Tyre radius	m²	0.309
Tyre inertia	kg.m²	0.7
Engine displacement	l	1.6
Engine inertia	kg.m²	0.125
Efficiency differential+gear		0.9
Transmission ratio of differential gear		4.25
Transmission ratio 1st to 5th gear		3.455/1.944/1.370/1.032/0.850

Key to the methodology was the requirement for all configurations to comply with a set of minimum performance criteria (Table 4.2) relevant to European customers while retaining similar characteristics of comfort, driveability and interior space.

Table 4.2 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 4th gear	s	*<13*
Time lag for 80-120 km/h in 5th 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.

4.1.2 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 on the basis of available 'real' data. The 2010+ performance were derived by establishing percentage improvement over the 2002 level.

The following combinations of fuels and powertrains have been assessed (Table 4.3). The entries in Table 4.3 indicate the time horizons of the technology assessments. The baseline situation (2002) has been simulated for conventional, available vehicles and fuels (PISI, DISI and DICI). For 2010 and beyond, viable technology options have been considered without any assumptions regarding availability, market share and customer acceptance.

Table 4.3 Simulated configurations

Powertrains	PISI	DISI	DICI
Fuels			
Gasoline	2002 2010+	2002 2010+	
Diesel fuel			2002 2010+
Diesel/Bio-diesel blend 95/5			2002 2010+
Gasoline/Ethanol blend 95/5	2002 2010+	2002 2010+	
Bio-diesel			2002 2010+
DME			2002 2010+
Synthetic diesel fuel			2002 2010+

PISI: Port Injection Spark Ignition

DISI: Direct Injection Spark Ignition

DICI: Direct Injection Compression Ignition

Simulations were carried out for each neat fuel separately (Gasoline and Diesel). For alternatives to gasoline (ethanol, 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 key properties of the fuels considered are shown in Table 4.4. For the 2010+ projections, gasoline and diesel fuel are assumed to comply with currently legislated specifications at that date, in particular with a maximum sulphur content of 10 mg/kg.

The ADVISOR simulation model was adapted to the NEDC cycle (described in section 4.1.5). The main modifications were corrections to gear changes during the cycle and fuel cut-off during deceleration. The simulation tool was adapted to specific technologies by using specific "fuel efficiency" maps. For conventional internal combustion engines and fuel cells, European Manufacturers supplied the relevant "fuel efficiency" maps on a proprietary basis.

Table 4.4 **Main properties of fuels**

Fuel		Density	LHV	Carbon	CO_2 emissions	
		kg/m^3	MJ/kg	%m	kg/kg	g/MJ
Gasoline	2002	750	42.9	87.0%	3.19	74.35
	2010	745	43.2	86.5%	3.17	73.38
Ethanol		794	26.8	52.2%	1.91	71.38
Gasoline/Ethanol	2002	752	42.1	85.2%	3.12	74.25
blend 95/5	2010	747	42.3	84.6%	3.10	73.31
ETBE(1)		750	36.3	70.6%	2.59	71.40
CNG/CBG(3)			45.1	69.2%	2.54	56.24
Diesel	2002	835	43.0	86.2%	3.16	73.54
	2010	832	43.1	86.1%	3.16	73.25
Bio-diesel(4)		890	36.8	76.5%	2.81	76.23
Diesel/bio-diesel	2002	838	42.7	85.7%	3.14	73.66
blend 95/5	2010	835	42.8	85.6%	3.14	73.39
Synthetic diesel		780	44.0	85.0%	3.12	70.80
DME(5)		670	28.4	52.2%	1.91	67.36

(4) Figures are for FAME (Fatty Acid Methyl Ester), more specifically RME (rape seed Methyl Ester)

Note: "bio-diesel" represents a generic vegetable oil ester.

For gasoline direct injection, an adjusted map of the Mitsubishi 1.8 litre displacement engine was used.

In order to simulate the NEDC, a number of modifications were brought to ADVISOR. For conventional vehicles the modifications were:

- Gear ratio management: during the NEDC, the gear shift sequence is imposed as a function of time. In the original version of ADVISOR, it was not possible to run the vehicle at the same speed with two different gear ratios, as required under the NEDC (50 km/h has to be achieved in both 3rd and 4th gear).
- Fuel cut-off during vehicle deceleration.
- At idling, fuel consumption read from the data file.

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

The main vehicle simulation results delivered by ADVISOR are:

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

Note: total GHG emissions expressed in CO_{2eq} take N_2O and methane emissions into account, through estimates of their emissions, and using the appropriate IPCC factors.

All vehicles complied with the performance criteria presented in Table 4.2.

Table 4.5 Characteristics of 2002 ICE Euro III vehicles

		PISI	DISI	DICI
		Gasoline	Gasoline	Diesel/DME
Powertrain				
Displacement	l	1.6	1.6	1.9
Powertrain	kW	77	70	74
Engine mass	kg	120	120	145
Gearbox mass	kg	50	50	50
Storage System				
Tank pressure	MPa	0.1	0.1	0.1/1
Tank net capacity	kg	31.5	30	25/40
Tank mass empty	kg	15	15	15/30
Tank mass increase including 90% fuel	kg	0	0	0/28
Vehicle				
Reference mass	kg	1181	1181	1248
Vehicle mass	kg	1181	1181	1248/1276
Cycle test mass	kg	1250	1250	1360
Performance mass	kg	1321	1321	1388/1416

Concerning **gasoline**, both PISI and DISI configurations resulted in the same total mass.

The **Diesel version** was powered by a 1.9 l turbo-charged engine (74 kW). The higher engine mass and corresponding structure reinforcements increased the total vehicle mass by about 70 kg compared to gasoline. The same vehicle characteristics were used for other potential liquid diesel fuels (bio- and synthetic diesel fuel) either neat or in blends with conventional diesel fuel.

DME needs a “LPG-type” steel tank. The excess mass of this 60 l tank was estimated at 28 kg (tank: 15, fuel: 13) as compared to the Diesel reference. The inertia class was kept at 1360 kg so that the fuel efficiency was unaffected.

By 2010 a diversification of fuels and powertrains is expected.

The evolution of vehicle characteristics and the “technology-based” efficiency improvement assumed for 2010 were widely discussed and agreed between the EUCAR members on the basis of expected technological progress (e.g. friction reduction, engine control, combustion improvements etc). These options were considered for their technical feasibility in 2010. No consideration was given to actual implementation, availability, market share and customer acceptance. The expected fuel consumption reductions for the various technologies are presented below (Table 4.6).

Table 4.6 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 the vehicle-engine combinations using the SI engines, the main contribution to energy efficiency came from downsizing ((minus 20%[5]) associated with supercharging). The displacement of the gasoline engine could be reduced from 1.6 to 1.3 l, the full torque being restored by a turbo charging at 1.2:1.

This technology evolution had less scope for DISI 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 major additional benefit is expected through the “downsizing” route. Therefore, only the standard technology improvements are accounted for (e.g. friction). The DPF option, when applied, does carry a fuel penalty of about 2.5% for the regeneration of the filter.

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

4.1.3 "Stop-and-Go" influence evaluation on fuel consumption

The "Stop-and-Go" fuel saving was evaluated with the gasoline PISI 2002 conventional configuration over the NEDC (with cold start). The fuel consumption when the vehicle is idling was calculated by post treatment of the results. Idling represented 7.5% of the total fuel consumption over the regulatory emission test cycle and could theoretically account for the maximum expected gain of the Stop-and-Go system.

Indeed, each time the engine restarts, no additional fuel consumption was taken into account. If the energy losses due to the engine restart was to be considered the fuel consumption gain due to the Stop-and-Go system would be lower. In addition, the thermal effect of this strategy was not taken into account either: the warm up of the engine would be slightly slower than with thermal engine idling and may influence the efficient treatment of pollutants under cold start conditions. These effects would decrease the fuel saving potential of the Stop-and-Go strategy. Therefore, taking into account some of the limitations mentioned above, the full theoretical potential of the Stop-and-Go could not be retained: a figure of 3% was considered more realistic and was applied on all 2010 ICE configurations.

4.1.4 Conformance to performance criteria

With the adaptations (2002) and improvements (2010) described above all the vehicles were able to meet or exceed the performance criteria. Actual figures are summarised below (Table 4.7 for 2002 vehicles and Table 4.8 for 2010 vehicles).

Table 4.7 Performance of 2002 ICE vehicles

		Gasoline		Diesel	*Target*
		PISI	DISI	DICI	
Time lag for 0-50 km/h	s	4.0	4.1	3.9	*<4*
Time lag for 0-100 km/h	s	11.7	12.9	11.5	*<13*
Time lag for 80-120 km/h in 4th gear	s	11.3	11.7	9.6	*<13*
Time lag for 80-120 km/h in 5th gear	s	15.1	15.8	12.4	-
Gradeability at 1 km/h	%	54	50	84	*>30*
Top speed	km/h	191	178	187	*>180*
Acceleration	m/s^2	4.3	4.2	4.8	*>4.0*

Table 4.8 Performance of 2010 ICE vehicles

		Gasoline		Diesel	*Target*
		PISI	DISI	DICI	
Time lag for 0-50 km/h	s	3.9	4.1	3.8	*<4*
Time lag for 0-100 km/h	s	11.3	12.4	11.2	*<13*
Time lag for 80-120 km/h in 4th gear	s	10.8	11.2	9.2	*<13*
Time lag for 80-120 km/h in 5th gear	s	14.5	15.0	12.1	-
Gradeability at 1 km/h	%	56	52	88	*>30*
Top speed	km/h	193	180	190	*>180*
Acceleration	m/s^2	4.5	4.3	4.8	*>4.0*

For 2002 vehicles:

- Diesel fuel, DME, bio-diesel, synthetic diesel and diesel/bio-diesel blend configurations displayed the same performance as the diesel DICI configuration.
- The gasoline/ethanol blend configuration showed the same results as the gasoline configuration.

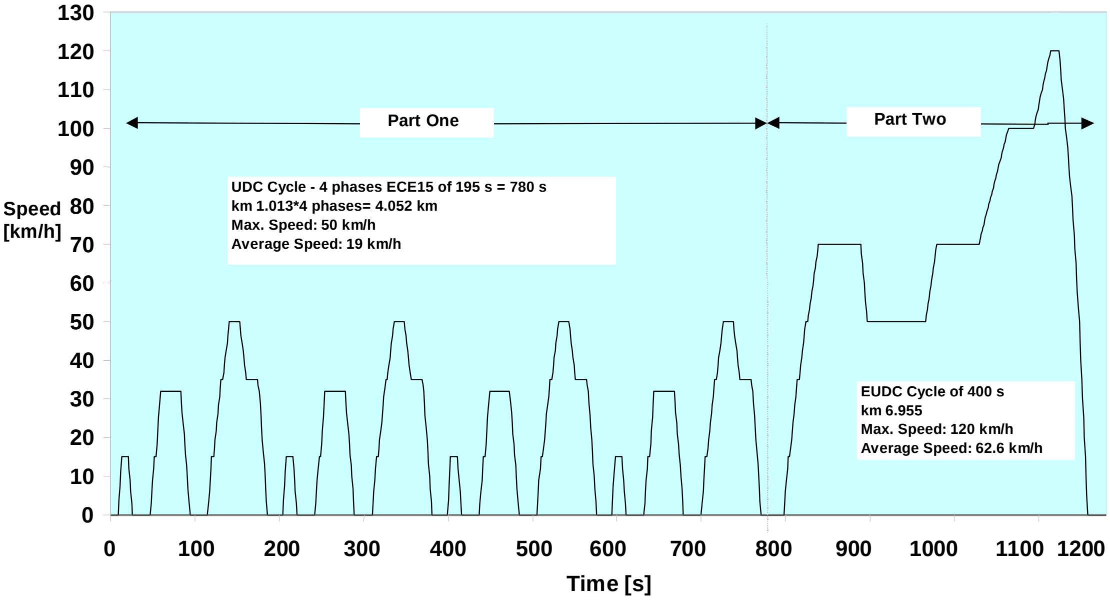
4.1.5 Reference road cycle

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 vehicle/fuel combination emissions.

Experimental data from Volkswagen for a Golf with a PISI 1.6l engine (2002 gasoline vehicle)) 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.

Cold start (20°C), as required by the standard certification tests, was included in the calculations. The steady-state fuel over-consumption (in percentage by reference to hot operation) is only a function of the engine temperature. The rate of rise of the engine temperature and the resulting over-consumption over the cycle were validated with experimental data for the PISI gasoline reference configuration.

Figure 2.2.3 Reference NEDC driving cycle



For the other configurations, such as DISI, the fuel over-consumption was calculated versus engine temperature with the same parameters. For the DISI configuration, the following assumptions were made:

- Below 50°C, the engine operates in “homogeneous” mode, at stoichiometric conditions (not “lean burn”),
- Above 50°C, in a range of low speed, low-to-mid load, the engine is under lean stratified conditions, with the typically lower fuel consumption of DI engines.

To account for the two different regimes on the DISI vehicle, a subsequent correction was applied. To comply with the “cold” stoichiometric conditions efficiency, the instantaneous fuel consumption was increased by 10% whenever the engine temperature was below 50°C and for the operating points appearing in the “lean burn stratified “zone of the relevant map.

For the simulated assessment of the various technologies the inertia class conditions were kept conform to the standard rules.

EURO III Diesel vehicles were assumed to be fitted only with an oxidation catalyst. EURO IV Diesel vehicles are considered to be equipped with a Diesel Particle Filter (DPF), with a fuel efficiency penalty resulting from the need for its periodic regeneration (+2.5). An exception was made for DME DICI vehicles which, because of the favourable properties of that fuel, would not require a DPF to meet the EURO IV standard. An alternative option was also calculated for 2010+ Diesel vehicles without DPF, to represent a case where advanced combustion strategy concepts alone would be able to achieve the EURO IV emissions standard.

AUXILIARIES and fuel economy

The fuel consumption simulation and the crosscheck tests included electrical or mechanical load due to components inherent to the powertrain. Fuel penalty due to auxiliary devices was assessed in terms of total GHG emissions (g CO_{2eq} / km) for a typical additional load of 300 W.

For the performance tests, the following conditions applied:

- Vehicle mass: curb weight + 140 kg.
- Auxiliaries: Not powered
- Acceleration: time from 80 to 120 km/h in 4th gear to be less than 13 s; time from 80 to 120 km/h in top gear given for information only.
- Maximum acceleration: time from 0 to 50 km/h, 0 to 100, and 80 to 120 km/h: the original conventional ADVISOR model was used.
- Top speed is the result of an analytical calculation

- Gradeability (%): the vehicle speed is 1 km/h and the torque is maximum
- e.g. 100 % gradeability represents a 45 ° angle slope

(Analytical calculation).

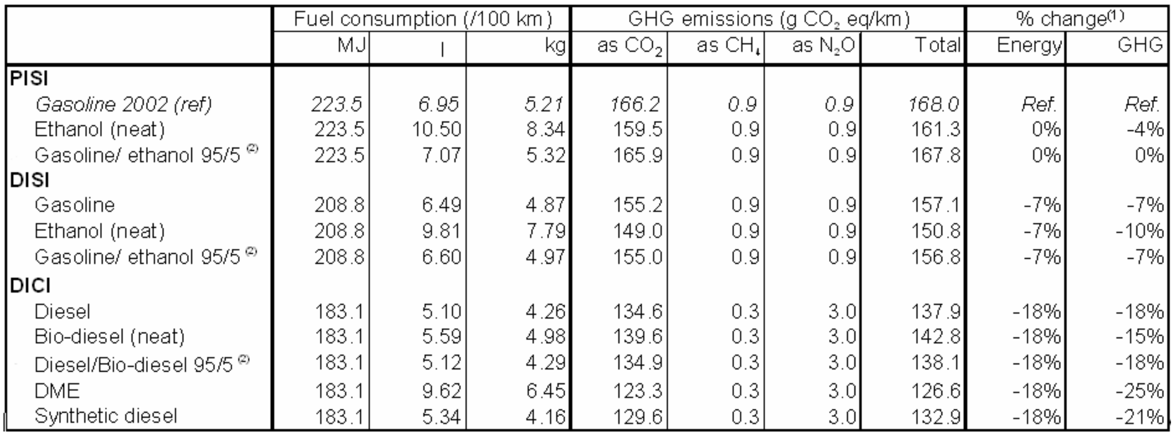
4.1.5.1 Energy and GHG emissions

Total GHG emissions were calculated. Methane (CH_4) and N_2O emissions were taken into account as CO_2 equivalent through their IPCC factor:

- For CH_4, the IPCC factor is 23. For gasoline, diesel fuel and DME, CH_4 emissions were considered to be 20 % of the applicable unburnt hydrocarbons limit.
- For N_2O, the IPCC factor is 296. For all configurations, N_2O emissions were considered to be 2% of the NOx emissions limit.

The average fuel consumption and total GHG emissions over the NEDC are shown in the tables and figures below (Table 4.9 for 2002 and Table 4.10 for 2010 ICE configurations).

Table 4.9 Average energy/fuel consumption and GHG emissions over the NEDC 2002 ICE vehicles

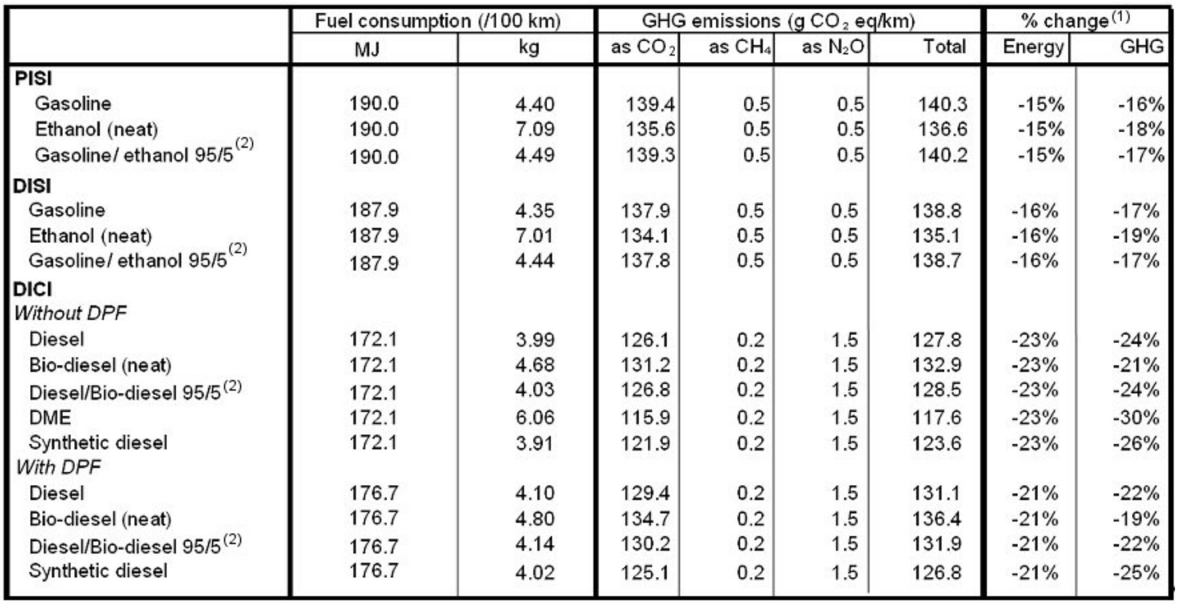


	Fuel consumption (/100 km)			GHG emissions (g CO_2 eq/km)				% change(1)	
	MJ	l	kg	as CO_2	as CH_4	as N_2O	Total	Energy	GHG
PISI									
Gasoline 2002 (ref)	*223.5*	*6.95*	*5.21*	*166.2*	*0.9*	*0.9*	*168.0*	*Ref.*	*Ref.*
Ethanol (neat)	223.5	10.50	8.34	159.5	0.9	0.9	161.3	0%	-4%
Gasoline/ ethanol 95/5 (2)	223.5	7.07	5.32	165.9	0.9	0.9	167.8	0%	0%
DISI									
Gasoline	208.8	6.49	4.87	155.2	0.9	0.9	157.1	-7%	-7%
Ethanol (neat)	208.8	9.81	7.79	149.0	0.9	0.9	150.8	-7%	-10%
Gasoline/ ethanol 95/5 (2)	208.8	6.60	4.97	155.0	0.9	0.9	156.8	-7%	-7%
DICI									
Diesel	183.1	5.10	4.26	134.6	0.3	3.0	137.9	-18%	-18%
Bio-diesel (neat)	183.1	5.59	4.98	139.6	0.3	3.0	142.8	-18%	-15%
Diesel/Bio-diesel 95/5 (2)	183.1	5.12	4.29	134.9	0.3	3.0	138.1	-18%	-18%
DME	183.1	9.62	6.45	123.3	0.3	3.0	126.6	-18%	-25%
Synthetic diesel	183.1	5.34	4.16	129.6	0.3	3.0	132.9	-18%	-21%

(1) from reference 2002 gasoline PISI

(2) blend figures were calculated assuming proportional contribution of each component

Table 4.10 Average energy/fuel consumption and GHG emissions over the NEDC 2010 ICE vehicles



	Fuel consumption (/100 km)		GHG emissions (g CO_2 eq/km)				% change(1)	
	MJ	kg	as CO_2	as CH_4	as N_2O	Total	Energy	GHG
PISI								
Gasoline	190.0	4.40	139.4	0.5	0.5	140.3	-15%	-16%
Ethanol (neat)	190.0	7.09	135.6	0.5	0.5	136.6	-15%	-18%
Gasoline/ ethanol 95/5(2)	190.0	4.49	139.3	0.5	0.5	140.2	-15%	-17%
DISI								
Gasoline	187.9	4.35	137.9	0.5	0.5	138.8	-16%	-17%
Ethanol (neat)	187.9	7.01	134.1	0.5	0.5	135.1	-16%	-19%
Gasoline/ ethanol 95/5(2)	187.9	4.44	137.8	0.5	0.5	138.7	-16%	-17%
DICI								
Without DPF								
Diesel	172.1	3.99	126.1	0.2	1.5	127.8	-23%	-24%
Bio-diesel (neat)	172.1	4.68	131.2	0.2	1.5	132.9	-23%	-21%
Diesel/Bio-diesel 95/5(2)	172.1	4.03	126.8	0.2	1.5	128.5	-23%	-24%
DME	172.1	6.06	115.9	0.2	1.5	117.6	-23%	-30%
Synthetic diesel	172.1	3.91	121.9	0.2	1.5	123.6	-23%	-26%
With DPF								
Diesel	176.7	4.10	129.4	0.2	1.5	131.1	-21%	-22%
Bio-diesel (neat)	176.7	4.80	134.7	0.2	1.5	136.4	-21%	-19%
Diesel/Bio-diesel 95/5(2)	176.7	4.14	130.2	0.2	1.5	131.9	-21%	-22%
Synthetic diesel	176.7	4.02	125.1	0.2	1.5	126.8	-21%	-25%

(1) from reference 2002 gasoline PISI

(2) blend figures were calculated assuming proportional contribution of each component

The energy efficiency improvement (2010 versus 2002) was more modest for CI Diesel engines than for their SI gasoline counterpart. As a result, the advantage of the “best in class” (Diesel) was gradually eroded from the current (2002) 19.3 % to as low as 7 % by 2010.

4.2 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 selected methodology has been used to estimate the retail price increment expectable at the 2010+ horizons for the various technologies under consideration (maintenance costs have not been considered).

Inspired from the MIT study "On the road in 2020"[6], the calculation delivered orders of magnitude in a simple and transparent way. The retail price has been obtained by subtracting the price impact of the original internal combustion engine and components and adding the impact of the new powertrain components.

For the retail prices detailed assessments, the following rules were used:

- When the powertrain could be identified as a spark ignition (SI) combustion technology, the retail price was evaluated relative to the 2002 PISI vehicle.
- When the powertrain could be identified as a compression ignition (CI) technology, the retail price was evaluated relative to the 2002 DICI vehicle.
- When the powertrain could not be identified as either a SI or a CI technology, the retail price was evaluated relative to the 2002 PISI vehicle.

From Table 4.11 a detailed assessment of each considered powertrain has been 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.

Table 4.11 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
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
DME	€	1500	a

The percent retail price increase for the 2010 vehicles has been calculated compared to the PISI ICE Gasoline 2010 vehicle (assumed retail price **19560 €**). These results are deemed to represent fair price differentials based on commercial realities or reflecting the lack of reliable consolidated data. The uncertainty ranges have also been estimated. The result indicates that the range is fairly narrow for established technologies but widens when it comes to less developed options.

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

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A Summary of WTT pathways codes and description

(New pathways are highlighted in yellow)

Code	*Short description*	*Details*
Conventional fuels		
COG1	Gasoline	
COD1	Diesel	
CBG: Compressed Biogas		
OWCG1	Municipal waste	Biogas produced from municipal waste, cleaned and upgraded
OWCG2	Liquid manure	As above with liquid manure
OWCG3	Dry manure	As above with dry manure
Ethanol		
SBET1	Sugar beet, pulp to fodder	Ethanol from sugar beet, pulp used for animal fodder
SBET3	Sugar beet, pulp to heat	As above but pulp used as fuel to produce process heat
WTET1a	Wheat, conv NG boiler, DDGS as AF	Ethanol from wheat, process heat from conventional NG-fires boiler, DDGS to animal feed
WTET1b	Wheat, conv NG boiler, DDGS as fuel	As above but DDGS used as fuel
WTET2a	Wheat, NG GT+CHP, DDGS as AF	As WTET1a but process heat from NG-fired gas turbine with combined heat and power scheme
WTET2b	Wheat, NG GT+CHP, DDGS as fuel	As WTET1b but process heat from NG-fired gas turbine with combined heat and power scheme
WTET3a	Wheat, Lignite CHP, DDGS as AF	As WTET1a but process heat from lignite-fired combined heat and power scheme
WTET3b	Wheat, Lignite CHP, DDGS as fuel	As WTET1b but process heat from lignite-fired combined heat and power scheme
WTET4a	Wheat, Straw CHP, DDGS as AF	As WTET1a but process heat from straw-fired combined heat and power scheme
WTET4b	Wheat, Straw CHP, DDGS as fuel	As WTET1b but process heat from straw-fired combined heat and power scheme
WWET1	W Wood	Ethanol from waste wood
WFET1	F wood	Ethanol from farmed wood
STET1	Wheat straw	Ethanol from wheat straw
SCET1	Sugar cane (Brazil)	Ethanol from sugar cane in Brazilian conditions
Ethers		
GRMB1	MTBE: remote plant	MTBE produced in a remote plant from locally produced methanol (from NG) and associated butanes
LREB1	ETBE: imported C4 and wheat ethanol	ETBE produced in EU from imported butanes and wheat ethanol
Bio-diesel		
ROFA1	RME: Gly as chemical	Rapeseed Methyl Ester, glycerine used as chemical
ROFA2	RME: Gly as animal feed	Rapeseed Methyl Ester, glycerine used as animal feed
ROFE1	REE: Gly as chemical	Rapeseed Ethyl Ester, glycerine used as chemical
ROFE2	REE: Gly as animal feed	Rapeseed Ethyl Ester, glycerine used as animal feed
SOFA1	SME: Gly as chemical	Sunflower seed Methyl Ester, glycerine used as chemical
SOFA2	SME: Gly as animal feed	Sunflower seed Methyl Ester, glycerine used as animal feed
Synthetic diesel		
GRSD1	Rem GTL, Sea, Diesel mix	Synthetic diesel from NG in remote plant , sea transport, blended with conventional diesel at refinery

GRSD2	Rem GTL, Sea, Rail/Road	As above but distributed separately
GRSD2C	Rem GTL, Sea, Rail/Road, CC&S	As above with capture and sequestration of CO_2 produced in production process
KOSD1	CTL, Diesel mix	Synthetic diesel from coal in EU plant , blended with conventional diesel at refinery
KOSD1C	CTL, CC&S, Diesel mix	As above with capture and sequestration of CO_2 produced in production process
WWSD1	W Wood, diesel mix	Synthetic diesel from waste wood in EU plant, blended with conventional diesel at refinery
WFSD1	F wood, diesel mix	Synthetic diesel from farmed wood in EU plant, blended with conventional diesel at refinery
BLSD1	W Wood, Black liquor	Synthetic diesel from waste wood in EU paper mill (Black Liquor route) , blended with conventional diesel at refinery
DME (Di-Methyl-Ether)		
GPDE1a	NG 7000 km, Syn, Rail/Road	DME from NG piped over 7000 km, distributed by rail + road
GPDE1b	NG 4000 km, Syn, Rail/Road	DME from NG piped over 4000 km, distributed by rail + road
GRDE1	Rem Syn, Sea, Rail/Road	DME produced remotely from NG, transported by sea, distributed by rail + road
KODE1	Coal EU-mix, Cen, Rail/Road	DME from large coal (average EU supply quality) gasification plant in EU, distributed by rail + road
GRDE1C	Rem Syn, Sea, Rail/Road, CC&S	As above with capture and sequestration of CO_2 produced in production process
WWDE1	W Wood, Road	DME from waste wood, distributed by road
WFDE1	F Wood, Road	DME from waste wood, distributed by road
BLDE1	W Wood, Black liquor	DME from waste wood in EU paper mill (Black Liquor route), distributed by road

B 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.

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

B.1 Crude oil based fuels

WTT Code	Powertrain	Energy MJ / 100 km												GHG g CO_{2eq} / km								
		Total									Fossil											
		TTW (MJ_f/100 km)			WTT (MJ_{xt}/100 km)			**WTW** (MJ/100km)			**WTW** (MJ_{fo}/100km)			TTW			WTT			**WTW**		
		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	31	4	6	**255**	4	6				168	0	0	28	3	5	**196**	3	5
	DISI 2002	209	8	8	29	4	6	**238**	10	11				157	6	6	26	3	4	**183**	7	8
	PISI 2010	190	6	6	26	4	5	**216**	7	8				140	4	4	24	3	4	**164**	5	6
	DISI 2010	188	9	9	26	4	5	**214**	11	12				139	7	7	24	3	4	**162**	8	9
COD1	Conventional diesel																					
	DICI 2002	183	5	5	29	4	4	**212**	7	7				138	4	4	26	3	3	**164**	6	6
	DICI 2010 no DPF	172	7	7	27	4	4	**200**	9	9				128	5	5	24	3	3	**152**	7	7
	DICI 2010 DPF	177	7	7	28	4	4	**205**	9	9				131	6	6	25	3	3	**156**	7	7

B.2 CBG

WTT Code	Powertrain	Energy MJ / 100 km												GHG g CO_{2eq} / km								
		Total									Fossil											
		TTW (MJ_f/100 km)			WTT (MJ_{xt}/100 km)			**WTW** (MJ/100km)			**WTW** (MJ_{fo}/100km)			TTW			WTT			**WTW**		
		Mean	Min	Max	Mean	Min	Max	**Mean**	Min	Max	**Mean**	Min	Max	Mean	Min	Max	Mean	Min	Max	**Mean**	Min	Max
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	195	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
OWCG2	CBG: liquid manure																					
	PISI bi-fuel 2002	227	12	6	219	40	34	**446**	53	41	**7**	12	7	132	7	4	-304	51	61	**-171**	36	52
	PISI dedicated 2002	223	14	6	215	39	33	**438**	55	40	**7**	14	6	130	8	4	-298	51	60	**-168**	33	51
	PISI bi-fuel 2010	188	12	8	182	33	28	**370**	46	37	**6**	12	8	108	7	4	-252	43	50	**-144**	28	40
	PISI dedicated 2010	187	13	8	181	33	28	**368**	47	36	**6**	13	8	108	7	4	-250	42	50	**-143**	26	40
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

B.3 Ethanol

WTT Code	Powertrain	Energy MJ / 100 km												GHG g CO_{2eq} / km								
		Total									Fossil											
		TTW (MJ_f/100 km)			WTT (MJ_{xt}/100 km)			**WTW** (MJ/100km)			**WTW** (MJ_{fo}/100km)			TTW			WTT			**WTW**		
		Mean	Min	Max	Mean	Min	Max	**Mean**	Min	Max	**Mean**	Min	Max	Mean	Min	Max	Mean	Min	Max	**Mean**	Min	Max
Ethanol pathways, as blended fuels																						
SBET1	EtOH: Sugar beet, pulp to fodder																					
	PISI 2002 95/5	224	2	2	50	31	31	**274**	31	32	**252**			168	2	2	25	3	5	**193**	4	5
	DISI 2002 95/5	209	9	9	47	29	29	**256**	32	32	**235**			157	6	6	23	3	5	**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
	DISI 2010 95/5	188	10	10	42	26	26	**230**	30	30	**212**			139	7	7	21	3	4	**160**	8	9
SBET3	EtOH: Sugar beet, pulp to heat																					
	PISI 2002 95/5	224	2	2	44	8	8	**268**	8	9	**245**			168	2	2	22	3	5	**190**	4	5
	DISI 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
	DISI 2010 95/5	188	10	10	37	6	7	**225**	13	13	**206**			139	7	7	18	3	4	**157**	8	9
WTET1a	EtOH: Wheat, conv NG boiler, DDGS as AF																					
	PISI 2002 95/5	224	2	2	49	14	9	**273**	15	9	**252**			168	2	2	25	4	5	**193**	4	6
	DISI 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
	DISI 2010 95/5	188	10	10	42	12	7	**229**	17	13	**212**			139	7	7	21	3	4	**160**	8	9
WTET1b	EtOH: Wheat, conv NG boiler, DDGS as fuel																					
	PISI 2002 95/5	224	2	2	44	9	9	**268**	10	9	**247**			168	2	2	24	4	5	**192**	4	6
	DISI 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
	DISI 2010 95/5	188	10	10	37	8	7	**225**	13	13	**207**			139	7	7	20	3	4	**159**	8	9
WTET2a	EtOH: Wheat, NG GT+CHP, DDGS as AF																					
	PISI 2002 95/5	224	2	2	47	11	9	**270**	12	9	**249**			168	2	2	24	4	5	**192**	4	6
	DISI 2002 95/5	209	9	9	44	11	8	**252**	15	13	**233**			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
	DISI 2010 95/5	188	10	10	39	10	7	**227**	15	13	**209**			139	7	7	20	3	4	**159**	8	9
WTET2b	EtOH: Wheat, NG GT+CHP, DDGS as fuel																					
	PISI 2002 95/5	224	2	2	41	6	9	**265**	7	9	**244**			168	2	2	23	4	5	**191**	4	6
	DISI 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
	DISI 2010 95/5	188	10	10	35	5	7	**223**	12	13	**205**			139	7	7	19	3	4	**158**	8	9
WTET3a	EtOH: Wheat, Lignite CHP, DDGS as AF																					
	PISI 2002 95/5	224	2	2	49	14	9	**273**	14	9	**251**			168	2	2	29	4	5	**197**	5	6
	DISI 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
	DISI 2010 95/5	188	10	10	41	12	7	**229**	17	13	**211**			139	7	7	24	3	4	**163**	8	9

WTET3b	EtOH: Wheat, Lignite CHP, DDGS as fuel																		
	PISI 2002 95/5	224	2	2	44	9	9	**267**	9	9	**246**			168	2	2	28	4	5	**196**	4	6
	DISI 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
	DISI 2010 95/5	188	10	10	37	7	7	**225**	13	13	**207**			139	7	7	24	3	4	**162**	8	9
WTET4a	EtOH: Wheat, Straw CHP, DDGS as AF																		
	PISI 2002 95/5	224	2	2	48	7	9	**272**	8	9	**245**			168	2	2	21	4	5	**189**	4	6
	DISI 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
	DISI 2010 95/5	188	10	10	41	6	7	**229**	13	13	**206**			139	7	7	18	3	4	**157**	8	9
WTET4b	EtOH: Wheat, Straw CHP, DDGS as fuel																		
	PISI 2002 95/5	224	2	2	43	2	9	**267**	3	9	**240**			168	2	2	20	4	5	**188**	4	6
	DISI 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
	DISI 2010 95/5	188	10	10	36	2	7	**224**	10	13	**202**			139	7	7	17	3	4	**156**	8	9
WWET1	EtOH: W Wood																		
	PISI 2002 95/5	224	2	2	51	7	7	**275**	8	8	**245**			168	2	2	21	3	4	**188**	4	5
	DISI 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
	DISI 2010 95/5	188	10	10	43	6	6	**231**	13	12	**206**			139	7	7	17	3	4	**156**	8	8
WFET1	EtOH: F wood																		
	PISI 2002 95/5	224	2	2	51	7	7	**275**	8	8	**245**			168	2	2	21	3	5	**189**	4	6
	DISI 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
	DISI 2010 95/5	188	10	10	43	6	6	**231**	13	13	**206**			139	7	7	18	3	4	**156**	8	9
STET1	EtOH: Wheat straw																		
	PISI 2002 95/5	224	2	2	44	5	7	**268**	6	7	**243**			168	2	2	20	3	4	**187**	4	5
	DISI 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
	DISI 2010 95/5	188	10	10	37	4	6	**225**	12	12	**204**			139	7	7	17	3	4	**155**	8	8
SCET1	EtOH: Sugar cane (Brazil)																		
	PISI 2002 95/5	224	2	2	50	4	7	**273**	5	8	**242**			168	2	2	20	3	4	**188**	4	5
	DISI 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
	DISI 2010 95/5	188	10	10	42	4	6	**230**	11	12	**204**			139	7	7	17	3	4	**155**	8	8

WTT Code	**Powertrain**	**Energy MJ / 100 km**												**GHG g CO$_{2eq}$ / km**							
		Total									**Fossil**										
		TTW (MJ$_f$/100 km)			WTT (MJ$_{xt}$/100 km)			**WTW** (MJ/100km)			**WTW** (MJ$_{fo}$/100km)			TTW			WTT			**WTW**		
		Mean	Min	Max	Mean	Min	Max	**Mean**	Min	Max	**Mean**	Min	Max	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	248	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	353	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	318	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	435	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

B.4 Ethers

WTT Code	**Powertrain**	**Energy MJ / 100 km**												**GHG g CO$_{2eq}$ / km**								
		Total									**Fossil**											
		TTW (MJ$_f$/100 km)			WTT (MJ$_{xt}$/100 km)			**WTW** (MJ/100km)			**WTW** (MJ$_{fo}$/100km)			TTW			WTT			**WTW**		
		Mean	Min	Max	Mean	Min	Max	**Mean**	Min	Max	**Mean**	Min	Max	Mean	Min	Max	Mean	Min	Max	**Mean**	Min	Max
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

B.5 Bio-diesel

WTT Code	**Powertrain**	**Energy MJ / 100 km**												**GHG g CO$_{2eq}$ / km**								
		Total									**Fossil**											
		TTW (MJ$_f$/100 km)			WTT (MJ$_{xt}$/100 km)			**WTW** (MJ/100km)			**WTW** (MJ$_{fo}$/100km)			TTW			WTT			**WTW**		
		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	39	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	**208**	12	11	**193**			128	6	6	21	5	5	**149**	8	8
	DICI 2010 DPF 95/5	177	8	8	37	8	7	**214**	12	11	**198**			132	6	6	21	5	5	**153**	8	8
ROFA2	RME: Gly as animal feed																					
	DICI 2002 95/5	183	6	6	39	9	7	**222**	11	10	**206**			138	4	4	23	5	5	**161**	7	7
	DICI 2010 no DPF 95/5	172	8	8	37	8	6	**209**	12	11	**194**			128	6	6	21	5	5	**150**	8	8
	DICI 2010 DPF 95/5	177	8	8	38	8	7	**214**	13	11	**199**			132	6	6	22	5	5	**154**	8	8
ROFE1	REE: Gly as chemical																					
	DICI 2002 95/5	183	6	6	39	8	7	**222**	11	10	**205**			138	4	4	22	5	5	**160**	7	7
	DICI 2010 no DPF 95/5	172	8	8	37	7	6	**209**	12	11	**193**			128	6	6	20	4	5	**149**	8	8
	DICI 2010 DPF 95/5	177	8	8	38	7	6	**215**	12	11	**198**			132	6	6	21	4	5	**153**	8	8
ROFE2	REE: Gly as animal feed																					
	DICI 2002 95/5	183	6	6	40	8	7	**223**	11	10	**206**			138	4	4	22	5	5	**160**	7	7
	DICI 2010 no DPF 95/5	172	8	8	37	8	6	**209**	12	11	**193**			128	6	6	21	4	5	**149**	8	8
	DICI 2010 DPF 95/5	177	8	8	38	8	6	**215**	12	11	**198**			132	6	6	21	4	5	**153**	8	8
SOFA1	SME: Gly as chemical																					
	DICI 2002 95/5	183	6	6	37	7	6	**220**	10	9	**205**			138	4	4	20	4	4	**158**	6	7
	DICI 2010 no DPF 95/5	172	8	8	34	7	5	**207**	11	10	**193**			128	6	6	19	4	4	**147**	7	7
	DICI 2010 DPF 95/5	177	8	8	35	7	6	**212**	12	11	**198**			132	6	6	19	4	4	**151**	7	8
SOFA2	SME: Gly as animal feed																					
	DICI 2002 95/5	183	6	6	37	8	6	**220**	11	9	**205**			138	4	4	21	4	4	**159**	6	6
	DICI 2010 no DPF 95/5	172	8	8	35	7	5	**207**	12	10	**193**			128	6	6	19	4	4	**148**	7	7
	DICI 2010 DPF 95/5	177	8	8	36	7	6	**213**	12	11	**198**			132	6	6	20	4	4	**152**	7	8
Bio-diesel pathways contribution based on neat fuel (netback calculation)																						
ROFA1	RME: Gly as chemical																					
	DICI 2002	183	5	5	218	16	20	**401**	23	27	**84**	10	11	143	4	4	-53	39	37	**90**	38	35
	DICI 2010 no DPF	172	7	7	205	15	18	**377**	25	28	**79**	12	13	133	6	6	-50	37	35	**83**	35	33
	DICI 2010 DPF	177	7	7	210	15	19	**387**	25	29	**81**	12	13	136	6	6	-51	38	35	**85**	36	34
ROFA2	RME: Gly as animal feed																					
	DICI 2002	183	5	5	227	21	19	**411**	28	26	**93**	13	12	143	4	4	-43	39	30	**100**	37	29
	DICI 2010 no DPF	172	7	7	214	19	17	**386**	29	27	**88**	14	13	133	6	6	-41	36	28	**92**	35	27
	DICI 2010 DPF	177	7	7	219	20	18	**396**	30	28	**90**	14	13	136	6	6	-42	37	29	**95**	36	28
ROFE1	REE: Gly as chemical																					
	DICI 2002	183	5	5	229	19	17	**412**	26	24	**75**	10	9	143	4	4	-59	35	37	**84**	33	35
	DICI 2010 no DPF	172	7	7	215	18	16	**387**	28	26	**70**	11	11	133	6	6	-55	33	35	**78**	31	33
	DICI 2010 DPF	177	7	7	221	18	16	**398**	28	27	**72**	12	11	136	6	6	-57	34	35	**80**	32	34
ROFE2	REE: Gly as animal feed																					
	DICI 2002	183	5	5	238	19	18	**421**	26	26	**83**	11	10	143	4	4	-50	35	43	**93**	34	42
	DICI 2010 no DPF	172	7	7	223	18	17	**396**	28	28	**78**	12	12	133	6	6	-47	33	40	**86**	31	39
	DICI 2010 DPF	177	7	7	229	18	18	**406**	29	28	**80**	12	12	136	6	6	-48	34	41	**88**	32	40
SOFA1	SME: Gly as chemical																					
	DICI 2002	183	5	5	179	19	17	**362**	25	23	**67**	11	10	143	4	4	-93	23	21	**50**	21	18
	DICI 2010 no DPF	172	7	7	168	18	16	**340**	26	24	**63**	12	11	133	6	6	-87	22	19	**46**	19	17
	DICI 2010 DPF	177	7	7	172	18	16	**349**	27	25	**64**	12	12	136	6	6	-90	22	20	**47**	19	17
SOFA2	SME: Gly as animal feed																					
	DICI 2002	183	5	5	188	17	15	**371**	23	22	**76**	11	10	143	4	4	-83	20	20	**60**	18	18
	DICI 2010 no DPF	172	7	7	177	16	14	**349**	25	23	**71**	12	11	133	6	6	-78	18	18	**55**	16	16
	DICI 2010 DPF	177	7	7	182	16	15	**358**	25	24	**73**	12	12	136	6	6	-80	19	19	**56**	17	17

B.6 Synthetic diesel fuel

WTT Code	**Powertrain**	**Energy MJ / 100 km**												**GHG g CO$_{2eq}$ / km**								
		Total									**Fossil**											
		TTW (MJ$_f$/100 km)			WTT (MJ$_{xt}$/100 km)			**WTW** (MJ/100km)			**WTW** (MJ$_{fo}$/100km)			TTW			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																						
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

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
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	35	4	4	**212**	9	10	**195**			131	6	6	18	3	3	**149**	7	7
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
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
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

B.7 DME

WTT Code	**Powertrain**	**Energy MJ / 100 km**												**GHG g CO_{2eq} / km**								
		Total									**Fossil**											
		TTW (MJ_f/100 km)			WTT (MJ_{xt}/100 km)			**WTW** (MJ/100km)			**WTW** (MJ_{fo}/100km)			TTW			WTT			**WTW**		
		Mean	Min	Max	Mean	Min	Max	**Mean**	Min	Max	**Mean**	Min	Max	Mean	Min	Max	Mean	Min	Max	**Mean**	Min	Max
DME pathways																						
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
WFDE1	DME: F Wood, Road																					
	DICI 2002	183	5	5	196	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
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

C Cost calculations

C.1 General assumptions

For those fuels manufactured in Europe production costs have been estimated on the basis of published literature. A capital charge of 12% has been used 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 ± 20% and ± 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.

Annual capital charge	12%	(corresponding to 8% real-terms IRR, no tax)
Capex uncertainty range		
Established	20.0%	
New	40.0%	
OCF	0.10	
Opex	% of capex	
Low tech	3.0%	
High tech	4.5%	
Retail	8.0%	

C.2 Feedstocks and raw materials

Fossil fuels

Crude oil	Density	LHV	Low scenario		High scenario		Reference
	t/m^3	GJ/t	€ /bbl	€ /GJ	€ /bbl	€ /GJ	
	0.820	42.0	25	4.6	50	9.1	
Road fuels of fossil origin				€ /GJ	OCF	€ /GJ	
Gasoline and diesel fuel		Ratio to crude 1.3		5.9	1.00	11.9	Historical trend

Biomass

(Delivered cost to processing plant)

	Moisture content	LHV	Low oil price (oil at 25 €/bbl)		Own	High oil price		
						OCF	(oil at 50 €/bbl)	
		GJ/t	€ /t	€ /GJ	variability		€ /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	

References: [FfE 1998], [Kaltschmitt 2001], [Fahrzeugbau Langendorf 2001], [Messer 1999], [ETSU 1996], [ESU 1996], [ADEME 2002],[NAS 1998], [DG AGRI 2005], [FAPRI 2005],[Lundmark 2004]

C.3 Production plants

All tables in this section are built on the same model detailing:

- Plant scale: product production rate in kt/a, PJ/a and MW and hours of operation per annum
- Feed rate in kt/a and PJ/a and feed cost in €/t and M€/a
- Capital expenditure (capex) in M€ and capital charge in M€/a
- Operating costs (opex) split into fixed (proportion of capex) and variable (net energy and chemicals, including energy credits)
- By-products credits including production rate in PJ/a, unit cost in €/t or GJ and value in M€/a

C.3.1 Bio-fuels

Ethanol from sugar beet **Oil at 25 €/bbl**

Pulp to		Animal feed	Energy
Pathway code		SBET1	SBET3
Plant scale			
Ethanol	kt/a	28	28
	PJ/a	0.76	0.76
	MW	59	59
	h/a	3600	3600
Sugar beet (76.5% moisture)	kt/a	375	375
	PJ/a	1.4	1.4
	€/t	*25+-16%*	
	M€/a	**9.4**	**9.4**
Capex	*M€*	*17+-20%*	*28+-20%*
Capital charge @ 12%	**M€/a**	**2.0**	**3.4**
Opex	**M€/a**	**1.6**	**1.0**
Fixed		0.5	0.8
Net energy and chemicals		1.1	0.2
Credit for pulp & slops	PJ/a	-0.3	-0.4
	€/GJ	*5.3*	
	M€/a	**-1.6**	**-1.2**
Total annual production cost	**M€/a**	**11.4**	**12.6**
Total specific production cost	**€/GJ**	**15.0**	**16.5**
of which:			
Sugar beet		12.3	12.3
Capex		2.7	4.4
Opex		2.1	1.3
Credits		-2.1	-1.5

Ethanol from sugar beet **Oil at 50 €/bbl**

Pulp to		Animal feed	Energy
Pathway code		SBET1	SBET3
Plant scale			
Ethanol	kt/a	28	28
	PJ/a	0.76	0.76
	MW	59	59
	h/a	3600	3600
Sugar beet (76.5% moisture)	kt/a	375	375
	PJ/a	1.4	1.4
	€/t	*26+-16%*	
	M€/a	**9.8**	**9.8**
Capex	*M€*	*19+-20%*	*31+-20%*
Capital charge @ 12%	**M€/a**	**2.2**	**3.7**
Opex	**M€/a**	**2.5**	**1.3**
Fixed		0.6	0.9
Net energy and chemicals		2.0	0.4
Credit for pulp & slops	PJ/a	-0.3	-0.4
	€/GJ	*5.6*	
	M€/a	**-1.6**	**-2.1**
Total annual production cost	**M€/a**	**13.0**	**12.7**
Total specific production cost	**€/GJ**	**17.1**	**16.7**
of which:			
Sugar beet		13.0	13.0
Capex		3.0	4.9
Opex		3.3	1.7
Credits		-2.2	-2.8

Capex Source:[FfE 1998]

Ethanol from wheat grain **Oil at 25 €/bbl**

DDGS to		Animal feed				Energy			
Energy production scheme		Conv. Boiler	CCGT	Coal CHP	Straw CHP	CCGT	CCGT	Coal CHP	Straw CHP
Pathway code		WTET1a	WTET2a	WTET3a	WTET4a	WTET1b	WTET2b	WTET3b	WTET4b
Plant scale									
Ethanol	kt/a	100							
	PJ/a	2.7							
	MW	93							
	h/a	8000							
Wheat grain (13% moisture)	kt/a	338							
	PJ/a	5.0							
	€/t	*95+-16%*							
	M€/a	**32.1**							
Capex	*M€*	*60+-20%*	*78+-20%*	*105+-20%*	*105+-40%*	*60+-20%*	*78+-20%*	*105+-20%*	*105+-40%*
Capital charge @ 12%	**M€/a**	**7.2**	**9.4**	**12.6**	**12.6**	**7.2**	**9.4**	**12.6**	**12.6**
Opex	**M€/a**	**9.1**	**1.8**	**4.7**	**7.3**	**9.1**	**1.8**	**4.7**	**7.3**
Fixed		1.8	2.3	4.7	4.7	1.8	2.3	4.7	4.7
Net energy and chemicals		7.3	-0.5	0.0	2.6	7.3	-0.5	0.0	2.6
Credit for DDGS	kt/a	-114							
	€/t	*74*				*24*			
	M€/a	**-8.4**				**-2.7**			
Total annual production cost	**M€/a**	**39.9**	**34.8**	**41.0**	**43.5**	**45.6**	**40.5**	**46.7**	**49.2**
Total specific production cost	**€/GJ**	**14.9**	**13.0**	**15.3**	**16.2**	**17.0**	**15.1**	**17.4**	**18.4**
of which:									
Wheat grain		12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Capex		2.7	3.5	4.7	4.7	2.7	3.5	4.7	4.7
Opex		3.4	0.7	1.8	2.7	3.4	0.7	1.8	2.7
Credits		-3.2	-3.2	-3.2	-3.2	-1.0	-1.0	-1.0	-1.0

Capex source: [LowCVP 2004]

Ethanol from wheat grain **Oil at 50 €/bbl**

DDGS to		Animal feed				Energy			
Energy production scheme		Conv. Boiler	CCGT	Coal CHP	Straw CHP	CCGT	CCGT	Coal CHP	Straw CHP
Pathway code		WTET1a	WTET2a	WTET3a	WTET4a	WTET1b	WTET2b	WTET3b	WTET4b
Plant scale									
Ethanol	kt/a	100							
	PJ/a	2.7							
	MW	93							
	h/a	8000							
Wheat grain (13% moisture)	kt/a	338							
	PJ/a	5.0							
	€/t	*100+-16%*							
	M€/a	**33.7**							
Capex	*M€*	*66+-20%*	*86+-20%*	*116+-20%*	*116+-40%*	*66+-20%*	*86+-20%*	*116+-20%*	*116+-40%*
Capital charge @ 12%	**M€/a**	**7.9**	**10.3**	**13.9**	**13.9**	**7.9**	**10.3**	**13.9**	**13.9**
Opex	**M€/a**	**14.8**	**6.8**	**6.5**	**7.7**	**14.8**	**6.8**	**6.5**	**7.7**
Fixed		2.0	2.6	5.2	5.2	2.0	2.6	5.2	5.2
Net energy and chemicals		12.8	4.3	1.4	2.5	12.8	4.3	1.4	2.5
Credit for DDGS	kt/a	-114							
	€/t	*82*				*39.6*			
	M€/a	**-9.3**				**-4.5**			
Total annual production cost	**M€/a**	**47.1**	**41.5**	**44.8**	**46.0**	**51.9**	**46.3**	**49.6**	**50.8**
Total specific production cost	**€/GJ**	**17.6**	**15.5**	**16.7**	**17.2**	**19.4**	**17.3**	**18.5**	**18.9**
of which:									
Wheat grain		12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6
Capex		3.0	3.8	5.2	5.2	3.0	3.8	5.2	5.2
Opex		5.5	2.6	2.4	2.9	5.5	2.6	2.4	2.9
Credits		-3.5	-3.5	-3.5	-3.5	-1.7	-1.7	-1.7	-1.7

Ethanol from cellulose **Oil at 25 €/bbl**

Feedstock		Wheat straw	Wood farmed	Wood waste
Pathway code		STET1	WFET1	WWET1
Plant scale				
Ethanol	kt/a	71	71	
	PJ/a	1.90	1.90	
	MW	66	66	
	h/a	8000	8000	
Feed (0% moisture)	kt/a	251	308	
	PJ/a	4.5	5.5	
	€/t	*42+-13%*	*77+-5%*	*50+-13%*
	M€/a	**10.5**	**23.7**	**15.4**
Capex	*M€*	*136+-20%*	*119+-40%*	
Capital charge @ 12%	**M€/a**	**16.3**	**14.3**	
Opex	**M€/a**	**11.5**	**8.2**	
Fixed		8.2	7.1	
Net energy and chemicals		3.3	1.1	
Total annual production cost	**M€/a**	**38.2**	**46.2**	**37.9**
Total specific production cost	**€/GJ**	**20.1**	**24.3**	**19.9**
of which:				
Feed		5.5	12.5	8.1
Capex		8.6	7.5	7.5
Opex		6.0	4.3	4.3

Capex source: [Wooley 1999]

Ethanol from cellulose **Oil at 50 €/bbl**

Feedstock		Wheat straw	Wood farmed	Wood waste
Pathway code		STET1	WFET1	WWET1
Plant scale				
Ethanol	kt/a	71	71	
	PJ/a	1.90	1.90	
	MW	66	66	
	h/a	8000	8000	
Feed (0% moisture)	kt/a	251	308	
	PJ/a	4.5	5.5	
	€/t	*44+-13%*	*81+-5%*	*53+-13%*
	M€/a	**11.0**	**24.9**	**16.2**
Capex	*M€*	*136+-20%*	*131+-40%*	
Capital charge @ 12%	**M€/a**	**16.3**	**15.7**	
Opex	**M€/a**	**13.1**	**10.0**	
Fixed		8.2	7.8	
Net energy and chemicals		4.9	2.1	
Total annual production cost	**M€/a**	**40.4**	**50.5**	**41.8**
Total specific production cost	**€/GJ**	**21.3**	**26.6**	**22.0**
of which:				
Feed		5.8	13.1	8.5
Capex		8.6	8.3	8.3
Opex		6.9	5.2	5.2

Bio-diesel from oil seeds **Oil at 25 €/bbl**

Glycerine to		Animal feed			Chemical		
Feedstock		Rape MeOH	Rape EtOH	Sunflower MeOH	Rape MeOH	Rape EtOH	Sunflower MeOH
Pathway code		ROFA1	ROFE1	SOFA1	ROFA2	ROFE2	SOFA2
Plant scale							
Bio-diesel production	kt/a	100	100	100	100	100	100
	PJ/a	3.7	3.8	3.7	3.7	3.8	3.7
	MW	148	150	148	148	150	148
	h/a	7000	7000	7000	7000	7000	7000
Oil seeds (10% moisture)	kt/a	268	258	249	268	258	249
	PJ/a	6.4	6.1	5.9	6.4	6.1	5.9
	€/t	*237+-14%*	*237+-14%*	*265+-14%*	*237+-14%*	*237+-14%*	*265+-14%*
	M€/a	**63.3**	**60.9**	**66.0**	**63.3**	**60.9**	**66.0**
Alcohol	kt/a	11	21	11	11	21	11
	PJ/a	0.2	0.4	0.2	0.2	0.4	0.2
	€/GJ	*9.6*	*13.0*	*9.6*	*9.6*	*13.0*	*9.6*
	M€/a	**2.1**	**5.4**	**2.1**	**2.1**	**5.4**	**2.1**
Capex	*M€*	*30+-20%*					
Capital charge @ 12%	**M€/a**	**3.5**					
Opex	**M€/a**	**3.0**	**3.0**	**2.9**	**3.0**	**3.0**	**2.9**
Fixed		0.9					
Net energy and chemicals		2.1	2.1	2.0	2.1	2.1	2.0
Credits							
Cake(1)	kt/a	-159	-153	-159	-159	-153	-159
	€/t	*76*					
Glycerine(2)	kt/a	-11	-10	-11	-11	-10	-11
	€/t	*108*			*130*		
	M€/a	**-13.2**	**-12.7**	**-13.2**	**-13.5**	**-12.9**	**-13.5**
Total annual production cost	**M€/a**	**58.7**	**60.1**	**61.4**	**58.4**	**59.9**	**61.1**
Total specific production cost	**€/GJ**	**15.8**	**15.9**	**16.5**	**15.7**	**15.8**	**16.4**
of which:							
Oil seeds		17.0	16.1	17.8	17.0	16.1	17.8
Alcohol		0.6	1.4	0.6	0.6	1.4	0.6
Capex		1.0	0.9	1.0	1.0	0.9	1.0
Opex		0.8	0.8	0.8	0.8	0.8	0.8
Credits		-3.6	-3.3	-3.6	-3.6	-3.4	-3.6

Capex sources: [VDI 22 November 2002], [UBA 1999], [Oelmühle Leer Connemann 2000], [ETSU 1996]

(1) Price based on soya meal, 0.80 replacement ratio

(2) Animal feed price based on dry wheat grain, 0.99 replacement ratio

Bio-diesel from oil seeds **Oil at 50 €/bbl**

Glycerine to		Animal feed			Chemical		
Feedstock		Rape MeOH	Rape EtOH	Sunflower MeOH	Rape MeOH	Rape EtOH	Sunflower MeOH
Pathway code		ROFA1	ROFE1	SOFA1	ROFA2	ROFE2	SOFA2
Plant scale							
Bio-diesel production	kt/a	100	100	100	100	100	100
	PJ/a	3.7	3.8	3.7	3.7	3.8	3.7
	MW	148	150	148	148	150	148
	h/a	7000	7000	7000	7000	7000	7000
Oil seeds (10% moisture)	kt/a	268	258	249	268	258	249
	PJ/a	6.4	6.1	5.9	6.4	6.1	5.9
	€/t	*248+-14%*	*248+-14%*	*278+-14%*	*248+-14%*	*248+-14%*	*278+-14%*
	M€/a	**66.4**	**63.9**	**69.3**	**66.4**	**63.9**	**69.3**
Alcohol	kt/a	11	21	11	11	21	11
	PJ/a	0.2	0.4	0.2	0.2	0.4	0.2
	€/GJ	*13.5*	*15.5*	*13.5*	*13.5*	*15.5*	*13.5*
	M€/a	**2.9**	**6.5**	**2.9**	**2.9**	**6.5**	**2.9**
Capex	*M€*	*32+-20%*					
Capital charge @ 12%	**M€/a**	**3.9**					
Opex	**M€/a**	**4.7**	**4.7**	**4.6**	**4.7**	**4.7**	**4.6**
Fixed		1.0					
Net energy and chemicals		3.7	3.7	3.6	3.7	3.7	3.6
Credits							
Cake(1)	kt/a	-159	-153	-159	-159	-153	-159
	€/t	*84*					
Glycerine(2)	kt/a	-11	-10	-11	-11	-10	-11
	€/t	*114*			*218*		
	M€/a	**-14.5**	**-13.9**	**-14.5**	**-15.6**	**-14.9**	**-15.6**
Total annual production cost	**M€/a**	**63.5**	**65.1**	**66.2**	**62.4**	**64.0**	**65.1**
Total specific production cost	**€/GJ**	**17.1**	**17.2**	**17.8**	**16.8**	**16.9**	**17.5**
of which:							
Oil seeds		17.9	16.9	18.6	17.9	16.9	18.6
Alcohol		0.8	1.7	0.8	0.8	1.7	0.8
Capex		1.0	1.0	1.0	1.0	1.0	1.0
Opex		1.3	1.2	1.2	1.3	1.2	1.2
Credits		-3.9	-3.7	-3.9	-4.2	-3.9	-4.2

Biogas from organic waste **Oil at 25 €/bbl**

Feedstock		Manure liquid	Org. waste Liq. 0.2/0.8
Pathway code		OWCG2	OWCG3
Plant scale			
Biogas	kt/a	1.01	
	TJ/a	50.4	
	MW	2.0	
	h/a	7000	
Organic waste	TJ/a	97.6	97.6
	€/TJ	*4.1*	*3.3*
	k€/a	**205.4**	**164.3**
Capex	*k€*	*4000+-40%*	*2800+-40%*
Capital charge @ 12%	**k€/a**	**480**	**336**
Opex	**k€/a**	**389.1**	**279.8**
Fixed		400.0	280.0
Net energy and chemicals		-10.9	-0.2
Total annual production cost	**k€/a**	**1074**	**780**
Total specific production cost	**€/GJ**	**21.3**	**15.5**

Biogas from organic waste **Oil at 50 €/bbl**

Feedstock		Manure liquid	Org. waste Liq. 0.2/0.8
Pathway code		OWCG2	OWCG3
Plant scale			
Biogas	kt/a	1.01	
	TJ/a	50.4	
	MW	2.0	
	h/a	7000	
Organic waste	TJ/a	97.6	97.6
	€/TJ	*4.1*	*3.3*
	k€/a	**209.1**	**167.3**
Capex	*k€*	*4400+-40%*	*3080+-40%*
Capital charge @ 12%	**k€/a**	**528**	**370**
Opex	**k€/a**	**425.6**	**307.7**
Fixed		440.0	308.0
Net energy and chemicals		-14.4	-0.3
Total annual production cost	**k€/a**	**1163**	**845**
Total specific production cost	**€/GJ**	**23.1**	**16.8**

C.3.2 Synthetic fuels

Synthetic diesel **Oil at 25 €/bbl**

Feedstock		Wood farmed	Wood waste standard	Wood waste via BL
Pathway code		WFSD1	WWSD1	BLSD1
Plant scale				
Syn-fuels (diesel)	kt/a	63		119
	PJ/a	2.8		5.2
	MW	103		194
	h/a	7500		7500
Feedstock (dry)	kt/a	320		533
	PJ/a	5.8		9.6
	€/GJ	*4.3+-5%*	*2.8+-13%*	
	M€/a	**24.6**	**16.0**	**26.6**
Capex	*M€*	*260+-40%*		*263+-40%*
Capital charge @ 12%	**M€/a**	**31.2**		**31.5**
Opex	**M€/a**	**14.7**		**14.8**
Fixed		11.7		11.8
Net energy and chemicals		3.0		3.0
Total annual production cost	**M€/a**	**70.5**	**61.9**	**72.9**
Total specific production cost	**€/GJ**	**25.4**	**22.3**	**13.9**
of which:				
Feedstock		8.9	5.8	5.1
Capex		11.2	11.2	6.0
Opex		5.3	5.3	2.8

Capex sources:
KOSD1: [Gray 2001] (modified)
WF/WWSD1: [Woods 2003]
BLSD1: [ALTENER 2003]

Synthetic diesel **Oil at 50 €/bbl**

Feedstock		Wood farmed	Wood waste standard	Wood waste via BL
Pathway code		WFSD1	WWSD1	BLSD1
Plant scale				
Syn-fuels (diesel)	kt/a	63		119
	PJ/a	2.8		5.2
	MW	103		194
	h/a	7500		7500
Feedstock (dry)	kt/a	320		533
	PJ/a	5.8		9.6
	€/GJ	*4.5+-5%*	*2.9+-13%*	
	M€/a	**25.9**	**16.8**	**28.0**
Capex	*M€*	*286+-40%*		*318+-40%*
Capital charge @ 12%	**M€/a**	**34.3**		**38.1**
Opex	**M€/a**	**15.9**		**17.3**
Fixed		12.9		14.3
Net energy and chemicals		3.0		3.0
Total annual production cost	**M€/a**	**76.1**	**67.0**	**83.4**
Total specific production cost	**€/GJ**	**27.4**	**24.1**	**15.9**
of which:				
Feedstock		9.3	6.1	5.3
Capex		12.4	12.4	7.3
Opex		5.7	5.7	3.3

DME **Oil at 25 €/bbl**

Feedstock		Wood farmed	Wood waste standard	Wood waste via BL
Pathway code		WFDE1	WWDE1	BLDE1
Plant scale				
DME	kt/a	103		273
	PJ/a	2.9		7.8
	MW	102		269
	h/a	8000		8000
Feedstock (dry)	kt/a	320		640
	PJ/a	5.8		11.5
	€/GJ	*4.3+-5%*	*2.8+-13%*	
	M€/a	**24.6**	**16.0**	**32.0**
Capex	*M€*	*165+-40%*		*164+-40%*
		165		164
Capital charge @ 12%	**M€/a**	**19.8**		**19.7**
Opex	**M€/a**	**10.1**		**10.1**
Fixed		7.4		7.4
Net energy and chemicals		2.7		2.7
Total annual production cost	**M€/a**	**54.6**	**45.9**	**61.8**
Total specific production cost	**€/GJ**	**18.6**	**15.6**	**8.0**
of which:				
Feedstock		8.4	5.4	4.1
Capex		6.7	6.7	2.5
Opex		3.4	3.4	1.3

Capex sources: [Katofsky 1993], [Larsen 1998], [ALTENER 2003]

DME **Oil at 50 €/bbl**

Feedstock		Wood farmed	Wood waste standard	Wood waste via BL
Pathway code		WFDE1	WWDE1	BLDE1
Plant scale				
DME	kt/a	103		273
	PJ/a	2.9		7.8
	MW	102		269
	h/a	8000		8000
Feedstock (dry)	kt/a	320		640
	PJ/a	5.8		11.5
	€/GJ	*4.5+-5%*	*2.9+-13%*	
	M€/a	**25.9**	**16.8**	**33.6**
Capex	*M€*	*182+-40%*		*180+-40%*
		182		180
Capital charge @ 12%	**M€/a**	**21.8**		**21.6**
Opex	**M€/a**	**10.9**		**10.8**
Fixed		8.2		8.1
Net energy and chemicals		2.7		2.7
Total annual production cost	**M€/a**	**58.5**	**49.4**	**66.1**
Total specific production cost	**€/GJ**	**19.9**	**16.8**	**8.5**
of which:				
Feedstock		8.8	5.7	4.3
Capex		7.4	7.4	2.8
Opex		3.7	3.7	1.4

Notes:

- Minimum cost for DME was taken as per methanol cost in sec. C.2 (energy content basis). Cases giving lower values are presented for reference only.

C.4 Final fuels distribution and retail

Oil at 25 €/bbl

Fuel	*Energy consumption*			Energy cost	Distribution infrastructure(16)	Refuelling station		
	Diesel	*Electricity kWh/GJ*				Capex	Opex	Annual cost
	MJ/GJ	*MV*	*LV*	€/GJ	€/GJ	k€	k€/a	k€/a
Liquid fuels								
Conv. gasoline and diesel(1)					(2)			
Gasoline	*4.6*	*0.6*	*0.9*	0.1	0.2			
Diesel	*4.6*	*0.6*	*0.9*	0.1	0.2			
Ethanol(3)	*11.3*	*0.7*	*0.9*	0.2	0.6 (4)			
Bio-diesel(3)	*8.1*	*0.7*	*0.9*	0.1	0.5 (4)			
Syn-diesel					(4)			
Large scale or import(5)	*4.6*	*0.6*	*0.9*	0.1	0.2			
Small scale(6)	*6.9*	*0.2*	*0.9*	0.1	0.5			
DME						125	10	25
Large scale import(7)	*11.5*	*0.5*	*0.9*	0.2	2.9 (9)			
Large scale EU(7)	*11.5*	*0.5*	*0.9*	0.2	1.8			
Small scale(8)	*6.9*		*0.9*	0.1	0.5			

(1) 250 km, barge/rail/pipeline + 150 km road, also includes ethers

(2) Notional cost for marginal tankage, railcars, trucks, etc

(3) 2 x 150 km, road

(4) Notional cost for additional tankage, railcars, trucks, etc

(5) 250 km, barge/rail/pipeline + 150 km road

(6) 2 x 150 km, road (e.g. small scale wood-based plant)

(7) 500 km, 50/50 rail/road

(8) 150 km, road (e.g. small scale wood-based plant)

(9) Including long-distance shipping

(16) Land transport + allowance for extra tankage for bulk imports

Oil at 50 €/bbl

Fuel	*Energy consumption*			Energy cost	Distribution infrastructure(16)	Refuelling station		
	Diesel	*Electricity kWh/GJ*				Capex	Opex	Annual cost
	MJ/GJ	*MV*	*LV*	€/GJ	€/GJ	k€	k€/a	k€/a
Liquid fuels								
Conv. gasoline and diesel(1)					(2)			
Gasoline	*4.6*	*0.6*	*0.9*	0.2	0.2			
Diesel	*4.6*	*0.6*	*0.9*	0.2	0.2			
Ethanol(3)	*11.3*	*0.7*	*0.9*	0.3	0.7 (4)			
Bio-diesel(3)	*8.1*	*0.7*	*0.9*	0.2	0.6 (4)			
Syn-diesel					(4)			
Large scale or import(5)	*4.6*	*0.6*	*0.9*	0.2	0.2			
Small scale(6)	*6.9*	*0.2*	*0.9*	0.2	0.5			
DME						138	11	28
Large scale import(7)	*11.5*	*0.5*	*0.9*	0.3	3.2 (9)			
Large scale EU(7)	*11.5*	*0.5*	*0.9*	0.3	1.9			
Small scale(8)	*6.9*		*0.9*	0.2	0.6			

C.5 Road fuel and vehicle market assumptions

		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*]

C.6 Substitution scenarios (oil @ 25 €/bbl)

C.6.1 Conventional fuels, CBG

Fuel		**Gasoline**	**Diesel**	**CBG**
Primary resource		Oil		Waste
		COG1	COD1	org. waste liq. manure 0.2/0.8
Power train (2010+)		**PISI**	**DICI**	**PISI (BF)**
TTW energy	MJ/km	1.63	1.46	1.88
Distance covered	Tm	105	82	187
Fuel consumed	PJ/a	**171**	**120**	**353**
WTW total energy	MJ/km	1.86	1.69	3.67
WTW fossil energy	MJ/km	1.86	1.69	0.11
WTW GHG	g/km	141	129	-109
WTW Savings				
Total energy	PJ/a	**32**	**30**	**-291**
Fossil energy	PJ/a	**32**	**30**	**376**
GHG	Mt/a	**2.4**	**2.2**	**50.4**
Conventional fuels substituted	PJ/a			
Gasoline		200		200
Diesel			145	145
Refuelling stations required	k			20.0
WTT costs	M€/a	-178	-160	4905
Conventional fuel (saving)		-178	-160	-2159
Alternative fuel				5665
Distribution infrastructure				1399
Vehicle costs(1)				
Substituted fleet	M/a			0.90
Gasoline		0.60		0.60
Diesel			0.30	0.30
Base cost substituted fleet	MEUR/a	0	-548	-548
Alternative vehicle costs	*€/unit*	*6220*	*8030*	*2538*
	M€/a	3723	2446	2292
Net total cost	M€/a	**3545**	**1738**	**6649**
Cost of substitution	€/t			**832**
(per unit conv. Fuel)	€/GJ			**19.3**
Cost of CO_2 avoided	€/t	**1454**	**778**	**132**

(1) Over base cost of 2010 gasoline PISI

C.6.2 Bio-fuels

Fuel		**Ethanol (5% blend)**													**Bio-diesel (5% blend)**					
Primary resource		**Sugar beet**		**Wheat grain**								**Straw**	**Wood**		**Rape**		**Sunfl.**	**Rape**		**Sunfl.**
													Farmed	Waste						
		SBET1	SBET3	WTET1a	WTET2a	WTET3a	WTET4a	WTET1b	WTET2b	WTET3b	WTET4b	STET1	WFET1	WWET1	ROFA1	ROFE1	SOFA1	ROFA2	ROFE2	SOFA2
Power train (2010+)		**PISI**													**DICI+DPF**					
TTW energy	MJ/km	1.90													1.77					
Distance covered	Tm	105													82					
Fuel consumed	PJ/a	**200**													**145**					
WTW total energy	MJ/km	5.43	4.36	5.28	4.81	5.21	5.11	4.38	3.91	4.31	4.21	4.41	5.60	5.59	3.87	3.98	3.49	3.96	4.06	3.58
WTW fossil energy	MJ/km	1.65	0.59	1.68	1.23	1.64	0.53	0.84	0.38	0.79	-0.32	0.20	0.52	0.51	0.81	0.72	0.64	0.90	0.80	0.73
WTW GHG	g/km	111	58	114	90	178	49	98	74	161	33	19	43	36	85	80	47	95	88	56
WTW Savings																				
Total energy	PJ/a	**-343**	**-231**	**-328**	**-278**	**-321**	**-310**	**-233**	**-184**	**-226**	**-216**	**-236**	**-361**	**-360**	**-150**	**-158**	**-118**	**-157**	**-165**	**-126**
Fossil energy	PJ/a	**54**	**166**	**50**	**98**	**55**	**172**	**140**	**187**	**145**	**261**	**206**	**173**	**174**	**102**	**109**	**115**	**94**	**102**	**108**
GHG	Mt/a	**5.6**	**11.1**	**5.3**	**7.8**	**-1.4**	**12.1**	**7.0**	**9.5**	**0.3**	**13.8**	**15.3**	**12.7**	**13.5**	**5.8**	**6.3**	**9.0**	**5.1**	**5.6**	**8.2**
Conventional fuels substituted	PJ/a																			
Gasoline		200																		
Diesel															145					
Refuelling stations required	k																			
WTT costs	M€/a	1911	2210	1884	1503	1965	2154	2309	1929	2391	2580	2930	3765	2891	1476	1490	1580	1467	1481	1571
Conventional fuel (saving)		-1251	-1251	-1251	-1251	-1251	-1251	-1251	-1251	-1251	-1251	-1251	-1251	-1251	-908	-908	-908	-908	-908	-908
Alternative fuel		3162	3461	3134	2754	3216	3405	3560	3180	3641	3831	4181	5016	4142	2384	2398	2489	2375	2390	2480
Distribution infrastructure																				
Vehicle costs[1]																				
Substituted fleet	M/a																			
Gasoline																				
Diesel																				
Base cost substituted fleet	MEUR/a																			
Alternative vehicle costs	*€/unit*																			
	M€/a																			
Net total cost	M€/a	**1911**	**2210**	**1884**	**1503**	**1965**	**2154**	**2309**	**1929**	**2391**	**2580**	**2930**	**3765**	**2891**	**1476**	**1490**	**1580**	**1467**	**1481**	**1571**
Cost of substitution	€/t	**413**	**478**	**407**	**325**	**425**	**466**	**499**	**417**	**517**	**558**	**634**	**814**	**625**	**438**	**442**	**469**	**436**	**440**	**467**
(per unit conv. fuel)	€/GJ	**9.6**	**11.1**	**9.4**	**7.5**	**9.8**	**10.8**	**11.6**	**9.7**	**12.0**	**12.9**	**14.7**	**18.8**	**14.5**	**10.2**	**10.3**	**10.9**	**10.1**	**10.2**	**10.8**
Cost of CO_2 avoided	€/t	**342**	**198**	**358**	**193**		**178**	**331**	**203**		**186**	**192**	**296**	**215**	**254**	**237**	**176**	**290**	**264**	**191**

(1) Over base cost of 2010 gasoline PISI

C.6.3 Synthetic fuels

Fuel		**Syn-Diesel**			**DME**		
Primary resource		**Wood**			**Wood**		
		Farmed WFSD1	Waste WWSD1	Waste (BL) BLSD1	Farmed WFDE1	Waste WWDE1	Waste (BL) BLDE1
Power train (2010+)		**DICI+DPF**			**DICI**		
TTW energy	MJ/km	1.77			1.72		
Distance covered	Tm	82			82		
Fuel consumed	PJ/a	**145**			**141**		
WTW total energy	MJ/km	3.88	3.88	3.38	3.56	3.56	2.67
WTW fossil energy	MJ/km	0.11	0.12	0.06	0.10	0.10	0.05
WTW GHG	g/km	15	10	6	14	10	6
WTW Savings							
Total energy	PJ/a	**-150**	**-150**	**-109**	**-124**	**-124**	**-51**
Fossil energy	PJ/a	**159**	**159**	**163**	**160**	**160**	**164**
GHG	Mt/a	**11.6**	**12.0**	**12.3**	**11.7**	**12.0**	**12.4**
Conventional fuels substituted	PJ/a						
Gasoline							
Diesel		145					
Refuelling stations required	k				20.0		
WTT costs	M€/a	2864	2413	1195	2311	1896	814
Conventional fuel (saving)		-908	-908	-908	-908	-908	-908
Alternative fuel		3773	3321	2104	2720	2304	1222
Distribution infrastructure					500	500	500
Vehicle costs(1)							
Substituted fleet	M/a				0.30		
Gasoline							
Diesel					0.30		
Base cost substituted fleet	MEUR/a				-548		
Alternative vehicle costs	*€/unit*				*2775*		
	M€/a				845		
Net total cost	M€/a	**2864**	**2413**	**1195**	**2608**	**2193**	**1111**
Cost of substitution	€/t	**851**	**717**	**355**	**775**	**651**	**330**
(per unit conv. fuel)	€/GJ	**19.7**	**16.6**	**8.2**	**18.0**	**15.1**	**7.7**
Cost of CO_2 avoided	**€/t**	**246**	**201**	**97**	**223**	**182**	**90**

(1) Over base cost of 2010 gasoline PISI

C.7 Substitution scenarios (oil @ 50 €/bbl)

C.7.1 Conventional fuel, CBG

Fuel		**Gasoline**	**Diesel**	**CBG**
Primary resource		Oil		Waste
		COG1	COD1	org. waste liq. manure 0.2/0.8
Power train (2010+)		**PISI**	**DICI**	**PISI (BF)**
TTW energy	MJ/km	1.63	1.46	1.88
Distance covered	Tm	105	82	187
Fuel consumed	PJ/a	**171**	**120**	**353**
WTW total energy	MJ/km	1.86	1.69	3.67
WTW fossil energy	MJ/km	1.86	1.69	0.11
WTW GHG	g/km	141	129	-109
WTW Savings				
Total energy	PJ/a	**32**	**30**	**-291**
Fossil energy	PJ/a	**32**	**30**	**376**
GHG	Mt/a	**2.4**	**2.2**	**50.4**
Conventional fuels substituted	PJ/a			
Gasoline		200		200
Diesel			145	145
Refuelling stations required	k			20.0
WTT costs	M€/a	-348	-313	3489
Conventional fuel (saving)		-348	-313	-4226
Alternative fuel				6176
Distribution infrastructure				1539
Vehicle costs[1]				
Substituted fleet	M/a			0.90
Gasoline		0.60		0.60
Diesel			0.30	0.30
Base cost substituted fleet	MEUR/a	0	-548	-548
Alternative vehicle costs	*€/unit*	*6220*	*8030*	*2538*
	M€/a	3723	2446	2292
Net total cost	M€/a	**3375**	**1585**	**5233**
Cost of substitution	€/t			**655**
(per unit conv. Fuel)	€/GJ			**15.2**
Cost of CO_2 avoided	€/t	**1385**	**710**	**104**

[1] Over base cost of 2010 gasoline PISI

C.7.2 Bio-fuels

Fuel		**Ethanol (5% blend)**													**Bio-diesel (5% blend)**					
Primary resource		**Sugar beet**		**Wheat grain**								**Straw**	**Wood**		**Rape**		**Sunfl.**	**Rape**		**Sunfl.**
		SBET1	SBET3	WTET1a	WTET2a	WTET3a	WTET4a	WTET1b	WTET2b	WTET3b	WTET4b	STET1	Farmed WFET1	Waste WWET1	ROFA1	ROFE1	SOFA1	ROFA2	ROFE2	SOFA2
Power train (2010+)		**PISI**													**DICI+DPF**					
TTW energy	MJ/km	1.90													1.77					
Distance covered	Tm	105													82					
Fuel consumed	PJ/a	**200**													**145**					
WTW total energy	MJ/km	5.43	4.36	5.28	4.81	5.21	5.11	4.38	3.91	4.31	4.21	4.41	5.60	5.59	3.87	3.98	3.49	3.96	4.06	3.58
WTW fossil energy	MJ/km	1.65	0.59	1.68	1.23	1.64	0.53	0.84	0.38	0.79	-0.32	0.20	0.52	0.51	0.81	0.72	0.64	0.90	0.80	0.73
WTW GHG	g/km	111	58	114	90	178	49	98	74	161	33	19	43	36	85	80	47	95	88	56
WTW Savings																				
Total energy	PJ/a	**-343**	**-231**	**-328**	**-278**	**-321**	**-310**	**-233**	**-184**	**-226**	**-216**	**-236**	**-361**	**-360**	**-150**	**-158**	**-118**	**-157**	**-165**	**-126**
Fossil energy	PJ/a	**54**	**166**	**50**	**98**	**55**	**172**	**140**	**187**	**145**	**261**	**206**	**173**	**174**	**102**	**109**	**115**	**94**	**102**	**108**
GHG	Mt/a	**5.6**	**11.1**	**5.3**	**7.8**	**-1.4**	**12.1**	**7.0**	**9.5**	**0.3**	**13.8**	**15.3**	**12.7**	**13.5**	**5.8**	**6.3**	**9.0**	**5.1**	**5.6**	**8.2**
Conventional fuels substituted	PJ/a																			
Gasoline		200																		
Diesel															145					
Refuelling stations required	k																			
WTT costs	M€/a	1156	1081	1256	841	1084	1172	1612	1197	1440	1528	1992	3059	2141	813	827	920	770	788	877
Conventional fuel (saving)		-2448	-2448	-2448	-2448	-2448	-2448	-2448	-2448	-2448	-2448	-2448	-2448	-2448	-1778	-1778	-1778	-1778	-1778	-1778
Alternative fuel		3604	3529	3704	3289	3532	3620	4061	3645	3889	3976	4440	5507	4589	2591	2605	2698	2548	2567	2655
Distribution infrastructure																				
Vehicle costs(1)																				
Substituted fleet	M/a																			
Gasoline																				
Diesel																				
Base cost substituted fleet	MEUR/a																			
Alternative vehicle costs	*€/unit*																			
	M€/a																			
Net total cost	M€/a	**1156**	**1081**	**1256**	**841**	**1084**	**1172**	**1612**	**1197**	**1440**	**1528**	**1992**	**3059**	**2141**	**813**	**827**	**920**	**770**	**788**	**877**
Cost of substitution	€/t	**250**	**234**	**272**	**182**	**234**	**253**	**349**	**259**	**311**	**330**	**431**	**661**	**463**	**241**	**246**	**273**	**229**	**234**	**260**
(per unit conv. fuel)	€/GJ	**5.8**	**5.4**	**6.3**	**4.2**	**5.4**	**5.9**	**8.1**	**6.0**	**7.2**	**7.6**	**10.0**	**15.3**	**10.7**	**5.6**	**5.7**	**6.3**	**5.3**	**5.4**	**6.0**
Cost of CO_2 avoided	€/t	**207**	**97**	**239**	**108**		**97**	**231**	**126**		**110**	**130**	**240**	**159**	**140**	**131**	**102**	**152**	**141**	**107**

(1) Over base cost of 2010 gasoline PISI

C.7.3 Synthetic fuels

Fuel		**Syn-Diesel**			**DME**		
Primary resource		**Wood**			**Wood**		
		Farmed WFSD1	Waste WWSD1	Waste (BL BLSD1	Farmed WFDE1	Waste WWDE1	Waste (BL) BLDE1
Power train (2010+)		**DICI+DPF**			**DICI**		
TTW energy	MJ/km	1.77			1.72		
Distance covered	Tm	82			82		
Fuel consumed	PJ/a	**145**			**141**		
WTW total energy	MJ/km	3.88	3.88	3.38	3.56	3.56	2.67
WTW fossil energy	MJ/km	0.11	0.12	0.06	0.10	0.10	0.05
WTW GHG	g/km	15	10	6	14	10	6
WTW Savings							
Total energy	PJ/a	**-150**	**-150**	**-109**	**-124**	**-124**	**-51**
Fossil energy	PJ/a	**159**	**159**	**163**	**160**	**160**	**164**
GHG	Mt/a	**11.6**	**12.0**	**12.3**	**11.7**	**12.0**	**12.4**
Conventional fuels substituted	PJ/a						
Gasoline							
Diesel		145					
Refuelling stations required	k				20		
WTT costs	M€/a	2298	1824	629	1702	1266	93
Conventional fuel (saving)		-1778	-1778	-1778	-1778	-1778	-1778
Alternative fuel		4076	3602	2407	2931	2495	1322
Distribution infrastructure					550	550	550
Vehicle costs(1)							
Substituted fleet	M/a				0.30		
Gasoline							
Diesel					0.30		
Base cost substituted fleet	MEUR/a				-548		
Alternative vehicle costs	*€/unit*				*2775*		
	M€/a				845		
Net total cost	M€/a	**2298**	**1824**	**629**	**1999**	**1563**	**390**
Cost of substitution	€/t	**683**	**542**	**187**	**594**	**464**	**116**
(per unit conv. fuel)	€/GJ	**15.8**	**12.6**	**4.3**	**13.8**	**10.8**	**2.7**
Cost of CO_2 avoided	€/t	**198**	**152**	**51**	**171**	**130**	**32**

(1) Over base cost of 2010 gasoline PISI

C.8 Cost summary

C.8.1 Oil @ 25 €/bbl

Fuel	*Powertrain*	Alt. fuel consumed	Fuel substituted		Base case	WTW savings(1,2)				Incremental cost over ref. scenario			Cost of substitution		Cost of CO_2 avoided
			Gasoline	Diesel	GHG	Energy (PJ/a)		GHG		G€ /a			€ /t fossil fuel	€ / 100 km	
Oil price @25 €/bbl		PJ/a	PJ/a		Mt CO_{2eq}/a	Total	Fossil	Mt CO_{2eq}/a	% of base	WTT	Vehicles	Total			€ /t CO_{2eq}
Gasoline															
Diesel															
Both fuels															
CBG (mixed sources)	PISI (BF)	353				-291	**376**	**50.4**	**167%**	4.9	1.7	6.6	832	3.55	**132**
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	**8481**
Straw CHP						-216	**261**	**13.8**	**80%**	2.6		2.6	558	2.45	**186**
Ex straw						-236	**206**	**15.3**	**89%**	2.9		2.9	634	2.79	**192**
Ex wood						-361	**173**	**12.9**	**75%**	3.6		3.6	776	3.41	**279**
Bio-diesel	CIDI+DPF	145		145	12.8										
Glycerine as chemical															
RME						-150	**102**	**5.8**	**45%**	1.5		1.5	438	1.80	**254**
REE						-158	**109**	**6.3**	**49%**	1.5		1.5	442	1.81	**237**
SME						-118	**115**	**9.0**	**70%**	1.6		1.6	469	1.92	**176**
Glycerine as animal feed															
RME						-157	**94**	**5.1**	**39%**	1.5		1.5	436	1.79	**290**
REE						-165	**102**	**5.6**	**44%**	1.5		1.5	440	1.80	**264**
SME						-126	**108**	**8.2**	**64%**	1.6		1.6	467	1.91	**191**
Synthetic diesel fuels		145		145	12.8										
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 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**

(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

C.8.2 Oil @ 50 €/bbl

Fuel	*Powertrain*	Alt. fuel consumed	Fuel substituted		Base case	WTW savings$^{(1,2)}$				Incremental cost over ref. scenario			Cost of substitution		Cost of CO_2 avoided
			Gasoline	Diesel	GHG	Energy (PJ/a)		GHG		G€ /a			€ /t fossil fuel	€ / 100 km	
Oil price @50 €/bbl		PJ/a	PJ/a		Mt CO_{2eq}/a	Total	Fossil	Mt CO_{2eq}/a	% of base	WTT	Vehicles	Total			€ /t CO_{2eq}
Gasoline															
Diesel															
Both fuels															
CBG (mixed sources)	PISI (BF)	353				-291	**376**	**50.4**	**167%**	3.5	1.7	5.2	655	2.79	**104**
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	**5110**
Straw CHP						-216	**261**	**13.8**	**80%**	1.5		1.5	330	1.45	**110**
Ex straw						-236	**206**	**15.3**	**89%**	2.0		2.0	431	1.89	**130**
Ex wood						-361	**173**	**12.9**	**75%**	2.9		2.9	621	2.73	**223**
Bio-diesel	CIDI+DPF	145		145	12.8										
Glycerine as chemical															
RME						-150	**102**	**5.8**	**45%**	0.8		0.8	241	0.99	**140**
REE						-158	**109**	**6.3**	**49%**	0.8		0.8	246	1.01	**131**
SME						-118	**115**	**9.0**	**70%**	0.9		0.9	273	1.12	**102**
Glycerine as animal feed															
RME						-157	**94**	**5.1**	**39%**	0.8		0.8	229	0.94	**152**
REE						-165	**102**	**5.6**	**44%**	0.8		0.8	234	0.96	**141**
SME						-126	**108**	**8.2**	**64%**	0.9		0.9	260	1.07	**107**
Synthetic diesel fuels		145		145	12.8										
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 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

D Description of individual processes and detailed input data

All WTT data was stored in LBST's E^3 database and that software was used to calculate the energy and GHG balances of the pathways. This appendix provides full detail of the input data. It consists in two elements:

- A series of tables giving input data to each process,
- A textual description and justification of each process.

The information has been split into logical sections each incorporating the processes involved in a number of related pathways. The process that are new to this version are highlighted in yellow.

Both energy and GHG figures are shown per unit energy content of the output of the particular process (MJ), NOT of the output of the total pathway (e.g. the energy required for wheat farming is shown per MJ of wheat grain, rather than MJ of ethanol).

The energy figures are expressed as net total energy expended (MJ_{xt}) in each process (i.e. excluding the energy transferred to the final fuel) per unit energy content of the output of the process (MJ). Where intermediate energy is involved (e.g. electricity) the relation between primary and intermediate energy is expressed in efficiency terms and in terms of total primary energy (MJ_p) per unit energy actually expended in the process (MJ_x).

This description are better clarified in sec. D.1 of this appendix.

All energy is accounted for regardless of the primary energy source, i.e. including renewable energy. This is necessary to estimate the energy efficiency of each process and each pathway. The share of fossil energy in each complete pathway is shown in the overall pathway energy balance (*see* Appendix E).

The CO_2 figures represent the actual emissions occurring during each process. When CO_2 emissions stem from biomass sources only the net emissions are counted. The figures exclude the CO_2 emissions associated with the combustion of the final fuel when it is of fossil origin. For carbon-containing fuels of renewable origin, however, a credit is given for an amount of CO_2 equivalent to that released during combustion. In the TTW section of the study, all fuels can then be treated in the same way and allocated CO_2 emissions corresponding to their carbon content regardless of its origin.

The figures used in the WTW study and described in this appendix are generally based on literature references as given. In a number of cases, particularly with regards to oil-based pathways, figures considered as typical in the industry and generally representing the combined views of a number of experts have been used. Where no specific reference is given, the figures are the result of standard physical calculations based on typical parameters.

Most processes include a line labelled "Primary energy consumption and emissions": this is an approximate and simplified calculation intended for the reader's guidance. The full calculation has been carried out by LBST's E^3 database resulting in the figures in Appendix E.

Where appropriate a range of variability has been specified associated to a probability distribution either normal (Gaussian), double-triangle for asymmetrical distribution or equal (all values in the range equally probable). The equal distribution has been used when representing situations where a range of technologies or local circumstances may apply, all being equally plausible. For the complete pathway, a variability range is estimated by combining the individual ranges and probability distributions with the Monte-Carlo method.

D.1 Calculation methods

The process of ethanol from sugar beet (process code SB3a, sec. D.12.1, pag. 157) is taken as example to describe the parameters of a process and to show how the input data have been treated.

Such process is represented in the following scheme:

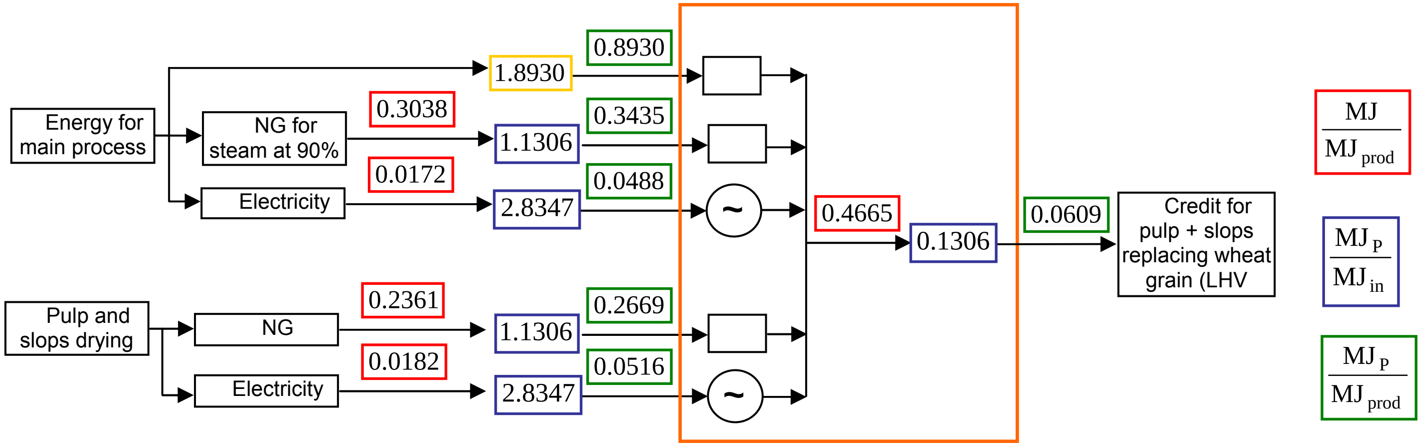


Figure 5.1: input and output data for the process of ethanol from sugar beet (used units are shown in the coloured box at the rigth side; the yellow box represent the energetic content of the bio-feed, sugar beet).

So:

- if sugar beet has an energetic content of 1.8930 MJ/MJ_{prod} (yellow box), this indicates the energy content in MJ of the bio-feed per 1MJ of final product.

- If the process requires 2.8347 MJ of electricity per MJ of bio-feed, the expended energy is expressed as 2.8347 MJ_x/MJ. Knowing how many MJ of bio-feed are needed per 1MJ of final product (0.0182), the primary energy expended per 1 MJ of final product could be found (0.0182 x 2.8347 = 0.0516 MJ_P/MJ_{prod})

- The process 🟧 has a consumption of net primary energy of: $\Delta E_{consumption} = E_{in} - E_{out} = 1.5429 \left[\frac{MJ_P}{MJ_{prod}} \right]$

and produces net GHG emissions of: $GHG_{emissions} = 32.57 \left[\frac{g_{CO_{2,eq}}}{MJ_{prod}} \right]$

Furthermore:

- If electricity is generated with a 33% efficiency, the primary energy associated to 1 MJ of electricity is 3 MJ_p (1/0.33 [1/MJ_P]).
- The total primary energy 'x' associated to a process requiring 0.1 MJ of electricity per MJ of final fuel is then x= 0.1/0.33=0.3 MJ_p/MJ_{prod}

D.2 Factors for individual fuels

LIQUIDS

Gasoline	MW	GJ/d	PJ/a	kg/h	kg/d	t/a	m_3/d
MW (MJ/s)		86.4	28.8	83.1	1995	665	2.68
GJ/d	0.01		0.33	0.96	23.1	7.70	0.03
PJ/a (8000 h)	0.03	3		2.89	69.3	23.1	0.09
kg/h	0.01	1.04	0.35		24	8	0.03
kg/d		0.04	0.01			0.333	
t/a (8000 h)		0.13	0.04	0.13	3		
m_3/d		32.3	10.8	31.0	745	248	

DME	MW	GJ/d	PJ/a	kg/h	kg/d	t/a	m_3/d
MW (MJ/s)		86.4	28.8	126.6	3039	1013	4.54
GJ/d	0.01		0.33	1.47	35.2	11.72	0.05
PJ/a (8000 h)	0.03	3		4.40	105.5	35.2	0.16
kg/h	0.01	0.68	0.23		24	8	0.04
kg/d		0.03	0.01			0.333	
t/a (8000 h)		0.09	0.03	0.13	3		
m_3/d		19.0	6.3	27.9	670	223	

Diesel	MW	GJ/d	PJ/a	kg/h	kg/d	t/a	m_3/d
MW (MJ/s)		86.4	28.8	83.5	2005	668	2.41
GJ/d	0.01		0.33	0.97	23.2	7.73	0.03
PJ/a (8000 h)	0.03	3		2.90	69.6	23.2	0.08
kg/h	0.01	1.03	0.34		24	8	0.03
kg/d		0.04	0.01			0.333	
t/a (8000 h)		0.13	0.04	0.13	3		
m_3/d		35.9	12.0	34.7	832	277	

Ethanol	MW	GJ/d	PJ/a	kg/h	kg/d	t/a	m_3/d
MW (MJ/s)		86.4	28.8	134.3	3224	1075	4.06
GJ/d	0.01		0.33	1.55	37.3	12.44	0.05
PJ/a (8000 h)	0.03	3		4.66	111.9	37.3	0.14
kg/h	0.01	0.64	0.21		24	8	0.03
kg/d		0.03	0.01			0.333	
t/a (8000 h)		0.08	0.03	0.13	3		
m_3/d		21.3	7.1	33.1	794	265	

FT diesel	MW	GJ/d	PJ/a	kg/h	kg/d	t/a	m_3/d
MW (MJ/s)		86.4	28.8	81.8	1964	655	2.52
GJ/d	0.01		0.33	0.95	22.7	7.58	0.03
PJ/a (8000 h)	0.03	3		2.84	68.2	22.7	0.09
kg/h	0.01	1.06	0.35		24	8	0.03
kg/d		0.04	0.01			0.333	
t/a (8000 h)		0.13	0.04	0.13	3		
m_3/d		34.3	11.4	32.5	780	260	

SOLIDS

Wood	MW	GJ/d	PJ/a	kg/h	kg/d	t/a
MW (MJ/s)		86.4	28.8	200.0	4800	1600
GJ/d	0.01		0.33	2.31	55.6	18.52
PJ/a (8000 h)	0.03	3		6.94	166.7	55.6
kg/h	0.01	0.43	0.14		24	8
kg/d		0.02	0.01			0.333
t/a (8000 h)		0.05	0.02	0.13	3	

D.3 Fuels properties

D.3.1 Standard properties of fuels

Liquids		Crude	Gasoline	Diesel	Syn diesel	DME	Ethanol	RME	REE	ETBE
Density	kg/m^3	820	745	832	780	670	794	890	890	750
LHV	MJ/kg	42.0	43.2	43.1	44.0	28.4	26.8	37.2	37.9	36.3
	kg/kWh	0.086	0.083	0.084	0.082	0.127	0.134	0.097	0.095	0.099
	kWh/kg	11.67	12.00	11.97	12.22	7.90	7.44	10.33	10.53	10.07
C content	% m	86.5%	86.4%	86.1%	85.0%	52.2%	52.2%	76.5%	76.5%	70.6%
CO_2 emission factor (assuming total combustion)										
	g CO_2/MJ	75.5	73.3	73.2	70.8	67.3	71.4	75.4	74.0	71.4
	kg CO_2/kg	3.17	3.17	3.16	3.12	1.91	1.91	2.81	2.81	2.59

Solids		Wood	Wheat	S beet	Rapeseed	SunFseed	SB pulp	SB slops	Wheat straw	DDGS	Sugar cane
Moisture content		0.3	0.16	0.765	0.1	0.1	0.09	0.09	0.16	0.1	73%
LHV (dry matter)	MJ/kg	18.0	17.0	16.3	26.4	26.4	15.6	15.6	17.2	16.0	19.6
	kg/kWh	0.200	0.212	0.221	0.136	0.136	0.231	0.231	0.209	0.225	0.184
	kWh/kg	5.0	4.7	4.5	7.3	7.3	4.3	4.3	4.8	4.4	5.4
C content	% m	50.0%									
CO_2 emission factor (assuming total combustion)											
	g CO_2/MJ	101.9									
	kg CO_2/kg	1.83									

D.4 Common processes

Code	**Process**	Assoc. process	MJex/ MJ	g CO2/ MJ	g CH4/ MJ	g N2O/ MJ	g CO2 eq/ MJ	Eff	MJp/ MJex	g CO2/ MJex	g CH4/ MJex	g N2O/ MJex	MJex/ t.km	Min	Max	Probability distribution	Reference
	Transport fuels simplified production processes (used for auxiliary transport fuel requirements)																
Z1	**Diesel production** Crude oil		0.1600	14.30													CONCAWE
Z2	**Road tanker** Diesel									73.25			0.936				LBST

Z1 Diesel production

This process is used to compute the energy associated to the consumption of diesel fuel for transportation purposes in a given pathway. The figures stem from the Diesel provision pathway COD.

Z2 Road tanker

This process represents the diesel fuel consumption and CO_2 emissions of a standard diesel-powered road tanker per t.km transported, including the return trip of the empty vehicle.

When calculating the total energy and emissions associated to road transport, the figures corresponding to diesel production are added.

D.5 Crude oil – based fuels provision

D.5.1 Crude oil, diesel fuel

Code	**Process**	Assoc. processes	Expended energy and emissions per MJ of main product of the process					Transport distance	Transport energy	Transport requirement	Range		Probability distribution	Reference
			MJex/ MJ	g CO2/ MJ	g CH4/ MJ	g N2O/ MJ	g CO2eq/ MJ	km or Nm	MJex/ t.km	t.km/ MJ	Min	Max		
CO1	**Crude oil production**													
	Energy as crude oil		0.0250	1.89			1.89				0.010	0.040	Normal	Oil companies average value
	CO2 eq emissions			1.45			1.45							
	Total CO2 eq			3.33			3.33							

CD1	**Crude oil refining, marginal diesel**													
	Crude oil		0.1000	8.60			8.60				0.0800	0.1200	Normal	CONCAWE
CD2	**Diesel transport**													Total
	Barge, 9000 t (33%)													
	Energy as Diesel	Z1	0.0011	0.08			0.08							
	Energy as HFO		0.0052	0.39			0.39							
	Total CO2			0.48			0.48							
	Primary energy consumption and emissions		*0.0070*	*0.53*			*0.53*							
	Rail, 250 km (33%)													
	Distance	Z5						250		0.0058				
	Primary energy consumption and emissions		*0.0035*	*0.15*	*0.0004*	*0.0000*	*0.16*							
	Pipeline (33%)													
	Electricity (EU-mix, LV)	Z7b	0.0002											
	Primary energy consumption and emissions		*0.0006*	*0.02*	*0.0001*	*0.0000*	*0.03*							
	Total Primary energy consumption and emissions		*0.0037*	*0.23*	*0.0001*	*0.0000*	*0.24*							
CD3	**Diesel depot**													
	Electricity (EU-mix, LV)	Z7b	0.0008											Total
	Primary energy consumption and emissions		*0.0024*	*0.10*	*0.0002*	*0.0000*	*0.11*							
CD4	**Diesel distribution and dispensing**													
	Tanker load and distance	Z2, Z1						150		0.0037				
	Diesel consumption and emissions		0.0035	0.31			0.31							
	Retail, Electricity (EU-mix, LV)	Z7b	0.0034											Total
	Primary energy consumption and emissions		*0.0138*	*0.72*	*0.0010*	*0.0000*	*0.75*							

CO1 Crude oil production

These figures include all the energy and GHG emissions associated with crude oil production and conditioning at or near the wellhead (such as dewatering and associated gas separation). The total CO_2eq figure includes emissions of GHGs other than combustion CO_2.

Production conditions vary considerably between producing regions, fields and even between individual wells and it is only meaningful to give typical or average energy consumption and GHG emission figures for the range of crudes under consideration, hence the wide variability range indicated. These figures are best estimates for the basket of crude oils available to Europe [*Source: CONCAWE*].

CD1 Crude oil refining, marginal diesel

This represents the energy and GHG emissions that can be saved, in the form of crude oil, by not producing a marginal amount of diesel in Europe, starting from a 2010 "business-as-usual" base case [*Source: CONCAWE*, see Appendix F for details].

CD2 Diesel transport

Road fuels are transported from refineries to depots via a number of transport modes. Water has been included (inland waterway or coastal), rail and pipeline (1/3 each). The energy consumption and distance figures are typical averages for EU.

Barges and coastal tankers are deemed to use a mixture of marine diesel and HFO. Rail transport consumes electricity. The consumption figures are typical [*Source: Total*]. The road tanker figures pertain to a notional 40 t truck transporting 26 t of diesel in a 2 t tank (see also process Z2).

CD3 Diesel depot

A small amount of energy is consumed in the depots mainly in the form of electricity for pumping operations [*Source: Total*].

CD4 Diesel distribution

From the depots, road fuels are normally trucked to the retail stations where additional energy is required, essentially as electricity, for lighting, pumping etc. This process includes the energy required for the truck as well as the operation of the retail station [*Source: Total*].

D.6 Gasoline

Code	**Process**	Assoc. processes	Expended energy and emissions per MJ of main product of the process					Transport distance	Transport energy	Transport requirement	Range		Probability distribution	Reference
			MJex/ MJ	g CO2/ MJ	g CH4/ MJ	g N2O/ MJ	g CO2eq/ MJ	km or Nm	MJex/ t.km	t.km/ MJ	Min	Max		
CG1	**Crude oil refining, marginal gasoline**													
	Crude oil		0.0800	6.50			6.50				0.0600	0.1000	Normal	CONCAWE
CG2	**Gasoline transport**													Total
	Barge, 9000 t (33%)													
	Energy as Diesel	Z1	0.0011	0.08			0.08							
	Energy as HFO	Z3	0.0052	0.39			0.39							
	Evaporation losses		0.0000											
	Total CO2			0.47			0.47							
	Primary energy consumption and emissions		*0.0070*	*0.53*			*0.53*							
	Rail, 250 km (33%)													
	Distance	Z5						250		0.0058				
	Primary energy consumption and emissions		*0.0034*	*0.14*	*0.0004*	*0.0000*	*0.16*							
	Evaporation losses		0.0004											
	Pipeline (33%)													
	Electricity (EU-mix, LV)	Z7b	0.0002											
	Primary energy consumption and emissions		*0.0006*	*0.02*	*0.0001*	*0.0000*	*0.03*							
	Total Primary energy consumption and emissions		*0.0037*	*0.23*	*0.0001*	*0.0000*	*0.01*							

CG3	**Gasoline depot**													
	Electricity (EU-mix, LV)	Z7b	0.0008											Total
	Primary energy consumption and emissions		*0.0024*	*0.10*	*0.0002*	*0.0000*	*0.11*							
	Evaporation losses		0.0000											
CG4	**Gasoline distribution and dispensing**													
	Tanker load and distance	Z2, Z1						150		0.0037				
	Diesel consumption and emissions		0.0035	0.31										
	Filling station, Electricity (EU-mix, LV)	Z7b	0.0034											Total
	Primary energy consumption and emissions		*0.0138*	*0.72*	*0.0010*	*0.0000*	*0.75*							
	Evaporation losses		0.0008											

CG1/4 Gasoline

These processes are essentially the same as for diesel with some specific adjustments for the gasoline case, mostly in terms of evaporation losses.

D.7 Ethers

Code	**Process**	Assoc. processes	Expended energy	GHG emissions				Efficiency	Total energy and emissions per MJ of expendable energy				Transport requirement			Range		Probability distribution	Reference
			MJx/ MJ prod.	g CO_2/ MJ prod.	g CH_4/ MJ prod.	g N_2O/ MJ prod.	g CO_2eq/ MJ prod.		MJ/ MJx	g CO_2/ MJx	g CH_4/ MJx	g N_2O/ MJx	km or N m	MJx/ t.km	MJx/MJ /100km	Min	Max		
BU1	**n-butane to isobutene**																		CONCAWE
	Electricity	Z7a	0.0044																
	NG for steam (90% eff.)	Z6	0.1627	10.27	0.0325	0.0000	11.02												
	Hydrogen		-0.0196																
	Credit for hydrogen produced by NG steam ref.		-0.0062	-1.42	-0.0003	0.0000	-1.43												
	Primary energy consumption and emissions		*0.1690*	*9.38*	*0.0334*	*0.0000*	*10.16*												
EH1	**Isobutene + ethanol to ETBE**																		CONCAWE
	Isobutene	BU1	0.7000																
	Ethanol		0.3640																
	Electricity	Z7a	0.0010																
	NG	Z6	0.0240																
	Primary energy consumption and emissions		*0.0028*	*0.1194*	*0.0003*	*0.0000*	*0.13*												

BU1 n-butane to isobutene

This process of isomerisation and dehydrogenation is required to produce isobutene, one of the building blocks of MTBE or ETBE. It is an energy-intensive process.

EH1ETBE manufacture (large plant)

This process describes the manufacture of ETBE from isobutene and ethanol. This could occur in Europe with imported butanes (turned into isobutene with BU1) and domestically produced bio ethanol.

D.8 Farming processes

Here it has been tabulated and summed the fossil energy and GHG emissions attributable to farming processes, including the upstream emissions and energy needed to make the fertilizers etc. The agrochemicals processes described later describe these upstream processes in more detail. In the first version of this report, most of the agricultural resources for growing biofuels came from land which would otherwise be used for growing export cereals, in accordance with [*DG-AGRI 2002*] agricultural outlook. This led to the conclusion that no “reference crop” was needed. However, DG-AGRI have since updated their outlook: due to changes in the agricultural subsidy regime, they now expect more set-aside and a smaller cereals surplus in EU25-2012. That means that most of the biofuel crops would now come from set-aside. The result is that there is now a reference crop representing the land cover in set-aside: unfertilized grass has been chosen. Because this has low agricultural inputs, the only significant GHG effect is in the reference nitrous oxide emissions. [*LBST 2002*], which otherwise shares much of the same agricultural data with this report, has more intensive reference crops.

All figures are related to the **water-free** Lower Heating Value of the biomass products. This is necessary to avoid confusion: for example apparent increases in LHV as wood dries out during transport and storage. However, the actual water content is taken into account when calculating transport and processes. Agricultural yields are expressed at the conventional % moisture: 16% for wheat; 10% for oilseeds; 9% for DDGS by-product of wheat-ethanol, sugar beet pulp and dried slops (“solubles”); 0% for wood. This helps comparability with other studies.

Unlike with a process making fossil fuel from a fossil resource, the primary energy and emissions from diesel use in biomass processes include the LHV and the carbon (as CO_2) content of the diesel itself, because the fossil CO_2 is released at this stage.

Best estimate figures are shown. It is not worth including a range of energy inputs, because these are low for farming compared to the whole chain. The main source of uncertainty is in the GHG emissions, caused by the N_2O emission calculation (details below).

The processes for making fertilizers and “pesticides” (in which other complex agro-chemicals have been included such as fungicides and plant hormones) are detailed in the table below.

Seeds have been called “seeding materials” to avoid confusion with oilseeds as a crop.

Code	Process	Assoc. processes	Input		Expended energy		GHG emissions				N_2O emissions	
			kg/ MJ prod.	MJ/ MJ prod.	Primary MJx/ kg or MJ	Primary MJx/ MJ prod.	g CO_2/ MJ prod.	g CH_4/ MJ prod.	g N_2O/ MJ prod.	g CO_2eq/ MJ prod.	Min	Max
WF1	**Wood farming and chipping**											
	N fertilizer	AC1	0.0005			0.0246	1.51	0.0041	0.0048	3.03		
	Diesel for harvest, sowing etc.	Z1		0.0060		0.0070	0.53	0.0000	0.0000	0.53		
	Land emissions								0.0034	1.01		
	Diesel for chipping			0.0040	4.18	0.0046	0.35	0.0000	0.0000	0.35		
	Primary energy consumption and emissions					*0.0362*	*2.39*	*0.0041*	*0.0082*	*4.92*		
	…including 2.5% dry-mass losses in chipping and storage					***0.0371***	*2.45*	*0.0042*	*0.0084*	***5.04***		
SB1	**Sugar Beet Farming**											
	CaO fertilizer	AC4	0.0020		2.04	0.0042	0.24	0.0006	0.0000	0.25		
	K_2O fertilizer	AC3	0.0007		9.73	0.0068	0.38	0.0011	0.0000	0.41		
	P_2O_5 fertilizer	AC2	0.0003		15.47	0.0043	0.28	0.0004	0.0000	0.29		
	N fertilizer	AC1	0.0005		49.17	0.0253	1.55	0.0043	0.0050	3.12		
	Pesticides	AC5	0.0000		272.55	0.0018	0.11	0.0002	0.0000	0.11		
	Seeding material		0.0000		33.38	0.0010	0.06	0.0000	0.0000	0.06		
	Diesel	Z1		0.0320	4.18	0.0371	2.80	0.0000	0.0000	2.80		
	Net emissions from field							0.0001	0.0118	3.50	0.0081	0.0156
	Farm primary energy consumption and emissions					*0.0806*	*5.42*	*0.0066*	*0.0168*	*10.53*		
	…including 4.5% sugar loss during storage					***0.0842***	*5.66*	*0.0069*	*0.0175*	***11.01***		
WT1	**Wheat farming**											
	K_2O fertilizer	AC3	0.0005		9.73	0.0051	0.29	0.0008	0.0000	0.31		
	P_2O_5 fertilizer	AC2	0.0005		15.47	0.0081	0.52	0.0007	0.0000	0.53		
	N fertilizer	AC1	0.0013		49.17	0.0646	3.97	0.0109	0.0127	7.96		
	Pesticides	AC5	0.0000		272.55	0.0069	0.42	0.0006	0.0000	0.44		
	Seeding material		0.0011		2.88	0.0030	0.17	0.0000	0.0000	0.17		
	Diesel (includes drying)	Z1		0.0369	4.18	0.0428	3.23	0.0000	0.0000	3.23		
	Net emissions from field								0.0189	5.59	0.0064	0.0314
	Sum primary energy consumption and emissions					***0.1306***	*8.60*	*0.0130*	*0.0315*	***18.24***		
SC1	**Sugar cane farming (Brazil)**											
	CaO fertilizer	AC4	0.0036		0.5669	0.0020	0.11	0.0003	0.0000	0.12		
	K_2O fertilizer	AC3	0.0007		2.7023	0.0019	0.11	0.0003	0.0000	0.12		
	P_2O_5 fertilizer	AC2	0.0003		4.2959	0.0012	0.07	0.0001	0.0000	0.08		
	N fertilizer	AC1	0.0006		13.6591	0.0083	0.51	0.0014	0.0016	1.02		
	Pesticides	AC5	0.0000		75.7090	0.0014	0.09	0.0001	0.0000	0.09		
	Seeding material		0.0000		1.9837	0.0000	0.00	0.0000	0.0000	0.00		
	Diesel	Z1		0.0053	1.1600	0.0062	0.46	0.0000	0.0000	0.46		
	Net emissions from field						0.39	0.0531	0.0055	3.24		
	Sum primary energy consumption and emissions					***0.0211***	*1.75*	*0.0553*	*0.0071*	***5.13***		

WF1 Wood Farming

This represents short-rotation forestry on agricultural land. Poplar or willow are generally the best-yielding species in central and Northern Europe. Willow shoots are harvested typically every 3 years; poplar trunks after 8-15 years. After about 15-20 years the trees are uprooted and new ones planted. Inputs comprise sowing, thinning, fertilizer, but mostly harvesting. Yields for a given amount of fertilizer are better than for annual crops because roots are already established at the start of the growing season. Perennial grasses share this advantage. A neutral review of European experiments with *miscanthus* [*Scurlock 1999*] indicates a realistic yield is similar to farmed wood. Switchgrass has lower yield, but has better drought resistance, enabling it to be grown in more marginal areas. Grasses generally have a higher mineral content than wood, which can cause problems of ash sintering and corrosion if one tries to use the same conversion plant (the salt content can however be lowered by delayed harvesting or washing). For this reason, farmed wood chips command a higher price at power stations, which makes it the preferred biomass crop in EU at the moment. LCA studies show results for perennial grasses between wood and arable bio-crops. SRF have been considered because there is more data, but do not wish to exclude grasses as a possible alternative with fairly similar characteristics.

Inputs vary widely, depending on soil quality, yield and the intensiveness of the farming; [*Bauen 2000*] gives a range of 0.004 to 0.065 MJ primary energy per MJ dry wood. [*Mathews 1994*] quotes figures of 0.03 to 0.04 MJ/MJ. The WTW data on wood farming (short rotation forestry) are from original Oeko-Institut studies in the [*GEMIS 2002*] database, used also in [*LBST 2002*]. Inputs are low compared to other energy crops, so the uncertainty is not important when comparing pathways.

Nitrous oxide emissions for forestry cannot be calculated with the JRC soil model. Instead, the range of measured values has been used for direct emissions from poplar, reported by [*Flesse 1998*]. A range for indirect emissions was estimated, using the procedure based on IPCC guidelines described in [*LBST 2002*], for the 25 kg/ha nitrogen fertilizer rate reported by [*Murach 2003*] for poplar plantation. Since this procedure assumes that nitrous oxide emissions are proportional to the nitrogen fertilizer rate, the emissions from the WTW reference crop (unfertilized grass) are effectively already subtracted. For the nitrous oxide and farming input calculations, the yield is taken to be 10 tonnes/ha, and the LHV of dry farmed wood (poplar) chips 18 GJ/ dry tonne [*GEMIS 2002*].

Dry mass losses during chipping and storage are partly from dust and spillage, and partly from respiration, rotting and evaporation of volatiles, in line with *[Hamelinck 2002]*.

SB1Sugar Beet Farming

Sugar beet gives a high yield of easily-fermented sugar. Following [*LBST 2002*], the data on farming inputs have been selected given by [*FfE 1998*], which are also close to the input data of the [*ADEME 2003*] study. The yield in [*FfE 1998*] is 51.2 t/ha/a at a water content of 76%. This is about the present average yield for EU-25 (but bear in mind that sugar beet is only grown on good farmland). Better growing conditions generally increase the optimum amount of nitrogen fertilizer together with the yield, so the exact yield considered is not very critical in terms of nitrogen input per MJ product. However, there is considerable variation in the literature on optimum nitrogen inputs even for similar yields [*LBST 2002*]. Processes for making fertilizer are detailed in the following table.

N_2O emissions from the field dominate the GHG emissions. An average for sugar beet grown in EU15 is calculated using the JRC's EU GHG emissions model, as detailed in the *WTT main report*. The reference crop is unfertilized grass. The sugar beet leaves have been assumed to be ploughed back into the soil after harvest, which is the usual practice.

Storage of sugar beet has been included in this farming process, even though it may take place at the processing site. That is so that sugar beet results could be compared with those of wheat farming, where drying and storage is already included in the WTW input data. In store, beet loses about 0.1% of its sugar per day by respiration [*Wiltshire 2000*]. For a representative beet processing campaign of 90 days (see sugar beet to ethanol process SB3a) the average loss on storage is therefore about 4.5%.

WT1 Wheat Farming

Wheat is the highest-yielding cereals crop, but it also takes the highest inputs. This process is for 'soft wheat', which accounts for most of EU production, gives the highest yield, and has the highest fermentable content. Straw use is discussed in the main WTT report. Data on wheat farming inputs is not included in [*FfE 1998*], so data from [*ETSU 1996*] have been taken, which includes energy for drying and storage. N_2O emissions are calculated from GREASE. There is no "reference crop" (see main *WTT report*).

SC1 Sugar cane farming (Brazil)

Figures are derived from data for “scenario 2” in the thorough LCA study by [*Macedo 2004*] which describes best-current-practice in the Centre-South region, where 85% of Brazil’s sugar cane is grown, and where it is claimed there is still plenty of grazing land which could be planted to increase the supply if there is a market. It is a very long way from any rainforest. Some sugar cane is also produced in NE Brazil, near some areas of surviving Atlantic rainforest, but the conditions are much less suitable there, so that production needed subsidies, and is unlikely to increase.

There are usually 5 harvests, with an average yield of 82.4 t/ha (moist), but these take place over 6 years, so the annualized yield is 68.7 t/ha/y. Macedo gives inputs per tonne of moist cane. These have been converted to figures per MJ (LHV) dry cane using 72.5%, water content of harvested sugar cane [*Kaltschmitt 2001*] and LHV heat content of 19.6 MJ per kg dry matter [*Dreier 2000*] (Macedo also describes the process per tonne of cane, so these conversion factors cancel out in the overall calculation). To keep the pathway comparable with other crops, the WTW usual chemical processes have been used to calculate the energy and emissions from producing the agricultural inputs, not the values used by Macedo.

In this best-practice scenario, the solid “filter mud cake” and liquid “vinasse” residue from the distillation process (equivalent of wet DDGS in the wheat-to-ethanol process) are sent to the closer fields to recycle the water and much of the minerals. The figures represent a weighted average of nearer and more distant fields. The average nitrogen rate over 5 years is about 75 kg/ha.

The farming emissions include CO2, methane and nitrous oxide from burning the foliage to make harvesting easier: this is still the most common practice, although it is banned near towns. Macedo’s calculation of N_2O, CH_4 and CO_2 emissions from burning, using factors recommended in [*IPCC 2001*], has been used.

Nitrous oxide emissions were calculated from the nitrogen fertilizer additions using IPCC default coefficients. Fortunately they are low, so the related uncertainty is acceptable in this case.

Sugar cane resembles more a perennial biomass crop like miscanthus than it does an arable crop. Unlike arable crops in Europe, planting sugar cane on grazing land is believed to actually increase the soil carbon stocks. The risk of soil erosion (a major concern in Brazil) is heightened in the first year of establishment, compared to grazing land, but not in subsequent years.

Code	Process	Assoc. processes	Input		Expended energy		GHG emissions				N2O emissions	
			kg/ MJ prod.	MJ/ MJ prod.	Primary MJx/ kg or MJ	Primary MJx/ MJ prod.	g CO2/ MJ prod.	g CH4/ MJ prod.	g N2O/ MJ prod.	g CO2eq/ MJ prod.	Min	Max
RF1	**Rapeseed Farming**											
	CaO fertilizer	AC4	0.0003		2.04	0.0005	0.03	0.0001	0.0000	0.03		
	K2O fertilizer	AC3	0.0004		9.73	0.0041	0.23	0.0007	0.0000	0.24		
	P2O5 fertilizer	AC2	0.0007		15.47	0.0115	0.73	0.0010	0.0000	0.75		
	N fertilizer	AC1	0.0020		49.17	0.1001	6.16	0.0169	0.0196	12.35		
	Pesticides	AC5	0.0000		272.55	0.0047	0.29	0.0004	0.0000	0.30		
	Seeding material		0.0001		7.14	0.0006	0.02	0.0000	0.0000	0.02		
	Diesel	Z1		0.0414	4.18	0.0480	3.62	0.0000	0.0000	3.62		
	Net emissions from field							0.0001	0.0436	12.91	0.0261	0.0611
	drying (electricity EU mix LV)	Z7b		0.0028	10.33	0.0080	0.34	0.0008	0.0000	0.36		
	Sum primary energy consumption and emissions					***0.1776***	*11.42*	*0.0199*	*0.0633*	***30.60***		
SF1	**Sunflower seed Farming**											
	K2O fertilizer	AC3	0.0004		9.73	0.0037	0.21	0.0006	0.0000	0.22		
	P2O5 fertilizer	AC2	0.0005		15.47	0.0080	0.51	0.0007	0.0000	0.53		
	N fertilizer	AC1	0.0007		49.17	0.0331	2.03	0.0056	0.0065	4.08		
	Pesticides	AC5	0.0000		272.55	0.0094	0.57	0.0009	0.0000	0.60		
	Seeding material		0.0001			0.0006	0.02	0.0000	0.0000	0.02		
	Diesel	Z1		0.0510	4.18	0.0592	4.46	0.0000	0.0000	4.46		
	Net emissions from field							0.0001	0.0264	7.81	0.0186	0.0342
	drying (electricity)			0.0028	10.33	0.0080	0.33	0.0008	0.0000	0.36		
	Sum primary energy consumption and emissions					***0.1220***	*8.14*	*0.0086*	*0.0329*	***18.08***		

RF1 Rapeseed Farming

Plant oils are the closest nature gets to a liquid transport fuel, so relatively little energy is lost in the conversion process. Rape gives the highest oil yield in the Northern half of Europe. However, it still has much lower yield than cereals: it is grown as a low-input break crop, to rest the soil between more profitable cereal crops. The rape straw is invariably ploughed back into the soil, because it contains most of the nitrogen and minerals taken up by the crop, is needed to improve the organic content of the soil.

Again, N_2O emissions are calculated from the JRC's EU soil emissions model, and farming inputs are from [*FfE 1998*]. The yield from these inputs is 3 t/ha, which is also about the average EU-15 yield [*EUROSTAT 2003*]. No reference crop (see main *WTT report*).

Nitrogen fertilizer rates (and rapeseed yields) in UK are typically higher than in Germany: 180kg N/ha *[Groves 2002]* compared to 145 in the WTW data from [*FfE 1998*]. The WTW diesel farming inputs are between those in [*Groves 2002*] and [*ADEME 2002*]. The dry LHV of rapeseed is 23.8 GJ/t at standard 10% moisture [*FfE 1998*].

SF1 Sunflower Seed Farming

Rapeseed does not grow well in the drier parts of Europe: here, sunflower is grown in rather the same way, mostly as a break-crop between cereals, although average yields are lower. Inputs are from [*FfE 1998*], and average EU-15 N_2O emissions from the rapeseed field are calculated from JRC soil model. It has been assumed the straw is ploughed in the soil, which is the usual practice. No reference crop. The same LHV for sunflower seed as for rapeseed has been assumed.

No literature data have been found on energy and emissions for providing seeding materials for sunflower. Farming experts told that sunflower requires slightly less kg seed-per-MJ-crop than rapeseed; however, the energy inputs for sunflower seed crop production are higher. Therefore, the WTW best estimate is that fraction of energy input due to seeding materials is very roughly the same as for rapeseed: small compared to the other farming inputs.

Code	Process	Assoc. processes	Input		Expended energy		GHG emissions			
			kg/kg	MJ/ kg prod.	MJx /MJ	MJx/ kg prod.	g CO_2/ kg prod.	g CH_4/ kg prod.	g N_2O/ kg prod.	g CO_2eq/ kg prod.
SY1	**Soya bean farming (US) for finding animal feed credits**									
	K2O fertilizer	AC3	0.0080			0.0778	4.37	0.0125	0.0000	4.67
	P2O5 fertilizer	AC2	0.0040			0.0619	3.94	0.0052	0.0000	4.07
	N fertilizer	AC1	0.0020			0.0983	6.05	0.0165	0.0000	12.13
	Pesticides	AC5	0.0005			0.1363	8.31	0.0127	0.0001	8.63
	Diesel (US)	Z1		0.8400	1.1860	0.9962	75.19	0.0000	0.0000	75.19
	Net emissions from field								1.2530	370.89
	Sum primary energy consumption and emissions					**1.3706**	97.86	0.0470	1.2531	**475.57**

SY1 Soy Bean Farming

Soy bean meal is the main protein-rich animal feed in EU. Most is imported from the US. Primary energies and emissions for growing it have been calculated in order to find the credits to apply to by-products which would substitute it. The substitution is done on a mass basis, taking into account the protein contents of the different feeds. So the inputs per kg, not per MJ, have been needed.

Fertilizer and diesel inputs for growing soy in the USA are derived from *[UBA 1999]*. The data for US refineries [*ANL/1 1999*] have been used in calculating primary energy and emissions from the diesel consumed. In the absence of better data, nitrous oxide emissions are calculated from IPCC default values, using the procedure explained in [*LBST 2002*].

N_2O EMISSIONS CALCULATION FOR ARABLE CROPS IN EU

Nitrous oxide emissions dominate the greenhouse gas emissions from farming, and are important for all biomass-based pathways. Therefore the best possible estimate of EU emissions have been carefully used. The IPCC guidelines are highly simplified and therefore need a very wide error range. The method used by JRC to estimate average GHG emissions for the different biofuels crops is described in the main *WTT report*. This is for EU-15, but the average nitrous oxide emissions per MJ crop produced has been expected to be similar for EU-25. The method could not be used for short-rotation forestry and for sugar cane farming in Brazil, because these crops are not covered in the DNDC soils model used. Here, IPCC default emission factors [*IPCC 1996/1*] had to be used which estimated nitrous oxide emissions based on nitrogen fertilizer rates.

D.9 Production of agro-chemicals

All data on fertilizer and fuel inputs for agro-chemicals provision come from [*Kaltschmitt 1997*]. These data include the transport of the fertilizer. In these processes, the “MJ primary energy per MJ input” of fuel inputs includes the LHV and fossil carbon (as CO2) content of the fuel itself, as well as the upstream energy/emissions to make it.

However, [*Kaltschmitt 1997*] do not include upstream energies and emissions, so the WTW figures are moderately higher, especially where a lot of electricity is used. The WTW primary energies are similar to those in the new [*ADEME 2003*] report.

Code	Process	Assoc. processes	Input	Expended energy			GHG emissions			
			kg/ kg prod.	As used MJ/ kg prod.	MJx/ MJ	Primary MJx/ kg prod.	g CO_2/ kg prod.	g CH_4/ kg prod.	g N_2O/ kg prod.	g CO_2eq/ kg prod.
AC1	**Nitrogen Fertilizer Provision**									
	Electricity (EU-mix, MV)	Z7a		0.6	2.83	1.78	74.8	0.18	0.0034	80.0
	Hard coal	KO1		3.9	1.09	4.32	405.8	1.51	0.0011	440.8
	Diesel	Z1		0.9	1.16	1.00	75.3	0.00	0.0000	75.3
	Heavy fuel oil	Z3		4.4	1.09	4.77	384.1	0.00	0.0000	384.1
	NG	Z6		33.0	1.13	37.31	2083.0	6.58	0.0008	2234.7
	N2O from process								*9.6300*	
	Primary energy and emissions/kg					***49.17***	*3022.9*	*8.27*	*9.6353*	***6065.3***
AC2	**P fertilizer provision**									
	Electricity (EU-mix, MV)	Z7a		1.6	2.83	4.54	191.2	0.47	0.0086	204.5
	Hard coal	KO1		0.6	1.09	0.62	58.6	0.22	0.0002	63.6
	Diesel	Z1		1.1	1.16	1.30	98.1	0.00	0.0000	98.1
	Heavy fuel oil	Z3		5.0	1.09	5.44	438.3	0.00	0.0000	438.3
	NG	Z6		3.2	1.13	3.56	198.8	0.63	0.0001	213.3
	Primary energy and emissions/kg					***15.47***	*985.0*	*1.31*	*0.0089*	***1017.8***
AC3	**K fertilizer provision**									
	Electricity (EU-mix, MV)	Z7a		0.2	2.83	0.62	26.2	0.06	0.0012	28.0
	Diesel	Z1		0.5	1.16	0.63	47.3	0.00	0.0000	47.3
	NG	Z6		7.5	1.13	8.48	473.4	1.50	0.0002	507.8
	Primary energy and emissions/kg					***9.73***	*546.9*	*1.56*	*0.0014*	***583.2***
AC4	**CaO fertilizer provision (85%CaCO3+15%CaO,Ca(OH)2)**									
	Electricity (EU-mix, MV)	Z7a		0.4	2.83	1.13	47.7	0.12	0.0022	51.0
	Coal	KO1		0.3	1.09	0.35	33.3	0.12	0.0001	36.2
	Diesel	Z1		0.2	1.16	0.21	16.2	0.00	0.0000	16.2
	NG	Z6		0.3	1.13	0.34	18.9	0.06	0.0000	20.3
	Primary energy and emissions/kg					***2.04***	*116.1*	*0.30*	*0.0023*	***123.7***
AC5	**Pesticides (etc) provision**									
	Electricity (EU-mix, MV)	Z7a		28.5	2.83	80.72	3398.9	8.29	0.1535	3635.0
	Hard coal	KO1		7.6	1.09	8.35	784.2	2.91	0.0021	851.9
	Diesel	Z1		58.1	1.16	67.40	5086.9	0.00	0.0000	5086.9
	Heavy fuel oil	Z3		32.5	1.09	35.37	2849.9	0.00	0.0000	2849.9
	NG	Z6		71.4	1.13	80.71	4505.9	14.24	0.0018	4834.0
	Primary energy and emissions/kg					***272.55***	*16625.8*	*25.45*	*0.1573*	***17257.6***

All inputs are quoted PER kg ACTIVE INGREDIENT. The kg/MJ input of fertilizer to the farming processes are also per kg active ingredient. The name of the process indicates what is considered the active ingredient. Thus, for example, “K2O fertilizer provision” is per kg potassium content as K_2O. The quantities of fertilizer specified in the farming pathways use the same convention. The active ingredient may actually be present in a mixture of compounds.

AC1 Nitrogen Fertilizer Provision

This is the main source of GHG emissions from agro-chemicals manufacture. Most of the GHG emissions come from NOx released from the process itself. The active ingredient is considered the nitrogen content, so the data are per kg nitrogen.

AC4 Lime ($CaO+CaCO_3$) Provision

Lime contains roughly 85 % m/m $CaCO_3$ and15% CaO, partially hydrated to $Ca(OH)_2$. When used as a fertilizer, the CaO content neutralizes the carbonic acid produced by decaying vegetable matter. This carbonic acid would otherwise release its CO_2 to the air. Therefore the CO_2 produced by the calcining process (“process emissions” in [*Kaltschmitt 1997*]) is later effectively reabsorbed, and should be left out of GHG calculations.

Lime requirements for a particular crop vary greatly depending on soil type. Fortunately, though, it never represents a major energy input to the WTW farming pathways, so the effect of the uncertainty is small.

AC5 Pesticides (etc.) Provision

This comprises all complex organic compounds; pesticides, fungicides, plant hormones…; used in the farming processes. The input energy and emissions data (from [*Kaltschmitt 1997*]) are necessarily a very approximate guess. [*ADEME 2003*] give range of 175-576 MJ/kg primary energy for various ‘plant health products’: the WTW value of 266 MJ/kg compares with their best-estimate of 297 MJ/kg. The WTW emissions are considerably higher than those calculated by [*Kaltschmitt 1997*] from the same data: it looks like they forgot to add in the process emissions. The final fate of the carbon in the pesticides themselves is uncertain, but the amount of CO_2 involved is negligible. In fact, in general, the mass of pesticides in farming processes is so small that the choice of data has negligible influence on the calculations of farming emissions.

D.10 Biomass transport

Code	Process	Assoc processes	one-way distance km	t.km/ MJ prod.	MJ diesel/ t.km	MJx/ t.km	gCO_2eq/ t.km	MJx/ MJ prod.	gCO_2eq/ MJ prod.	Loss MJ/MJ
Standard biomass transporters										
Z8	**Truck for dry product (round trip considered)**									
	Diesel	Z1,Z2			0.97	1.13	85.10			
Z9	**Ship for inland/coastal navigation**									
	Marine diesel	Z1			0.43	0.50	37.76			
Z10	**Ocean-going bulk carrier**									
	Fuel oil	Z3			0.20	0.22	17.77			
Solid biomass road transport										
WC2a	**Wood chips road transport, 50 km**	Z8	50	0.004	0.97	1.13	85.10	**0.0045**	**0.34**	0.000
WC2b	**Wood chips road transport, 12 km**	Z8	12	0.001	0.97	1.13	85.10	**0.0011**	**0.08**	0.000
SB2	**Sugar beet road transport**	Z8	50	0.013	0.97	1.13	85.10	**0.0147**	**1.11**	0.000
WT2a	**Wheat grain road transport**	Z8	50	0.004	0.97	1.13	85.10	**0.0039**	**0.30**	0.010
WT2b	**Wheat straw road transport**	Z8	50	0.003	0.97	1.13	85.10	**0.0039**	**0.29**	0.000
SC2	**Sugar cane road transport**	Z8	20	0.004	0.97	1.13	85.10	**0.0042**	**0.32**	0.000
RO2	**Rapeseed road transport**	Z8	50	0.002	0.97	1.13	85.10	**0.0024**	**0.18**	0.010
SO2	**Sunflower seed road transport**	Z8	50	0.002	0.97	1.13	85.10	**0.0024**	**0.18**	0.010
Solid biomass shipping										
WC2c	**Coastal/river shipping wood chips (200MW plant)**	Z8	400	0.034	0.43	0.50	37.76	**0.0171**	**1.29**	0.000
Manure transport										
BG1a	**Liquid manure transport, 10 km**	Z2	10	0.013	0.94	1.09	81.95	**0.0146**	**1.10**	
BG1b	**Dry manure transport, 10 km**	Z2	10	0.004	0.94	1.09	81.95	**0.0047**	**0.35**	
Long-distance biofuel transport			Naut. Miles							
SC4	**Sugar cane ethanol from Brazil**	Z4	5500	0.380				**0.0512**	**4.11**	
SY2	**Soya bean transport**			t.km/kg prod.						
	Truck transport of soya beans	Z8	50	0.050	0.97	1.13	85.10	**0.0564**	**4.25**	
	River transport of soya beans	Z9	250	0.250	0.43	0.50	37.76	**0.1251**	**9.44**	
	Ocean transport of soya beans	Z10	5000	5.000	0.20	0.22	17.77	**1.1085**	**88.86**	0.010
	Primary energy consumption and emissions							***1.2899***	***102.56***	

Z8 Truck for dry products

Nominal 23 t truck from [*ESU 1996*] obeying EURO IV emissions restrictions. Fuel consumption takes an empty return trip into account. The actual payload depends on the density of the material. This is taken into account when calculating effective t-km in each individual trucking process. According to [*Kaltschmitt 2001*] such a truck can actually carry up to 27 t for dense material, but usually for biomass the capacity is often limited by the maximum volume, which is 100 m^3. For rapeseed, for example, the actual payload is 22 t, close to the nominal payload. Cost is approximately 0.07EUR/t.km [*ESU 1996*].

Z9 Ship for inland/coastal navigation

For 8,800 t dry product carrier for coastal navigation (e.g. Baltic) or on inland waterways (e.g. Rhine) from [*ESU 1996*]; emissions data from [*Kaltschmitt 1997*]. Marine gasoil is the fuel: emissions are approximated to those of diesel. For discussion of transport distances, see below. Empty return trip considered.

Z10 Ocean-going bulk carrier

40,000 t dry product carrier; consumption of heavy fuel oil from [*Kaltschmitt 1997*]. Calculation methodology is the same as for oil transport (see above).

BIOMASS TRANSPORT DISTANCES

FARMED WOOD

For a catchment area is shaped like the WTW map, 50 km average transport distance gives access to about 0.6 Mha. If 50% of this area is assumed as arable land, and 10% of this arable land is farmed wood, with a yield of 10 dry t/ha, then annual production from whole area is 300 dry kt.

A 10 MW plant (based on feed) requires 16.8 dry kt wood per year (at 18 GJ/t). By quadratic scaling, transport distance of 12 km is needed. For a 200 MW plant 336 dry kt wood per year are needed; implying a single catchment area with transport distance about 50 km.

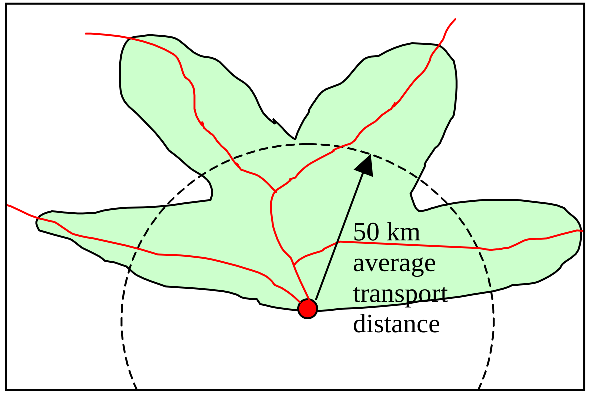
STRAW

In the good wheat-growing areas where straw may be harvested, the straw yield from wheat is about 5 t/ha. But these are prime agricultural areas with a high % of cereals farms. If 60% of the land is assumed to be arable, and 70% of that grows wheat (or other suitable cereal), then the transport distance is reduced to 25 km for a 200 MW plant. Note that the projected Iogen plant is about 150 MW.

FOREST RESIDUALS

The Pietarsaari cogeneration plant in Finland collects up to 200 000 m^3 per year forest residuals, with MAX transport distance 80 km [*TEKES 2002*]. That means 90 dry kt/a for a dry-matter density of 0.4 dry t/m^3. The average transport distance would then be about 50km. These forest residuals give a total water-free-LHV energy input of 54 MW. For a 200 MW plant, for example on the Baltic coast, one would need to ship wood in from about 4 collecting points like this. Looking at a map of the Baltic that means maybe 400km average shipping distance. A central-European scenario, with barge transport on the Rhine or Danube, gives a similar results.

For a 10 MW plant, about 12 km road transport distance by quadratic scaling from the Pietarsaari example are get.



BIO-CROPS

In the literature one can find transport distances from the farm gate to the processing plant anything from 10 to almost 200 km. The first represents theoretical calculations of the radius needed to grow sufficient crop to feed the factory. The second represents the actual trucking distance for some existing plants: their supplies come from scattered farms which have opted to grow designated energy crops under existing rules for agricultural subsidies. The WTW distance represents what it is thought to be reasonable for the medium-term future, if energy farming becomes much more common.

The calculation of t.km per MJ product takes into account the real payload of the truck, bearing in mind the volume limitation of the truck (see trucking processes). The return journey is already taken into account in the truck fuel consumption. For fine materials, 1% losses during loading and transport are considered.

MANURE

This is used for biogas, usually at fairly small scale, hence the short transport distance taken into account.

SB2 Soy bean transport

This process is used in the pathway for calculating animal feed (soy meal) credits (see after ‘biofuels processes’): everything in this pathway is related to mass of soy meal, since there were no LHV data on soy bean meal . The pathway represents soy bean trucking to a river-port, and than trans-shipping to a transatlantic vessel (e.g. near New Orleans). This scenario is from [*UBA 1999*].

D.11 Biogas from organic waste

Three sources of organic waste are considered namely municipal waste, "liquid" manure and dry manure. The process is described in the main *WTT report*. The anaerobic fermentation produces raw biogas that, depending on the intended use may need to be treated (to remove contaminants such as sulphur) and/or upgraded (to remove CO_2). The plant usually produces its own heat and electricity (CHP). Data for municipal waste is from [*Börjesson 2004*], [*Börjesson 2005*] and from [*Boisen 2005*] for manure. All three options include a small credit for use of the residual organic material as fertiliser. When left untreated, stored manure produces methane that is vented to the atmosphere. This is particularly so for liquid manure where the right conditions for anaerobic fermentation are met. Using manure for biogas production therefore offers a credit for avoided field methane emissions, particularly large for liquid manure.

Code	**Process**	Assoc. processes	Bio-feed	Expended energy			GHG emissions				Overall energy efficiency	Range		Probability distribution
			MJ bio-en/ MJ prod.	As used MJ/ MJ prod.	MJx/ MJ	Primary MJx/ MJ prod.	g CO2/ MJ prod.	g CH4/ MJ prod.	g N2O / MJ prod.	g CO2eq / MJ prod.		Min	Max	
	Raw biogas production from municipal waste													
	Municipal waste		1.4286								*70%*	1.2286	1.6286	
	Heat (for info, internally generated)			0.0865								0.0778	0.0952	
	Electricity (for info, internally generated)			0.0622								0.0311	0.0933	
	Methane losses							0.2000						
	Raw biogas production from liquid manure													
	Municipal waste		1.4286								*70%*	1.2286	1.6286	
	Heat (for info, internally generated)			0.1500								0.1400	0.1700	
	Electricity (for info, internally generated)			0.0430								0.0400	0.0500	
	Methane losses							0.2000						
	Methane field emissions credit							-2.8571				-1.4286	-4.2857	
	Raw biogas production from dry manure													
	Municipal waste		1.4286								*70%*	1.2286	1.6286	
	Heat (for info, internally generated)			0.1500								0.1400	0.1700	
	Electricity (for info, internally generated)			0.0430								0.0400	0.0500	
	Methane losses							0.2000						
	Methane field emissions credit							0.2857				-0.1429	-0.4286	
	Biogas treatment and upgrading													
	Raw biogas		1.0100											
	Electricity (for info, internally generated)			0.0300								0.0200	0.0400	
	Methane losses							0.2000						
	Biogas CHP plant													
	Raw biogas		1.7000									1.6200	1.7900	
	Heat generation		0.0000											
	Electricity generation		0.0000											
	Methane losses							0.0533						

Processes BG2a/b/c represent the integration of these steps to produce upgraded biogas from the different feedstocks. This gas is then suitable for use as automotive fuel or to be introduced into a natural gas grid. Processes BG3a/b/c represent direct small scale electricity production from raw biogas.

Code	**Process**	Assoc. processes	Bio-feed	Expended energy			GHG emissions				Overall energy efficiency	Range		Probability distribution
			MJ bio-en/ MJ prod.	As used MJ/ MJ prod.	MJx/ MJ	Primary MJx/ MJ prod.	g CO2/ MJ prod.	g CH4/ MJ prod.	g N2O / MJ prod.	g CO2eq / MJ prod.		Min	Max	
BG2a	**Municipal waste to biogas (upgraded)**													
	Municipal waste		1.6916			0.6916								
	Electricity import	Z7a		0.0524	2.8347	0.1485				6.69				
	Methane losses							0.4423			g/MJ			
	N-fertiliser credit					-0.0299				-1.01	-0.18			
	Primary energy consumption and emissions					***0.8102***		*0.4423*		***15.85***				
BG2b	**Liquid manure to biogas (upgraded)**													
	Liquid manure		1.9367			0.9367								
	Electricity import	Z7a		-0.0134	2.8347	-0.0380				-1.71				
	Methane losses							0.4820		11.09				
	Methane field emissions credit							-3.8773		-89.18	g/MJ			
	N-fertiliser credit					-0.0215				-0.73	-0.13			
	Primary energy consumption and emissions					***0.8772***		*-3.3953*		***-80.53***				
BG2c	**Dry manure to biogas (upgraded)**													
	Dry manure		1.9367			0.9367								
	Electricity import	Z7a		-0.0134	2.8347	-0.0380				-1.71				
	Methane losses							0.4820		11.09				
	Methane field emissions credit							-0.3877		-8.92	g/MJ			
	N-fertiliser credit					-0.0215				-0.73	-0.13			
	Primary energy consumption and emissions					***0.8772***		*0.0943*		***-0.27***				

D.12 Conversion processes for “conventional biofuels”

The range of energy and emissions reported by different authors for processing biomass into ‘conventional biofuels’ is much smaller than the uncertainty in farming emissions, especially N_2O emissions. Therefore it has not been complicated by giving an error range. Where there are significantly different processes (e.g. lignocellulose-to-ethanol) separate calculations for the two processes have been made.

Large variations in the energy and emissions reported in the literature are due to different treatment of by-products, as discussed in the main body of this report.

D.12.1 Ethanol from sugar beet

Code	Process	Assoc. processes	Bio-feed	Expended energy			GHG emissions				Overall energy efficiency	Range		Probability distribution
			MJ bio-en/ MJ prod.	As used MJ/ MJ prod.	MJx/ MJ	Primary MJx/ MJ prod.	g CO2/ MJ prod.	g CH4/ MJ prod.	g N2O / MJ prod.	g CO2eq / MJ prod.		Min	Max	
Sugar beet to ethanol														
SB3a	**Sugar beet to ethanol, pulp and slops to animal feed**													
	Basic process without slop or pulp credits													
	Sugar beet		1.8930			0.8930						1.7980	1.9880	
	Energy for main process													
	NG for steam at 90% eff.	Z6		0.3038	1.1306	0.3435	19.18	0.0606	0.0000	20.57		0.2886	1.1872	
	Electricity (MV)	Z7a		0.0172	2.8347	0.0488	2.05	0.0050	0.0001	2.20		0.0163	2.9788	
	Primary energy and emissions (no by-product credits)					**1.2852**	21.23	0.0656	0.0001	**22.77**	kg/kg biomass			
	Sugar beet pulp			-0.3850							0.050			
	Slops			-0.1770							0.023			
	Combined pulp and slops by-products			-0.5620							0.073			
	Pulp and slops drying													
	NG			0.2361	1.1306	0.2669	14.90	0.0471	0.0000	15.99	kWh wheat/kWh	0.2243	1.1872	
	Electricity (MV)	Z7a		0.0182	2.8347	0.0516	2.17	0.0053	0.0001	2.32		0.0173	2.9788	
	Credit for pulp+slops replacing wheat grain (LHV basis)	WT1		-0.4665	0.1306	-0.0609	-4.01	-0.0061	-0.0147	-8.51	0.83			
	Net primary energy consumption and emissions					***1.5429***	*34.29*	*0.1120*	*-0.0145*	***32.57***				
SB3c	**Sugar beet to ethanol, pulp and slop to biogas digestor and CHP**													
	Basic process without credits		1.8930			**1.2852**	21.23	0.0656	0.0001	**22.77**		1.7980	1.9880	
	Pulp plus slops to biogas digester			-0.5620										
	Credits from biogas plant													
	NG	Z6		-0.2279	1.1306	-0.2577	-14.39	-0.0455	0.0000	-15.43				
	Electricity (MV)	Z7a		-0.0214	2.8347	-0.0607	-2.56	-0.0062	-0.0001	-2.73				
	Net primary energy consumption and emissions					***0.9668***	*4.29*	*0.0139*	*0.0000*	***4.60***				

SB3a Ethanol from sugar beet; by-products used as animal feed

Sugar factories usually dry the by-product sugar beet pulp and sell it for animal feed, because it is worth more as feed than as fuel. Dried slop from the fermentation is a more valuable feed than the pulp.

Sugar factories using beet do not work all year round because of sugar loss from the beet in storage (see SB1 farming pathway). Beet processing ‘campaigns’ last between 60 days (Poland) and 150 days (Britain). Average for EU25 is about 90 days (also the German figure). However, it may be possible to keep the ethanol part of the plant working continuously by storing pasteurised syrup.

Following [*LBST 2002*] a conventional fermentation plant has been chosen, not integrated with a sugar refinery, as analysed by [*FfE 1998*]. First the process is shown without any credits for use of the pulp or slop. The size of the plant is not very important for efficiency, but has a big effect on costs. [*FfE 1998*] made a cost analysis on a hypothetical 59MW (ethanol) plant.

The main steps in the basic process are cleaning, slicing, sieving out the pulp by-product, syrup pasteurisation, fermentation, distillation, and final purification. Per MJ ethanol output, these steps use a total of 4.8KJ electricity and 0,27 MJ heat [*FfE 1998*], which it has been assumed to be supplied by a natural gas burner with 90% efficiency; i.e. 0,30 MJ natural gas. Distillation and final ethanol purification (drying with zeolite) consumes most of the energy. It takes 2.02 Kg sugar beet (at 76.5% water content) to make 1MJ ethanol.

There are two by-products: sugar beet pulp sieved from the syrup (0.050 kg/kg pulp, or 0.385 MJ/MJ ethanol), and the slop filtered from the fermented mash (0.023 dry kg/kg pulp, or 0.177 MJ/MJ ethanol). When the equivalent products from cereals fermentation are sold for animal feed, they are called “brewers’ dried grains” and “solubles”; usually sold together. Both beet by-products have a dry LHV of 15MJ/kg [*FfE 1998*], contain initially 35-40% water, and have to be dried to about 9% water [*FfE 1998*], [*NRC 1998*]. The heat energy for drying and pelleting pulp is given in [*FfE 1998*] as 0.295MJ/moist kg sugar beet input: if slops have been assumed to need the same heat-per-dry-kg, the heat for drying both, per MJ ethanol, is 0.295*(0.05+0.023)/0.05/2.02 = 0,213 MJ/MJ ethanol. Again heat comes from a natural gas burner with 90% efficiency. In addition there is a small amount of electricity required for the blowers: 0.007 kWh/(kg moist sugar beet) for the pulp drying, or 0.018 MJ/MJ ethanol for drying both sugar beet and slop.

FODDER CREDIT CALCULATION

There is only 8.6 dry % m/m protein in dried sugar beet pulp [*NRC 1998]*, but slop contains protein from the yeast: “solubles” from maize fermentation contain 26.7%m protein [about 25 dry %m could be guessed for dried slops. So the combined feed has about 13.4 dry % m/m protein, which is within the range for wheat. But wheat grain has a greater digestible energy content: according to [*NRC 1998*], pigs can digest 16.2 MJ/dry kg, compared to 13.2 MJ/dry kg for sugar beet pulp, and 13.9 MJ in “solubles”. Taking into account the difference in LHV values; 17 MJ/dry kg for wheat grain [*Kaltschmitt 2001*] compared to 15.6 MJ/dry kg for pulp and slop [*FfE 1998*]; it has been calculated that 1 water-free MJ pulp replaces 0.83 water-free MJ wheat grain. The primary energy and emissions credits are then easily calculated from the WTW wheat farming process WT1. The feed must be transported to the animals whatever they eat, so it has been assumed the transport energy for the feed cancels out.

Note: it costs more energy (and emissions) to dry the animal feed than you get credit for fodder saved. Nevertheless, this is the most likely destination for the by-products on economic grounds. To improve the energy balance and keep rational economics, one could make a process in which process heat comes from woody waste or straw, for example, but that applies to any process using heat.

SB3c Ethanol **From Sugar Beet; Pulp Added To The Biogas Fermentor**

The sieved pulp mash and is added to an anaerobic digester, which is already producing biogas from the waste-water. Furthermore, the slop is no longer filtered from the waste-water, and also makes biogas. The plant is simpler than one burning the by-products because they do not need to be dried. But the process is still probably less attractive economically than selling the by-products as animal feed.

To calculate the heat credit from the biogas burning the efficiency data of the biogas plant in [*FfE 1998*] has been used (proposed for making methane for transport fuel). This plant incorporates a small gas engine for providing its own electricity, together with a small excess, which has been treated as an electricity credit (you would not bother with this engine in practice but its effect on the overall energy and emissions balance is negligible). For each MJ biomass in, this plant produces 0.405 MJ biogas and 0.038 MJ electricity. It has been assumed 1MJ biogas substitutes 1MJ natural gas.

The waste from the biomass fermentor would probably be used as fertilizer. However, the quantity is much smaller than the uncertainty in fertilizer use in the sugar beet farming process, so it is pointless to account for this.

Ethanol From Sugar Beet; By-Products Burnt For Process Heat

Animal feed is usually worth much more per MJ than biomass fuel: it would normally be cheaper to fuel the burner on some sort of waste. However, in order to allow comparison with other studies, this option has been included. The drying process for pulp and slop (taken from the SB3a) consumes about half the heat content of the by-products. The dried (9% water) by-products are burnt in a biomass boiler at 85% efficiency [*GEMIS 2002*], and replace natural gas burnt at 90% efficiency. The results of this process are almost the same as those for SB3c; pulp added to the biogas fermentor.

D.12.2 Ethanol from wheat grain

Code	**Process**	Assoc. processes	Bio-feed	Expended energy			GHG emissions				Overall energy efficiency	Range		Probability distribution
			MJ bio-en/ MJ prod.	As used MJ/ MJ prod.	MJx/ MJ	Primary MJx/ MJ prod.	g CO2/ MJ prod.	g CH4/ MJ prod.	g N2O / MJ prod.	g CO2eq / MJ prod.		Min	Max	
WT3	**Wheat grain handling and drying (to dwg, 3% moisture)**													
	Wheat grain (16% moisture)		1.0000											
	Electricity (MV)			0.0026	2.8347	0.0072	0.30	0.0007	0.0000	0.33				
	Diesel			0.0400	1.1600	0.0464	0.57	0.0000	0.0000	0.57				
	Net primary energy consumption and emissions					***0.0536***	*0.88*	*0.0007*	*0.0000*	***0.90***				
WT4a	**Wheat grain to ethanol, conventional boiler**												t dw g/t EtOH	
	Dried wheat grain (dwg, 3% moisture)		1.8644			0.8644							3.03	
	Heat to process			0.3640										
	NG for steam at 90% eff.	Z6		0.4044	1.1306	0.4573	25.53	0.0807	0.0000	27.39				
	Electricity (MV)	Z7a		0.0540	2.8347	0.1531	6.45	0.0157	0.0003	6.89				
	Net primary energy consumption and emissions					***1.4747***	*31.97*	*0.0964*	*0.0003*	***34.28***				
WT4b	**Wheat grain to ethanol, NG CCGT**												t dw g/t EtOH	
	Dried wheat grain (dwg, 3% moisture)		1.8644			0.8644							3.03	
	Heat to process			0.3640										
	Electricity to process			0.0540										
	NG to CCGT			0.6794	1.1306	0.7681	42.88	0.1356	0.0000	46.00				
	Electricity net surplus			-0.1867										
	Credit for electricity surplus based on NG to state-of-the-art stand-alone CCGT			-0.3395	1.1306	-0.3839	-21.43	-0.0677	0.0000	-22.99				
	Net primary energy consumption and emissions					***1.2486***	*21.45*	*0.0678*	*0.0000*	***23.01***				
WT4c	**Wheat grain to ethanol, Lignite CHP**												t dw g/t EtOH	
	Dried wheat grain (dwg, 3% moisture)		1.8644			0.8644							3.03	
	Heat to process			0.3640										
	Electricity to process			0.0540										
	Lignite to CHP plant			0.7761	1.0156	0.7882	89.28	0.0000	0.0000	89.28				
	Electricity net surplus			-0.0775										
	Credit for electricity surplus based on lignite-fired conv. power station			-0.1937	1.0156	-0.1967	-22.15	0.0000	0.0000	-22.15				
	Net primary energy consumption and emissions					***1.4559***	*67.13*	*0.0000*	*0.0000*	***67.13***				
WT4d	**Wheat grain to ethanol, Straw CHP**												t dw g/t EtOH	
	Dried wheat grain (dwg, 3% moisture)		1.8644			0.8644							3.03	
	Heat to process			0.3640										
	Electricity to process			0.0540										
	Straw to CHP plant			0.7761	1.0165	0.7889	0.96	0.0000	0.0000	0.97				
	Debit for additional fertilisers (net)				kWh/kg						kgex/MJ EtOH			
	N				13.6591	0.0000	0.00	0.0000	0.0205	6.06	0.0000			
	P				4.2959	0.0011	0.07	0.0001	0.0000	0.07	0.0001			
	K				2.7023	0.0037	0.21	0.0006	0.0000	0.22	0.0004			
	Total					0.0047	0.27	0.0007	0.0205	6.35				
	Electricity net surplus			-0.0775										
	Credit for electricity surplus based on Straw-fired conv. power station			-0.2460	1.0165	-0.2500	-0.31	0.0000	0.0000	-0.31				
	Net primary energy consumption and emissions					***1.4080***	*0.93*	*0.0007*	*0.0205*	***7.01***				

WTDa	**Credit for DDGS as animal feed**										kg/MJ EtOH	Protein factor		
	Soya substitution	SYML				-0.3074	-4.01	-0.0115	-0.0199	-10.17	0.043	0.78		
WTDb	**Credit for DDGS as fuel**										kg/MJ EtOH			
	Electricity			-0.2042	1.1306	-0.4197	-23.43	-0.0741	0.0000	-25.14	0.043			

The data used here are essentially derived from [*LowCVP 2004*]. Process Wt3 describes the grain drying step to arrive at "dry wheat grain" (dwg, 3% moisture). Processes WT4a/b/c/d describe the ethanol plant proper. They all assume the same energy requirement for the plant but different utility generation schemes.

WT4a Conventional natural gas boiler

Heat is supplied by a conventional natural gas fired boiler and electricity is imported. This can be considered as representative of the vast majority of existing installations and is also by far the cheapest solution.

WT4b Combined cycle gas turbine

A natural gas fired gas turbine with a heat recovery steam generator (HRSG) provides both heat and electricity. As more heat than electricity is required supplementary firing is applied in the HRSG. As the heat is required only as low pressure steam, a back pressure turbo-generator is also installed behind the HRSG. The plant is assumed to be sized and operated to produce the heat required for ethanol manufacture. There is, however, a surplus of electricity which is exported into the grid, thereby generating an energy and GHG credit.

This solution is considerably more energy efficient but also significantly more complex and expensive to build and operate.

WT4c Lignite boiler CHP

High pressure steam is produced in a lignite boiler. A back pressure turbo-generator produces electricity and low pressure steam for the process. Here again the plant is assumed to be sized and operated to produce the heat required for ethanol manufacture but it nevertheless generates an electricity surplus.

Lignite (or brown coal) is a cheap and abundant fuel in certain parts of Europe and actual plants are either operating or under construction in Eastern Germany.

WT4d Straw boiler CHP

Wheat cultivation produces large amounts of straw. Some LCA studies have considered straw as a by-product but this is not necessarily the case. In most of the EU it should be ploughed back to maintain the water-retention properties of the soil (see also straw availability, *WTT report, section 5*). Where it may be removed from the field it is partly already used for litter and other applications. Therefore it is misleading to systematically assume that straw can be used to fuel the ethanol production process. In practice this should only be proposed where there is little water stress, a high density of cereals production and a low density of livestock. These conditions would apply to concentrated wheat-producing areas in Northern Europe excluding the Low Countries and Denmark. In any case removing straw will reduce soil nutrients, which needs to be compensated by an additional fertiliser input.

This scheme is similar to the previous case but straw in used instead of lignite. The main advantage of this scheme is to use a renewable source of energy to drive the process. It must be realised, however, that handling and burning of solids is considerably more complex and costly than with liquids or gases, particularly in the case of a low energy density material such as straw. This will therefore be the most expensive option.

WTDa Credits for DDGS as animal feed

Ethanol production produces a by-product known as DDGS (Distiller's Dried Grain with Solubles) which is the solid residue after digestion of the carbohydrates. DDGS is a protein-rich material and is therefore a useful animal feed component. Its nearest equivalent is corn gluten feed, a by-product of maize milling the supply of which is fixed by the amount of maize milled. Wheat DDGS contains 38.5% dry matter crude protein [*Univ. Minnesota 2002*] more than DDGS from maize). In the EU marginal animal feed is soy bean meal imported from the USA. The meal made from pure soy beans has a protein content of 49% [*NRC 1998*]. Since protein feeds are much more valuable than energy feeds [*DG-AGRI 2003*], farmers would use 1kg DDGS to replace 38.5/49 = 0.78 kg soy bean meal (the digestible energy ratio is anyway similar). The equivalent quantity of soy bean meal is calculated on the basis of the protein content using data from [*NRC 1998*]. The energy and emissions for the soy meal is calculated according to a scenario of soy beans grown in the US, and crushed in EU, following [*UBA 1999*] (see sec. D.12.6).

WTDb Credits for DDGS as fuel

Although animal feed is by far the most lucrative usage and therefore the most likely, DDGS may also be used as fuel, for instance in solid-burning (i.e. coal) power plants that need to meet their renewable energy obligations. The calorific energy content of DDGS is considerably greater than the energy required to produce the equivalent animal feed, so burning DDGS gives a higher energy credit.

D.12.3 Ethanol from sugar cane (Brazil)

Code	**Process**	Assoc. processes	Bio-feed	Expended energy			GHG emissions				Overall energy efficiency	Range		Probability distribution
			MJ bio-en/ MJ prod.	As used MJ/ MJ prod.	MJx/ MJ	Primary MJx/ MJ prod.	g CO2/ MJ prod.	g CH4/ MJ prod.	g N2O / MJ prod.	g CO2eq / MJ prod.		Min	Max	
SC3	**Sugar cane to ethanol**													
	Sugar cane		2.7720			1.7720								
	Credit for surplus heat (diesel)			-0.1150	1.2609	-0.1450	-10.94			-10.94				
				kg/kWh EtOH	kWh/kg									
	H2SO4	C7		0.00047	4.0052	0.0019	0.09	0.0003	0.0000	0.10				
	CaO	C6		0.00043	4.9835	0.0021	0.46	0.0004	0.0000	0.47				
	Cyclohexane			0.00003	9.9000	0.0003	0.01			0.01				
	Primary energy consumption and emissions					***1.6313***	*-10.39*	*0.0006*	*0.0000*	***-10.37***				

Data for this process were taken from the careful life-cycle analysis by [*Macedo 2004*],adopting his “scenario 2” describing best-current-practice in the Centre-South region of Brazil, where 85% Brazilian ethanol is produced. His analysis also takes into account the energy for plant construction and some minor inputs which it has been neglected to be consistent with the WTW calculations for other processes.

The data refer to the production of *anhydrous* ethanol, in Macedo’s best-current-practice scenario. Cyclohexane is used in the drying process. The yield corresponds to 91.8 litres ethanol per tonne of moist cane. Inputs were converted from quantities per-tonne-of-cane to per-MJ-ethanol using the same LHV and water content for sugar cane as used in the sugar cane farming process, and standard values for ethanol (see sec. D.2).

Plant capacity is 120 000 litres ethanol per day, and it operates for 180 days per year. A very important factor is that the bagasse to raise steam which provides all the process heat, and electricity via a steam turbine. In fact modern plants have a surplus of bagasse. Although this could be used to generate electricity exports, usually the surplus bagasse is simply sold as a fuel for nearby factories (e.g. for food processing), where it mostly replaces fuel oil (almost identical to diesel; used for the WTW credit).

D.12.4 Bio-diesel from plant oil

Code	Process	Assoc. processes	Bio-feed	Expended energy			GHG emissions				Overall energy efficiency	Range		Probability distribution
			MJ bio-en/ MJ prod.	As used MJ/ MJ prod.	MJx/ MJ	Primary MJx/ MJ prod.	g CO2/ MJ prod.	g CH4/ MJ prod.	g N2O / MJ prod.	g CO2eq / MJ prod.		Min	Max	
RO3	**Rapeseed to raw oil: extraction**													
	Rapeseed		1.6326			0.6326								
	Electricity (MV)	Z7a		0.0084	2.8347	0.0238	1.00	0.0024	0.0000	1.07				
	NG for steam at 90% eff.	Z6		0.0442	1.1306	0.0500	2.79	0.0088	0.0000	2.99				
	n-hexane	see notes		0.0031	1.1600	0.0036	0.27	0.0000	0.0000	0.27	kg/MJ prod.			
	Rapeseed cake										-0.0408			
	Soya meal / rapeseed cake replacement ratio										0.80			
	Credit for rapeseed cake	SYML			0.7862	-0.1155	-8.09	-0.0020	0.0211	-1.89				
	Primary energy consumption and emissions					***0.5945***	*-4.03*	*0.0092*	*0.0212*	***2.44***				
SO3	**Sunflower seed to raw oil: extraction**													
	Sunflower seed		1.5201			0.5201								
	Electricity (MV)	Z7a		0.0078	2.8347	0.0222	0.93	0.0023	0.0000	1.00				
	NG for steam at 90% eff.	Z6		0.0412	1.1306	0.0465	2.60	0.0082	0.0000	2.79				
	n-hexane	see notes		0.0029	1.1600	0.0033	0.25	0.0000	0.0000	0.25	kg/MJ prod.			
	Sunflower seed cake										-0.0361			
	Soya meal / sunflower seed cake replacement ratio										0.61			
	Credit for sunflower cake	SYML				-0.0779	-5.46	-0.0014	0.0142	-1.43				
	Primary energy consumption and emissions					***0.5142***	*-1.67*	*0.0091*	*0.0143*	***2.60***				
RO4 /SO4	**Raw oil to refined oil**													
	Crude plant oil		1.0417			0.0417								
	Electricity, MV	Z7a		0.0006	2.8347	0.0017	0.07	0.0002	0.0000	0.08				
	NG for steam at 90% eff.	Z6		0.0091	1.1306	0.0103	0.58	0.0018	0.0000	0.62				
	Primary energy consumption and emissions					***0.0537***	*0.65*	*0.0020*	*0.0000*	***0.70***				

RO3 Rapeseed Oil Extraction

Rapeseed is crushed and the oil is extracted with the aid of n-hexane solvent and heat. The WTW data from [*UBA 1999*], [*Groves 2002*] and [*ADEME 2002*] have slightly better yield, with slightly higher inputs. The hexane is a refinery product made almost entirely from crude oil: the other primary energy inputs listed in [*FfE 1997*] have been simplified to crude oil equivalents. In all conversion processes, it is assumed process heat or steam is supplied by a NG boiler working at 90% efficiency.

Rapeseed cake is the by-product: a high-protein animal feed. Farmers decide how much of it to feed to animals on the basis of the protein content. The crude protein content of rapeseed cake (39.6% dry mass) and pure soy bean meal (49% dry mass) is given in [*NRC 1998*]. Therefore one kg rapeseed cake will replace 39.6/49 = 0.80 kg soy bean meal. The process for making 1 kg soy meal is described below. The LHV of plant oil is 36 MJ/kg [*FfE 1998*].

SO3 Sunflower Oil Extraction

A similar process to rapeseed oil extraction: data from [*UBA 1999*]: the oil yield is slightly lower than for rapeseed, so more kg of cake are produced per MJ. However, the sunflower seed cake contains less protein (30% dry matter), so the credit for replacing soy beans meal is smaller.

RO/SO4 Plant Oil Refining

This process, from [*UBA 1999*], uses, in addition to the fossil energy inputs listed, 6 kg fullers' earth per t of plant oil for adsorbing impurities. Fullers' earth is a cheap mineral, with negligible energy input for this quantity. Data are similar to [*Groves 2002*] and [*ADEME 2002*].

Code	**Process**	Assoc. processes	Bio-feed	Expended energy			GHG emissions				Overall energy efficiency	Range		Probability distribution
			MJ bio-en/ MJ prod.	As used MJ/ MJ prod.	MJx/ MJ	Primary MJx/ MJ prod.	g CO2/ MJ prod.	g CH4/ MJ prod.	g N2O / MJ prod.	g CO2eq / MJ prod.		Min	Max	
RO5 /SO5	**Refined oil to FAME: esterification**													
	Refined plant oil		1.0065			0.0065								
	Electricity EU mix, MV	Z6a		0.0029	2.8347	0.0082	0.35	0.0008	0.0000	0.37				
	Methanol	GA1		0.0585	1.6584	0.0969	5.41	0.0171	0.0000	5.81		0.0556	0.0614	
	NG for steam at 90% eff.	Z6		0.0410	1.1306	0.0464	2.59	0.0082	0.0000	2.78		0.0401	0.0430	
	Various other chemicals	see notes				0.0103	0.14	0.0000	0.0000	0.14				
	Primary energy and emissions (no glycerine credit)					0.1683	8.49	0.0261	0.0000	9.09	kg/MJ prod.			
	Glycerine										-0.0028			
5a	Credit for typical chemical replaced by glycerine	C10				-0.0591	-5.95	-0.0070	-0.0002	-6.16				
	Glycerine purification			0.0388	1.1306	0.0439	2.45	0.0077	0.0000	2.63				
	Primary energy consumption and emissions					***0.1531***	*4.98*	*0.0269*	*-0.0001*	***5.56***				
5b	Credit for glycerine replacing wheat grain (LHV basis)	WT1				-0.0061	-0.40	-0.0006	-0.0014	-0.84	0.99	kg/kg dry wheat grain		
	Glycerine purification			0.0388	1.1306	0.0439	2.45	0.0077	0.0000	2.63				
	Primary energy consumption and emissions					***0.2061***	*10.54*	*0.0333*	*-0.0014*	***10.89***				
RO6 /SO6	**Refined oil to FAEE: esterification**													
	Refined plant oil		0.9509			-0.0491								
	Electricity EU mix, MV	Z6a		0.0029	2.8347	0.0082	0.35	0.0008	0.0000	0.37				
	Ethanol	GA1		0.1100	1.5318	0.1685	1.14	0.0028	0.0007	1.42		0.1045	0.1155	
	NG for steam at 90% eff.	Z6		0.0410	1.1306	0.0464	2.59	0.0082	0.0000	2.78		0.0401	0.0430	
	Various other chemicals	see notes				0.0030	0.14	0.0000	0.0000	0.14				
	Primary energy and emissions (no glycerine credit)					0.1770	4.21	0.0118	0.0008	4.71	kg/MJ prod.			
	Glycerine										-0.0026			

6a	Credit for typical chemical replaced by glycerine	C10				-0.0591	-5.95	-0.0070	-0.0002	-6.16				
	Glycerine purification			0.0388	1.1306	0.0439	2.45	0.0077	0.0000	2.63				
	Primary energy consumption and emissions					***0.1618***	*0.70*	*0.0126*	*0.0006*	***1.18***				
6b	Credit for glycerine replacing wheat grain (LHV basis)	WT1				-0.0003	-0.02	0.0000	0.0000	-0.02	0.99	kg/kg dry wheat grain		
	Glycerine purification			0.0388	1.1306	0.0439	2.45	0.0077	0.0000	2.63				
	Primary energy consumption and emissions					***0.2206***	*6.64*	*0.0196*	*0.0008*	***7.31***				
Note: in the case of FAEE methanol is replaced by bio-ethanol from pathway WTET2a. The energy used in this process is deemed to remain the same														

RO/SO5 Esterification (methanol)

The process is the same for rapeseed oil and sunflower seed oil. Plant oil consists of 3 fatty acid chains on a 3-carbon backbone. 3 molecules of methanol combine with the fatty acids to make 3 molecules of fatty acid methyl ester (FAME), leaving their three alcohol groups stuck on the 3-carbon backbone to form glycerine. 0.1 t methanol reacts with 1 t plant oil to make 0.1 t glycerine and 1 t FAME.

Input data are similar to [*Groves 2002*] and [*ADEME 2002*]. The LHV RME is 36.8 GJ/t, that of glycerine is 16.0 GJ/t [JRC calculation] and methanol is 19.9 GJ/t. Methanol is made mostly from natural gas. “Various other chemicals” aggregates the primary energy inputs and emissions fro a list of minor inputs (NaOH, Na_2CO_3, H_3PO_4, HCl) detailed in [*UBA 1999*] and [*GM 2002*].

Two credit calculations are made for glycerine. In RO5a/SO5a it is for a typical chemical product; data for propylene glycol have been found, in [*GEMIS 2002*], which differs from glycerine only by 1 oxygen atom, and is one of many chemicals which glycerine might displace. It uses much less primary energy than synthetic glycerine according to [*GM 2002*], presumably because the data for the latter includes energy for distilling a pharmaceutical-quality product. RO5b/SO5b include a credit for glycerine replacing wheat as an animal feed credit. Glycerine is easily digestible, but there is no numerical data in the literature. It has been assumed that its digestible energy content is 95% of the LHV: the same fraction as for wheat. Then glycerine replaces wheat 1:1 on an LHV basis; the WTW wheat-farming process could be used to calculate the credit.

RO/SO6 Esterification (ethanol)

Same as RO/SO5 replacing methanol by ethanol.

D.12.5 Processes to make materials needed for biomass processing and credit calculations

These processes make ingredients for biofuels. As with other biomass processes, the LHV and fossil C (as CO_2) content of the input fuels have been included in the WTW “MJ primary energy” and CO_2 emissions figures associated with fuels inputs.

Materials needed for biomass processing and credit calculations

Code	Process	Assoc. processes	Input	Expended energy			GHG emissions			
			kg/ kg prod.	As used kWh/ kg prod.	kWhx/ kWh	Primary kWhx/ kg prod.	g CO_2/ kg prod.	g CH_4/ kg prod.	g N_2O/ kg prod.	g CO_2eq/ kg prod.
C6	**Pure CaO for processes**									
	Natural gas	Z6		1.13	1.1306	1.28	257.7	0.8146	0.0001	276.5
	Diesel	Z1		0.05	1.1600	0.05	16.9			16.9
	Electricity (EU-mix, MV)	Z7a		0.02	2.8347	0.05	7.4	0.0179	0.0003	7.9
	CaCO3=CaO+CO2						785.7			785.7
	Primary energy and emissions/kg					***1.38***	*1067.6*	*0.8326*	*0.0004*	***1086.9***
C7	**Sulphuric acid**									
	Electricity (EU mix-MV)	Z7a		0.21	2.8347	0.60	90.7	0.2211	0.0041	97.0
	NG	Z6		0.46	1.1306	0.51	103.4	0.3268	0.0000	110.9
	Primary energy and emissions/kg					***1.11***	*194.1*	*0.5479*	*0.0041*	***207.9***
C8	**Ammonia**									
	NG	Z6		10.9	1.1306	***12.32***	*2323.3*	*4.3077*		***2422.3***
C10	**Propylene glycol (alternative credit for esterification process)**									
	Propylene from crude oil		0.79	2.34		1.84	1500.0	0.9984	0.0263	1530.7
	Electricity (EU mix-MV)	Z7a		1.39	2.8347	3.94	597.3	1.4566	0.0270	638.8
	Primary energy and emissions/kg					***5.78***	*2097.3*	*2.4550*	*0.0533*	***2169.5***

C6 Pure CaO for Processes

Calcium oxide is used for neutralization in SSCF processes and elsewhere. A more pure grade is required than the lime used in agriculture. Another difference is that the carbon dioxide driven off from limestone in the calcining process is not reabsorbed when the product is used for neutralizing sulphuric acid, for example. So, unlike in lime-for-agriculture, the CO_2 emissions from the calcining process should be included. Data from [*GEMIS 2002*].

C7 Sulphuric Acid

Used in SSCF digestion. Data from [*ESU 1996*]. Sulphur mining is neglected

C8 Ammonia

Used in SSCF processes. Data from [*Kadam 1999*].

C10 Propylene Glycol

This is a solvent and antifreeze which could represent the sort of bulk chemical replaced by glycerol from FAME, considering that the extra supply far exceeds the amount of synthetic glycerine still produced The electricity consumption is a preliminary estimate in [*GEMIS 2002*], and this source also gives primary energies for propylene. Propylene is a refinery product: almost all the input energy is from crude oil, but there are minor credits for gas and coke by-products which can be converted to crude-oil equivalents. To convert to MJ, JRC calculated the LHV of propylene; 45.9GJ/tonne, using “HSC for Windows” thermo-chemistry programme. Propylene is a chemical input here, not a fuel being processed. That means its LHV and fossil carbon contents (as CO_2) have been included in its “primary energy and emissions”. This saves having to add them separately when calculating the credit

D.12.6 Soy bean meal production

Code	Process	Assoc. processes	Input	Expended energy			GHG emissions			
			kg/ kg prod.	As used kWh/ kg prod.	kWhx/ kWh	Primary kWhx/ kg prod.	g CO_2/ kg prod.	g CH_4/ kg prod.	g N_2O/ kg prod.	g CO_2eq/ kg prod.
SY3	**Soya bean meal from crushing US beans, per kg bean meal (inc.transport from US)**									
	Electricity (EU mix-MV)	Z7a		0.07	2.8347	0.21	31.8	0.0774	0.0014	34.0
	NG for steam at 90% eff.	Z6		0.38	1.1306	0.43	86.4	0.2730	0.0000	92.7
	n-hexane			0.01	1.1600	0.01	3.9			3.9
	Plant oil by-product credit		-0.23			-0.58	-121.0	-0.3458	-1.0303	-433.9
	Primary energy and emissions/kg					***0.07***	*1.1*	*0.0046*	*-1.0288*	***-303.3***
SYML	**Soya bean meal supply**									
				kg biomass/kg meal						
	Soybeans farming/kg meal	SY1		1.23	0.3807	0.47	120.5	0.0579	0.3819	241.9
	Soyabeans transport/kg meal	SY2		1.23	0.3583	0.44	126.3			126.3
	Soyabean meal from beans crushing	SY3		1.00	0.0726	0.07	1.1	0.0046	-1.0284	-303.2
	Primary Energy and emissions per kg					***0.98***	*247.9*	*0.0625*	*-0.6465*	**65.0**

SY3 Soy bean meal from crushing soy beans

This is a mass-based process which is needed to calculate the credits per kg of protein-rich animal feeds. The overall process comes from [*UBA 1999*].

Hexane (solvent used to increase oil recovery) is an oil-refinery product made almost entirely from crude oil. The primary energy inputs listed in [*Kaltschmitt 1997*] were simplified by converting them to crude oil equivalents.

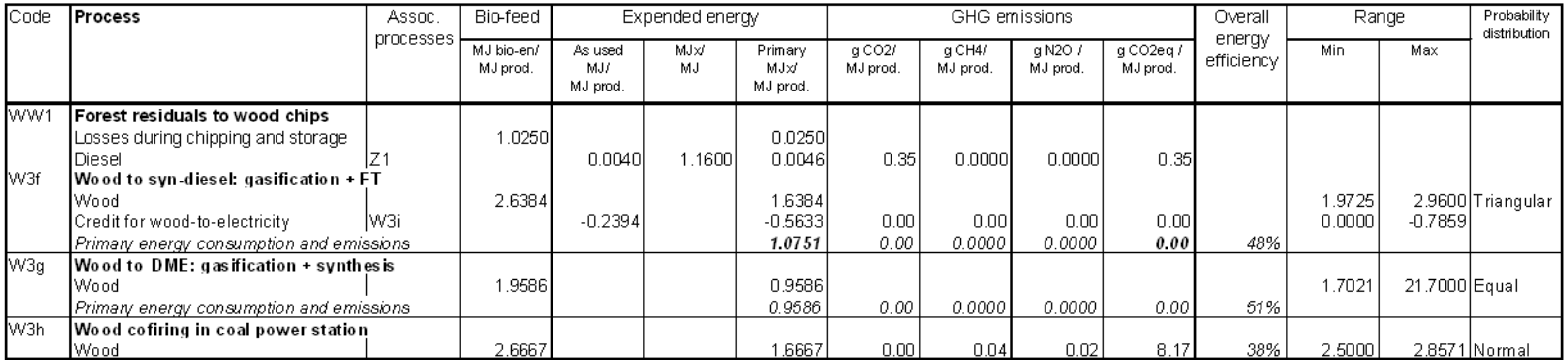
The soy bean oil is treated as a by-product. It attracts an energy and CO_2 credit by substituting rapeseed oil. This is how the credit has been calculated: the energy and emissions for making 1MJ rapeseed oil have been found starting with the energy and emissions from the oil mill (process RO3), and adding (energy and emissions from the rapeseed farming, per MJ rapeseed)*(MJ of rapeseed need to make 1 MJ oil). Then all this has been multiplied by the LHV of plant oil (always around 36 MJ/kg) to find the energy and emissions per kg of oil.

Since rape oil extraction itself has a credit for rapeseed cake, which replaces soy bean meal, there is a ‘loop’. However, this is not a problem (a basic software capable of an iterative calculation to converge on the correct solution is enough to find the solution).

SYML Complete soy bean meal production chain

Soy bean extraction is the last step in the production chain for soy bean meal. Soy bean farming is included with the farming processes and the transport with the transport processes. Following the scenario in [*UBA 1999*], the soy beans are imported from the USA and crushed in EU, where the oil replaces rapeseed oil: there is no transport of soy oil. So now there are all the data needed to link the three together to get the total primary energy and emissions from provision of soy meal.

D.13 Synthetic fuels from farmed wood and wood waste



Code	Process	Assoc. processes	Bio-feed	Expended energy			GHG emissions				Overall energy efficiency	Range		Probability distribution
			MJ bio-en/ MJ prod.	As used MJ/ MJ prod.	MJx/ MJ	Primary MJx/ MJ prod.	g CO2/ MJ prod.	g CH4/ MJ prod.	g N2O / MJ prod.	g CO2eq / MJ prod.		Min	Max	
WW1	**Forest residuals to wood chips**													
	Losses during chipping and storage		1.0250			0.0250								
	Diesel	Z1		0.0040	1.1600	0.0046	0.35	0.0000	0.0000	0.35				
W3f	**Wood to syn-diesel: gasification + FT**													
	Wood		2.6384			1.6384						1.9725	2.9600	Triangular
	Credit for wood-to-electricity	W3i		-0.2394		-0.5633	0.00	0.00	0.00	0.00		0.0000	-0.7859	
	Primary energy consumption and emissions					***1.0751***	*0.00*	*0.0000*	*0.0000*	***0.00***	*48%*			
W3g	**Wood to DME: gasification + synthesis**													
	Wood		1.9586			0.9586						1.7021	21.7000	Equal
	Primary energy consumption and emissions					*0.9586*	*0.00*	*0.0000*	*0.0000*	*0.00*	*51%*			
W3h	**Wood cofiring in coal power station**													
	Wood		2.6667			1.6667	0.00	0.04	0.02	8.17	*38%*	2.5000	2.8571	Normal

WW1 Forest residuals chipping

The branches, tops and roots are stripped from the trunks in the forest: losses of forest residuals during collection and forwarding to the chipper stay in the forest, and are already taken into account in the ratio of residuals to stemwood. The losses which remain are from chip making, handling and storage, due to spillage, evaporation of volatiles, respiration and rotting. The figures (from forestry experts) are more or less in line with those in [*Hamelinck 2002*]. Diesel use by the roadside chipper is from [*Hartmann 1995*]. There are some lower values for different scenarios in the literature, but anyway this energy is insignificant for the whole pathway.

D.14 Synthetic fuels from wood gasification

W3f Synthetic Diesel from Wood

The WTW “best estimate” is based on the study by [*Tijmensen 2002*]. In the variant chosen, syngas from the BCL gasifier (the same as in the 200 MW_{th} hydrogen process) passes cold gas cleaning, a reformer and shift-reactor as in the hydrogen process. An amine process removes the CO_2, and the rest of the syngas enters a fixed-bed Fischer-Tropsch reactor, which builds alkanes from reacting CO and hydrogen on the surface of the catalyst. The reaction conditions are adjusted to maximize the direct production of liquids (gasoil, kerosene and naphtha), which are condensed from the off-gas. Co-products are unreacted gas, LPG vapour and wax. The wax is hydrocracked to make more diesel and naphtha. In the WTW chosen variant, which maximizes diesel yield, up to 2/3 of the unreacted gas (+LPG) is recycled to pass the FT reactor again. The LPG in the recycle does not react: once the alkyl chain is terminated, it cannot be re-opened by the FT catalyst.

The off-gas that is not recycled in the WTW variant is burnt in a condensing combined cycle for process heat and electricity. This produces an excess of electricity, for which a wood credit has been given, using process W3K: electricity from BCL gasifier. This simulates an electricity-neutral process as explained above.

The process yield, efficiency and the product mix depends on the performance of the FT catalyst, which determines the chain growth probability (CGP). [*Tijmensen 2002*] took a range of likely CGP values, because the catalyst performance is difficult to predict. Their average CGP (0.85) has been taken for the WTW best-estimate case.

The composition of the FT liquids condensed after the reactor has to be found from figure 2 of [*Tijmensen 2002*]: about 35% m/m naphtha and 65% m/m middle distillates (= gasoil + kerosene). To this should be added the products of wax cracking. The mass of wax produced is 19% of the FT liquids, and if cracked so as to maximize gasoil, yields 15% of its mass in naphtha and 85% diesel. Bearing in mind also that naphtha has slightly higher LHV than diesel (44.5 vs. 44.0 MJ/kg) the overall product mix turns out to be 68% diesel and 32% naphtha in energy terms.

For the WTW worst-case it has been taken the lowest CGP (0.8) considered by [*Tijmensen 2002*]. Then the overall product mix has been calculated (57% diesel and 43% naphtha in LHV terms). There is a wood credit for electricity as before.

For the WTW best case, no variant in [*Tijmensen 2002*] can match the yield and efficiency (51%) claimed by [*CHOREN 2003*] for a projected biogas-to-liquids process based on the DMT gasifier. The CHOREN process is electrically neutral. They project 100% diesel product. That means all the non-diesel components, which are an inevitable product of the FT reaction, have to be fed back to the gasifier (the FT reactor cannot grow chains which are already terminated). For calculations using W3f a triangular probability distribution drawn between the three cases has been taken.

W3g Wood to DME

DME can be thought of as dehydrated methanol: the only difference between the synthesis processes is in the final catalyst reactor so that the efficiencies are more or less the same.

The WTW “best-case” process is based on [*Katofsky 1993*], using the BCL indirectly-heated gasifier with wet gas cleaning and reforming of higher hydrocarbons. The rest of the process is similar to methanol synthesis from natural gas. A conventional, fixed bed methanol reactor is used. With all fuel synthesis routes, it might be possible to improve efficiency by using slurry reactors or hot gas cleaning. However, neither has been demonstrated for synthesis from bio-syngas: there are question marks about gas quality [*Tijmensen 2002*]. Furthermore, the use of conventional processes enables to compare all routes on a fair basis.

The WTW “worst case” is based on oxygen-blowing the Värnamo autothermal pressurized fluidized bed gasifier, modelled by [*Atrax 1999*]. Although this is a state-of-the art gasifier, it is not as sophisticated and expensive as the BCL gasifier. The process uses the hot gas filtration demonstrated at Värnamo to allow the gas to go hot into the 950°C steam reformer, where some tar is also decomposed. However, after the shift water-gas shift reactor (to boost the H2/CO ratio), it is still necessary to use a scrubbing process to remove impurities (including HCl, H_2S…) before the gas is pure enough for synthesis. In the Altrax process the purification is combined with CO_2 removal by scrubbing with methanol (Rectisol Process). The DME synthesis process (by Haldor Topsoe A/S) is similar to that in the 200 MW plant.

The efficiency is lower than the BCL-gasifier process because of the energy consumption by the oxygen separation plant, and because the H_2/CO ratio in the raw syngas is lower. Again it has been assumed that methanol could be produced at the same efficiency as DME.

D.15 Ethanol from cellulosic biomass (farmed wood, wood waste and straw)

Code	Process	Assoc. processes	Bio-feed	Expended energy			GHG emissions				Overall energy efficiency	Range		Probability distribution
			MJ bio-en/ MJ prod.	As used MJ/ MJ prod.	MJx/ MJ	Primary MJx/ MJ prod.	g CO2/ MJ prod.	g CH4/ MJ prod.	g N2O / MJ prod.	g CO2eq / MJ prod.		Min	Max	
W3j	**Woody biomass to ethanol (SSCF)**										kgex/ MJprod.			
	Biomass input		2.9170			1.9170						2.7550	3.0790	Equal
	Credit for wood-to-electricity	W3a		-0.0995	3.125	-0.3108	0.00	-0.0026	-0.0002	-0.13				
	Diesel	Z1		0.0358	1.160	0.0415	3.13	0.0000	0.0000	3.13				
	H_2SO_4	C7			1.113	0.0142	0.69	0.0019	0.0000	0.74	0.0035			
	NH_3	C8			12.324	0.1205	6.31	0.0117	0.0000	6.58	0.0027			
	$(NH_4)_2SO_4$	C7,C8			3.983	0.0107	0.55	0.0011	0.0000	0.58	0.0007			
	Antifoam	see notes			50.000	0.0776	0.43	0.0000	0.0000	0.43	0.0004			
	Corn Steep Liquor	see notes			0.500	0.0068	0.03	0.0000	0.0000	0.03	0.0038			
	CaO	C6			1.384	0.0068	1.45	0.0011	0.0000	1.47	0.0014			
	Primary energy consumption and emissions					***1.8843***	*12.59*	*0.0133*	*-0.0002*	***12.83***	*35%*			
W3k	**Wheat straw to ethanol (logen)**													
	Straw		2.3770			1.3770					0.4891			
	Transport of straw	WT2b				0.0093	0.22	0.0000	0.0000	0.22				
	Credit for straw-to-electricity	W3a		-0.0520	3.125	-0.1651	0.00	-0.0014	-0.0001	-0.07				
	H_2SO_4	C7			1.113	0.0167	0.81	0.0023	0.0000	0.87	0.0042			
	NH_3	C8			12.324	0.0456	2.39	0.0044	0.0000	2.49	0.0010			
	$(NH_4)_2SO_4$	C7,C8			3.983	0.0040	0.21	0.0004	0.0000	0.22	0.0003			
	Antifoam	see notes			50.000	0.0292	0.16	0.0000	0.0000	0.16	0.0002			
	Corn Steep Liquor	see notes			0.500	0.0025	0.03	0.0000	0.0000	0.03	0.0014			
	CaO	C6			1.384	0.0079	1.70	0.0013	0.0000	1.73	0.0016			
	Debit for additional fertilisers													
	N				13.6591	0.0000	0.00	0.00	0.00	0.00	0.0000			
	P				4.2959	0.0049	0.31	0.00	0.00	0.32	0.0003			
	K				2.7023	0.0164	0.92	0.00	0.00	0.98	0.0017			
						0.0213	1.23	0.0030	0.0000	1.30				
	Primary energy consumption and emissions					***1.3485***	*6.75*	*0.0101*	*-0.0001*	***6.95***	*43%*			

W3j Ethanol from woody biomass; worst/best case

This corresponds to the “base case” of the detailed study by NERL [*Wooley 1999*] on wood-to-ethanol via SSCF (Simultaneous Saccharification and Co-Fermentation). The base case combined the best equipment and processes which were had been demonstrated in 1999. The WTW “best case” is the ”best of industry” case in [*Wooley 1999*], which incorporates the technical advances which could be foreseen to flow from laboratory developments known in 1999. It was not considered that NREL’s more futuristic projections fitted in the time-frame of the WTW study.

Wood consists principally of hemicellulose, cellulose and lignin. Wood chips are ground, steamed and then hydrolysed in dilute sulphuric acid to release the sugars from the hemicellulose. The product is neutralised and detoxified, and part goes to breed enzyme-producing aerobic bacteria with the aid of additional nutrients (such as corn steep liquor). The bacteria-rich stream then joins the main stream in the main fermentor, where enzymatic breakdown of cellulose (saccharification) occurs simultaneously with fermentation of the different sugars released. After several days, the “beer” is sent for distillation. The slops (including lignin) are dried and burnt to raise steam, along with biogas from the waste water treatment. Surplus steam goes to turbine to make electricity.

The NREL process has an excess of electricity. Like the other wood conversion processes, the WTW process is made electricity-neutral by giving a wood credit for the electricity produced. Since this is not a gasifier-based process, it has been calculated the credit using a conventional wood-fired steam turbine condensing power station, based on LBST data from the plant at Altenstadt, Germany (see wood-to-electricity processes).

The processes to make the input chemicals are described above (sec. D.9), with two exceptions, for which no quantitative data could not have been found: corn steep liquor (CSL) and antifoam. CSL is a by-product from corn syrup manufacture, used as a culture medium for bacteria, and as animal feed. Usually it is neglected in LCA studies. To check if it could be significant, a (MJ primary energy input)/ (MJ digestible energy) ratio the same as wheat has been given. This confirmed that it could have been neglected. Antifoam is a simple silicone compound. Instead of neglecting it *a priori* a primary energy per kg typical of a process chemical has been attributed, which showed it to be of no unimportant in the energy balance.

W3k Ethanol from straw

Data for a 150 MW straw-to-ethanol SSCF plant was supplied to the study by Iogen corp., who operate a commercial plant for straw to ethanol in Iowa [*Iogen 2003*]. A biomass credit is given for electricity export again based on the Altenstadt wood-burning power station (the straw-burning power plant at Sanguesa in Spain has a similar efficiency). Of the chemicals inputs, Iogen only specified sulphuric acid consumption, which is lower than for the wood-to-ethanol process because of a more favourable composition. It has been assumed that the other chemicals (e.g. for neutralization) mentioned by [*Wooley 1999*] are also needed by the straw process, in proportion to the lower sulphuric acid requirements.

The yield calculation applied to wood gives about the wood-to-ethanol yields claimed in [*Wooley 1999*]. Furthermore, the same procedure has been used for the straw-to-SSCF part of process, and came up with energy and emissions figures almost the same as for a commercial state-of-the art straw-to-ethanol process.

The distillation steps and possibly fermentation steps could be combined with the main process: however, for the sake of energy calculation the processes are kept separate. The first paragraph shows that to get 1 MJ ethanol from the combined process 0.198/(1+0.198) = 0.165 MJ are needed from the new pulp-to SSCF process (without pulp credits), and 0.835 MJ from the conventional sugar-beet process.

D.15.1 Synthetic fuels from waste wood via Black Liquor

Code	**Process**	Assoc. processes	Bio-feed	Expended energy			GHG emissions				Overall energy efficiency	Range		Probability distribution
			MJ bio-en/ MJ prod.	As used MJ/ MJ prod.	MJx/ MJ	Primary MJx/ MJ prod.	g CO2/ MJ prod.	g CH4/ MJ prod.	g N2O / MJ prod.	g CO2eq / MJ prod.		Min	Max	
BLH	**Wood waste to hydrogen via black liquor**													
	Wood waste		1.2410			0.2410						1.1790	1.3031	Equal
	Primary energy consumption and emissions					***0.2410***	*0.00*	*0.0000*	*0.0000*	***0.00***	*81%*			
BLD	**Wood waste to DME via black liquor**													
	Wood waste		1.4851			0.4851						1.4108	1.5594	Equal
	Primary energy consumption and emissions					***0.4851***	*0.00*	*0.0000*	*0.0000*	***0.00***	*67%*			
BLM	**Wood waste to methanol via black liquor**													
	Wood waste		1.5180			0.5180						1.4421	1.5939	Equal
	Primary energy consumption and emissions					***0.5180***	*0.00*	*0.0000*	*0.0000*	***0.00***	*66%*			
BLS	**Wood waste to syn diesel via black liquor**													
	Wood waste		1.8280			0.8280						1.7366	1.9194	Equal
	Primary energy consumption and emissions					***0.8280***	*0.00*	*0.0000*	*0.0000*	***0.00***	*55%*			

Wood waste to DME via black liquor gasification

Black liquor is the residue of the pulp making process: a water-based slurry, 70 to 80% of which consists of lignin and spent pulping chemicals. In conventional pulp mills it is burned in a so-called "recovery boiler" to provide process heat; boiler efficiency is limited to about 65% because of the corrosive nature of the molten salts present (mostly Na_2S and Na_2CO_3). With the addition of steam from a “hog boiler” burning bark and other wood waste produced on site, a modern pulp mill is self-sufficient in heat, and can even export some electricity.

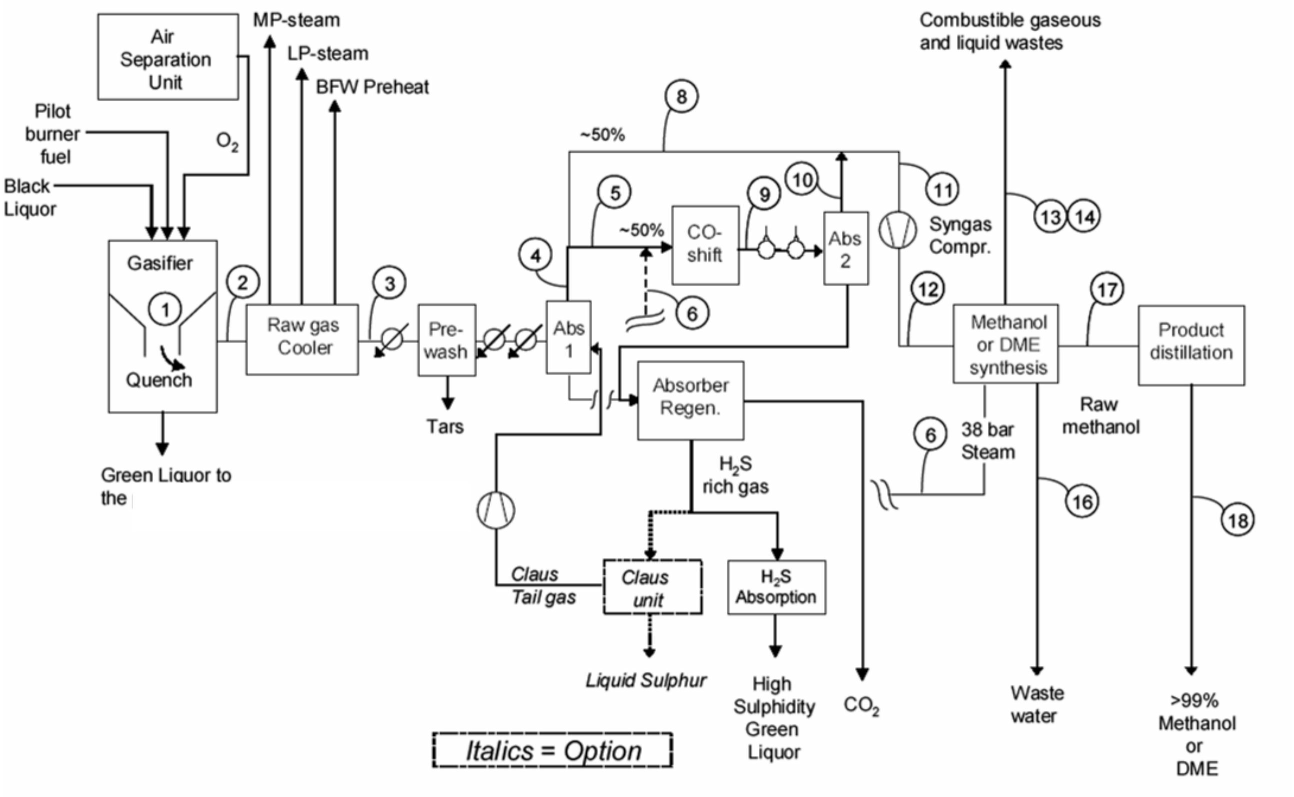
For “black liquor gasification for motor fuels” (BLGMF), one gasifies the black liquor instead of burning it in a recovery boiler. The gasifier is oxygen-blown, so an air separation unit is needed. The syngas produced is then transformed to motor fuel. As part of the energy content of the black liquor ends up in the fuel, additional heat is needed for the pulping process. This is provided by increasing the amount of biomass fed to the hog boiler. The cheapest source of extra biomass is forest residuals (branches, tops, undersize trees and occasionally roots), which can be collected at the time of felling and brought to the pulp mill using the same transport infrastructure as the stem-wood.

Taking the original pulp mill as reference, and adjusting the new process to give the same pulp production and electricity balance, one can calculate the extra wood residuals required to produce a given amount of road-fuel. This effective efficiency turns out to be appreciably higher than that of a stand-alone gasifier conversion processes. The reason is that the additional burning of forest residuals increases the thermal capacity of the plant, whilst the stack losses are reduced because the hog-fuel boiler has higher efficiency than the replaced recovery boiler. Almost all the heat from the syngas is recovered.

The WTW data are from the thorough technical and commercial feasibility study of DME production via black liquor gasification carried out for DG-TREN’s ALTENER programme [*Ekbom 2003*]. The study first modelled a modern reference pulp mill (“KAM2” model mill), recycling all wood wastes produced in the mill, but not importing residuals from the forest. This is self-sufficient in heat, and produces a small electricity surplus from a condensing steam turbine generator. Production capacity is 2000 dry tonnes pulp per day. Then [*Ekbom 2003*] model the BLGMF plant also self-sufficient on heat and with the same pulp production and electricity export. The electricity is also produced by a condensing steam turbine, even though higher efficiencies could be obtained from an advanced combined cycle generator incorporating a gas turbine. The difference between the BLGMF model and the KAM2 reference mill showed that 272.8 MW methanol would be produced with an additional biomass consumption of 414.1 MW biomass. Thus 1 MJ methanol requires 1.518 MJ biomass, and the energy conversion efficiency is 65.9%. For the process producing DME, which differs from the methanol process only in the catalyst and conditions in the final synthesis stage, 275 MW DME are produced from 408 MW biomass, so **1 MJ methanol requires 1.485 MJ biomass, a conversion efficiency of 71**%. A ±5% error range has been added to these figures.

[*Ekbom 2003*] also provides estimates of the incremental plant investment, assuming that the recovery boiler in the pulp mill was anyway due for replacement. Their estimates of 150.3 M€ for the methanol plant and 164.2 M€ for the DME plant in the WTW costing calculations have been used.

Figure D. 1:*Schematic process flow diagram of the BLGMF-methanol plant, reproduced with permission from [Ekbom 2003]*



Wood waste to FT via black liquor gasification

A calculation of this efficiency has been made by replacing the methanol synthesis in [*Ekbom 2003*] with the FT process described in [*Shell 1990*]. The process uses stream 11 in Figure D. 1. The FT process consists of an FT synthesis step in which hydrocarbons are grown on catalysts by the reaction of CO and hydrogen. To get a high diesel yield and little unreacted gas, FT synthesis is allowed to continue to produce heavy hydrocarbons, which are then cracked downstream in a hydrogen cracker. Nevertheless, a distribution of hydrocarbons is produced. [*Shell 1990*] does not specify the distribution of <C10, so this had to model it from chain growth statistics, in order to calculate the energy balance. The Shell process yields about 77 % m/m C10-C20 products (diesel+kerosene; usable in diesel engines) and 23% naphtha on either energy or mass basis. Compared to the reference pulp mill, the whole BGLF-FT process produces 194 MW C10-C20 hydrocarbons and 59.1 MW naphtha from 414 MW extra biomass. Thus 1 MJ extra biomass would produce a total of 0.47 MJ of kerosene/diesel mixture together with 0.14 MJ naphtha (<C9).

If one wishes to produce only diesel and kerosene (to compare with the claims for the Choren wood-FT process, for example), the other products must be recycled. It has been assumed that the naphtha is added to the hog boiler to produce electricity. To keep the electricity generation the same as the reference pulp plant, the same MJ of biomass should be removed. Therefore only 0.86 MJ biomass are needed to make 0.47 MJ kerosene/diesel by itself. Thus the **efficiency to kerosene/diesel is 55% and 1.83 MJ biomass are needed to make 1 MJ kerosene/diesel.**

Before this report was finalized, [*Ekbom 2005*] produced their own, more detailed, calculation of FT-diesel efficiency using BLGMF process, incorporating product fractionation. It is difficult to compare the WTW model with theirs, because they calculated product mixtures from fractionation rather than simply assigning carbon numbers. Their results indicate that each 1MJ extra biomass would produce 0.43 MJ diesel-quality distillate together with 0.22 MJ naphtha. If the same credit for recycling the naphtha is performed as for the WTW calculation above, it could be deduced that an extra 0.78 MJ biomass in the pulp mill would give 0.43 MJ diesel-quality distillate. That corresponds to an efficiency to diesel fuel of 55%: exactly the same as in the WTW calculation. Such close agreement is fortuitous, but is an independent confirmation.

The consortium estimated that the incremental cost of installing a BLGMF-FT plant in a pulp mill which needs a new recovery boiler would be about 260 M€ ±20%. Subsequently, [*Ekbom 2005*] estimated the figure to be 205 M€. Considering that this is the cost of the new plant minus 171 M€, representing the saved cost of a new recovery boiler, the difference between the two estimates of the cost of a BLGMF-FT plant is only 13%.

D.16 Synthetic fuels distribution and dispensing (all sources)

Code	**Process**	Assoc. processes	Expended energy	GHG emissions				Transport requirement			Range		Probability distribution
			MJx/ MJ prod.	g CO_2/ MJ prod.	g CH_4/ MJ prod.	g N_2O/ MJ prod.	g CO_2eq/ MJ prod.	km or Naut. Miles	MJx/ t.km	t.km/ MJ prod.	Min	Max	
DS1	**Syn diesel handling and loading (remote)**												
	Energy as Electricity (on-site generation)	GG2	0.0008										
	Primary energy consumption and emissions		*0.0015*	*0.08*	*0.0000*	*0.0000*	*0.09*						
DS2	**Syn diesel sea transport**												
	Distance (nautical miles)							5500			5000	6000	
	Energy requirement as HFO for product carrier									0.2315	0.2105	0.2525	Square
	Primary energy consumption and emissions	*0.00*	*0.0312*	*2.50*			*2.50*				*0.0284*	*0.0341*	
DS3	**Syn diesel depot**												
	Electricity (EU-mix, LV)	Z7b	0.0008										
	Primary energy consumption and emissions		*0.0024*	*0.36*	*0.0009*	*0.0000*	*0.38*						
DS4	**Syn diesel distribution (blending component**	CD2/3/4	See conventional diesel processes										
DS5	**Syn diesel distribution (neat)**												
	Distance, Rail	Z5, Z7a						250		0.0057			
	Distance, road	Z2, Z1						250		0.0061			
	Primary energy consumption and emissions												
DS5a	*Rail+Road*		*0.0100*	*0.6413*	*0.0003*	*0.0000*	*0.65*						
DS5b	*Road only*		*0.0066*	*0.4995*	*0.0004*	*0.0000*	*0.51*						

DS1Synthetic diesel loading and handling (remote)

This represents the energy required to store, handle and load the synthetic diesel near its (remote) production site. The assumed electricity consumption is that of a standard conventional diesel depot (see process CD3). This process (and the next one), are only relevant to GTL plants inasmuch as diesel from biomass is unlikely to be transported across large distances. The source of electricity is here deemed to be the gas-fired power plant part of the GTL complex (process GG2).

DS2Synthetic diesel sea transport

Synthetic diesel can be transported in essentially standard product carriers (see process Z4). The distance considered here is typical of a trip from the Arab gulf to North West Europe (via Suez). The energy figure includes an allowance for the return trip.

DS3Synthetic diesel depot

This is the same process as CD3. This energy is deemed to be spent at a receiving terminal.

DS4Synthetic diesel distribution (blending component)

Synthetic diesel is a valuable blending component for modern diesel and the limited quantities available are most likely to be used as such. In this case the product will enter the refinery system near the point of production. The applicable processes are thus the same as for conventional diesel (CD2/3/4).

DS5a/b Synthetic diesel distribution (neat)

The use of neat synthetic diesel in niche applications cannot be ruled out. Transport of neat synthetic diesel within Europe can be envisaged either by road, rail or a combination of both. The limited volumes involved would make pipeline transportation inappropriate. Two scenarios have been considered depending on the synthetic diesel source. Material imported from remote plants would have to be transported from a small number of ports for which an average distance of 500 km (split 50/50 between rail and road) has been considered. Material manufactured within Europe would be more “distributed” and a distance of 250 km (road) has been considered as appropriate. The transport mode parameters are in accordance with processes Z5 and Z2.

Code	**Process**	Assoc. processes	Expended energy	GHG emissions				Transport requirement			Range		Probability distribution
			MJx/ MJ prod.	g CO_2/ MJ prod.	g CH_4/ MJ prod.	g N_2O/ MJ prod.	g CO_2eq/ MJ prod.	km or Naut. Miles	MJx/ t.km	t.km/ MJ prod.	Min	Max	
DE1	**DME handling and loading (remote)**												
	Energy as Electricity (on-site generation)	GG2	0.0013										
	NG consumption and emissions		0.0024	0.13	0.0000	0.0000	0.13						
DE2	**DME sea transport**												
	Distance (nautical miles)			gCO2/tkm				5500		0.358	0.326	0.391	Normal
	Energy to DME carrier (as HFO)	Z3		13.11					0.163				
	Primary energy consumption and emissions		*0.06343*	*5.09*			*5.09*						
DE3	**DME depot**												
	Electricity (EU-mix, LV)	Z7b	0.0013										
	Primary energy consumption and emissions		*0.0037*	*0.56*	*0.0014*	*0.0000*	*0.59*						
DE4a	**DME distribution and dispensing**												
	Distance, Rail	Z5, Z7a						250		0.0088			
	Distance, road	Z2, Z1						250		0.0123			
	Filling station, Electricity (EU-mix, LV)	Z7b	0.0034										
	Primary energy consumption and emissions												
DE4a	*Rail+Road*		*0.0284*	*1.64*	*0.0015*	*0.0000*	*1.68*						
DE4b	*Road only*		*0.0231*	*1.42*	*0.0010*	*0.0000*	*1.45*						

ME1 station energy requirement is inferred from the gasoline figure (see process CG4).

DE1-4 DME distribution and dispensing

These processes are similar to those for methanol with figures adapted to DME which is transported in compressed liquid form. DME is deemed to be carried on a ship similar to an LPG carrier [*Kawasaki 2000*]. The road tanker is assumed to transport 2 t of DME in a 20 t tank.

D.17 Bio-fuels distribution

Code		Assoc processes	one-way distance km	t.km/ MJ prod.	MJ/ MJ prod.	MJx/ MJ	MJx/ MJ prod.	g CO_2/ MJ prod.	g CH_4/ MJ prod.	g N_2O/ MJ prod.	g CO_2eq/ MJ prod.	Loss MJ/MJ
ETd	**Ethanol distribution (blended)**											
	Road tanker to gasoline depot	Z1,Z2	150	0.022	0.0056	1.1600	0.0065	0.49			0.49	
	Gasoline depot (elect. EU-mix, LV)	CG3, Z7b			0.0024	2.8687	0.0069	0.29	0.0007	0.0000	0.31	
	Road tanker to filling station	Z1,Z2	150	0.022	0.0056	1.1600	0.0065	0.49			*0.49*	
	Filling station	CG4, Z7b			0.0034	2.8687	0.0098	0.41	0.0010	0.0000	*0.44*	
	Primary energy consumption and emissions						***0.0298***	*1.69*	*0.0017*	*0.0000*	***1.74***	
FAd	**Bio-diesel distribution (blended)**											
	FAME road tanker to diesel depot	Z1,Z2	150	0.004	0.0041	1.1600	0.0047	0.36	0.0000	0.0000	0.36	
	Diesel depot (elec. EU-mix, LV)	CD3, Z7b			0.0024	2.8687	0.0069	0.29	0.0007	0.0000	0.31	
	Road tanker to filling station	Z1,Z2			0.0041	1.1600	0.0047	0.36	0.0000	0.0000	0.36	
	Filling station	CD4, Z7b			0.0034	2.8687	0.0098	0.41	0.0010	0.0000	0.44	
	Primary energy consumption and emissions						***0.026***	*1.41*	*0.0017*	*0.0000*	***1.46***	
MEd	**Biomethanol distribution direct from plant**											
	Methanol road tanker	Z1,Z2	150	0.008	0.0076	1.16	0.009	0.67	0.0000	0	0.67	
	Filling station, Electricity (EU-mix, LV)	Z7b			0.0034	2.87	0.010	0.41	0.0010	0.0000	0.44	
	Primary energy consumption and emissions						***0.019***	*1.08*	*0.0010*	*0.0000*	***1.10***	
DEd	**Bio-DME distribution direct from plant**											
	DME road tanker	Z1,Z2	150	0.007	0.0069	1.16	0.008	0.61	0.0000	0	0.61	
	Filling station, Electricity (EU-mix, LV)	Z7b			0.0034	2.87	0.010	0.41	0.0010	0.0000	0.44	
	Primary energy consumption and emissions						***0.018***	*1.02*	*0.0010*	*0.0000*	***1.04***	
SDd	**Bio-(synthetic diesel) distribution (blended)**											
	Road tanker to diesel depot	Z1,Z2	150	0.004	0.0034	1.16	0.004	0.30	0.0000	0	0.30	
	Diesel depot (elec. EU-mix, LV)	CD3, Z7b			0.0008	2.87	0.002	0.10	0.0002	0.0000	0.11	
	Road tanker to filling station	Z1,Z2	150	0.004	0.0034	1.16	0.004	0.30	0.0000	0.0000	0.30	
	Filling station	CD4, Z7b			0.0034	2.87	0.010	0.41	0.0010	0.0000	0.44	
	Primary energy consumption and emissions						***0.020***	*1.11*	*0.0012*	*0.0000*	***1.15***	

The energy for biofuel distribution is not very important to the overall pathway. Ethanol and FAME, and synthetic diesel are blended with fossil fuels, so they are transported to the appropriate depot, and then distributed like fossil fuel. DME is identical to the fossil products and could be distributed directly to local filling stations.

E Description and detailed energy and GHG balance of individual pathways

This appendix gives the detailed results of the energy and GHG balance for all pathways. Pathways new to this version have been highlighted in yellow.

It details the processes included in each pathway (discussed in Appendix D) and gives the resulting energy and GHG balance for the total pathway as well as the contribution of each of the main stages.

Energy figures are expressed as net energy *expended* (MJ_x) (i.e. excluding the energy transferred to the final fuel) per MJ energy content of the final fuel (MJ_f). “Total primary” refers to all energy regardless of the primary energy source, i.e. including renewable energy. The portion of this total energy that comes from fossil sources is given in the “fossil” column.

Note*: the use of the EU-mix electricity as a generic power source for e.g. transport or operation of refuelling stations introduces a small amount of renewable energy in most pathways.*

The best estimate and the range of variability are given for both energy and GHG. The ranges are obtained via a Monte Carlo simulation combining the range of variation of individual processes (see Appendix D). The minimum value is taken as P20 (20% of observed values will be below that value) and the maximum as P80. The range of energy variation is also indicated for those steps that make a significant contribution.

In order to facilitate comparison of pathways of a different nature the final table regroups the actual processes into five standard stages namely

Stage 1: Production and conditioning at source

Includes all operations required to extract, capture or cultivate the primary energy source. In most cases, the extracted or harvested energy carrier requires some form of treatment or conditioning before it can be conveniently, economically and safely transported.

Stage 2: Transformation at source

Is used for those cases where a major industrial process is carried out at or near the production site of the primary energy (e.g. gas-to-liquids plant).

Stage 3: Transportation to EU

Is relevant to energy carriers which are produced outside the EU and need to be transported over long distances. This step is also used where a significant transport vector is required to move the raw material to a processing plant (e.g. biomass).

Stage 4: Transformation in EU

Includes the processing and transformation that takes place near the market place in order to produce a final fuel according to an agreed specification (e.g. oil refineries or hydrogen reformers).

Stage 5: Conditioning and distribution

Relates to the final stages required to distribute the finished fuels from the point of import or production to the individual refuelling points (e.g. road transport) and available to the vehicle tank (e.g. compression in the case of natural gas).

E.1 Conventional fuels

Pathway code		**COD**	**COG**	**CON**
		1	**1**	**1**
Code	Process			
Crude oil				
CO1	Crude oil production	✓	✓	✓
CO2	Crude oil transportation	✓	✓	✓
CD1	Crude oil refining, marginal diesel	✓		
CD2	Diesel transport	✓		
CD3	Diesel depot	✓		
CD4	Diesel distribution and dispensing	✓		
CG1	Crude oil refining, marginal gasoline		✓	
CG2	Gasoline transport		✓	
CG3	Gasoline depot		✓	
CG4	Gasoline distribution and dispensing		✓	
Common processes				
Z1	Diesel production	✓	✓	✓
Z2	Road tanker	✓	✓	✓

COG1 Crude oil to gasoline

COD1 Crude oil to diesel

The gasoline and diesel fuel pathways are the reference against which all others need to be evaluated.

		Standard step	Energy consumed (MJx/MJf)				Net GHG emitted (g CO_2eq/MJf)			Individual GHG		
			Total primary			Fossil						
			Best est.	min	Max		Best est.	min	Max	g CO_2/MJ	g CH_4/MJ	g N_2O/MJ
COG1	**Crude oil to gasoline**											
	Crude Extraction & Processing	1	0.03	0.01	0.04		3.6			3.6	0.00	0.000
	Crude Transport	3	0.01				0.9			0.9	0.00	0.000
	Refining	4	0.08	0.06	0.10		7.0			7.0	0.00	0.000
	Distribution and dispensing	5	0.02				1.0			1.0	0.00	0.000
	Total pathway		**0.14**	0.12	0.17	**0.14**	**12.5**	11.1	14.6	12.5	0.00	0.000
COD1	**Crude oil to diesel**											
	Crude Extraction & Processing	1	0.03	0.01	0.04		3.7			3.7	0.00	0.000
	Crude Transport	3	0.01				0.9			0.9	0.00	0.000
	Refining	4	0.10	0.08	0.12		8.6			8.6	0.00	0.000
	Distribution and dispensing	5	0.02				1.0			1.0	0.00	0.000
	Total pathway		**0.16**	0.14	0.18	**0.16**	**14.2**	12.6	16.0	14.2	0.00	0.000

E.2 Compressed gas from biomass (CBG)

Pathway code		**OWCG**		
		1	**2**	**3**
Code	Process			
Biogas				
BG1a	Liquid manure transport, 10 km		✓	
BG1b	Dry manure transport, 10 km			✓
BG2a	Municipal waste to biogas (upgraded)	✓		
BG2b	Liquid manure to biogas (upgraded)		✓	
BG2c	Dry manure to biogas (upgraded)			✓
BG3a	Municipal waste to electricity (small scale, local)	✓		
BG3b	Liquid manure to electricity (small scale, local)		✓	
BG3c	Dry manure to electricity (small scale, local)			✓
NG distribution				
GG4	NG local distribution	✓	✓	✓
GG5	CNG dispensing (compression 0.4-25 MPa)	✓	✓	✓
Common processes				
Z7a	Electricity (EU-mix, MV)	✓	✓	✓
Z7b	Electricity (EU-mix, LV)	✓	✓	✓

OWCG1 Municipal waste to CBG

Municipal waste, already collected is turned into biogas. The biogas is treated and upgraded before being fed into an existing NG grid to be used as automotive fuel.

OWCG2/3 Municipal waste to CBG

Liquid or dry manure is collected from farms and turned into biogas in a central plant serving a small community. The biogas is treated and upgraded before being fed into an existing NG grid to be used as automotive fuel.

		Standard step	Energy consumed (MJx/MJf)				Net GHG emitted (g CO_2eq/MJf)			CO_2	CH4	N_2O
			Total primary			Fossil						
			Best est.	min	Max		Best est.	min	Max	g/MJ	g/MJ	g/MJ
OWCG1	**CBG: municipal waste**											
	Production, treating and upgrading	4	0.81				32.31			-51.9	0.45	-0.006
	Distribution (pipeline)	5	0.00				0.00			0.0	0.00	0.000
	Refuelling station	5	0.06				2.85			2.7	0.01	0.000
	Total WTT GHG emitted						**35.2**	32.6	37.9	-49.2	0.46	-0.006
	Credit for renewable combustion CO_2						-75.5			-75.5		
	Total pathway		**0.87**	0.73	1.01	**0.17**	**-40.4**	-42.9	-37.7			
OWCG2	**CBG: liquid manure**											
	Manure transport	3	0.03				-86.92			2.1	-3.87	0.000
	Production, treating and upgrading	4	0.88				25.83			16.2	0.47	-0.004
	Distribution (pipeline)	5	0.00				0.00			0.0	0.00	0.000
	Refuelling station	5	0.06				2.85			2.7	0.01	0.000
	Total WTT GHG emitted						**-58.3**	-81.6	-28.5	21.0	-3.39	-0.004
	Credit for renewable combustion CO_2						-75.5			-75.5		
	Total pathway		**0.97**	0.79	1.12	**0.03**	**-133.8**	-157.1	-104.0			
OWCG3	**CBG: dry manure**											
	Manure transport	3	0.01				-8.22			0.7	-0.39	0.000
	Production, treating and upgrading	4	0.88				25.83			16.2	0.47	-0.004
	Distribution (pipeline)	5	0.00				0.00			0.0	0.00	0.000
	Refuelling station	5	0.06				2.85			2.7	0.01	0.000
	Total WTT GHG emitted						**20.5**	17.2	23.3	19.6	0.09	-0.004
	Credit for renewable combustion CO_2						-75.5			-75.5		
	Total pathway		**0.95**	0.77	1.11	**0.01**	**-55.1**	-58.3	-52.2			

E.3 Ethanol

		S. beet		Wheat								S. cane	Straw			Wood waste via BL	
Pathway code		**SBET**		**WTET**								**SCET**	**STET**	**WFET**	**WWET**	**BLCH**	**BLME**
		1	**3**	**1a**	**1b**	**2a**	**2b**	**3a**	**3b**	**4a**	**4b**	**1**	**1**	**1**	**1**	**1**	**1**
Code	Process																
Farming																	
SB1	Sugar Beet Farming	✓	✓														
WT1	Wheat farming			✓	✓	✓	✓	✓	✓	✓	✓						
SC1	Sugar cane farming (Brazil)											✓	✓				
Crop transport and processing																	
SB2	Sugar beet road transport	✓	✓														
SB3a	Sugar beet to ethanol, pulp and slops to animal feed	✓															
SB3c	Sugar beet to ethanol, pulp and slop to biogas		✓														
WT2a	Wheat grain road transport			✓	✓	✓	✓	✓	✓	✓	✓						
WT2b	Wheat straw road transport									✓	✓		✓				
WT3	Wheat grain handling and drying (to dwg, 3%			✓	✓	✓	✓	✓	✓	✓	✓						
WT4a	Wheat grain to ethanol, conventional boiler			✓	✓												
WT4b	Wheat grain to ethanol, NG CCGT					✓	✓										
WT4c	Wheat grain to ethanol, Lignite CHP							✓	✓								
WT4d	Wheat grain to ethanol, Straw CHP									✓	✓						
WTDa	Credit for DDGS as animal feed			✓		✓		✓		✓							
WTDb	Credit for DDGS as fuel				✓		✓		✓		✓						
W3k	Wheat straw to ethanol (Iogen)												✓				
SC2	Sugar cane road transport											✓					
SC3	Sugar cane to ethanol											✓					
SC4	Sugar cane ethanol from Brazil											✓					
Wood (farmed)																	
WF1	Wood farming and chipping													✓			
Wood (waste)																	
WW1	Forest residuals to wood chips														✓	✓	✓
Wood transport & processing (all sources)																	
WC2a	Wood chips road transport, 50 km													✓	✓	✓	✓
WC2c	Coastal/river shipping wood ships (200MW plant)														✓		
W3j	Woody biomass to ethanol (SSCF)													✓	✓		
Biofuels transport & distribution																	
ETd	Ethanol distribution (blended)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Common processes																	
Z1	Diesel production	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Z2	Road tanker	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓

SBET1/3 Sugar beet to ethanol

Two alternatives use for the pulp and slop by-products are described, namely animal feed and conversion to biogas for cogeneration.

		Standard step	Energy consumed (MJx/MJf)				Net GHG emitted (g CO_2eq/MJf)			CO_2	CH4	N_2O
			Total primary			Fossil						
			Best est.	min	Max		Best est.	min	Max	g/MJ	g/MJ	g/MJ
SBET1	**EtOH from sugar beet, animal feed export**											
	Cultivation	1	0.16				20.83			10.5	0.01	0.034
	Road transport	3	0.03				2.12			2.1	0.00	0.000
	Ethanol plant	4	1.64				33.00			35.0	0.11	-0.016
	Ethanol road transport, 150 km	5	0.02				1.10			1.1	0.00	0.000
	Refuelling station	5	0.01				0.44			0.4	0.00	0.000
	Total WTT GHG emitted						**57.5**	54.3	61.0	49.1	0.13	0.018
	Credit for renewable combustion CO_2						-71.4			-71.4		
	Total pathway		**1.86**	1.74	1.99	**0.87**	**-13.9**	-17.1	-10.4			
SBET3	**Ethanol from Sugar beet, pulp to heat**											
	Cultivation	1	0.16				20.83			10.5	0.01	0.034
	Road transport	3	0.03				2.12			2.1	0.00	0.000
	Ethanol plant	4	1.08				5.20			4.9	0.01	0.000
	Ethanol road transport, 150 km	5	0.02				1.10			1.1	0.00	0.000
	Refuelling station	5	0.01				0.44			0.4	0.00	0.000
	Total WTT GHG emitted						**29.7**	27.0	31.6	19.0	0.03	0.034
	Credit for renewable combustion CO_2						-71.4			-71.4		
	Total pathway		**1.30**	1.18	1.42	**0.31**	**-41.7**	-44.4	-39.8			

WTET Wheat grain to ethanol

The first version of the study only considered a single pathway depicting a production plant with a conventional steam boiler and imported electricity. DDGS was deemed to be used as animal feed. More variants have now been incorporated based on the work done in the framework of the UK's Low carbon Vehicle Partnership [*LowCVP 2004*].

1a/b This is the conventional process where heat for the ethanol plant is provided by a NG-fired steam boiler and electricity is imported from the grid. DDGS is used as either as animal feed (a) or as co-fuel in a coal power station (b). The straw is not used and assumed to be ploughed back into the field (the fertiliser inputs are adjusted accordingly).

2a/b The energy to the ethanol plant is provided by a NG-fired CCGT sized to provide the required heat. Surplus electricity is produced and exported, which generates a credit calculated by comparison to a state-of-the-art stand-alone NG-fired CCGT (the benefit stems from the use of CHP in the ethanol plant). DDGS is used either as animal feed (a) or as co-fuel in a coal power station (b). Although option b is more favourable from an energy point of view, option a is likely to be preferred for economic reasons. The straw is not used (see 1a).

3a/b The energy for the ethanol plant is provided by a lignite (or brown coal) -fired CHP power plant sized to provide the required heat. Surplus electricity is produced and exported, which generates a credit calculated by comparison to a state-of-the-art stand-alone lignite power plant (the benefit stems from the use of CHP in the ethanol plant). Both DDGS use options are presented (see 3a/b) and straw is not used (see 1a).

4a/b The energy for the ethanol plant is provided by a straw-fired CHP power plant sized to provide the required heat. Surplus electricity is produced and exported, which generates a credit calculated by comparison to a state-of-the-art stand-alone straw power plant (the benefit stems from the use of CHP in the ethanol plant). The fertiliser inputs are adjusted to compensate fort the lost of soil nutrients from straw. Both DDGS use options are presented (see 3a/b).

		Standard step	Energy consumed (MJx/MJf)				Net GHG emitted (g CO$_2$eq/MJf)			CO$_2$	CH4	N$_2$O
			Total primary			Fossil						
			Best est.	min	Max		Best est.	min	Max	g/MJ	g/MJ	g/MJ
WTET1a	**Ethanol from Wheat, Conv NG boiler, DDGS as animal feed**											
	Cultivation	1	0.24				31.92			14.3	0.03	0.058
	Road transport	3	0.03				0.54			0.5	0.00	0.000
	Ethanol plant	4	1.49				25.17			32.2	0.10	-0.031
	Ethanol road transport, 150 km	5	0.02				1.10			1.1	0.00	0.000
	Refuelling station	5	0.01				0.44			0.4	0.00	0.000
	Total WTT GHG emitted						**59.2**	51.8	67.2	48.5	0.13	0.026
	Credit for renewable combustion CO$_2$						-71.4			-71.4		
	Total pathway		**1.78**	1.76	1.80	**0.89**	**-12.2**	-19.6	-4.1			
WTET1b	**Ethanol from Wheat, Conv NG boiler, DDGS as fuel**											
	Cultivation	1	0.24				31.92			14.3	0.03	0.058
	Road transport	3	0.03				0.54			0.5	0.00	0.000
	Ethanol plant	4	1.02				16.54			15.7	0.04	0.000
	Ethanol road transport, 150 km	5	0.02				1.10			1.1	0.00	0.000
	Refuelling station	5	0.01				0.44			0.4	0.00	0.000
	Total WTT GHG emitted						**50.5**	43.7	57.2	32.0	0.07	0.057
	Credit for renewable combustion CO$_2$						-71.4			-71.4		
	Total pathway		**1.30**	1.28	1.33	**0.44**	**-20.8**	-27.7	-14.1			
WTET2a	**Ethanol from Wheat, NG GT+CHP, DDGS as animal feed**											
	Cultivation	1	0.24				31.92			14.3	0.03	0.058
	Road transport	3	0.03				0.54			0.5	0.00	0.000
	Ethanol plant	4	1.24				12.56			20.8	0.07	-0.033
	Ethanol road transport, 150 km	5	0.02				1.10			1.1	0.00	0.000
	Refuelling station	5	0.01				0.44			0.4	0.00	0.000
	Total WTT GHG emitted						**46.6**	39.2	53.2	37.2	0.09	0.025
	Credit for renewable combustion CO$_2$						-71.4			-71.4		
	Total pathway		**1.53**	1.51	1.55	**0.65**	**-24.8**	-32.1	-18.2			
WTET2b	**Ethanol from Wheat, NG GT+CHP, DDGS as fuel**											
	Cultivation	1	0.24				31.92			14.3	0.03	0.058
	Road transport	3	0.03				0.54			0.5	0.00	0.000
	Ethanol plant	4	0.77				3.93			4.3	0.01	-0.002
	Ethanol road transport, 150 km	5	0.02				1.10			1.1	0.00	0.000
	Refuelling station	5	0.01				0.44			0.4	0.00	0.000
	Total WTT GHG emitted						**37.9**	31.6	44.7	20.7	0.03	0.056
	Credit for renewable combustion CO$_2$						-71.4			-71.4		
	Total pathway		**1.06**	1.04	1.08	**0.20**	**-33.5**	-39.8	-26.7			

WTET3a	**Ethanol from Wheat, lignite CHP, DDGS as animal feed**											
	Cultivation	1	0.24				31.92			14.3	0.03	0.058
	Road transport	3	0.03				0.54			0.5	0.00	0.000
	Ethanol plant	4	1.46				58.58			68.1	0.00	-0.032
	Ethanol road transport, 150 km	5	0.02				1.10			1.1	0.00	0.000
	Refuelling station	5	0.01				0.44			0.4	0.00	0.000
	Total WTT GHG emitted						**92.6**	84.8	100.0	84.5	0.03	0.025
	Credit for renewable combustion CO$_2$						-71.4			-71.4		
	Total pathway		**1.74**	1.74	1.75	**0.86**	**21.2**	13.5	28.6			
WTET3b	**Ethanol from Wheat, Lignite CHP, DDGS as fuel**											
	Cultivation	1	0.24				31.92			14.3	0.03	0.058
	Road transport	3	0.03				0.54			0.5	0.00	0.000
	Ethanol plant	4	0.98				49.95			51.6	-0.06	-0.001
	Ethanol road transport, 150 km	5	0.02				1.10			1.1	0.00	0.000
	Refuelling station	5	0.01				0.44			0.4	0.00	0.000
	Total WTT GHG emitted						**83.9**	77.7	91.5	68.0	-0.03	0.056
	Credit for renewable combustion CO$_2$						-71.4			-71.4		
	Total pathway		**1.27**	1.27	1.27	**0.41**	**12.6**	6.3	20.1			
WTET4a	**Ethanol from Wheat, Straw CHP, DDGS as animal feed**											
	Cultivation	1	0.24				31.92			14.3	0.03	0.058
	Road transport	3	0.03				0.54			0.5	0.00	0.000
	Ethanol plant	4	1.40				-9.18			0.3	0.00	-0.032
	Ethanol road transport, 150 km	5	0.02				1.10			1.1	0.00	0.000
	Refuelling station	5	0.01				0.44			0.4	0.00	0.000
	Total WTT GHG emitted						**24.8**	17.6	31.5	16.7	0.03	0.025
	Credit for renewable combustion CO$_2$						-71.4			-71.4		
	Total pathway		**1.69**	1.69	1.70	**0.28**	**-46.6**	-53.8	-39.9			
WTET4b	**Ethanol from Wheat, Straw CHP, DDGS as fuel**											
	Cultivation	1	0.24				31.92			14.3	0.03	0.058
	Road transport	3	0.03				0.54			0.5	0.00	0.000
	Ethanol plant	4	0.93				-17.82			-16.2	-0.06	-0.001
	Ethanol road transport, 150 km	5	0.02				1.10			1.1	0.00	0.000
	Refuelling station	5	0.01				0.44			0.4	0.00	0.000
	Total WTT GHG emitted						**16.2**	8.5	22.9	0.2	-0.03	0.056
	Credit for renewable combustion CO$_2$						-71.4			-71.4		
	Total pathway		**1.22**	1.21	1.22	**-0.17**	**-55.2**	-62.9	-48.5			

SCET1 Sugar cane to ethanol (Brazil)

Sugar cane is grown and turned into ethanol in Brazil. The bagasse is used as fuel (as is current practice), also generating surplus heat. The data is based on [*Macedo 2004*]. Ethanol is shipped into Europe where it is blended with gasoline.

STET1 Wheat straw to ethanol

This pathway specifically refers to the Iogen process [*Iogen 2003*] which hydrolyses cellulose into fermentable sugars. Additional agricultural inputs to compensate for the removal of straw from soils are taken into account.

W/F-WET1 Waste/Farmed wood to ethanol

These are more generic cellulose-to-ethanol pathways where wood (poplar) is a proxy for a number of possible feedstocks (e.g. perennial grasses). The process is based on an earlier reference from NERL [*Wooley 1999*].

		Standard step	Energy consumed (MJx/MJf)				Net GHG emitted (g CO$_2$eq/MJf)			CO$_2$	CH4	N$_2$O
			Total primary			Fossil						
			Best est.	min	Max		Best est.	min	Max	g/MJ	g/MJ	g/MJ
SCET1	**EtOH from sugar cane (Brazil)**											
	Cultivation	1	0.06				13.09			3.7	0.15	0.020
	Road transport	3	0.01				0.85			0.8	0.00	0.000
	Ethanol plant	4	1.63				-10.31			-10.2	0.00	0.000
	Ethanol transport	5	0.08				0.99			1.0	0.00	0.000
	Refuelling station	5	0.01				5.82			5.8	0.00	0.000
	Total WTT GHG emitted						**10.4**	10.2	10.7	1.1	0.15	0.020
	Credit for renewable combustion CO$_2$						-71.4			-71.4		
	Total pathway		**1.79**	1.79	1.80	**0.02**	**-60.9**	-61.2	-60.7			
WWET1	**Ethanol from waste wood**											
	Waste collection and chipping	1	0.08				0.95			0.9	0.00	0.000
	Transport (road + sea)	3	0.04				3.18			3.0	0.01	0.000
	Ethanol plant	4	1.80				12.31			12.6	0.02	-0.002
	Ethanol road transport, 150 km	5	0.02				1.10			1.1	0.00	0.000
	Refuelling station	5	0.01				0.44			0.4	0.00	0.000
	Total WTT GHG emitted						**18.0**	17.8	18.1	18.0	0.03	-0.002
	Credit for renewable combustion CO$_2$						-71.4			-71.4		
	Total pathway		**1.94**	1.84	2.05	**0.27**	**-53.4**	-53.6	-53.3			

WFET1	**EtOH from farmed wood**											
	Cultivation	1	0.11				6.96			3.1	0.00	0.013
	Road transport	3	0.01				0.88			0.9	0.00	0.000
	Ethanol plant	4	1.80				12.31			12.6	0.02	-0.002
	Ethanol road transport, 150 km	5	0.02				1.10			1.1	0.00	0.000
	Refuelling station	5	0.01				0.44			0.4	0.00	0.000
	Total WTT GHG emitted						**21.7**	19.0	28.2	18.1	0.02	0.010
	Credit for renewable combustion CO_2						-71.4			-71.4		
	Total pathway		**1.95**	1.84	2.05	**0.27**	**-49.7**	-52.3	-43.2			
STET1	**EtOH from wheat straw (Iogen)**											
	Collection	3	0.05				3.35			3.3	0.00	0.000
	Road transport	3	0.01				0.62			0.6	0.00	0.000
	Ethanol plant	4	1.24				3.42			3.3	0.00	0.000
	Ethanol road transport, 150 km	5	0.02				1.10			1.1	0.00	0.000
	Refuelling station	5	0.01				0.44			0.4	0.00	0.000
	Total WTT GHG emitted						**8.9**	8.9	9.0	8.7	0.01	0.000
	Credit for renewable combustion CO_2						-71.4			-71.4		
	Total pathway		**1.32**	1.32	1.32	**0.11**	**-62.4**	-62.5	-62.4			

E.4 Bio-diesel

Pathway code		**ROFA**		**ROFE**		**SOFA**	
		1	**2**	**1**	**2**	**1**	**2**
Code	Process						
Farming							
RF1	Rapeseed Farming	✓	✓	✓	✓		
SF1	Sunflower seed Farming					✓	✓
Crop transport and processing							
WT2a	Wheat grain road transport			✓	✓		
WT3	Wheat grain handling and drying (to dwg, 3% moisture)			✓	✓		
WT4b	Wheat grain to ethanol, NG CCGT			✓	✓		
WTDa	Credit for DDGS as animal feed			✓	✓		
RO2	Rapeseed road transport	✓	✓	✓	✓		
RO3	Rapeseed to raw oil: extraction	✓	✓	✓	✓		
SO2	Sunflower seed road transport					✓	✓
SO3	Sunflower seed to raw oil: extraction					✓	✓
RO4/SO4	Raw oil to refined oil	✓	✓	✓	✓		
RO5/SO5	Refined oil to FAME: esterification						
5a	Glycerine as chemical	✓		✓		✓	
5b	Glycerine as animal feed		✓		✓		✓
Biofuels transport & distribution							
FAd	FAME distribution (blended)	✓	✓	✓	✓	✓	✓
Common processes							
Z1	Diesel production	✓	✓	✓	✓	✓	✓
Z2	Road tanker	✓	✓	✓	✓	✓	✓

ROFA1/2 Rape to FAME (RME)

SOFA1/2 Sunflower seed to FAME

For both crops two alternatives disposal routes for the glycerine are considered either as a chemical (replacing a bulk chemical such as propylene glycol) or as animal feed. These represent the extremes of GHG and fossil energy credits: reality will be in between.

ROFE1/2 Rape to FAEE (REE)

The same pathways as ROFA above where methanol has been replaced by (bio)ethanol. Although it is technically feasible, this process has not been commercially used so far. It has been assumed that the process energy is the same for both alcohols.

		Standard step	Energy consumed (MJx/MJf)				Net GHG emitted (g CO_2eq/MJf)			CO_2	CH4	N_2O
			Total primary			Fossil						
			Best est.	min	Max		Best est.	min	Max	g/MJ	g/MJ	g/MJ
ROFA1	**RME, glycerine as chemical**											
	Cultivation	1	0.29				51.26			18.2	0.03	0.109
	Drying	1	0.01				0.66			0.6	0.00	0.000
	Transport, road 50 km	3	0.02				0.30			0.3	0.00	0.000
	FAME manufacture	4	0.84				-6.95			1.9	0.04	-0.033
	Transport and distribution	5	0.02				1.26			1.2	0.00	0.000
	Total WTT GHG emitted						**46.5**	25.3	66.6	22.2	0.08	0.076
	Credit for renewable combustion CO_2						-75.4			-75.4		
	Total pathway		**1.19**	1.10	1.30	**0.46**	**-28.9**	-50.1	-8.8			
ROFA2	**RME, glycerine as animal feed**											
	Cultivation	1	0.29				51.26			18.2	0.03	0.109
	Drying	1	0.01				0.66			0.6	0.00	0.000
	Transport, road 50 km	3	0.02				0.30			0.3	0.00	0.000
	FAME manufacture	4	0.89				-1.71			7.4	0.05	-0.035
	Transport and distribution	5	0.02				1.26			1.2	0.00	0.000
	Total WTT GHG emitted						**51.8**	30.7	68.3	27.8	0.09	0.074
	Credit for renewable combustion CO_2						-75.4			-75.4		
	Total pathway		**1.24**	1.13	1.34	**0.51**	**-23.6**	-44.7	-7.1			
ROFE1	**REE, glycerine as chemical**											
	Cultivation	1	0.28				48.42			17.2	0.03	0.103
	Drying	1	0.01				0.62			0.6	0.00	0.000
	Transport, road 50 km	3	0.02				0.28			0.3	0.00	0.000
	FAEE manufacture	4	0.92				-7.29			0.4	0.03	-0.029
	Transport and distribution	5	0.02				1.25			1.2	0.00	0.000
	Total WTT GHG emitted						**43.3**	24.2	63.4	19.7	0.07	0.074
	Credit for renewable combustion CO_2						-75.4			-75.4		
	Total pathway		**1.25**	1.15	1.34	**0.41**	**-32.1**	-51.2	-12.0			
ROFE2	**REE, glycerine as animal feed**											
	Cultivation	1	0.28				48.42			17.2	0.03	0.103
	Drying	1	0.01				0.62			0.6	0.00	0.000
	Transport, road 50 km	3	0.02				0.28			0.3	0.00	0.000
	FAEE manufacture	4	0.97				-2.56			5.4	0.04	-0.030
	Transport and distribution	5	0.02				1.25			1.2	0.00	0.000
	Total WTT GHG emitted						**48.0**	28.9	71.4	24.6	0.08	0.073
	Credit for renewable combustion CO_2						-75.4			-75.4		
	Total pathway		**1.30**	1.20	1.40	**0.45**	**-27.4**	-46.5	-4.0			
SOFA1	**SME, glycerine as chemical**											
	Cultivation	1	0.18				28.03			12.0	0.01	0.053
	Drying	1	0.01				0.61			0.6	0.00	0.000
	Transport, road 50 km	3	0.02				0.28			0.3	0.00	0.000
	FAME manufacture	4	0.74				-5.44			3.3	0.04	-0.032
	Transport and distribution	5	0.02				1.26			1.2	0.00	0.000
	Total WTT GHG emitted						**24.7**	12.2	36.1	17.4	0.06	0.021
	Credit for renewable combustion CO_2						-75.4			-75.4		
	Total pathway		**0.98**	0.87	1.07	**0.36**	**-50.7**	-63.3	-39.3			
SOFA2	**SME, glycerine as animal feed**											
	Cultivation	1	0.18				28.03			12.0	0.01	0.053
	Drying	1	0.01				0.61			0.6	0.00	0.000
	Transport, road 50 km	3	0.02				0.28			0.3	0.00	0.000
	FAME manufacture	4	0.79				-0.19			8.9	0.04	-0.034
	Transport and distribution	5	0.02				1.26			1.2	0.00	0.000
	Total WTT GHG emitted						**30.0**	19.2	40.7	22.9	0.06	0.019
	Credit for renewable combustion CO_2						-75.4			-75.4		
	Total pathway		**1.03**	0.94	1.11	**0.41**	**-45.4**	-56.2	-34.7			

E.5 Synthetic fuels

E.5.1 Synthetic diesel

		Farmed wood	Waste wood	Black liquor
Pathway code		**WFSD**	**WWSD**	**BLSD**
		1	**1**	**1**
Code	Process			
Wood (farmed)				
WF1	Wood farming and chipping	✓		
Wood (waste)				
WW1	Forest residuals to wood chips		✓	✓
Wood transport & processing (all sources)				
WC2a	Wood chips road transport, 50 km	✓	✓	✓
WC2b	Wood chips road transport, 12 km			
WC2c	Coastal/river shipping wood ships (200MW plant)		✓	
W3f	Wood to syn-diesel: gasification + FT	✓	✓	
Wood waste via black liquor				
BLS	Wood waste to syn diesel via black liquor			✓
Syn diesel transport & distribution				
DS1	Syn diesel handling and loading (remote)			
DS2	Syn diesel sea transport			
DS3	Syn diesel depot	✓	✓	
DS4	Syn diesel distribution (blending component)			
DS5	Syn diesel distribution (neat)			
SDd	Bio-(synthetic diesel) distribution (blended)	✓	✓	✓
Common processes				
Z1	Diesel production	✓	✓	✓
Z2	Road tanker	✓	✓	✓

W/F-WSD1 Waste/Farmed wood to synthetic diesel

This is the Biomass-to-Liquids (BTL) pathway: wood gasification followed by Fischer-Tropsch synthesis.

BLSD1 Waste wood via black liquor to synthetic diesel

Black liquor is the residue of extraction of cellulose fibres from wood for paper pulp manufacturing. It contains the lignin and is used as fuel for the large power plant required by a paper mill. Black liquor is also suitable for gasification, the syngas being then available for either electricity hydrogen or synthetic fuels production. The shortfall of energy available to the paper mill can be made up by burning waste wood. Compared to a reference case with a traditional black liquor boiler and all other parameters being the desired fuel can be produced with significantly higher net energy efficiency than in a more conventional scheme.

		Standard step	Energy consumed (MJx/MJf)				Net GHG emitted (g CO$_2$eq/MJf)			CO$_2$	CH4	N$_2$O
			Total primary			Fossil						
			Best est.	min	Max		Best est.	min	Max	g/MJ	g/MJ	g/MJ
WWSD1	**Syn diesel, wood waste**											
	Waste collection and chipping	1	0.06				0.8			0.7	0.00	0.000
	Transport (road + sea)	3	0.04				2.9			2.7	0.01	0.000
	Gasifier + FT plant	4	1.08				0.0		`	0.0	0.00	0.000
	Diesel distribution & dispensing	5	0.02				1.1			1.1	0.00	0.000
	Total WTT GHG emitted						**4.8**	4.6	5.0	4.6	0.01	0.000
	Credit for renewable combustion CO$_2$						-70.8			-70.8		
	Total pathway		**1.19**	1.08	1.30	**0.07**	**-66.1**	-66.3	-65.9			
WFSD1	**Syn diesel, farmed wood**											
	Wood farming and chipping	1	0.09				5.5			2.5	0.00	0.010
	Road transport	3	0.01				0.7			0.7	0.00	0.000
	Gasifier + FT plant	4	1.08				0.0			0.0	0.00	0.000
	Diesel distribution & dispensing	5	0.02				1.1			1.1	0.00	0.000
	Total WTT GHG emitted						**7.4**	4.4	13.8	4.3	0.00	0.010
	Credit for renewable combustion CO$_2$						-70.8			-70.8		
	Total pathway		**1.19**	1.08	1.29	**0.06**	**-63.4**	-66.4	-57.0			
BLSD1	**Syn diesel, black liquor**											
	Wood farming and chipping	1	0.05				0.7			0.6	0.00	0.000
	Road transport	3	0.01				0.6			0.6	0.00	0.000
	Black liquor gasifier + FT plant	4	0.83				0.0			0.0	0.00	0.000
	Diesel distribution & dispensing	5	0.02				1.1			1.1	0.00	0.000
	Total WTT GHG emitted						**2.4**	2.4	2.5	2.4	0.00	0.000
	Credit for renewable combustion CO$_2$						-70.8			-70.8		
	Total pathway		**0.91**	0.86	0.97	**0.04**	**-68.4**	-68.4	-68.4			

E.6 DME

						Coal	Farmed wood	Waste wood	Black liquor
Pathway code		GPDE		GRDE		KODE	WFDE	WWDE	BLDE
		1a	1b	1	1C	1	1	1	1
Code	Process								
Wood (farmed)									
WF1	Wood farming and chipping						✓		
Wood (waste)									
WW1	Forest residuals to wood chips							✓	✓
Wood transport & processing (all sources)									
WC2a	Wood chips road transport, 50 km						✓	✓	✓
WC2b	Wood chips road transport, 12 km								
WC2c	Coastal/river shipping wood chips (200MW plant)							✓	
W3g	Wood to methanol or DME: gasification + synthesis						✓	✓	
Wood waste via black liquor									
BLD	Wood waste to DME via black liquor								✓
DME transport & distribution									
DE1	DME handling and loading (remote)			✓	✓				
DE2	DME sea transport			✓	✓				
DE3	DME depot			✓	✓	✓			
DE4a	DME distribution and dispensing	✓	✓	✓	✓				
DEd	Bio-DME distribution direct from plant						✓	✓	✓
Common processes									
Z1	Diesel production	✓	✓	✓	✓	✓	✓	✓	✓
Z2	Road tanker	✓	✓	✓	✓	✓	✓	✓	✓

W/F-WDE1 Waste/Farmed wood to DME

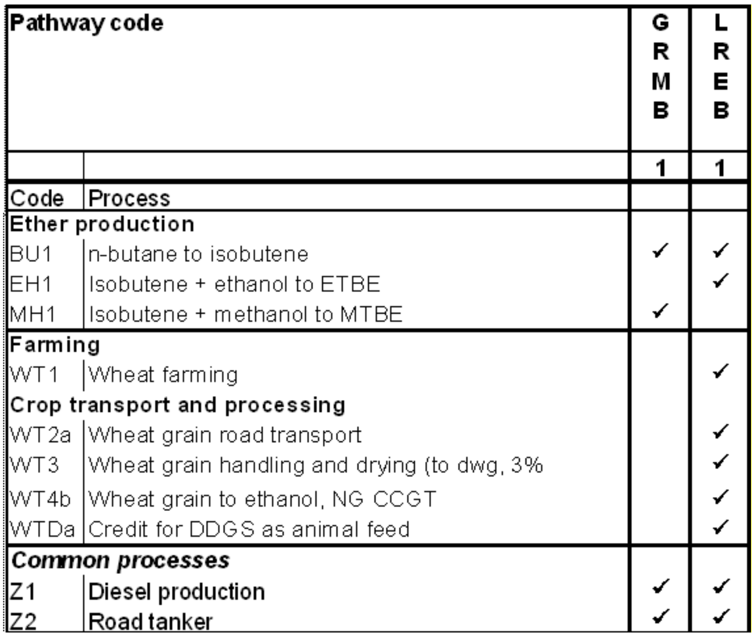
Wood gasification followed by DME synthesis.

BLDE1 Waste wood via black liquor to DME

Black liquor is the residue of extraction of cellulose fibres from wood for paper pulp manufacturing. It contains the lignin and is used as fuel for the large power plant required by a paper mill. Black liquor is also suitable for gasification, the syngas being then available for either electricity hydrogen or synthetic fuels production. The shortfall of energy available to the paper mill can be made up by burning waste wood. Compared to a reference case with a traditional black liquor boiler and all other parameters being the desired fuel can be produced with significantly higher net energy efficiency than in a more conventional scheme.

		Standard step	Energy consumed (MJx/MJf)				Net GHG emitted (g CO_2eq/MJf)			CO_2	CH4	N_2O
			Total primary			Fossil						
			Best est.	min	Max		Best est.	min	Max	g/MJ	g/MJ	g/MJ
GPDE1a	**Piped NG, 7000 km, EU central plant**											
	NG Extraction & Processing	1	0.04	0.02	0.08		5.2			1.9	0.14	0.000
	NG Transport	3	0.28	0.09	0.31		20.7			14.4	0.26	0.001
	NG Distribution (HP)	3	0.01				0.8			0.8	0.00	0.000
	DME plant	4	0.41	0.39	0.43		10.6			10.5	0.00	0.000
	DME distribution & dispensing	5	0.03				1.7			1.6	0.00	0.000
	Total pathway		**0.77**	0.63	0.79	**0.77**	**38.9**	30.8	39.9	29.2	0.41	0.001
GPDE1b	**Piped NG, 4000 km, EU central plant**											
	NG Extraction & Processing	1	0.04	0.02	0.07		4.7			1.7	0.13	0.000
	NG Transport	3	0.13	0.04	0.15		10.3			6.8	0.15	0.000
	NG Distribution (HP)	3	0.01				0.8			0.8	0.00	0.000
	DME plant	4	0.41	0.39	0.43		10.6			10.5	0.00	0.000
	DME distribution & dispensing	5	0.03				1.7			1.6	0.00	0.000
	Total pathway		**0.62**	0.56	0.64	**0.62**	**28.1**	24.3	29.2	21.4	0.28	0.000
GRDE1	**Remote plant**											
	NG Extraction & Processing	1	0.03	0.02	0.07		4.3			1.6	0.12	0.000
	DME plant	2	0.41	0.39	0.43		10.6			10.5	0.00	0.000
	DME transport	3	0.06				4.3			4.3	0.00	0.000
	DME distribution & dispensing	5	0.03				1.7			1.6	0.00	0.000
	Total pathway		**0.53**	0.51	0.56	**0.53**	**20.9**	19.8	22.5	18.0	0.12	0.000
GRDE1C	**Remote plant, CC&S**											
	NG Extraction & Processing	1	0.03	0.02	0.07		4.3			1.6	0.12	0.000
	DME plant	2	0.42	0.40	0.42		0.6			0.6	0.00	0.000
	DME transport	3	0.06				4.3			4.3	0.00	0.000
	DME distribution & dispensing	5	0.03				1.7			1.6	0.00	0.000
	Total pathway		**0.54**	0.54	0.61	**0.54**	**10.9**	10.8	14.9	8.1	0.12	0.000
WWDE1	**Wood waste**											
	Waste collection and chipping	1	0.06				0.7			0.7	0.00	0.000
	Transport (road + sea)	3	0.03				2.7			2.6	0.01	0.000
	Gasifier + DME synthesis	4	0.96				0.1			0.1	0.00	0.000
	DME distribution & dispensing	5	0.02				1.0			1.0	0.00	0.000
	Total WTT GHG emitted						**4.5**	4.3	4.8	4.3	0.01	0.000
	Credit for renewable combustion CO_2						-67.3			-67.3		
	Total pathway		**1.07**	0.95	1.22	**0.06**	**-62.7**	-63.0	-62.5			
WFDE1	**Farmed wood**											
	Wood farming and chipping	1	0.08				5.2			2.3	0.00	0.010
	Road transport	3	0.01				0.7			0.7	0.00	0.000
	Gasifier + MeOH synthesis	4	0.96				0.1			0.1	0.00	0.000
	DME distribution & dispensing	5	0.02				1.0			1.0	0.00	0.000
	Total WTT GHG emitted						**7.0**	5.2	11.8	4.1	0.00	0.010
	Credit for renewable combustion CO_2						-67.3			-67.3		
	Total pathway		**1.07**	0.94	1.20	**0.06**	**-60.3**	-62.10	-55.45			
BLDE1	**DME from black liquor**											
	Waste collection and chipping	1	0.04				0.5			0.5	0.0	0.000
	Transport (road)	3	0.01				0.5			0.5	0.0	0.000
	Black liquor gasification + DME synthesis	4	0.49				0.1			0.1	0.0	0.000
	DME distribution & dispensing	5	0.02				1.0			1.0	0.0	0.000
	Total WTT GHG emitted						**2.2**	2.1	2.2	2.1	0.00	0.000
	Credit for renewable combustion CO_2						-67.3			-67.3		
	Total pathway		**0.55**	0.51	0.61	**0.03**	**-65.1**	-65.17	-65.10			

E.7 Ethers



Pathway code		GRMB	LREB
		1	1
Code	Process		
Ether production			
BU1	n-butane to isobutene	✓	✓
EH1	Isobutene + ethanol to ETBE		✓
MH1	Isobutene + methanol to MTBE	✓	
Farming			
WT1	Wheat farming		✓
Crop transport and processing			
WT2a	Wheat grain road transport		✓
WT3	Wheat grain handling and drying (to dwg, 3%		✓
WT4b	Wheat grain to ethanol, NG CCGT		✓
WTDa	Credit for DDGS as animal feed		✓
Common processes			
Z1	Diesel production	✓	✓
Z2	Road tanker	✓	✓

LREB1 Bio-ethanol and field butane to ETBE

Isobutene prepared in Europe from imported field butane is reacted with bio-ethanol (from wheat according to pathway WTET2a) to form ETBE. ETBE is used in blend with gasoline.

Note: *evaluating the fossil energy is a little more complex in this case as only part of the feedstock is renewable. The figure of 0.07* MJ_{xf}/MJ_f *shown in the table below assumes that all combustion energy is fossil i.e. the total fossil energy for the WTW pathway is 1.07* MJ_{xf}/MJ_f*. Following the same logic, only 1/3 of the* CO_2 *emissions is credited as renewable (2 out of 6 carbon atoms in the ETBE molecule).*

		Standard step	Energy consumed (MJx/MJf)				Net GHG emitted (g CO_2eq/MJf)			CO_2	CH4	N_2O
			Total primary			Fossil						
			Best est.	min	Max		Best est.	min	Max	g/MJ	g/MJ	g/MJ
LREB1	**ETBE from imported C4 and wheat ethanol (WTET2a)**											
	Wheat cultivation	1	0.09				11.63			5.2	0.01	0.021
	Road transport	3	0.01				0.20			0.2	0.00	0.000
	Ethanol plant	4	0.42				-0.23			2.8	0.02	-0.012
	ETBE plant	4	0.22				7.69			7.2	0.02	0.000
	ETBE road transport, 150 km	5	0.01				0.67			0.7	0.00	0.000
	Refuelling station	5	0.01				0.44			0.4	0.00	0.000
	Total WTT GHG emitted						**20.4**	65.5	70.8	16.4	0.05	0.009
	Credit for renewable combustion CO_2						-23.8			-23.8		
	Total pathway		**0.75**	0.75	0.77	**0.07***	**-3.4**	-5.9	-0.6			

E.8 Summary of energy and GHG balances

E.8.1 Oil-based fuels, CBG, Ethanol, Ethers, Bio-diesel

Pathway		**Energy expended (MJex/MJ final fuel)**											**Net GHG emitted (g CO_2eq/MJ final fuel)**											
Code	Description	**Total energy**	Fossil energy	Production & conditioning at source	Transformation at source	Transportation to market	Transformation near market	Conditioning & distribution	Range				**Total GHG inc. renew comb. CO2 credit**	Production & conditioning at source	Transformation at source	Transportation to market	Transformation near market	Conditioning & distribution	Total WTT GHG emitted	Credit for renewable combustion CO_2	Range			
COG1	Conventional gasoline	**0.14**	0.14	0.03		0.01	0.08	0.02	0.12	0.17	0.02	0.03	**13**	4		1	7	1	13		11	15	1	2
COD1	Conventional diesel	**0.16**	0.16	0.03		0.01	0.10	0.02	0.14	0.18	0.02	0.02	**14**	4		1	9	1	14		13	16	2	2
OWCG1	CBG: municipal waste	**0.87**	0.17				0.81	0.06	0.72	1.02	0.15	0.15	**-40**				32	3	35	-76	-43	-38	3	3
OWCG2	CBG: liquid manure	**0.97**	0.03		0.03		0.88	0.06	0.80	1.12	0.17	0.16	**-134**		-87		26	3	-58	-76	-161	-106	27	28
OWCG3	CBG: dry manure	**0.95**	0.01		0.01		0.88	0.06	0.78	1.11	0.17	0.16	**-55**		-8		26	3	20	-76	-58	-52	3	3
SBET1	EtOH: Sugar beet, pulp to fodder	**1.86**	0.87	0.16		0.03	1.64	0.03	1.74	1.96	0.12	0.11	**-14**	21		2	33	2	57	-71	-18	-10	4	4
SBET3	EtOH: Sugar beet, pulp to heat	**1.30**	0.31	0.16		0.03	1.08	0.03	1.17	1.41	0.13	0.12	**-42**	21		2	5	2	30	-71	-44	-39	2	3
WTET1a	EtOH: Wheat, conv NG boiler, DDGS as AF	**1.78**	0.89	0.24		0.03	1.49	0.03	1.76	1.80	0.02	0.02	**-12**	32		1	25	2	59	-71	-19	-5	7	7
WTET1b	EtOH: Wheat, conv NG boiler, DDGS as fuel	**1.30**	0.44	0.24		0.03	1.02	0.03	1.28	1.33	0.02	0.02	**-21**	32		1	17	2	51	-71	-28	-13	7	8
WTET2a	EtOH: Wheat, NG GT+CHP, DDGS as AF	**1.53**	0.65	0.24		0.03	1.24	0.03	1.51	1.55	0.02	0.02	**-25**	32		1	13	2	47	-71	-32	-19	7	6
WTET2b	EtOH: Wheat, NG GT+CHP, DDGS as fuel	**1.06**	0.20	0.24		0.03	0.77	0.03	1.04	1.08	0.02	0.02	**-33**	32		1	4	2	38	-71	-41	-27	7	7
WTET3a	EtOH: Wheat, Lignite CHP, DDGS as AF	**1.74**	0.86	0.24		0.03	1.46	0.03	1.74	1.75	0.00	0.00	**21**	32		1	59	2	93	-71	14	28	7	7
WTET3b	EtOH: Wheat, Lignite CHP, DDGS as fuel	**1.27**	0.41	0.24		0.03	0.98	0.03	1.27	1.27	0.01	0.00	**13**	32		1	50	2	84	-71	5	20	8	7
WTET4a	EtOH: Wheat, Straw CHP, DDGS as AF	**1.69**	0.28	0.24		0.03	1.40	0.03	1.69	1.70	0.00	0.00	**-47**	32		1	-9	2	25	-71	-53	-39	7	7
WTET4b	EtOH: Wheat, Straw CHP, DDGS as fuel	**1.22**	-0.17	0.24		0.03	0.93	0.03	1.21	1.22	0.00	0.00	**-55**	32		1	-18	2	16	-71	-62	-48	7	7
WWET1	EtOH: W Wood	**1.94**	0.27	0.08		0.04	1.80	0.03	1.84	2.05	0.10	0.11	**-53**	1		3	12	2	18	-71	-54	-53	0	0
WFET1	EtOH: F wood	**1.95**	0.27	0.11		0.01	1.80	0.03	1.85	2.05	0.10	0.10	**-50**	7		1	12	2	22	-71	-52	-44	2	6
STET1	EtOH: Wheat straw	**1.32**	0.11	0.05		0.01	1.24	0.03	1.32	1.32	0.00	0.00	**-62**	3		1	3	2	9	-71	-62	-62	0	0
SCET1	EtOH: Sugar cane (Brazil)	**1.79**	0.02	0.06		0.01	1.63	0.09	1.79	1.80	0.00	0.00	**-61**	13		1	-10	7	10	-71	-61	-61	0	0
LREB1	ETBE: imported C4 and wheat ethanol	**0.75**	0.07	0.09		0.01	0.64	0.02	0.75	0.77	0.01	0.01	**-3**	12		0	7	1	20	-24	-6	0	2	3
ROFA1	RME: Gly as chemical	**1.19**	0.46	0.31		0.02	0.84	0.02	1.10	1.30	0.09	0.11	**-29**	52		0	-7	1	47	-75	-50	-9	21	20
ROFA2	RME: Gly as animal feed	**1.24**	0.51	0.31		0.02	0.89	0.02	1.13	1.34	0.11	0.10	**-24**	52		0	-2	1	52	-75	-45	-7	21	17
ROFE1	REE: Gly as chemical	**1.25**	0.41	0.29		0.02	0.92	0.02	1.15	1.34	0.10	0.09	**-32**	49		0	-7	1	43	-75	-51	-12	19	20
ROFE2	REE: Gly as animal feed	**1.30**	0.45	0.29		0.02	0.97	0.02	1.20	1.40	0.10	0.10	**-27**	49		0	-3	1	48	-75	-46	-4	19	23
SOFA1	SME: Gly as chemical	**0.98**	0.36	0.20		0.02	0.74	0.02	0.87	1.07	0.10	0.09	**-51**	29		0	-5	1	25	-75	-63	-39	13	11
SOFA2	SME: Gly as animal feed	**1.03**	0.41	0.20		0.02	0.79	0.02	0.94	1.11	0.09	0.08	**-45**	29		0	0	1	30	-75	-56	-35	11	11

E.8.2 Synthetic diesel, DME

Pathway		**Energy expended (MJex/MJ final fuel)**											**Net GHG emitted (g CO_2eq/MJ final fuel)**											
Code	Description	**Total energy**	Fossil energy	Production & conditioning at source	Transformation at source	Transportation to market	Transformation near market	Conditioning & distribution	Range				**Total GHG inc. renew comb. CO2 credit**	Production & conditioning at source	Transformation at source	Transportation to market	Transformation near market	Conditioning & distribution	Total WTT GHG emitted	Credit for renewable combustion CO_2	Range			
GPDE1a	DME: NG 7000 km, Syn, Rail/Road	**0.77**	0.77	0.04		0.29	0.41	0.03	0.63	0.79	0.14	0.02	**39**	5		21	11	2	39		31	40	8	1
GPDE1b	DME: NG 4000 km, Syn, Rail/Road	**0.62**	0.62	0.04		0.14	0.41	0.03	0.56	0.64	0.06	0.02	**28**	5		11	11	2	28		24	29	4	1
GRDE1	DME: Rem Syn, Sea, Rail/Road	**0.53**	0.53	0.03	0.41	0.06		0.03	0.51	0.56	0.02	0.03	**21**	4	11	4		2	21		20	23	1	2
KODE1	DME: Coal EU-mix, Cen, Rail/Road	**0.93**	0.92			0.16	0.74	0.03	0.83	1.01	0.10	0.08	**128**			27	100	2	128		118	137	10	8
GRDE1C	DME: Rem Syn, Sea, Rail/Road, CC&S	**0.54**	0.54	0.03	0.42	0.06		0.03	0.54	0.61	0.00	0.07	**11**	4	1	4		2	11		11	15	0	4
WWDE1	DME: W Wood, Road	**1.07**	0.06	0.06		0.03	0.96	0.02	0.95	1.22	0.12	0.15	**-63**	1		3	0	1	5	-67	-63	-63	0	0
WFDE1	DME: F Wood, Road	**1.07**	0.06	0.08		0.01	0.96	0.02	0.94	1.20	0.13	0.13	**-60**	5		1	0	1	7	-67	-62	-55	2	5
BLDE1	DME: W Wood, Black liquor	**0.55**	0.03	0.04		0.01	0.49	0.02	0.51	0.61	0.04	0.05	**-65**	1		1	0	1	2	-67	-65	-65	0	0

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

The WTW study is about alternative road fuels and their potential to replace conventional gasoline and diesel fuels. When these alternatives have been evaluated their potential to save energy and GHG had to be considered. 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 a marginal analysis of the European refining system has been performed 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.

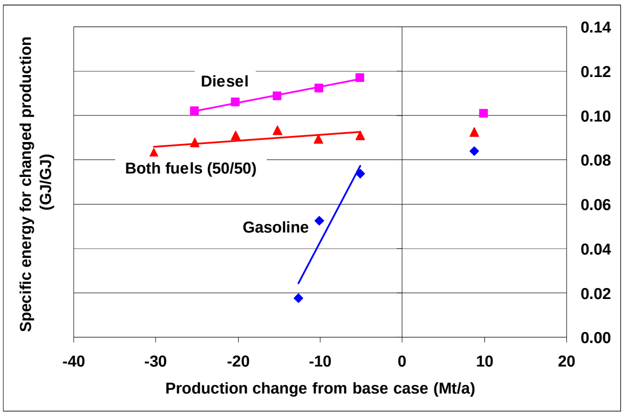
The difference in energy consumption and GHG emissions between the base case and an alternative can be credibly attributed to the single change in gasoline or diesel fuel production

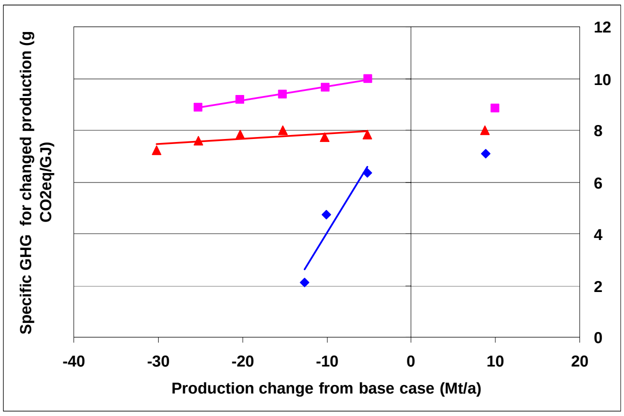
The CONCAWE model is fully carbon and energy balanced so that the differentials between two cases take into account small changes in energy and carbon content of all products.

The outcome of this work is shown in the figure below where the energy and CO_2 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.

The first striking point is that more energy/CO_2 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.





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

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, it is believed these latter figures are the most relevant. Accordingly it has been proposed to use 0.08 and 0.10 MJ_{ex}/MJ_f and 6.5 and 8.6 g CO_2/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.

The WTW 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. Therefore to use the European figures means to err on the conservative side.

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

- Although the WTW 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. This trend has been assumed to continue a/o under pressure of site CO_2 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 SO_2 emissions regulations. This trend has the potential to increase somewhat in the future either because of increased pressure on SO_2 emissions or actions to reduce site CO_2 emissions. Such a change would not impact energy efficiency figures, but would slightly reduce CO_2 emissions. Again the effect is small compared to other sources of variability.

G Vehicle retail price estimation

G.1 Main price assumptions for components and systems

- Prices given for specific components are on a 'supplier retail' (equivalent to delivered costs to vehicle manufacturers). A mark-up to include further costs, e.g. warranty, is not included.
- The cost estimates are based on recent cost studies (see Chapter References) and the WTW study has been focused on estimating the costs for various key powertrain components, such as motors, batteries, hybrid and fuel cell systems. Costs for upgrading some vehicle components were included for some configurations.
- Costs assume a volume of >50k units per annum and are projected for 2010+. The cost reduction estimates through volume production for some of the key components could be very optimistic and it is uncertain how much and at what rate future costs will decline under different circumstances.
- To cover these uncertainties a large upward range is included for future technologies.
- The study does not consider other associated costs beyond the key components for a certain technology. For example, vehicle body modifications are likely to vary depending on the base vehicle and the technology systems integration. For a more detailed cost calculation these additional costs need to be added.

The components or systems costs assessed for the technologies are shown in Table G. 1.

Table G. 1 Components, systems costs

Component or System			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
DME	€	1,500	a

G.1.1 2002 vehicles

The retail prices assessed for the 2002 technologies are shown in Table G. 2. All technologies are assessed against the reference gasoline PISI engine vehicle.

Notes: -Although the cost of the direct injection system is partly compensated by the lower power requirement the DISI vehicle is slightly more expensive than the reference.

-The price of the DME vehicle includes the special tank.

Table G. 2 2002 vehicles

Fuel	Gasoline		Diesel	DME
Propulsion system	PISI (reference)	DISI	DICI	DICI
Engine Power (kW)	77	70	74	74
Prices (€)				
Baseline vehicle	18,600	18,600	20,300	20,300
Gasoline tank	*125*			-125
Alternative fuel tank				1,500
Baseline engine + transmission	*2,310*	-2,310	*2,220*	*2,220*
Alternative engine + transmission		2,100		
DISI		500		
DICI			*1500*	*1,500*
Double injection system				
Total Vehicle Retail Price	18,600	18,890	20,300	21,675
Difference to the 2002 reference		**290**	**1,700**	**3,075**
		1.6%	9.1%	16.5%

Numbers in italic are for information only. They are not used in the calculations

G.1.2 2010+ ICE vehicles

For all 2010+ vehicles the reference is the 2010+ gasoline PISI vehicle, the price of which is derived from the 2002 version including additional cost for downsizing, turbo-charging, stop & go system and Euro IV exhaust after treatment. The overall price increase is 5%.

Notes: -The differential between gasoline DISI and PISI generally remains the same as in 2002.

-The diesel vehicle price increases by 300 € to cover the EURO IV exhaust after treatment requirements and by 700 € if a DPF is installed. The stop & go system is also dearer than for SI engines.

-The DME vehicle price remains higher than its diesel counterpart because of the cost of the tank.

Table G. 3 2010+ conventional ICE vehicles

Fuel	Gasoline		Diesel		DME
Propulsion system	PISI (reference)	DISI	DICI +DPF	DICI	DICI
Engine Power (kW)	77	70	74	74	74
Prices (€)					
Baseline vehicle	18,600	18,600	20,300	20,300	20,300
Gasoline tank					-125
Alternative fuel tank					1,500
Baseline engine + transmission	-2,310	-2,310	-3,720	-3,720	-3,720
Alternative engine + transmission(1)	2,590	2,380	2,280	2,280	2,280
Turbo	180	180			
DISI		500			
DICI			1500	1500	1500
Stop & go system	200	200	300	300	300
EURO IV exhaust after treatment	300	300	700	300	300
Double injection system					
Total Vehicle Retail Price	19,560	19,850	21,360	20,960	22,335
Difference to the 2010 reference		**290**	**1,800**	**1,400**	**2775**
		1.5%	9.2%	7.2%	14.2%

(1) Gasoline: includes downsizing and friction improvement; Diesel: friction improvement only

G.1.3 Results

The following table (Table G. 4) summarises the results and also shows the estimated uncertainty ranges. The range is fairly narrow for established technologies but widens when it comes to less developed options.

Table G. 4 Cost differentials of 2010+ vehicles compared to the 2010+ PISI vehicle

Engine technology	Fuel	Price differential (€)	Uncertainty range	
			-	+
ICEs conventional				
DISI	Gasoline	290	5%	5%
DICI	Diesel	1,400	5%	5%
DICI + DPF	Diesel	1,800	5%	5%
DICI	DME	2,775	10%	10%

European Commission

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Abstract

An extract of the JRC-EUCAR-CONCAWE (JEC) Well-to-Wheels Report (WTW) Version 2c, March 2007 has been made to form an easily readable reference for people interested only in biofuels.

Thus, among all alternative fuels analysed in the WTW study, only the biofuels have been extracted. Conventional fuels, namely standard gasoline and diesel, have been incorporated for comparison.

In particular, the following biomass types are considered: a)Sugar beet, sugar cane, wheat and straw to ethanol (and further conversion from ethanol to ETBE (Ethyl-Tertiary-Butyl Ether); b) Oil seeds -rapeseed, sunflower- (to bio-diesel); c) Wood (to ethanol and to synthetic liquid fuels); d) Organic wastes (to compressed biogas).

The extract incorporates the complete pathway of the biofuel, from the production of the raw material to the final biofuel use in the car.

It means to have listed in the report for each biofuel: a) availability in EU at given cost; b) costs involved in the processing, transportation, infrastructures; c) GHG emissions and energetic balance.

Natural gas sources, hydrogen, fossil fuels and uses to electricity are not part of this report.

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