CE
Solutions for environment, economy and technology

Oude Delft 180
2611 HH Delft
The Netherlands
tel: +31 15 2 150 150
fax: +31 15 2 150 151
e-mail: ce@ce.nl
website: www.ce.nl
KvK 27251086

Biofuels under development

An analysis of currently available and future biofuels, and a comparison with biomass application in other sectors

Report

Delft, May, 2005
Author(s): B.E. (Bettina) Kampman
L.C. (Eelco) den Boer
H.J. (Harry) Croezen

Publication Data

Bibliographical data:
B.E. (Bettina) Kampman, L.C. (Eelco) den Boer, H. (Harry) Croezen
Biofuels under development
An analysis of currently available and future biofuels, and a comparison with biomass application in other sectors
Delft, CE, 2005

Fuels / Vegetable / Biomass / Quality / Costs / Greenhouse gasses / Reduction / Prognoses / Scenarios

Publication number: 05.4894.11

CE-publications are available from www.ce.nl

Commissioned by: Netherlands Petroleum Industry Association (VNPI)
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Management summary

In response to EU Directive 2003/30/EC the Dutch government plans to introduce biofuels in 2006 as a means of reducing the greenhouse gas emissions of the transport sector. A number of biofuels are already available in various countries worldwide. However, there a number of new biofuel production processes currently under development.

Following an earlier study by CE on biofuels and alternative use of biomass in the period up to 2010[1], the Netherlands Petroleum Industry Organisation (VNPI) commissioned CE to carry out a study to examine various aspects of the biofuels that might become available in the period 2010 – 2020. This report discusses the most promising of these future biofuels: ethanol from lignocellulosic (woody) biomass, ETBE produced from such bio-ethanol, Fischer-Tropsch diesel produced from biomass and HTU diesel.

Future ethanol, biomass Fischer-Tropsch diesel and HTU diesel are all expected to perform considerably better than current biofuels: they will probably be significantly cheaper to produce while having double the greenhouse gas reduction potential. The associated cost of GHG reduction is thus expected to fall below 100 €/tonne CO_2 eq[2], from several hundred Euro/tonne for current biofuels. These performance improvements stem mainly from the fact that future biofuels will be produced from woody biomass or, in the case of HTU diesel, from wet organic biomass. Current biofuels are produced from food crops or residues.
Admixture of low percentages (<20%) of ethanol to petrol may lead to blending and fuel quality problems that can be solved by converting ethanol to ETBE. However, this cuts the CO_2 reduction potential by approximately half. On the other hand, the cost of future ETBE may be comparable or even lower than the current cost of MTBE (a component of petrol), which it can replace.

Given the current status of the various future biofuel production technologies, first-of-a-kind commercial-scale installations may be feasible within the next ten years. However, commercial application of these biofuels requires further technological development and cost reductions, which could be encouraged by government incentives.

The main potential sustainability issues of these future biofuels relate to large-scale cultivation of the required biomass feedstock. Even though future biofuels will require comparatively less land than current biofuels, overall developments are likely to increase pressures on ecosystems, potentially reducing biodiversity in the regions where the biomass is cultivated.

In line with the previous study, future biofuels were compared with use of biomass for electrical power generation (in the period 2010 – 2020). Results

[1] *Biomass, for vehicle fuels or power generation? A comparison to 2010,* CE, 2003.
[2] Assuming current fossil fuel and biomass prices.

show that biomass-based power generation is likely to remain more cost effective than biofuel production. Only if the more optimistic cost predictions for future biofuels prove correct is there a possibility of biofuels comparing more or less favourably with biomass for power generation in this respect.

Summary

Introduction

Since EU Directive 2003/30/EC on biofuels came into force, the introduction of biofuels has been high on the political agenda. This Directive sets indicative targets for EU countries to introduce transport biofuels by 2005. The Netherlands plans to introduce biofuels as of 2006, as a means of reducing the greenhouse gas emissions of the transport sector.

A number of biofuels are already available in various countries worldwide. In the EU these biofuels are typically produced from crops such as rapeseed, cereals or sugar beet. Alternatively, residual products from the food and cattle feed industry may be used as a feedstock.

There are a number of biofuel production processes under development that are expected to perform better environmentally (e.g. lower net CO_2 emissions, less fertiliser use), at lower cost. Other benefits are also anticipated, among them the fact that these processes can convert lignocellulosic (i.e. woody) biomass, which requires less land for cultivation and does not compete with the food chain.

Following an earlier study by CE on biofuels and alternative use of biomass in the period up to 2010[3], the Netherlands Petroleum Industry Organisation (VNPI) commissioned CE to carry out this study examining prospects for the period 2010 – 2020. The study collates state-of-the-art information on a variety of issues, ranging from biomass availability to fuel quality, costs and greenhouse gas (GHG) reduction potential. In addition, potential future biofuels are compared with currently available biofuels and the alternative use of biomass for electrical power generation. The study is based on the available literature and discussions with experts.

Potential future biofuel processes

There are a number of future biofuels that may potentially come onto the market over the next 10 to 15 years. In this report the most promising of these are discussed, *viz.*:

- Ethanol from lignocellulosic (woody) biomass, which can be blended with petrol.
- ETBE made from ethanol from lignocellulosic biomass, which can replace MTBE (a petrol component) or petrol.
- Biomass Fischer-Tropsch diesel, which can be blended with diesel or used as neat fuel.
- HTU diesel, which is expected to be blended with diesel or used as neat fuel.

All these potential future biofuels are still under development, with conversion processes not yet operational in large-scale production facilities.

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3 *Biomass, for vehicle fuels or power generation? A comparison to 2010,* CE, 2003.

Biomass availability in the Netherlands and import requirements
All future biofuels will be produced from woody residues or cultivated wood. They will therefore not compete with the fuel chain, as current biofuels might. In addition, HTU diesel can also be produced from wet organic biomass. Although in the Netherlands there is considerable potential biomass feedstock for these biofuels (sufficient to replace about 10% of transport fuel by biofuels), its fate is currently different, being ploughed back into the soil, added to animal feed or used for power generation, for example. If the biofuels industry were to attract an increasing share of this biomass, this would probably lead to increased import of biomass, there being only limited scope for greater biomass cropping in the Netherlands.

Technical, economical and environmental limitations
The potential future biofuels cited above are all still in the research and development phase and are not yet available on the market because of ***technical*** limitations.

In terms of ***economics***, significant investments are still required to develop these new biofuel technologies. Under the most optimistic estimates, the cost of future biofuels might approximate the current cost of their fossil counterparts, provided they are marketed on a large scale. Until then, however, they are likely to remain more expensive than conventional fossil fuels. Market access will then depend on government incentives.

Whether or not this reduction of cost can indeed be achieved will depend on:
- Technological developments.
- Biomass prices (which in turn depend on competition with other potential users of the biomass or land, such as the food or energy sector[4]).
- Conversion process operating costs (e.g. cost of enzymes for producing lignocellulosic ethanol and ETBE).
- Government incentives and related policies promoting research, development and market implementation of these better performing biofuels.

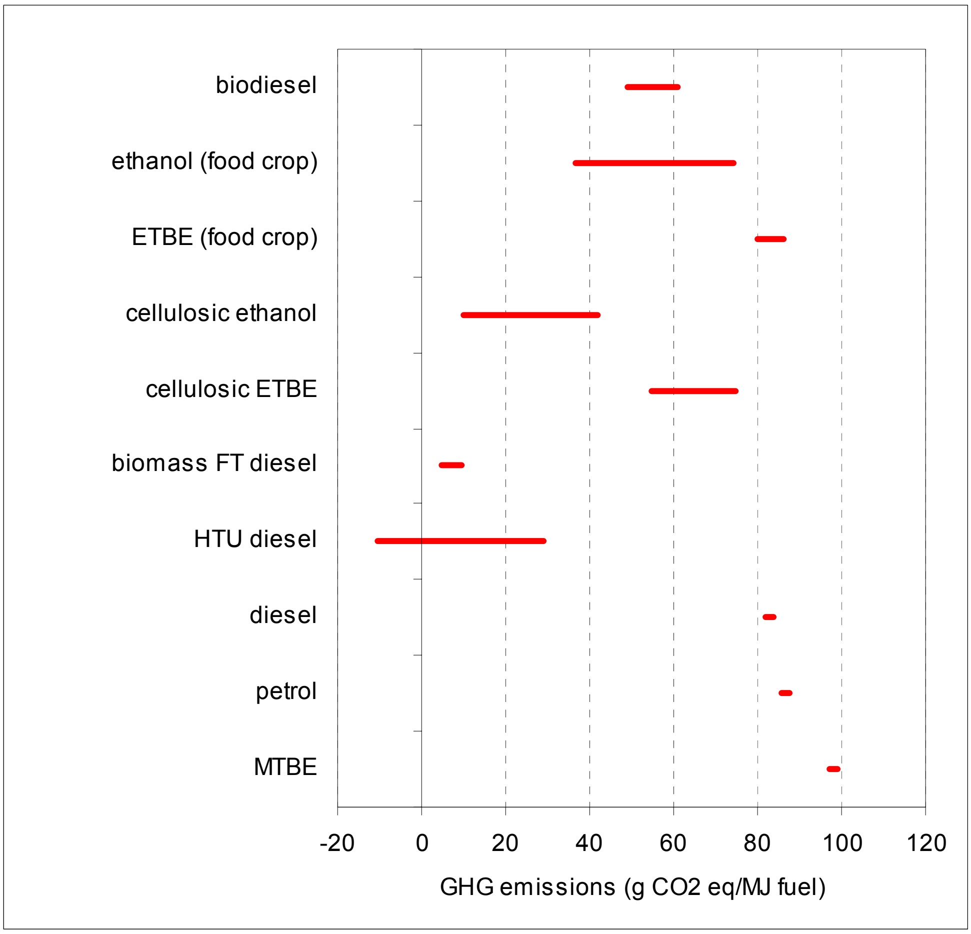
The main ***environmental*** drawback of the future biofuels examined concerns the potential farming and harvesting methods used for the biomass. All of these future biofuels can potentially use woody waste streams as a feedstock. Wood from plantations can probably be used without significant environmental impact if it is produced under sustainability regulations. If the wood is imported without sustainability guarantees, there may well be environmental problems (clear-felling of rainforests, for example, or failure to replant), as the conventional timber market has shown. The HTU technology may have potential environmental advantages over the other biofuel routes, as it can convert wet organic waste streams of little value in other applications.

[4] Note that other sectors, such as power generation, are also moving towards increased use of biomass feedstocks.

Net greenhouse gas reduction

In Figure 1 the well-to-wheel greenhouse gas emissions of the various biofuels analysed in this report are compared, both with each other and with their fossil counterparts. Cellulosic ethanol, biomass FT diesel and HTU diesel are expected to yield higher GHG reductions than currently available biodiesel and ethanol from wheat or sugar beet. Converting ethanol to ETBE has clear advantages from the perspective of biofuel quality control (see Figure 1), but has significantly less GHG reduction potential because it is produced only partly from ethanol and partly from 'fossil' isobutylene. The superior performance of the future biofuels examined is due mainly to their potential for using lignocellulosic biomass as a feedstock.

Figure 1 Overview of the well-to-wheel GHG emissions of each of the biofuels analysed, compared with those of diesel, petrol and MTBE (g CO_2 eq./MJ fuel)



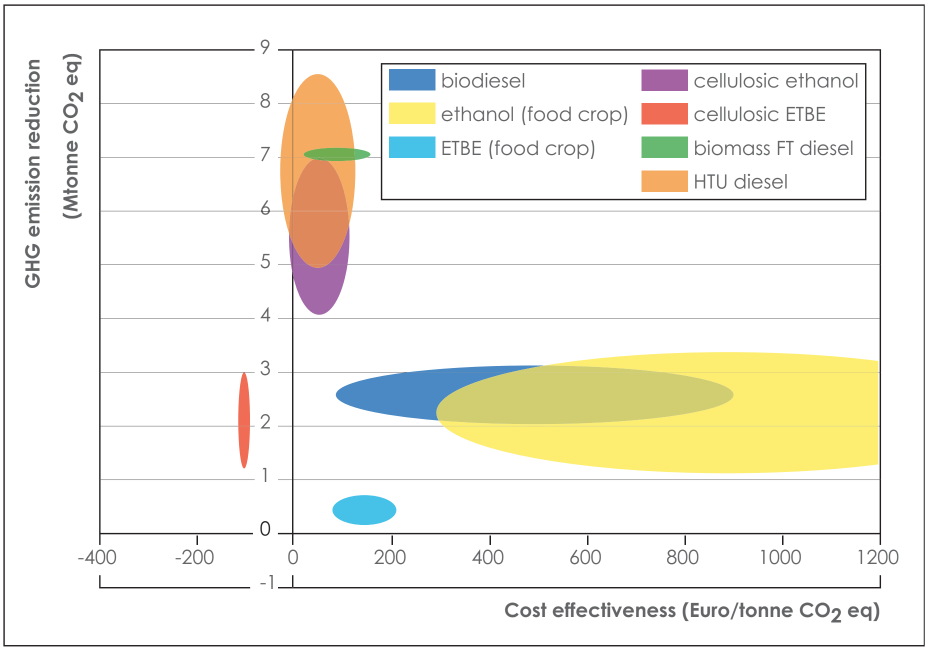
To provide an indication of the total GHG reduction potential of the various biofuels for 2020, two hypothetical cases were investigated:

a Scenario in which the biofuels are blended with their fossil counterparts, up to the maximum percentage currently permitted (5% for ethanol, biomass FT diesel and HTU diesel and 15% for ETBE), and b scenario in which biofuels replace 20% of total road transport fuels in the Netherlands in 2020[5].

The results for the second scenario are shown in Figure 2, together with the calculated cost effectiveness of the various fuels. The future biofuels clearly perform better than current biofuels in terms of both GHG reduction and cost effectiveness.
In this scenario, biomass FT diesel, HTU and cellulosic ethanol were all found to give a GHG reduction of approx. 4.5 to 8 Mtonne CO_2 eq, or about 14-18% of total road transport emissions in 2020. In the first scenario, in which maximum specifications are adhered to, these figures fall to 0.3–1.6 Mtonne CO_2 eq, or 0.6 – 3.6%. On average, these biofuels can be expected to reduce CO_2 emissions by about two to three times as much as biodiesel and current bio-ethanol.
If ethanol is converted to ETBE, GHG emissions reduction is more than halved because of the addition of (fossil) isobutylene and the extra processing requirements. If cellulosic ETBE were to replace 20% of road transport fuels in 2020, there would be a reduction of 1.2-3 Mtonne CO_2 eq, or about 3-7% of road transport CO_2 emissions (0.3-0.7 Mtonne CO_2 eq or 0.7-1.6% at maximum blending percentages).
Cost effectiveness is defined here as the ratio between the additional cost of biofuels (relative to respective current fossil fuel) and the specific GHG reduction the biofuel achieves. The figure shows that the cost effectiveness of the future biofuels is expected to improve significantly compared with current biofuels, owing to improvements in both cost and GHG reduction. Whereas 1 tonne of CO_2 eq reduction with current biofuels may cost several hundred Euro, future biofuels have the potential to reduce this figure to less than 100 €/tonne. Cellulosic ETBE is expected to become cheaper than MTBE (at current costs), resulting in a negative cost effectiveness in the figure. The same may also hold for the other future biofuels if optimistic cost estimates prove correct.

[5] Note that in this case current maximum blend percentages are by far exceeded.

Figure 2 Synopsis of cost effectiveness versus GHG reduction potential of the various biofuels, for the case in which each fuel replaces 20% of road transport fuels in the Netherlands in 2020 at current fossil fuel prices



NB. The height and width of the 'blobs' represent current uncertainties in the data, according to available literature.

Timing of availability

Given the current status of the various future biofuel production technologies, first-of-a-kind commercial-scale installations may be achievable within the next ten years if no major technical bottlenecks are encountered and if sufficient efforts and funds are expended.

From the available information it is difficult to predict which technological hurdles will be taken soonest and whether expectations regarding cost reductions and upscaling will be met.

Quality of the future biofuels

Current and future biofuels in the Netherlands would have to meet current fuel specifications. Their use is not expected to lead to any improvement in local air quality, except in the case of Fischer Tropsch diesel from biomass, which has the advantage, compared with fossil diesel, of not containing any sulphur or aromatics, thereby reducing particulate emissions.

Future bio-ethanol will have the same properties as the bio-ethanol produced today and there may therefore be problems when it is blended with petrol at low percentages (<20%), as this increases fuel vapour pressure. If over 20% ethanol is used, these problems no longer occur, but at higher percentages certain vehicle modifications become necessary. If ethanol is converted to ETBE, it can be blended into petrol up to the maximum allowed by fuel standards without any problems.

Biomass Fischer-Tropsch diesel can be blended with conventional diesel at any blending grade or used as neat fuel. Little is currently known about the fuel quality of HTU diesel, but there are no indications that the fuel will not meet current specifications.

Opportunities for the Dutch economy

As demand for biofuels increases both within and outside the Netherlands, opportunities will develop for the Dutch economy. In this project there was no scope for any extensive analysis of these opportunities and their possible impact. However, two sectors were identified that might potentially benefit economically: the port of Rotterdam, which could benefit from increased demand for imports of biomass and biofuels, and biofuel research and production facilities that might be located in the Netherlands.

Comparison of future biofuels with biomass for power generation

Biomass can substitute fossil fuels not only in transport, but also in the electricity sector. CE's earlier study for the VNPI on biofuels (see above) showed that in the period up to 2010, the latter option is clearly the more cost effective route to reducing GHG gases. In this report, a similar analysis was carried out for the period 2010 – 2020.

The results show that in that time frame biomass-based power generation is likely to remain more cost effective than biofuel production. Only if the more optimistic cost predictions for future biofuels prove correct is there a possibility of biofuels comparing more or less favourably with biomass for power generation in this respect.

Key issues to be resolved to achieve the full potential of future biofuels

From this study it appears that the main issues that need to be resolved before the full potential of future biofuels can be achieved are:

- *Technological development and cost reduction*, both prerequisites for commercial application.
- *Demonstration of the environmental and social sustainability* of large-scale biomass cultivation. Even though future biofuels will require comparatively less land than current biofuels, increased demand for biomass is likely to intensify pressure on ecosystems, potentially reducing biodiversity in the regions where the biomass is cultivated. To manage these risks it is therefore recommended to improve understanding of the worldwide socio-economic and environmental effects of increased biomass demand as well as assess the scope for biomass certification.

1 Introduction

1.1 Background

Since EU Directive 2003/30/EC on the introduction of biofuels came into force, biofuels have been high on the political agenda. This Directive sets indicative targets for EU countries to introduce transport biofuels by 2005. A recent Dutch policy document on transport emissions (*Nota Verkeersemissies*) has identified the introduction of biofuels in the Dutch transportation sector as a means of reducing the sector's greenhouse gas emissions. The document sees the introduction of biofuels as an important step towards less carbon-intensive transport.

A number of biofuels are already available, in particular biodiesel[6], bio-ethanol and ethyl-tertiary-butyl-ether (ETBE). In France, Italy and the USA, for example, biodiesel is blended with diesel in percentages up to 25%, while in Germany 100% biodiesel can be found [IEA, 2004]. Bio-ethanol blends are available in countries like Sweden, the USA and Brazil, while in France and Spain, for example, ethanol is first converted to ETBE and then added to petrol.

In the EU these biofuels are typically produced from crops such as rapeseed, cereals or sugar beet. Alternatively, residual products from the food and cattle feed industry may be used as a feedstock for bio-ethanol and ETBE production. The resultant hydrocarbons are used either directly as a transport fuel or added to conventional fossil fuels, in both EU and non-EU countries. Most of these fuels lead to a reduction in greenhouse gas emissions compared with fossil fuels, as the CO_2 emitted when biofuels are burned is equivalent to that taken up by the feedstock plants during growth. However, the total net greenhouse gas reduction achieved with these biofuels is usually no more than 30-60%, for two main reasons. First, there are CO_2 emissions associated with the energy needed to cultivate the biomass and convert it into a transport fuel. Second, other greenhouse gases are emitted during biomass cultivation (mainly N_2O, due mainly to use of artificial fertilisers)

There are a number of biofuel production processes under development but not yet ripe for commercial application that are expected to perform better environmentally (e.g. lower net CO_2 emissions, less fertiliser use) at lower cost. Other benefits are also anticipated, among them the fact that these processes can convert lignocellulosic (i.e. woody) biomass, which requires less agricultural land and does not compete with the food chain.

Before these improved biofuels can be commercially marketed, however, there are still substantial technical problems to be solved. Given the potential benefits, the Dutch state secretary for the environment asked the Netherlands Petroleum

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6 Throughout this report, the term 'biodiesel' is used for Fatty Acid Methyl Esters, often referred to as FAME. Note that FAME is not the same as pure vegetable oil, sometimes also referred to as biodiesel.

Industry Association (VNPI) to assist in evaluating the potential for swift introduction of the more advanced biofuels to achieve greater reductions of greenhouse gas emissions. The VNPI subsequently commissioned CE to assemble the existing data on both current and potential future biomass conversion processes and compare the different routes on a number of criteria.

1.2 Research questions

This study seeks to gather state-of-the-art information on the following issues:
- Currently known potential future biofuel processes.
- Biomass availability in the Netherlands and import requirements.
- Technical, environmental and economical limitations of these potential processes on a commercial scale.
- Their potential for net greenhouse gas reduction.
- Timing of availability (for the period through to 2010 and in the longer term).
- Quality of the fuels (e.g. potential problems in meeting current fuel quality specifications, blend characteristics).
- Impact on the Dutch economy (where will the fuels be made?).
- Comparison of costs and greenhouse gas reduction potential of these future biofuels with those of currently available biofuels and other applications of biomass (mainly in the electricity sector).

It is assumed that both the current and potential future biofuels and their blends will meet current European fuel specifications.

The horizon of the study is the year 2020 and the analysis has therefore been restricted to biofuels and conversion technologies which, on current expert opinion, have the potential to become commercially available within the next 15 years (see section 2.2).

1.3 Project approach

In recent years, biofuels have been studied extensively by various research institutions worldwide. The present study is based mainly on the results of several recent review studies that have looked at both currently available processes and future fuels.

For the overall picture and a general understanding of the topic as well as greenhouse gas emission data, the following two reports were used:
- A study by Concawe [Concawe, 2004].
- A study by General Motors [GM, 2002].

These studies analyse both current and future biofuels, using the same basic assumptions and methodology. In addition, a number of other reports were used, including a Dutch fact-finding study by Ecofys [Ecofys, 2003], a recent IEA study on biofuels [IEA, 2004], a study by the German institute IFEU [IFEU, 2004] and reports and publications on specific fuels. A complete list of the literature used can be found at the end of this report.

The information gathered in this literature study was then augmented with information from various experts, scientific institutes, oil companies, biofuel producers, car manufacturers and so on.

Nevertheless, the reader should bear in mind that this report (in fact any report on future biofuels) can be no more than a 'scouting study', an exploration of potential biofuel developments over the next 10 to 15 years. Biofuel processes as well as the biomass market will be under continuous development in the coming years, under the influence of both changes in government incentives – national and international, and for biofuels as well as other biomass applications – and the success or otherwise of technological research. These developments are clearly very difficult if not impossible to predict. There is no way to disperse these uncertainties, however, and governments still need to decide what policies to implement and businesses what investments to make in R&D and production facilities. This report therefore aims to provide insight into potential biofuel developments, the main improvements these developments are expected to embody, and the problems that need to be resolved before the full potential of the fuels is achieved.

1.4 Report outline

The report is organised as follows:

In chapter 2, *potential future biofuel processes* are identified (section 2.2) and various methodological issues addressed.

Since all biofuels have in common that they are produced from biomass, chapter 3 is devoted to an analysis of the *various types of biomass and their availability in the Netherlands and internationally*, as well as to *potential negative side-effects* of large-scale biomass use.

In chapter 4, the (potential) *technical, environmental and economical performance* of both current and future biofuels are evaluated. For each biofuel investigated in this study, the potential for *net greenhouse gas reduction* is given, as well as its (expected) *cost*. In addition, their *quality and blend characteristics* are discussed.

In chapter 5, the current status of the technologies required for future biofuel production is described as well as tangible activities in the Netherlands. Based on these data, conclusions are drawn regarding the potential *timing of availability* of these biofuels.

In chapter 6, the costs and greenhouse gas reduction potential of the future biofuels are compared with future use of biomass in the electricity sector.

The conclusions of the study and the resulting recommendations are given in chapter 7.

2 Methodology

2.1 Introduction

In this chapter we discuss several key methodological issues:

- The fuel chains covered by this report.
- The aspects analysed.
- The methodology used to calculate net greenhouse gas reductions.
- The conventional fuels chains used to define the reference situation.

2.2 Selection of biofuel chains

This study focuses on those biofuel routes considered to have the potential for being commercially available before the year 2020. However, all the processes for future biofuels that are currently under development still face technical problems and high costs. Only time will tell whether the technical hurdles can indeed be taken and costs sufficiently reduced over the next 10-15 years for large-scale market introduction to become a reality.

We have based our selection of potential future biofuel routes on the conclusions and recommendations that came out of the first two phases of the Dutch Biomass Transition programme [EZ, 2003] and other literature such as the recent IEA report 'Biofuels for Transport' [IEA, 2004]. In the Biomass Transition programme, being carried out under the supervision of the Ministry of Economic Affairs, a number of promising, so-called 'transition paths' have been identified, some relating to automotive fuels. The resulting list of potential future biofuel routes included in this report is shown in Table 1. In this table we have included the fossil fuel or fuel component that is likely to be replaced by the various biofuels. Most of these petrol and diesel substitutes can either be used as a pure, 100% fuel or blended with fossil fuels. In some cases engines need to be adapted if the biofuel percentage is over 5-15%, or fuels modified to adhere to current fuel specifications. These technical issues will be discussed later in more detail.

Table 1 Potential future biofuel routes included in this report

Conversion routes not yet commercially available	**Fossil fuel counterpart**
Bio-ethanol	
from cereal residues	Petrol
from residues containing lignocellulose	Petrol
from cultivated, short-cycle wood	Petrol
Ethyl Tertiary Butyl Ether (ETBE)	
from bio-ethanol	Fossil MTBE / Petrol
Hydrothermal Upgrading (HTU)	
from residual organic feed with high water content	Diesel
Biomass FT-diesel[7]	
from dry residues	Diesel
from cultivated, short-cycle wood	Diesel

Pyrolysis is also considered an attractive technology for converting biomass to oil. However, it is expected to be used rather as a pre-treatment option for biomass, as the resultant oil cannot be used directly as an automotive fuel or blended with diesel. Given the very limited information available on the conversion of pyrolysis oil to automotive fuels, this option has not been included in this study.

To illustrate the potential benefits of these future fuels compared to those produced using today's technologies, we also include a brief review of currently available biofuels. This analysis is limited to those biofuels considered in the report ‘Biofuels in the Dutch market: a fact-finding study’ [Ecofys, 2003]. The fuels in question are listed in Table 2. Throughout this report, the term ‘biodiesel’ is used for Fatty Acid Methyl Esters, often referred to as FAME. Note that FAME is not the same as pure vegetable oil, sometimes also referred to as biodiesel. Both may be produced from vegetable oil, but the latter is chemically unmodified.

Table 2 Currently available biofuels included in this report.

Commercially available conversion routes	**Fossil fuel counterpart**
Biodiesel	Diesel
Bio-ethanol from cereal and sugar residues	Petrol
ETBE from bio-ethanol	Fossil MTBE / Petrol

2.3 Aspects analysed

To assess these fuel chains, the following aspects have been examined.

- Technological status.
- Technical, environmental and economical limitations of these potential processes on a commercial scale.
- Potential for net greenhouse gas reduction.

7 FT stands for the Fischer-Tropsch process, in which syngas is converted into diesel fuel and naphtha (basic petrol), among other products. Syngas is the product of a biomass gasification process.

- Biofuel costs (€/litre) and cost efficiency (€/tonne CO_2 reduced).
- Timing of availability.
- Biofuel quality.
- Biomass availability in the Netherlands and import requirements.
- Impact on the Dutch economy (where will the fuels be made?).

Some of these topics will be discussed separately for each biofuel, while others will be discussed in more general terms.

2.4 Methodology for calculating GHG emissions reduction

In discussions on the environmental performance of biofuels, one of the main issues is usually the net reduction of greenhouse gas (GHG) emissions to be achieved. These emissions are generally calculated using the methodology of Life Cycle Analysis (LCA). The net greenhouse gas reduction per unit of fuel is then determined by comparing:

- The total direct and indirect emissions of greenhouse gases associated with production of the fuel, taking into account the entire route from cultivation of the biomass through to use of the biofuel in motor vehicles (including transport of biomass or fuel, conversion of feedstock to biofuel, etc.).
- The total direct and indirect emissions of greenhouse gases associated with both production and consumption of the equivalent amount of the fossil fuels substituted by the biofuel[8] (i.e. the reference situation).

The net greenhouse gas reduction per unit of biofuel is then given by the difference between these two aggregated figures.

In the biofuel routes, the amount of CO_2 taken up by the biomass from the air during cultivation is equal to the CO_2 emissions resulting from combustion of the biofuels (during driving). These are part of the carbon cycle, and have not been taken into account. When analysing emissions from fossil fuels, on the other hand, the CO_2 emissions from combustion are included in the analysis, as this is carbon that was removed from the earth's atmosphere many million years ago.

It has been assumed, furthermore, that consumption of biofuels is equal to consumption of their fossil counterparts, in terms of energy content. This means, for example, that 1 GJ petrol will be replaced by 1 GJ bio-ethanol.

A description of the methodology used for these calculations, and data on energy content of the fuels, are provided in Appendix A.

2.5 Emissions and costs of conventional fuel chains

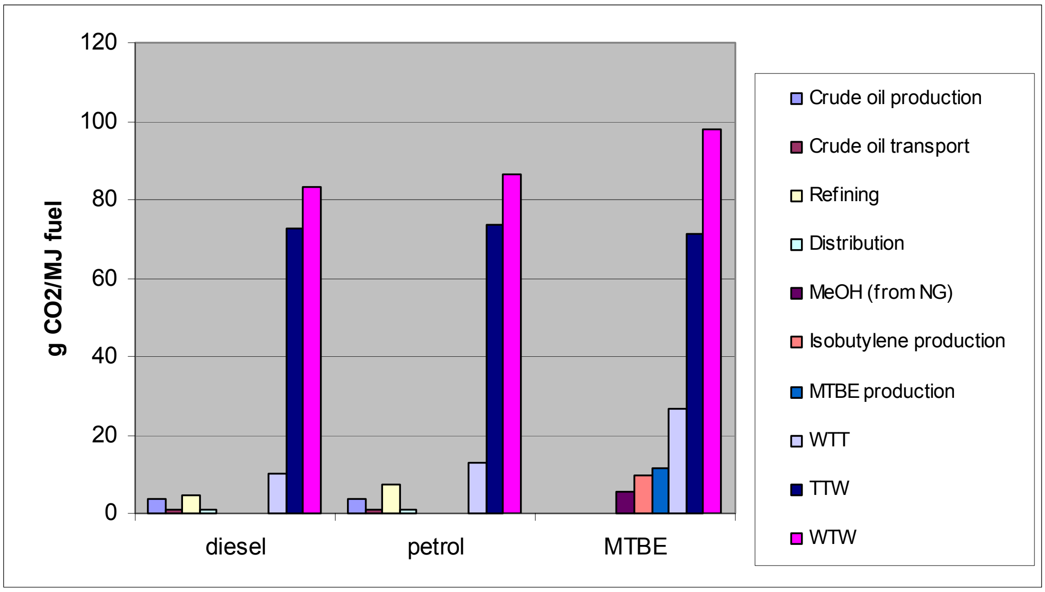
In calculating the GHG reduction potential of the various biofuels, the fuel chains are compared with the emissions of the petrol, diesel or MTBE they replace. The data given in Figure 3 represent an average of GHG emissions over the various links of the petrol and diesel fuel chains, as supplied by European oil companies

8 For ethanol this would be petrol, for ETBE it would be MTBE, etc..

[GM, 2002]. These data are valid for 2010. The indirect and direct GHG emissions of MTBE are based on research by IFEU [IFEU, 2005].

The figure shows the total GHG emissions of the various fuels (from well to wheel, WTW), as well as the direct emissions occurring during fuel combustion (tank to wheel, TTW) and the emissions occurring in the phase between well and tank (well to tank, WTT). The latter have also been broken down, being somewhat different for MTBE than for petrol and diesel.

Figure 3 Greenhouse gas emissions of diesel, petrol and MTBE. WTT = Well to Tank; TTW = Tank to wheel; WTW = well to wheel (i.e. total emissions over the fuel chain) Note that the first four bars (from crude oil production to distribution) apply to diesel and petrol only, the next three (MeOH to MTBE production) to MTBE only



Source: [GM, 2002] and [IFEU, 2005].

The Concawe study [Concawe, 2004] gives WTT GHG emissions for petrol and diesel that are well within the same range: 13 and 14 grams indirect GHG emissions per MJ fuel, respectively, for petrol and diesel. It is noteworthy, however, that Concawe assigns a higher WTT emission to diesel than petrol, the opposite of the GM results.

The average fuel price (excluding taxes) used in this study is € 0.34 per litre for diesel and € 0.36 per litre for petrol. As fuel prices are prone to wide fluctuation, we chose to use a three-year average of Dutch fuel prices (2002-2004), based on information from DG TREN [TERM, 2005].

2.6 Calculating total GHG reduction potential

To illustrate the GHG reduction potential of the various fuels, two scenarios are presented for each biofuel.

- First, the total GHG reduction potential is calculated for the case in which the biofuels are blended with their fossil counterparts, up to the maximum percentage currently permitted (5% for ethanol, biomass FT diesel and HTU diesel and 15% for ETBE). All the biofuels considered can be blended (at least) up to these limits without any modifications to vehicles.
- Second, the GHG reduction potential is calculated for the case in which the biofuel has replaced 20% of all transport fuels. This would mean the overall EU target for use of alternative fuels in 2020 being met solely by the biofuel in question[9].

The second scenario enables fair comparison of the impact of the various biofuels analysed, since their potential is not limited by the shares of petrol and diesel in the total transport fuel market, as in the first scenario. This scenario has been included for illustrative purposes only, for achieving it would require very significant efforts and costs.

The various data are calculated for the year 2020. Fuel consumption figures for diesel and petrol in that year have been taken from the latest Dutch 'Reference Study' [RIVM, 2003]. According to that study, total road transport CO_2 emissions in the Netherlands are projected to be about 39.1 Mtonne in 2020 (both direct and indirect)[10].

It should be noted that the petrol-to-diesel ratio assumed in the first scenario may well change, owing either to introduction of biofuels or to other developments not included in the cited 'Reference Study'. As this will depend on factors as yet unknown (such as government incentives and trends in biofuel costs) this issue has not been taken into account here.

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9 Which is not in fact the aim or intention of the EU Green Paper setting this target [EC, 2001]. The document sets a target of 20% for all fuel substitutes by the year 2020, of which 7% is to be achieved using biofuels.

10 Of these 44 Mtonnes, 5 are indirect emissions (extraction, refinery, distribution). 28 Mtonne can be allocated to diesel vehicles, 9.3 Mtonne to petrol vehicles and 1.7 Mtonne to LPG vehicles.

3 Biomass for biofuels

3.1 Introduction

Because all biofuels require biomass and several biofuels use similar or even the same type of biomass, there are several common issues that can be discussed at a general, i.e. non-specific level.

We start this chapter with a brief review of the different types of biomass used for production of the various biofuels (both current and future). We then discuss the availability of biomass in the Netherlands, other EU countries and the rest of the world. In sections 3.4 and 3.5 we examine several other key issues, such as potential competition with food production, effects on land use and biodiversity, and the possible impact of large-scale biomass use on the Dutch economy.

3.2 Types of biomass

There are several different types of biomass that can be used for the production of biofuels. For the purpose of this study we distinguish the following three categories:

- Residues (from the food, beverage or fodder industry, or organic waste from households).
- Food crops (such as rapeseed, sunflowers, cereals or sugar cane).
- Short-cycle wood and other lignocellulosic biomass (such as poplar, certain grasses, etc.).

As we shall see later in this report, the GHG reduction potential of a biofuel, its cost and potential competition with food production all depend on the type of biomass employed as a feedstock.

3.3 Availability

The main issues determining the availability of biomass for biofuel and energy purposes are the following[11]:

1 Future demand for food, a function of population growth and future diet.
2 The efficiency and yield of food production, especially in developing countries.
3 The yield from forests and energy crops.
4 The use of biomass for other purposes.
5 The availability of marginal or set-aside land.
6 Competition between various land use options, for example between biomass cultivation and reforestation.

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[11] From '*Beschikbaarheid biomassa voor energieopwekking*' (GRAIN), GAVE, August 2000.

3.3.1 Availability in the Netherlands

In [Ecofys, 2003] a best estimate for biomass availability was made using a number of studies devoted to the topic. The best estimate for total Dutch bio-energy potential was found to be about 180 PJ/y. This figure is considered to hold for the current situation as well as for 2010. The food and beverage industry is the major source of biomass (animal fat, vegetable oils). Of this potential, only 32 PJ/y is suitable for the production of currently commercial biofuels (i.e. fuels meeting fuel quality standards). However, most of this biomass can also be used for other applications. Therefore, when these products are used for biofuels, other buyers need to switch to alternative products. For example, of these 32 PJ/y, 15 PJ/y are feed grains. When these are being used as a biofuel feedstock, (which assumes bio-ethanol producers paying more than the Dutch fodder industry), additional feed would then have to be imported.

In the longer term, we estimate that a fairly substantial share (over 60 PJ) of the total bio-energy potential is non-food biomass that could be used in the more advanced biofuel production processes (e.g. for HTU or Fischer-Tropsch conversion). However, the actual availability of biomass for biofuels depends on the economics, with the following main drivers:

- The higher the price biofuel producers are willing to pay, the more biomass they will be able to buy.
- The more demand there is for biomass (from the food and fodder industry and electricity, chemical and transport sectors), the higher the price.

For comparison: the amount of biofuel needed in the Netherlands to meet the indicative 2010 target of the EU Biofuels Directive is 29 PJ (fuel), which requires approximately 65 PJ biomass.

3.3.2 Availability of biomass in the EU and worldwide

Since the amount of biomass available for fuel production in the Netherlands is limited and costs are relatively high, large-scale biofuel use will mean that either the biomass or the biofuels themselves will have to be imported. In both cases, the biomass may come either from other EU countries or from elsewhere.

The Ecofys study [Ecofys, 2003] gives a best estimate of around 7,000 PJ/y for biomass production in the EU, consisting mainly of energy crops. This is considerably higher than total EU demand for bio energy in 2010, projected to be about 4,000 PJ. However, the issue of competition with other biomass applications makes it difficult to draw any solid conclusions about the amount of biomass that will be available for biofuels.

At present, the amount of biomass available in the EU for today's biofuels as well as its cost depend intimately on EU agricultural policy, especially with respect to set-aside land (relevant for the crops used for biodiesel) and sugar policy (relevant for bio-ethanol and ETBE). Future biofuel routes are expected to be able to convert lignocellulosic biomass, which is not affected by current EU agricultural policy.

Scenarios for future biomass availability cover an enormous range, with the following variables constituting the main unknowns:

- Population growth.
- Average diet.
- Agricultural productivity.

Scenario studies show that forecasts of biomass availability may vary by a factor five, depending on the parameters used.

3.4 Potential negative side-effects

In the following, a number of potential negative side-effects of large-scale biomass cultivation for biofuels are being discussed. There is currently no form of certification or other regulation in place to address or control these effects [CE, 2005b].

3.4.1 Competition with food and fodder

As we shall see in the next chapter, today's biofuels require biomass feedstock that:

a Is grown on set-aside land[12], or
b Is grown on soil that could also be used for growing food crops, or
c Uses by-products from the food and fodder industry that would otherwise be used for fodder.

In the first case, competition with food crops is unlikely. In the second case, competition with the food chain will occur if agricultural land is scarce, fertile soils being suitable for growing either food, fodder crops or biofuel (energy) crops. If cultivation of biofuel crops is more profitable to a farmer than growing food or fodder crops, they will switch. This will increase the prices of food and fodder crops. In the latter case, there is also competition with the food chain, albeit indirectly, via the fodder industry. Additional fodder will need to be cultivated, either in the Netherlands or elsewhere (depending on costs and possibly taxes and subsidies). This will have the same effect as in the first case.

As the potential of set-aside land is limited, large-scale production of current biofuels is likely to lead to competition with food production. This might result in increased food prices, which could have significant socio-economic effects, especially in third-world countries. The effects are as yet uncertain, however. Although the impact will obviously increase as demand for biomass in the transport sector grows, it will depend very much on future global food consumption, which, as already mentioned, is very hard to predict. Some experts

[12] Set-aside land is productive land that is currently 'surplus' as a result of European regulations on food production or left fallow for healthy soil management. Farmers with holdings over a certain size are obliged to leave 10% of total cultivated acreage fallow, receiving a per-hectare payment to compensate for lost income. Under the regulations, non-food crops may be cultivated on set-aside lands. Cultivation of energy crops like oilseed rape and sunflower might generate additional farmer income, thereby increasing the feasibility of energy crops.

do not necessarily expect there to be undue competition (GRAIN study[13]), while others do.

The future biofuel production processes discussed in chapter 4 are expected to result in much less competition with the food chain. They have the advantage that they can also convert lignocellulosic biomass, which can grow on different types of soil than the biomass needed for today's biofuels and requires substantially less land to cultivate. In addition, these processes can use lignocellulosic by-products from the food and fodder industry, which are less valuable products than sugar or cereal residues, for example, as cattle cannot digest them as easily. These can therefore be replaced by far less valuable and demanding products like grass.

However, if demand for these kinds of biomass and biofuels increases beyond a certain point, the impact on land use may still be significant.

3.4.2 Effects on biodiversity and ecosystems

The EU has set itself the goal of halting the loss of biodiversity in Europe by 2010. Protecting the natural values of European farmland still characterised largely by extensive farming practices has been identified as one of the key elements of achieving this goal. A recent report by the United Nations Environment Programme and the EEA [EEA, 2004] highlights the importance of such farmland and points to the serious decline in the conservation status of these areas. If extensively farmed land or even forest is converted to energy crop production or intensive food production under increasing demand for land, biodiversity will be lost as a result, because in most cases this will mean an intensification of production patterns.

Ecosystems may also be harmed by more intensive forms of biomass farming, among other things through changes in the water table, the impact of increased pesticide use on surface water quality and encroachment on wildlife habitats.

With the exception of HTU, the future biofuels processes are expected to mainly convert woody biomass. Feedstock can then either be woody organic residues or wood or grasses grown in plantations. The latter involves environmental risks that are similar to that of the current biomass plantations. The environmental impact of wood plantations could be reduced if the wood is produced under sustainability regulations like the FSC system which is currently in place for wood products. If the wood is imported without sustainability guarantees environmental problems like cutting down of rain forests or no replantation are possible, as the conventional wood market has shown. These effects may be avoided by using residues. However, as explained earlier, this may cause alternative users of these residues to switch to wood grown in plantations, resulting in a similar impact.

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13 This study was a co-production of Utrecht University, RIVM, Wageningen University, ECN and Ecofys, commissioned by Novem (2000).

3.4.3 Transport of biomass

Given the limited amount of farmland still available in the Netherlands, the bulk of' the biomass required for Dutch transport fuels is likely to be imported. This might mean large volumes of biomass being transported from more sparsely populated but fertile regions, in South America or Eastern Europe, for example. If the biomass itself is transported, there may be a significant increase of fuel-related transport volumes, because of the much lower energy density of biomass compared with fossil oil. This could result in increased transport emissions compared with the current situation[14].

3.5 Import: effects on the Dutch economy

The Netherlands are currently a significant player in the EU fossil fuel market. Much of EU refinery capacity is situated in the Rotterdam area and large import and export flows of crude oil and oil products pass through the area and the port of Rotterdam itself. While European substitution of fossil fuels by biofuels will lead to some depression of the activities in the industries in question, the economic effects could of course be compensated by growth of biofuel production and refinery operations as well as the transport and distribution of both biomass and biofuels.

The impact of any biofuels on the Dutch economy depends mainly on where the biomass is cultivated and where the biofuel is produced. Both steps in the biofuel chain can generate employment and added value for the Netherlands. Furthermore, the port of Rotterdam is actively seeking to become a major harbour for importation and distribution of biomass or biofuels in the EU.

If and when a global market for biomass and biofuels evolves, the Netherlands is unlikely to play more than a marginal role as a feedstock producer, given our high labour costs and shortage of space. Whether the Netherlands can build up an industry in the field of biofuel production and imports of biofuel or biofeedstock will probably depend very much on the policies put in place both nationally and internationally. Given the tax benefits and other incentives already implemented or soon to be implemented in many EU countries, various biofuel producers will be building production facilities in the EU in the coming years for the current generation of biofuels. Plans to build such plant in the Netherlands have, to the best of our knowledge, not yet come to fruition. Dutch policies regarding incentives for current and future biofuels will obviously play a part in shaping those plans. Overall industry policy and the appeal of Rotterdam port as a key biomass import terminal also remain important.

From a logistical point of view, it is certainly very feasible for the biofuel production industry to be located near the seaport of Rotterdam, which already plays such a pivotal role in imports of raw materials from outside Europe. In addition, the Rotterdam region is already well established as a competitive location for fuel production.

[14] Note that there are no fuel taxes on bunker fuels for international shipping and that marine shipping is not included in either the Kyoto agreement or the NEC directive.

For the different scenarios, input-output (IO) analysis can be used to calculate the share of expenditures that will end up abroad and the share added to the national economy. Such analysis leads to the conclusion that feedstock production, conversion and distribution create substantial added value in the form of wages, as long as the crops are grown on set-aside land.

If biofuel feedstocks are produced on non set-aside land, they will substitute food crops that, given stable demand, will need to be additionally imported. This implies that under circumstances where feedstocks are produced on non set-aside land, the macro effects on the economy will be approximately the same as the macro effects of feedstock import [15].

We expect future biofuels to have a broadly similar impact on the Dutch economy and to create similar opportunities. As conversion of lignocellulosic material becomes commercially feasible, the potential for biomass cultivation in the Netherlands will also increase. Once any significant amount of these biofuels is required, however, we still expect most of the required biomass to be imported. As for today's biofuels, whether or not biofuel production companies opt to locate their production facilities here will depend very much on the policies put in place by Dutch governments, compared with those of other European countries.

[15] Exactly the same in the case of wheat-to-ethanol, since additional wheat will be imported.

4 Current and future biofuels

4.1 Introduction

In this chapter currently available and potential future biofuels are analysed individually, discussing for each fuel the following issues:

- Technology.
- Greenhouse gas reduction potential.
- Costs.
- Cost effectiveness (Euro/tonne CO_2 eq. reduced).
- Biofuel quality and operational aspects.
- Total CO_2 reduction potential.

In our present context, *currently available biofuels* are the biofuels produced within the EU and elsewhere that, when blended (up to a given percentage) with diesel or petrol, can be used by the current Dutch fleet of passenger cars and trucks. In line with the approach taken in the Ecofys study [Ecofys, 2003], this means we consider the following biofuels:

- Biodiesel from rapeseed.
- Bio ethanol and ETBE from sugar beet and wheat.

The *future biofuels* considered in this analysis are currently under development. Though not yet on the market, they seem to have the potential for significantly improved environmental and cost performance compared with current biofuels. The following biofuels are considered:

- Ethanol and ETBE produced from lignocellulosic biomass.
- FT-diesel.
- HTU-diesel.

In the next chapter we report on the current status of these emerging technologies and estimate when marketing of the respective biofuels is to be anticipated on any significant scale. The principal conclusions of this analysis will be drawn later, in chapter 7.

As already stated, the main focus of the present report is on future biofuels, currently available biofuels having recently been analysed in depth in [Ecofys, 2003] and other literature. In this chapter we discuss them together, however, to allow comparison between the various future options (clearly, current biofuels will also be available in the future) and provide insight into the potential improvements that future biofuel production processes may embody.

4.2 Biodiesel (RME)

Technology

Biodiesel is the general name given to methyl esters produced from organic feedstock[16]. In Europe, the most commonly used feedstock is rapeseed oil. However, other oils like palm oil, for example, can also be used. The General Motors study [GM, 2002] provides a comprehensive review of the various steps in the rapeseed to biodiesel chain and the assumptions made in the literature and employed in their analysis; here we merely use the results. In a processing plant the oil is extracted with hexane, refined and esterified with methanol. The esterification process yields glycerine as a by-product[17].

Biodiesel is currently widely available and marketed in several European countries.

GHG reduction potential

The General Motors study assumes rapeseed is grown in a rotational system on set-aside land and takes rye grass as the reference system (i.e. the crop that would otherwise have been grown on the land)[18]. The GM-study assumes fertiliser use of between about 100 and 145 kg per ha and a crop yield of about 3 tonnes per ha. N_2O emissions are calculated according to the IPCC method, with average assumptions. Crop residues are ploughed in, as is usual in the case of rape crops. The by-product glycerine will generally replace glycerine produced conventionally in the chemical industry. If the amount produced exceeds market demand (as biodiesel output increases beyond a certain point), the glycerine will be used as a fuel, i.e. for heat generation.

Using these assumptions and ranges, the GM-study calculates the total GHG emissions per MJ biodiesel. The results are reproduced in Figure 4, for the two alternative applications of the glycerine by-product and for low and high fertiliser use. Biodiesel GHG emissions are found to be 21-73% of diesel emissions. Most of these emissions occur during cultivation of the rapeseed, as is illustrated in Figure 5, showing the share of GHG emissions attributable to the various links in the biodiesel chain, for the case with glycerine used as a fuel and low fertiliser inputs. Note that CO_2 emissions from biodiesel combustion (emitted during driving) have not been included in these figures because these emissions are equal to the amount of CO_2 taken up by the biomass during growth (see Appendix A.3).

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[16] As mentioned above, in this report we do not consider pure vegetable oil, which is sometimes also referred to as 'biodiesel'.

[17] Although by-product glycerine is produced in most scenarios, a biodiesel production process has been developed by the Axens company (www.axens.net) that does not use methanol nor yield glycerine as a by-product.

[18] In contrast to the review of bio-ethanol below, Egyptian clover has been ignored as a reference system here, as the difference with rye grass is fairly limited. Moreover, we assume rye grass is a better reference for growing energy crops on set-aside land in the Netherlands.

Figure 4 Greenhouse gas emissions of biodiesel (g CO_2 eq./MJfuel) for different scenarios. Results are given for 2 different applications of glycerine by-product, and for low and high fertiliser use (approx. 100 vs. 145 kg N per ha). For comparison, the total GHG emissions of diesel are also shown

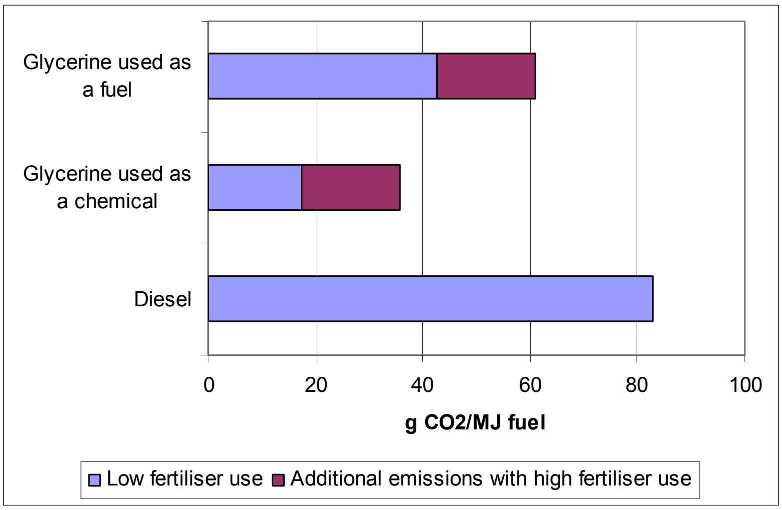
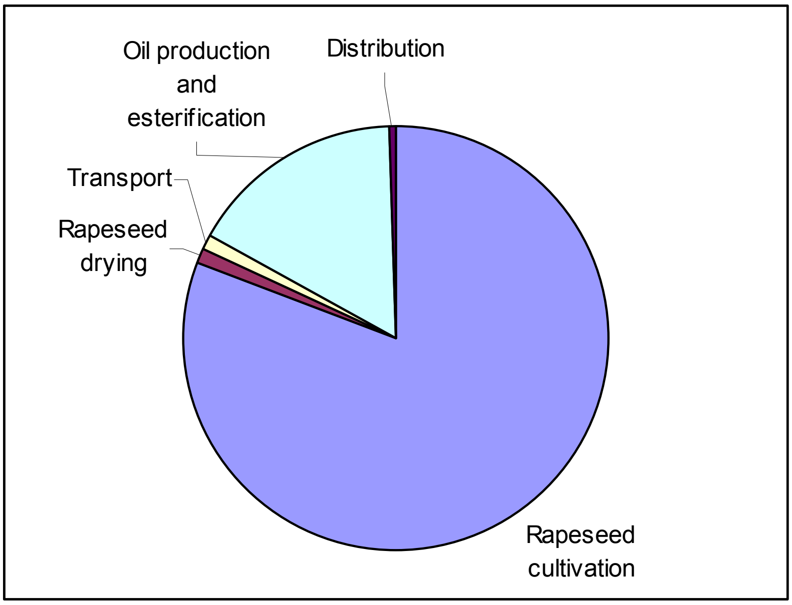


Figure 5 Greenhouse gas emissions associated with successive links of the biodiesel chain (with glycerine by-product used as a fuel and low fertiliser use: about 100 kg N/ha)



These results are based on average emission factors for nitrous oxide. In reality, however, emissions of this greenhouse gas are highly variable, differing per soil type, climate and fertiliser input. They are consequently of major influence on total GHG emissions. For most regions of the Netherlands emissions are probably somewhat higher than calculated using default IPCC values, because of soil moisture levels and climate.

In view of the uncertainties involved, it is not surprising that other studies make different assumptions, yielding different results. The Concawe study gives best estimates of between 54 (32-73) g CO_2 eq/MJ with animal feed as a by-product and 49 (29-69) g CO_2 eq/MJ with chemical feedstock as a by-product. The latter figure is somewhat more conservative than the GM results, due mainly to different assumptions being made with respect to the production phase. The GM-study assumes the glycerine is of pharmaceutical quality, with a very good energy ratio. According to the Concawe study, however, this market is small and they therefore assume the glycerine will replace antifreeze, giving substantially less by-product 'credits'.

Recent insights [CE, 2005d] show that in Dutch and German rapeseed cultivation, per-hectare yield as well as fertiliser use are on average higher than assumed in the GM-study. However, the two effects roughly cancel one another out (the former reducing GHG emissions, the latter increasing them).

These results lead to the following conclusions:

- Biodiesel GHG emissions are approximately 21-73% of diesel GHG emissions. This wide range is due mainly to the bandwidths and uncertainties in fertiliser use, the per-hectare yield assumed and the fate of the by-product, glycerine. If fertiliser use is limited and the glycerine can be sold to the chemical industry, emissions will be low. If more fertiliser is used and the glycerine cannot be sold as a chemical, the GHG emissions of the biodiesel will be higher. The range becomes even larger if uncertainties in N_2O emission factors are included.
- Most of these GHG emissions occur during rapeseed cultivation and are due to the N_2O emissions from nitrogen fertiliser.

As mentioned earlier, biodiesel can also be produced from other types of vegetable oil. However, different plants will have different requirements regarding fertiliser and energy use, for example, giving the resulting biodiesel a different GHG reduction potential. As an example, according to [Patel, 1999] production of palm oil methyl ester, or PME, is associated with a global warming potential burden of 370 kg/tonne, or 10 kg/GJ. Our own research [CE, 2005c] suggests, by contrast, that that burden is 3,500 kg/tonne, or 94 kg/GJ crude palm oil, taking into account allocation of part of the environmental burden of palm oil tree cultivation and crude oil extraction to co-product palm kernel. This would mean that substitution of diesel by PME leads to an *increase* in greenhouse gas emissions.

Costs

The costs of biodiesel depend very much on rapeseed costs and yield, conversion factors, the price of glycerine, etc. In [Ecofys, 2003] a literature study was carried out to assess these costs, yielding estimates ranging from € 0.49 – 0.95 per litre (15.1 – 29.3 €/GJ), with a best estimate of € 0.73 per litre (22.5 €/GJ).

To run on blends containing over about 20% biodiesel, vehicles require modification, as the fuel can cause certain types of elastomers and natural rubbers to degrade [NREL, 2001; IEA, 2004]. Various rubber hoses, seals and gaskets may therefore need to be replaced with more resistant materials. A number of car manufacturers have specified which components of their cars and engines are compatible with biodiesel (see, for example, the list at www.biodiesel.de). All other vehicles will need to be adapted, generally at a cost of a few hundred Euros.

Cost effectiveness
With such substantial ranges in estimates of both cost and net GHG reduction, the resultant range in cost effectiveness is even larger: approximately 90 to 900 €/tonne CO_2. Using the best cost estimate from the Ecofys study [Ecofys, 2003] and the assumptions of glycerine being used as a fuel and average fertiliser use, the cost effectiveness is 320 €/tonne CO_2.

Biofuel quality and operational aspects
Biodiesel is currently available in blends or as neat fuel in several EU countries, for example in France (5% blend), Austria and Germany. Biodiesel is more aggressive to some coatings and elastomers than conventional diesel [NREL, 2004; IEA, 2004]. It can therefore only be blended with conventional diesel up to a certain point (with the exception of several vehicle models, mainly German). Low percentages can be used without difficulty, as has been proven in France.

The European Committee for Standardization (CEN) has produced a standard for FAME (Fatty Acid Methyl Ester – standard EN 14214), laying down technical specifications for biodiesel. The new (fossil) diesel standard limits the volumetric content of FAME in diesel to 5% by volume. Therefore, blends over 5% require specific labelling at the sales point [EC, 2003].

Total CO_2 reduction potential
As explained in section 2.6, we now consider the total CO_2 reduction potential in 2020 for two cases:

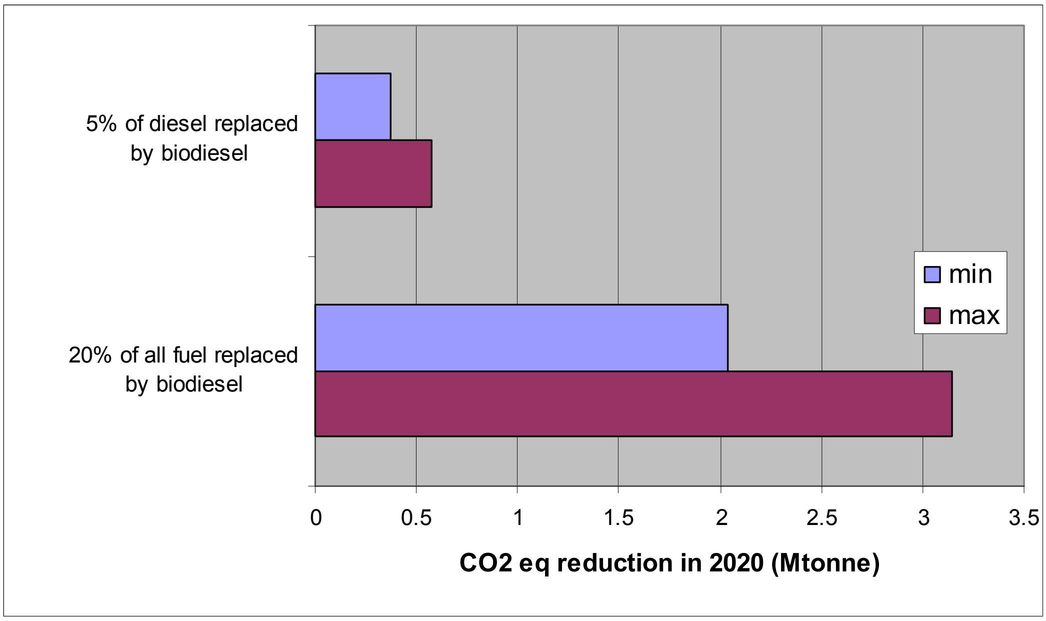
- A scenario in which 5% (on energy basis) of all diesel consumed in the Netherlands in 2020 is replaced by biodiesel. In this scenario, no additional costs of vehicle modification are implied.
- A scenario in which 20% of all transport fuel is replaced by biodiesel. This scenario probably requires large-scale vehicle overhaul, the full extent depending on whether this market share is achieved with 100% biodiesel in specific markets[19] or with biodiesel blended with regular diesel fuel. Consequently, the CO_2 reduction potential given is more an approximate indication than a realistic scenario.

The results are shown in Figure 6. The range in reduction potential (indicated by the minimum and maximum estimate) is based on the various fuel chain scenarios discussed above. The fuel consumption figures for both diesel and petrol in 2020 are taken from [RIVM, 2000]. For comparison, total road transport emissions (direct and indirect) are projected to be about 44 Mtonne in 2020.

The results show that in the first scenario, the use of biodiesel can be expected to reduce approximately 0.4 – 0.6 Mtonne CO_2 eq, which represents 0.8 – 1.3% of total road transport emissions in 2020. In the second scenario, about 2 – 3 Mtonne CO_2 eq is reduced, 4.6 – 7.1% of road transport emissions.

[19] It is currently expected that 100% biodiesel will be attractive in certain niche applications only.

Figure 6 Estimated GHG reduction to be achieved with biodiesel in 2020, in two scenarios: a) 5% biodiesel blended in diesel, and b) 20% of all transport fuel replaced by biodiesel. Both minimum and maximum estimates are given



4.3 Bio ethanol

Bio ethanol can currently be synthesised from a wide variety of biomass, as long as it contains readily fermentable sugars or starch. In Europe, bio ethanol is commonly produced from sugar beet and cereals. It can be produced from biomass grown specifically for bio ethanol production (such as sugar cane, sugar beet or cereals), or by converting by-products (secondary products) from the sugar and cereal industry. In Brazil, the world's largest bio ethanol producer, sugar cane is used as a feedstock.

At the same time, a number of companies and research institutes worldwide are working on further development of bio ethanol production processes to enable (ligno-)cellulosic biomass to be used as a feedstock. As discussed in chapter 3, this would yield a number of benefits compared to current technology [IEA, 2005]:

- Access to a much wider array of potential feedstocks.
- Less conflict with land use for food and fodder production.
- Greater net GHG reduction potential.
- More fossil fuel replaced.

Below, the options in which ethanol is produced from sugar beet, cereals or wheat by-products are first discussed, followed by an analysis of ethanol from cellulosic biomass. As the quality and composition of the end product of these options, the ethanol, is independent of the biomass feedstock and conversion process, issues of biofuel quality and operational performance are discussed separately at the end of this section.

4.3.1 Ethanol from sugar beet, wheat or residual C-starch

Technology

If sugar beet is used to produce bio ethanol (E100), the beets are cultivated and transported to an ethanol plant, where the biomass is broken down by fermentation into sugar beet pulp, the by-product, and a water-ethanol mixture. The latter is converted into pure ethanol via distillation. The beet pulp can be used as animal fodder or fuel.

Ethanol can be produced from wheat grains by milling, hydrolysis, fermentation and distillation. The process is more complex and expensive than with sugar beet. Milling and distilling are the most energy-consuming of the unit operations.

In addition, ethanol can be produced from residual organic biomass, for example from by-products of the wheat and sugar beet industry (see for example [CE, 2005a]), as long as these contain sufficient amounts of readily convertible sugars (C6 sugars such as glucose).

GHG reduction

The calculations in the GM-study show what is currently feasible using available technology. As with biodiesel, energy use and GHG emissions are associated with farm equipment use, fertiliser and pesticide use, field N_2O emissions and energy use for feedstock-to-fuel conversion.

Three kinds of by-product allocation are used in the GM-study, and these are found to have a major influence on results:

- Heat credit (by-products are used as a process fuel).
- Sugar beet pulp replaces animal fodder (US soybeans).
- Ethanol is produced in a sugar refinery; in this case, ethanol is produced in conjunction with sugar and seen as a by-product of sugar refinery.

Sugar beets are cultivated in a rotational system and the crop residues are ploughed into the soil. Fertiliser use is approximately 100 kg N/ha/y, while the ethanol yield is estimated at around 4,800 litres per ha. Two different reference systems (i.e. replaced crops) are considered: Egyptian clover and rye grass. The results are shown in Figure 7. Ethanol GHG emissions are found to be 41-86% of those associated with petrol production, depending mainly on use of the by-product. The greatest GHG reduction is achieved with the by-product used as a process fuel, but this option is unlikely, as selling the beet pulp as animal fodder is economically more attractive. The choice of reference crop is less important for the results[20]. The results of the Concawe study are well in line with these results.

Ethanol production from wheat is not analysed in the GM-study, and for this route we therefore used the Concawe results. In their analysis, Concawe do not use a reference crop. The reasoning behind this is that the emissions credit that one

[20] Taking Egyptian clover as a reference results in a somewhat greater GHG reduction for ethanol, as clover binds nitrogen, requiring more fertiliser inputs for subsequent cultivation in the reference cycle. As only the difference between the N_2O emissions of sugar beet and the reference crop is attributed to the ethanol, ethanol N_2O emissions are reduced.

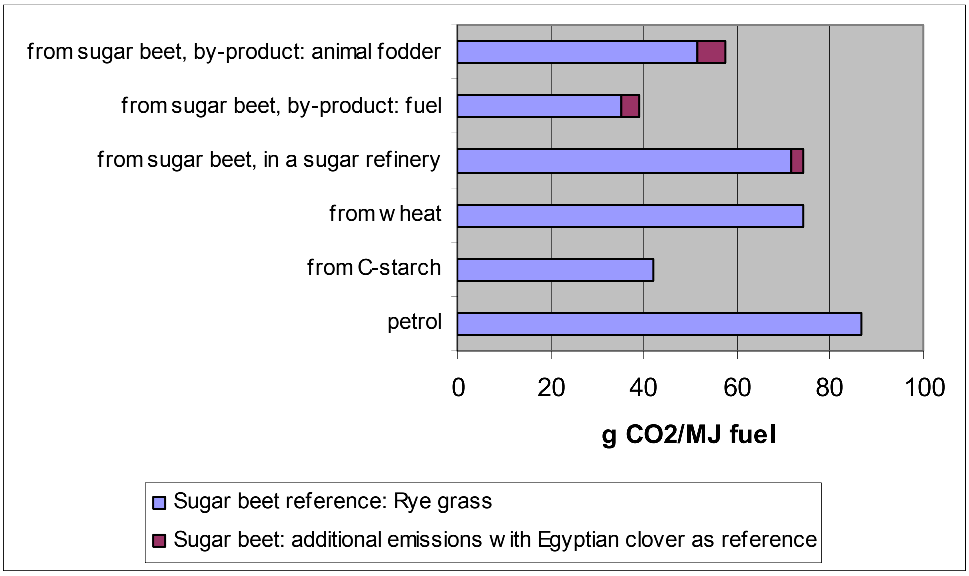
might attribute to a reference cereal crop in the EU is compensated by a debit for growing those cereals elsewhere. In other words, the total amount of wheat grain on the world market will not decrease if EU wheat is used for ethanol production. In any case, we expect the effect of considering a reference crop to be only modest, the range in results associated with by-product allocation and uncertainties in N_2O emissions being far larger.

The Concawe study furthermore assumes that the by-product straw does not have any significant economic value, being generally ploughed back into the soil in the EU to prevent soil degradation. The by-products from the conversion process are given credit for their use as a high-protein fodder supplement. The equivalent quantity of soybean meal replaced by this by-product is calculated on the basis of protein content. The energy and emissions for the soy meal are calculated according to a scenario of US-grown soybeans. The graph shows Concawe's best estimate. GHG emissions are found to be relatively high, about 86% of those of petrol. This is due mainly to the fact that wheat growing is associated with higher GHG emissions that sugar beet cultivation. The ranges given in Concawe are large, between 50-92 g CO_2/MJ fuel, i.e. 57-106% of petrol emissions. According to these calculations then, in the worst case the GHG emissions associated with bio-ethanol from wheat may exceed those of petrol.

CE recently performed an analysis of an ethanol production facility planned by the firm Nedalco that would run on C-starch, a by-product of the wheat industry [CE, 2005a]. In figure 5, the results of this analysis have been included. The GHG emissions of this route are about 50% of those associated with the petrol substituted.

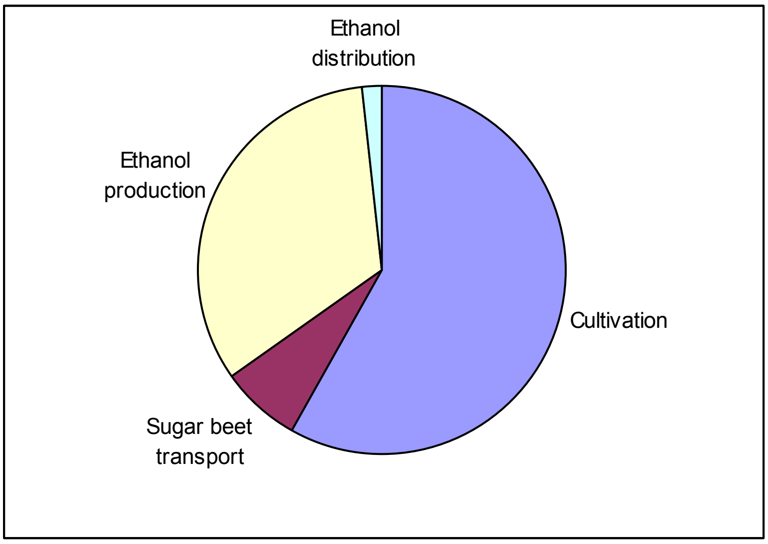
As in the case of biodiesel, most GHG emissions occur during cultivation of the biomass, as can be seen in Figure 8 (for ethanol from sugar beet) and Figure 9 (for ethanol from cereals). However, the contribution of biomass cultivation to total GHG emissions is somewhat less than in the case of biodiesel, and ethanol production also leads to considerable emissions. Ethanol production emissions are higher if wheat is used than in the case of sugar beet, because of the preprocessing required. When residue streams are used, such as C-starch, these products are effectively removed from the cattle feed market. Their use will then have to be compensated by growing additional cattle feed such as cereals, causing additional GHG emissions.

Figure 7 Greenhouse gas emissions of bio ethanol from sugar beet or wheat or C-starch (g CO_2 eq./MJ fuel). In the case of sugar beet, results are given for different applications of the by-product and for two different reference crops. For comparison, the total GHG emissions of petrol have also been included



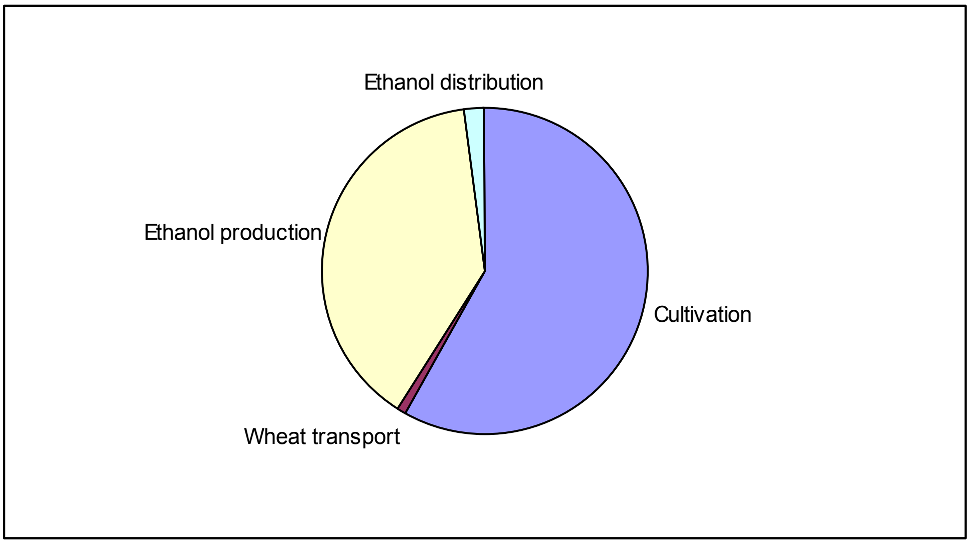
Source: [GM, 2002] and [Concawe, 2004].

Figure 8 Greenhouse gas emissions associated with successive links of the bio ethanol from sugar beet chain (with by-product used as animal fodder and Egyptian clover as reference crop)



Source: [GM, 2002].

Figure 9 Greenhouse gas emissions associated with successive links of the bio ethanol from wheat chain.



As with biodiesel, the calculated GHG emissions depend on a wide variety of assumptions, the most significant of which is the range of emission factors for N_2O emissions. In the above, average IPCC-emission factors have been used[21].

Costs

In the Ecofys study, the costs of ethanol are estimated at € 0.55 (residues), € 0.59 (sugar beet) and € 0.63 (wheat) per litre (26.0, 27.9 and 29.8 €/GJ, respectively), based on a number of available cost studies. A wide range of values is reported in the literature, probably because of differences in raw material costs, different assumptions regarding yield, conversion efficiency, etc.

If the ethanol content of the fuel exceeds about 5%, the additional costs of vehicle adaptation need to be taken into account. These are relatively low, however: currently a few hundred Euro for a new passenger car.

Cost effectiveness

Taking the ranges into account, the cost effectiveness is 450-1,500 €/tonne CO_2. Ethanol from sugar beet is slightly more cost effective than ethanol from wheat, the former route being cheaper and the GHG reduction higher in the best cases.

Total GHG reduction potential in the Netherlands

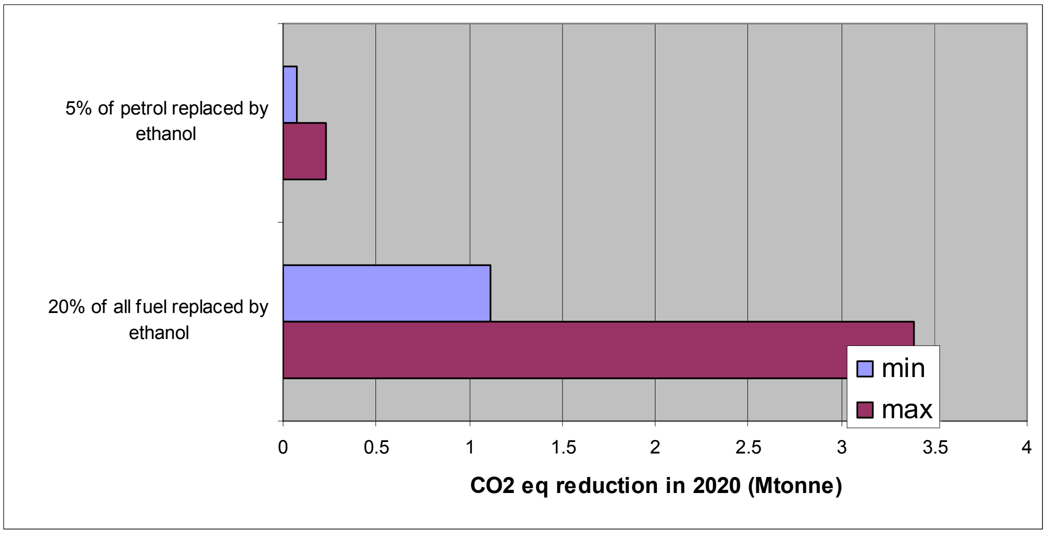
Ethanol can be blended with petrol at different concentrations. We estimate the GHG reduction for two scenarios to indicate the bandwidth in GHG reduction:

- A scenario in which 5% (energy basis) of all petrol consumed in 2010 is replaced by bio ethanol. In this scenario there are no additional vehicle costs.
- A scenario in which 20% of all petrol is replaced by ethanol. This scenario probably requires nationwide introduction of a large fleet of Flexible Fuel Vehicles (FFV), leading to additional costs. The calculated reduction potential is therefore more of a first impression than a realistic scenario.

[21] Different parameter values in the IPCC-guidelines lead to a bandwidth of 0.98 tot 13.70 kg/ha/y.

The results are shown in Figure 10. The range in reduction potential is due to the different fuel chain scenarios available. As the figure shows, 1.1 – 3.4 Mtonne CO_2 eq can be reduced in 2020 if ethanol from sugar beet and wheat replaces 20% of all road transport fuel in the Netherlands (2.4 – 7.7% the transport sector's GHG emissions). In the first scenario, these figures are reduced to 0.1 – 0.2 Mtonne, or 0.2 – 0.5%.

Figure 10 Relative GHG reduction potential of various food crop ethanol scenarios



4.3.2 Ethanol from lignocellulosic biomass

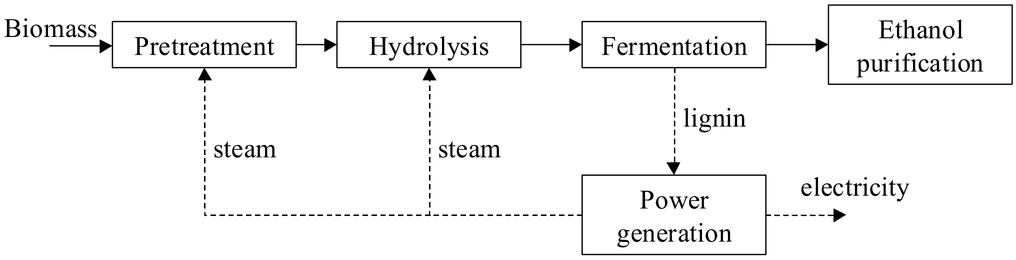
Technology

Ethanol production from lignocellulosic biomass requires additional pre-treatment of the feedstock, to enable fermentation of the sugars contained in the biomass. The fermentation process itself needs to be adapted, furthermore, new kinds of enzymes being required to convert the C5 sugars into ethanol (in the production of ethanol and alcohol today it is only C6 sugars, the main constituent of the current feedstock, that are converted). The process consists basically of four steps, as depicted in Figure 11:

- Pre-treatment.
  This stage is necessary to make the material accessible to enzymes mediating enzymatic hydrolysis and to break down hemicellulose[22] into C5 sugars.
- Hydrolysis of cellulose.
- Fermentation of C5 sugars (xylose) and C6 sugars (glucose).
- Distillation.

[22] Hemicellulose consists mainly of sugars and sugar acids.

Figure 11 Main steps in cellulosic ethanol production



Today's research is directed mainly towards three issues: improvement of the pre-treatment stage, integration of hydrolysis and fermentation in fewer reactors to cut costs, and improvement (incl. cost reduction) of the C5 fermentation process [ECN, 2003]. The progress and success of these developments will determine the future potential of this route and when these biofuels can first be marketed on any significant scale. Both issues are discussed briefly below and in chapter 5; for a more in-depth discussion readers are referred to the literature (for example, [ECN, 2003]).

Pre-treatment

Pre-treatment is necessary to improve fermentation efficiency. The goals of pre-treatment are:

- To make the material accessible to enzymes for hydrolysis, by reducing its volume and opening up the fibrous material.
- To mobilise the lignin and (hemi)cellulose biopolymers and achieve further break-down of structural components to optimise enzymatic access in the following steps.

Several methods are available for pre-treatment, including:

- Dilute acid hydrolysis.
- Alkaline pre-treatment.
- Steam explosion.
- Liquid hot water pre-treatment.

Dilute acid hydrolysis is currently state-of the art and at present the best of these options. The method also has its drawbacks, though, and pre-treatment is still the subject of ongoing research.

Hydrolysis and fermentation

The various potential process configurations for ethanol recovery using enzymatic hydrolysis of cellulose differ in their degree of integration, as depicted in Table 3. SSF is the current state of the art. CBP is considered to be the logical end-point of the evolution of bio ethanol production technology. Co-fermentation of C5 and C6 sugars is the focus for near-term development (SSCF) [Hamelinck, 2004]. The gradual, ongoing integration of reactors will improve the performance of ethanol production from lignocellulosic biomass.

Table 3 Degree of integration of various processing strategies

<table>
<tr><th rowspan="2">Biological event</th><th colspan="4">Processing strategy [a]</th></tr>
<tr><th>SHF</th><th>SSF</th><th>SSCF</th><th>CBP</th></tr>
<tr><td>**Cellulase production**</td><td></td><td></td><td></td><td rowspan="4"></td></tr>
<tr><td>**Cellulose hydrolysis**</td><td></td><td rowspan="2"></td><td rowspan="3"></td></tr>
<tr><td>**Fermentation of C_6 sugars**</td><td></td></tr>
<tr><td>**Fermentation of C_5 sugars**</td><td></td><td></td></tr>
</table>

[a]SHF: Separate hydrolysis and fermentation
SSF: Simultaneous saccharification and fermentation, separate pentose fermentation
SSCF: Simultaneous saccharification and co-fermentation
CBP: Consolidated bioprocessing. The term direct microbial conversion (DMC) is synonymous
Source: [Lynd, 1996]

The organisms that are currently used fall short of CBP, as cellulose production takes place in an aerobic environment and fermentation in an anaerobic. In addition, optimum reaction temperatures are not the same for all the processes.

Bottlenecks for commercial application

Ethanol production from ligonocellulosic biomass has several advantages compared with the conventional technology:

- Use of cellulosic feedstock for fuel production, and
- Therefore a better GHG balance, and
- Lower feedstock costs because of higher feedstock yields (in MJ per hectare).

It is not yet clear which pre-treatment method will find commercial application, as they all have their benefits and drawbacks. An ECN study [ECN, 2003] indicates that while improving the pre-treatment technology will be key to reducing the costs of bio ethanol, there are also other bottlenecks.

In the first place, the current dilute acid hydrolysis process has a number of drawbacks, including inorganic side-streams, high capital costs due to corrosiveness, small particle sizes and high temperatures and pressures. Research programmes are underway to address these issues [ECN, 2003].

A second important factor is enzyme technology. Cellulase enzymes are produced commercially, but in low volumes geared to high-value products. The industrial cellulases currently available are not effective enough and too costly for use in large-scale production [ECN, 2003].

Thirdly, pentose can be converted no more than partially, there being no fermentation systems available that can use the entire pentose fraction. To address this issue, several different approaches have been tried:

- Genetic modification of baker's yeast.
- Co-culture of different strains of *Zymomonas mobilis.*
- Transfer of pentose-converting genes into ethanol-resistant strains of *E.Coli.*

Although a certain amount of progress is reported in research journals, there is still a lack of experience at the industrial scale.

Genetically modified organisms (GMO)
One of the possibilities for cellulose conversion is to use genetically modified yeast, as is currently being researched by Nedalco and Delft Technical University, for example. The use of GMO in an industrial process requires government approval and permits.

GHG reduction potential
In both studies considered here (GM and Concawe), ethanol from lignocellulosic biomass is assumed to be produced in a SSCF (Simultaneous Saccharification and Co-Fermentation) plant, such as is operated by the US company Iogen to produce ethanol from straw. This state-of-the-art technology comprises the following steps:

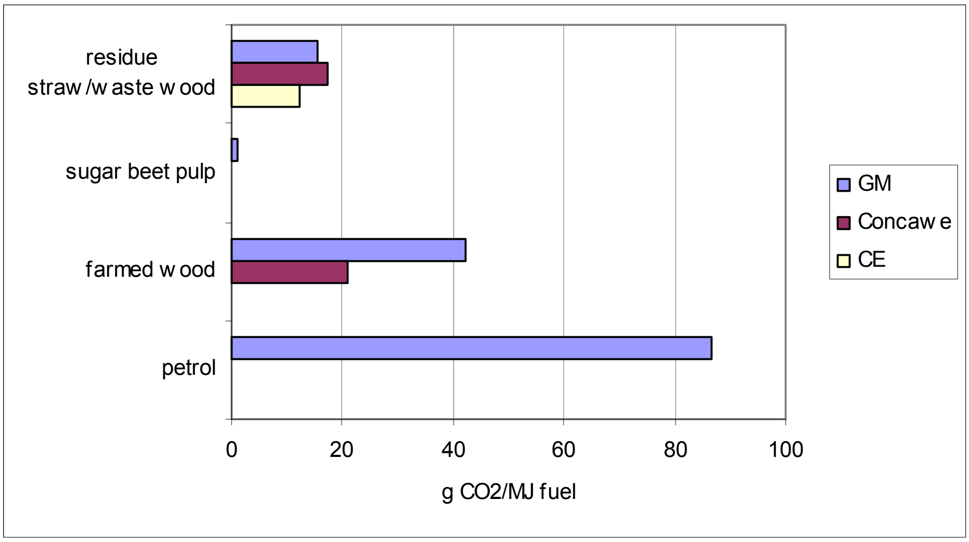
- Pre-hydrolysis of hemicelluloses.
- Enzymatic hydrolysis of cellulose and fermentation of C5 and C6 sugars (SSCF).
- Distillation.

The GM study reports GHG emissions for three different pathways, presented in Figure 12. For comparison, the results of the Concawe and CE studies have also been added. The Concawe study was limited to waste wood and woody biomass crops, whereas the CE study analysed only conversion of residue straw.

Clearly, these processes have a far greater greenhouse gas reduction potential than ethanol from sugar beat or wheat, especially if woody residues are used as the biomass feedstock. This feedstock cannot be used as fodder and its use does not therefore need to be compensated by additional cereal cultivation. In the CE study, additional hay cultivation is assumed as a compensatory measure, which requires much less fertilisation and mechanical agricultural work.
According to the GM study, the GHG emissions of ethanol from woody biomass crops are 20-30% lower than for ethanol from sugar beet or cereals. The Concawe result for this route is even better, though, with GHG emissions only half those cited in the GM study. The main difference between the two studies is that the GM study assumes much higher emissions for biomass cultivation than Concawe.

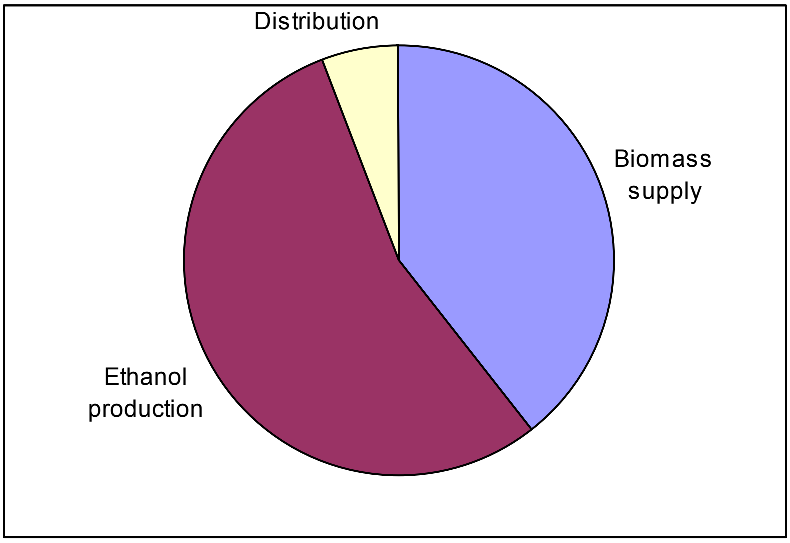
According to the GM calculations, the GHG emissions of ethanol from sugar beet pulp are very low. This is due to their allocating no emissions to the pulp, it being a by-product of the sugar beet industry. This would seem to underestimate emissions, though, as use of sugar beet pulp for ethanol production must be compensated by cultivation of a similar alternative. Alternatively, the emissions of sugar beet cultivation should be allocated to both the sugar and the pulp.

Figure 12 Greenhouse gas emissions of bio ethanol from lignocellulosic biomass (g CO_2 eq./MJ fuel). The results of three studies are shown: GM, Concawe and CE, each involving different assumptions. In the top category, residue straw (analysed by GM and CE) is compared with waste wood (analysed by Concawe). For comparison, the total GHG emissions of petrol are also included



Source: [GM, 2002], [Concawe, 2004], [CE, 2005a].

figure 13 Greenhouse gas emissions associated with successive links of the bio ethanol from residue straw chain, according to the GM-study

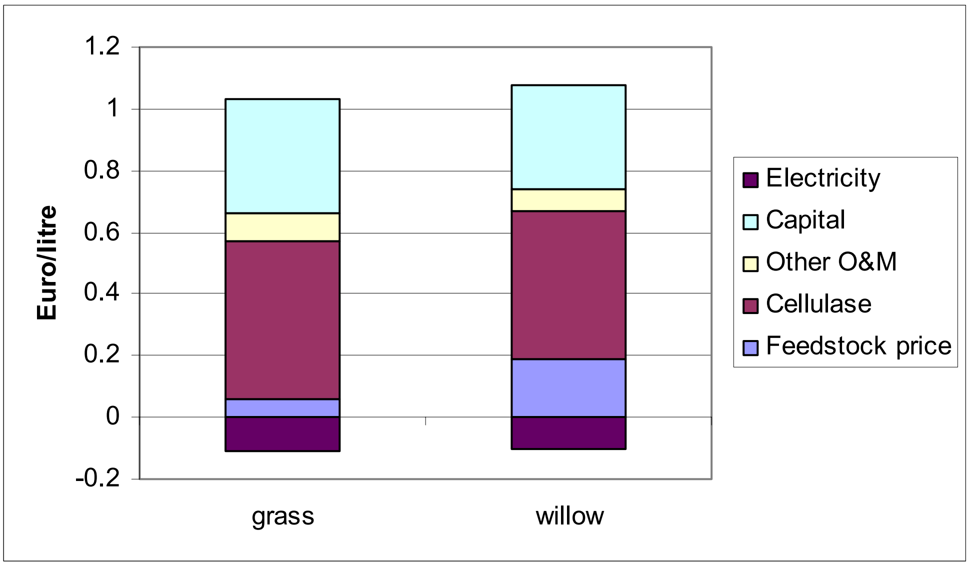


Costs

As this technology is not yet mature, the costs of cellulosic ethanol are still uncertain. The will depend very much on improving the activity of the enzymes used for biomass hydrolysis. The cost calculations currently reported in the literature lead to an estimate of 0.35 €/litre (16.5 €/GJ), with a future estimated cost price of 0.23 €/l (10.9 €/GJ) [ECN, 2003]. This would be comparable to the average cost of petrol in the years 2002-2004 (see section 2.5). The fall in price will derive from a reduction of capital costs (incl. pre-treatment) and cost savings on acquisition of cellulose enzyme to convert the C5 sugars to ethanol.

As an indication of the composition of the costs, Figure 14 provides an estimated cost breakdown for both grass (from roadside verges) and willow (from short-rotation forestry) as a feedstock [ECN, 2003]. The calculations are for a 2 million m^3 per annum ethanol production facility located in the Netherlands. The costs of the cellulase (enzymes) and the capital investment costs are expected to be the main items, with biomass costs also adding approx. 20% to the total. Note that these cost estimates result in fuel costs of approx. 0.92 €/l (grass) and 0.98 €/l (willow), much higher than the figures reported by other researchers. As a comparison: the current cost price of ethanol is around 0.6 €/l (according to [Ecofys, 2003]), while the current average price of petrol is about 0.36 €/l (excl. taxes, see section 2.5).

Figure 14 Breakdown of ethanol production costs



Source: [ECN, 2003].

From these data we can conclude that future ethanol costs are still very uncertain and that actual costs will depend mainly on:

- The costs of the pre-treatment (currently under development).
- The costs of the enzymes to convert the C5 sugars to ethanol (currently under development).
- The costs of the biomass feedstock.

The latter costs are related to the type of feedstock used (residues vs. cultivation), but also to potential competition with alternative applications of woody biomass, such as power generation (see chapter 6).

Apart from the actual ethanol costs, vehicles will need to be adapted to run on ethanol at fuel ethanol contents of over 10-15%, giving rise to additional costs (as discussed in section 4.3.3).

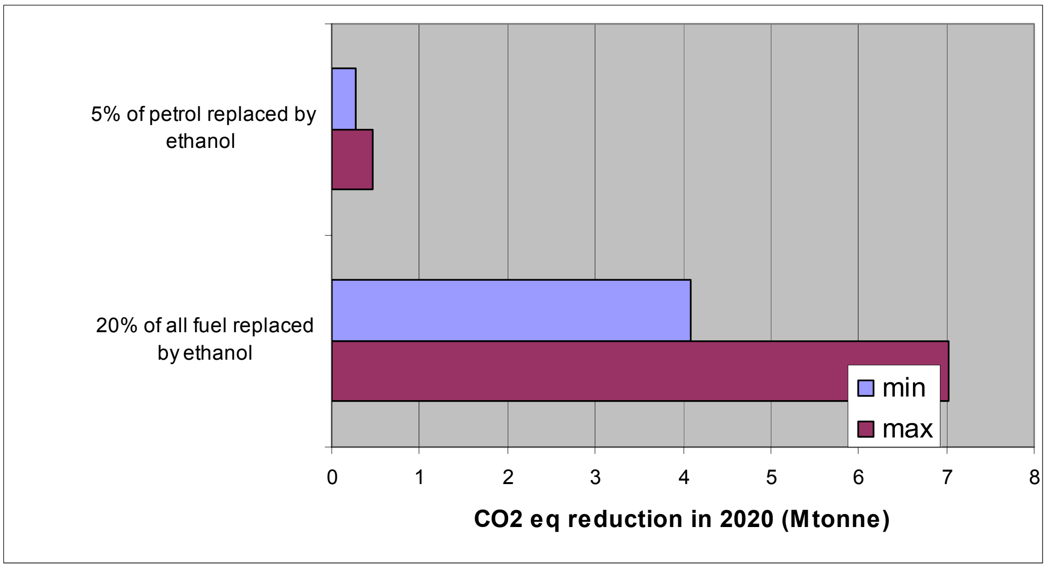
Cost effectiveness
The GHG emission reductions and estimated costs of lignocellulose ethanol are both still very uncertain, and the possible bandwidth of estimated cost effectiveness is consequently extremely large.

For currently available biofuels, it is the range of estimated GHG reduction that is the main source of bandwidth in cost effectiveness, deriving from uncertainties and variations in emissions during feedstock cultivation. In the case of future biofuels, however, the uncertainties are compounded further by the wide range of cost estimates available.

If the lowest future cost estimate proves correct, use of lignocellulosic ethanol would not involve any additional cost compared with petrol. The ethanol would then, by definition, be cost effective. If the higher estimate proves correct, the cost effectiveness of the production of cellulosic ethanol is between 70 and 120 €/tonne CO_2 eq., depending on the GHG emissions reduction achieved.

Total GHG reduction potential in the Netherlands
For bio ethanol from lignocellulosic biomass we again elaborate two scenarios, a 5% blend scenario and a scenario in which ethanol accounts for 20% of all transport fuel sold in the Netherlands. Based on the above results, the GHG reduction potential for the Netherlands is shown in Figure 15. Clearly, the potential to reduce GHG emissions is significantly higher than for today's bio-ethanol, shown in Figure 10, above. In the first scenario, 5% replacement of all petrol would lead to a reduction of 0.3 – 0.5 Mtonne in transport sector GHG emissions in 2020, i.e. a decrease of 0.6 – 1.1%. 20% replacement of all fuel (the second scenario) would lead to a reduction of 4 – 7 Mtonne in transport sector GHG emissions in 2020, i.e. a decrease of 9 - 16%.

Figure 15 Different scenarios with cellulosic ethanol as a biofuel. Total transport CO_2 emissions in 2020 are projected to be 44 Mtonne



4.3.3 Bio ethanol quality and operational aspects

Ethanol is a proven vehicle fuel, as a low-percentage blend as well as an 85% mixture (E85). In the USA, for example, ethanol is used as a 10% mixture as an octane enhancer in petrol. To avoid problems with the ethanol/fuel blends, the ethanol is mixed with the petrol just before transport to refuelling stations. Because ethanol is hygroscopic, the fuel must be kept water-free to avoid fuel systems malfunctions. Current petrol standards allow a maximum of 5% ethanol, therefore blends of over 5% require specific labelling at the sales point [EC, 2003]. The European Committee for Standardization (CEN) is currently developing standards for ethanol blends.

When ethanol is mixed with petrol at low percentages (<20%) the vapour pressure of the petrol increases, first rising as the ethanol concentration increases to around 5% and then falling as the ethanol concentration rises further. A graph of this phenomenon is provided in the Ecofys study [Ecofys 2003].

The vapour pressure of a given ethanol-petrol mixture can be lowered by reducing the content of high volatiles. While allowing EU vapour pressure limits to be met, this is a costly operation, however. In addition, the vapour pressure is found to rise again when a low-percentage ethanol/petrol mixture is blended with petrol containing no ethanol. The vapour pressure of the resultant mixture may exceed the EU-limits, in which case the product can no longer be sold. As it is common practice throughout the Netherlands for petrol from various oil companies to be mixed, this currently poses a serious technical obstacle to market introduction of low-percentage blends, which becomes even more problematical in summertime, when vaporisation specifications are narrower than in winter.

It should be noted, further, that ethanol has a much lower energy density than petrol. Although there is some evidence that the fuel efficiency of low-percentage ethanol blends is higher than to be expected on the basis of energy content alone, this evidence derives only from small-scale trials, with no large-scale scientific testing yet performed.

Given the high octane number of ethanol, vehicle fuel efficiency can be optimised by adjusting injection timing and increasing the compression ratio. Certain newer vehicles detect the higher octane number automatically. However, it is as yet unclear how great the potential efficiency improvements will be [IEA, 2003].

4.4 ETBE

Ethanol can be converted to ETBE (ethyl-tertiary-butyl-ether), which can be used to replace MTBE, a constituent of petrol. While the percentage of MTBE in petrol is usually between 1 and 5% (by volume), more ETBE can be added: up to 15%. ETBE is produced from ethanol and fossil isobutylene. More information on MTBE and ETBE can be found in [Ecofys, 2003].

ETBE can be produced using any one of the previously discussed ethanol variants, regardless of the feedstock or conversion process used. This means that:

a ETBE can currently be produced from ethanol made using cereals or sugar beet (or secondary products yielded as by-products of the food and fodder industry) as a feedstock.

b The environmental and cost performance of ETBE and its potential availability will benefit from any improvements in the ethanol production process (in particular, the expected development of technology enabling conversion of (ligno)cellulosic biomass).

Compared with ethanol, ETBE has the advantage that it can be blended with petrol without changing the vapour pressure, as in the case of low-percentage ethanol blends. In a number of EU countries (e.g. France, Spain and Italy) ETBE is already added to petrol as an alternative to MTBE.

4.4.1 ETBE from sugar beet bio ethanol

Technology

As stated, ETBE is produced from ethanol and fossil isobutylene. Isobutylene is a by-product of the oil refining industry, deriving from steam cracking and catalytic cracking, amongst other processes.

GHG reduction potential

To assess its GHG reduction potential, ETBE should be compared with both MTBE and petrol. MTBE is generally blended with petrol at concentrations between 1 and 5%. A comparison with MTBE is therefore valid for ETBE percentages of up to 5%. For higher concentrations, the replaced product is petrol.

Compared with ethanol production, the additional step in the production process causes additional GHG emissions. First, fossil isobutylene is added. Only part of the ETBE is therefore of biological origin and the GHG emissions of the isobutylene need to be added to the total. Second, ETBE production at the refinery requires energy, causing additional GHG emissions.

The result is that the GHG emissions of ETBE are higher that those of ethanol, as can be seen in Figure 16. This effect is compensated only partly by the fact that MTBE causes higher emissions than petrol. In Figure 17, the GHG emission reductions of the three applications of ethanol from sugar beet are compared:

- As ethanol that replaces petrol.
- Converted to ETBE that replaces MTBE.
- Converted to ETBE that replaces petrol.

The results are shown for the three different applications of the by-product of the ethanol production process, assuming sugar beet as feedstock. Clearly, the highest GHG reduction can be achieved if ethanol is used directly in petrol. If it is converted to ETBE, GHG reduction is greater if it replaces MBTE than if it replaces petrol, because of the higher GHG emissions of the MTBE. The graph clearly illustrates the effect of the isobutylene in the ETBE on its total GHG emissions. Because of its fossil provenance, the direct emissions associated with isobutylene production are also included in the graph.

The emissions of each link in the ETBE from sugar beet chain are presented in Figure 18. Again, the major contribution of the isobutylene to total GHG emissions per MJ ETBE can clearly be seen. Two-thirds of the direct GHG emissions of ETBE are of fossil origin, since every 4 of the 6 carbon atoms in ETBE derive from isobutylene. This results in 47.4 g CO_2 per MJ_{ETBE} during combustion.

Figure 16 Greenhouse gas emissions of ETBE from sugar beet (g CO_2 eq./MJ fuel). Results are shown for different applications of the by-product and for two different reference crops. ETBE emissions stem partly from the biological fraction (from the ethanol route), partly from isobutylene. For comparison, the total GHG emissions of MTBE and petrol are also included

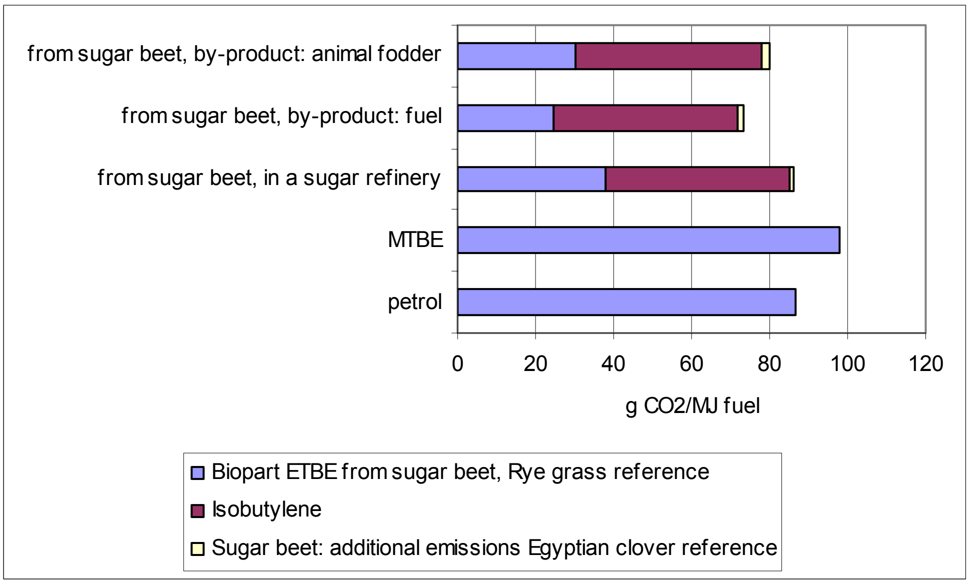


Figure 17 Comparison of GHG reduction potential of the various applications of ethanol from sugar beet, for three different modes of by-product use (reference crop: Egyptian clover)

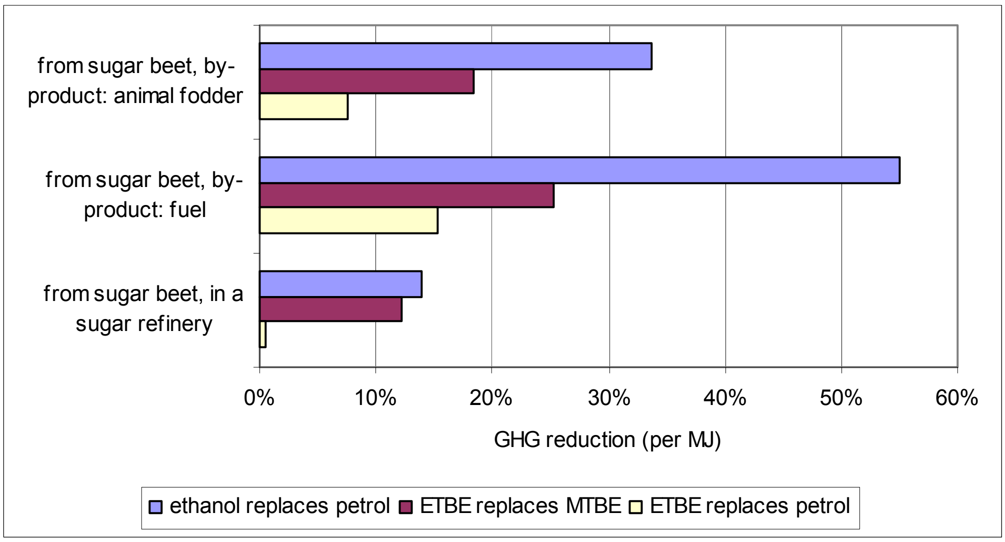
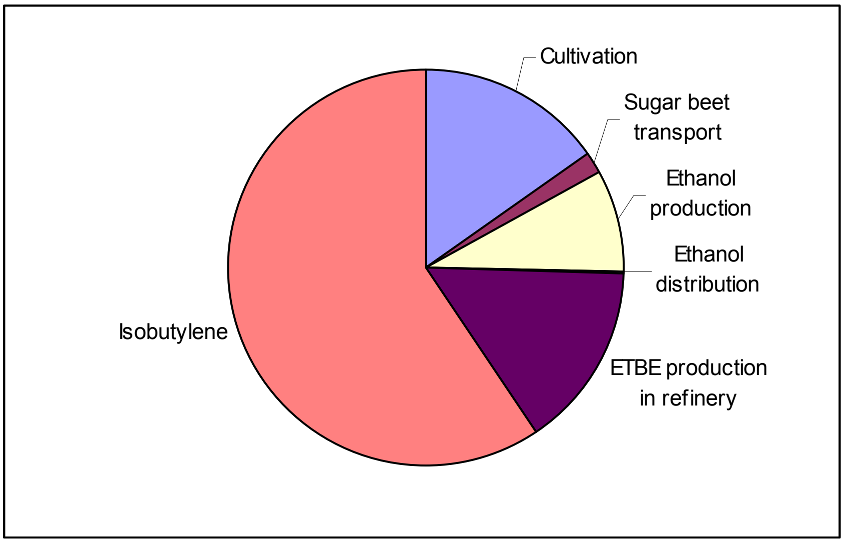


Figure 18 Greenhouse gas emissions associated with successive links of the ETBE from sugar beet chain (by-product used as animal fodder, reference crop: Egyptian clover)



Isobutylene can in principle also be produced from biomass. While this is likely to improve the GHG-balance of the ETBE, it will also increase its cost.

Costs

The current cost of ETBE have been estimated by Ecofys [Ecofys, 2003] to be about 19% higher than that of MTBE: approximately 0.45 €/l (16.6 €/GJ) if ethanol from residues is used, 0.46 €/l (17.0 €/GJ) if ethanol from sugar beet is used, and 0.48 €/l (17.7 €/GJ) if the ETBE is produced from ethanol from wheat.

Cost effectiveness

Based on the above assumptions, the cost effectiveness of ETBE from agricultural products ranges from approximately 80 to 210 €/tonne CO_2 eq.

Biofuel quality and operational aspects

Clearly, ETBE synthesis causes additional GHG emissions. However, the result of this extra process step is a high-quality fuel component with excellent blend characteristics very similar to those of its fossil counterpart MTBE.

According to current CEN fuel specifications (EN 228), ETBE (and MTBE) can be added to petrol up to a maximum of 15%.

Total GHG reduction potential in the Netherlands

We assess two different scenarios for ETBE introduction in the Netherlands:

- In the first scenario, 15 % of all petrol sold in 2020 in the Netherlands is replaced by ETBE, the maximum concentration allowed by current European fuel specifications. We assume that in this case all MTBE is replaced by the ETBE (7.4% of the petrol, based on energy content [Ecofys, 2003], 420 ktonne/y[23]), and some of the petrol.

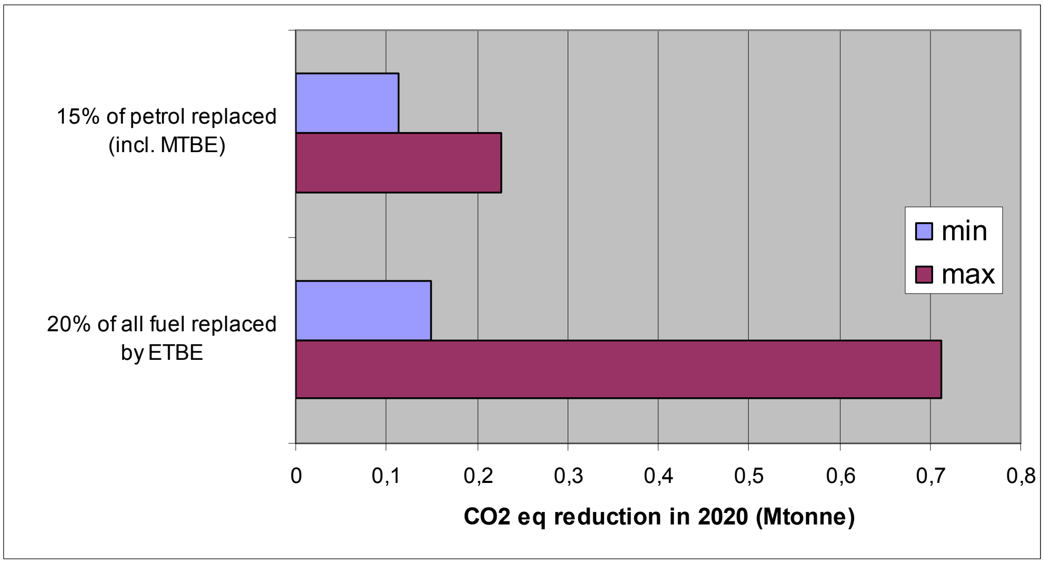
[23] This corresponds with 14.7 PJ (source: VNPI).

- In the second scenario, 20 % of all road transport fuel in the Netherlands is replaced by ETBE. Note that in this case, the maximum concentration allowed by European fuel specifications is exceeded by far. We assume that in this case all MTBE is replaced by the ETBE, and a large part of the petrol.

No vehicle adaptations are needed in either of these scenarios.

The results are shown in Figure 19. In the first scenario, 0.1 – 0.2 Mtonne CO_2 eq is reduced (0.3 – 0.5% of total road transport emissions in 2020), the second scenario leads to 0.2 – 0.7 Mtonne CO_2 eq reduction (0.3 – 1.6%).

Figure 19 Total GHG reduction potential, for two scenarios with ETBE from sugar beet as a biofuel



NB: It is assumed that MTBE consumption will grow with petrol consumption. The figure for current MTBE consumption was provided by VNPI.

4.4.2 ETBE (from ethanol from lignocellulosic biomass)

Technology

This ETBE pathway comprises two processes that have already been discussed:

- Ethanol production from lignocellulosic biomass (see section 4.3.2), and
- Conversion of ethanol to ETBE using isobutylene (see previous section).

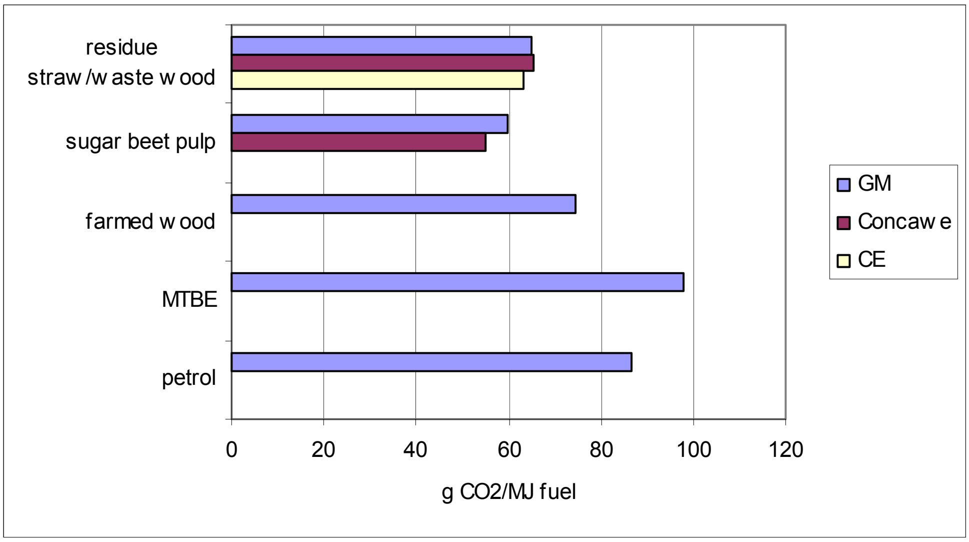
The latter step is already commercially available. The first is still to be developed, though (see section 4.3.2.).

GHG reduction potential

ETBE production from woody biomass has not been studied in any of the literature sources used for the present study. However, from the ETBE from sugar beet cycle and the ethanol from sugar beet cycle it is known that about 36% of the GHG emission during ethanol production can be allocated to ETBE. Combining this assumption with the GHG emission results for lignocellulosic ethanol leads to an estimate of the GHG emissions of this type of ETBE.

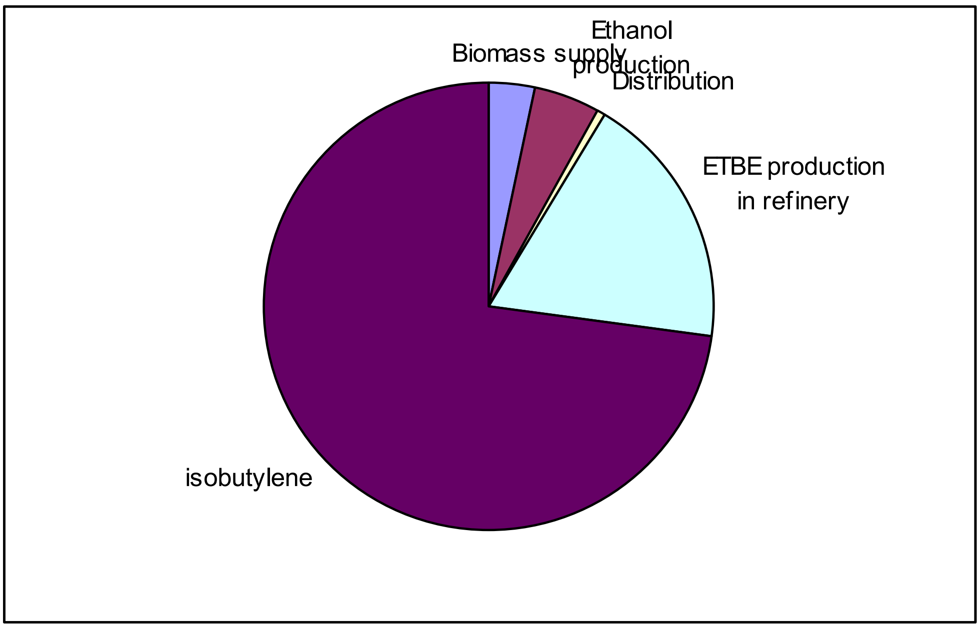
In the case of ETBE from lignocellulosic biomass, moreover, actual ETBE synthesis is responsible for a high proportion of GHG emissions. Comparison of the GHG emissions of ETBE-production from lignocellulosic materials with those of ETBE-production from sugar beet shows that use of woody materials can reduce GHG emissions substantially.

Figure 20 Greenhouse gas emissions of ETBE from lignocellulosic biomass (g CO_2 eq./MJ fuel). The results of three studies are shown: GM, Concawe and CE, each involving different assumptions. In the top category, residue straw (analysed by GM and CE) is compared with waste wood (analysed by Concawe). For comparison, the total GHG emissions of petrol are also included



Source: [GM, 2002], [Concawe, 2004], [CE, 2005a].

Figure 21 Greenhouse gas emissions associated with successive links of the ETBE from residue straw chain, according to the GM-study



As already mentioned, the GHG emissions of ETBE can in principle be reduced by producing the isobutylene from biomass, too. However, this will increase the cost of the ETBE.

Costs
As ETBE is produced from ethanol, the cost of ETBE can be expected to fall as the cost of ethanol decreases. As already mentioned, using lignocellulosic biomass as an ethanol feedstock may reduce costs significantly, by 40-60%. Assuming that ethanol costs account for about 60% of ETBE costs [Ecofys, 2003], the latter can be expected to fall to approx. 0.29-0.35 €/l (10.7-12.9 €/GJ). This would be lower than current MTBE costs of about 0.39 €/l (15.0 €/GJ).

Cost effectiveness
Based on the above assumptions, the cost effectiveness of ETBE from agricultural products ranges from approximately 80 to 210 €/tonne CO_2 eq.

Biofuel quality and operational aspects
ETBE from woody biomass is identical to ETBE from wheat or sugar beet (see previous section).

Total GHG reduction potential in the Netherlands
We assess the same two scenarios for ETBE-introduction in the Netherlands as above:

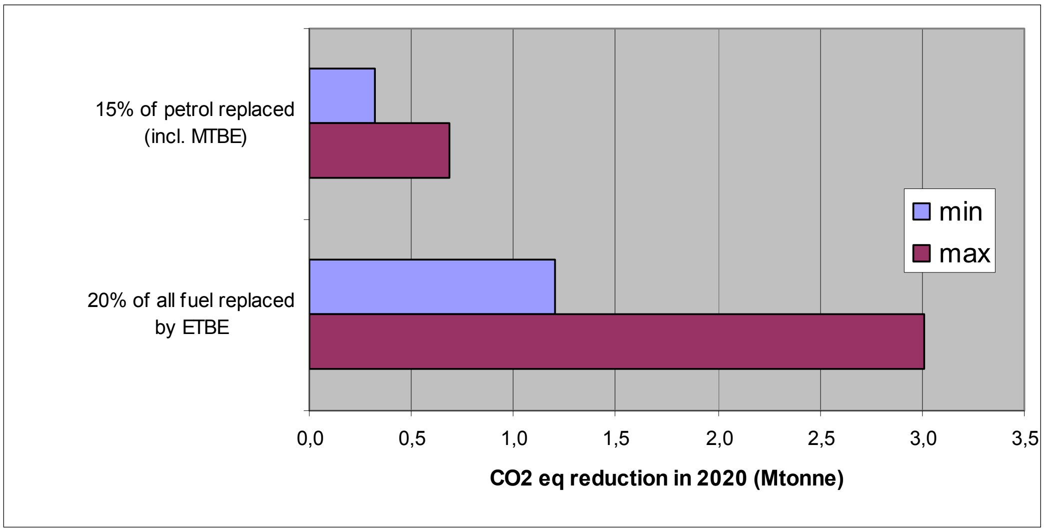
- In the first scenario, 15% of all petrol sold in 2020 in the Netherlands is replaced by ETBE, the maximum concentration allowed by current European fuel specifications. We assume that in this case all MTBE is replaced by the ETBE (7.4% of the petrol, based on energy content [Ecofys, 2003], 420 ktonne/y[24]), and some of the petrol.
- In the second scenario, 20% of all petrol is replaced by ETBE, the maximum concentration allowed by European fuel specifications. We assume that in this case all MTBE is replaced by the ETBE, and a large part of the petrol.

No vehicle adaptations are required in either of these scenarios.

The results are shown in Figure 22. The In the first scenario, 0.3 – 0.7 Mtonne CO_2 eq is reduced (0.6 – 1.1% of total road transport emissions in 2020), the second scenario leads to 1.2 – 3 Mtonne CO_2 eq reduction (about 3 – 7%).

[24] This corresponds with 14.7 PJ (source: VNPI).

Figure 22 Total GHG reduction potential, for 2 scenarios with ETBE from lignocellulosic biomass as a biofuel



4.5 Biomass Fischer-Tropsch diesel

Technology

Fischer-Tropsch (FT) hydrocarbons can be produced by gasification of biomass, followed by downstream gasification. The Fischer-Tropsch process itself is well known. In South Africa, FT-liquids have been produced from coal for many years and Malaysia has a plant producing FT-liquids from natural gas. Using biomass as a feedstock for FT-synthesis is relatively new, however, and brings with it several problems that still need resolving, most of them in the gas cleaning phase (see below).

The biomass FT plant comprises:

- Biomass pre-treatment (chipping, drying).
- Gasification (resulting in syngas).
- Gas cleaning[25] and conditioning.
- FT-reactor.
- Hydro-cracker.

As with the ethanol production process, different configurations are possible. Most configurations produce electricity and heat as by-products. Overall process efficiencies vary with plant design from 40% to 60-65% [Ecofys, 2003].

Fischer-Tropsch technology is one of the options available for utilising cellulosic biomass for fuel production. As discussed earlier, this reduces the amount of land needed for biomass production compared with current biofuels. It also leads to cost reductions and thus to more cost effective GHG reduction.

25 The syngas needs to be purified to remove, *inter alia*, organic (BTX) and inorganic impurities and tars as well as impurities that can deactivate the FT and other catalysts.

Bottlenecks for commercial application

At the same time, though, several technical limitations still stand in the way of commercial application [Hamelinck, 2004]:

- A very critical step is the cleaning of the syngas (mixture of CO and H_2). According to [Hamelinck, 2004] it is not clear whether the strict cleaning requirements for biomass FT synthesis can be achieved (some impurities need to be removed down to levels of less than 10 ppb by volume).
- Pressurised (oxygen) gasifiers are known to have higher efficiencies, but these still require further development. As yet, only small-scale atmospheric gasifiers have proved reliable.

While the latter hurdle must be taken to further improve the efficiency of biomass FT fuel production, the first is of major importance for the technical viability of the process. Proper gas cleaning is an essential prerequisite for reliable operation of an FT plant.

A recent study by ECN and Shell (ECN, 2004) on a gas cleaning demonstration study states that: "*It seems too early to implement BG-FT technology on a commercial scale*". Strikingly, the problem of syngas cleaning is not cited as one of the main bottlenecks, merely as a key focus for optimisation. This report concludes that:

- The very large capital investment required poses a "capital hurdle". Since the capital investments are relatively high compared with other options, the scale of production needs to be big (typically 50 PJ per year in ECN 2004a[26]), to produce fuels competitively. Conceptual plant designs that can produce as much fuel as total Dutch diesel consumption are not unusual.
- The resulting product is two to three times more expensive than mineral diesel. Without support mechanisms, the *economic viability* of this route is therefore in doubt (under current economic conditions).

GHG reduction potential

In the GM study, the GHG reduction potential of biomass FT diesel is estimated for the case of woody biomass from forest residues being used as feedstock [GM, 2002]. The biomass is gasified by means of allothermal gasification[27]. Overall plant efficiency is assumed to be 47%, a figure amenable to slight improvement. The Concawe study presents two pathways for the production of FT liquids, using waste wood and farmed wood [Concawe, 2004].

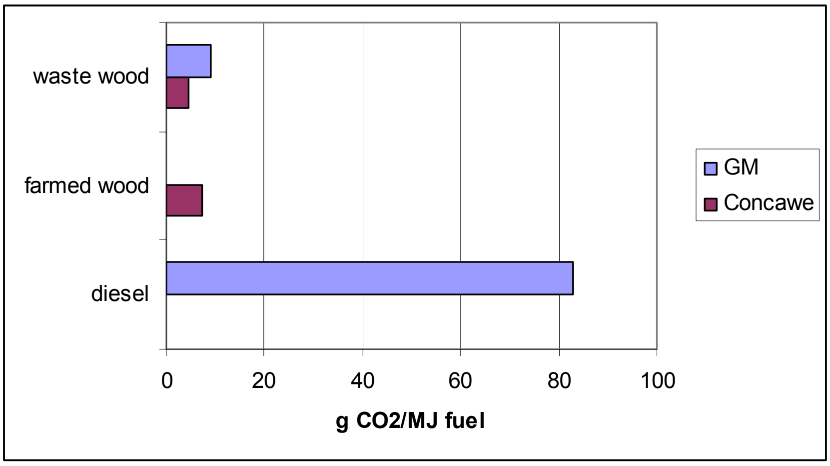
The results of the two studies are shown in Figure 23. Their differences derive from different assumptions about the energy required to collect, prepare and transport the waste wood and the exact process design and requirements. For example, in the Concawe study the wood conversion process is designed to be 'electricity-neutral', with all necessary power being generated from the wood. In the GM-study, only the heat required for distillation is provided by the FT plant, so that additional electricity inputs are needed. The different set-ups of the

[26] The Netherlands needs about 29 PJ in 2010 to meet the EU Biofuel Directive.

[27] Allothermal gasification (with steam in a fluidised bed) of coal was demonstrated some 15 years ago. With minor modifications, this technology can also be used for biomass.

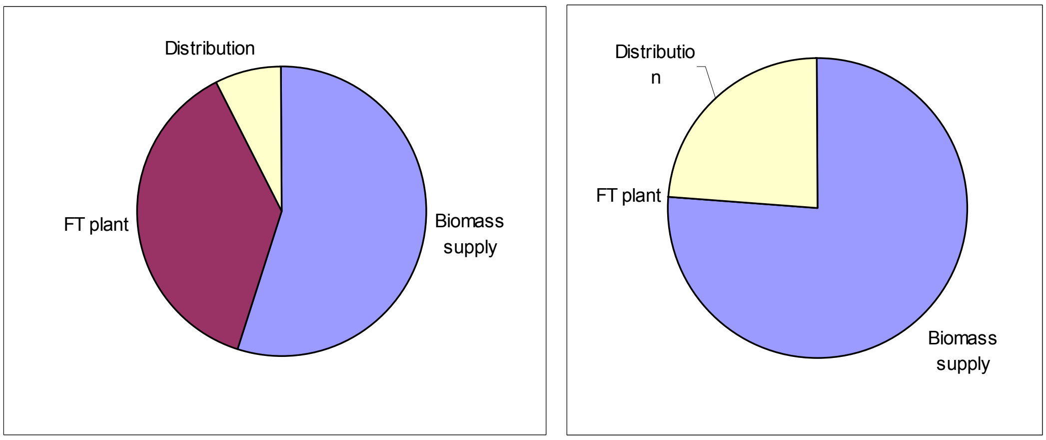
processes studied lead to very different detailed results, as can be seen in Figure 24.

Figure 23 Greenhouse gas emissions of Fischer Tropsch diesel from woody biomass (g CO_2 eq./MJ fuel). The results of both the GM and the Concawe study are shown. For comparison, the total GHG emissions of diesel are also included



Source: [GM, 2002], [Concawe, 2004].

Figure 24 Greenhouse gas emissions associated with successive links of the Fischer-Tropsch diesel from woody biomass chain, for the processes analysed in the GM-study (left) and Concawe study (right)



Costs

In the short term, the costs of biomass Fischer-Tropsch diesel are estimated at € 0.76 per litre (11.1 €/GJ). This is the figure cited by Choren Industries, which is building a biomass-fed pilot plant in Germany. A longer-term estimate is € 0.40 per litre (21.1 €/GJ). This estimate is based on a large-scale FT plant fed with biomass at € 2 per GJ, a lower-bound estimate of the biomass costs reported in the literature. Average costs for biomass are about 4 €/GJ, with an upper bound of around 6 €/GJ [Ecofys, 2003].

Cost effectiveness
As with cellulosic ethanol, the cost effectiveness of the GHG reduction associated with biomass Fisher-Tropsch diesel depends very much on technical developments (in this case gas purification and efficiencies) and scaling benefits. Using the above estimates, in the short term the cost effectiveness is expected to be around € 147 per tonne of CO_2 eq., increasing in the longer term to about € 22 per tonne.

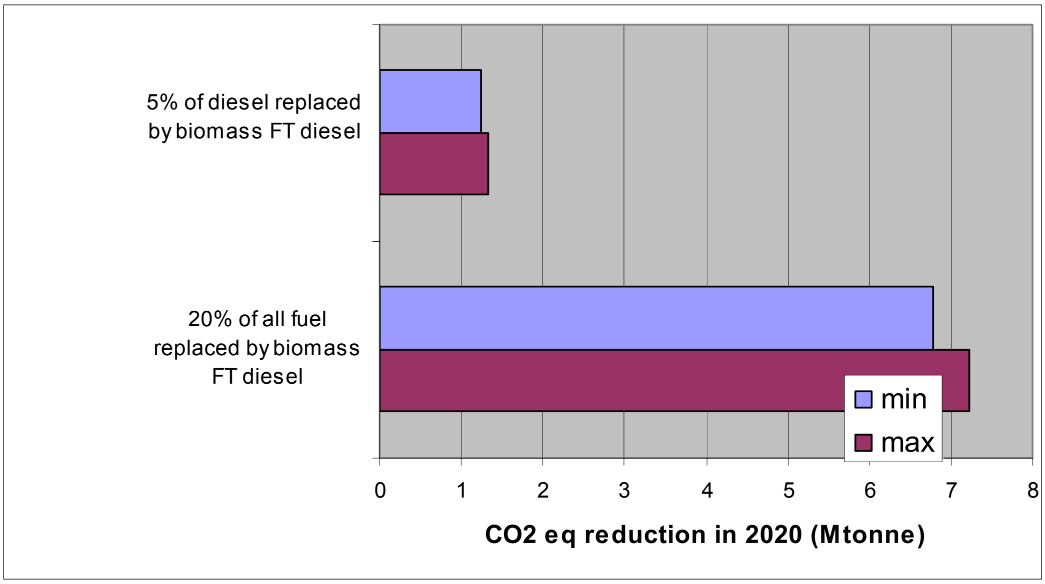
Biofuel quality and operational aspects
Compared with conventional fuels, biomass FT-fuels have the advantage of containing no sulphur or aromatics. They can be used directly in conventional diesel vehicles at any blending grade or as a neat fuel. As the cetane number[28] of FT-diesel is higher, it can be used to improve the ignition quality of conventional diesel. A major advantage of FT-diesel is that it is a 'design fuel', i.e. can be designed to meet future fuel specifications. This might yield a synergy advantage between vehicle technology and fuel development.

Total GHG reduction potential
For biomass Fischer Tropsch diesel we again elaborate two scenarios: a 5% blend scenario and a scenario in which 20% of all transport fuel is replaced by biomass FT-diesel. There are no additional vehicle costs associated with these scenarios.

As Figure 25 shows, in the second scenario biomass Fischer-Tropsch diesel has the potential to reduce the transport sector's total GHG (direct and indirect) emissions by about 7 Mtonne (about 16% of 2020 road transport emissions) without any modifications to vehicles. In the first scenario, these numbers reduce to about 1.3 Mtonne GHG reduction, i.e. 3%.

[28] The cetane number is a measure of the ignition quality of a diesel fuel. More precisely, it is a measure of the ignition delay: the time between the start of injection and start of combustion (ignition) of the fuel. In a given diesel engine, higher cetane fuels will give a shorter ignition delay than lower cetane fuels.

Figure 25 Total GHG reduction potential of biomass Fischer-Tropsch diesel as a biofuel, in two scenarios



4.6 HTU diesel

The Hydro Thermal Upgrading process is based on depolymerisation and deoxygenation of biomass by means of hydrolysis and decomposition. The process converts biomass into a 'biocrude' using highly pressurised water (100 – 200 bar) at 300-360°C. This biocrude is non-miscible with water and has a relatively high energy content. For application, two routes are possible:

- Power generation.
- Diesel fuel production by catalytic hydrodeoxygenation (HDO).

The potential of both routes was analysed in [CE, 2005e].

The HTU process is well suited to converting both dry and very wet biomass, such as residues from food processing, agriculture and forestry. Given this capacity to process wet biomass, a low-cost feedstock, it is likely that this is the type of biomass that will be used in the HTU process.

Bottlenecks for commercial application

The HTU technology is still in the experimental phase. In particular, upgrading of the biocrude to create a transport fuel and actual use of the fuel in vehicles are still to be proven [Ecofys, 2003]. We know of demonstration projects addressing the following issues:

- HDO of biocrude, until now demonstrated at laboratory scale only.
- Assessment of HTU diesel quality.
- Engine testing and monitoring.

GHG reduction potential

The GM study [GM, 2002] provides information on the GHG emissions of the HTU pathway from waste wood, while the CE-study [CE, 2005e] analyses the GHG emissions of HTU diesel produced using wet biomass residues. These results are presented in Figure 26. Note that the CE-study analyses two different reference situations. In the first, it is assumed that the wet biomass would be dumped and then decay if it were not used for the HTU process. In the second, this biomass is assumed to be incinerated, with a low efficiency (η_e= 20%) owing its high water content. Compared with dumping and decay, the HTU route has a negative GHG emission, i.e. GHG is effectively removed from the atmosphere. This is due to the use of some of the HTU-product for electricity production. If the second reference is taken, the GHG emissions of the HTU route are about 35% of those of the diesel chain. According to the GM estimate, the use of residual woody biomass would lead to over 90% emission reduction. The detailed results of the GM-study are shown in Figure 27.

Figure 26 Greenhouse gas emissions of HTU-diesel from woody biomass or wet organic residues (g CO_2 eq./MJ fuel). Results are given for both the GM-study and the results for 2020 in the CE-study. The latter analyses two reference situations: 1, biomass is dumped and decays, and 2, biomass is used for (low-efficiency) power generation. For comparison, the total GHG emissions of diesel are also included

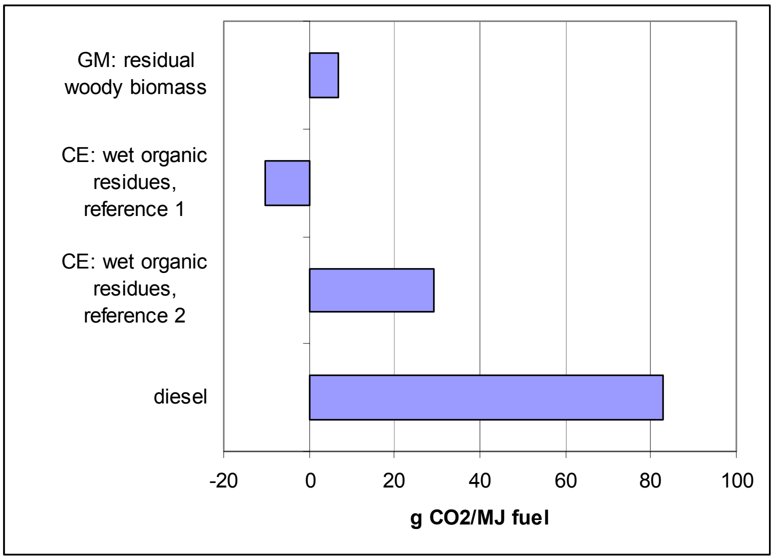
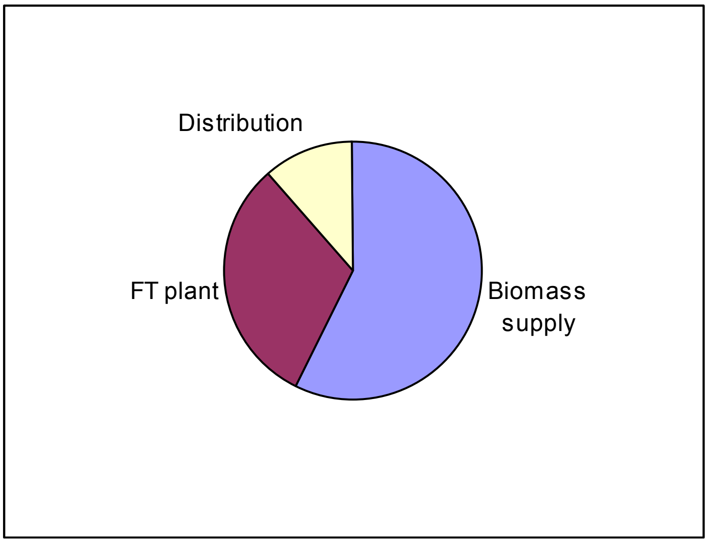


Figure 27 Greenhouse gas emissions associated with successive links of the HTU diesel from woody biomass chain



Costs

As the HTU process is still in a relatively early stage of development, cost estimates are very difficult to make. According to the 1999 GAVE analysis [ADL, 1999], the cost of HTU diesel will amount to around 0.58 €/l (16 €/GJ). A study by ATO and CE, however, estimates future costs to be about 0.25 €/l (7 €/GJ) [ATO, 2002]. This would mean HTU diesel costs lower than the average price of diesel in the period 2002-2004.

A comparative advantage of the HTU process is that it can process biomass streams with otherwise limited application potential that are therefore low-priced. While most biomass conversion techniques require dry biomass, the HTU process can process wet biomass.

Cost effectiveness

In view of the uncertainties regarding both future costs and GHG reduction in the case of the HTU process, the cost effectiveness cannot yet be reliably calculated. Clearly, if the low-cost estimate were to prove accurate, HTU would be cheaper than diesel (at current diesel price), which would make this a cost-effective route. If the higher cost estimate proves valid, cost effectiveness ranges from 75 to 128 €/tonne CO_2 eq., depending on the GHG emission achieved (the low estimate holds for the CE analysis, reference 1, the high estimate for the same analyses, reference 2).

Biofuel quality and operational aspects

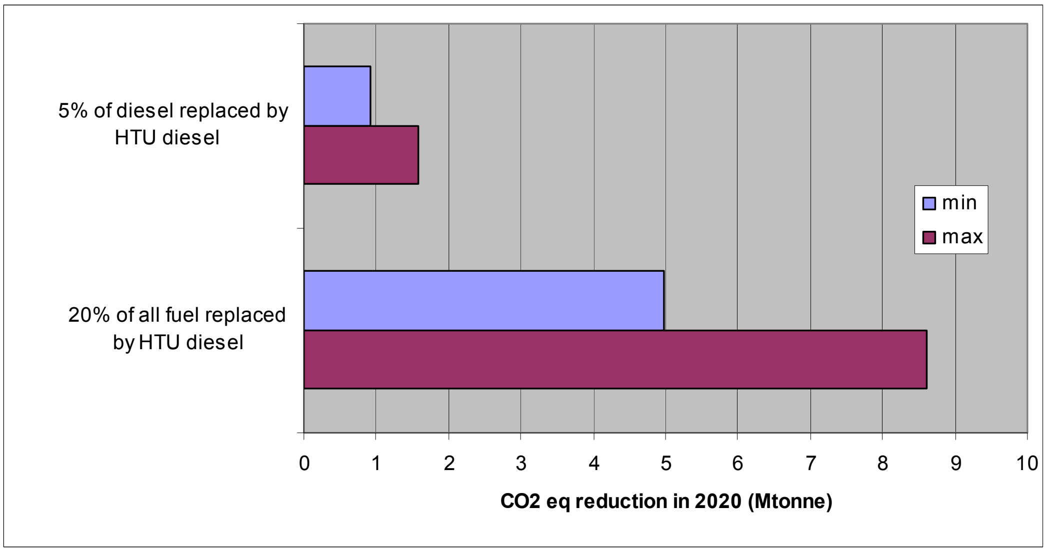
The fuel quality of HTU diesel is as yet unclear. Several tests have been planned, but the results are not yet available. A sample of HTU-diesel was tested at the Shell Products Laboratory at Thornton in the UK back in 1983. From this test it appeared that the ignition properties were better than those of average petroleum diesel from that time [Biofuel, 2003].

Although, from the above, it does not seem that fuel quality will give rise to any problems, the planned tests are a welcome initiative to reproduce the 1983 tests.

Total GHG reduction potential
Again, we consider two scenarios for 2020 to illustrate the total GHG reduction potential of HTU: a 5% blend scenario and a scenario in which 20% of all road transport fuels is replaced by HTU-diesel. No additional vehicle costs are expected in either of these scenarios.

The results are shown in Figure 28. In the first scenario, the GHG reduction potential was found to be 0.9 – 1.6 Mtonne CO_2 eq, which about 2 – 4% of total road transport emissions in 2020. The second scenario lead to a GHG reduction of 5 – 9 Mtonne GHG reduction, 11 – 20% of the sectors total emissions.

Figure 28 Total GHG reduction potential, for 2 scenarios with HTU diesel as biofuel



4.7 Other forms of environmental impact

Other forms of environmental impact include:
- Emissions to air.
- Emissions to water.
- Production of ash and other residues to be disposed of (ultimately) by landfilling.

Emissions to air generally relate to firing of fuels and diffuse emissions of volatile compounds. When it comes to combustion-related emissions, biomass Fischer-Tropsch synthesis will have the lowest emissions of the three future biofuel routes considered, as this technology burns the least fuel. Production of ethanol from lignocellulosic feedstock will give the highest emissions per unit biomass feedstock. If clean gas is used as a fuel, emissions will be limited to NO_x and CO and a few hydrocarbons, but if there is direct combustion of lignine and other residual materials during ethanol production from lignocellulosic feedstock, emissions of SO_2 and dust will also occur.

Table 4 Assumptions regarding percentage of biomass input that will be combusted, fuel types and installations used for the future biofuel processes

Process	Percentage of biomass input combusted	Fuel type	Type of installation used
Biomass Fischer-Tropsch (Choren)	5% - 10%	Clean gas	Gas turbine
HTU and HDO	25% - 30%	Clean gas	Gas turbine
Lignocellulosic ethanol (wood, corn stover) |Aden, 2002|	55%	Lignine and other residual materials	Boiler

As for odour and other forms of emission of volatile compounds, HTU and ethanol production from lignocellulosic feedstock have a higher potential for such emissions, as both processes produce large amounts of off-gases containing high concentrations of short-chain organic compounds.

With respect to emissions to water, production of ethanol from lignocellulosic feedstock will probably produce no emissions. Hydrolysis and fermentation consume water and with a dry feedstock like naturally dried wood or corn stover, water will have to be added to the process, see [Aden, 2002]. The HTU process produces a large amount of effluent consisting of all biomass-associated water and part of the organic materials converted during chemical processing. As already mentioned, the effluent will contain high levels of dissolved light organic molecules. During Fischer-Tropsch synthesis, clean water of drinking-water quality is produced in large amounts. If wet gas cleaning is applied, wastewater will be produced.

The amount of residues requiring landfill is hard to predict. For ethanol production and biomass Fischer-Tropsch synthesis, the amount depends mainly on the thermochemical conversion technology used. Low-temperature combustion or gasification will produce ash which under Dutch law must be disposed of as chemical waste, as illustrated by practical experiences with the 80 MW_{fuel} wood-fired Cuijk power station, for example.

To our knowledge, the HTU process produces no or only a minimal amount of residual materials. The ash dissolves and can potentially be isolated for use as a fertiliser or later converted into a vitreous slag during high-temperature gasification of heavy biocrude.

The following table provides a synopsis of the estimated environmental impact of the three future biofuel production technologies considered here, the number of stars giving the relative size of the impact. It should be noted, however, that all three processes are expected to be able to comply with emission regulations.

Table 5 Relative environmental impact of future biofuel production technologies considered

	Emissions to air		Emissions to water	Residues for landfill
	Combustion-related	Volatile substances		
Biomass Fischer-Tropsch (Choren)	* [a]	*	*	**?**
HTU diesel	* *	* * *	* * *	**0 or -**
Lignocellulosic ethanol (wood, corn stover)	* * *	* * *	**0**	**?**

[a] The number of stars represent the relative size of the impact.

5 Current status of future biofuel technologies

5.1 Introduction

This chapter provides a fuller review of the current status of the technologies required for production of the future biofuels included in this study. Many of these are still at the research stage, while others are already being piloted on a larger scale. We also briefly describe the developments and plans of potential biofuel producers in the Netherlands. At the end of the chapter, we draw several conclusions regarding the potential timing of market introduction of the various biofuels analysed.

5.2 Status of the technologies

5.2.1 Ethanol from lignocellulosic biomass

At the moment, three technologies appear to be in the demonstration phase or on the brink of being demonstrated on a commercial scale.

BC International is trying to construct a commercial-scale ethanol from wood facility by adding a wood hydrolysis facility to a mothballed ethanol plant in Jennings, Louisiana. The combined facility will have an annual production capacity of 30 million gallons of ethanol. BC international has now collected enough funds to start construction.

Iogen is operating a biomass demonstration facility in Ottawa, Canada. The $45 million plant is the final step before construction of full-scale, $250+ million commercial plants. The demonstration plant is designed to prove the feasibility of Iogen's EcoEthanol™ process by validating equipment performance and identifying and overcoming production problems prior to the construction of larger plants. The plant can handle all functions involved in the production of cellulose ethanol, including receipt and pretreatment of up to 40 tonnes per day of feedstock. Iogen is currently trying to gather enough funds for construction of the first industrial-scale demonstration plant

According to Nedalco, availability of highly active and cheap enzymes for hydrolysis of cellulose and fermentation of pentose is the crucial parameter for rapid further development of the lignocellulose to EtOH technology up to industrial scale. Papers from Genencore and other producers of GMO enzymes seem to indicate that such enzymes are currently available or will be available in the short term. If this is the case, and funds were to be freed for an industrial-scale demonstration plant, further development of the technology to maturity would require about 5 years of development.

Such funding has been lacking until now, however. Thus far, no large-scale demonstration facilities have been built and there is no certainty about the current status of enzyme development. Consequently, we feel unable to estimate the period of time before lignocellulose to EtOH technology might be introduced on a commercial scale. The role of Dutch companies in further technological development seems to be limited to Nedalco and partners.

5.2.2 Fischer-Tropsch diesel

Further development of Fischer-Tropsch synthesis using biomass-derived syngas is currently underway, primarily in Germany, Sweden and Austria.

In Germany the Choren company, with the support of the German government, Volkswagen and DaimlerChrysler, is constructing a demonstration plant with an annual production capacity of 15,000 tonnes of biofuels that is scheduled for operation in mid-2005. According to the company, project preparations for the next generation of plant with a production of 200,000 tonnes per annum (t/a) of CHORENFuel® have already begun. The amount of biomass required for an industrial plant of this size is approx. 1 million t/a. The plant is scheduled to come on stream in 2008. CHOREN Industries is planning to set up production facilities for 1 million t/a of renewable synthetic automotive fuels in Germany by 2010, corresponding to an investment volume of approx. € $2{\cdot}10^9$.
If the Choren plans are realised, a commercially proven technology for biofuels production will be available within 5 to 10 years.

Other initiatives to develop Fischer-Tropsch biofuels production technologies have been taken in the Netherlands, Sweden (Chrisgas project) and Austria (European RENEW project). The Dutch initiative at ECN has thus far been limited to bench-scale testing. The initiatives in Sweden and Austria are based on existing gasification installations of which the technical feasibility has been proven in long-term campaigns. In Sweden this is the mothballed Värnamo installation, in Austria the operational Güssing plant. The Chrisgas initiative is planned to last until 2009-2011. The first pilot-scale results of the RENEW project are expected in 2005. Fischer Tropsch synthesis is to be investigated at pilot-scale using a side-stream of the syngas produced by the gasifier.

One of the people involved in the Chrisgas project is less optimistic than Choren about the time frame for developing FT synthesis using biomass-derived syngas. According to Wiebren de Jong of Delft Technical University, it will take 5 years to demonstrate production of syngas of sufficiently high quality to permit FT synthesis on a scale of 20 MW_{fuel}. The next step in the Chrisgas project will be another 5-year research programme in which the FT technology itself will be optimised for processing syngas from biomass. Only after this goal has been achieved will it be possible to build a large-scale facility with acceptable technological and economic risks. This estimate of the situation means it will be 2015 or beyond before there is real clarity about the time frame for large-scale introduction of green Fischer-Tropsch diesel.

More generally, there are several practical examples of chemicals production using feedstocks other than gas, oil or coal:

- The Rheinbraun-Uhde (Germany) HTW (High Temperature Winkler) process is a commercially mature, pressurised bubbling fluidised-bed technology. The process was used to demonstrate production of 80,000 t/a of ammonia in the 1980s in Oulu, Finland, based on pressurised gasification of peat in the Kemira Oy facilities. It has operated successfully with biomass, though not extensively. Sawdust was used in test runs. The plant was shut down at the beginning of the 1990s following a decline in the world market price of ammonia. Additional testing would be needed to fully demonstrate the performance of the HTW process using biomass.
- Ebara has demonstrated the feasibility of gasifying waste plastics in a two-stage gasification process (EUP technology) and has constructed a 100,000 t/a processing plant that supplies medium-calorific syngas to an ammonia production plant. The plant has been in operation since July 2003.

These historical examples make it hard to understand why biomass gasification would require another 10 to 15 years of development before construction of the first large-scale biomass-fed FT production facility could start.

Summarising, in the most optimistic scenario construction and operation of a first-of-a-kind industrial-scale biomass-fed FT fuel production plant could begin around 2010 and in a more pessimistic scenario in 2020.

Although technological developments take place mainly outside the Netherlands, there are Dutch several research institutes (ECN Delft Technical University, Twente University, Eindhoven University) involved.

5.2.3 HTU

The HTU-technology was recently demonstrated on a pilot scale. As yet, no experience has been gained with hydrodeoxygenation (HDO) technology, and upgrading of the biocrude to transport fuel and use of this fuel in motor vehicles is still to be proven [Ecofys, 2003]. We know of demonstration projects addressing the following issues:

- HDO of biocrude, until now demonstrated at laboratory scale only.
- Assessment of HTU diesel quality.
- Engine testing and monitoring.

However, according to the plans of the technology owner – Biofuel B.V. – further development will go ahead full steam, with commercial maturity being reached 5 to 10 years from now.

Biofuel aims to build and put into operation a demonstration plant at the site of Amsterdam's new Waste Incineration Plant in early 2009. Processing capacity will be approx. 25,000 t/a of dry and ash-free biomass. This demonstration plant will be used to gain the information and experience required for a first-of-a-kind commercial facility, scheduled to be brought on stream in 2009 or 2010. The biocrude produced will also be used to demonstrate the feasibility of upgrading biocrude to premium diesel. From 2011 onwards, construction of several industrial-scale HTU-plants is anticipated and it is also from then on that development of industrial-scale HDO-technology is expected to take place. Because of the similarities between the required HDO-technology and similar, commercially proven technologies such as hydrocracking and Fischer Tropsch synthesis, this is likely to require only limited effort.

Summarising: the HTU-technology itself will probably be developed up to industrial scale within the next 10 years. Upgrading of light biocrude to diesel on an industrial scale is likely to take place somewhere from 2015 onwards.

Development of HTU-technology is largely a Dutch affair.

5.3 Conclusions

Given the current status of the three future biofuel production technologies, first-of-a-kind commercial-scale installations are likely to be built within the next ten years if no major technical bottlenecks are encountered and if sufficient efforts and funding are expended.

Which technology will develop fastest is difficult to predict from the available information. The initial impression is that FT-technology based on the CHOREN process may develop fastest and may have the best potential for further development and commercialisation.

When it comes to biofuel process development, Dutch input and influence currently seem limited to Nedalco, who are investing in bio-ethanol R&D and have plans to build an ethanol production facility, and Biofuel, involved in development of HTU technology.

6 Comparison: biomass for biofuels versus power generation

6.1 Introduction

Biomass can be used to produce biofuels for the transport sector, but it can also be used for heat and power generation or as a chemical feedstock. In [CE, 2003], the two options of biofuels and power generation were compared for the situation up to 2010. This analysis led to the conclusion that from both a cost and environmental perspective (greenhouse gas reduction and land use), biomass would be better employed for power generation than for transport biofuels. In this chapter, the two applications are again compared, but now for the future biofuels discussed in the previous chapter. As long as biomass for energy applications remains a scarce commodity and government incentives are employed to promote use in specific sectors, policy-makers can exercise some indirect control on the mode of application by prudent design of incentives.

In this chapter we undertake an exploratory analysis and comparison of the specific cost of greenhouse gas mitigation associated with application of biomass in the transportation and power generation sectors.

Because of the uncertainties surrounding future biofuels and especially the technologies to produce them, this analysis is by its very nature exploratory. Given the current development status of future biofuel production technologies – see chapters 4 and 5 – there are still major uncertainties on two key aspects:
- The direction in which the various technologies will develop, the winning process configurations and the resultant efficiencies of both biofuels and power generation.
- Cost aspects, both investments and operational costs.

At a wider level, there is also uncertainty about future market developments, in particular the market prices of automotive fuels and electricity on the liberalised intra-European market and the prices of coal and steel (for construction of process plant) on the global market. These prices have a significant influence on the cost effectiveness of biofuels and biomass power generation, but are difficult to predict, resulting in uncertainties in the estimated specific cost of GHG mitigation.

The scope of the analysis is limited to *future* biofuels and power generation, and thus complementary to [CE, 2003]. Production of biomass-based chemicals using the kinds of biomass considered in this study boils down to production of substances very similar to biofuels (naphtha, waxes, LPG) using the same technologies (Fischer-Tropsch, HTU). The conclusions with respect to biofuels will therefore also apply, by and large, to such chemicals.

6.2 Approach and aim of this analysis

The specific costs of greenhouse gas mitigation have been calculated in three stages:

- In the first step, the net avoided GHG-emissions per unit electrical power generation (in kg CO_2 eq./MWh_e) or substituted fossil fuels are estimated.
- In the second step, the net economic cost of substituting fossil fuels or fossil-fuelled power production are estimated.
- In the third step, the results of the first and second step are combined to yield the specific costs of GHG mitigation.

Net greenhouse gas emissions per unit biomass have been estimated in accordance with the methodology outlined in Appendix A.

Specific costs have been estimated using the '*Milieukostenmethodiek*', a standardised methodology developed for the Dutch environment ministry (VROM) for economic evaluation of emission reduction measures. More information on this methodology (in English) can be found at http://www.infomil.nl/contents/pages/21859/nerechapter4.13.pdf

The analysis in this chapter refers to different processes, systems and desktop studies from those considered in the Concawe and General Motor studies. Economic aspects were not analysed in these studies and data therefore had to be taken from other studies, in which other types of facility and technological configurations are considered. This means that the efficiencies adopted differ from those cited in chapter 4. However, this does not affect the main conclusions of this analysis – the uncertainties involved in predictions about future technologies are rather large anyway.

The results should therefore be interpreted as a rough estimate, designed merely to provide insight into the sensitivity of the specific mitigation costs to biomass cost and plant configuration and allow comparison of the various options for biomass processing. In the following the biofuels are first discussed, then use of biomass for power generation.

6.3 Biofuels

6.3.1 Cost of substituting conventional fuels

Basic assumptions

Calculation of the net substitution costs requires comparison between:

- The cost of producing automotive fuels from biomass, and
- The cost of producing fossil automotive fuels and fossil-based electricity (a by-product of many biofuel technologies).

In this analysis the notion of 'costs' has been simplified by narrowing it down to production costs, thereby neglecting other costs such as distribution costs and costs related to adaptation of vehicle technology to the specific properties of the alternative fuel. It should be noted, though, that the latter costs may be quite significant in the case of, say, 85% ethanol.

Biofuel production costs have been estimated as annual costs for industrial plant with a specific and – per production route – typical processing capacity (in $MW_{biomass}$). For comparison between technologies, these plant-specific annual costs have been converted to costs per unit of processed biomass (in €/$GJ_{biomass}$).

Fossil fuels
For fossil fuels, current production costs were adopted. In scenario studies such as PRIMES the average crude oil price is anticipated to remain at the current level up to 2030. From this estimate we conclude that production costs for fossil automotive fuels will also remain largely at current levels.

Current average European production costs for diesel and petrol amount to 9.5 and 11.0 €/GJ, respectively. For electricity, we used the average current European market price paid by industry (6.2 c€/kWh_e).

Biofuels
Plant-specific annual costs for automotive fuels and electricity were roughly estimated by taking into account four cost items:
- Depreciation costs.
- Fixed operation and maintenance costs (O&M).
- Biomass purchase costs.
- Profits from by-product sales (significant for current biofuel production routes).

These costs were determined as a function of biomass prices (in €/GJ). Items such as disposal of residues from thermal conversion (e.g. fly ashes) have been neglected.

In the case of future biofuels, production costs are very uncertain because of:
- A lack of practical experience and data regarding specific investment costs and efficiencies.
- Uncertainty about the direction technological development of the various production routes will take.

For biomass Fischer-Tropsch synthesis, for example, both once-through designs and maximum conversion designs (with respect to CO-conversion) are a possibility and desktop studies have shown no clear economic or environmental advantage for either. In the case of ethanol from lignocellulose it is unclear how active the cellulose enzymes will be and how much they will cost.

The influence of system configuration on the investment costs and efficiency of future biofuel plants were taken into account by considering different configurations per technology:

a For lignocellulose-based ethanol production, three different configurations were considered:
    - A system with a BIG-CC for residues disposal and energy production, pre-treatment of wood or straw by hydrolysis with dilute acid, and cellulase of average activity [Reith, 2002] (for the current situation).
    - A system with a boiler for residues, pre-treatment of wood or straw by hydrolysis with dilute acid, but cellulase of higher activity [Aden, 2002].
    - An energetically optimised configuration, with a biomass gasifier and integrated STAG for residues disposal and energy production (BIG-CC), pre-treatment of woody biomass by steam explosion, and cellulase of high activity [Hamelinck, 2004].

b For biomass gasification and Fischer-Tropsch synthesis, the common 'desktop' designs were considered, see [Hamelinck, 2004]. The case selected for consideration here is an indirect gasifier based on BTC technology. However, we also considered the Choren technology soon to be realised on full industrial scale in Germany, for which investment costs were taken from the Choren website (http://www.choren.de).

The configuration, or rather system, considered for HTU consists of 7 HTU-installations with pre-treatment units and 2 centralised HDO units with gasifiers for conversion of heavy biocrude and H_2 production [Goudriaan, 2003].

The plant-specific assumptions made for the purpose of the analysis are shown in Table 6.

Table 6 Basic assumptions for economic analysis (for origin of figures, see also references in text)

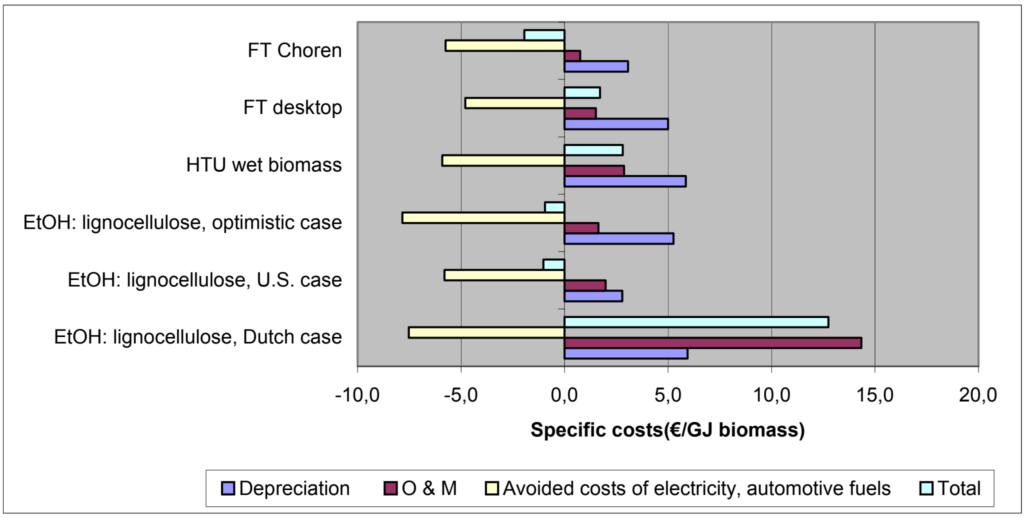
	ethanol: wood, low-activity cellulase	ethanol: high-activity cellulase, boiler, dilute acid	ethanol: high-activity cellulase, BIG-CC, steam explosion	HTU: wet biomass	biomass FT: bubbling fluidised bed, O_2	biomass FT: Choren
Efficiency						
- biofuels						
a) naphtha/kero/petrol	45%	43%	40%	15%	30%	10%
b) diesel				45%	10%	40%
- electricity	15%	5%	20%		7%	5%
	60%	48%	60%	60%	47%	55%
Economic parameters:						
Investment costs (M€)	300	197	310	800	320	400
Processing capacity (MW biomass)	290	405	340	785	370	750
specific investment (€/kW$_{input}$)	1035	490	920	1020	900	530
Fixed annual O&M (percentage of investment)	6%	5%	4%	8%	4%	4%
Catalysts, chemicals, cellulase, etc.(M€/year)	100	13	3.3		3	
Availability	90%	90%	90%	90%	90%	90%
Biomass feedstock type	short-rotation wood	short-rotation wood	short-rotation wood	waste	short - rotation wood	short-rotation wood

For biomass purchase costs, a range of –3 to 17 €/GJ was considered. The lower end of the range refers to solid residues like residual wood. The higher end is comparable to current market prices for agricultural crops such as corn and wheat. Realistic biomass costs for the technologies considered can be expected to remain below 6-8 €/GJ, the current price for short-rotation wood.

Resulting net costs

The resultant net fixed costs are given in figure 29.

Figure 29 Break-down of specific fixed conversion costs



The fact that the net or total costs are already comparable and sometimes clearly higher than the profits from sales of automotive fuels and electricity reflects the expected high investment costs and high O&M costs.

Estimates of specific investment costs and resultant depreciation costs vary by approximately 100% between the lowest and highest estimates, illustrating current uncertainties in the required investments for industrial-scale plant. The 'EtOH from wood, U.S. case' estimate refers to a desktop system analysis performed by NREL of an economically optimised industrial-scale plant. In the 'Dutch case' and the 'optimistic case' an energetically optimised configuration was considered, requiring higher investment costs for residues disposal and power generation.

Notably, a rough prognosis of the investment costs for an industrial-scale FT-plant made by Choren, to be realised in the short term, are lower than desktop estimates of investments for FT-systems.

O&M costs are estimated to be very high in the Dutch 'EtOH from wood' option. In this case, it is assumed that cellulase will be purchased from a third party and that it will have a low activity. With this cellulase costing € 6,000/tonne, this gives specific O&M costs of € 14/GJ biomass.

For EtOH production from wood, the higher investment costs of more energy-efficient configurations do not seem to be recovered via higher revenues from enhanced electricity sales. The difference in depreciation between configurations with low and high investment costs is approximately € 2.5 - € 3.0 per $GJ_{biomass}$. Extra income from enhanced electricity sales amounts to approximately €1.5- 2.0 per $GJ_{biomass}$.

6.3.2 Net avoided greenhouse gas emissions

For the sake of simplicity, only one kind of biomass – short-rotation wood – has been considered in this study as a feedstock for ethanol and biomass FT-synthesis. We took this crop because of its good fuel properties (for a biofuel) and because of the low production costs estimated in other desktop studies. We did not consider organic residues, because of the diversity of possible crops and derivative fuel properties as well as market prices. A consideration of by-products would have also complicated the analysis, because of the substituting crop(s) that would have had to be taken into account.

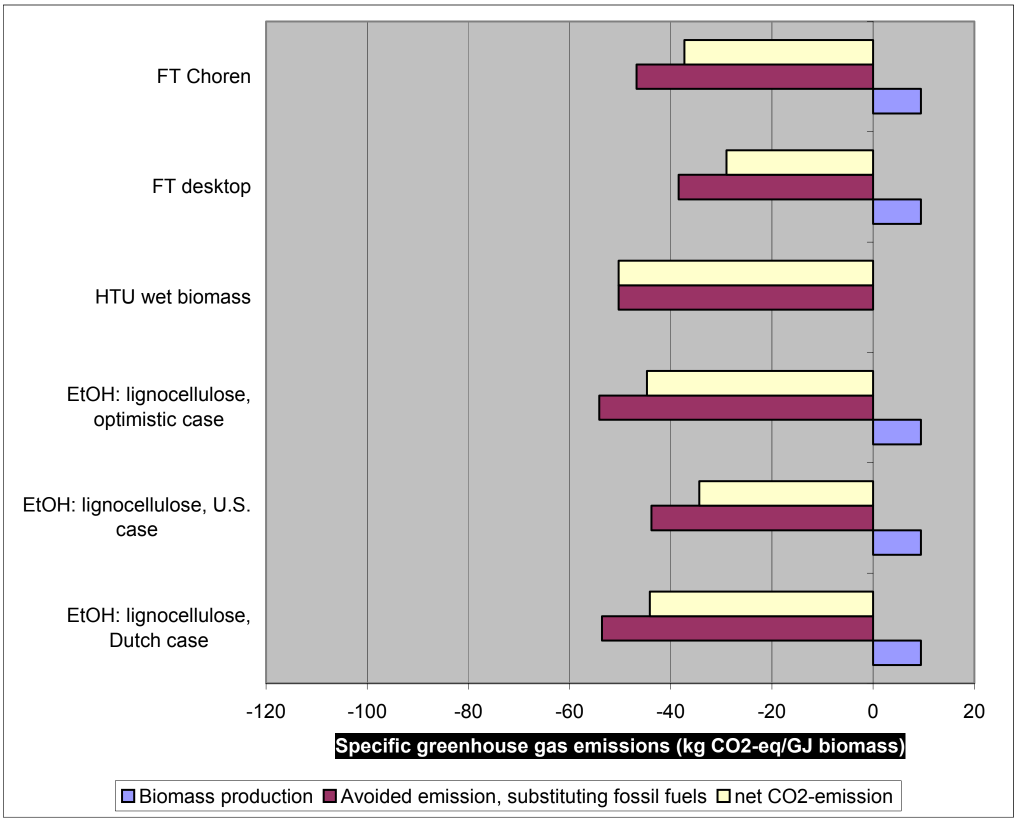
For the HTU process we considered wet biomass that would otherwise have to be disposed of as waste and would have no further useful application.

According to both the GE and Concawe study, cultivation of short-rotation wood gives a greenhouse gas emission of 9.4 kg/GJ. For the substituted automotive fuels and fossil electricity, the following basic assumptions were made:

- Production of diesel and gasoline gives respective GHG emissions of 83 and 86.5 kg CO_2 eq./GJ (see chapter 2).
- Average specific emissions for EU15 are estimated at 350 kg/MWh_e, a figure that includes GHG emissions during fossil fuel production.

Combining the avoided amounts of fossil electricity and fossil automotive fuels with the specific GHG emissions per unit electricity or fuel yields the net avoided GHG emissions per plant shown in Figure 30.

Figure 30 Composition of specific net avoided greenhouse gas emissions per unit of biomass



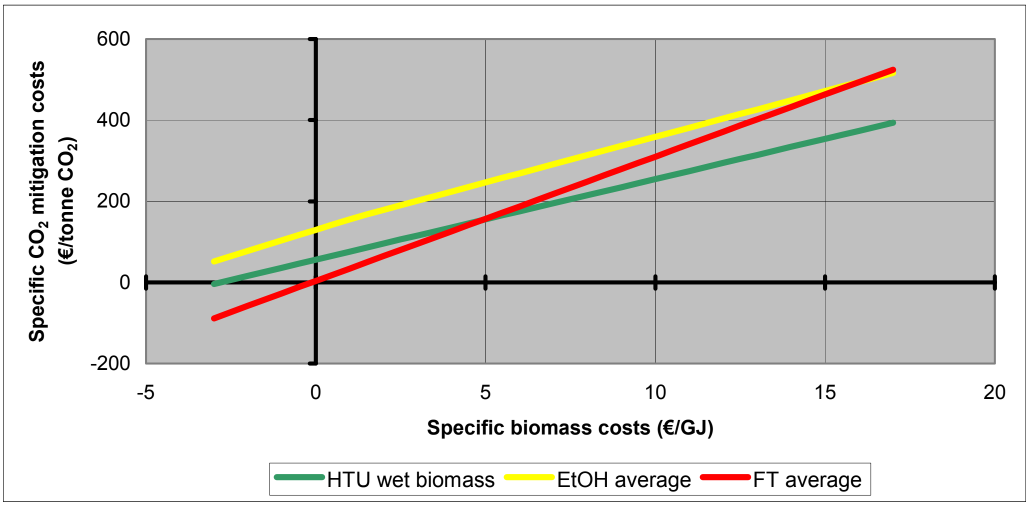
The gross avoided greenhouse gas emission per unit biomass is probably comparable for all technologies and configurations. This is to be expected, since the expected efficiencies are also comparable. The net avoided GHG emissions are also comparable for FT-synthesis, as the same biomass feedstock was assumed. The only exception is the HTU process, which is assumed to process wet waste that would otherwise have no useful application and does not therefore come with a greenhouse gas 'penalty'.

The presented specific net GHG emissions are somewhat distorted by the different kinds of biomass considered. No doubt biomass feedstocks without a greenhouse gas penalty can also be found for FT-synthesis and EtOH from lignocellulose.

6.3.3 Specific mitigation costs

Combining Figure 29 and 30 yields the relation between specific mitigation costs and biomass price illustrated in Figure 31.

Figure 31	Relation between specific mitigation costs and biomass price



For biomass FT-synthesis and ethanol from wood, the average specific mitigation costs are shown with a range of uncertainty. For ethanol from wood, these have been averaged over the three cases considered. The lower end of the range (lowest specific mitigation costs) for a given biomass price refers to the 'optimistic case'. For biomass FT-synthesis, the lower end of the uncertainty range refers to the estimates for the Choren technology.

For HTU an uncertainty range of 30% has been assumed, similar to the uncertainties assumed and accepted in pre-design investment cost estimates.

6.4 Biomass application in the power generation sector

Power generation on the basis of biomass is an option that can be realised both in existing power stations designed for fossil fuels and in dedicated plant designed specifically for biomass conversion. In the first case conventional fossil fuels are substituted, while in the second the entire energy production system is replaced. For both options there are a number of conversion technologies available.

For a selected and limited number of these biomass conversion technologies, specific GHG mitigation costs have been determined in three steps:

- In the first step, the net economic cost of substituting fossil fuels or fossil-fuelled power production were estimated.
- In the second step, the net avoided GHG emissions per unit power production (in kg CO_2 eq./MWh_e) or substituted coal were estimated.
- In the third step, the results of the first and second step were combined to yield the specific costs of GHG mitigation.

These steps are described in the second to fourth subsections below. First though, in subsection 6.4.1, we describe selection of the conversion technologies examined.

6.4.1 Selected technologies

For this analysis, we selected three potential conversion technologies for biomass to electricity. To this end we used the following criteria:

- The technology should be capable of processing the types of dry biomass considered in this project (dry residual biomass or short-rotation wood).
- The technology should be proven for biomass or at least have been demonstrated on semi-commercial scale. Given the time required for development or modification of combustion or gasification technologies, only technologies constituting a realistic option for large-scale commercial power production in 2010-2020 were considered.

Using these criteria, we selected the following technologies:

- Gasification/co-firing; gasification and co-combustion of raw syngas in a coal-fired power plant.
- Gasification/electricity production; pressurised circulating fluidised-bed gasification in combination with syngas utilisation in a combined cycle (PCFBG-STAG).
- Combustion/electricity production; large-scale FBC with high-pressure steam cycle and steam reheating.

Gasification and combustion of raw syngas in a coal-fired power station is technically proven and commercially available. The technology is applied at power plants at Zeltweg (A), Amer (NL), Lahti (Su) and will soon be on-line in Belgium. Although not all installations reach the desired level of plant availability – the Amer facility still suffers from technical problems, for example – others are performing according to design specifications. There are also positive experiences with gasification and co-firing of raw syngas in cement kilns, at Rüdersdorf and Greve, for example. In the case of co-firing in a coal-fired plant, energetic efficiency is approximately 90%, every GJ of biomass substituting 0.9 GJ of coal.

Atmospheric fluidised-bed combustion is a state-of-the-art technology for biomass combustion. The Alholmens Kraft 240 MWe boiler demonstrates the feasibility of large-scale biomass combustion plants with an efficiency of approximately 40%. Aker Kvaerner/Kvaerner Power is currently building two other large 'Cymic' boilers – comparable to the Alholmens boiler – in China and Indonesia. In the future, efficiency might increase to about 45% if this type of large boiler (or even larger) is combined with a supercritical steam cycle. For coal, a first commercial fluidised-bed boiler with supercritical steam cycle is being constructed in Poland (500 MW_e Lagisza power plant). Combination with an ultra-supercritical steam cycle may lead to an efficiency of from 48% (current technological status) to 52% in 2010-2015.

Gasification at high pressure in a circulating fluidised bed and application of the produced syngas in a combined cycle of gas turbine and steam turbine (in a PCFBG-STAG[29]) has been demonstrated on a 30 $MW_{biomass}$ scale at the facility in

[29] PCFBG-STAG = pressurised circulating fluidised-bed gasification + steam and gas turbine.

Värnamo. The combination of gasifier, hot gas cleaning and combined cycle has proved reliable and the ability to operate continuously demonstrated [Ståhl, 2004] [Morris, 2005]. The technology is ready for scaling up by a factor 3 to 10.

The 'gasification/electricity production' route was considered in this study because of its higher efficiency. Further development into a commercially proven and available technology remains uncertain, however. Specific investment costs for PCFBG-STAG (in €/kW$_e$ installed) are currently very high – at least twice the current specific investment for a large-scale boiler – while the anticipated efficiency is only slightly higher (50% versus 40-45% for a large-scale boiler). In addition, further development of large-scale fluidised-bed boilers is an autonomous process driven by power producers seeking more flexible and intrinsically cleaner combustion processes that can handle a wider range of fuels.

The specifications considered in this analysis are shown in Table 7.

Table 7 Specifications and basic assumptions for the biomass power production technologies considered

	Gasification / cocombustion	Combustion / electricity production	Gasification / electricity production
Current capacity range	50 – 100 MW$_{fuel}$	250 MW$_e$	5 – 10 MWe
Future capacity range	50 – 100 MW$_{fuel}$	250 - 500 MW$_e$[30]	200 MW$_e$[31]
Development status	Commercially available for biomass	Commercially available for biomass	Demonstrated on pre-comm. scale
Efficiency - now - future	 η_{th} = 90% η_{th} = 90%	 η_e = 40 - 41% η_e = 40 - 43% (comparable to coal firing)	 η_e = 30% η_e = 47 - 50%? (for 50 MW$_e$)
Specific investment costs (€/kW$_e$) - now - future	 450 450	 1,000 – 1,200 1,000 – 1,200 (for coal)	 > 2,500 1,800? (for 30 MW$_e$)

For comparison:
For the Alholmens 240 MW$_e$ CFB plant an investment of M€ 170 is cited [Vainikka, 2004], [OPET] giving specific investment costs of € 700/kW$_e$. Investment costs are expected to be somewhat higher in the Netherlands, among other reasons because of higher site costs and also because a more extensive flue gas cleaning system will probably be required, especially if residues are burned.

- For gasification and co-combustion of syngas the following investment quotes were found [Granat, 2003]:
  a Approx. € 600/kW$_e$ for the 60 MW$_{fuel}$ Lahti gasifier.

30 The new coal fired boiler with super critical steam cycle and reheating that is currently realized in Lagisza, Poland and will start production in 2008 will have a net production capacity of approximately 460 MW$_e$.
31 As assumed in THE GE study.

b Approx. € 1,000/kW_e for the 10 MW_{fuel} gasifier in Zeltweg, Austria.

c Approx. € 1,300/kW_e for the 80 MW_{fuel} Amer gasifier.

The Lahti and Zeltweg gasifiers have no syngas cleaning, while the syngas cleaning system at the Amer power plant is extensive but also hampers efficient operation and results in low availability. The latter plant was therefore not taken as a reference.

6.4.2 Potential options not considered here

One future option for biomass to electricity conversion may be combustion in pulverised fuel furnaces. At present, the maximum percentage of biomass co-fired in pulverised fuel boilers is 70%, achieved in the retrofitted Avedore 2 ultra-supercritical boiler with pulverised wood pellet fuel [AEAT, 2003], [Leach]. Perhaps this rate can be increased in the future to 100%. Pulverised fuel boilers permit high-capacity generation (500-1,000 MW_e) and combination with ultra-supercritical steam cycles (steam at 600/620°C and 300 bar), resulting in efficiencies of 47-48% now and up to 52% within 10-20 years [DEA, 2004], [Lako, 2004]. Owing to uncertainties regarding technical feasibility, this option was not considered here.

Another option not investigated in this study is combination of a number of different furnaces with the same boiler. This is the configuration used, for example, at one of the most modern Danish power plants, Avedoere 2. At this power station heat for the boiler is provided by a straw-fired grate furnace, a gas and wood pellet-fired furnace capable of operating on 70% wood (thermal input) and a number of gas turbines. The steam cycle has an efficiency of 48% (LHV); see [Leach]. Another example is the Red Hills power plant in the USA, consisting of a single 500 MW_e steam cycle fed by two CFB boilers.

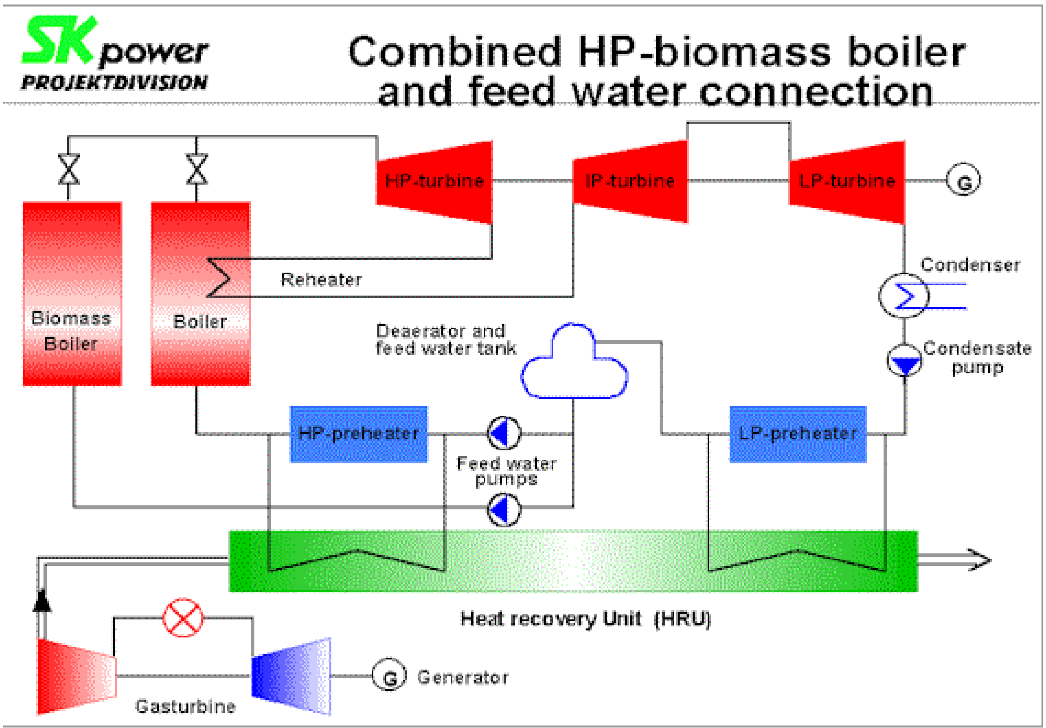
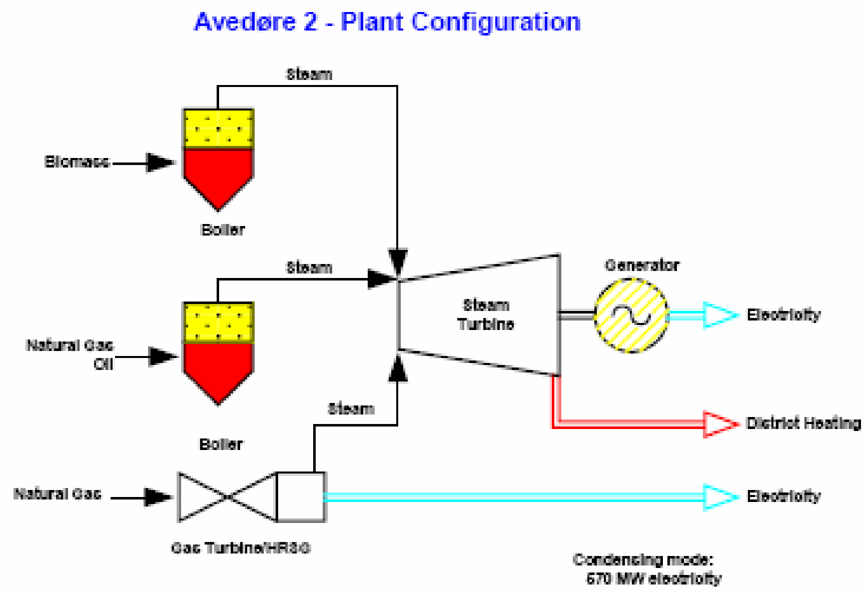


Figure 32 Configuration of the Avedoere 2 power plant [32]



This kind of configuration can also be used for biomass, e.g. by combining a number of biomass-fired CFBC furnaces with an ultra-supercritical boiler, as integrated in the Avedoere 2 power plant. Given the fact that such a plant is already operational, it may already even be a feasible option for biomass. The possibility of such a configuration came to our attention too late for inclusion in the present study. Furthermore, it is unclear how the overall investment of approx. M€ 550 for the 570 MW_e plant is to allocated to the various component units, making estimation of specific GHG mitigation costs unfeasible.

6.4.3 Costs of substituting coal and fossil electricity

Calculation of the net substitution costs requires a comparison between the costs of biomass application on one hand and those of coal and fossil-based electricity on the other.

In the case of gasification and co-combustion of the produced hot syngas in a coal-fired power station, biomass application involves not only the costs of biomass purchase but also those of gasifier operation. Partially offsetting these, however, are the savings on purchase costs of coal that would have otherwise been fired.

In the case of power production, the net substitution costs are given by comparing the production costs of electricity generated using biomass and the average sales price of electricity in the EU market. The former include biomass purchase costs and the cost of operating the biomass power plant in question.

[32] http://www.worldenergy.org/wec-geis/publications/default/tech_papers/17th_congress/2_2_02.asp.

6.4.4 Basic assumptions

The production costs for electricity were roughly estimated in accordance with the *'Milieukostenmethodiek'* mentioned earlier. Items such as disposal of residues from chemo thermal conversion or extra income from selling by-products were neglected.

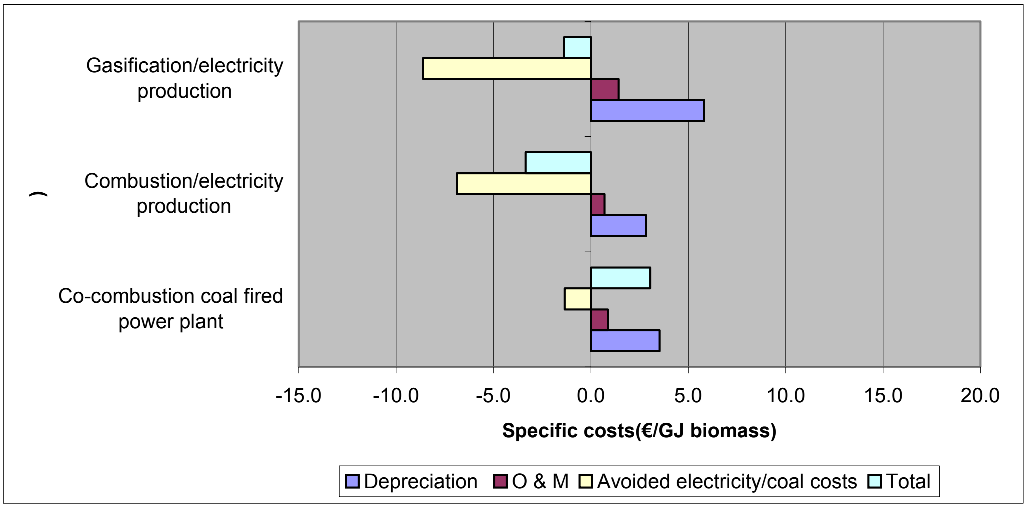
Depreciation costs were calculated for future specific investments and anticipated scale of technology:
- 83 MW_{fuel} for gasification and co-combustion of syngas.
- 250 MW_e for ACFBC.
- 200 MW_e for PCFBG-STAG.

Avoided coal purchase costs and avoided power production costs were estimated using market prices of € 1.5/GJ for coal and € 0.055/kWh_e for electricity. These figures are valid for the current market situation.

For all technologies, a load factor of 80% was assumed. Such load factors are typical for base-load power plant in the Netherlands.

The resultant specific costs (in €/$GJ_{biomass}$) are given in Figure 33.

Figure 33 Specific costs of the power generation routes (in €/$GJ_{biomass}$)



The cost estimates shown in the figure illustrate that the higher efficiency of the gasification/electricity production route and resultant higher revenues from electricity sales will probably not offset the higher depreciation and O&M costs.

Gasification and co-firing probably leads to somewhat higher specific costs because the low coal prices compensate only a fraction of depreciation and O&M costs.

6.4.5 Net avoided greenhouse gas emissions

The net avoided GHG emissions were determined in accordance with LCA methodology as the difference between (cf. subsection 6.3.2):

- The GHG emissions resulting from production of fossil fuels and their application in power generation.
- The GHG emissions resulting from making biomass available for power generation.

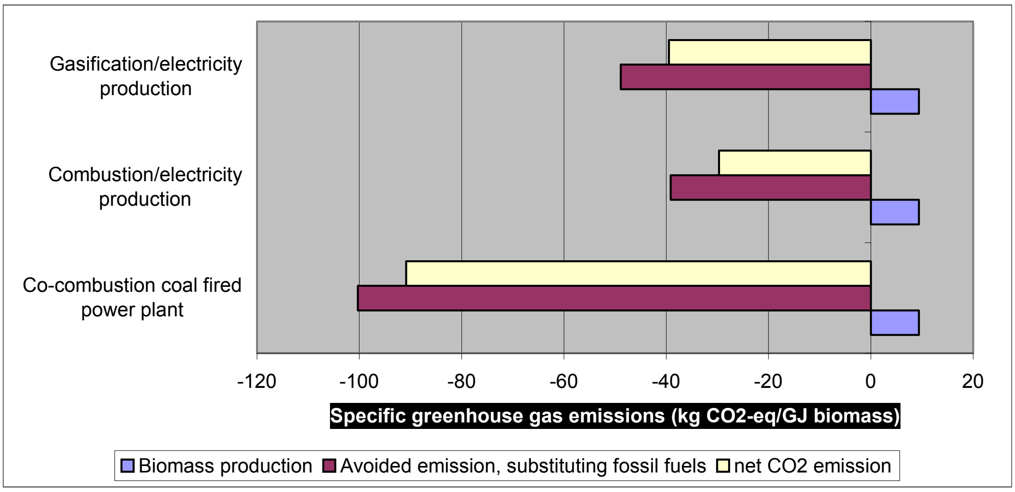
For the sake of simplicity, and in line with the biofuels analysis, only one form of biomass – short-rotation wood – was considered in this analysis. According to the GM and Concawe studies, cultivation of short-rotation wood is associated with a GHG emission of 9.4 kg/GJ.

For the substituted coal and fossil electricity, the following basic assumptions were made:

- Coal production gives a GHG emission of 15.3 kg CO_2 eq./GJ (|Concawe|).
- Coal combustion gives a GHG emission of 96 kg CO_2 eq./GJ.
- Because of the higher share of nuclear and hydropower in the average EU power generation mix, the average specific emission for EU15 is estimated at 350 kg CO_2 eq./MWh_e (incl. GHG emissions during fossil fuel production).

Combining the avoided amounts of coal and fossil electricity with the specific GHG emissions per unit fuel or electrical power results in the net avoided GHG emissions per plant shown in Figure 34.

Figure 34 Specific emissions of the power generation routes (in kg CO_2 eq./$GJ_{biomass}$)

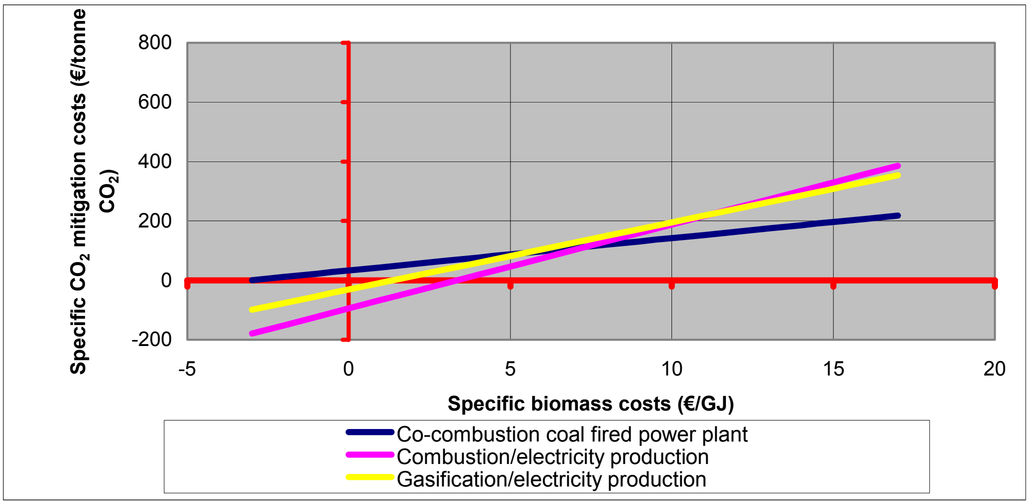


As can be expected from the efficiencies taken or assumed, gasification and co-firing give the highest net avoided greenhouse gas emissions.

6.4.6 Specific mitigation costs

Combining the results of the two previous subsections – dividing annual costs by the net greenhouse gas balance – yields the following specific GHG=mitigation costs as a function of biomass cost price.

Figure 35 Relation between specific GHG mitigation costs (€/tonne CO_2 reduction) and biomass cost (€/GJ)



Despite large differences in investment costs and differences in avoided greenhouse gas emissions per GJ biomass, 'combustion/electricity production' and 'gasification/electricity production' give comparable specific GHG mitigation costs, the higher efficiency of the latter compensating for the higher specific investment costs at high biomass prices.

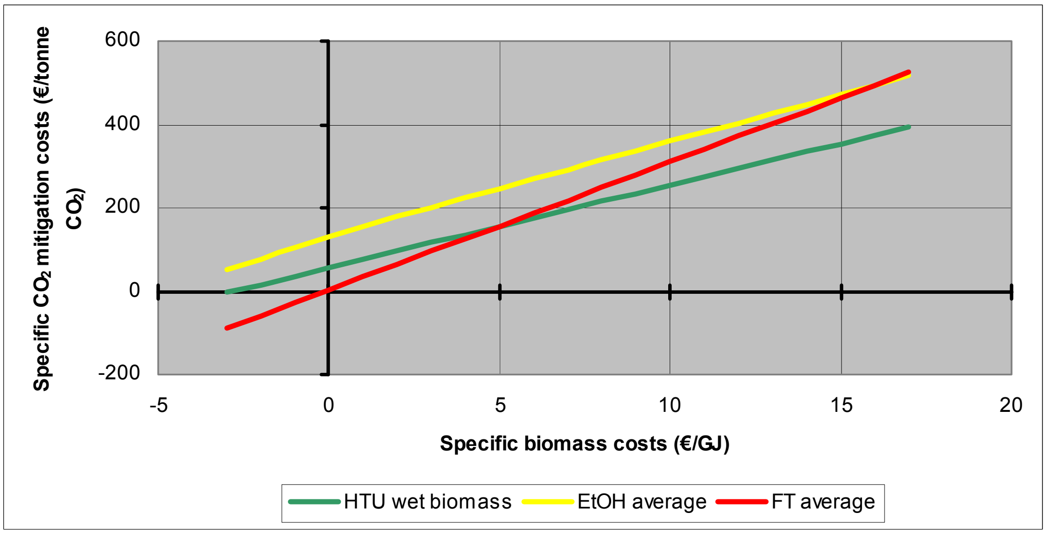
The low coal price results in relatively high costs per unit biomass. Combining these relatively high costs with the substantial avoided GHG emissions per unit coal gives specific mitigation costs comparable to those for the two other routes, at low biomass market prices. If biomass prices are high, the specific mitigation costs will clearly be lower than those for both other routes because of the greater net avoided GHG emissions per unit biomass.

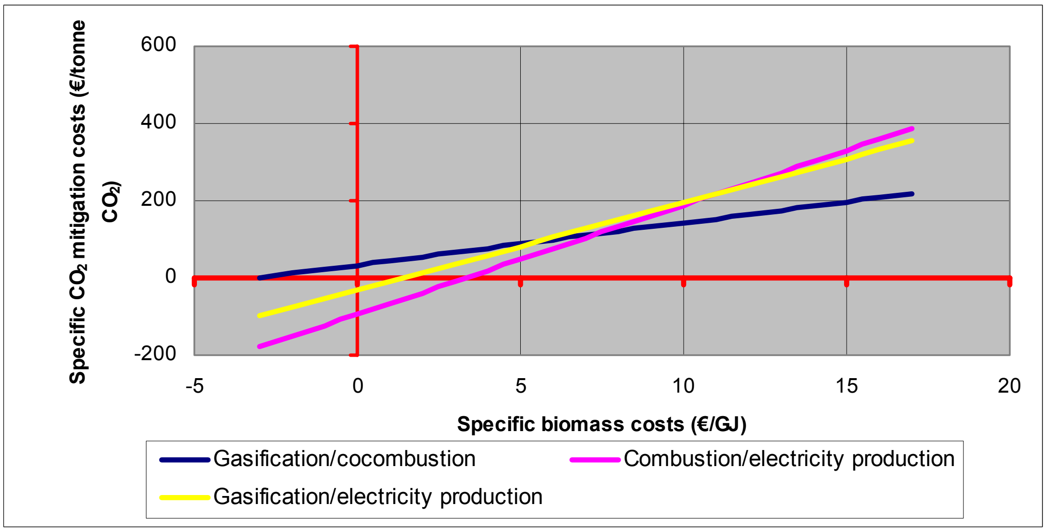
Uncertainties in the specific mitigation costs have not been estimated. For both of these commercially available technologies, efficiencies and investment costs are relatively well-known.

6.5 Comparing specific mitigation costs of the two biomass applications

In Figure 36 (combining Figure 31 and Figure 35) the results of the two cost estimates are shown below one another to allow comparison between the resultant specific mitigation costs for power production and automotive fuels production.

Figure 36 Comparison of specific mitigation costs





The figure illustrates that biobased electricity generation is probably a more cost effective application for biomass than production of future biofuels. This is certainly the case for the future specific biomass costs anticipated of € 6,-/GJ for 2010 and beyond on a free biomass trade market[33]. This conclusion of course refers to a comparison for the same type of biomass applied in both routes.

Specific mitigation costs for biofuels might become more or less comparable if the more optimistic predictions in relation to the production technologies prove to be right. But there is no indication that they will become lower than specific greenhouse gas mitigation costs related to biobased electricity generation. This is not so much the result of higher investment costs or lower efficiency's – which are both comparable to those for biobased power generation – but simply because the product electricity has a higher market value than biofuels.

[33] See MEP program.

The following remark further indicates the correctness of this conclusion. The analysis conducted in this study with regard to biomass fired Carnot power generation technology mainly considered current conventional technology and focused less on state-of-the-art technology – such as implemented in the Avedøre power plant. Implementation of this kind of technology might result in higher efficiency's (up to 50% - 52%) and lower specific production costs for biobased power generation and thus in even lower specific mitigation costs.

7 Conclusions and recommendations

7.1 Potential future biofuel processes

There are a number of future biofuels that might potentially come onto the market in the next 10 to 15 years. In this report we have discussed the most promising of these, *viz.*:
- Ethanol and ETBE from lignocellulosic (woody) biomass.
- Fischer-Tropsch diesel from lignocellulosic biomass.
- HTU diesel.

All these potential future biofuels are still under development, with conversion processes not yet fully operational on any substantial scale.

Compared with current biofuels, these new products are expected to show superior performance in terms of cost, environmental impact and socio-economic effects.

This superior performance derives mainly from these new processes being able to convert alternative types of biomass feedstock. Current biofuels require biomass cultivated on agricultural land or products that could otherwise be used for food or cattle feed. These types of biomass need relatively intensive farming, i.e. relatively high fertiliser inputs and energy-intensive management. Future biofuel technologies on the other hand are expected to be able to process woody biomass residues, cultivated wood (in the case of ethanol, ETBE and Fischer-Tropsch diesel) or wet organic residues (for HTU diesel). These residues have only a few, low-value, alternative applications and wood can be farmed on land of less agricultural value, using less fertiliser and energy.

7.2 Biomass availability in the Netherlands and import requirements

All future biofuels will be produced from woody residues or cultivated wood. They will therefore not compete with the food chain, as current biofuels might. In addition, HTU diesel can also be produced from wet organic biomass. Although in the Netherlands there is considerable potential biomass feedstock for these biofuels (sufficient to replace about 10% of transport fuel by biofuels), its fate is currently different, being ploughed back into the soil, added to animal feed or used for power generation, for example. If the biofuels industry were to attract an increasing share of this biomass, this would probably lead to increased import of biomass, there being only limited scope for greater biomass cropping in the Netherlands.

7.3 Technical, economical and environmental limitations

The potential future biofuels cited above are all still in the research and development phase and are not yet available on the market because of ***technical*** limitations.

In terms of ***economics***, two limitations can be distinguished. First, significant investments are still required for developing these new biofuel technologies. Second, even when these technical problems have been solved, economical limitations could hamper large-scale application. At least until these biofuels are marketed on a large scale or the costs of other fuels increase significantly, they are likely to remain more expensive than conventional fossil fuels. Market access will then be dependent on government incentives. In the longer term, however, costs are predicted to fall, so that eventually all of the future biofuels discussed here will be able to compete with their fossil counterparts as well as with current biofuels.

Whether or not this cost reduction can indeed be achieved will depend on:
- Technological developments (resulting in a specific process design, conversion efficiency, etc.).
- Biomass prices (which, in turn, depend on competition with other potential users of the biomass or land, such as the food or energy sector[34]).
- Conversion process operating costs (e.g. cost of enzymes for producing lignocellulosic ethanol and ETBE).
- Fossil fuel prices.
- Government incentives and policies that promote the developments and market introduction of these fuels.

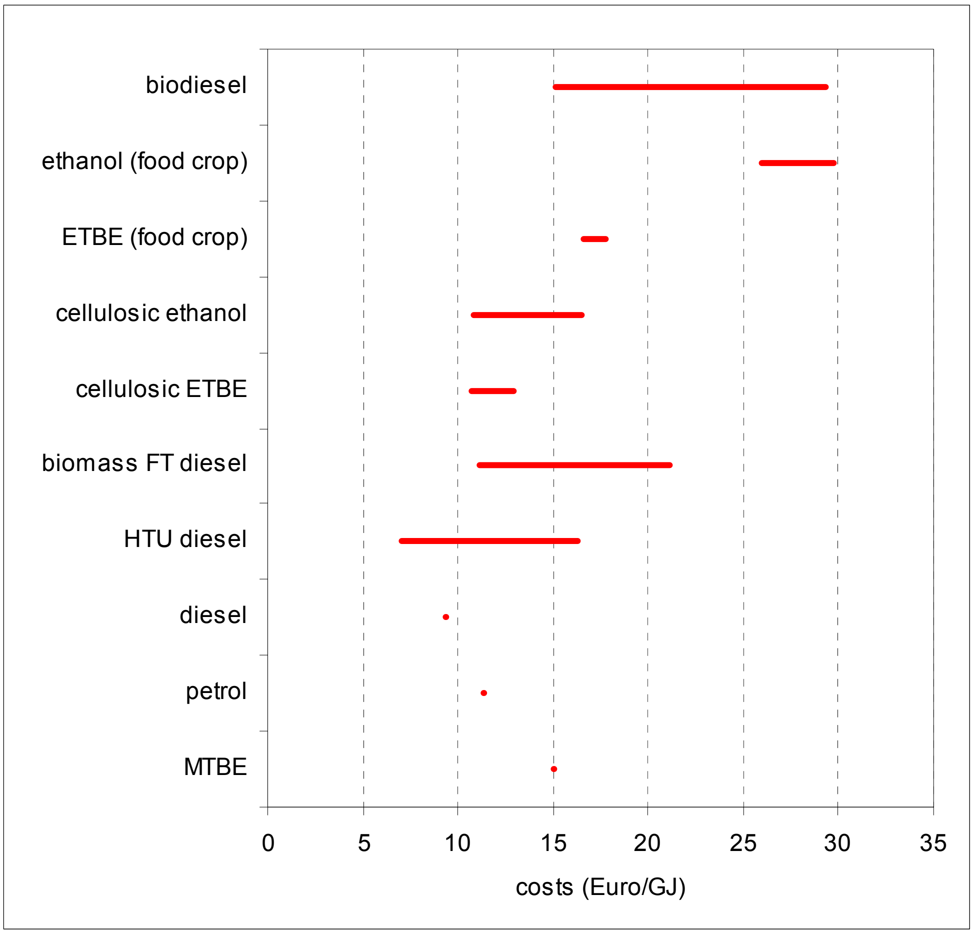
Once these biofuels gain any significant market share, biomass prices (and therefore costs) can be expected to increase (owing to increased demand). On the other hand, upscaling of biofuel production facilities will generally reduce costs.

Despite these uncertainties, a number of cost estimates for future biofuels are available in the literature. These are shown in Figure 37, where they are compared with the cost of current biofuels and petrol and diesel (excl. taxes). Clearly, future biofuels are likely to be cheaper than current biofuels. However, they will be only priced comparably to current fossil fuels (excl. taxes) if optimistic cost estimates prove correct – or if fossil fuel prices increase. If not, fossil transport fuels will probably remain significantly cheaper than future biofuels. Note that cost estimates are quite similar for all the future biofuels considered. Estimated production costs for HTU diesel are comparable to current diesel production costs if wet organic residues with a negative market value are applied as a feedstock.

In one of the sections below, we will show how these biofuel costs are related to CO_2 emission reduction, in terms of Euro per Mton CO_2 eq reduced.

[34] Note that other sectors, such as power generation, are also moving towards increased use of biomass feedstocks. As woody biomass may be an attractive feedstock for all the sectors concerned, they will compete with one another on the biomass market. This can be expected to result in higher biomass prices and increased demand for wood farming.

Figure 37 Cost estimates of the various biofuels, compared with the average cost of diesel and petrol in 2002-2004

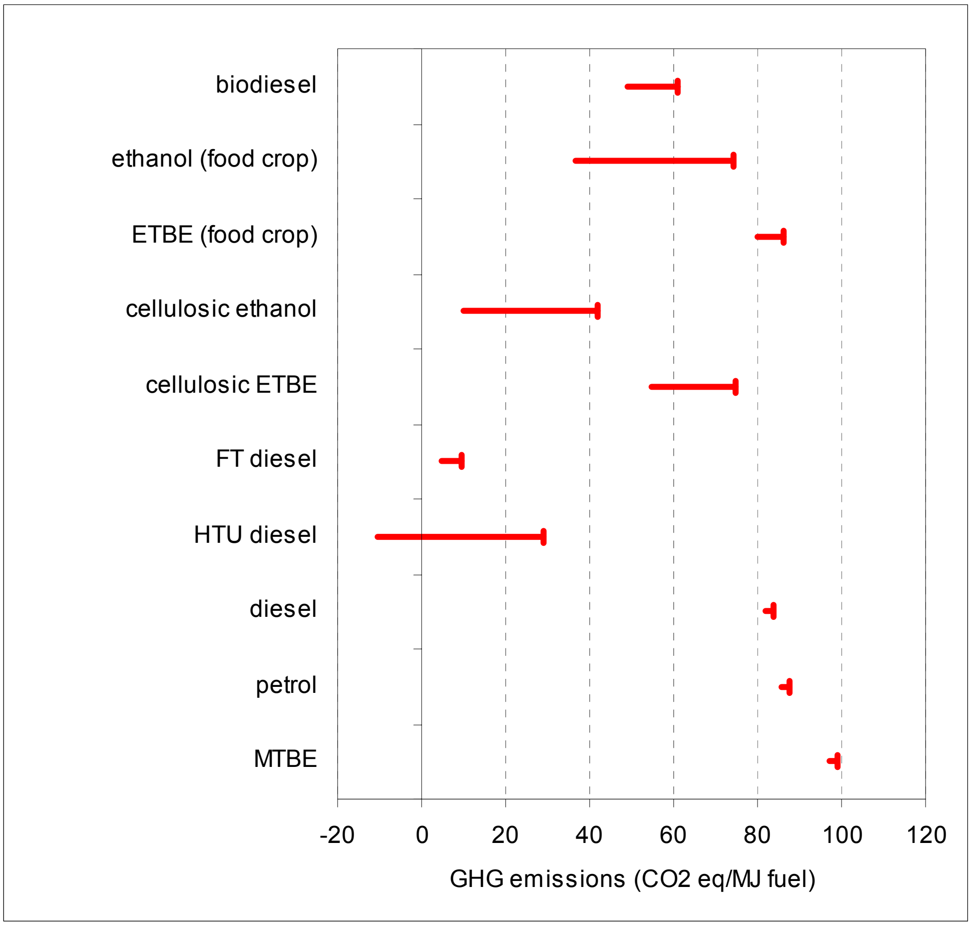


The main ***environmental*** drawback of the future biofuels examined concerns the potential farming of the biomass required. All of these future biofuels can potentially use woody waste streams as a feedstock, which can probably be used without significant environmental impact if this wood is produced under sustainability regulations like the FSC system which is currently in place for wood products. If the wood is imported without sustainability guarantees environmental problems like cutting down of rain forests or no replantation are possible, as the conventional wood market has shown. If waste streams are all used (either for biofuels or for other applications), or if high-quality feedstock is required (for example, for the gasification process for biomass FT-diesel), the biomass will need to be cultivated. A considerable forested area as well as water inputs will then be required if these biofuels are to be produced and sold on a large (international) scale. Among other things, this will increase pressure on the world's remaining rainforests and other habitats.

7.4 Potential for net greenhouse gas reduction

In Figure 38 the greenhouse gas emissions of the various biofuels analysed in this report are compared, both with each other and with their fossil counterparts, and using only the most realistic estimates. Cellulosic ethanol, biomass FT diesel and HTU diesel are expected to yield far higher GHG reductions than currently available biodiesel and ethanol from wheat or sugar beet. Total GHG reductions of over 90% are in fact expected from biomass FT and HTU diesel. The ranges of uncertainty are relatively high for the HTU route, which might even remove greenhouse gases. Converting ethanol to ETBE has clear advantages from the perspective of biofuel quality control (see Figure 38), but reduces GHG reduction potential significantly because it is produced only partly from ethanol and partly from fossil isobutylene. Since the production of MTBE involves more energy and thus CO_2 emissions than petrol, ETBE that replaces MTBE leads to greater GHG reductions than when it replaces petrol.

Figure 38 Overview of the GHG emissions of each of the biofuels analysed, compared with those of diesel, petrol and MTBE (CO_2 eq./MJ fuel)



The GHG reductions of the various biofuels were found to depend strongly on the emissions associated with the biomass feedstock – either with its cultivation or with the cultivation of a compensating product. The superior performance of the future biofuels examined is therefore due mainly to their potential for using lignocellulosic biomass as a feedstock:

- Bio-ethanol and ETBE are currently produced from biomass that may also be used in the food or fodder industry or that is grown on farmland that might otherwise be used for food or fodder production. This is not the case for biodiesel, as long as the rapeseed is grown on set-aside land.
- Competition with the food or fodder industry means that the price of agricultural products may rise, in both EU and global markets. Woody biomass can be grown on different soils, in different parts of the world. Moreover, less land mass is needed to yield a given amount of fuel.
- Woody biomass is generally cheaper than agricultural products.
- Future biofuel production facilities can be designed energy-neutral, by using process by-products to generate heat and power. In some cases, more electricity can be produced than required.

Figure 39 and Figure 40 show the total GHG reduction potential and cost effectiveness of the various biofuels for 2020, for the two (hypothetical) cases analysed in this report. In the first graph, it is assumed that the various biofuels are blended up to the maximum currently allowed: 5% of ethanol in petrol, 5% of biomass FT diesel and HTU diesel in diesel, and 15% of MTBE in petrol. The second graph illustrates the GHG reduction potential in the case of these biofuels replacing 20% of total road transport fuels in 2020. Both cases are based on the most recent projections of petrol and diesel consumption in 2020 by the Dutch National Institute for Public Health and the Environment [RIVM, 2003]. As a comparison: total road transport CO_2 emissions are predicted to be about 44.2 Mtonne in 2020 (direct and indirect emissions), in the Netherlands. The height and width of the ellipses in the figures represent the ranges in GHG reduction potential and cost effectiveness as given in chapter 4.

Figure 39 Comparison of greenhouse gas reduction potential vs. cost effectiveness of the various biofuels in 2020, assuming that they are blended into road transport fuels up to the maximum percentage allowed: i.e. for biodiesel, FT and HTU diesel it is assumed that 5% of all diesel used in the Netherlands is replaced, for ethanol 5% of all petrol, for ETBE 15% of all petrol

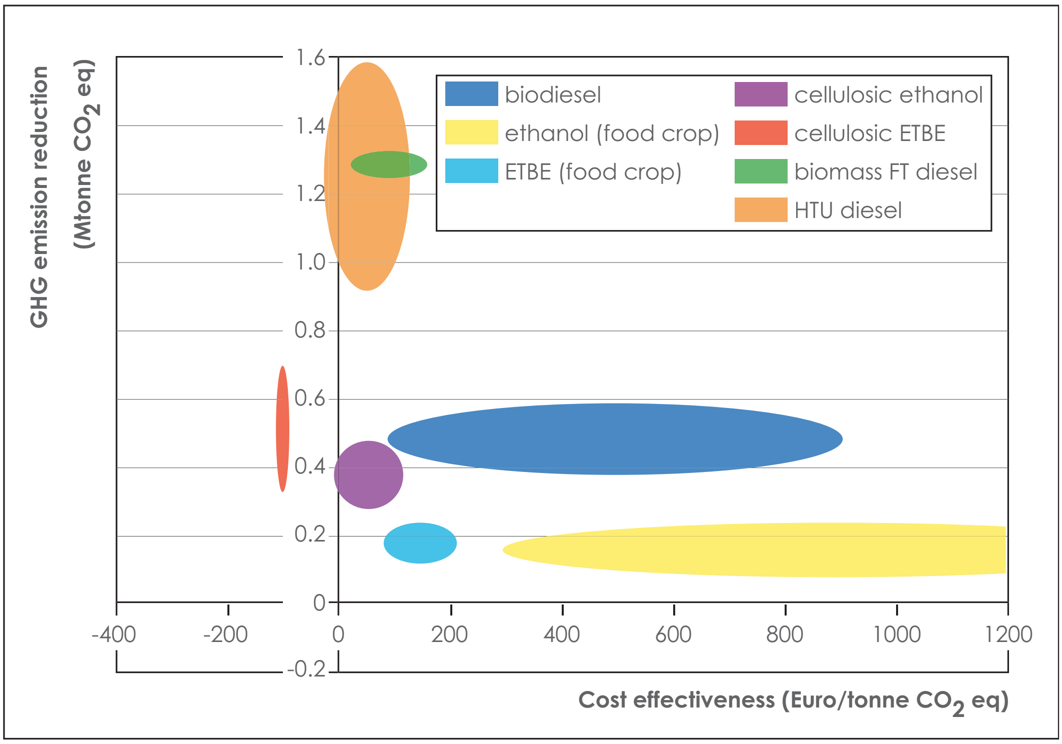
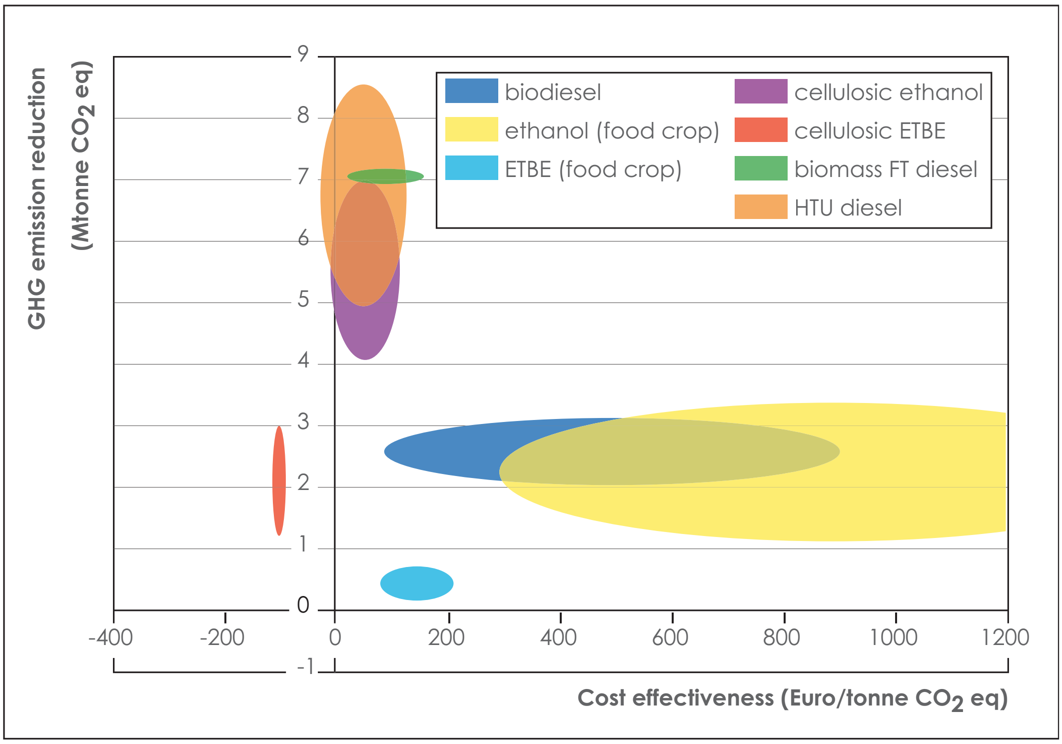


Figure 40 Comparison of greenhouse gas reduction potential of the various biofuels in 2020, assuming 20% replacement of total road transport fuels. For ETBE, only 15% is considered, this being the maximum percentage allowed by current fuel standards



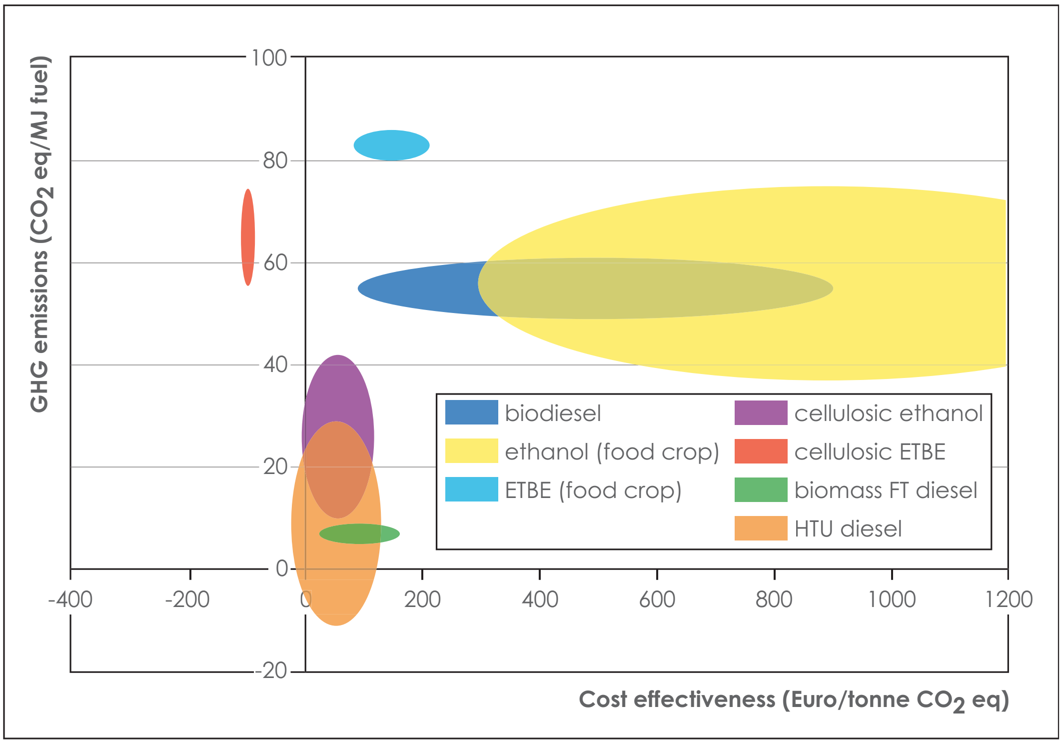
These results show that the GHG reduction results for 2020 of the various biofuels depend on the assumptions used: the biofuels score quite differently in these two cases. In the first scenario, where the biofuels are blended into their fossil counterparts up to the maximum allowed, those that replace diesel achieve relatively high CO_2 emission reductions. However, this is mainly due to the prediction that 72% of all road transport fuel sold in 2020 is diesel. In this scenario, the diesel replacements biomass FT and HTU diesel have the potential to reduce about 1 - 1.6 Mtonne CO_2 eq. (2 – 3.5% of road transport CO_2 emissions in 2020). Cellulosic ethanol can be expected to reduce about 0.3 – 0.5 Mtonne CO_2 eq (0.6 – 1.1% of the total). Converting ethanol to ETBE improves the GHG reduction potential in this scenario, because of the higher blending percentage that is allowed for ETBE: 0.3 – 0.7 Mtonne CO_2 eq, i.e. 0.7 – 1.6% of total road transport emissions.

In the second scenario, all biofuels have an equal share in the road transport fuel market (20%). In this case, biomass FT diesel, HTU and cellulosic ethanol were all found to give a GHG reduction of approx. 4.5 to 8 Mtonne CO_2 eq, or about 14 - 18% of total road transport emissions in 2020. On average, these biofuels can be expected to reduce CO_2 emissions by about two to three times as much as biodiesel and current bio-ethanol. ETBE from food crop achieves the least CO_2 emission reduction, ETBE from cellulosic material is likely to perform much better in this respect. If ethanol is converted to ETBE, GHG emissions reduction is more than halved because of the addition of (fossil) isobutylene and the extra processing requirements. If cellulosic ETBE were to replace 20% of road transport fuels in 2020, there would be a reduction of 1.2-3 Mtonne CO_2 eq, or about 3-7% of road transport CO_2 emissions.

Cost effectiveness is defined here as the ratio between the additional cost of biofuels (relative to the respective current fossil fuel) and the specific GHG reduction the biofuel achieves. The figures show that the cost effectiveness of the future biofuels is expected to improve significantly compared with current biofuels, owing to improvements in both cost and GHG reduction. Whereas 1 tonne of CO_2 eq reduction with current biofuels may cost several hundred Euro, future biofuels have the potential to reduce this figure to less than 100 €/tonne. Cellulosic ETBE is expected to become cheaper than MTBE (at current costs), resulting in a negative cost effectiveness in the figure. The same may also hold for the other future biofuels if optimistic cost estimates prove correct. Note also that the ranges in the cost effectiveness data are relatively large, due to uncertainties in both cost and GHG emission reductions of the biofuels.

To conclude the comparison, Figure 41 shows the GHG emissions per MJ biofuel versus the cost effectiveness of the various biofuels (again, in Euro per tonne CO_2 reduction). The expected improvements to future biofuels in terms of both cost and GHG emissions result in a clear improvement of performance on both aspects, compared to the current biofuels.

Figure 41 Synopsis of cost effectiveness of GHG reduction versus the cost effectiveness of the various biofuels



7.5 Timing of availability

Given the current status of the various future biofuel production technologies, first-of-a-kind commercial-scale installations may be achievable within the next ten years if no major technical bottlenecks are encountered and if sufficient efforts and funds are expended. With the exception of HTU, technological development is taking place mainly on an international scale.

From the available information it is difficult to predict which technological hurdles will be taken soonest and whether expectations regarding cost reductions and upscaling will be met.

Our initial impression is that an FT process based on CHOREN technology may be quickest to develop and have greatest potential for further development and commercialisation. Furthermore, FT technology can also be used in other sectors such as the petrochemical industry, where gasification is being applied increasingly. FT diesel has the advantage of having properties such that it can meet (or even exceed) present diesel standards. It can therefore be readily introduced into the current fuel system, either by blending it into diesel or by selling it neat, without any need for engine modifications.

The production of ethanol (and thus ETBE) from lignocellulosic biomass is currently in the demonstration phase. In the years to come it will become clearer whether upscaling to a large-scale (demonstration) facility is feasible. Large-scale market introduction of ethanol requires special flexible-fuel vehicles, which may hamper implementation. Additional costs to vehicles are limited, however. ETBE does not require any engine modifications, but under current standards blending is limited to a maximum of 15% of the petrol.

The HTU technology currently seems to be the least mature of the biofuel routes analysed here. This technology yields additional benefits compared with the other biofuels, however, as it can convert wet organic waste streams that are of little value in other applications.

7.6 Quality of the future biofuels

The properties of future bio-ethanol are the same as those of the bio-ethanol currently produced from wheat, sugar beet or agricultural residues. Problems may occur when it is blended with petrol at low percentages (<20%), because this will increase the vapour pressure of the fuel. This can be solved by reducing the high-volatiles content of the fuel, but problems may reoccur when the fuel is then blended with petrol without ethanol or with a different percentage thereof. If over 20% ethanol is used, these problems no longer occur.

If ethanol is converted to ETBE, up to 15% may be added to petrol according to current European fuel specifications. Its blend characteristics are very good.

Fischer-Tropsch diesel can be blended with conventional diesel at any blending grade or used as neat fuel. Compared with fossil diesel, it has the advantage of not containing any sulphur or aromatics.

Little is currently known about the fuel quality of HTU diesel, but there are no indications that the fuel will encounter quality problems. Initial testing indicated has better ignition properties than conventional diesel, but more extensive trials are needed before definite conclusions can be drawn on the properties of this biofuel.

7.7 Opportunities for the Dutch economy

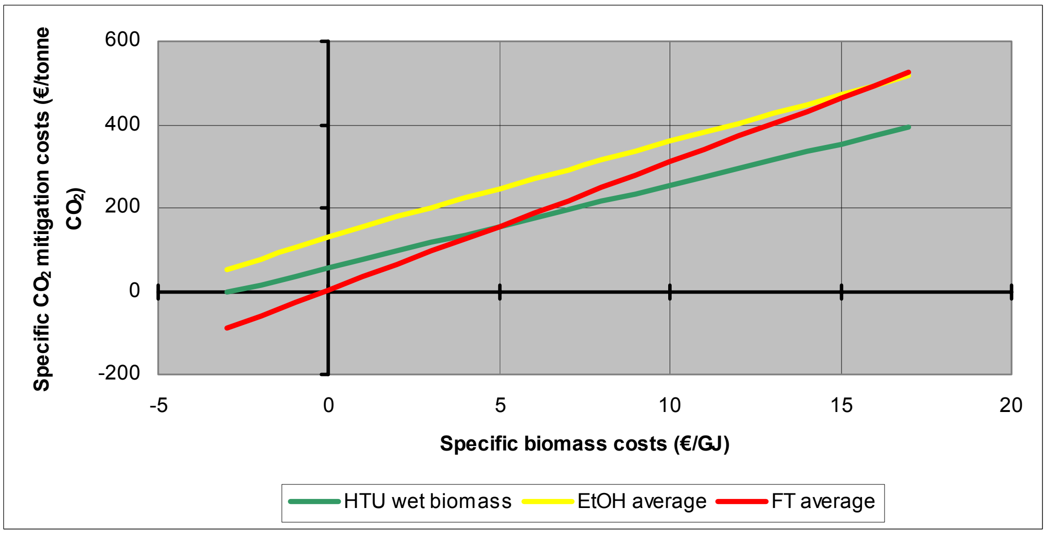
As demand for biofuels increases both within and outside the Netherlands, opportunities develop for the Dutch economy. In this project, there was no room for an extensive analysis of these opportunities and their potential impact. However, we can identify two potential sectors that could benefit economically:
- The port of Rotterdam can benefit from increased demand for biomass and biofuel imports, and
- Biofuel research and production facilities can be located in the Netherlands.

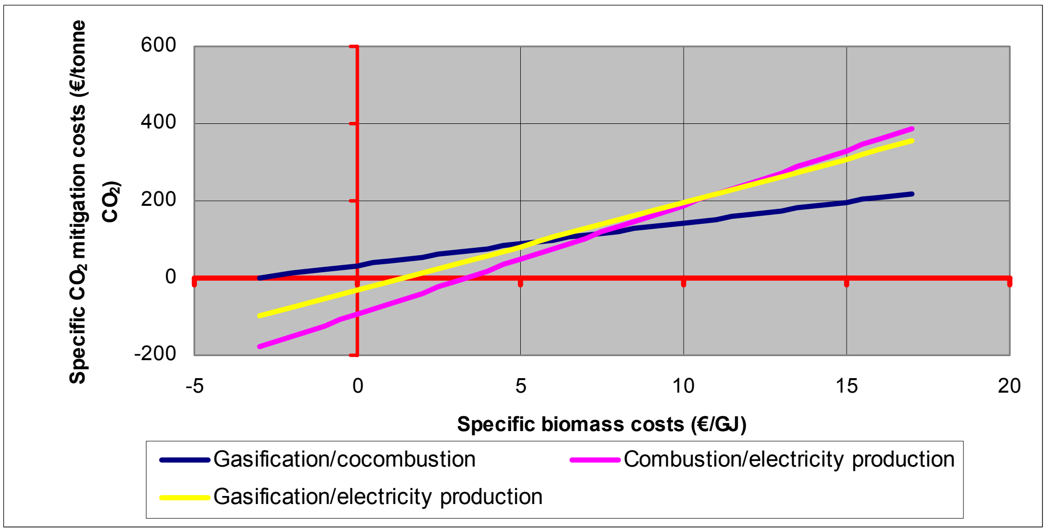
The Rotterdam area may provide an attractive location for the latter facilities, providing there are indeed port facilities for biomass import. There are currently two serious Dutch players in development of future biofuels: Nedalco BV is involved in lignocellulocis ethanol R&D and is also considering building a large-scale ethanol plant, and Biofuels BV is developing HTU technology. Also Shell (an AngloDutch company) is conducting research in second generation biofuels but these efforts are currently concentrated outside of the Netherlands.

7.8 Comparison of costs and greenhouse gas reduction potential of these future biofuels with other biomass applications

There are two basic options for using biomass to substitute fossil fuels and thereby reduce greenhouse gas emissions. It can be converted to biofuels or used as a feedstock for electrical power generation. Costs and GHG reduction potential of both routes were analysed, and a comparison of the specific GHG mitigation costs of these two options is shown in Figure 42.

Figure 42 Comparison of specific mitigation costs





The figure illustrates that biobased electricity generation is probably a more cost effective application for biomass than production of future biofuels. This is certainly the case for the future specific biomass costs anticipated of € 6,-/GJ for

2010 and beyond on a free biomass trade market[35]. This conclusion of course refers to a comparison for the same type of biomass applied in both routes.

Specific mitigation costs for biofuels might become more or less comparable if the more optimistic predictions in relation to the production technologies prove to be right. But there is no indication that they will become lower than specific greenhouse gas mitigation costs related to biobased electricity generation.

[35] See MEP program.

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CE
Solutions for
environment,
economy and
technology

Oude Delft 180
2611 HH Delft
The Netherlands
tel: +31 15 2 150 150
fax: +31 15 2 150 151
e-mail: ce@ce.nl
website: www.ce.nl
KvK 27251086

Biofuels under development

An analysis of currently available and future biofuels, and a comparison with biomass application in other sectors

Annexes

Report

Delft, May, 2005
Author(s): B.E. (Bettina) Kampman
L.C. (Eelco) den Boer
H.J. (Harry) Croezen

A Methodology used for calculating GHG emissions

A.1 Introduction

The greenhouse gas emissions of biofuels are generally calculated using the methodology of Life Cycle Analysis (LCA). The net GHG reduction per unit fuel is then determined by comparing:

- The total direct and indirect emissions of greenhouse gases associated with production of the fuel, taking into account the entire route from cultivation of the biomass to biofuel use in motor vehicles (including transport of biomass or fuel, feedstock-to-biofuel conversion, etc.).
- The total direct and indirect emissions of greenhouse gases associated with both production and consumption of the equivalent amount of fossil fuels substituted by the biofuel[36] (i.e. the reference situation).

The net GHG reduction per unit biofuel is the difference between these two aggregated figures.

In accordance with LCA methodology, all GHG are here expressed in terms of CO_2 equivalents. Emissions of non-CO_2 greenhouse gases must be multiplied by so-called characterisation factors expressing the greenhouse potential of the gas relative to CO_2[37].

Furthermore, the LCA analysis must make due allowance for the following two issues.

- If biofuel production uses biomass that would otherwise be applied for other purposes (e.g. as fodder), additional biomass will need to be cultivated to compensate for that use. For example, if biomass is consumed that would otherwise be used as cattle feed, additional fodder crops need to be cultivated. The associated emissions then need to be included in the LCA analysis of the biofuel.
- Some biofuel processes generate useful by-products that will also be sold. Part of the emissions relating to cultivation and production of the biofuel can then be allocated to these by-products. Here we have based allocation on the economic value of the various products produced[38].

Below, various aspects of this methodology are explained in more detail.

A.2 Biomass-to-biofuel chains

In biofuel LCAs, vehicle CO_2 emissions are equal to the amount of CO_2 that is taken up at the beginning of the biofuel route, when the biomass is cultivated. Both can thus be ignored in the LCA.

36 For ethanol this would be petrol, for ETBE it would be MTBE, etc.
37 According to IPCC, this characterisation factor is 310 for N_2O and 21 for CH_4 (and 1 for CO_2).
38 This approach is in line with the guidelines issued by the Biomass Transition Sustainability Workgroup.

There are several other greenhouse gas emissions arising during the biomass-to-biofuel chain that do have to be taken into account, however, including specifically:

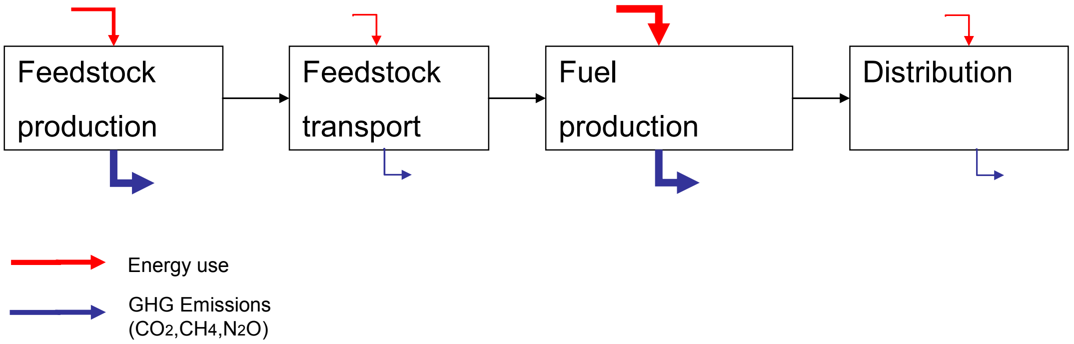
- CO_2 emissions associated with the fossil energy used during conversion processes like fermentation, gasification and oil extraction from oil seeds.
- In the case of biomass cultivation:
  - a Emissions of CH_4 and N_2O related to fertiliser production and application.
  - b CO_2 emissions from agricultural machinery if it is fossil-fuelled.
  - c CH_4 emissions associated with manure application.
  - d CO_2 emissions associated with changes in soil carbon content following vegetational changes due to biomass feedstock cultivation for biofuel production[39].

For N_2O emissions, the GM study [GM, 2002] uses the revised 1996 IPCC guidelines. The Concawe study uses the JRC[40] model, which is cited as the best method in EU-15 for calculating N_2O emissions. We assume both methods to be useful for the present study.

Last but not least, transportation of the biomass feedstock or the biofuel and distribution of the biofuel also cause CO_2 emissions that must be taken into due account.

Figure 43 illustrates this chain schematically, distinguishing the four main links of relevance to the GHG analysis. The GHG emissions of each of these steps have been identified for all the fuel chains studied (in chapter 4). This approach makes visible where in the chain most emissions occur and how the various biofuels and feedstocks differ in this respect. It will be shown later that the most important process steps with regard to emissions and energy use are feedstock production (e.g. biomass cultivation) and fuel production (e.g. conversion of the biomass). The width of the lines indicates the level of energy use and GHG emissions.

Figure 43 Schematic overview of chain steps and phases of energy consumption and emissions



[39] Cultivation of biomass feedstock for biofuel production may also have an effect on soil structure and composition, especially when natural vegetation is removed to make room for fields and plantations to cultivate the desired feedstock.

[40] JRC: Joint Research Centre, the European Commission's research organisation.

A.3 Presentation

In the main report, the GHG (CO_2, CH_4 and N_2O) emissions occurring during fuel production are tabulated for different biofuels per MJ of fuel produced. These emissions are referred to as indirect emissions. Vehicle tailpipe emissions are not taken into account, as these are assumed to be part of the carbon cycle. The carbon in the biofuel is basically the result of photosynthesis (CO_2 fixation) and is returned to the atmosphere as CO_2 during combustion. ETBE is a special case, since it is only partly of biological origin. This is further elaborated in the sections on ETBE.

In the case of conventional fuels, indirect as well as tailpipe (direct) emissions are taken into account, since both are of fossil origin and contribute to climate change.

To compare the fossil fuels and biofuels, the total (direct + indirect) emissions of fossil fuels (section 2.5) need to be compared with the indirect emissions of biofuels.

A.4 Land use change: effects on carbon equilibrium

In the cases of native vegetation or long-term set-aside plots being converted to arable land, soil is known to emit CO_2 until a new carbon equilibrium has been established. On the other hand, if arable land is converted to a type of vegetation leading to a higher soil carbon content (as in the case of forest), CO_2 from the atmosphere is sequestered in the soil, again until a new carbon equilibrium has been reached.

The CO_2 emissions generated by land-use changes, which are largely uncertain, have not been included in the calculations for this study. This is in line with the GM and Concawe studies.

A.5 Oil-based fuel chains

The direct emissions related to production of the substituted fossil fuel are the emissions occurring during flaring, venting, steam production, transportation and firing of furnaces during:

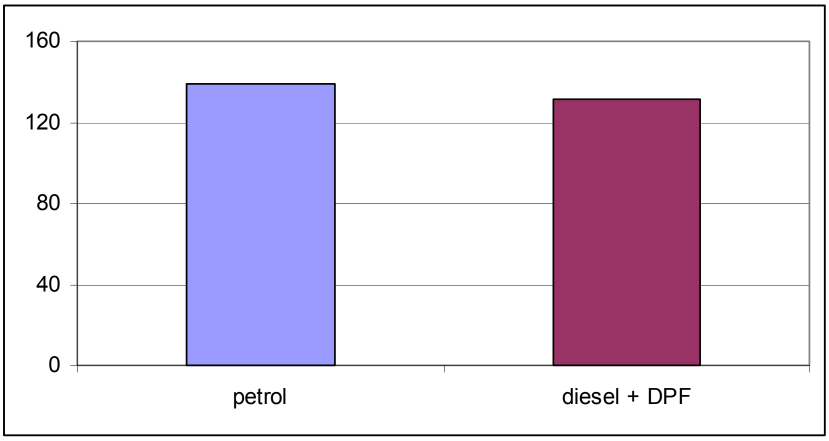
- Crude production.
- Crude transportation by tanker or pipeline.
- Crude refining.
- Fuel distribution.

Direct emissions related to fuel consumption refer, of course, to vehicle CO_2 emissions. With fossil fuels these need to be taken into account. The indirect GHG emissions are related to the production of energy carriers and chemicals consumed during crude production, crude transportation and crude refining. Examples of such energy carriers or chemicals are electricity, hydrogen and oxygen.

A.6 Tank-to-wheel emissions

In this study, the Tank-To-Wheel section of the fuel chains has not been taken into account. With the introduction of diesel particle filters and direct injected petrol engines, the energy consumption and GHG emissions of comparable petrol and diesel cars are expected to converge [Concawe, 2004]. In 2010 the difference in efficiency will have been reduced to 5%, as depicted in Figure 44. This figure is expected to fall even further after 2010, with further penetration of direct-injection petrol cars [IFEU, 2004].

Figure 44 GHG emissions of an average petrol and diesel car (CO_2 eq. per km) in 2010



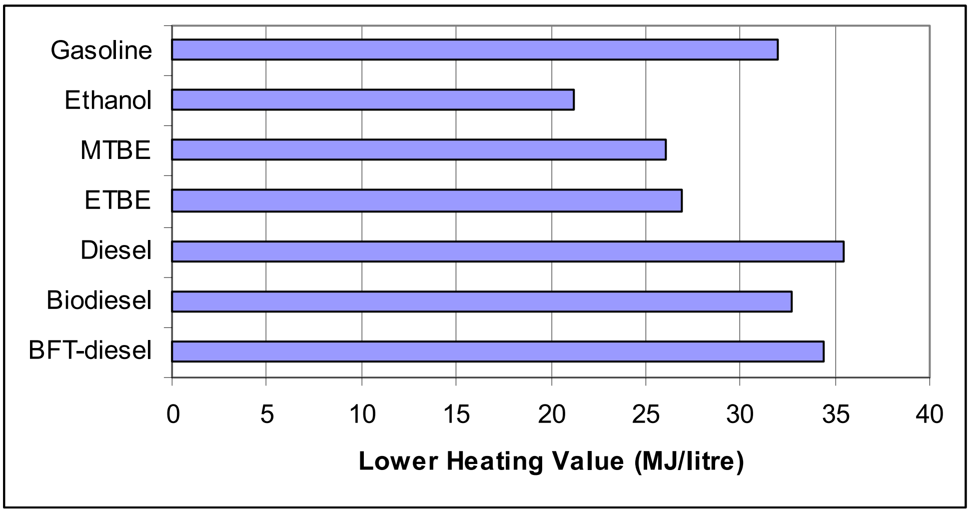
Source: [IFEU, 2004]

It has been assumed, furthermore, that consumption of biofuels is equal to consumption of their fossil counterparts, in terms of energy content. This means, for example, that 1 GJ petrol will be replaced by 1 GJ bio-ethanol. The energy content of the various fuels, commonly expressed in terms of lower heating value, is given in Figure 45.

For example, since the energy content of bio-ethanol is significantly less than that of petrol, the number of litres of ethanol required to drive a certain distance will be greater than if petrol is used. To replace gasoline by 5.0% ethanol on an energy basis, the ethanol content should be 7.5% on volume basis. To replace diesel by 5.0% FAME on an energy basis, the FAME content should be 5.4 % on volume basis

There are a number of reports that cite that petrol blended with small amounts of bio-ethanol (up to 10%) has a higher fuel efficiency than one would expect on the basis of energy content. However, since no large-scale scientific tests have been performed on this issue, this effect has not been taken into account here.

Figure 45 Lower heating values, or net caloric value, of the various fuels analysed in this report.



A.7 By-product accounting

If biomass is used to produce fuel, in most cases additional products will be produced that may have a financial value. For example, when ethanol is produced from sugar beets, beet pulp remains as a by-product. This can be sold as animal fodder, reducing the need to cultivate other fodder crops. According to common LCA practice, part of the GHG emissions occurring during biofuel production will then be allocated to the by-product, reducing those allocated to the biofuel. As already mentioned, this allocation has been based on economic value.

By-products, and especially their use and economic value, may therefore have quite a substantial effect on the outcome of calculations. In this study it has been assumed that by-products will be used as economically as possible (for example, the heat credits of beet pulp have not been taken into account, as it is far more attractive economically to market this product as animal fodder). As we look further ahead into the future, however, markets for these by-products become more and more likely to change: if large quantities of a particular biofuel are produced, output of the by-product will also increase, which may reduce its economic value. With biodiesel production, for example, some studies assume that glycerine will be put on the cosmetics market, giving this fuel a highly positive by-product account. With 5% penetration of biodiesel in the EU, however, the supply of glycerine will go far beyond the amount needed in the cosmetics market. In this study it has therefore been assumed that glycerine will be sold to the bulk chemicals market, for a lower price.

A.8 Reference systems

In an LCA on biofuels, the chosen reference system is extremely important for the results of calculations. It also limits the applicability of the conclusions to be drawn from those calculations. The net GHG emissions of an energy crop that is cultivated under a rotational set-aside scheme are, for instance, valid only for the scenario in which biofuels are introduced on a relatively limited scale. With large-scale introduction, the reference of set-aside land becomes unrealistic, as bio-energy crops will then also be cultivated on other (i.e. non-set-aside) land. In such a case, other food crops may be a better reference, which would lead to a different outcome of the LCA analysis.

In other words: the reference system chosen has a major impact on the results and any conclusions drawn remain valid only as long as the reference used is valid. This should be borne mind when reading this report.