

LCA of Transportation Biofuels

Elisabeth Adlam

Master of Science in Energy and Environment

Submission date: July 2007

Supervisor: Edgar Hertwich, EPT

Problem Description

The EU aims to cover a significant share of its need for transportation fuels with biomass. A number of different fuels are possible. Today, blends with bioethanol can be used in modified gasoline cars (i.e. spark ignition engines), while biodiesel can be used in Diesel engines. These fuels are today essentially produced from foodstuff and hence require intensive agriculture. Technologies to produce biofuels from wood and other cellulose are under development, but these "second generation biofuel" technologies are not yet mature.

The aim of this thesis is to shine some light on the environmental impacts of increased biofuel usage and to contrast first generation and second generation biofuels.

Elements:

1. A review of existing LCA studies of transportation biofuels.
2. A discussion of the status of second generation technologies.
3. An LCA of a prospective second generation technology producing biofuel from fire wood harvested in Norway, using the hybrid LCA modeling tool and data developed by NTNU's LCA laboratory.

Assignment given: 14. March 2007

Supervisor: Edgar Hertwich, EPT



Rapportnummer

Gradering

POSTADRESSE

NTNU
INSTITUTT FOR ENERGI OG
PROSESSTEKNIKK
Kolbjørn Hejes vei 1A
N-7491 Trondheim - NTNU

TELEFONER

Sentralbord NTNU: 73 59 40 00
Instituttkontor: 73 59 27 00
Vannkraftlaboratoriet: 73 59 38 57

TELEFAX

Instituttkontor: 73 59 83 90
Vannkraftlaboratoriet: 73 59 38 54

Rapportens tittel LCA of Transportation Biofuels	Dato 25.07.07
	Antall sider og bilag 78,18
Saksbehandler / forfatter Elisabeth Adlam	Ansv. sign.
Avdeling Department of Energy and Process Engineering	Prosjektnummer
ISBN nr.	Prisgruppe
Oppdragsgiver	Oppdragsgivers ref.

Ekstrakt

An increasing need to find alternatives to fossil fuels, and a growing awareness of the global warming effect has resulted in substantial research and development on biofuels. Biofuels are being considered a potential substitution of petroleum based fuels in the transport sector.

With this increasing interest in biofuels comes the need to establish the environmental effect of the fuels. Results from several life cycle assessments reviewed in this report show that there are some benefits of biofuels in global warming impact compared to conventional fuels. How great this benefit is varies between the studies. Differences in critical issues such as allocation, carbon sequestration, and fertilizer use have significant impact on the results of the life cycle assessments.

There is a lack of studies dedicated to investigating other environmental areas. The studies that have, show little consistency in their results, but indicate an increase of damage in categories such as acidification and eutrophication. No consistent results were shown on impact categories such as human toxicity potential or photochemical smog.

Second generation fuels are claimed to be more sustainable than first generation fuels. There are many different types of second generation fuels being developed. Research and Development have resulted in technologies such as hydrolysis, pyrolysis, gasification and hydrothermal upgrading . Technology challenges and high costs still exist with these technological solutions, the second generation bio-fuels being 2-3 times more expensive than conventional fuels.

Most of the second generation fuels are in their pilot phase, but several successful pilot projects exist for both hydrolysis and gasification.

Gasification to produce bio-fuels is especially promising. The company Choren, who uses this technique, is planning to produce and sell their products in 2007. One of the main products of the company is Fischer-Tropsch (FT) diesel.

A life cycle assessment on a second generation biofuel was performed. This was done by doing a Hybrid analysis on a Fischer-Tropsch diesel following the gasification route. The Hybrid analysis consists of a foreground and background system. The foreground system comprises important processes in the fuels lifetime. This includes biomass production, transport, production and use of the fuel. The background system contains economic data taken from the Norwegian background. The aim of the LCA is to compare the environmental effects of a second generation biofuel with first generation biofuels, and the impact category chosen in the impact assessment is global warming potential.

The results of the work show that the global warming impact throughout the life cycle of the biofuel is 39 CO_2 eq g/km. This proves to show a considerable reduction in the category, compared to both conventional diesel and average values of first generation biofuels. This implies that Fischer – Tropsch diesel is a more sustainable transport solution, yet more work is suggested to be taken on investigating the overall environmental impact of both second generation and first generation biofuels.

	Stikkord på norsk	Indexing Terms English
Gruppe 1	Biodrivstoff, LCA	Biofuels, LCA
Gruppe 2	Andre generasjons biodrivstoff, hydrolyse, pyrolyse, gasifisering	Second generation biofuels, hydrolysis, pyrolysis, gasification
Egenvalgte stikkord	FT-diesel, hybrid analyse	FT-diesel, hybrid analysis

Preface

I want to thank, Edgar Hertwich and Christian Solli for being my supervisors and helping me with performing the life cycle assessment. I would also like to thank Øyvind Skreiberg and Edd Blekkan for providing me with information on gasification technologies and Fischer-Tropsch synthesis. Finally I would like to thank my family, for their constant love and support.

Without these people, this thesis would not have been possible.

Summary

An increasing need to find alternatives to fossil fuels, and a growing awareness of the global warming effect has resulted in substantial research and development on biofuels. Biofuels are being considered a potential substitution of petroleum based fuels in the transport sector.

With this increasing interest in biofuels comes the need to establish the environmental effect of the fuels. Results from several life cycle assessments reviewed in this report show that there are some benefits of biofuels in global warming impact compared to conventional fuels. How great this benefit is varies between the studies. Differences in critical issues such as allocation, carbon sequestration, and fertilizer use have significant impact on the results of the life cycle assessments.

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Most of the second generation fuels are in their pilot phase, but several successful pilot projects exist for both hydrolysis and gasification. Gasification to produce bio-fuels is especially promising. The company Choren, who uses this technique, is planning to produce and sell their products in 2007. One of the main products of the company is Fischer-Tropsch (FT) diesel.

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Sammendrag

Økende oljepris, etterspørsel etter energi og interesse for å beskytte miljøet har ført til stadig mer forskning på biodrivstoff. Det er håp om at biodrivstoff kan erstatte fossilt drivstoff i transportsektoren.

Med den økende interessen for biodrivstoff er det viktig å studere virkningen på miljøet ved denne bruken. Resultater fra flere livsløpsanalyser vurdert i denne rapporten viser at biodrivstoff reduserer global oppvarming. Hvor stor denne reduksjonen er varierer i de forskjellige studiene. Variasjon mellom kritiske faktorer slik som allokering, karbonsekvestrasjon og gjødsling, har en betydelig virkning på resultatene i livsløpsanalysene. Det er få studier som fokuserer på andre miljøområder, og de studiene som gjør dette indikerer en økning av negative effekter i kategorier som forsuring og eutrofiering. Også her er resultatene varierende. I andre miljøkategorier finnes ingen samsvarende resultater.

Andre generasjons biodrivstoff skal være en mer bærekraftig løsning enn førstegenerasjons biodrivstoff. Det er mange ulike typer andre generasjons drivstoff i utvikling. Velkjente eksempler er hydrolyse, pyrolyse, gasifisering og hydrotermisk oppgradering. Teknologiske utfordringer og høye kostnader eksisterer fremdeles ved disse teknologiske løsningene, annen generasjons biodrivstoff er fremdeles 2-3 ganger dyrere enn konvensjonelle drivstoff. De fleste andre generasjons biodrivstoff er i pilotfasen. Flere vellykkete eksempler eksisterer, spesielt for hydrolyse og gasifisering. Firmaet Choren bruker gasifisering, og planlegger kommersiell produksjon av Fischer-Tropsch diesel i løpet av 2007.

En livsløpsanalyse for en andre generasjons biodrivstoff er utført i rapporten. Dette er gjort ved å ta i bruk hybridanalyse for en Fischer-Tropsch diesel produsert ved gasifisering. Hybridanalysen baserer seg på et forgrunn- og et bakgrunnssystem. Forgrunnssystemet viser til viktige prosesser i drivstoffets livsløp. Dette inkluderer biomasseproduksjon, transport, produksjon og bruk av drivstoffet. Bakgrunnssystemet består av økonomiske data tatt fra Norsk bakgrunn. Formålet med livsløpsanalysen er å sammenligne miljøpåvirkningene fra et andre generasjons biodrivstoff med førstegenerasjons biodrivstoff. Miljøkategorien valgt for sammenligningen er global oppvarming.

Resultatene fra analysen viser at drivhuseffekten gjennom livsløpet av Fischer-Tropsch diesel er 39 CO_2 eq g/km. Dette er en betydelig reduksjon sammenlignet med både konvensjonell diesel og gjennomsnittlige verdier av førstegenerasjons biodrivstoff. Dette indikerer at Fischer-Tropsch er en mer bærekraftig transportløsning. Det er anbefalt ytterligere studier for å finne den totale miljøpåvirkningen for både første- og andre generasjons biodrivstoff.

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Abbreviations

BTL-Biomass-To-Liquid Fuels
CFB-Circulating fluidised bed gasifier
CI-Compression Ignition Engines
DME- Dimethyl Ether
ETBE-Ethyl Tertiary Butyl Ether
FT – Fischer Tropsch diesel
GHG-Green House Gases
HTU-Hydro Thermal Upgrading
IFP- Innovation Energy Environment
IOA-Input Output Analysis
FCV-Fuel Cell Vehicle
LCA- Life Cycle Assessment
LHW- Liquid Hot Water Reactor
LPMEOH-Liquid Phase Methanol
MTBE- Methyl Tertiary Butyl Ether
NEB-Net Energy Benefits
NREL-National Renewable Energy Laboratory
RME-Rape Methyl Ester
R&D-Research and Development
SHF-Separate Hydrolysis and Fermentation
SI-Spark Ignition Engines
SSCF-co-fermentation of hexoses and pentoses sugars
SSF-Simultaneous Saccharification and Fermentation
TCI-Total Capital Investment
WGS-Water gas shift reaction
WTW-Well to Wheels

Introduction

The aim of this report is to discuss the environmental impacts with using biofuels in the transport sector, and compare second generation biofuels with first generation biofuels. Different types of biofuels are investigated, section 1 includes a review over different life cycle assessments (LCA) done on first generation biofuels. The resulting environmental effects as well as the different methods of performing the analysis is also discussed in this section. Part 2 of the report presents the status and technological descriptions of different second generation biofuels. Section, 3, explains the method chosen for performing the LCA in this study. The results are discussed in section 4 and compared with the environmental impacts of the biofuels presented in the first section.

Limitations of Study

First hand data of second generation technologies proved difficult to obtain. None of the technologies are commercially available yet, and technological/economic detail of pilot projects are kept confidential. Therefore most of the data used in the LCA were found in literature and were based on simulations done in the program Aspen Plus. The impact studied in most of the first generation biofuels is global warming potential, few studies have looked at other categories, so global warming potential is the only impact category that is compared with the second generation biofuels. There are many types of second generation biofuels, and due to time limits one technology was chosen for the LCA.

1. First Generation Biofuels

1.1 Background Information

The following section includes some general background information, such as reason for interest in biofuels, definition of biofuels and discussion of carbon cycle of biofuels. This is important information to keep in mind when reading the rest of the report.

1.1.1 Background

Biofuel is not a new source of energy, before the industrial revolution biomass dominated the supply of fuels. Use of traditional biomass based fuels is associated with environmental problems, poor indoor and outdoor air quality being an example. Soil degradation, desertification and reduced generation of hydroelectricity are also problems associated with traditional biomass use. Today there exists a more environmental modern type of biomass-based fuels. Research and development(R&D) in the bioenergy field has led to discoveries of new technologies for conversion of biomass into fuels. [Reijnders .L, p2-3, 2006]As can be seen from figure 1 below, there has been a steady increase in the area of biotech crops in the world since 1996. The increasing interest in biofuels matches the increasing need to replace fossil fuels as a transportation fuel. As the worlds population and major economies such as China continues to grow the demand for energy and transportation fuels also increase. The sources of fossil fuels are limited and the alternatives in the transport sector is needed, at the same time the attention on the global warming effect has increased resulting in the wish of finding an energy solution that is more sustainable.

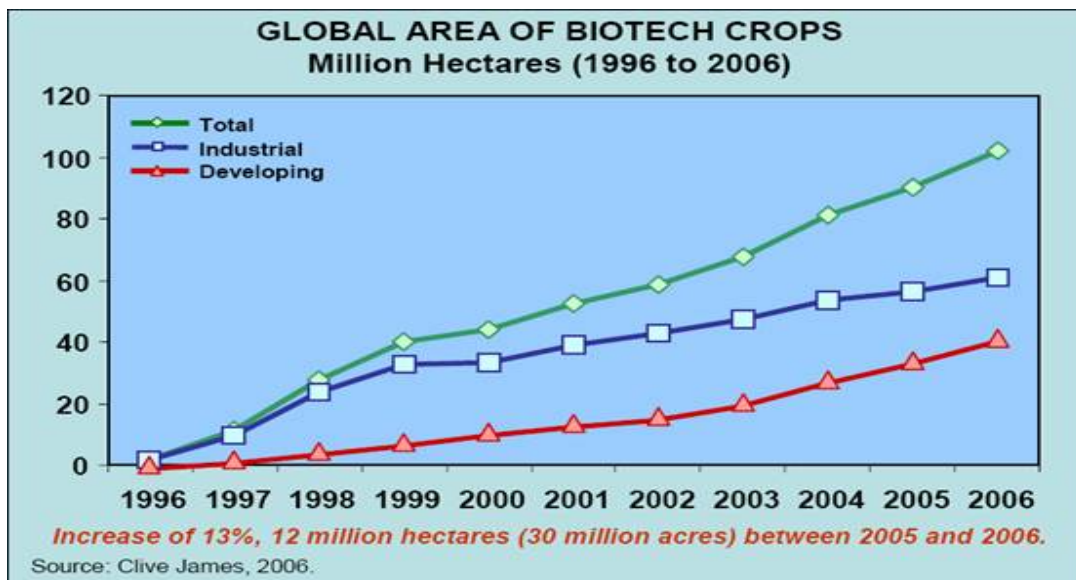


Figure 1: Showing the global growth of area of biotech crop[ISAAA, 2006]

The interest and investments of biofuels is expected to continue to rise during 2006-2015. The global hectareage of of biofuels is predicted to be up to 20 million hectares, with 20 million farmers growing biotech crops in 40 countries or more by 2015.[Isaa,2006] The diagram below shows the expected rise of energy demand and depletion of fossil fuels during the next 50 years. The importance of finding alternatives to the current fossil fuel supply can be seen by the increasing use of biofuels in the diagram.

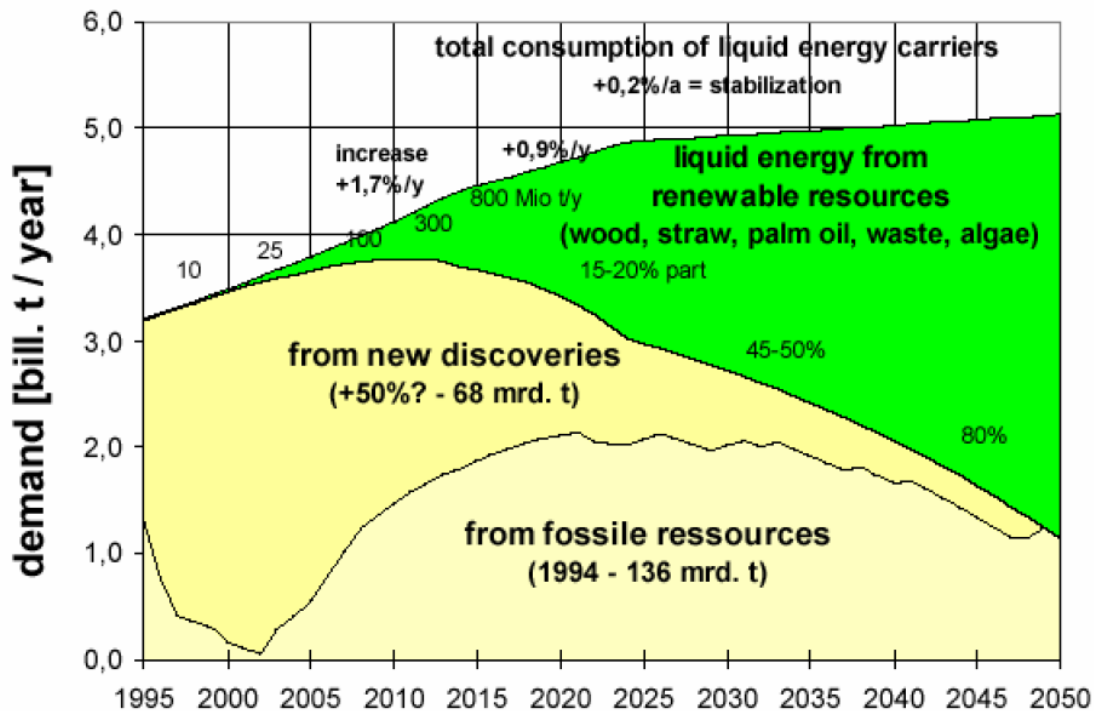


Figure 2: Demand and supply of mineral oil in coming decades.[Puppan .D,p.96 2001]

The Biofuel Directive 2003, demands all European Countries to substitute 5,57% of all fossil derived fuels in the transport sector with biofuels by the year 2010.

With this growth of production and use of biofuels it is important to establish an overview over the environmental impacts with the fuels. [EEA, p.1,2004]

The different types of biofuels and their environmental implications is investigated more closely in section 1.2.

1.1.2 Carbon Cycle

Biofuels are considered CO_2 neutral, meaning no additional CO_2 is added to the atmosphere. This is one of the reasons why biofuels are considered an attractive alternative to fossil derived fuels, they can help reduce the increasing CO_2 pollution from the transport sector, and thus help to achieve the goals of the Kyoto Protocol in the European Union. [EEA Briefing, 2004]. The reason why biofuels are CO_2 neutral is because the amount of CO_2 emitted into the atmosphere is the same as the CO_2 absorbed from the atmosphere by the plants through photosynthesis. Photosynthesis creates more mass than what is being consumed through respiration however, and the excess mass is removed from the carbon cycle, and deposited as fossil fuels. When burning this excess carbon stock additional CO_2 is let into the atmosphere, this is what we want to avoid, and using biofuels which are a part of the carbon cycle the amount of additional CO_2 to the atmosphere may be reduced. [Quirin .M, Gartner .S.O, Pehnt .M, Reinhardt A.G.,p.12-14,2005] This does not mean that biofuels are completely carbon neutral , there will be energy requirements in the production that results in fossil derived emissions. Experts differ in their views on how to tackle CO_2 emitted from the soil where the biomass grow. More of this will be discussed in section 1.4.3.

Figure 3 shows the open carbon cycle considered with fossil fuels and the closed cycle considered with biofuels.

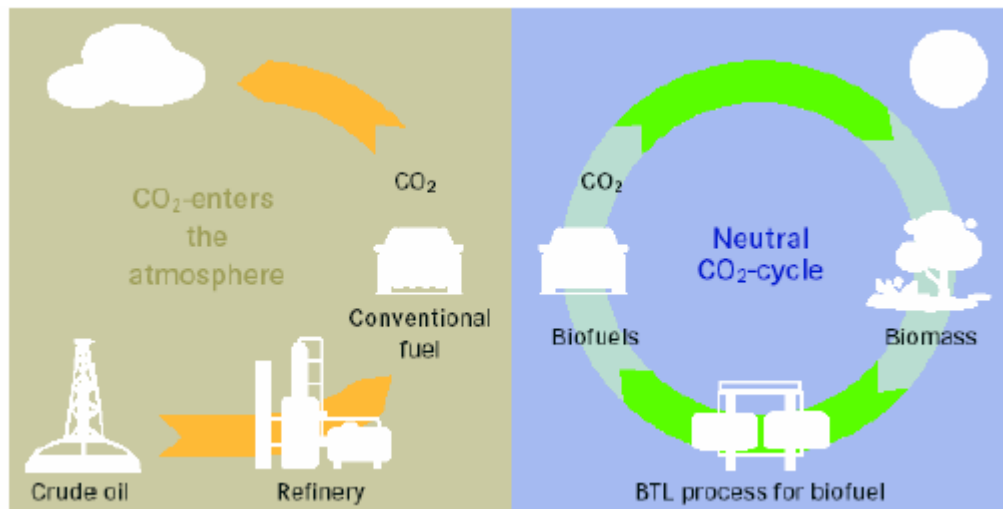


Figure 3: Open and closed carbon cycles [Kavalo .B, Peteves .S.D, p.60,2005]

1.1.3 Biofuels

Biofuels is the general term referring to all the fuels that are derived from organic materials, except fossil fuels. The variable biomass sources results in many different types of biofuels and routes of production. There are two main types of biofuels differing mainly in their production technology, namely second generation technology and first generation technology biofuels. The latter will be discussed more closely in part 2, whereas the former will be covered in this section.

As mentioned in the paragraph above, there are many different types of biofuels, depending on their biomass feedstock, technology and fuel that they substitute.

The biomass includes different forms of organic material, the resource base can generally be divided into 4 main groups, starches, oil-seed crops, organic waste material and cellulosic materials. Second generation biofuels use the two latter feedstock where organic waste material includes fish waste, marine and animal oil, and cellulosic materials are grasses, trees, wood processing and different types of waste products and residuals from crops. First generation biofuels are made from food crops and oil seed crops. Food crops feedstock includes starches such as cereals, grains and sugar crops. Whereas there are three types of oil-seed crops, namely rapeseed, soybean and sunflower crops.

[<http://www.Zero.no>, 18.04.07]

Names of some important biofuels are Bioethanol, biodiesel, Ethyl Tertiary Butyl Ether(ETBE) and vegetable oil.

Bioethanol (EtOH)

Bioethanol is currently in use today. Ethanol is made by fermenting plant sugars produced by plants. It is the biofuel that is produced on the largest level today. Most of the ethanol is produced and used in Brazil, where sugar cane is used as feedstock. In North America the same fuel is produced from corn.

Biodiesel

Bioesters are produced from a chemical reaction between vegetable oil and alcohol, the properties of the bioesters enables it to be mixed with diesel fuel and used as a transport fuel. This blend is known as biodiesel. In Europe biodiesel is mainly made from rapeseed oil. In North America, biodiesel is mainly produced from palm oil and recycled vegetable oil is used as a source for biodiesel in Germany, Austria and Great Britain.

Vegetable Oil

There is little research done on pure vegetable as fuel, and only a small part of the amount is used as fuel. In the USA soybean is used and in Germany mainly locally pressed rapeseed oil.

ETBE(Ethyl Tertiary Butyl Ether)

This fuel is produced by the same rawmaterials as bioethanol, starch-rich food, sugar canes, corn. ETBE is usually blended with gasoline.

Below is a diagram showing the different biofuels and the different routes of production. In addition to the biofuels mentioned above there are other biofuels, that are not currently massed produced. Examples of these are Pyrolysis oil diesel, HTU diesel, MTBE(Methyl Tertiary Butyl Ether), DME(Dimethyl Ether) shown in figure 3 below. The technological routes of these second generation fuels will be described closer in section 2.

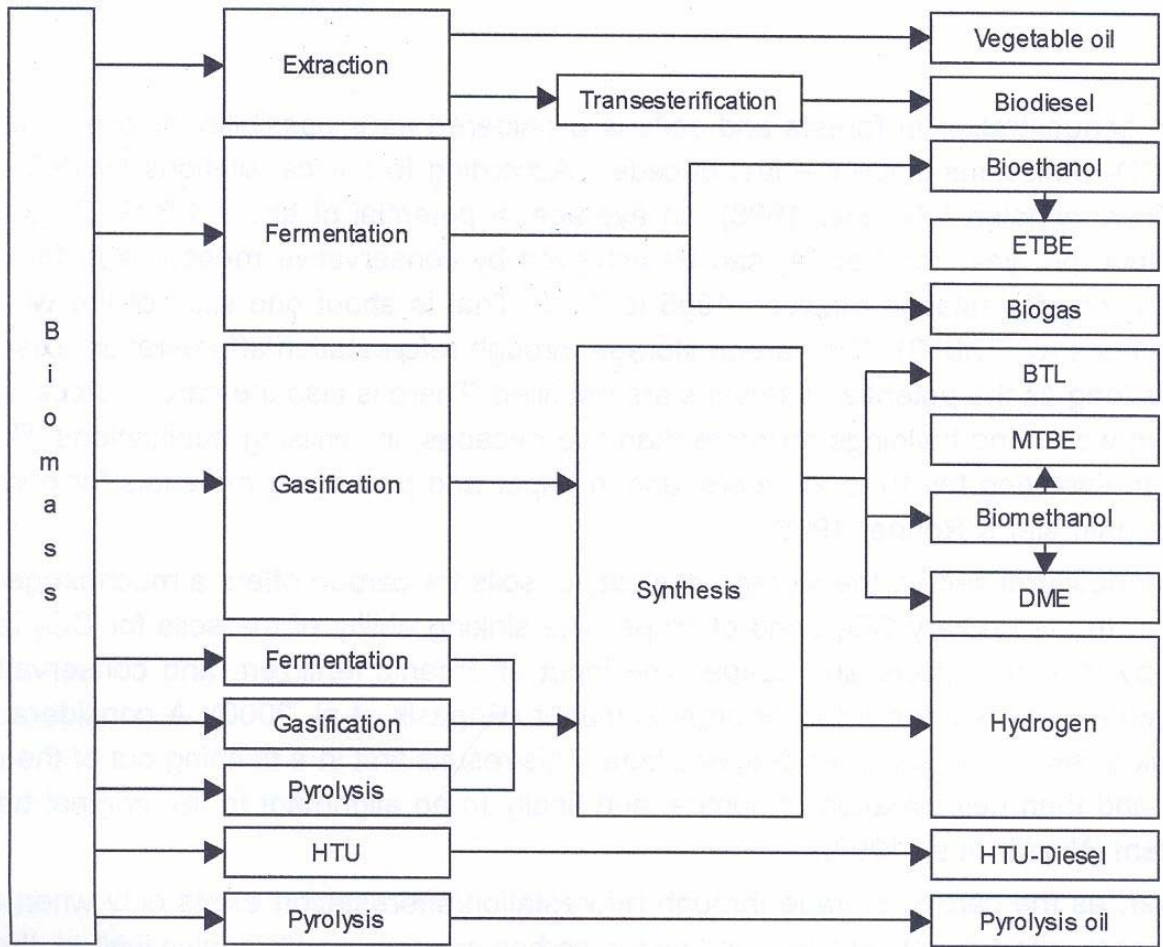


Figure 4: Diagram showing the different biofuel paths [Quirin et al., p.15, 2005]

1.2 Life Cycle Assessments of Biofuels

Life Cycle Assessment (LCA) is an important tool to evaluate the environmental performance of products and services. This section presents a discussion of the general thinking of LCA of biofuels.

1.2.1 Life Cycle Assessment

Life Cycle Assessment has frequently been used as a tool for evaluating the environmental performance of biofuels. In LCAs the whole life of the product is taken into consideration, from production to use and end of life. It is the only environmental method covered by international standards (ISO 14040-14043). Having a holistic view of the products life cycle is important as it avoids shifting environmental problems from one stage of the life cycle to another. If one step, for example combustion of the fuel, was optimized separately from the other stages in the life cycle, environmental impacts associated with the use might be shifted to the production stages, thus ignoring significant environmental impacts of the fuel. Figure 4 below shows the value chain of the production of biodiesel made from rapeseed oil compared to that of conventional diesel. For biofuels the value chain usually involves the production of biomass, transport of feedstock, production processes to produce the biofuel, distribution of fuel and the combustion of the biofuel. The latter is an important step to consider as this is usually where the largest reduction of GHG emissions occur. The biomass production step is also an important step to consider when assessing the environmental impacts of biofuels, as major contributions to GHG emissions occur from farming such as the use of fertilizers. Production of the resource refers to biomass cultivation, collection and harvest. Transportation includes the transport from the production of biomass to the place where it will be transformed to a fuel. This step can involve many different types of transport modes, pipelines, rail, road, maritime, waterway or combined transport system. The value chain would also normally include transportation from the plant producing the biofuel to a distribution terminal. The transformation process depends on the type of biomass and biofuel, and usually generates large quantities of co-products. [Panorama, p.2, 2007]

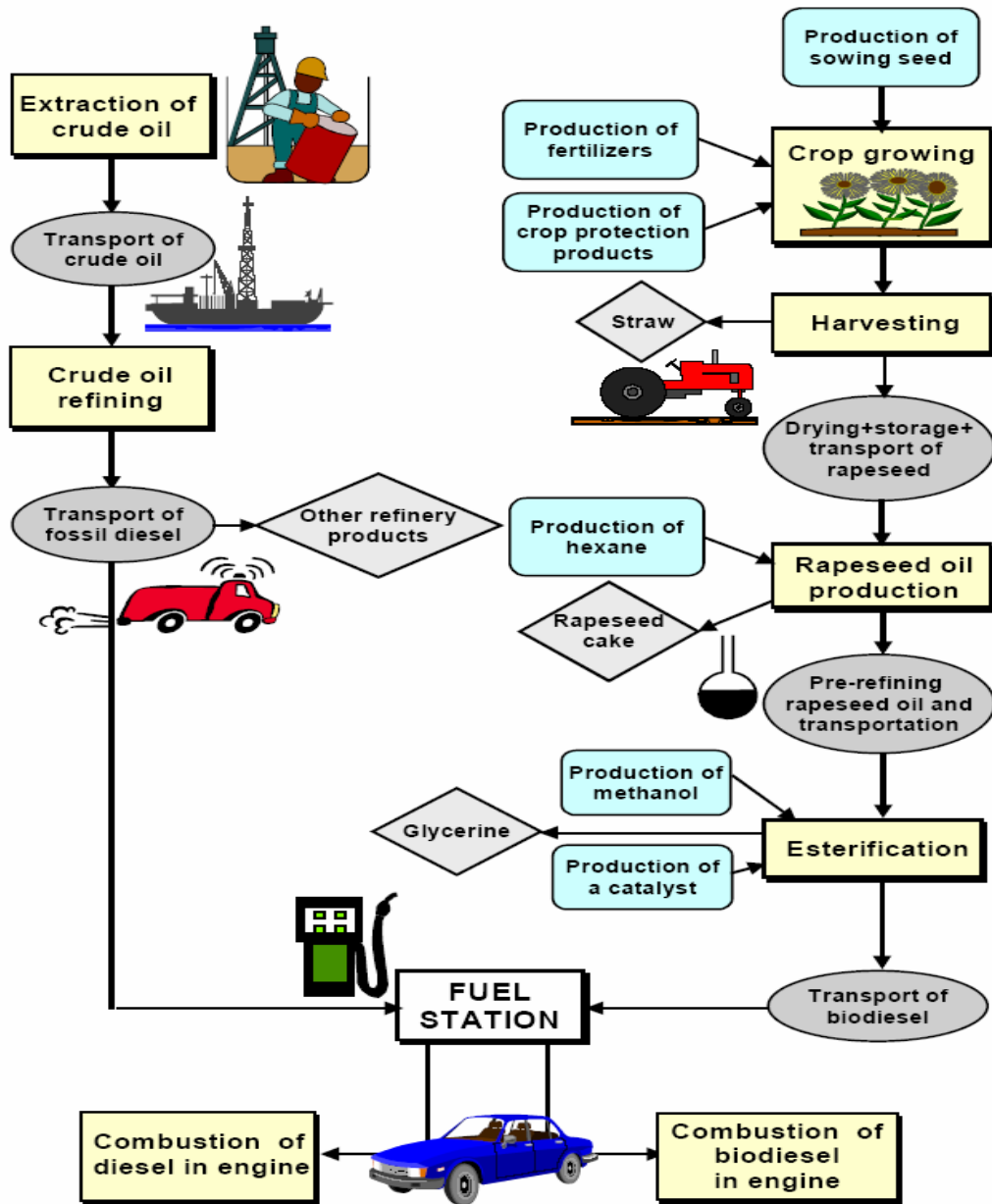


Figure 5: Value chain throughout the life cycle of biodiesel and fossil diesel fuel.[Nocker .D.L, Spirinckx .C, Torfs .R, p.3, 1998]

1.3 LCA Results of First Generation Biofuels

Many publications have been issued on the environmental impacts of biofuels. From these various conclusions have been drawn, there is therefore a need to do a review over the existing studies. Over the weaknesses and strengths of these studies, why their results differ and if there are any agreements on an overall conclusion on the environmental effects from these studies. This section will draw upon results and discuss some of these issues from previous LCA studies, based on previous reviews and individual LCA studies. It has been attempted to evaluate studies from different regions, biofuels and feedstock.

1.3.1 Green House Gas Emissions and Net Energy Benefits

Several LCA studies exist on biofuels, due to differences in methodologies and assumptions fair comparisons of the results could be difficult to achieve. In order to overcome obstacles in comparing the different studies, Quirin .M, et al established a spectrum for all the biofuels considered, where different options such as yields, co-products and assumption of data basis of the biofuel production was considered. These aspects were set to consistent values, and calculations and assumptions were made when necessary. The review was done by the IFEU institute Heidelberg commissioned by the Association for Combustion Engine FVV in 2004. The institute reviewed more than 800 studies, yet many were excluded on the basis of not being representative and in the end 109 different fuel chains were compared. [Quirin et al, p.5-10, 2004]. Results of energy and green house gas balances in the comparison between analysed biofuels and their fossil counterparts are shown in the figure 5 below, in MJ saved primary energy and g saved CO_2 equivalent/km. Negative values show the potential benefits of using biofuels rather than their fossil counterparts. The arrows with a question mark are used for all biofuels with organic residues as potential sources to compensate for the losses associated with not taking advantage of the alternative uses of the wastes. The alternative uses include grease as animal feed and residual wood to generate electricity. These alternative uses are equated to zero in most studies, the advantage of these uses may reduce the benefits of biofuels. The arrows in the figure below show that in some cases biofuels can be worse than fossil fuels, on both energy benefits (NEB) and green house gas (GHG) emissions. It is important to be aware that in environmental analysis there is seldom a simple straightforward answer, it depends on the assumptions underlying the studies and the data collected.

Conclusions that can be drawn from the comparison of the different studies is that there is generally an advantage of NEB and GHG with biofuels. The extent to which they are advantageous depends largely on the raw materials. This is for example evident in comparison between biodiesel and bioethanol. Among all the forms of ethanol and biodiesel, ethanol from sugar cane is the most beneficial option. Biodiesel from rapeseed is more favourable than pure rapeseed oil as glycerine produced in transesterification in the biodiesel production process, can be used to substitute technically produced glycerine.

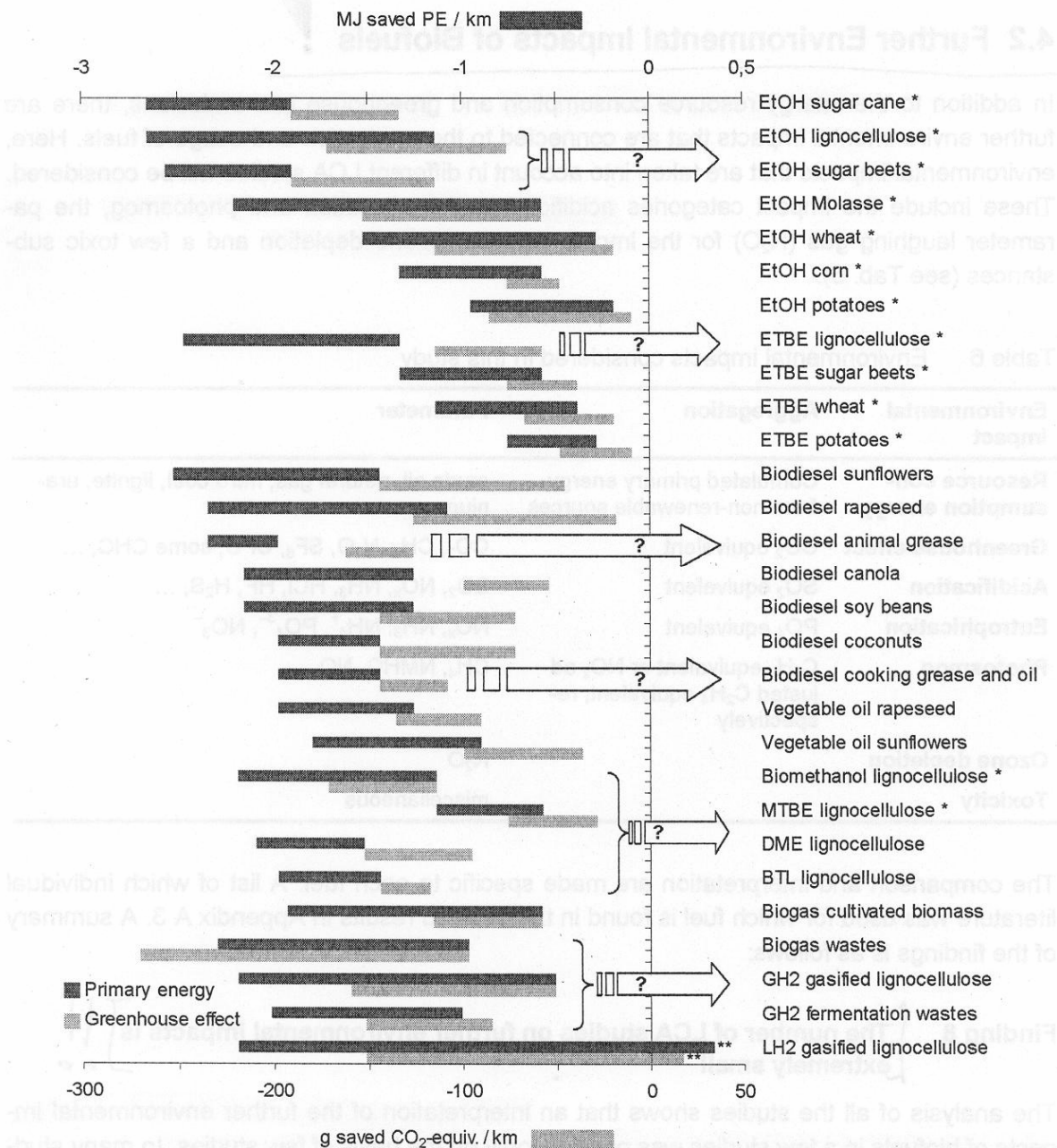


Figure 6: showing reductions of primary energy and greenhouse effect reached with the use and production of biofuels compared to conventional fuels. [Quirin et al, p. 15, 2005]

In 2004 EUCAR, CONCAWE and JRC performed an evaluation of the Well-to-Wheels (WTW) energy use and GHG emissions for several potential future fuel options. General results from the study on the environmental damages of the fuels relevant for this thesis are as follows. Conventional biofuels such as ethanol provide some benefits in GHG emissions, but the routes are energy intensive. Second generation fuels such as Biomass-to-Liquids (BTL) fuels were also considered. In the evaluation the synthetic fuels give lower overall GHG emission than both fossil fuels and first generation biofuels, but the energy use is still high. These general results from the study can be seen in the diagram 6 below, where SME is Sunflower Methyl Ester, biodiesel derived from sunflower oil, and RME is Rapeseed Methyl Ester, biodiesel derived from rapeseed oil.

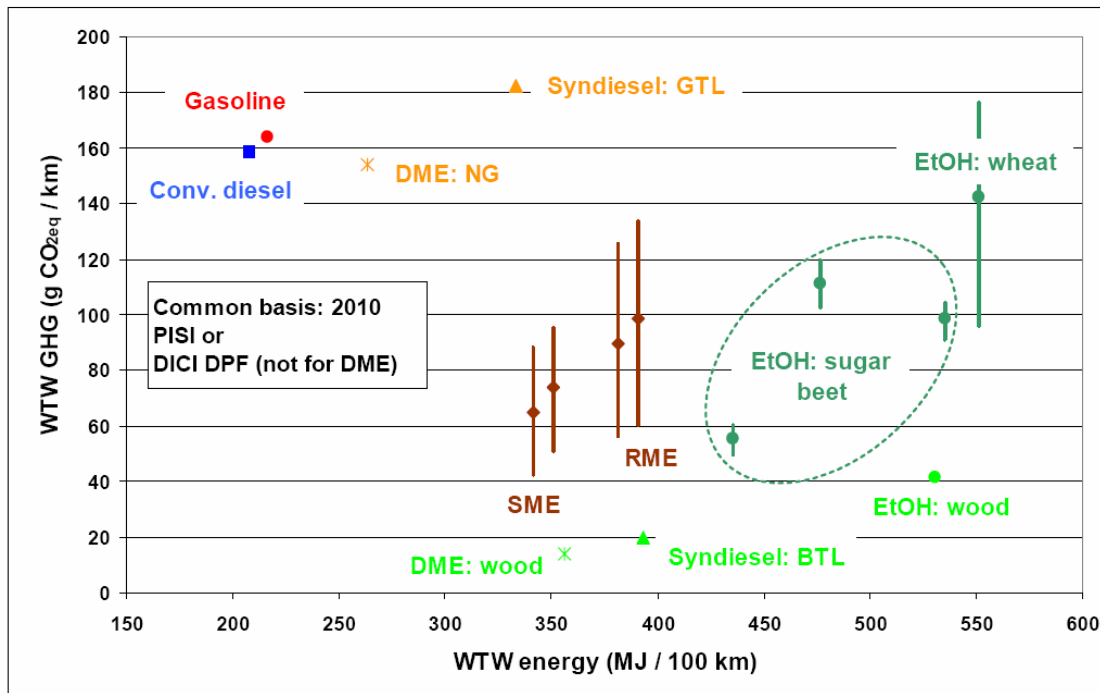


Figure 7: showing the results of the CONCAWE study for alternative liquid fuels.[Hass .H, Larive .J.F, Mahieu .V, p.21, 2004]

The results from the CONCAWE study once again show that although there is a general qualitative advantage of using biofuels rather than conventional fuels, the extent in which it is beneficial varies. Larson points out that in the WTW study the reductions of GHG emissions per vehicle-km for RME compared to petroleum based fuels varies from 15-65%. The range of ethanol from wheat also shows a large range, from 38% reductions of GHG emissions to 10% penalty per vehicle km.[Larson .E.D, p.3, 2005]

Other LCA studies show the same qualitative results Larson .E.D, Blottnitz and Curran are examples of two biofuel LCA reviews also used in this report, the former discussing LCA on all types of biofuels and the latter mainly focusing on bioethanol. [Larson .E.D, 2005],[Von Blottnitz .H, Curran .M.A,2007]. For more biofuel LCA's please see the reference list of this report. Example of a study showing negative results for biofuels is the study of Pimentel (2003). The methods of this study has been criticised however, for ignoring environmental credits with production of by-product

From the discussion of results from LCA studies, it is evident that making a general quantitative conclusions on the GHG emission savings and NEB of biofuels is difficult, due to the large variations among the results of the same biofuel pathways. Quantitative results will only be meaningful for each case specific LCA.

GHG emissions and energy balances are the only environmental aspects considered in many studies. There is a need for more research on the information of environmental damages in all environmental aspects, especially when comparing different technologies and feedstock. Biofuels from organic residues for example, will greatly differ from biofuels from cultivated biomass, as agricultural activities includes large nitrogen emissions and therefore also less favourable in the categories for eutrophication and acidification.[Quirin et al,p.27, 2004]

1.3.2 Other Impacts

It was concluded in the last section that few of the studies have examined Life cycle impacts on other areas such as local air pollution, eutrophication, acidification, ozone depletion. The ones who do, however generally show an increase of negative effects from biofuels compared to conventional fuels. Therefore it is important not to ignore these impacts as that can lead to problem shifting, and false beliefs in the environmental performance of biofuels. The impacts are often more site specific than GHG and NEB and therefore complicates drawings of general conclusions. The figure 7 below shows conclusions drawn from seven different LCA studies on ethanol produced from waste and agricultural feedstock. From the figure it is evident that there are differences in several impact categories. Three of the six studies that looked on acidification show an increase, whereas two reported no significant changes in the category compared to conventional fuels. Acidification is mainly caused by nitrogen, sulphur oxides and ammonia which are released during growing of biomass such as rapeseed. The majority also show negative increase in the ozone depletion and eutrophication categories. Eutrophication occurs when there is an excessive growth of algae in surface waters. This is due to nitrate and phosphate run off. The results are serious as eutrophication makes the water unsuitable for other organisms. Photochemical smog is mainly influenced by the release of volatile organic compounds released from the production of biofuels, the diagram shows that this is another category that has been ignored in many assessments. The studies that have attempted to assess photochemical smog show varied results. The apparent lack of consistency in which categories and which pollutants are investigated, is also evident from the figure. All of the 7 compared studies have investigated and reached the same results on global warming and resource depletion, but on the other impacts differences occur. Surprisingly ecotoxicology and land use are amongst the categories that are the least investigated. This is surprising as biomass production is an important step in the value chain, and usually involves land use and disruption of the living nature. [Puppan. D, p.110, 2002]

Table 1: Comparison of the benefits associated with different routes of ethanol production. [Blottnitz .V.H, et al. , 2007]

	Agricultural Feedstocks				Waste Feedstocks		
	Kaltschmitt 1997 [10] Sugar beet Wheat Potato	Puppan 2001[15] Sugar beet Winter wheat Potato	Reinhardt 2002 [17] Sugar beet Wheat Potato	Hu 2004 [18] Cassava	Kadam 2002 [14] Waste Bagasse	Sheehan 2004 [19] Corn Stover	Tan & Culuba 2002 [20] Agricultural Cellulosic Waste
	Germany	Germany	Europe	China	India	USA	Philippines
Resource Depletion	↓	↓	↓	↓	↓	↓	↓
Global Warming	↓	↓	↓	NA	↓	↓	↓
CO2	NA	NA	↓	↓	NA	NA	NA
Acidification	—	—	↑	NA	↓	↑	↑
SOx	↑	NA	↑	NA	NA	NA	NA
NOx	↓	NA	↑	↑	NA	NA	NA
Eutrophication	NA	NA	↑	NA	↓	NA	↑
Human Toxicity	NA	—	NA	NA	↓	NA	↑
CO	NA	NA	↑	↓	NA	NA	NA
PM	NA	NA	↑	↓	NA	NA	NA
Ecological Toxicity	NA	—	NA	NA	NA	NA	NA
Photochemical Smog	NA	NA	↓	NA	NA	↑	↓
HC	NA	NA	↓	↓	NA	NA	NA
Solid Waste	NA	NA	NA	NA	↓	NA	NA
Land Use	NA	NA	NA	NA	NA	—	NA
Water Use	NA	NA	NA	NA	—	NA	NA
Ozone Depletion	↑	↑	NA	NA	NA	↓	NA
Odour	NA	NA	NA	NA	↓	NA	NA

NA – Not Assessed ↑ – Increased impact for bio-ethanol
 — – No significant change ↓ – Decreased impact for bio-ethanol

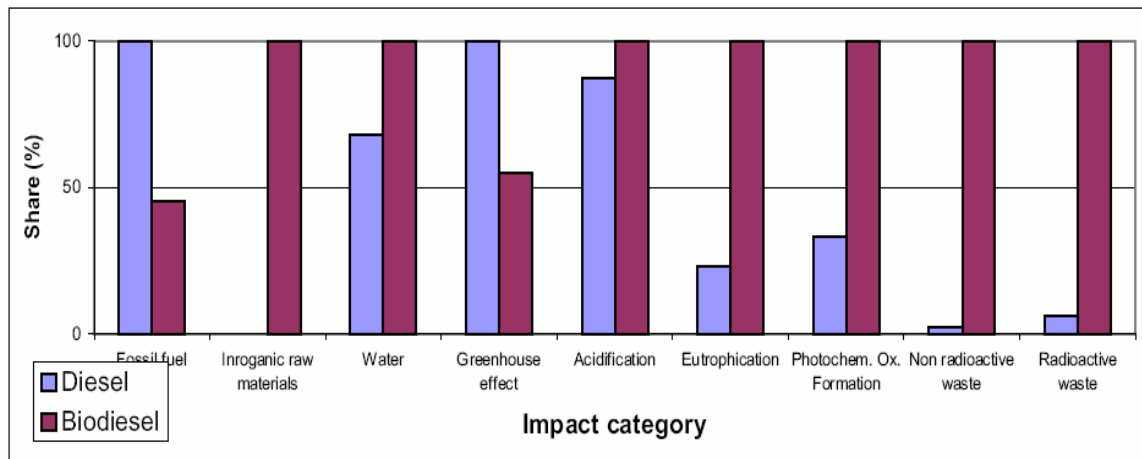


Figure 8: Comparison of two environmental profiles [Puppan. D, p.112, 2002]

Table 1 only shows the environmental effects for ethanol, but the same trends exist for other first generation biofuels. Figure 8 for example, shows comparison of the environmental profiles of conventional diesel and biodiesel produced from winter rapeseed in Belgium. The figure shows that biodiesel only has benefits over petroleum based diesel in two of the nine categories. For a more detailed summary of the seven different LCA studies in table 1 [Von Blottnitz .H, Curran .M.A,2007] Except for NEB and GHG it's difficult to draw conclusions on impacts on the environment from biofuels, however damages such as eutrophication and acidification increases in many cases of biofuel production.

1.4 Uncertainties with Biofuel LCA Studies

As several of the LCA studies done on biofuels show great variations in results, it is important to create an understanding over why this is the case and not to accept the results from one study at face value. This section includes a brief discussion over different issues that are important to consider while either doing an analysis or when reading the results of an environmental analysis done on biofuels.

1.4.1 Allocation

During processes to produce biofuels other products may be produced. Examples of this is , distillers dry grain with soluble (DDGS) from corn and soy bean meals and glycerol from soy beans. Rapeseed meal that results from the extraction of rapeseed oil can be used as feeding stuff. How to treat these products in the LCA methodology differ among many studies and has been a topic for debate. System expansion has been suggested as the most accurate representative of the real situation and the real environmental impacts, however some disagree with this view. [Panorama, p.1,2007] The correct allocation is largely dependent on the goal of the LCA study. An example on how allocation can alter results can be seen in the diagram 8 below. This shows the net energy benefits (Energy output-energy input) of corn grain ethanol and soybean biodiesel production. In the one example the energy is calculated with environmental credits, showing a larger energy net benefit compared to when ignoring the by-products. Further Larsson comments that co-product allocation assumptions in LCA's in the literature for making bioethanol from wheat grain have values from 15% to 95% this gives a wide range of results for the GHG advantage relative to petroleum ranging from nearly negligible advantage to as much as a four fold advantage.[Larsson E.D,p.11,2005]

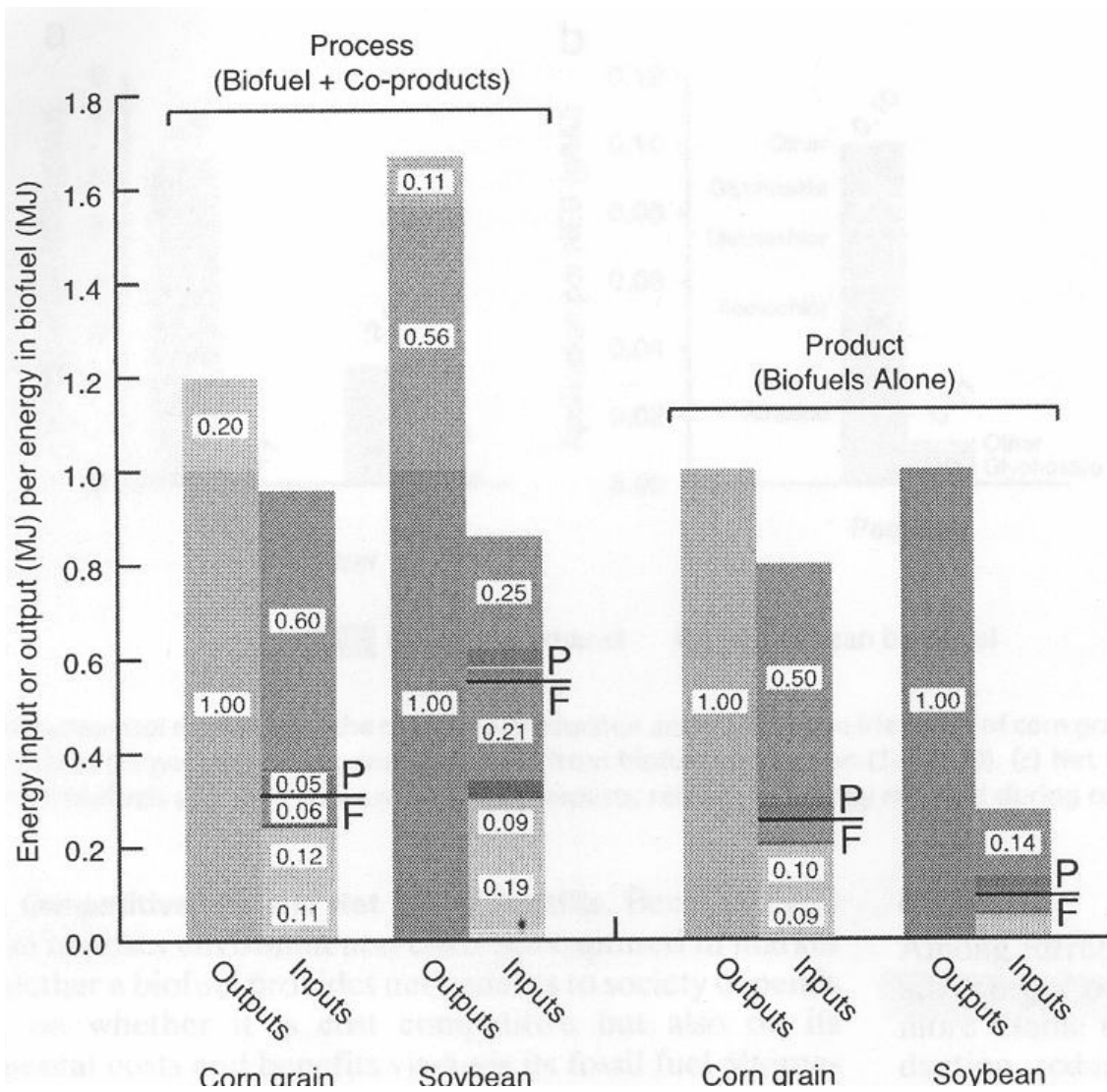


Figure 9: Showing how allocation affects the environmental results of a ethanol and biodiesel. [Hill .J., Nelson .E, Tilman .D, Polasky .S, Tiffany .D,p.11207, 2006,]

1.4.2 Regional Differences

Nearly all the studies reviewed are from a European or North American context, few studies are done in developing countries. This is an important aspect to consider as several of the results are site specific, and figure 1 shows that production of biofuels is increasing in developing countries as well as in industrial countries. Country or region specific studies are important for providing quantitative meaningful results.

[Larson .E.D, p.1, 2005]

1.4.3 Carbon Sequestration

Different LCA's on biofuels differ in the degree they consider the fuels to be carbon neutral. Whereas some consider the combustion of the fuel to be completely carbon neutral, and the CO_2 emission throughout the value chain to only occur where there are direct energy inputs derived from fossil energy sources, others also consider CO_2 emission from the biofuel when used and emission from the soil where the wood is collected. When forest production is disturbed for production of biofuels carbon in the soil is converted into carbon containing gases, this is known as carbon sequestration. After cutting, harvested biomass is usually transported, stored and treated before being used further in the production processes. The pre-treatment of biofuels therefore also leads to a rise of emissions of CO_2 . These CO_2 emissions are usually not considered, and if they were would probably give higher results on the global warming impacts than what is recorded in many studies today. According to Reijnders and Huijbregts article on carbon sequestration, this difference might be large enough not to support use of biofuels over that of photovoltaic cells for electricity production. The studies neglecting carbon sequestration in their analysis support their decisions by assuming a time frame that starts with the seed of the tree and ends with the burning of the biofuel, this balancing previous sequestration. Carbon sequestration from soil is left out by many biofuel LCA studies. [Reijnders .L, Huijbregts J.A.M,2002]

1.4.4 Reference point

Larson observes that the ranges seem to be smaller for biofuels such as RME; on a per-hectare basis than when presented on a per km basis. He also states that there is a lack of studies that focus on the land efficiency for different biofuel routes, this is a weakness as already mentioned as land is the primary resource for biofuel production. The energy demand and greenhouse gas emissions can be presented in different ways, according to the fuels energy unit (MJ), mileage (km) or area coverage(ha).One can also refer to an overall balance (biofuels-fossil), that compares a biofuel with its fossil fuel counterpart. [Quirin.M , et al.,p.2, 2004] Quirin does this in his study, however most studies present their results on a per-GJ of biofuel produced basis [Larson. E. D , p.4,2005] . In this project the studies considered will mainly focus on a km basis as the functional unit of the LCA done in part 3 is 1-v-km, and it is crucial to have the same function while comparing different studies.

1.4.5 Nitrous Oxide Emissions

Farming is an important step in the biofuel production.

Nitrogen fertilizer and emissions of nitrous oxide N_2O from the field are two major GHG . Even though the amounts emitted are small the greenhouse effect is about 300 times that of CO_2 and would still have a significant contribution to the impact category. The amount of fertilizer used is site specific, depending on the soil type, crop, climate and fertilizer and manure rates, this results in enormous variations in fertilizer use and is another reason for why studies differ quantitatively in their global warming effects. Variations in N_2O emissions between three different studies can be seen in table 2. [Hass .H, et al.,p.34, 2004],[Panorama.p.2, 2007]

Table 2 : Differences between three studies in N2O emission assessment.[Dohy .M, Poitrait .E,p.9,2006]

	g N2O / kg		
	ADEME	Concawe/Eucar	GM
Wheat	0.162	0.278 (+/- 0.185)	
Sugar Beet	0.533	0.046 (+/- 0.014)	0.11 [-0.02, 0.12]
Rapeseed	0.405	1.030 (+/- 0.407)	0.947 (+/- 0.683)
Sunflower	0.210	0.625 (+/- 0.186)	

1.4.6 Vehicle Assumptions and Energy Yields

One complication with comparing results from different LCA studies through to v-km, is the different assumptions of vehicles characteristics. Compression ignition (CI) and spark ignition (SI) engines for example, have different efficiencies, CI having an advantage of 15% over SI engines. Reference vehicles also have impacts on the results. European studies such as the CONCAWE study used a typical compact car similar to Volkswagen Golf, whereas the wells to wheels study led by GM in North America used a projected 2010 model year, full sized Silverado pick-up truck.[Larsson D.E ,p.16 ,2005]Few analysis have investigated the impact of using the same biofuel pathway with different energy yields, Larson states that the differences here also could have substantial impact on the results.

As can be understood from the two last sections, determining the environmental effects from biofuels is not straightforward. There are several issues to consider that have significant contributions on the results. On several of these issues no common method is followed. Therefore when choosing to look at the environmental impacts of one biofuel, its specific region, fertilizer use, allocation method, carbon sequestration should be taken into consideration. At the same time acidification, eutrophication, human toxicity, land use and ecotoxicity are all environmental concerns that should be studied more closely. All these critical issues make differences on studies reviewing the same biofuel and production route, and makes it difficult to make direct comparisons. According to the IFP(Innovation Energy Environment) certain studies attempts to broaden the assessment of biofuel pathways to include more impact categories, and projects are undertaken to develop multi-criteria analysis methodology based on LCA principles. This methodology takes technical, economic, social and environmental criteria into account. [Panorama,2007]

1.5 Discussion of Sustainability

Sustainability is a term that is frequently used when addressing biofuels, and the question arises whether biofuels really are more sustainable than fossil derived fuels. Sustainability has several definitions, but in this project it is defined as the use of biomass that can be continued without increasing negative effects on the environment, at the same time enabling future generations to enjoy the same natural resources and beneficial functions of nature as the present generation. [Reijnders .L, p.4, 2006]As already shown, the use of biofuels offers reduction of the global warming potential compared to fossil fuels. The net energy benefits are also shown to be higher in the former case. Both these factors implies but is not enough to prove that biofuels are more sustainable than fossil fuels.

Critical environmental damages occur in other impact categories such as acidification and eutrophication, and human toxicology.

At the same time, it is important to be aware that biofuels will only continue to be a renewable resource as long as the use does not exceed the growth of the feedstock.

Another critical factor when considering biofuels is the land use. In order to produce biomass, land is needed, and thus production of biofuels competes with food production. This is an important fact to consider as a growing population increases both food and energy demand. Other crucial environmental issues include stocks of natural resources, mobilisation of elements and the effect on the ecosystem. The living nature existing on the location where harvesting from forests take place are influenced by the changes. Both vegetation cover and animal biomass has shown to be negatively affected. This can in turn lead to loss of ecosystem services. Lowered primary production, soil erosion and loss of minerals and nutrients to ground and surface waters are other potential results of biomass production. [Reijnders .L, p.14, 2006]

Biofuels have the potential to be a more sustainable solution than fossil fuels, however in order to reach this goal, major effort has to be made. One of the more promising biofuels in terms of sustainability is second generation biofuels, and will be discussed in the next sections.

2. Second Generation Biofuels

Second generation biofuels are claimed to be a more sustainable solution than first generation biofuels. Section 2.1 takes this discussion further, presenting advantages and differences with second generation technologies compared to first generation technologies.

2.1 Definition of Second Generation Biofuels

Second generation fuels differ from first generation fuels in technology and in that their biomass sources may contain (ligno)-cellulose. Examples of ligno- cellulosic material is woody materials. This gives the materials a more complex structure that needs special treatment before producing the biofuel. Therefore, whereas first generation fuels such as ethanol are traditionally produced by fermentation, fermenting the sugar directly into alcohol, second generation fuels need to break down the lingo-cellulose into sugar before fermenting. Some of the technologies existing as second generation technology also enable the use of wet organic waste materials.

[Faaij .A.P.C, p.362, 2006]

Second generation fuels are not commercially available yet, however they have gained both importance and attention in the 5-10 latest years due to an increasing need to reduce pollution from vehicles and to improve energy security. As discussed earlier in section there are doubts as to what extent first generation fuels are environmentally friendly, second generation fuels are deemed to be the only sustainable solution to large scale production of bio fuels.

There are several aspects that makes second generation bio fuels considered a more sustainable solution than first generation bio fuels. Some of these reasons are the following:

- Decrease competition with food production, as technology enables use of non-food feedstock.
- Use of waste from agriculture and wood industries, results in lower feedstock costs.
- Higher efficiency as the whole growth and not just the seeds are used.
- Some bio fuels have the potential to become more efficient in engines
- Increasing incomes of farmers
- Higher sugar yield per hectare.(compared do sugar and starch), good for northern parts of the world with less sun radiation
- More flexible as more types of feed stocks can be used, and several of these are not dependent on climatic conditions such as sugar cones for ethanol.

[Vessia .O, p.27 ,2005]

There are three main second generation technologies, namely, gasification, hydrolysis and pyrolysis, description of these technologies will be provided in the following sections. These technologies result in a number of different fuels. Table 3 is presented below to provide an overview over second and first generation biofuels and their respective technological routes.

Table 3: Overview over main second and first generation biofuels, [Girard .P, Falot .A, Dauriac .F,p.19 ,2005]

	Name of bio fuel	Name by EU directive	Production process
1 st	Straight vegetable oil	Pure vegetable oil	Mechanical or chemical extraction, refining
1 st	Ethanol	Bio ethanol	Sugar fermentation, starch hydrolysis and fermentation
1 st	Fatty acids esters	Bio diesel	Triglycerides etherification and purification
2 nd	Fischer-Tropsch (FT) diesel	Synthetic bio fuel	Gasification, gas-shift, synthesis, hydrocracking
2 nd	Methanol	Bio methanol	Gasification, gas-shift, synthesis
2 nd	DME	Biodimethylether	Gasification, gas-shift, synthesis
2 nd	SNG from syngas	Biogas, synthetic bio fuel	Gasification, gas-shift, synthesis, CO ₂ H ₂ O-removal
2 nd	Ethanol from celluloses	Bio ethanol	Advanced hydrolysis, fermentation, distillation
2 nd	Pyrolysis-diesel	Synthetic bio fuel	Pyrolysis, hydro de oxygenation, refining

2.3 Hydrolysis

Hydrolysis is a second generation technology route to produce ethanol, this section describes the technology, feedstock and challenges associated with the chosen technology.

2.3.1 Biomass Input

Biomass input for hydrolysis is lingo cellulosic materials.

Cellulose materials contain lignin which is difficult to separate and break down into sugars. Once it is separated however it can be used to power the ethanol plant operations. [Mahy .H, Szabo .C, Woods .L, p.7, 2003]

2.3.2 Technological Description

Hydrolysis is the technology where woody or lingo - cellulosic materials are broken down into simple sugars before being used to produce ethanol.

There are 4 different steps in hydrolysis, Pre-treatment, hydrolysis, fermentation and distillation. A schematic diagram of the general steps in hydrolysis is provided in figure 9 , below.

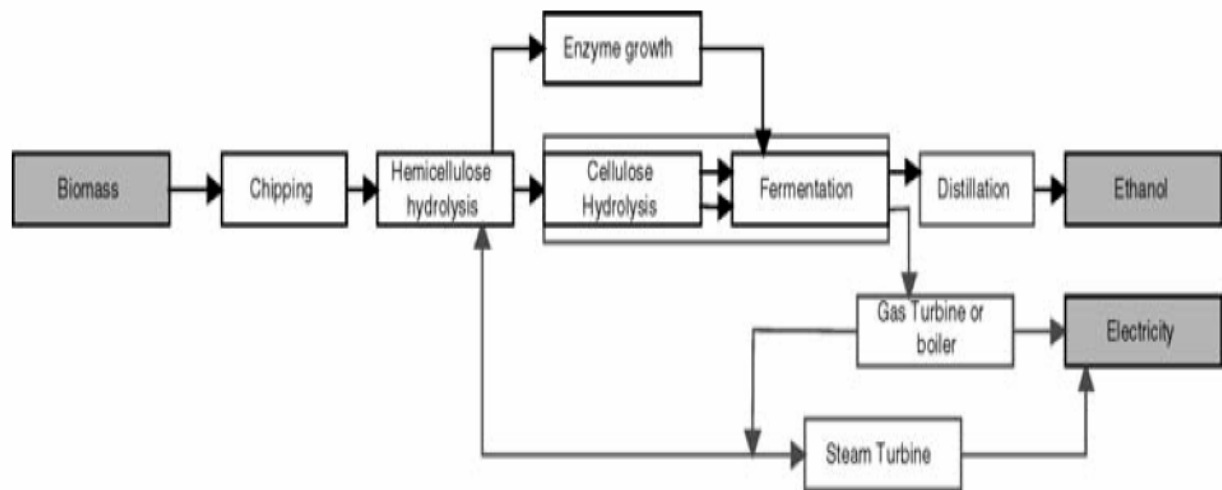


Figure 10: Schematic diagram of production of ethanol by, hydrolysis and fermentation.
 [Faaij .A, p.363,2005]

Pre-treatment

In order to perform an efficient hydrolysis step, the feedstock needs to be modified. More specifically a step is needed, where the porosity of the material is increased and the cellulose crystallinity decreased and lignin and hemicellulose are removed.[Vessia .O, p.27, 2005] This is done in a pre-treatment step, of which there exist several different types. They are described in detail in Hamelinck's review, where steam explosion is considered the most promising pre-treatment method [Hamelinck .C.N, Van Hooijdonk .G, Faaij .A.P.C, 2003] The method is predicted to be commercially available in 3 years time. Since this is considered the most relevant pre-treatment known today this is the only pre-treatment method that will be explained here.

In steam explosion pre-treatment, wood chips are heated with high pressure, 7-48 bar, and saturated steam, 160-260 °C . After being heated for several seconds to few minutes the wood is exposed to atmospheric pressure which results in a sudden decompression. The high temperatures causes hemi-cellulose to hydrolyse into simpler sugars, and lignin to be removed from the biomass.[Vessia .O, p.28, 2005]

Hydrolysis

Hydrolysis is the breaking of the cellulose into fermentable sugars such as glucose. There are several possibilities of doing this.

- 1) Concentrated acid hydrolysis.
- 2) Dilute Acid hydrolysis.
- 3) Enzyme technology.

Acid treatment is available process today, however it is still expensive and inefficient, and more research is needed to improve this process.

Dilute and concentrated acid hydrolysis are the oldest and most common methods today. In this method sulphuric or nitric acid is used to break down the cellulose into sugars. A drawback with acid hydrolysis is that the sugars can be broken too far, preventing fermentation. Of the three methods the latter, which uses enzymes to break down the cellulose, has many advantages. Enzyme technology is not commercially available, however development of hydrolysis techniques have gained importance during the last 10 years and several pilot projects exists on the subject, especially in Sweden and United States, see section 2.8 for description of pilot projects.

Different levels of integration are available for enzymatic hydrolysis, Separate Hydrolysis and Fermentation(SHF), Simultaneous Saccharification and Fermentation (SSF), co-fermentation of hexoses and pentoses sugars (SSCF). These will not be covered here but are explained in more details in [Hamelinck,p.395,2005],[van Thuijl .E, Roos .C.J, Beurskens .L.W.M, p.16 2003]and. Enzymatic technology is viewed, by many as the most cost effective ethanol production in the long term perspective. There are several aspects that makes enzymatic technology more attractive than acid technology, it ferments the sugar immediately thus avoiding problems with sugar accumulation, and corrosion problems caused by alkaline and acid solutions, condition of the process is also mild giving high yields.[Hamelinck et al.,p.392, 2005] Acid treatment is available today, but the costs are high and the processes are inefficient. Due to little potential being shown in increasing the efficiency in the processes, research is mainly focussed on enzymatic technology.

Fermentation

This is the step where ethanol is produced by the biological process. Under oxygen free conditions, micro organisms ferment the carbohydrates into ethanol. Work has been done on investigating the possibilities of CO_2 capture from this step. In woody biomass there is lignin, and lignin is a substance that cannot be fermented, but it can be used to produce power in a steam turbine or gas turbine. This would mean that the CO_2 should be captured before the gas enters the turbine, which would be more expensive than capture of pure CO_2 from starch or sugar rich biomasses. However it is still possible and can contribute to increase the efficiency of ethanol production. This is mentioned in [Faaij .A.P.C, 2006, p.364,] After fermentation ethanol is recovered by distillation. Depending on the use of ethanol, blended, pure, engines, the ethanol might be modified further.

2.3.3 Challenges

Process efficiency is an important aspect to consider as it influences the costs and impact on environment. Research is made on enzymatic technology in order to increase its efficiency, predicting when the technology reaches a sufficient level of efficiency is difficult. There are some obstacles and drawbacks that needs to be overcome,

*Problems with C_5 sugars such as xylose, cellulose enzymes have problems breaking down all types of carbohydrates.

* Commercially available pre-treatment technologies can be improved, and be made more cost efficient and more environmental friendly.

*Integration with reactors.

*Development of a liquid hot water (LHW) reactor.

Hamelinck identifies 3 stages of development with ethanol production from hydrolysis:

- 1) short term (5 years)
- 2) middle term (10-15 years)
- 3) Long term (>20 years)

2004 is used as a reference year. The middle term includes steam explosion as an available pre-treatment step. This is identified as the most efficient pre-treatment method and a more environmental friendly option as the waste stream of gypsum is reduced. Several conversions are combined into fewer reactors. In the long term Hamelinck mentions the possibility of including LHW, which will allow higher yields for hemi cellulose and cellulose sugars and microbiological conversions to take place in just one reactor. In the short term, however they are predicted to occur in different reactors and dilute acid pre treatment is used, having a larger gypsum waste stream.

The current available technology has an estimated efficiency of 35% and is based on dilute acid hydrolysis, whereas the overall efficiency with electricity produced from lignin is about 60%. Improvements concerning challenges mentioned earlier in the section can increase the efficiency further to 48% and 68% respectively.

2.4 Pyrolysis

Whereas hydrolysis technology uses microbial conversion routes, pyrolysis uses thermal conversions. The technology produces pyrolysis oil that can either be used directly or as a step in the gasification technology described in section 2.5.

2.4.1 Biomass Input

Lignocellulosic biomass is preferred, however any biomass material can be used in pyrolysis. Some pre-treatment is needed before the material can be added to the process.

2.4.2 Technology

Pyrolysis is the process of thermally converting biomass in the absence of oxygen. The amount and nature of the final products from pyrolysis depends on residence time, heating rate, temperature and the composition of the biomass used. [Girard .P, Fallot .A, Dauriac .F, 2005]The result is pyrolysis oil, which is a liquid that can be applicable in various uses. Here it will be considered as a possible substitute for diesel. There are different types of pyrolysis processes, slow pyrolysis, fast pyrolysis and flash pyrolysis. Flash pyrolysis will be discussed here, for more information on the other pyrolysis processes, see [Van Thuijl .E, Roos .C.J, Beurskens .L.W.M, p.20,2003]

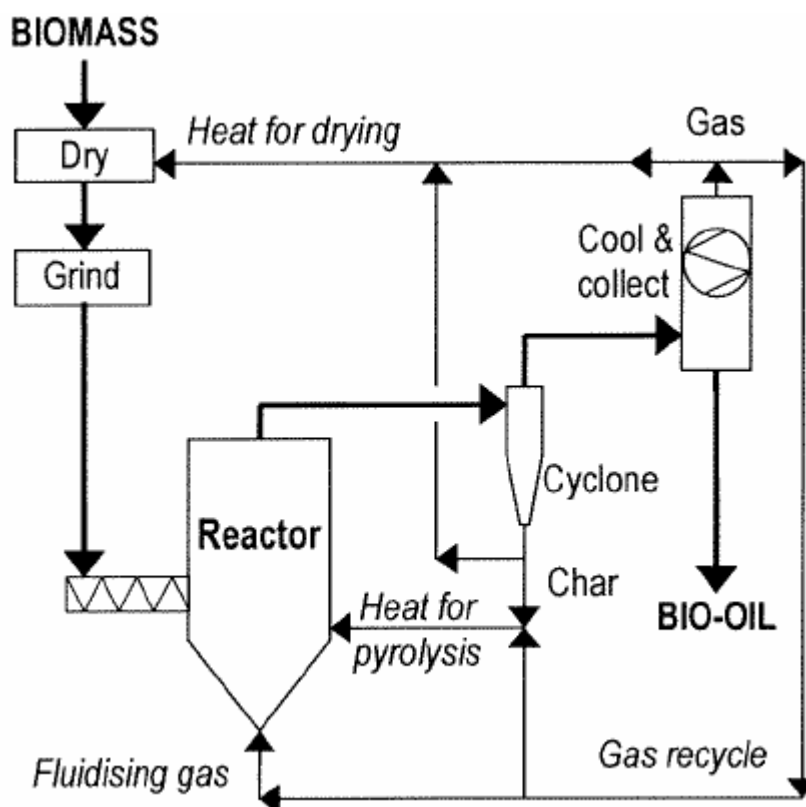


Figure 11: Schematic diagram of flash pyrolysis, with fluidised bed reactor.[Van Thuijl .E, et al.,p.20,2003]

The different steps in pyrolysis process includes:

- 1) Pre-treatment
- 2) Reactor
- 3) Cyclone
- 4) Cooling

Pre-treatment

Before reaching the reactor the material needs to meet specific requirements. Its particle size must be smaller than 6mm and moisture content below 10 weight-%. Therefore the biomass must be dried and grinded first.

Pyrolysis

After pre-treatment, the biomass particles are fed to a reactor where they are heated. In flash pyrolysis high temperatures are applied 700-1000 °C and the residence time is below one second. The high temperatures maximises the production of gaseous components compared to other pyrolysis processes. Flash pyrolysis is therefore used to produce liquid from biomass, and is most relevant for pyrolysis oil production. Several reactors can be used, such as fluid bed reactors. In this reactor the biomass particles are fed to a reactor with a bed made of an inert component like sand. Then, a hot gas is blown from bottom to top in the reactor heating the biomass. The velocity of the carrier makes the bed voluminous, which causes the reaction to take place in the entire reactor.

Other technologies include rotating cone technology. Here, the reactor has a compact design and problems with collecting the gas is avoided as there is no need for a carrier gas like in fluidised bed reactors. Instead the biomass particles are fed to the bottom of the reactor and are transported upwards by the rotating action of the cone. This simplifies the collection of the pyrolysis products after the reaction has taken place. A disadvantage of this technology is that the wood particle size has to be below 2 mm.

Separation

After pyrolysis reaction the products are transported to a cyclone where they are separated. The gaseous components are transported to a cooler whereas the char can be burned with air to provide heat. This heat can be used for drying the biomass or in the pyrolysis process.

Cooler

Here, the gaseous components are condensed to bio-oil. The rest is non-condensable and include gases such as CO_2 , CO , H_2 , CH_4 . These gases can be recycled and used as or applied in a gas engine.

2.4.3 Challenges

The possibilities of producing automotive fuels from pyrolysis is limited and therefore not the aim of research and development. Use of pyrolysis oil has been tested directly in automotive engines, but failed in substituting diesel, as acidity in the oil causes corrosion of the engine. The oil needs to be upgraded and stabilised to diesel quality. This can be done with catalytic upgrading. The technology however is currently too expensive to be taken into use and more research is needed. Research is mainly focused on development of new types of reactors for fast pyrolysis processes. The technology is still at an early stage of development compared to gasification.

Challenges include:

- *Upscaling of reactors
- *Meeting desired oil quality
- *No market for pyrolysis oil yet
- *Removal of contaminants from produced products
- *Final quality of pyrolysis oil diesel will always remain lower than that of fossil diesel.

The energetic efficiency of conversion of biomass to raw bio-oil is about 60-70% (2003). When hydrogenation technologies are used to upgrade the oil, however the efficiency is reduced. Utrecht Centre for Energy research et al (2000) estimates that partially upgraded bio-oil may be produced with an overall efficiency of 50% in the long term.

Another possibility is the use of pyrolysis as an input for a gasification process. Gasification is explained in the section below.[Van Thuijl .E, et al.,p.20-22, 2003]

2.5 Gasification

Gasification is another important second generation technology. Gasification produces a synthetic gas that can be further processed to produce several types of biofuels. Explanation of technology, products and some challenges is given in this section.

2.5.1 Biomass Input

Any type of biomass can be used as a feedstock to produce synthesis gas or syngas. One of the advantages of gasification is its ability to convert all biomass compounds, hemicellulose, cellulose and lignin into synthesis gas. Wet biomass, like agricultural residues and municipal waste can also be used but will result in a lower efficiency.

2.5.2 Technology

As can be seen from the table 2, several fuels can be converted from synthetic gas, and there are several different technologies used in gasification. Technologies are influenced by the operating conditions and composition of the biomass. However the first steps are similar for all the fuel types and is described in the paragraph below, only the conditioning and the synthesis will be different for the different fuels. The technologies of the specific fuels will be dealt with later in the same chapter.

The process is also known as biomass to liquid (BTL) route. Biomass is converted into syngas following 4 main steps:

- 1) Pre-treatment
- 2) Conversion of feedstock into CO and H_2 rich gas
- 3) Gas cleaning and conditioning
- 4) Synthesis

Where step3 depends upon the desired final product.

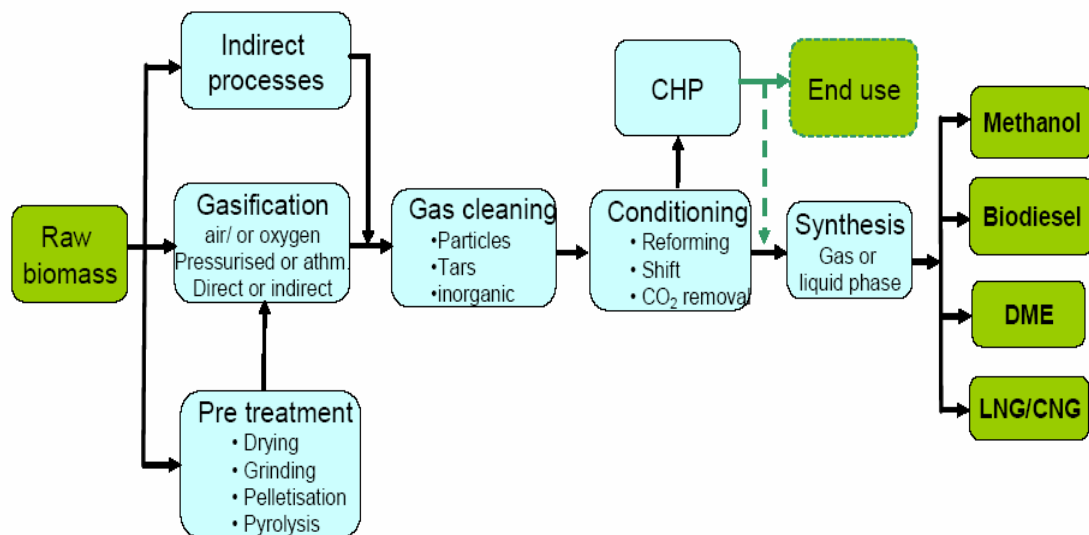


Figure 12 : General biomass gasification conversion scheme to biofuels.[Girard .P, Fallot .A, Dauriac .F, p.29, 2005]

Step 2 is the gasification step, this yields a gas containing mainly CO_2 , CO , H_2 , CH_4 , N_2 and water. Gasification is an exothermic reaction that occurs by the partial oxidation of the biomass as a result of adding a sub-stoichiometric amount of oxygen at high temperatures, 900 °C. The gasification agent can either be steam, air, oxygen or hydrogen. Gasification is carried out either by indirect or direct gasification. In the latter, both air-blown and oxygen-blown gasifiers can be used. The heat is produced by internal sub-stoichiometric combustion of part of the biomass fed into the gasifier. In the case of indirect gasification heat is created by burning some of the biomass or the produced gas outside the gasifier. This heat is then fed to the gasifier generally with steam. For synthesis gas generated from biomass, the indirectly heated reactors or directly heated, oxygen blown reactors with partial oxidation is preferred.[Boerrigter et al.,2002] There exist several different reactors for gasification. They differ in how the reactants and products are moved around in the reactor, and are explained more closely in the system description chapter of this report, section 3.4 and in the appendix D1 of this report.

Conditioning

After gasification, the gas contains some elements of impurities that need to be removed. Impurities like char particles, alkali metals, nitrogen compounds, tar and sulphur are removed in a cyclones or ceramic filters. After cleaning, the syngas is conditioned. During conditioning of the gas hydrocarbons are converted to H_2 and CO . Due to the gas after gasification containing smaller amounts of hydrogen than needed, the proportions of the components needs to be shifted. This is done by a water-gas shift reaction (WGS), where water reacts with CO to produce CO_2 and H_2 . Chemical or physical absorption is then used to remove the CO_2 . After this, the synthesis gas is compressed before it is transported to the final synthesis reactor, where the reaction takes form under a catalyst. The type of catalyst depends on the fuel targeted as the final product. After the final synthesis reaction, the gas is collected by distillation.[Van Thuijl .E, et al., p. 27-28 2003]

Production of methanol

Conventional methanol reactors operates in the gas phase and uses fixed beds of catalyst. Slurry technologies are under development. These technologies have higher efficiencies and eliminates the need for gas recycling loop. An example of a slurry technology is the liquid phase process. Here the reactants, catalyst and product are suspended in a liquid, when heat is transferred it is done so efficiently between the solid catalyst and the liquid phase. This increases the conversion per pass. Different reactors can be used in this process, for example the slurry bubble column reactor of the Liquid Phase Methanol (LPMEOH). The main concern for biomass is the quality of the gas. The syngas must be very clean in order to meet the requirements of the process and to protect the copper catalyst. The purge gas is often used for electricity generation. This process of methanol conversion can reach an efficiency of 95%.

Methanol can be used directly as a fuel or it can be converted into hydrocarbons. One of the advantages with methanol is its high hydrogen to carbon ratio, 3:1. It is considered a potential hydrogen carrier for on board reformer in fuel cell technologies on the long term. [Van Thuijl .E, et al., p.29, 2003]

Production of Fischer-Tropsch liquids

The reaction is exothermic and the catalyst use is either iron or cobalt based. At 180-250°C diesel and waxes are produced, at higher temperatures (300°C) gasoline and olefins are produced. Many products can be produced from the synthesis, and it is therefore important to apply specific conditions for the diesel production. For diesel production a high degree of selectivity is needed. FT processes produces diesel fuel with energy density comparable to conventional diesel. For more on FT-diesel production see section 3.4.

Dimethylether (DME)

Dimethylether, DME can be produced directly from syngas in a slurry type reactor like that one used for methanol synthesis. DME can also be produced from methanol, but it is argued that direct route would be more efficient as it involves less process steps. [Girard.P, et al, p.41, 2005] DME is mostly used as propellant in spray cans and as ignition improver in methanol engines, and research on the use of DME as a transportation fuel has only started recently. It proved an attractive diesel substitute as it reduces exhaust emissions of NOx. It can be produced from different feedstock, biomass and natural gas.

2.5.3 Challenges

One of the greatest challenges with gasification technologies with downstream catalytic gas processing equipment is the severe cleaning needed of the gas. This is due to the strict cleanliness requirements of the catalysts. Other development challenges includes scale-up of processes and process integration. By combining fuel production with production of electricity the overall efficiency can be reduced. [Faaij .A.P.C, p.357, 2005] In comparison with other routes to use cellulosic biomass however, gasification is well proven and one of the possible technologies to be introduced commercially as a major part of the energy route to biofuel .[Vessia .O, p.22, 2005]

2.6 Hydrothermal Upgrading HTU

Hydrothermal upgrading is the last technology being described in the report. Hydrothermal upgrading associated with biofuels is rarer than the other technologies described in section 2.3-2.5, yet has important characteristics that makes it a unique technological opportunity for biofuels.

2.6.1 Biomass Input

Various types of feedstock can be used in hydrothermal upgrading, one of the special advantages of the method is the possibility of using wet biomass. Due to the characteristics of the technology therefore, biomass does not have to be dried first.

2.6.2 Technology

Under high pressure and low temperature the biomass reacts with liquid water. The result of the conversion is called bio crude. This is the main product, however other products include, H_2 and CO_2 gases and water. The water can be used to produce biogas, which is then fed to a furnace with the rest of the gases. Like the other technologies (HTU) includes different steps, and an overview can be seen in figure 12.

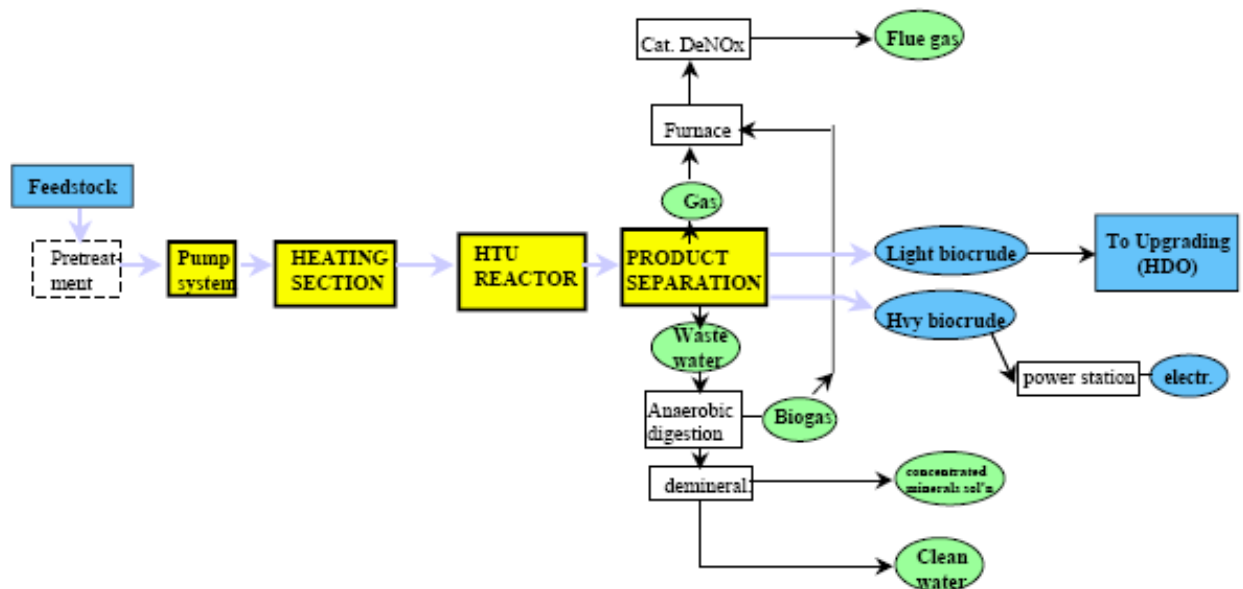


Figure 13: Process block scheme of the HTU process.
[\[http://ec.europa.eu/research/energy, 16.07.07\]](http://ec.europa.eu/research/energy)

Pre-treatment for dry biomass includes soaking, as the technology is meant for wet materials. The soaking often occurs at temperatures in the range, 200-250°C, and pressure at around 30 bar. The conversion process takes place after the wet biomass is heated, at pressure of 120-180 bar and temperature 300-350°C.

The bio crude can be separated into light and heavy bio crude, where the lighter bio crude can be used for production of diesel fuel components. Before being used in fuel engines, the bio crude needs to be upgraded into diesel quality. For this purpose, Hydrogenation techniques, such as HydroDeOxygenation is used. In this process, hydrogen is added, resulting in the removal of oxygen. This step is one of the challenges with HTU technology as the hydroDeOxygenation is an expensive process, both economically and energetically.

The end product from HTU is meant as a substitute to fossil diesel. The HTU diesel can therefore be mixed with conventional diesel.

2.6.3 Challenges

As with all the technologies presented in this section the hydrothermal upgrading has a number of challenges that still needs to be researched on and areas that needs to be improved. Topic of R & D with HTU technology is the following:

- *complex chemical properties of reaction processes.
- *testing of different feedstock types.
- *removal of contaminants of the produced products.
- *HydroDeOxygenation technology (upgrading)
- *Introduction of feed
- *heating of reactants
- *treatment of wastewater.

[Van Thuijl. E, et al., p.25, 2003]

According to literature the use of HTU as an automotive fuel is one of the rarer uses of the bio crude, and the focus of this application is therefore limited in literature. It is not likely therefore that HTU will be the route to biofuel. [Vessia.O, p.24, 2005]

Thermal efficiency of process, from biomass to bio crude is estimated at 80%. The overall efficiency, however with the upgrading by means of hydrogenation processes, the efficiency decreases to that of 60% (partially upgraded bio-crude).

2.7 Costs of Second Generation Biofuels

Economy is an important factor to take into consideration whenever evaluating new products and technologies. Section 2.7 includes a discussion of production and investment costs with ethanol produced by hydrolysis and BTL-fuels produced by gasification.

2.7.1 Ethanol

Ethanol derived from woody biomass uses the technology of hydrolysis described in section 2.3, the cost analysis of this technology has been taken from the article, ‘*Ethanol from lignocellulosic biomass: techno-economic performance in short-, middle- and long-term*’ [Hamelinck .C.N, Van Hooijdonk .G, Faaij .A.P.C, 2005] and the results of the analysis is shown in figure 13 below. The figure above shows that while the efficiencies increase the investment costs decrease. The specific investments are found to 2,1 $kEuro/kW_{HHV}$ for ethanol produced by the plant on the short term to 1,2-1,6 $kEuro/kW_{HHV}$ for the middle term. Ethanol from lignocellulosic biomass, techno-economic performance in short-, middle-, and long-term (5,10-15,20 years) is shown in figure 13 below. The technologies represent cellulose hydrolysis, and development that might occur through time. The short term takes use of the dilute acid pre-treatment with several reactors for microbiological conversions, whereas the middle term uses steam explosion, an the ultimate facility may adopt LHW allowing for higher yields and with all microbiological reactions taking place in one reactor. The total efficiencies of the different processes ate 38%, 67% and 52% respectively.

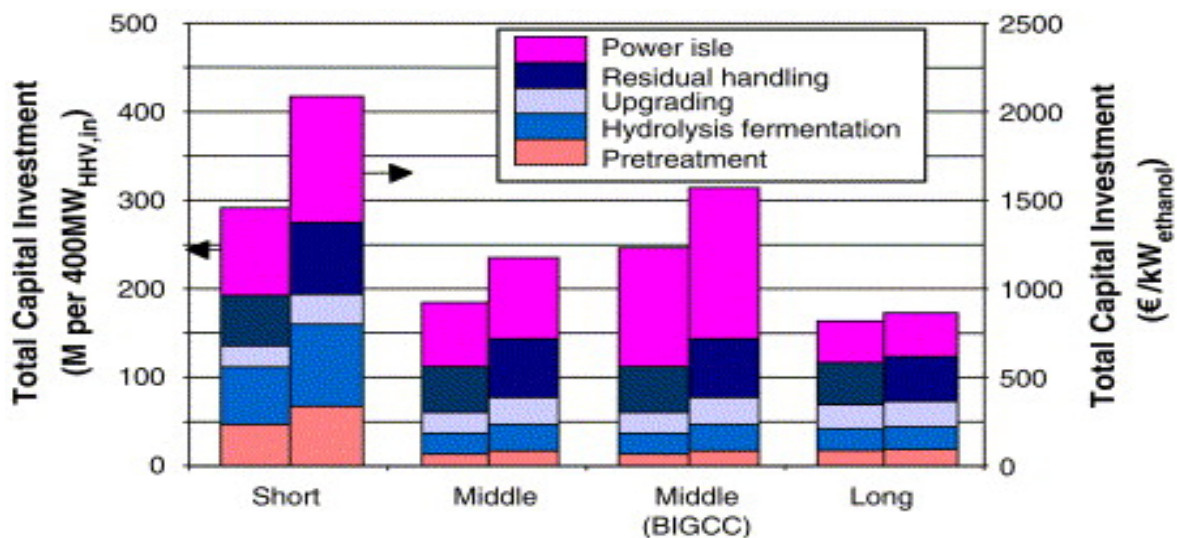


Figure 14: Showing investment costs of wood derived ethanol [Hamelinck C.N, et al., p. 405, 2005]

The figure above shows that while the efficiencies increase the investment costs decrease. The specific investments are found to 2,1 $kEuro/kW_{HHV}$ for ethanol produced by the plant on the short term to 1,2-1,6 $kEuro/kW_{HHV}$ for the middle term.

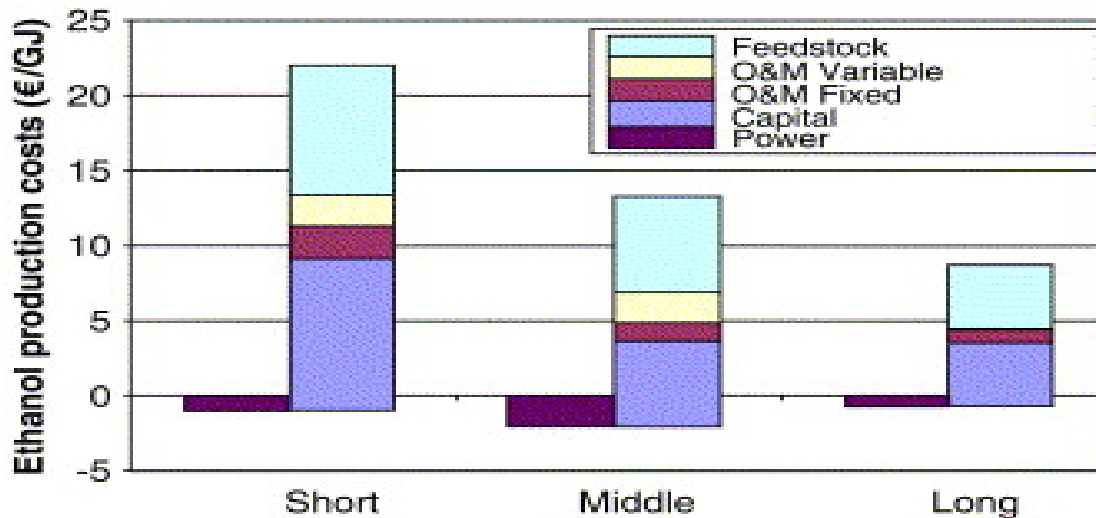


Figure 15: Showing production costs of wood derived ethanol [Hamelinck .C.N, et al., p. 406, 2005]

Costs are dependent on several factors, and according to figure 14 above the costs of ethanol production will decrease in the future. Combined effect of higher hydrolysis-fermentation efficiencies, cheaper feedstock costs, lower specific capital investment and larger scale can reduce the production costs of ethanol from 22 Euro/ GJ_{HHV} , 5 years, 13 Euro/ GJ_{HHV} (10-15 years, 8.7 Euro/ GJ_{HHV} in 20 or more years. [Hamelinck .C.N, et al., p.406-408, 2005]),[Faaij A.P.C, p.363, 2006] The results show that cellulosic ethanol on the short term might be competitive with ethanol derived from starch but not from sugar cane. According to Hamelinck it is unlikely that wood derived ethanol will be cost-competitive with current fossil derived gasoline or renewable fuels such as bio-methanol, 8-12 to eventually 5-7 Euro/ GJ_{HHV} , which has both higher efficiency and lower investment costs. [Hamelinck et al., p.406-408, 2005]

2.7.2 BTL-fuels

Significant parameters influencing the biosynfuels competitiveness are capital costs, operating costs from plants, and feedstock costs. BTL-fuels are usually 2-3 times more expensive to produce than conventional petrol diesel. Feedstock cost is a major component of the BTL cost, varying from 15-50% depending on the raw material being cheap or expensive. Further the biosyngas costs accounts for the largest share in the total production costs, as much as 50-75%. The figure 15 shows the production costs of BTL fuels depending on technology and feedstock. Direct capital cost for bio-DME and bio-methanol plants are slightly lower than that of FT plants, this is due to higher conversion efficiencies in the two aforementioned plants. [Girard .P, et al, p.41-42, 2005]

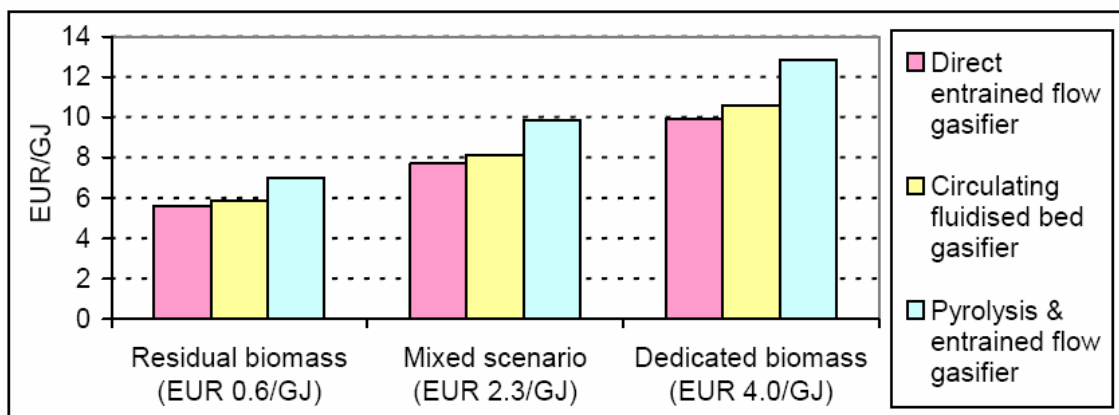


Figure 16 : production costs of BTL-fuels depending on technology and feedstock[Kavalo et al,p.73 , 2005]

Production of methanol, DME, ethanol, FT-diesel derived from lingo cellulosic biomass, offer better perspectives and competitive fuel prices in the longer term >20 years, than most first generation biofuels. This is mainly due to second generation fuels having more flexible feedstock and development of technology improving efficiencies.[Faaij.A.P.C, p.369, 2005]

2.8 Pilot Projects

There are several pilot plants and projects with the aim of doing R&D on second generation technologies. However, few of the technologies are commercially available today. Some of the major projects will be discussed briefly in the following section. The pilot projects will be mentioned in connection with their relevant technologies.

2.8.1 Hydrolysis

As mentioned earlier there are several challenges in hydrolysis technology. Pilot plants and projects exist in order to overcome some of these challenges. Important pilot projects involved with these challenges include: DOE Bioethanol Pilot Plant (dilute acid treatment with enzymatic hydrolysis, pre-treatment, enable fermenting of 5C) , Iogen Canada (enzymatic hydrolysis of straw hardwood), BC-International (working with E.Coli bacterium, fermenting of C_5), EthanolTeknik- hydrolysis of soft wood(diluted acid in two steps and third step enzymes).

BC-International, and the DOE Bioethanol pilot plant, are discussed more thoroughly in the following pages.

BC-International

One company that looks closer at the challenges with fermentation is BC-International. The technology used is dilute acid hydrolysis with separate fermentation. A genetically modified E.coli bacterium, that the company has patented, is used to convert the xylose/pentose into ethanol. This was one of the challenges mentioned earlier in section 2.3, of lignin containing special types of sugars that the conventional hydrolysis processes can't convert. One of the drawbacks of the process is that it includes hydrolysis in two stages and therefore produces an amount of residual materials. Figure 16, below shows a schematic overview over the main process steps used by BC-International.

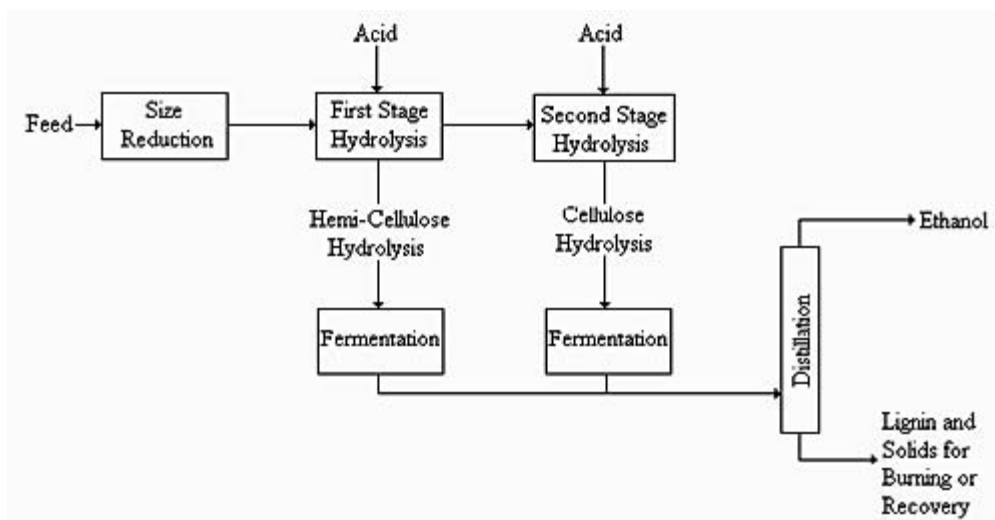


Figure17: Process diagram BC-International [<http://journeytoforever.org>, 15/07/07]

DOE Bioethanol Pilot Plant

NREL is a leading national laboratory of the virtual Bioenergy Research Centre, which was established for the aim of supporting research on biomass activities. Among other projects the company operates a pilot plant in Golden Colorado, aimed at testing bioprocessing technologies for production of biofuels or chemicals from cellulosic biomass. Although they work on developing conversion routes for all biofuels, NREL focuses on cellulosic ethanol.

They are investigating different pre-treatments methods for lignocellulosic material. Further NREL biomass researchers have focused on a process model of dilute acid hydrolysis of hemicellulose followed by enzymatic hydrolysis of cellulose. This technology is often referred to as SSFC. NREL is also doing research on enzymes, attempting to reduce the cost of the enzyme unit. Metabolic engineering techniques to enable the fermenting of the xylose, five carbon sugar existing in the hemi - cellulosic material.

The NREL pilot plant is made for research purposes only and the technology is not available yet. The areas of research on cellulosic technology from NREL can be divided into three main parts:

- 1) Pre-treatment
- 2) Cellulase enzymes
- 3) Catalysts for products from sugar.

NREL is for research and improving knowledge in the field of biofuels only, and plans of constructing plants on commercial scale is therefore non-existent. The interest however and collaboration with different firms shows the importance of development of this technology. Below is a diagram depicting the technology being developed at NREL.

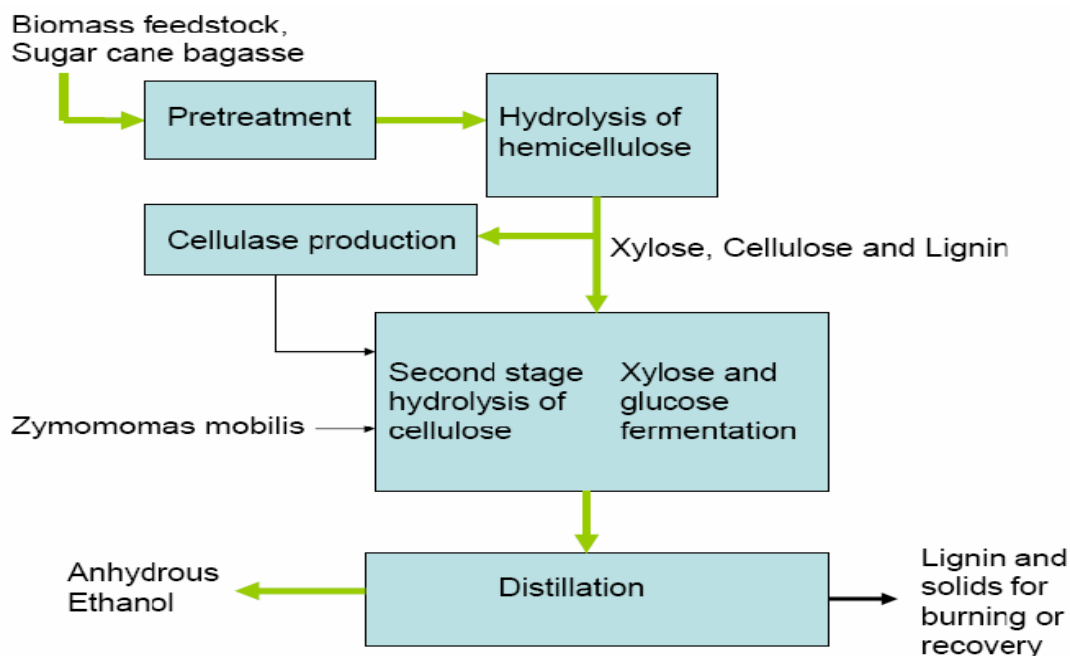


Figure 18: Diagram showing the process step in the technology used at NREL [<http://www.nrel.gov/>, 30/04/07]

2.8.2 Pyrolysis

Research and development concerning pyrolysis is usually aimed at other aspects rather than the use as automotive fuel, as there are several problems concerning substitution of diesel. The costs of upgrading equipments so that the process meets EU specifications are above commercial budget. [Vessia .O, p.25, 2005]

2.8.3 Gasification

Gasification or BTL, is still at an early stage of development and at present production of fuels using this technology is only at an experimental state. The European commission states that gasification technology will not start playing a significant role in the transport sector before 2010. Beyond 2010, however it is predicted to have a much larger production potential, and the costs are predicted to decrease below that of conventional biofuels. [kavallo .B, et al., p.1-2, 2005] Most of the R&D in gasification is concerned around development of new reactors.

Choren Industries GMBH, Germany - gasification, Fischer – Tropsch diesel (tar free process).

Choren is one of the worlds leading providers of liquid fuels from solid biomass, producing Fischer-Tropsch diesel and methanol. A high-temperature oxygen-blown slagging entrained flow gasification was developed by Choren in 1994, and patented in 1995 under the name Carbo-V process. In the section about gasification, the problem of tar in the process was mentioned as one of the challenges with the technology. Choren is an example of one of the companies that looks at this challenge and makes production of tar-free synthetic combustion gas possible. The process includes gasification in three stages, low temperature gasification, high temperature gasification and endothermic entrained bed gasification. FT-synthesis is used to convert the gas into diesel. The diesel produced from Choren goes under the name SunDiesel. The BTL automotive fuel was added to the plant in 2002, with the support of Volkswagen A.G. and DaimlerChrysler A.G.

The claimed thermal efficiency of the Carbo-V Process is 95-98 %. The overall efficiency of production of SunDiesel at the Beta-plant is achieved at 45-55% depending upon the operating methods used. Whereas the thermal efficiency is 82 % for capacities larger than 10MW. The claimed conversion efficiency is among the highest reported in literature. [Kavallo., et al, p.41, 2005] [Vessia O., p.64, 2005] [<http://www.choren.com>, 02/05/07]

The company is constructing the world's first commercial industrial scale BTL plant at its Freiberg sight. This plant is planned to produce 15000 t/a BTL(Beta-Plant) by Autumn 2007.

Further, the company plans to install 1 million tonnes of annual BTL capacity in Germany by 2010. Figure 18 is a picture of the Beta-plant at the Freiberg site.



Figure 19: Beta plant at the Freiberg site [http://www.choren.com, 15/07/07]

Chemrec A.B

Chemrec has developed gasification method specialised to run on residual products from the paper and pulp industries, to produce BTL transport fuels, such as methanol, DME and hydrogen. This is known as the black liquor gasification concept. The first plant of such type for methanol, DME and hydrogen. 'DP-1' is situated in Piteå in Sweden, and started in May 2005. In January 2007 it was stated that the same plant has demonstrated over 1100 operating hours. The production of syngas and green liquor are of good quality so the technology is proven. The 'DP-1' plant uses a black liquor gasification combined cycle (BLGCC), with an oxygen blown entrained flow gasification, and a system for black liquor gasification for producing alternative automotive fuels and hydrogen (BLGAMF/ H_2). Figure 19 below

demonstrates the concept of BLGFM.

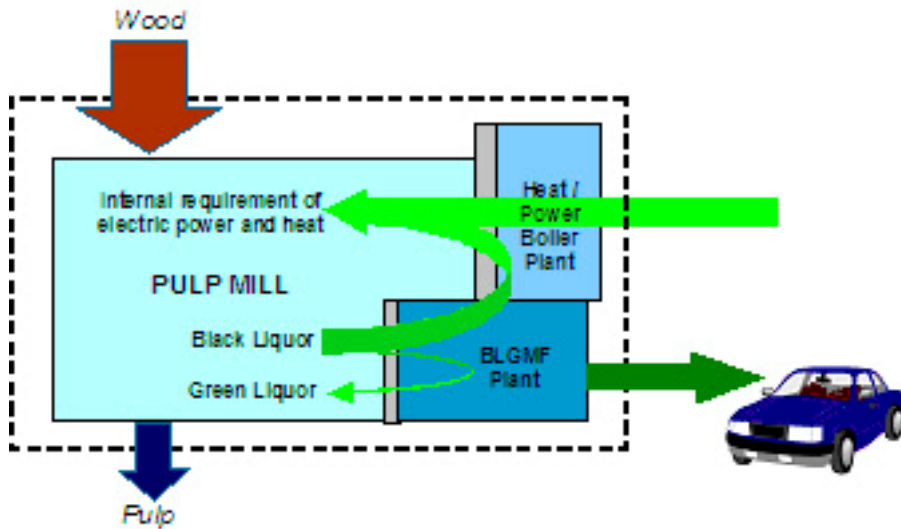


Figure 20: Concept of BLGFM [<http://www.chemrec.se/forsta.htm>, 02/05/07]

The efficiency of biomass to methanol and DME (BLGFM-process) is estimated to be 65-75%, slightly higher than FT-synthesis. The energy efficiency to produce Hydrogen is claimed to be higher than 75%. According to the homepage the process is cost effective enough to make the fuels competitive with conventional fuels without tax incentives. The cost and technical evaluations were done based on a modern pulp mill. [<http://www.chemrec.se/forsta/htm,02/05/07>] [kavalo et al, p.44, 2005]

None of the plants have been producing/constructed on a commercial scale yet. However, A DP-2 and DP-3 plant will be constructed. Based on the results from the first year of operation of the DP-1 plant, the DP-2 plant will be constructed for more than 10 times scale up of the DP-1 capacity. A first near to commercial scale demonstration of the BLGAMF concept is now planned by the company. There is no information on the company's homepage of when the plant is to be constructed, but during 2006 the company made a report on investment costs of and a preliminary engineering package for the planned DP-3 plant. Volvo will be testing the diesel fuel produced by the plant. [<http://www.chemrec.se/forsta.htm>, 26/04/07]

There are several other success stories of pilot projects using gasification technology. Examples of these are, Varnamo Demonstration Plant Sweden, The Viking Gasifier DTU Denmark and CHP(combined heat and power) -plant Gussing Austria. Most of the plants produce fuel and power, but all of the plants use slightly different technologies. The Waste gasification plant in Italy for example, uses refuse derived fuel and a three stage gasification process and produces electrical power and fuel. Whereas the CFB- Plant Rudersdorf plant in Germany has only one gasification step and supplies 40% of the energy demand for the cement process. The Viking demonstration plant in Denmark is a CHP plant, with a two stage gasification process, which uses wood chips as raw materials. For more detailed descriptions of the different processes and for examples of more pilot projects please see the '*Handbook Biomass Gasification*' [Knoef .H.A.M, 2005] From all the success stories mentioned in the Gasification handbook there are two projects stated as especially promising, namely the Carbo-V process at Choren in Germany and the CHP- Viking - demonstration plant in Denmark.

2.8.4 HTU - Hydrothermal Upgrading

As mentioned earlier HTU is not seen as the most likely technology for biofuels, and there are not as many pilot projects existing for this technology as there is for gasification or hydrolysis. It is worth mentioning, however, that the successful running of a pilot plant by TNO Apeldoorn, confirmed the HTU process principles. Conceptual designs and technical and economical studies were done for a commercial plant at a scale of 25.000 tons biomass(dry)/year. They showed that the process was both economically and technologically feasible. The project will not be discussed further here.[Goudriaan .F, Van de Beld .B, Boerefijn .F.R, Bos .G.M, Naber .J.E, Van der Wal .S, Zeevalkink .J.A, 2000]

3. LCA of a Second Generation Biofuel

3.1 Theory

Hybrid Life Cycle Assessment is used to assess the environmental pressure caused by production of a second generation biofuel. The theoretical background for these methods will be discussed in this chapter.

3.1.1 LCA

LCA is an analytical tool used to assess the total environmental impact of a product's or a service system's entire life cycle, such as raw material acquisition, production, use and disposal. The environmental impacts including health, ecological consequences and resource use are known as the three general categories considered.[Baumann H, Tillman A,p.22,2004] The purpose of the tool is to create a better understanding of production process and production fate, so as to allow for improvements. It can be used to indicate the most significant processes and change these or in comparison of different technology solutions. Therefore the tool is not used to make political decisions but rather as a decision tool support. The framework has been standardised under the International Organisation for Standardisation within the ISO 14040 series on LCA. There are 4 main phases in doing an LCA, goal and scope, inventory, impact assessment and interpretation. These will be discussed more thoroughly in the following sections.

Goal and Scope

When doing an LCA it is necessary to do certain assumptions and simplifications. In order to ensure consistency it is important to clearly define the goal and scope of the study. This is done before the other phases are performed, yet it should not be a static document, there should be possibilities of changing the initial options throughout the assessment. According to ISO the following requirements exist in the goal definition:

- The reason for the study.
- The intended audience.

This is important to state as it might affect the structure of the assessment. For example, a study that is used externally and is used to compare different technologies, is not allowed by the ISO standards to include weighting. The scope of the study describes important limitations, assumptions and methodological choices. Initial definitions of functional unit, system boundaries and allocation and inclusion of input output flows, are all issues dealt with in this phase. The functional unit is a quantitative description of the function of a product or a service. It is especially important in comparisons as in order to be able to compare to different systems they have to have the same functional unit. Product systems can be interrelated in very complex ways, and it is necessary to decide what should be included and excluded in the study. Should for example, a product include the vehicles used to transport the different materials? A boundary has to be made and the rest of the processes excluded from the project, the cut offs can have considerable influence of the result of the study.

Inventory

This phase describes the system in a mathematical, structured way. Where quantitative data on inter process relationships and emission data on all processes is searched and collected. All the data is systemized, using matrix algebra. A detailed flow chart is often illustrated in this phase. This is often the most time –consuming phase in the assessment, and often one of the most challenging as the relevant information can be unavailable or non-existent.

Impact assessment

Impact assessment is defined as the phase used to understand and evaluate the magnitude of potential environmental impacts from a product system. First, impact categories have to be chosen and related for the different pollutants, this step is called classification. Examples of categories can be ‘acidification potential’ or ‘global warming potential’. After this step, it is necessary to perform a ‘characterisation step’, where the relative contribution of each LCI item to the impact categories are calculated. Normalisation and weighing are two other steps in this phase but according to the ISO 14042, these are regarded as optional steps in an LCA and will not be covered here. Please see appendix for explanations of formula used to assess impact in this project.

Interpretation

Interpretation is the step where reliability and uncertainties in the study are evaluated. Interpretation involves several checks to be done, in order to assess whether the conclusion drawn from the study are supported by the procedure and the data used. According to ISO 14043 these steps involve, uncertainty (Monte Carlo analysis), sensitivity analysis, contribution analysis and gravity analysis.[Goedkoop M, Oele M,2005]

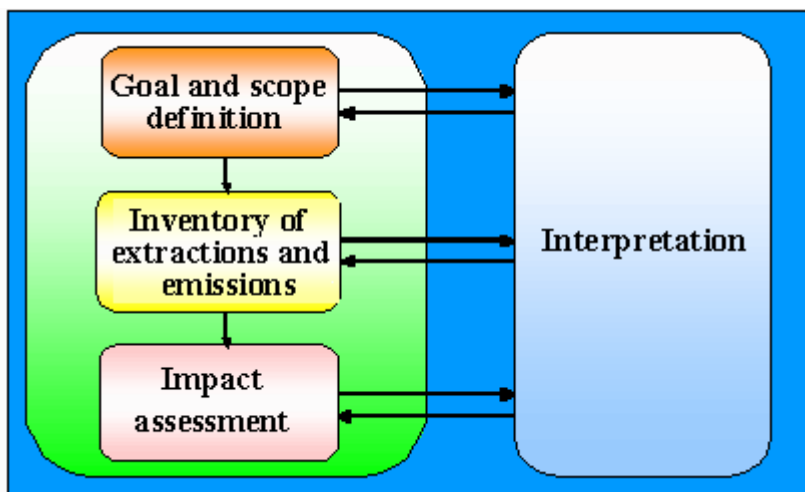


Figure 21 : Overview over the different phases in an LCA
[<http://www.unep.org/pc/sustain/lcinitiative/background.htm>]

As can be seen from figure 20 the relationship between the different phases is not static, due to LCA having an iterative approach. One major weakness with LCA is that of the system boundary. The method of choosing the system boundary has been criticised of being based on subjective judgment rather than on a scientific basis, and results in significant environmental impacts to be excluded from the study. [Goedkoop M, Oele M , April 2005]

3.1.2 Input-Output

Input-Output analysis (IOA) is an important theoretical framework in economics. Francois Quesnay's Tableau Economique serves as the fundamental contribution to input-output in economics, this is a table describing the relationship of sales and purchases between different consumers and producers in the economy. This table was later transformed by Leontief into a coefficient table. The system assumes linear and fixed coefficients, so that for each product there exists only one technology. This is justified by the argument that a technique for production will not change much over a short period of time. It is also assumed that an industry produces only one type of products and does not involve any secondary production.

Table 4: Simplified Input-Output accounting framework.[United Nations,1999,p.6]

	Industries	Net final demand	Total output
Industries	F	Y	X
Value added (Primary inputs)	V		
Total input	X		

An input-output table shows the interdependence of different industries within an economy. The economy is divided into different sectors/industries, F, that are listed on the top of the table as consuming sectors and on the side as supplying sectors. Value added represents the inputs such as labour costs that are not directly needed for production. Net Final demand (Y) is the external demand put on the system. An exogenous system that exists independent of the economic system is assumed. The total output (X) is the total output from the industries needed to fulfil the final demand.

The basic input-output system of equations is the following:

$$AX + Y = X$$

Where A represents the inter-industry flows, Y final demand put on the system and X the total outputs required from the industry to meet Y. Solving the equation mathematically results in the equation:

$$x = (I - A)^{-1} y$$

IOA has been expanded to include environmental analysis, by multiplying with a matrix showing the environmental intensities associated with the economic flows the environmental impacts resulting from a demand on the economy can be assessed. The same formulas apply for the LCA system, where y is the final demand determined by the functional unit, x is the total output from the processes required to fulfil the demand, and A is the matrix that show the interdependencies between the different processes in the system.

$$e = S(I - A)^{-1} y$$

Where S is the stressor matrix with emission factors from the industries and e is the environmental stressor matrix.

[Strømman Hammer A, Hertwich G. E, 2005, p.2]

Leontief Inverse

$(I - A)^{-1}$ is the Leontief inverse and has a special economic meaning. The meaning is to encompass all the indirect effects resulting from an exogenous demand. A , as discussed earlier shows the direct effects by a demand, ie the inputs needed form different industries. However, it does not show how much the industries acting as inputs for industry B need of inputs from other industries in order to produce the required input for this industry. The chain of these interactions goes into infinity, and the sum of these is determined from the value of the Leontief inverse. The Leontief inverse also has an important meaning in the system defined by the LCA. The system can be divided into different layers or tiers defined by the expansion of the Taylor series:

$$(I - A)^{-n} = (I + A + A^2 + A^3 + \dots + A^n)F$$

This allows for study of the structure of the system/economy, to investigate how the different economies affect each other in an IOA and how the different processes contribute in the LCA system. The difference between the LCA and the IOA is that in the former the expansion is only preoccupied with one demand, whereas in the latter the expansion encompasses all the activities in the whole economy. [United Nations,1999,p8-9]

The information covered by IO compared to LCA is that it is very aggregated, accounting for all the environmental loads form the different sectors, but showing less details than in an LCA. Information is also easier to obtain in IOA as most nations track the economic interdependencies [Miller E.R, Blair D.P, 1985]

3.1.3 Hybrid Analysis

As mentioned earlier, weaknesses exist in LCA as significant inputs and outputs are left out from the study. Weaknesses also exist in IO analyses as the information tends to be aggregated, making it difficult to perform detailed studies. Hybrid analysis maximises the strong points of both, by combining the two methods. The different data is combined in a matrix where the indirect results are covered by the IO data as background information, and the important processes information, is covered by the LCA data. In this way, invalidity caused by the cut-off criteria is avoided. [Suh S, Lenzen M, Treloar G.J, Hondo H, Horvath A, Huppes G, Joliet O, Klann U, Krewitt W, Moriguchi Y, Munksgaard J, Norris G, 2003,p.660]

The hybrid requirement matrix A, consists generally of four of sub-systems.

$$A = \begin{pmatrix} Aff & Afb \\ Abf & Abb \end{pmatrix}$$

Where the Aff matrix describes the foreground processes and the interdependency of these, the Abf describes the inputs of background commodities to the foreground processes. The foreground processes are the processes assessed in detail by the practitioner, whereas background information are the indirect effects from the upstream processes. The Abb matrix describes the interdependencies between the sectors in the background economy. The Afb sub system shows the dependency of the background economy on the foreground processes. In tiered hybrid analysis this is normally assumed to be zero. Explanation of how these sub systems were constructed in the project is presented in section. The boundary between the foreground and background processes are unclear, but generally depends on the information available, accuracy required and time and labour cost. [Heijungs R, Suh S, p.124-129,2002]

3.1.4 Leontief's Price Model

Establishing the sub systems in the inventory of the hybrid LCA, is a time consuming process due to difficulties with collecting data. In some cases data may be difficult or even impossible to obtain and the practitioner is forced to assume that these processes have values of zero. Doing this increases the risk of omitting important data. A method, described as Leontief's price model is used to fill in these holes.

There are three key elements to the approach.

The correspondence between the processes identified in the foreground system and the aggregated sectors in the economy is established. This is defined in a concordance matrix, consisting of zeroes and ones. This means that each process is a subset of a sector in the economy.

Then the average input-output data is extracted in order to identify the average input structure of the value added and emission intensities to the sectors that the processes are allocated to.

The average datasets are adapted, and the unit of the base data set is converted so that the final data established is per unit physical output of the foreground processes.

The lacking data is filled in, proportionally to the distribution that exists in the input-output background information. The method uses the requirement that the column sum and the row sum, of each producer in the flow table are equal, and that the price of each product can be found from the prices of inputs that are used to produce that product. The column of an input output matrix together with the value added accounts for all the expenditures of a producer.

The approach results in three matrixes, a complete coefficient matrix(A), emission matrix(F) and value added matrix (V), these matrixes are then used further in calculations to obtain stressor and impact vectors. The method was implemented by a matlab script developed by Anders Hammer Strømman and Christian Solli. [United Nations,1999] [Strømman Hammer A, Solli C,2006]

3.2 General System Description

In every LCA, important decisions and assumptions need to be made before and during the assessment. This section discusses the goal and scope, functional unit and allocation of the LCA. A general overview over the main foreground systems is also given.

3.2.1 Important Decisions

Goal and Scope

The goal of this LCA is to compare the environmental performance of a second generation biofuel with first generation biofuels, by looking at the global warming effect and acidification potential.

Compared to first generation biofuels, there are few studies done on second generation biofuels. This study contributes to the growth of LCA studies on secondary generation fuels, and will hopefully help to motivate further work in this area.

Functional Unit.

The reason for making biofuels is primarily so that we can use them in vehicles as a substitute to fossil fuels. Most LCA studies done on first generation fuels uses 1 vehicle-km (v-km) as a functional unit and that is also chosen in this study.

Allocation

In a process several by-products usually form in the production of one main product. This is also the case for biofuels. The environmental damages should be distributed to all the products if they in any way substitute other products or services. In the formation of FT-diesel, different fuels are formed in the form of, Naphtha, distillates and wax, according to the distribution shown below.

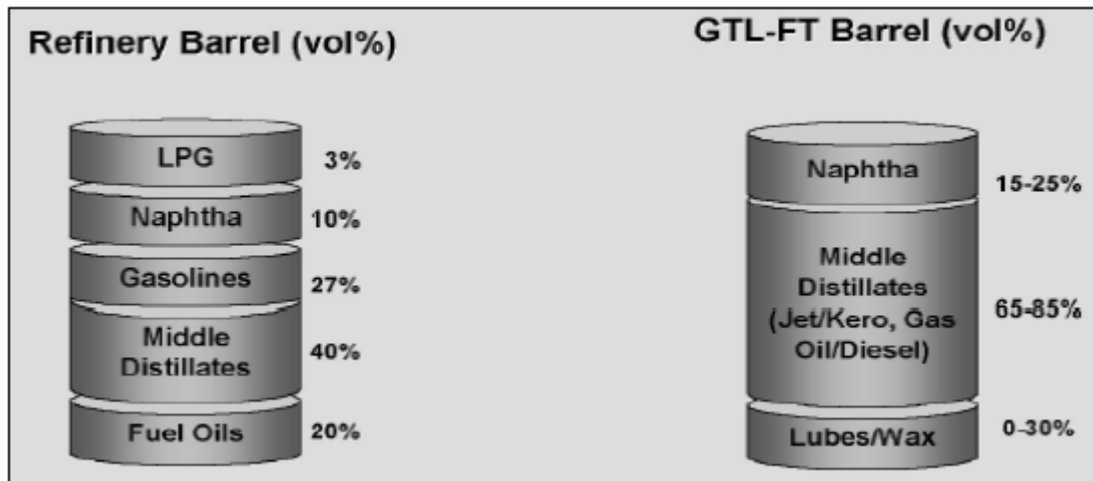


Figure 22: Showing the general distribution of products from an oil refinery and products from FT-synthesis [Kavalo.B et.al, p.33,2005]

The C5-10 fraction is separated from the heavier products, this might have a high market value in the future as it is suitable for FCV vehicles, and as a raw material in green plastics production. This fraction is considered as waste in this study as there doesn't really exist a market for the fuel today. The naphtha (C_{5+}), distillates and wax fractions are recovered in the hydrocarbon recovery plant for further processing. The waxy part is hydrocracked to form a middle distillate. The Naphtha is of the same nature as diesel fuel and is usable in applications where it also displaces petroleum products. In this LCA the differences between all the middle distillates, naphtha, reformed wax and diesel, are considered to be negligible, behaving as the main product of the process. [Hass .H, et al., p.37,2004], [Hamelinck .C.N, et al, p.15 ,2003]

Electricity, however is also produced by the process, this is due to the fact that several of the reactions taking place are exothermic. The steam and off gas is passed through a steam turbine to generate electricity. A part of the produced electricity is used to cover all the electricity needed at the plant, whereas the rest is sold. It is assumed that this electricity would have been produced elsewhere if not for the biofuel production, and a method of allocation is needed. Which method to use is widely disputed amongst LCA practitioners. Allocation by exergy is used in this study.

3.2.2 System Description

In hybrid LCA it is paramount to choose a foreground system comprising of unit processes that are relevant to the goal of the LCA. The processes chosen in the foreground are the most important process, and have more specific data, compared to the processes defined in the background system. The following section includes description of all the foreground processes. Every process is considered first in isolation and the important outputs and inputs into the process are considered, before the relationship between the other processes are established in the A_{ff} sub system, this method is known as the unit process, where for a specified output all the inputs and emissions are registered.

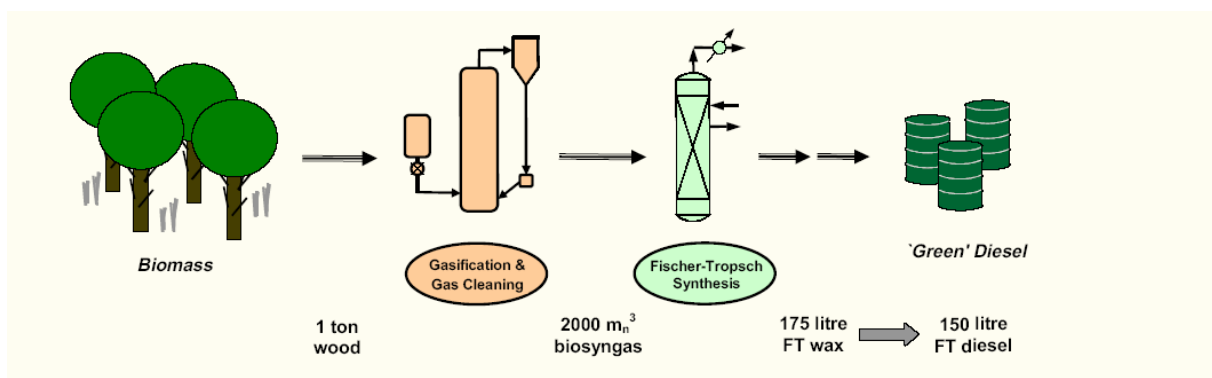


Figure 23: Main processes in the production chain of FT diesel [Boerrigter H.,p.1, 2002]

3.3 System Overview

A description of the foreground processes considered in the study is provided in section 3.3. Production of FT-fuel is briefly mentioned, but a closer description is given in section 3.4.

3.3.2 Biomass Production

Relevant Biomass in Norway

The most important bioenergy resource in Norway is wood from forests, and as much as 38% of Norway is covered with it. It has been calculated that there is enough wood in Norway to be a sustainable source of energy for biofuel production. This is because the yearly growth of forests is 25.4 mill. m³ which is about 3 times higher than what is being used today. [Vessia .O, p.20 ,2005] Further, Bioenergy resources in Norway, suggests that between 15-20 TWh energy from wood can be further used, showing a high potential to substitute fossil fuels. The wood types existing in Norway are mainly Spruce, Pine and Birch .Of these wood types, spruce is the dominating sales product.[Opdal .O.A, p.16, 2006]

Operations associated with biomass production includes, seed production, cultivation of forest seedlings, cut over clearing to facilitate harvesting or regeneration treatment, soil scarification, natural or artificial regeneration, cleaning, logging operations and secondary haulage. Scarification is the act of loosening the top soil or breaking up the forest floor in preparation of natural or artificial regeneration. The secondary haulage is the transport of biomass to plant and is considered in a separate process in this LCA. The logging operations is energy intensive and consumes large amounts of diesel.

3.3.3 Transport

There are two processes of transportation considered in the foreground system. One is the transport of biomass to plant and the other is transport of FT-diesel to a distribution terminal. The transport occurs at land in both cases and the trucks are assumed to use conventional diesel. The amount of times the trucks drive to and from the plant is dependent on the capacity of the trucks, the need of biomass from the plant, the amount produced and the speed of the trucks. The biomass production is assumed to be in a distance of 30 km and the distribution terminal is assumed to be of a distance of 100 km. These are approximately the same distances assumed by production, plant and distribution made by other articles written about biofuel production.[Marano .J.J, Ciferno, 2001], [Opdal .O.A, 2006]

3.3.4 Construction and Demolition of Plant

As pointed out in second part of this report, second generation technology is more expensive and complicated than first generation technologies. Assessing costs and environmental damages associated with the technology used is therefore important. Construction and demolition of the plant is needed to produce FT-diesel. Additional costs and emissions are associated with these phases. It is therefore decided to include construction of plant and demolition of plant in the foreground system.

3.3.5 Use of Fuel

FT diesel derived from biomass, produce diesel with a very high purity compared to oil-derived diesel. There are no sulphur, nitrogen, nickel, vanadium, asphaltenes or aromatics that are typically found in mineral oil products.

The cetane number indicates how quickly the fuel will auto ignite and how evenly it will combust in the engine as well as decreasing the formation of NO_x. FT diesel has a cetane number over 70, and most countries require a minimum cetane number of 40-50. Further FT-diesel is especially well suited to fit in fuel cell vehicles (FCV's), this is an important aspect to consider in the long term when FCV's become more important in the market. [Girard P.,et al.p.38-40,2005][Tijmensen .M.J.A, et al.,p.133-134, 2002]

In this project the use of FT-diesel will be considered, it is an important step to consider as the first generation fuels have different characteristics. The fuel can be used in many different type of blends in the engine, but in this project it is assumed to be used in its pure form. For a diesel engine few or none changes need to be made for FT-diesel. This is not the case for all first generation fuels. Table 4 shows some characteristic differences between FT-diesel and conventional diesel fuels used in USA. Due to its properties FT-diesel is said to combust more efficiently than other biofuels. This is not taken into account in this LCA, as the efficiencies are assumed to be equal so as to allow for direct comparisons between the fuels. This should be kept in mind, however.

Table 5: Properties of Three Diesel Fuels[Greene D.L, p.19,1999]

Parameter	Standard U.S. No. 2 Diesel	California ARB Diesel	“Straight-Run” F-T Diesel
Cetane No.	46	49	60–80
Specific Gravity	.85	.83	.81
C/H weight ratio	6.50	5.95	5.80
Aromatics wt. %	28–32	<10	0.0–1*
Sulfur wt. %	<0.05	<0.05	0.001–0.03*

3.3.7 Production of FT-diesel

In this study FT-diesel was chosen as the secondary generation fuel. This was chosen as it replaces diesel, which is most widely used conventional fuel used in vehicles in Norway today. It is also one of the technologies that show great promise, the technology is proven, the relevant feedstock exists in Norway, and Choren is planning the first mass production of a second generation biofuel in the world. The second generation fuel they are planning to sell in 2007 is the FT-diesel.

3.4 General understanding of Gasification technology

This section gives a more detailed description of gasification and FT-synthesis. Different technological options are presented, before the final technological choices are explained and summarized in section 3.4.6. History background of FT-diesel is also briefly given in section 3.4.5.

An overview over energy distribution of the production of FT-fuel shows that the majority of energy is spent on the gasifier and FT-reactor. [Opdal .O.A,p.58, 2006] The technology is the main aspect that will differ from the first generation technology fuels. The production processes of FT-diesel is therefore clearly an important process.

A general description of the gasification technology and the different products are mentioned in section 2. It can be seen from the description that gasification is a complex process with several routes and technologies existing for the products. In order to perform an LCA it is necessary to look at the processes in more details, decide which steps are the most important and which technology is the most relevant today for the production of FT-diesel. The following section describes the general process steps / routes to FT-diesel derived from biomass. Below is a diagram showing the main general steps and options in FT-fuel production. Five general steps shown in the diagram will be explained in this section, 1 pre-treatment, 2 gasification, 3 Gas Cleaning, 4 Conditioning, 5 Synthesis.

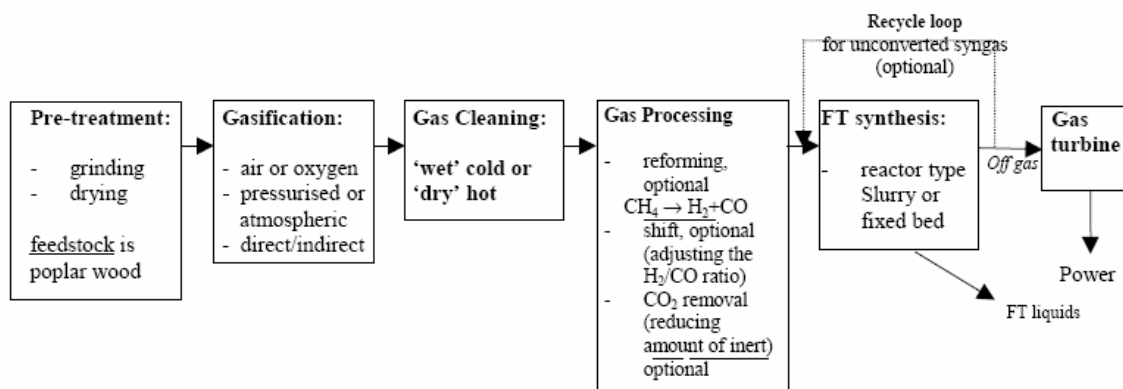


Figure 24: Key components,FT-diesel from biomass.[Tijmensen M.J.A, et al.,p.2,2002]

3.4.1 Pre-treatment

In order to maximize the efficiency of the gasification process it is important to pre-treat the biomass. The following steps can be identified before the pre-treatment and gasification step, Harvesting, sizing, storage, drying, sizing, densification and transportation. The two most important steps though are drying of feed stock and reduction in size. The pre-treatment step depends on the properties of the feedstock and type of reactor used.

The most important characteristics of woody biomass is moisture content, density and volatile material, ash and fixed carbon content in the material. The density of wood can influence the technology used, and the densities may differ considerably between the different forests. Some densities typical for forests in Norway can be seen in the table below. [Vessia .O,p.16 ,2005]

Table 6: Showing different densities of wood in Norway. [Vessia .O, p.18, 2005]

	Density* [kg/m ³]:
Scandinavian Spruce	380
Scandinavian Pine	440
Scandinavian Birch	500

*kg dry wood per solid cubic

Specific moisture content and particle size of the feedstock needs to be fulfilled before the gasification step. Drying demands energy, and it is suggested that this energy can be provided by the FT-process heat. Drying increases the efficiency of the process, however the hydrogen content of the produced gas is reduced, something that is unfavourable with FT-diesel. Drying costs increase quickly with moisture content below 10%, drying to a moisture content to 15% is assumed. As mentioned in section 2, any biomass can be used as feedstock. However in the LCA a specific type of biomass has to be chosen.[Hamelinck .C.N, et.al , p.1746, 2003].

Feedstock for gasification

The only requirement for feedstock possible to be used in a FT-route is that it should contain carbon, and hydrogen will increase the efficiency of the process. However there are some materials that are more advantageous to use than others. Harvest, transportation and pre-treatment are important steps determining the efficiency of the process and these are dependent on the properties of the biomass.

Moisture content is another important parameter, as more moisture means less energy is available (as water evaporate amounts of energy). Typical moisture content of freshly felled wood is usually between 45-58% on a weight basis, and as discussed in the section on pre-treatment, the wood needs to be dried to moisture content between 5-25% before entering the gasification step. The wood drying can be divided into natural or forced drying, where natural drying is the recommended method. In this method however, indoor or outdoor drying is applied, making length of time and climatic conditions determine the rate of drying. Forced drying is often used in integration in gasification plants. [Opdal .O.A, p.17, 2006]

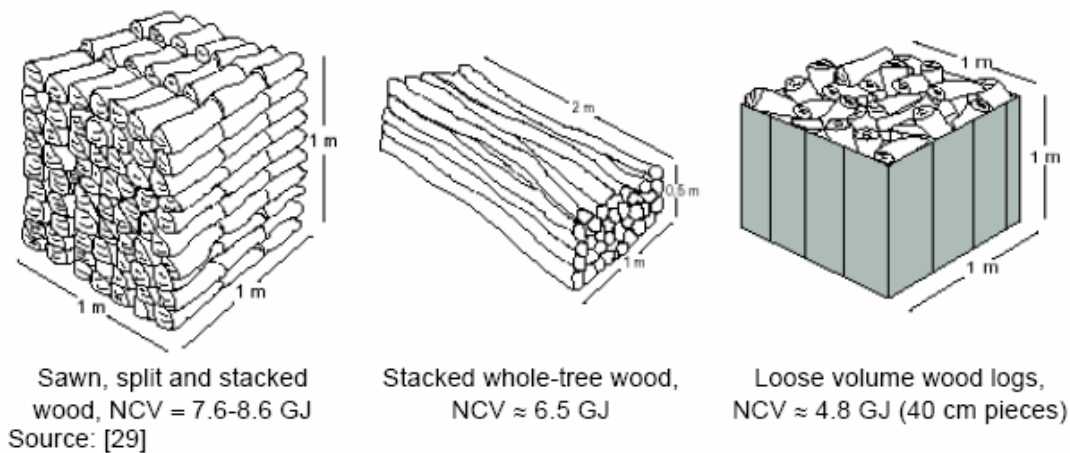


Figure 25: Wood feedstock [Kavallo .B, et al., p.12, 2005]

3.4.2 Gasification Step

Step 2 is the gasification step, this yields a gas containing mainly CO , CO_2 , CH_4 , H_2 , N_2 and water. Gasification is an exothermic reaction that occurs by the partial oxidation of the biomass as a result of adding a sub-stoichiometric amount of oxygen at high temperatures, 900 °C. The gasification agent can either be steam, air, oxygen or hydrogen. Gasification is carried out either by indirect or direct gasification. In the latter, both air-blown and oxygen-blown gasifiers can be used. The heat is produced by internal sub-stoichiometric combustion of part of the biomass fed into the gasifier. In the case of indirect gasification heat is created by burning some of the biomass or the produced gas outside the gasifier. This heat is then fed to the gasifier usually with steam. For synthesis gas generated from biomass, the indirectly heated reactors or directly heated, oxygen blown reactors with partial oxidation is preferred. There exist several different reactors for gasification. They differ in how the reactants and products are moved around in the reactor. The main classification type of reactors include, fluid beds, entrained beds and fixed beds and are shown in the diagram 24 below.

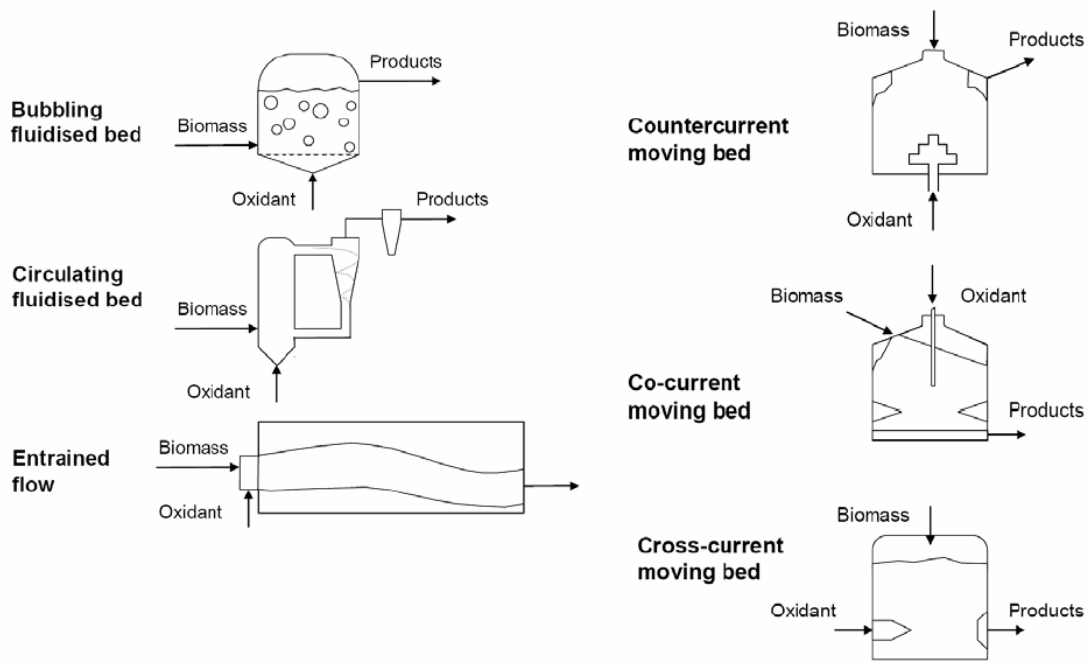


Figure 26: Different types of reactors [Vessia .O, 2005]

The different types of gasifiers displayed in figure 24 above can be classified by gasification agent, heat for gasification (indirect, or direct), pressure in gasifier and design of reactor. Direct gasification with air is often ruled out as the nitrogen dilution increases the downstream equipment size and costs. Oxygen as an oxidative agent is discussed as a good choice for FT diesel production as it provides higher partial pressures for relevant components in FT. Pure oxygen is expensive, but the possibility of using oxygen enriched air is suggested. Circulated fluidised bed (CFB) gasifiers are claimed to be suitable for large-scale syngas production. This is especially decided on the bases of efficiency and costs. [Hamelinck .C.N .et al, p.1746, 2003]

3.4.3 Cleaning

After gasification, the gas contains some elements of impurities that need to be removed. Impurities like char particles, alkali metals, nitrogen compounds, tar and sulphur are removed in a cyclone or ceramic filters. These impurities exist depending on the design of the gasifier and type of biomass used, and it is therefore important to choose a gasifier that suits the end use of the product. The composition of the syngas varies, depending on the raw biomass composition and operating condition.

Depending on the size of the plant, the way of handling problems is different. Biomass tars is a serious problem in biomass gasification systems, as it is responsible for corrosion and soot formation. Tars need to be removed, and is done so by cleaning devices such as fabric filters and scrubbers under dry and hot or wet and cold conditions. The cold gas cleaning methods such as wet scrubbers and cyclones are well known and proven, however attention has been increased on development of hot gas cleaning devices. The synthesis catalyst is sensitive towards impurities and therefore require very strict requirements on the syngas. The diagram below shows typical composition of the syngas after the gasification step.[Girard .P,et al., p.37,2005].

Table 7: Table showing main components and properties of gases obtained via different gasification concepts.[Girard .P, et al., p.37,2005]

Gas composition vol. % dry	Air blown atmospherics CFB	O ₂ Atmospherics CFB	O ₂ pressurized CFB-	Atmospherics H ₂ O	O ₂ Pressurised entrained flow
CO,	19.3	26.9	16.1	42.5	46.1
H ₂ ,	15.6	33.1	18.3	23.1	26.6
CO ₂ ,	15.0	29.9	35.4	12.3	26.9
CH ₄ ,	4.2	7.0	13.5	16.6	0.0
N ₂ ,	44.5	0.7	12.3	0.0	0.4
C ₂ ,	1.4	2.4	4.4	5.5	0.0
NCV, (MJ/m ³)	5.76	8.85	8.44	13.64	7.43
H ₂ /CO ratio	0.81	1.23	1.14	0.54	0.58

Table 7 below, shows the strict purity requirements from the catalyst in the FT-reactor, this is the main reason for why the end product is such a clean fuel.

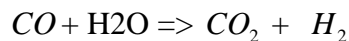
Table 8: Fischer-Tropsch Feedgas specifications [Boerrigter .H, Calis .H.P, Slort .D.J, Bodenstaff .H, Kaandorp .A.J, den Uil .H, Rabou .L.P.L.M, p.19, 2004]

Impurity	Removal level
H ₂ S + COS + CS ₂	< 1 ppmV
NH ₃ + HCN	< 1 ppmV
HCl + HBr + HF	< 10 ppbV
alkaline metals	< 10 ppbV
solids (soot, dust, ash)	essentially completely
organic compounds ^a (tars)	below dew point
- class 2 ^b (hetero atoms)	< 1 ppmV

^a Organic compounds include also BTX. ^b Class 2 tars comprise phenol, pyridine, and thiophene.

3.4.4 Conditioning

After cleaning, the syngas is conditioned. Gas conditioning includes all gas treatment steps needed to adjust the gas composition of the gas to meet the specifications of the gas application. Main issues are adjustments of H_2/CO ratio and removal of CO_2 . During conditioning of the gas hydrocarbons are converted to H_2 and CO . Due to the gas after gasification containing smaller amounts of hydrogen than needed, proportions of the components needs to be shifted. This is done by a water-gas shift reaction (WGS), where water reacts with CO to produce CO_2 and H_2 . This is especially important for FT-diesels as they require a ratio of 2/1 of H_2 an CO respectively.



[Knoef, p.227, 2005]

Chemical or physical absorption is then used to remove the CO_2 .

The CO_2 concentration can be removed, approximately 0.1 vol% by these processes. The choice for chemical or physical absorption depends upon the partial pressures of the gas. The cleaning and conditioning of the syngas is similar to the existing systems for natural gas or coal systems.[Girard.P,et al, p.34,2005]

After the WGS reaction, the synthesis gas is compressed before it is transported to the final synthesis reactor, where the reaction takes form under a catalyst. The type of catalyst depends on the fuel targeted as the final product. After the final synthesis reaction, the gas is collected by distillation.[Van Thuijl .E, et al., p. 27-28 2003]

3.4.5 Fischer-Tropsch Synthesis

FT-history background

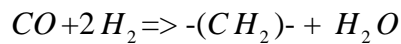
The process of converting hydrogen and carbon monoxide into liquid fuels was invented by Prof. Franz Fischer and Dr. Hans Tropsch in 1923, and in 1932 the first pilot plant was constructed by Prof. Franz Fischer and his co-workers in Mulheim. Due to large coal reserves and lack oil in Germany and the British and American oil embargo, liquid hydrocarbons were produced and used in Germany during WW II.

The oil crisis during the 1970's increased the interest in synfuels in the United States and the European Union, as well. Financial support for R & D increased substantially in the mentioned regions during the crisis, resulting in technological development. In 1993 Shell and Petrol AS opened a Gas-to-liquid (GTL) plant in Malaysia (Bintulu), and in South Africa (Mossel bay).

In Germany research on BTL has continued especially on liquid fuels derived from biomass. Rising oil prices, concern for the environment and need for greater energy security continues to promote R&D on liquid fuels from biomass.
[Opdal .O.A, p.35-36 , 2006]

FT-Reactors

The reactions taking place in the FT reactors produce hydrocarbons of variable chain lengths from the conditioned syngas produced from the gasification process. So the conversion of the syngas is a chain growth reaction of carbon monoxide and hydrogen by means of a catalyst. There are several reactions taking place inside the reactor, however uncertainty exists on exactly what reactions take place and it has been a matter of controversy since the 1930's. The principle of the mechanism of the FT-reaction is the following:



$$\Delta H_{FT_0} = -165 \text{ kJ mol}^{-1}$$

The products made by the FT-synthesis are varied and depends upon the liquid selectivity of the process. Liquid selectivity is determined by 'the chain growth probability', this is in other words the chance that a hydrocarbon chain grows with another CH_2 -group rather than stopping.

The probability of chain growth can be referred to as α , and the relation between the hydrocarbon yield and chain growth probability can be described by the Anderson-Schulz-Flory (ASF) distribution. This model can only be used if α is assumed to be constant. Despite the controversy existing on the product distribution it is agreed in literature to have some sort of exponential function. Usually only a few of the carbon chains are wanted, with the example of diesel, production of longer chains are wanted, and this is achieved at lower temperatures. Typical product distribution can be seen in the diagram below.

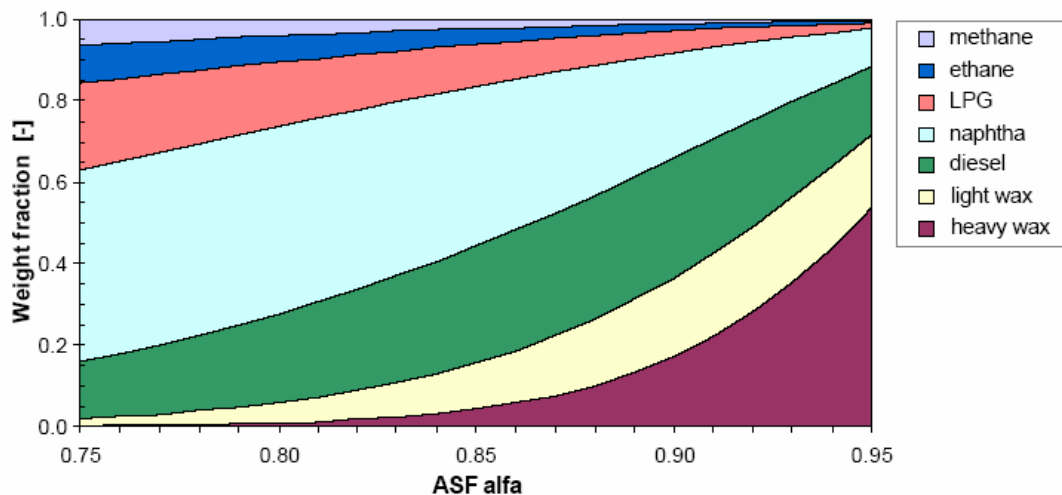


Figure 27: Theoretical Anderson-Schulz-Flory (ASF) product distribution for Fischer-Tropsch synthesis. [Tijmensen M.J.A., et al., p.132, 2002]

Selectivity is dependent on many factors including type of catalyst, operating conditions and reactor. FT- processes can be operated at high temperatures (HTFT) or low temperatures (LTFT). Mostly diesel and waxes are produced at the lower temperatures, and at higher 330 °C mostly gasoline and olefins are produced. Therefore the FT process is normally operated at pressures from 20-40 bar and temperatures between 180-250 °C . A high degree of selectivity, long product chains, are required for FT diesel, this is achieved with high reactant partial pressure as well as low temperatures. It is therefore important to keep the syngas clean, free from contaminants such as nitrogen. The catalyst used for Low temperature processes can either be cobalt or iron based. The reaction is highly exothermic, and there is a need for cooling in order to keep the temperature stable. As can be seen from the diagram above of product distribution, selectivity increases with the probability of chain growth close to 1.

In addition to FT-products, the reactor product stream contains unreacted carbon monoxide and hydrogen. The concentration of these additional compounds depends upon the reactor type and the limitations of conversion in the reactor.[Hamelinck .C.N, et al, p.1749, 2003]

FT-Reactors

There are different reactors existing for FT-synthesis. The three main reactors are the fluidised bed reactor, the fixed bed, and the slurry phase reactor. Among these reactors the fluidised and fixed bed reactors are considered the most relevant for FT-diesel production. The drawback with the slurry phase reactor is the challenges associated with the separation of wax/catalyst. Publicly available information seems to be lacking on this problem. Among the experts there are differing opinions over which of the two reactors are the most advantageous for FT synthesis.[Tijmensen M.J.A, et al., p.133, 2002]

Hydrocracking

Due to high levels of wax being formed by the process, there is often a need to remove this. The wax can be converted into diesel by a hydro cracking step. Here, hydrogen is added to remove double bonds. The carbon efficiency of the hydrocracking step is close to 100%. [Tijmensen .M.J.A, et al., p.133, 2002]

3.4.6 Technological Decisions

The production processes of the FT production is the unit process that has been investigated most carefully of the processes in the foreground system. Several choices on technology and equipment had to be made. The production processes and assumptions follows that of the system described in the article ' Production of FT transportation fuels from biomass; technical options, process analysis and optimisation, and development potential' [Hamelinck .C.N, Faaij .A.P.C, Uil .d.H, Boerrigter .H, 2003]. The article investigates the costs and mass flows of different pressures, reactors, agents and cleaning technologies, by doing simulations in the program Aspen Plus. The simulation results in numerical values of mass flows and equipment costs. See appendix B2 for overview of economics and mass flows of plant. The most important choices and assumptions made were the following.

Table 9: Table summarising important assumption with FT-production

Scale	400	MWth HHV
Feedstock	Spruce	
Pre-treatment	Forced drying from 50-15	
Gasification	CFB	
Agent	Oxygen	99 %
Pressure	25 bars	
Cleaning	Scrubbers and particle filters	
FT reactor	Solid phase	
Conversion efficiency	70 %	
Electricity	Provided by plant	
Allocation	Exergy	
Products	FT diesel and electricity	
Wax treatment	hydrocracking step	
Lifetime	25	years
Annual load	8000	hours

The FT-diesel production is one of the unit processes presented in the foreground system, figure 30 illustrates the different flows to and from the production. Power will not be an input/output in our case, as the production is considered self-sufficient, electricity is something that is produced inside the box.

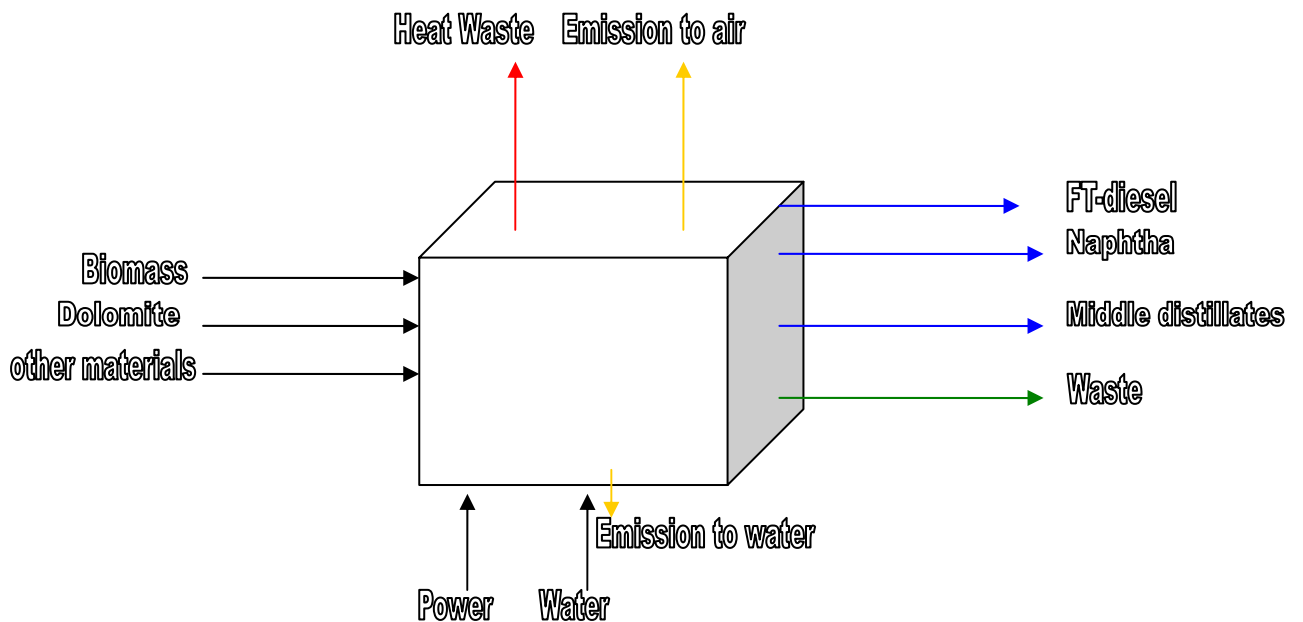


Figure 28: Showing the FT-production as a box with input and output flows.

3.5 INVENTORY

The system description is given in the section before. Explanation of inventory data, of what type of data was used and where it was found will be given in this section.

3.5.1 Biomass Production

Emission values were extracted from the Swedish study assuming that the conditions for biomass production would be approximately the same as in the Norwegian case. The emission values accounts for the sivilculture and logging[Lindholm E.L, 2006]. The emissions resulting from diesel consumption of forwarder was added, by calculating the emission values from consumption of diesel. The amount of diesel consumed by forwarder and in logging operations were found from the article on Norwegian forestry systems, by assuming average load .[Michelsen .O, Solli .C, Strømman .H.A, 2007]

The most energy intensive operations in the forestry system, except secondary haulage, are the operations from harvester and forwarder. To find the cost therefore, the price of the amount of diesel used by the forwarder and harvester was used to estimate the cost associated with manufacture of refined petroleum.

The price was found by using the price of $1 m^3$ of spruce in Norway of 221 NOK/ m^3 . This price was compared to the price of buying wood biomass in Europe 4 Euro/GJ. Value added was estimated by the Leontief principle, described in earlier section 3.1.4. [Kavalo B, et al., 2005]

3.5.2 Construction & Demolition of Plant

It is challenging to find data on emission from construction and demolition of plant, and the emission data are therefore estimated by comparing them to emission in the background system. This is calculated automatically by the script used to assemble the A and F matrixes.

The costs used for all the equipment needed for the production of FT diesel is extracted from Hamelinck et al,'s article. Here, the purchase equipment cost is estimated based on being a certain percentage of the total capital investment costs. This is compared to the costs at a solid fluid processing plant and also lies in the ranges of an ordinary chemical plant [Hamelinck C.A, et al, p.59 ,2003]. Please see appendix B2 for full overview of break down of capital investment costs and overview economics. The purchase of equipment were allocated to the manufacture of machinery and equipment sector, see appendix A1. It is more difficult to find the costs associated with demolition of plant. Some of the equipments are recycled and sold, deciding how much is challenging. Usually demolition is assumed to constitute a certain percentage of the construction in the industry .In this study the percentage is assumed to be 10% of all the construction costs.

The price of construction/demolition of plant was also found from the Hamelinck's article, as the total capital investment cost. This is approximately 286 MEuro. [Hamelinck C.A, et al, 2003]

3.5.3 Transport

The emission values from transportation, occurs by combustion of conventional diesel, based on values from the European standard emissions of heavy duty vehicles. Heavy duty trucks require more diesel than lighter vehicles. With losses the trucks are assumed to drive 2,65 km per liter. [<http://www.dieselnet.com/standards/>, 11/07/07]

The transport price is found by calculating the number of hours and km driven. By knowing the kr/hour and kr/km from a transport company, the price per t transported and per kg transported was calculated. [<http://www.able-transport.com/>, 20/07/07]

The price of diesel was found to be approximately 10,12 kr/l [<http://www.dinside.no/>, 07/06/07]

3.5.4 Production of FT-diesel

The pollutants emitted to air, associated with producing FT-diesel, are mainly CO_2 , NOx, HC and CH_4 . The amount of these are dependent on the purity of the wood feedstock, and the efficiency of conversion processes. The main pollutant associated with the production is CO_2 . The production in our case is carbon neutral, as the electricity is produced by the wood. The emission associated with CH_4 is relatively small compared to the emission from gasification using entrained flow gasifiers, and the CH_4 can be reformed by passing it through a reforming step to produce CO_2 which is then transported to the FT reactor to produce FT-diesel. The CH_4 , is presented in this LCA based on calculations from a table of the composition of the syngas from the gasifier appendix B1, and emissions of HC. The emission values from the Varnamo plant are also used to find emission values of NOx from our plant. It must be understood that values from the Varnamo plant will not be exactly the same in our plant due to differences in scale of plant and technology of the process. However, emission values from a plant operating on the same conditions as specified in this report is difficult to obtain, as there are few plants existing today that produces wood derived FT-diesel. So the emission values from the production are based on the table below with components of contaminants of mass stream exiting the gasifier, assumptions of cleaning technologies, see section 3.4.3 and 3.4.4 for more on this, assumptions of the purity of feedstock see appendix B1, and emission values from the Varnamo plant, appendix B1.

The connection between the foreground and background system was established, by the known amount of cost of dolomite required for the catalyst in the production process. The price of buying 1 t of FT diesel was calculated on the basis of the production cost 16 Euro/GJ, [Hamelinck C.A, et al, 2003].

3.5.5 Use of Fuel

The emission factors associated with use of FT-diesel are based upon the values from actual emission associated with a car running on FT diesel derived from natural gas. Although the sources are different the FT-diesel will end up having the same qualities and there should be no difference in the emission values except for the combustion in the former case being carbon neutral. The emission values found can be seen in appendix A1 and B1.

The diesel consumption is based upon the conventional diesel engine, 0,05 km/litre.

3.5.6 Background System

Whereas the data in the foreground system are mostly based on specific values calculated or found in literature, the relationship between the different sectors in the background system, and the emission values associated with the sectors in the background economy are based upon the I/O table for the entire Norwegian economy. The missing data on the relationship between the foreground and the background economy (the foreground-background system) is estimated from the background economy.

3.6 Impact assessment

The impact category chosen for the second generation biofuel, and method of impact assessment is discussed in section 3.6.

3.6.1 Impact Assessment of FT-diesel

The parameters chosen to be compared, are the green house gas emissions, and their associated global warming impact. The reason for choosing these pollutants are because transportation today is believed to be one of the greatest contributors to global warming, and one of the aims of using biofuels is to decrease this threat. First generation biofuels are generally considered to reduce this threat but only moderately so. Among the existing LCA studies today this is also one of the most investigated aspects, so that there will be studies that can be easily compared.

In order to calculate the global warming impact, a characterisation matrix is calculated, showing the relationship between the actual stressors being emitted and their impact on the environment. The impact on the environment for each stressor is found from the CML2 baseline 2000, extracted from the SimaPro7 program.

Hydro carbons is a pollutant emitted from several sources in the system, but is not registered in the CML 2 baseline. In order to include this pollutant HC was assumed to be approximately the same as CH_4 , this may have resulted in the greenhouse effect in being a little higher than it should due to CH_4 having a high potential, 23 times greater than CO_2 .

Overview over energy distribution shows that the majority of energy is spent on the gasifier and FT-reactor. The amount of energy spent on transport is nearly negligible in comparison. This being said, assumptions made for transport of feedstock and conditioning and distribution can be made without affecting the results significantly, and the wood could be transported over long distances without influencing the efficiency significantly. [Opdal .O.A,p.58, 2006]

4. Results

The following section includes a discussion of results obtained from this study. The final results were calculated by a program developed by Solli C., Strømman H.A and Peters .G, in the LCA lab at NTNU.

4.1 LCA Results For FT-diesel

4.1.1 Discussion of Results

Figure 29, and table 10 shows the distribution of different stressor obtained from the result. CO_2 is the largest pollutant with 35 g / km, NO_x is the second largest pollutant most of it being formed during combustion, and CH_4 is the third largest. This shows clearly that

although the combustion of biomass derived fuel is carbon neutral the life cycle of the diesel is not. Amount of CO_2 is not shown in the figure 29 but in table 10.

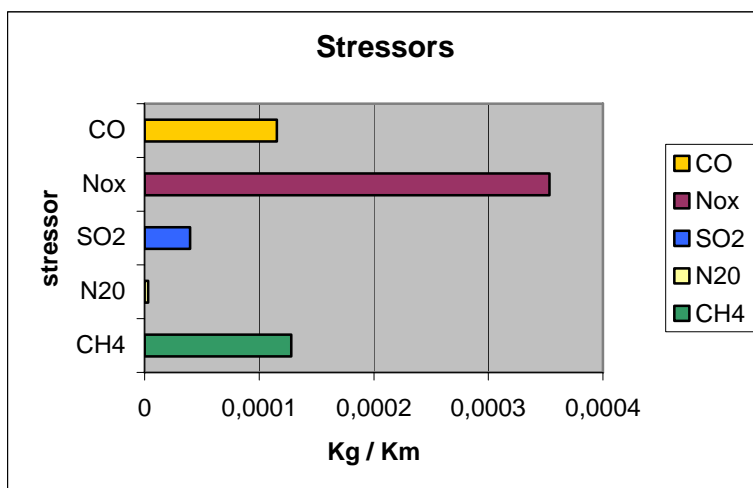


Figure 29: Stressors (except CO_2), for 1 km use of FT diesel

N_2O and SO_2 are mainly emitted from the biomass production process. Although the N_2O values are small compared to the other pollutants, this does not mean that its contribution to global warming is insignificant, having a potential of nearly 300 times that of CO_2 .

Table 10: Table with the values of all the stressors considered in the LCA

Pollutant	GHG emission (CO2kg-eq/km)
CO2	0,034944
CH4	0,000128
N2O	2,95E-06
SO2	3,97E-05
NOx	0,000353
CO	0,000115

The result when calculating Global Warming Impact Potential (GWP) is 39 CO_2 g-eq / km.

This means that for every km driven by a car using FT-diesel, 39 CO_2 g-eq are emitted, taking account of the entire value chain, the emissions associated with transportation, production and use. In order to get a better understanding of what the value means, figure 30 compares this with the global warming potential of conventional diesel. The value of the conventional diesel and the other FT-diesel, are extracted from the WTW analysis done by CONCAWE in 2004.[Hass .H, et al., 2004]

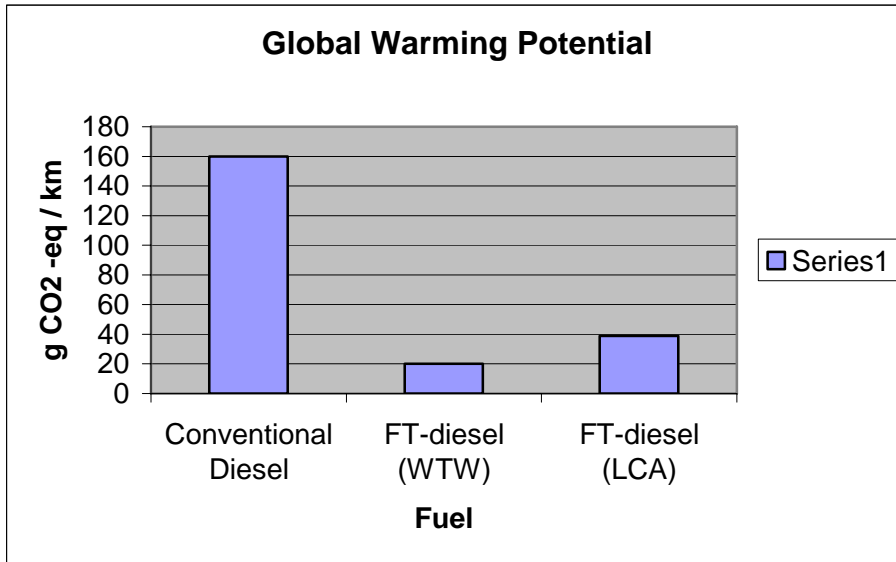


Figure 30: Comparing the Global Warming Potential with conventional diesel and the result from another FT-diesel study.

According to the diagram above, the FT-diesel from this study results in 76% reduction in GWP compared to conventional diesel. There is 19 CO_2 g-eq / km difference between the FT-diesel done by the CONCAWE study and the analysis performed in this report. There are possible reasons to why the results differ. Differences in system boundaries and assumptions are bound to occur and influence the results of the analysis. Despite this the GWP result is in the same ballpark, both are below 40 CO_2 g-eq / km, which is a significant reduction in emissions from that of petroleum - based diesel. Other studies done on wood derived FT-diesel have reached results in similar values. The 'Clear Views on Clean Fuels' (VIEWLS) a major study performed in 2005 at different institutions in Europe, reached the results in ranges of about 18-32 CO_2 g-eq / km for wood derived FT fuels.[Larson .E.D,p.312,2005]

Other Stressors

As can be seen from figure 29, and in the discussion of results above, there are more stressors than those contributing to global warming involved in the production and use of biofuels. SO_2 and NO_x are also included in the study. The impact category they contribute to is acidification potential. This category is not included in the comparison between second and first generation biofuels however. The reason for not doing this is that inconsistencies in LCA first generation studies made it difficult doing so, the results being dependent on fertilization use, climate and region. In order to make the comparison fair, all these conditions should be the same. Please see section 1.3.2 and 1.4 for more information on this. The stressors are still included in the discussion of the results to serve as a reminder of other environmental impacts associated with biofuels. It is also important to be aware of the importance of biomass production in the contribution of emission. In the D_pro table shown in appendix A2, biomass production and forestry/logging operations have a relatively large contribution in both categories.

4.1.2 Uncertainties with System

As well as checking the results by comparing with other studies such as the CONCAWE and VIEWLS study, the system was further investigated by using the structural path analysis program. The program is a powerful tool to check for inconsistencies and errors in the system, that otherwise would have been difficult to discover. The program performs a detailed analysis of the system by breaking it up into different tiers. From these tiers the program chooses the most significant contributors to the impact categories and present them in the table. A figure is also constructed that shows the impact accumulation throughout the different tiers. As well as structural path analysis the program includes, contribution of background and foreground system, stressors, impact, the stressors contribution to impact categories.

There are some other uncertainties with the system that should be discussed. The emission values of the biomass production for example has been remarked to be specifically influenced by region. The article '*Environmental Impact and value added in forestry operations in Norway*' comments that the emission values in the Norwegian case differs from cases in Sweden by as much as 40%. So that the environmental performance of FT-diesel is also dependent on the region where the biomass production takes place. This is important to be aware of when performing an LCA analysis, the biomass production should be carefully assessed.[Michelsen .O, et al.,2007]

The results and discussion of uncertainties show once again that there is no straightforward simple answer in an LCA analysis, but many possible scenarios depending upon data availability and quality, goal and assumptions. The results of the LCA presented in this section, are the outcomes of a scenario with certain sets of assumptions, if the assumptions are changed so will the outcome of the analysis.

Also assuming that the impact of HC is equivalent to that of CH_4 , which was done in this case, might make the resulting impact greater than what would be otherwise expected, CH_4 having an GWP impact 23 times higher than CO_2 .

Another source of uncertainty is the cost data for construction and demolition. The cost analysis that the values were based upon, were estimations done for a system that does not exist. The found in literature, may vary with as much as +/- 30%.

4.1.3 Results of Second and First Generation Biofuels

The first part of the report discusses the environmental effects of first generation biofuels and the previous section presented the results of an LCA done on a second generation biofuel. This section discusses further how the environmental performance between these two types of biofuels differ, by comparing their respective GWP's. The values for the first generation biofuels were taken from the CONCAWE [Hass.H, et al.,2004], VEWLS [VIEWLS, 2005], and results from Elsayed et al.[Elsayed, M.A., Matthews, R., Mortimer N.D, 2003] and the ranges of the results reviewed in the different studies are shown in the figure 31 below. Please see appendix C1 for Larson's summary of these studies.

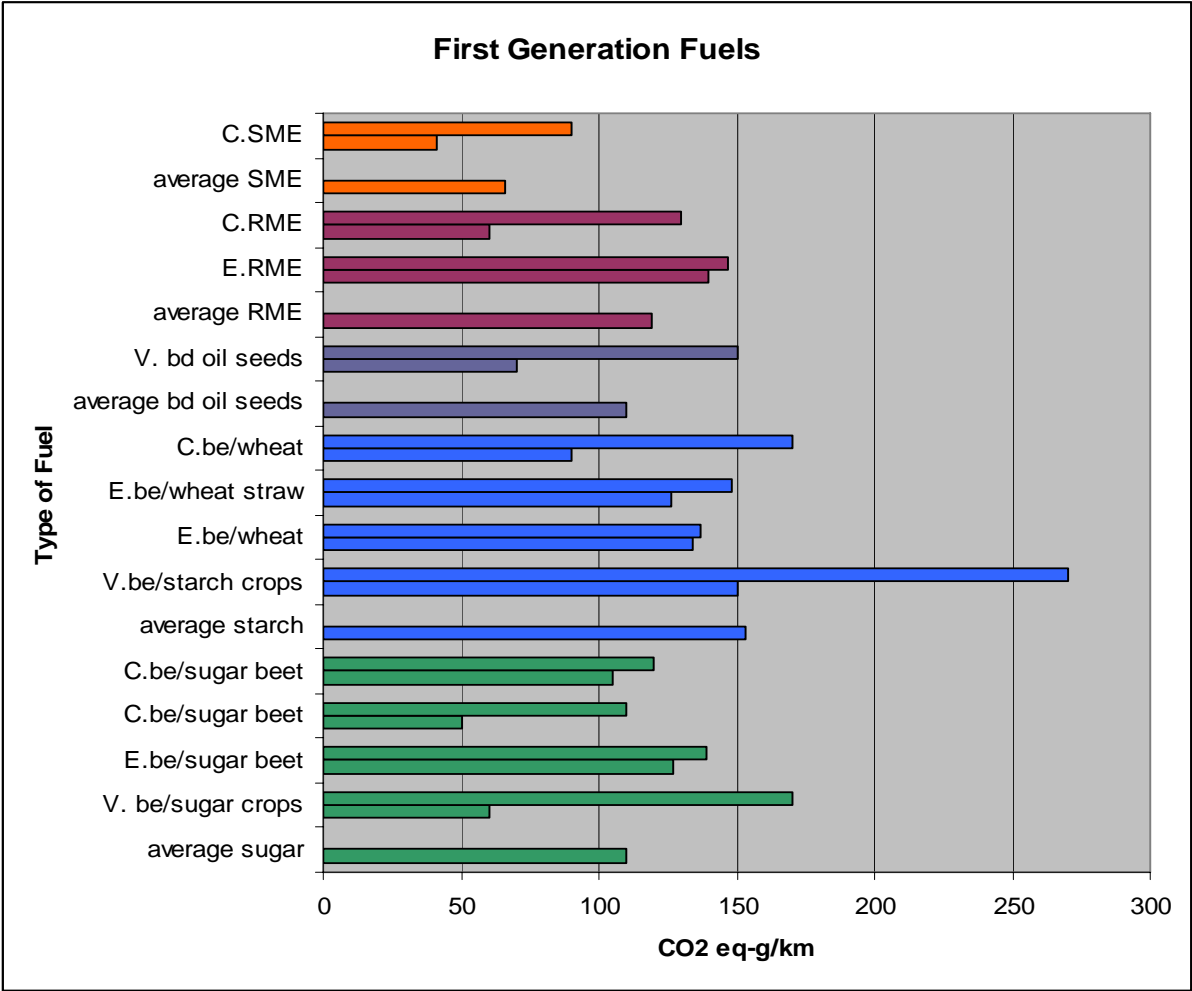


Figure 31: showing the ranges of the results reviewed in the three studies, where V=VIEWLS study, C=CONCAWE, E=Elsayed et al., bd=biodiesel, be=bioethanol.

The figure above shows the ranges of the first generation biofuel results from the three studies chosen to be compared with the second generation fuel. The second generation fuel and conventional diesel are compared with first generation fuels in figure 32 below. Some of the values of the first generation fuels are averages from the studies discussed on the previous page.

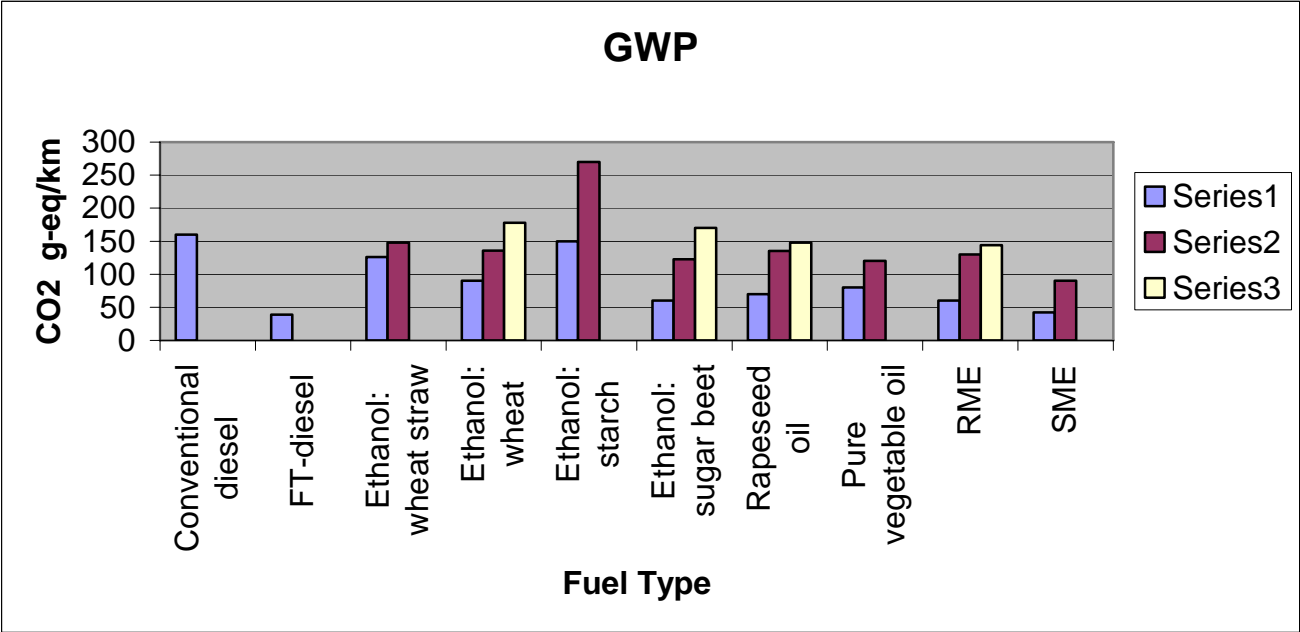


Figure 32 : Diagram comparing the global warming potential per km, of FT-diesel with different first generation fuels.

Figure 32, shows that FT-diesel LCA calculated in this project has a greater reduction of GHG emissions than all the first generation biofuels, having lower emission of CO_2 than the other biofuels presented by the three studies. Ranges are used to show the complexity involved with LCA's of biofuels. EtOH from sugar beet for example, gives three different results from about 55 g-170 g. It is difficult to establish an exact answer of how much benefit FT-diesel offers over the first generation biofuels. Reasons for variations in studies done on biofuels have already been discussed earlier, in part 1 of the report, and will therefore not be discussed any further. In the worst case for the first generation biofuels, the FT diesel shows a 70% benefit in the case of the biodiesel and a 78% benefit compared to bioethanol. Figure 33 below, shows the GWP of FT-diesel and 2nd generation bioethanol compared to average values of 1st generation biodiesel and bioethanol.

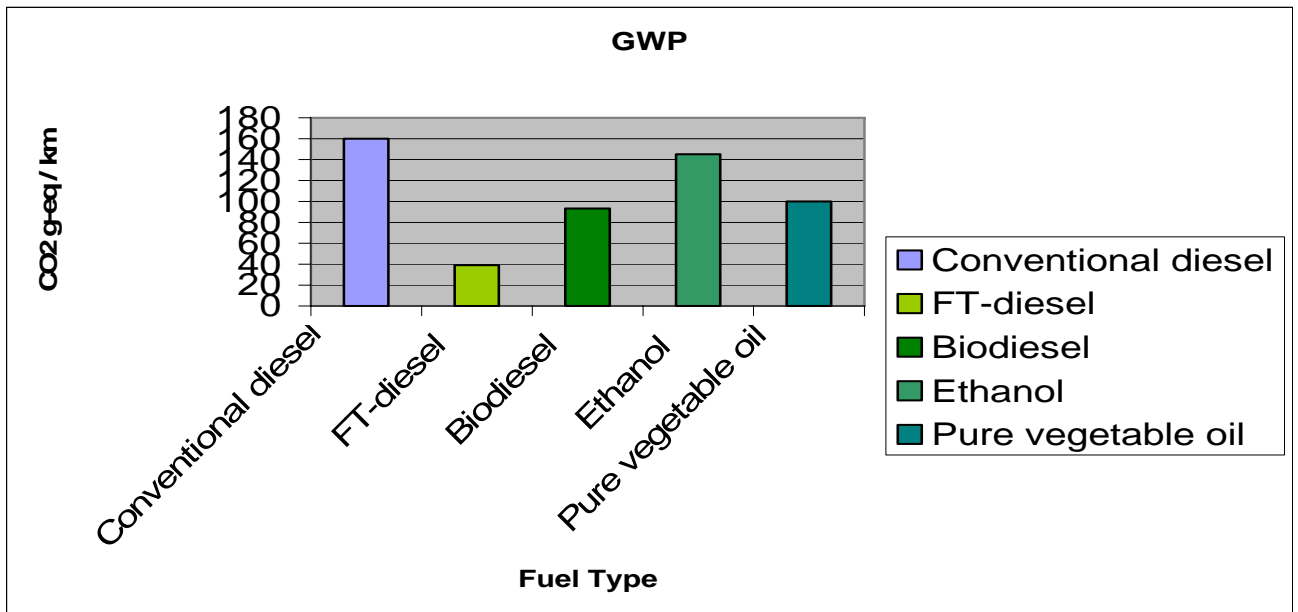


Figure 33: Average values of 1st generation biodiesel and bioethanol.

58 % and 73% reduction compared with average values of conventional biodiesel and bioethanol respectively. Compared to pure vegetable oil it has a 60% improvement, but the values of the latter are only based on one study. These are not exact percentages, being based upon averages, but is presented to give an indication of the relationship between the GWP of the main different types of biofuels. From the figure it is evident that biomass derived FT-diesel has a greater reduction of GWP than the biofuels analysed in the other studies, and a considerable improvement of GWP. Although wood derived FT-diesel shows promising results in the global warming impact, this does not necessarily mean that it has a better overall environmental performance. There are several impact categories that should be used when evaluating the environmental impact of a product or service. In this case only GWP were used as this is the most investigated impact category of conventional biofuels, and is an important impact from the transport sector that needs to be reduced.

4.1.4 Discussion of Other Second Generation Fuels

Part 2 discussed different types of second generation biofuels. Questions might come to mind on how these fuels compare with FT-diesel. Some studies have investigated other second generation fuels and some of their results are presented in the figure 34 below. According to the diagram wood derived DME had the largest GHG reduction. This is because of the higher efficiency of the synthesis process, which gives it an advantage compared to the FT-diesel.[Hass. H, et al.,p.37,2004] As already discussed, R&D in the field of biofuels is increasing and new solutions and technologies are being invented. Which one of the second generation fuels have the best environmental performance, is difficult to establish at this stage, but in the field of GWP they all look promising, giving considerable reductions compared to first generation fuels.

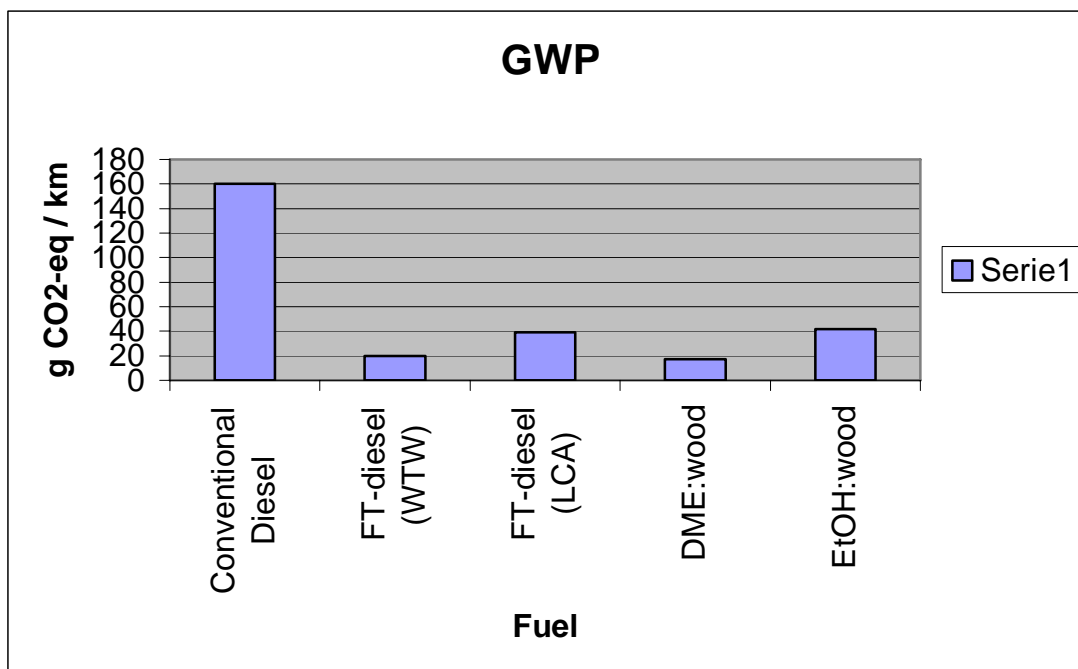


Figure 34: FT-diesel and other second generation fuels

5. Conclusion/Discussion

The result from the LCA done on FT-diesel, showed considerable improvements in greenhouse effect emissions than both conventional diesel and first generation fuels. In the former case it shows an improvement of 76%. The first generation fuels differ in their results but based on averages made from ranges from three different studies wood derived FT-diesel shows an improvement of 50-70% depending on the type of first generation fuel. This does not mean that second generation fuels are the solution to sustainable transportation, as damages in other impacts are being ignored. What is certain however, is that taking global warming and renewability of resources into account, second generation biofuels are a more sustainable solution than both conventional diesel and first technology biofuels. Damages in acidification and eutrophication potential increase compared to conventional diesel in the case of several studies, yet there are few LCA studies that do focus on impact categories other than global warming potential. Similarly the variations on results on photochemical smog, human toxicity potential are too great and the numbers of studies are too few to draw any conclusion on these impact categories. Therefore second generation biofuels may not be the answer to a sustainable solution, but is one step closer than the situation today.

The green house effect emissions and net energy benefits, of first generation and to some extent second generation biofuels has been thoroughly assessed. There is a lack of complete assessments of biofuels, and those that has attempted this show big differences in their results. Human toxicity potential, acidification potential, ecosystem potential, eutrophication, land use are all important environmental categories and more work should be put into establishing more solid results on the biofuels overall environmental performance. Only then can the biofuels sustainability truly be established. Results from this study and from other LCA studies show that second generation biofuels have greater reduction of GWP than other biofuels.

6. References

- Boerrigter .H, Calis .H.P, Slort .D.J, Bodenstaff .H, Kaandorp .A.J, den Uil .H, Rabou .L.P.L.M, Gas Cleaning for Integrated Biomass Gasification (BG) and Fischer-Tropsch (FT) Systems, Experimental demontstration of two BG-FT systems (“Proof-of-Principle”), ECN , 2004
- Baumann H, Tillman A, Hitch Hicker’s Guide to LCA : An orientation in life cycle assessment methodology and application, Studentlitteratur, 2004, Sweden.
- Dohy .M, Poitrait .E, Energy and GhG balances of biofuels and conventional fuels, Convergences and divergences of main studies, study realized for ADEME by Ecobilan, July 2006.
- Dufey .A, Biofuels production, trade and sustainable development: emerging issues, Sustainable Markets Discussion Paper Number 2, iied, November 2006
- EEA Briefing, Biodrivstoff for transport: I skjæringspunktet mellom energi og landbrukssektoren, Det europeiske miljøbyrå, 2004
- Elsayed, M.A., Matthews, R., Mortimer N.D, Carbon and Energy Balances for a Range of Biofuel Options, Resources Research Unit, Sheffield Hallam University, UK, 2003
- Faaji .A, Modern Biomass Conversion Technologies, mitigation and adaption strategies for global change, Copernicus Insitute, Utrecht University, Heidelberglaan2, 3584 CS, Utrecht, The Netherlands, 2005.
- Girard .P, Fallot .A, Dauriac .F, Technology state-of-the-art, Review of existing and emerging technologies for the large scale production of biofuels and identification of promising innovations for developing countries, Forest Department of CIRAD, 2005
- Goudriaan .F, Van de Beld .B, Boerefijn .F.R, Bos .G.M, Naber .J.E, Van der Wal .S, Zeevalkink .J.A, Thermal Efficiency for HTU Process for Biomass Liquefaction, ‘Progress in thermo chemical Biomass Conversion’ Conference, September 2000.
- Goedkoop M, Oele M , SimaPro6-Introduction to LCA with SimaPro, pRe Consultants, April 2005.
- Greene .D.L, An Assessment of Energy and Environmental Issues Related to the Use of Gas-To-Liquid Fuels in Transportation, Oak Ridge National Laboratory, Tennessee, 1999
- Hamelinck .C.N, Faaij .A.P.C, Uil .d.H, Boerrigter .H, Production of FT transportation fuels from biomass; technical options, process analysis and optimisation, and development potential, Utrech University, Copernicus Institute, Technology and Society, Energy research Centre of the Netherlands (ECN), the Netherlands, 2003

Hamelinck .C.N, Van Hooijdonk .G, Faaij .A.P.C, Ethanol from lignocellulosic biomass: techno-economic performance in short-, middle- and long-term, Copernicus Insititute for Sustainable Development and Innovation, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands, 2004.

Hass .H, Larive .J.F, Mahieu .V, “Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context”, CONCAWE, Joint Research Centre of the EU Commission, and European Council for Automotive R&D, Summary Report (version 1b), January, 60 pages, 2004.

Heijungs .R, Suh .S, The Computational Structure of Life Cycle Assessment, Kluwer Academic Publishers, Dordrecht, The Netherlands, 2002.

Hill .J, Nelson .E, Tilman .D, Polasky .S, Tiffany .D, Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels, Proceedings of the National Academy of Sciences of the United States of America (PNAS), 2006.

Kavalo B., Peteves S.D., Status and Perspectives of Biomass –To-Liquid Fuels in the European Union, The European Union Commission, Directorate General, Joint Research Centre, The Netherlands, 2005

Knoef .H.A.M, Handbok Biomass Gasification, GasNet, BTG biomass technology group BV, The Netherlands, 2005.

Larson .E.D, Liquid Biofuel Systems for the Transport Sector: a Background Paper Draft for discussion at the GEF/STAP workshop on Liquid Biofuels 29 August-1 September 2005, New Delhi.

Lindholm E.L, Energy Use in Swedish Forestry Systems and its Environmental Impact, Department of Biometry and Engineering, SLU, Uppsala, 2006.

Mahy .H, Szabo .C, Woods .L, 200 Proof Transportation: The Potential for Ethanol as an Alternative Fuel, University of Washington Global Commercialization of Environmental Technologies, ENVIR 550/BBUS 550, Gretchen Hund/Kevin Lavery, spring 2003

Marano .J.J, Ciferno .J.P, Life –Cycle Greenhouse-Gas Emission Inventory For Fischer-Tropsch Fuels, Energy and Environmental Solutions LLC, 2001

Miller E.R, Blair D.P, INPUT-OUTPUT ANALYSIS: FOUNDATIONS AND EXTENSIONS, University of Pennsylvania, Prentice-Hall, Englewood Cliffs, New Jersey, 1985.

Michelsen.O, Solli .C, Strømman .H.A, Environmental Impact and value added in forestry operations in Norway, Deparment of Industrial Economics and Technology Management, Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, 2007.

Nikolaou .A, Kavadaakis .G, Comparative Life Cycle Assessments of Bioenergy and Fossil energy Systems in Greece, 7th International Conference on Environmental Science and Technology Ermoupolis, Syros island, Greece, Sept.2001.

Nocker .D.L, Spirinckx .C, Torfs .R, Comparison of LCA and external-cost analysis for biodiesel and diesel, VITO, Flemish Institute for Technological Research, Brussels, 1998.

Olofsson .I, Nordin .A, Soderlind .U, Initial Review and Evaluation of Process Technologies and Systems Suitable for Cost-Efficient Medium – Scale Gasification for Biomass to Liquid Fuels, ETPC, Energy Technology & Thermal Process Chemistry, University of Umeå, Sweden, 2005.

Opdal .O.A., Production of synthetic biodiesel via Fischer-Tropsch synthesis, Biomass-To-Liquids in Namdalen, Norwegian University of Science and Technology, NTNU, Norway, 2006

Panorama, Biofuels and their Environmental Performance, Innovation Energy Environment (IFP), 2007

Puppan .D, Environmental Evaluation of Biofuels, *Periodica Polytechnica Ser. Soc. Man. Sci* Vol.10, No. 1, 2001, Hungary.

Quirin .M, Gartner .S.O, Pehnt .M, Reinhardt A.G, CO2 Mitigation through Biofuels in the Transport Sector, Status and Perspectives, supported by FVV, Frankfurt and UFOP, Heidelberg Germany, August 2004

Reijnders .L, Conditions for the sustainability of biomass based fuel use, IBED/ECDO, University of Amsterdam, Nieuwe Achtergracht 166, 1018 WV Amsterdam, The Netherlands, Energy Policy Vol.34, Issue 7, The Netherlands, May 2006.

Reijnders .L, Huijbregts J.A.M., Choices in Calculating life cycle emissions of carbon containing gases associated with forest derived biofuels, IBED/ECDO, University of Amsterdam, Nieuwe Achtergracht 166, 1018 WV Amsterdam, The Netherlands, Journal of Cleaner Production 11, 527-532, The Netherlands 2002.

Strømman Hammer A, Solli C, Applying Leontief's Price Modell to adapt IO data in LCI under imperfect information, Norwegian University of Science & Technology, Industrial Ecology Program, Department of Energy and Process Engineering, Høyskoleringen 5, 7491, Trondheim, Norway, 2006

Strømman Hammer .A, Hertwich .G.E, Hybrid Life Cycle Assessment of Large Scale Hydrogen Production Facilities, Norwegian University of Science and Technology, Department of Energy and Process Engineering, Programme for Industrial Ecology, Høyskoleringen 5, 7491 Trondheim, Norway, 2004

Suh S, Lenzen M, Treloar G.J, Hondo H, Horvath A, Huppes G, Jolliet O, Klann U, Krewitt W, Moriguchi Y, Munksgaard J, Norris G, System Boundary Selection in Life-Cycle

Inventories Using Hybrid Approaches, Vol.38, No. 3. 2004/environmental science & technology, published on web 12/18/2003.

Tijmensen M.J.A, Faaij A.P.C, Hamelinck C.A, Van Hardeveld M.R.M, *Exploration of the possibilities of producing Fischer Tropsch liquids and power via biomass gasification*, Department of Science, Technology and Society, Utrecht University, Shell, Global Solutions, International BV, Pergamon, The Netherlands, 2002

United Nations, *Studies in Methods, Handbook of National Accounting, Handbook of Input-Output table compilation and analysis*, New York, 1999

Van Thuijl .E, Roos .C.J, Beurskens .L.W.M, *An Overview of Biofuel Technologies, Markets and Policies in Europe*, ECN-C—03-008, January 2003

Vessia Ø., *Biofuels from lignocellulosic material- in the Norwegian context 2010-Technology, Potential and Costs*, Norwegian University of Science and Technology (NTNU), 2005.

VIEWLS(Clear Views on Clean Fuels), *Environmental and Economic Performance of Biofuels Volume I*, Main Report, SenterNovem, Utrecht, The Netherlands, 2005

Von Blottnitz .H, Curran .M.A, A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective, *Journal of Cleaner Production*, Vol.15, No.7, 2007

Internet:

Able Transport,
<http://www.able-transport.com/>, 08/06/07

Apeldoorn:
http://gave.novem.nl/novem_new/index.asp?id=27&newdetail=53, 04/05/07

Boerrigter .H, Uil D.H, *Green Diesel from Biomass first demonstration of integrated biomass gasification*, cleaning and Fischer Tropsch Synthesis,
<http://www.ecn.nl/> , 01/07/07

Choren:
http://www.choren.com/en/choren/information_press/press_releases/?nid=149 27/04/07

http://www.choren.com/en/biomass_to_energy/advantages_of_carbo-v/ , 02/05/07

Chemreck:
<http://www.chemrec.se.forsta/htm>, 03/05/07

Composition of spruce,
<http://www.ecn.nl/phyllis/DataTable.asp>, 04/06/07

Dieselnet,
<http://www.dieselnet.com/standards/eu>, 07/06/07

<http://www.uneptie.org/pc/sustain/lcinitiative/background.htm>, 24/07/07

Environment Canada,
http://journeytoforever.org/biofuel_library/WoodEthanolReport.html, 15/07/07

Eu-China workshop on liquid biofuels, European Commission,
http://ec.europa.eu/research/energy/pdf/35_peter_jansen_en.pdf , 16.07.07

IFP,
<http://www.ifp.fr/IFP/en/events/panorama/>, 19/07/07

ISAA Brief 35-2006: Executive Summary
<http://www.isaaa.org/resources/publications/briefs/35/executivesummary/default.html>, 19/04/07

NREL:
http://www.nrel.gov/biomass/biochemical_conversion.html, 30/04/07

Price of diesel,
<http://www.dinside.no/php/art.php?id=212599>, 07/06/07

Senternovem:

http://gave.novem.nl/novem_new/index.asp?id=27&newdetail=53, 04/05/07

shell-biofuels

<http://www.shell.com>, 19/04/07

United Nations Environment Program,

<http://www.unep.org>, 20/04/07

http://www.unep.org/stapgef/documents/Wshop_docs/liquid_biofuels_2005/Back%20Ground%20Papers/BackGround%20Paper%201St.pdf , 20/04/07

<http://www.uneptie.org/pc/sustain/lcinitiative/background.htm>, 24/07/07

Zero Emission Resource Organisation,

<http://www.Zero.no> , 18/04/07

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A1 Matrixes

Matrixes: A_ff, A_qf_s

	Use FT fuel (km)	Transport 1.kg to tern	FT-prod(t_out)	Construction	Demolition	Transport 1 t to p	Biomass prod (t_out)
Use FT fuel (km)	0	0	0	0	0	0	0
Transport 1.kg to term	0,041	0	0	0	0	0	0
FT-prod (t_out)	0	0,001	0	0	0	0	0
Construction	0	0	5,72141E-07	0	0	0	0
Demolition	0	0	5,72E-07	0	0	0	0
Transport 1 tonne to pl	0	0	10	0	0	0	0
Biomass prod (t_out)	0	0	0	0	0	1	0
01	0	0	0	0	0	0	0
02	0	0	0	0	0	0	0
05	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0
232	0	0,16	0	0	0	50	50
24	0	0	1287	0	0	0	0
25	0	0	0	0	0	0	0
261	0	0	0	0	0	0	0
269	0	0	0	0	0	0	0
271	0	0	0	0	0	0	0
274	0	0	0	0	0	0	0
275	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0
29	0	0	0	560164271	0	0	0
30	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0
34	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0
37	0	0	0	0	0	0	0
401	0	0	0	0	0	0	0
403	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0
45	0	0	0	0	56016427	0	0
50-52	0	0	0	0	0	0	0
55	0	0	0	0	0	0	0
601	0	0	0	0	0	0	0
602	0	0	0	0	0	0	0
603	0	0	0	0	0	0	0
611	0	0	0	0	0	0	0
619	0	0	0	0	0	0	0
62	0	0	0	0	0	0	0
63	0	0	0	0	0	0	0
64	0	0	0	0	0	0	0
65-67	0	0	0	0	0	0	0
70-74	0	0	0	0	0	0	0
75	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0
85	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0
91	0	0	0	0	0	0	0
92	0	0	0	0	0	0	0
93	0	0	0	0	0	0	0

A_ff: relationship between the different foreground processes

A_qf_s: relationship between the foreground processes and the sectors, the zeroes are estimated by the background data.

Stressors	use FT diesel (kg/km)	T Transp plant (kg/kg_transp)	FT prod.(kg/t)	Constr	Demol	Transport plant (kg/t)	Biomass prod. (kg/t_prod)
CO2				0	0	0	0,017
CH4	0,00004	8E-06	0,0007	0	0	0,0004	0,019
N2O				0	0		0,002
SO2				0	0		0,001
Nox	3,8E-05	2E-05	0,04	0	0	0,0012	0,437
CO		4E-05		0	0	0,0018	0,103

F_qf_s: the emission inventory for the foreground processes, the values for construction and demolition are estimated from average data in the background economy. The empty spaces are zero.

V_fk_s 0 0,06 0 672197125 67219712,5 21 0

V_fk_s: Value added for foreground processes, value added for transportation, and for construction/demolition are known, the rest are estimated from the background data.

A2 Results

Impacts:

GWP	kg CO2- eq.	Absolute	Relative
CO2		0,034944	0,897419
CH4		0,002946	0,075648
N2O		0,000872	0,022399
CO		0,000177	0,004534

Acidification	kg SO2- eq.	Absolute	Relative
Nox		0,000177	0,787714
SO2		4,76E-05	0,212286

Value Added	NOK	Absolute	Relative
Value added		0,62771	1

Total Impacts:

GWP	kg CO2-eq.	0,038938
Acidification	kg SO2-eq.	0,000224
Value Added NOK		0,62771

Stressors:

CO2	kg	0,034944
CH4	kg	0,000128
N2O	kg	2,95E-06
SO2	kg	3,97E-05
Nox	kg	0,000353
CO	kg	0,000115
Value added NOK		0,62771

D_pro: contribution from each process/sector

GWP	kg CO2-eq.	Absolute	Relative
Forestry, logging and related service activities		0,019301812	0,495707
Wholesale and retail trade; repair of motor vehicles, motorcycles and personal and household goods		0,007160024	0,183883
Post and telecommunications		0,002117209	0,054374
Manufacture of fabricated metal products, except machinery and equipment		0,001526077	0,039193
Manufacture of chemicals and chemical products		0,001495655	0,038411
Manufacture of machinery and equipment n.e.c.		0,000989312	0,025407
Supporting and auxiliary transport activities; activities of travel agencies		0,000973221	0,024994
Manufacture of refined petroleum products		0,000956606	0,024567
Use of FT diesel		0,00092	0,023627
Manufacture of other non-metallic mineral products		0,000476343	0,012233
Biomass production		0,000454957	0,011684
Other mining and quarrying		0,000441855	0,011348
Extraction of crude petroleum and natural gas; service activities incidental to oil and gas extraction excluding surveying		0,000385379	0,009897
Financial intermediation		0,000316168	0,00812
Fishing, operation of fish hatcheries and fish farms; service activities incidental to fishing		0,000271542	0,006974
Manufacture of food products and beverages		0,000243921	0,006264
Inland water transport		0,000138187	0,003549
Mining of coal and lignite; extraction of peat		0,000134658	0,003458
Real estate, renting and business activities		0,000118714	0,003049
Other service activities		5,53977E-05	0,001423
Construction of Plant		5,13526E-05	0,001319
Manufacture of glass and glass products		4,68261E-05	0,001203
Manufacture of basic precious and non-ferrous metals		4,56892E-05	0,001173
Casting of metals		3,99868E-05	0,001027

Acidification	kg SO2-eq.	Absolute	Relative
		9,02604E-05	0,4024
Biomass production		-05	11
Wholesale and retail trade; repair of motor vehicles, motorcycles and personal and household goods		3,37247E-05	0,1503
		2,49199E-05	0,1111
Post and telecommunications		-05	01
		0,000018	0,0835
Use of FT diesel		75	94
		1,62863E-05	0,0726
Forestry, logging and related service activities		-05	1
		1,51277E-05	0,0674
Supporting and auxiliary transport activities; activities of travel agencies		-05	44
		6,05285E-06	0,0269
Manufacture of fabricated metal products, except machinery and equipment		-06	86
		5,93141E-06	0,0264
Manufacture of chemicals and chemical products		-06	44
Extraction of crude petroleum and natural gas; service activities incidental to oil and gas extraction excluding surveying		2,65998E-06	0,0118
		-06	59
		1,32532E-06	0,0059
Manufacture of machinery and equipment n.e.c.		-06	09
		1,2869E-06	0,0057
Manufacture of refined petroleum products		06	37
Fishing, operation of fish hatcheries and fish farms; service activities incidental to fishing		1,25427E-06	0,0055
		-06	92
		9,23762E-07	0,0041
Manufacture of other non-metallic mineral products		-07	18
		0,000000	0,0036
FT-produced		82	56
		6,69745E-07	0,0029
Manufacture of food products and beverages		-07	86
		6,66394E-07	0,0029
Other mining and quarrying		-07	71
		5,80708E-07	0,0025
Financial intermediation		-07	89
		5,24666E-07	0,0023
Real estate, renting and business activities		-07	39
		0,000000	0,0021
kg FT diesel delivered at terminal		492	94
		4,8599E-07	0,0021
Inland water transport		07	67
			0,0010
Transport to plant		2,46E-07	97

D_str: Absolute and relative contribution from each stressor

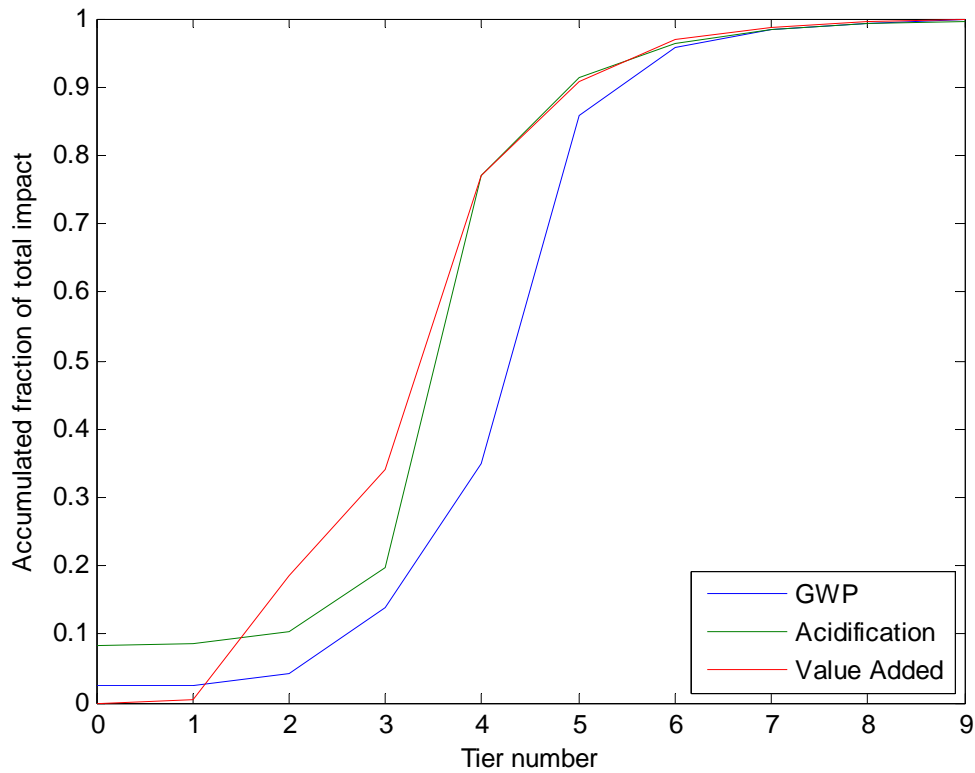
GWP	kg CO2-eq.	Absolute	Relative
CO2		0,034944	0,897419
CH4		0,002946	0,075648
N2O		0,000872	0,022399
CO		0,000177	0,004534

	kg SO2-	Absolute	Relative
Acidification eq.			
Nox		0,000177	0,787714
SO2		4,76E-05	0,212286

D_cat: The contribution of foreground/background system to each stressor

		Foreground system	Background economy
GWP	kg CO2-eq.	0,001447223	0,037490742
Acidification	kg SO2-eq.	0,000110754	0,000113545
Value Added	NOK	0,330179099	0,297530901

Accumulated Fraction of total impact:



B1 Inventory

The tables considered in B1 and B2 are numerical data and information being considered in the of the matrixes shown in A1.

Table showing emission in the 1996-97 forestry sytem, estimated emission per cubic metre of roundwood.

Substance	Silviculture & logging	Secondary haulage
Carbon monoxide (CO) g/m ³ s.u.b.	23.1	6.33
Hydrocarbons (HC) g/m ³ s.u.b.	5.14	3.10
Methane (CH ₄) g/ m ³ s.u.b.	0.476	0.534
Dinitrogen oxide (N ₂ O) g/ m ³ s.u.b.	0.566	0.313
Nitrogen oxides (NO _x) g/ m ³ s.u.b.	71.9	50.5
Particles g/ m ³ s.u.b.	0.420	0.971
Sulphur oxides (e.g. SO ₂) g/ m ³ s.u.b.	0.475	0.015
Carbon dioxide (CO ₂) kg/ m ³ s.u.b.	5.86	6.66

Table showing the pulpwood price of different types of woods

Standing productive forest:	[1000 m ³]:	Pulpwood price [NOK/m ³]
Spruce (softwood)	661 532	221
Pine	210 651	160
Broad-leaved	144 790	221

showing estimated diesel consumption in worst and best case scenarios

		Best	Average	Worst
Harvester	Average size of log (m ³)	0.50	0.24	0.1
	Diesel consumption (l/m ³)	0.50	0.83	1.48
Forwarder	Average distance to forest road (m)	50	740	3000
	Diesel consumption (l/m ³)	0.44	1.03	2.97
Truck	Distance to factory (km)	12	120	301
	Loading factor (%)	50	55	60
	Diesel consumption (l/m ³)	0.42	2.73	6.56
Total	Diesel consumption (l/m ³)	1.36	4.59	11.01

Different properties of different feedstock

	Bituminous Coal	Natural gas	Wood ⁹	Bark	Willow	Forest residues ¹⁰	Wood chips	Wood pellets	Cereal straw	Dedicated energy crops
Ash, d%	8.5-10.9	0	0.4-0.5	3.5-8	1.1-4.0	1-3	0.8-1.4	0.4-1.5	3-10	6.2-7.5
Moisture, w%	5-10	0	5-60	45-65	50-60	50-60	20-50	7-12	14-25	15-20
NCV, MJ/kg	26-28.3	48	18.5-20	18.0-23	18.4-19.2	18.5-20	19.2-19.4	16.2-19	16.5-17.4	17.1-17.5
Density, kg/m ³	1100-1500	n.a. ¹¹	390-640	320	120 ¹²	n.a. ¹³	250-350, 320-450 ¹⁴	500-780	100-170 ¹⁵	200 ⁹
Volatile matter, w%	25-40	100	>70	69.6-77.2	>70	>70	76-86	>70	70-81	>70
Ash melting point, T°C	1100-1400	-	1400-1700	1300-1700	n.a.	n.a. ¹⁶	1000-1400	>1120	700-1000	700-1200
C, d%	76-87	75	48-52	48-52	47-51	48-52	47-52	48-52	45-48	45.5-46.1
H, d%	3.5-5	24	6.2-6.4	4.6-6.8	5.8-6.7	6.0-6.2	6.1-6.3	6.0-6.4	5.0-6.0	5.7-5.8
N, d%	0.8-1.5	0.9	0.1-0.5	0.3-0.8	0.2-0.8	0.3-0.5	<0.3	0.27-0.9	0.4-0.6	0.50-1.0
O, d%	2.8-11.3	0.9	38-42	24.3-42.4	40-46	40-44	38-45	≈40	36-48	41-44
S, d%	0.5-3.1	0	<0.05	<0.05	0.02-0.10	<0.05	<0.05	0.04-0.08	0.05-0.2	0.08-0.13
Cl, d%	<0.1	-	0.01-0.03	0.01-0.03	0.02-0.05	0.01-0.04	0.02	0.02-0.04	0.14-0.97	0.09
K, d%	0.003	-	0.02-0.05	0.1-0.4	0.2-0.5	0.1-0.4	≈0.02	n.a.	0.69-1.3	0.3-0.5
Ca, d%	4-12	-	0.1-1.5	0.02-0.08	0.2-0.7	0.2-0.9	≈0.04	n.a.	0.1-0.6	9

Sources: Adapted from [29, 30, 42, 59, 120, 131, 148, 170, 200, 201, 209, 218, 249, 266, 272, 273, 304]

Characteristic of feedstock

Proximate analysis (wt. %)			Ultimate analysis (wt. %)			
	dry	daf ar		dry	daf ar	
Ash	-	-	C	50.1	-	Unk
Water			H	6	-	Unk
Volatiles	-	-	O	43.9	-	Cal
			N	-	-	ND
Calorific value (kJ/kg)			S	-	-	ND
	dry	daf ar	Cl	-	-	ND
HHV	20469	-	F	-	-	ND
LHV	19160	-	Br	-	-	ND
HHV _{Milne}	-	0	Total:	100	0	0

ID-number 161

Emissions from Varnamo plant:

NO_x	50 – 150 ppm_v (N_{fuel} 0.06 – 0.30 %)
SO_x	5 – 15 ppm_v
CO	50 – 200 ppm_v
HC	0 – 4 ppm_v
Dust	~ 5 mg / nm³, dry gas

Emission of use of FT-diesel in engine

Table 3.5
Exhaust emissions from the WVU 5-mile cycle in g/mile (Truck 2016)

	HC	CO	NOx	PM	CO ₂	mpg*	BTU/mile
California #2 Diesel	0.89	4.26	12.8	0.59	1755	5.67	22541
FT Diesel for heavy vehicle (Norton, 1998)	0.50	3.21	11.2	0.48	1634	5.63	21947
FT Diesel for light vehicle (Wang, 1999)	0.05	2.76	0.06	0.03	268	36	3118

* miles per liquid gallon (not corrected for energy content)

Table of composition of the syngas from the gasifier

Oxidative medium ¹⁾ pressure (bar)	Air			Enriched air			Oxygen		
	1.3	6	25	1.3	6	25	1.3	6	25
In (kg/s)									
Biomass ²⁾	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5
Oxidative medium ³⁾	32.5	30.2	28.0	8.50	7.76	7.09	6.79	6.21	5.67
Steam ^{4, 5)}	0	0	0	14.7	13.1	11.6	11.0	9.68	8.49
Out ⁶⁾ (kg/s)									
H ₂	0.661	0.559	0.462	0.808	0.663	0.533	0.791	0.648	0.520
CO	10.7	9.67	8.62	5.84	5.16	4.51	6.74	5.98	5.25
CO ₂	13.3	13.6	14.0	19.5	19.1	18.9	18.3	18.0	17.9
H ₂ O	5.32	5.12	4.88	17.5	15.9	14.5	13.9	12.7	11.5
CH ₄	1.76	2.28	2.78	2.32	2.90	3.42	2.34	2.91	3.44
C ₂ H ₄	0.328	0.310	0.29	0.315	0.293	0.272	0.279	0.260	0.242
C ₆ H ₆	0.365	0.346	0.33	0.351	0.326	0.303	0.311	0.289	0.270
N ₂	25.3	23.5	21.8	1.77	1.64	1.51	0.271	0.268	0.266
Tar ⁷⁾	0.338	0.338	0.338	0.338	0.338	0.338	0.338	0.338	0.338
Ash	0.428	0.428	0.428	0.428	0.428	0.428	0.428	0.428	0.428
C	0.551	0.551	0.551	0.551	0.551	0.551	0.551	0.551	0.551
Total (kg/s)	59.0	56.7	54.5	49.7	47.4	45.2	44.3	42.4	40.6

¹⁾ Air at 450 °C, Enriched air (80 % O₂) at 200 °C, oxygen (99.5 % O₂) at 200 °C.

²⁾ Feedstock is willow wood: moisture 15 wt %, ash 1.9 wt % d.b., C 49.9 wt % d.a.f., H 6.11 wt % d.a.f., O 42.9 wt % d.a.f. N 0.62 wt % d.a.f. HHV = 19.88 MJ/kg d.a.f. (Phyllis).

³⁾ It is assumed that carbon conversion is 95 % and heat loss is 2 % of the thermal input. The amount of medium is adjusted such that the desired temperature is reached.

⁴⁾ Steam at 450 °C.

⁵⁾ Steam replaces the heat capacity of nitrogen.

⁶⁾ The water-gas shift reaction is assumed to be at equilibrium. Tar yield from gasification is assumed to be 1.5 wt % of the dry feed. Ethane and benzene concentration in the product gas are assumed to be 0.5 and 0.2 vol % respectively. The methane yield is assumed to be in pseudo-equilibrium (Liinanki et al. 1985):

$$K \cdot \log \left(\frac{p_{H_2}^{1/3}}{p_{CH_4}} \right) = 3.0 \times 10^4 \exp \left(\frac{-1.17 \times 10^4}{T} \right)$$

⁷⁾ Tar is defined as C₁₄H₁₀, represented in Aspen Plus by phenanthrene.

B2 Overall Balance

Overall balance

	dry tonne/hour	7/4	7/4	7/4	7/4	7/4	7/4	7/4	7/4	7/4	7/4	7/4	7/4	7/4	7/4	7/4	7/4	7/4	7/4
Biomass input	MMWh HHV	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
Fuel output	kg/yr light	1087.8	1204.8	1289.1	1222.9	1281.5	1299.7	1292.9	1282.8	1204.8	1289.9	1222.8	1281.3	1299.3	1282.9				
	kg/yr HHV	48051.0	48111.2	48120.0	48112.3	48120.3	48113.3	48120.5	48058.8	48111.2	48120.0	48112.2	48120.2	48113.2	48120.5				
	kg/yr3	814.8	822.3	823.4	822.4	823.4	822.5	823.4	815.4	822.3	823.4	822.4	823.4	822.5	823.4				
	kg/yr heavy	8517.8	8344.1	8660.2	8452.5	8739.1	8551.2	8812.4	9151.7	8344.1	8660.2	8452.5	8739.1	8551.2	8812.4				
	kg/yr HHV	47508.0	47508.0	47508.0	47508.0	47508.0	47508.0	47508.0	47508.0	47508.0	47508.0	47508.0	47508.0	47508.0	47508.0				
	kg/yr3	87	87	87	87	87	87	87	89	87	87	87	87	87	87				
	MMWhHV	128.9	128.2	131.2	127.9	132.5	129.4	133.6	124.7	128.2	131.2	127.9	132.5	129.4	133.6				
Power Gas turbine	MWe	50.0	38.6	39.2	39.0	39.6	39.4	39.9	50.9	38.6	39.2	39.0	39.5	39.4	39.9				
Power Steam turbine	MWe	32.6	34.8	32.6	31.6	30.2	28.5	28.0	33.0	34.8	32.6	31.6	30.2	28.5	28.0				
Power needs Auxiliaries	MWe	37.5	28.2	28.8	17.4	18.6	12.2	11.3	37.5	28.2	28.8	17.4	16.6	12.2	11.3				
Power needs Oxygen production	MWe	0.0	6.5	6.7	5.9	6.1	5.4	5.6	0.0	6.5	6.7	5.9	6.1	5.4	5.6				
Net power output	MWe	45.1	38.7	38.2	47.3	47.1	50.2	51.0	46.4	38.7	38.2	47.3	47.1	50.2	51.0				
HHV efficiency		43.0%	41.2%	42.4%	43.8%	44.9%	44.9%	46.2%	42.8%	41.2%	42.4%	43.8%	44.9%	44.9%	46.1%				

The cost breakdown of an ordinary chemical plant, and a solid-fluid processing plant, that is used to estimate the total capital costs of a gasification plant

		Peters and Timmerhaus (1980)		Faaij (1998) ¹⁾	Williams (1995)
		ordinary chemical plant	solid-fluid processing plant		
f.o.b. ²⁾					
shipping and insurance					
Direct costs (DC)	ISBL ³⁾	Purchased Equipment ⁴⁾ (PE) Installation	25 – 55 % of PE	39 % of PE	
		Installed Equipment (IE) ⁵⁾			
		Instrumentation and controls	6 – 30 % of PE	13 % of PE	5 % of IE
		Piping, installed	10 – 80 % of PE	31 % of PE	4 % of IE
		Electrical, installed	10 – 40 % of PE	10 % of PE	7 % of IE
		Buildings, process and auxiliary	10 – 70 % of PE	29 % of PE	1.5 % of IE
		Civil works			10 % of IE
	OSBL ⁶⁾	Connection to grid / utilities		10 % of PE	5 % of IE
		Yard improvements ⁷⁾	} 40 – 100 % of PE	55 % of PE	0.5 % of IE
		Service facilities		6 % of PE	
		Land (if purchase is required)			
		utilities / auxiliaries			25 % of IE
subtotal = Direct costs (DC)		Land			1 % of DC
Indirect costs (IC)		Engineering and supervision	5 – 30 % of DC	32 % of PE	15 % of DC
		Construction expense	6 – 30 % of DC	34 % of PE	
		Contractor's fee		18 % of PE	
		Contingency	5 – 15 % of FCI	36 % of PE	10 % of DC
		Building interest			10 % of DC
		Fees / overheads / profits			10 % of DC
subtotal = Indirect costs (IC)					
Fixed capital investment (FCI)			DC + IC		
Working Capital (WC)			10 – 20 % of TCI	74 % of PE	10 % of DC
Start-up (SU)					5 % of DC
Total Capital Investment (TCI)			FCI+WC	DC + IC + WC	DC + IC + SU
Which is			266 – 1136 % of PE	487 % of PE	200 % of IE
					183 % of IE

C1 LCA Reviews

The text of the literature summaries of the three studies below is taken from Eric D. Larson's article '*Liquid Biofuel Systems for the Transport Sector: a Background Paper*'.

Elsayed, M.A., Matthews. R., Mortimer N.D, *Carbon and Energy Balances for a Range of Biofuel Options*, Resources Research Unit, Sheffield Hallam University, UK, 2003.

*The study examines a wide body of work to assess on as consistent basis as possible the LCA of biomass pathways in the UK context.

*The ISO 14041 standard is followed for reporting LCA results.

*The analysis of each pathway is supported by a detailed appendix giving overall mass balance for the process and all numerical inputs used to generate results.

*Multiple studies were reviewed by the authors for each fuel, and those judged to be the "best" were synthesized and put on as common a basis as possible to develop results. The analysis is well documented regarding assumptions and sources.

*The authors' preferred co-product allocation method is by displacement, but in many cases, the authors claim that this is not an appropriate approach, and market values are used instead for allocations.

VIEWLS (Clear Views on Clean Fuels), *Environmental and Economic Performance of Biofuels- Volume 1*, Main Report, SenterNovem, Utrecht, the Netherlands, 2005.

*This major study (>400 pages with appendices) was carried out as a collaborative project among a number of analysts at different institutions around Europe. The project (VIEWLS), maintains a website with an extensive library (downloadable) of the LCA-related documents.

*Approach similar to Quirin et al., in that goal is to analyze the life cycle based environmental and economic performance of different biofuels by reviewing existing international studies and attempting to synthesize their results to be able to make consistent comparisons among different biofuel pathways.

*Results are given in terms of reference (mid-range) values and range of values observed in different studies.

SUMMARY OF RESULTS	Current Technology	Future Technology	Compared to Fossil Fuels
Environmental performance			
CO ₂ -eq [g/km] *)	-270 to +200	-170 to +110	significantly lower
CO ₂ [g/km] *)	36 to 120	- 57 to 57	significantly lower
Economic performance			
biofuel cost at filling station [€/GJ]	17 to 47	15 to 35	higher (7 – 9)
total driving costs [€/100 km]	25 to 46	25 to 35	higher (24 -26)
mitigation costs [€/t CO ₂ -eq avoided]	210 to 1,800	40 to 2,300	-
*) Negative values when avoided emission of substituting conventional material with by-products and/or of avoided reference use of the biomass are higher than emissions from the biofuel chain.			

CONCAWE, Joint Research Centre of the EU Commission, and European Council for Automotive R&D, *Well-to-Wheels Analysis of Future Automotive Fuels and Power trains in the European Context*, Summary report (version 1b),2004

*This major report (hundred of pages across multiple reports and appendices) examines a variety of well-to-wheel pathways for automotive fuels and power trains considered to be relevant for Europe 2010 and beyond. The following tables show the fuels and power trains that were included in the study.

*The study draws heavily on the European GM study, with some updates to numbers and some new pathways added.

*Cost analyses are included in the study, along with LCA analyses.

*A standard 5-seat compact European sedan (e.g, VW Golf) is the type of vehicle considered in all cases.

*Detailed simulations of drive cycles and powertrain performance were used to establish fuel economy figures.

*Co-product credits were allocated using the displacement method.

*The authors recognize the uncertainties in LCA analysis and present results in terms of ranges.

*The authors draw the following broad conclusions(supported in most cases by detailed numerical results):

-Shifting to renewable/low carbon routes may significantly reduce GHG emissions but will - generally require more total energy use (counting fossil and renewable energies)

-Shifting to renewable/low carbon routes will always entail costs, but high costs do not always result in large GHG reductions.

-Transport applications may not maximize the GHG reduction potential of renewables.

-Optimum renewables use requires considering overall energy demand, including stationary applications.

-For conventional biofuels (FAME and starch-based ethanol), GHG balance is particularly uncertain due to N₂O emissions from agriculture. In any case, such fuels offer limited volume potential.

-BTL (biomass gasification-based liquids) have potential for much greater GHG emissions savings than conventional biofuels at comparable cost.

D1. Different Gasifiers.

Fixed bed

Fixed beds operate at temperatures 700-1200°C and can either be co-current (downdraft) or counter-current(updraft), depending on the flow directions of the solid flow and gas stream. Co-current and counter-current reactors can be seen in the diagram above...

In an updraft gasifier the biomass is fed at the top of the reactor and moves downwards as the biomass is converted and ashes removed. The biomass moves in opposite direction to gas flow, through the drying zone, pyrolysis zone, reduction zone and oxidation zone. The air intake is at the bottom and the gas leaves at the top. In a downdraft gasifier the gas leaves the bottom of the reactor so that the fuel and gas move in the same direction. More types of fixed bed reactor exists depending upon operating conditions.

The fixed beds however fail in producing a tar free producing gas and demand high quality fuel. Other weaknesses include fuel blockages, corrosion and possibilities of explosions. An example of a more flexible reactor is the fluidised bed reactors. (charcoal is used in the process)[Knoef et al., p.22-28, 2005]

Fluidised Bed Gasifiers

Fluidised bed gasification was originally developed for large scale coal gasification, it is now applied to biomass in order to overcome some of the challenges with fixed bed gasifiers. To make homogenous conditions and rapid heat transfer in the fluidised bed, the reactor has an inert layer of sand. The sand bed strengthens the heat exchange between the fuel particles and so the overall gasifier efficiency is improved. Unlike the fixed bed gasifiers there is no boundary between the different zones in the gasifier. In contrast to fixed bed gasifiers the air-biomass ratio can be changed and the bed temperature controlled(usually between 700-900 °C). Air is usually the fluidisation medium in fluidised bed gasifiers, although steam and oxygen can also be used. The air is added at the bottom of the bed and the velocity is increased so that it reaches a minimum fluidising velocity (MFV). At this point particles become suspended, making the solids behave as a fluid. The fluidisation medium heats up the sand by a fossil fuel, once the biomass is added to the bed and mixed with the hot sand, the biomass is quickly decomposed into a combustible gas. Fluidised bed gasification can both be atmospheric or pressurised.

[Knoef et al., p.30-31,2005]

Fluidised bed gasifiers have several advantages compared to fixed bed gasifiers, such as uniform temperature profile without hot spots, toleration of many different types of feedstocks and ability to handle larger range of moisture, ash content and bulk density. However there also exist drawbacks in the technology including need for power supply for compression of the gas stream, complex operation and production of gas with high tar and dust contents.

[Knoef et al, p.30, 2005]

Bubbling Fluidised Beds.

Increasing the velocity further than the MFV increases the movement, bubbles are formed in the sand and the bed begins to float. This is called the Bubbling fluidized bed (BFB). The technique allows for continuous ash removal, long operation periods and bed removal. The syngas however tends to contain high amounts of tar.

Circulating Fluidized Bed (CFB)

In Circulating fluidised bed reactor the state of suspension is high. Velocity is increased from the Bubbling Fluidised Bed (BFB) so that the bubbles increase. The movements become vigorous, so that bed material may follow the air from the reactor and to the furnace. In order to recycle this bed material a cyclone is put at the top of the furnace. Char conversion is higher and reactor unit costs can be reduced relative to the BFB. This (CFB) has been stated as one of the most promising gasifiers for medium size plants.[Olofsson .I, et al.,p.9,2005]

Entrained Flow Gasifiers (EF).

EF has recently been considered for biomass but was originally designed for coal. In entrained beds there is no bed material and pulverised fuel is needed (<100 microm). Because the reactor operates above ash melting point (1000°C), ash is liquefied and tar content is very low. The high temperatures also increase the amount of hydrogen in the gas and makes CH₄ as well as tar content negligible. EF gasifiers are characterised with short residence time (-1 sec), high temperatures (1300-1600 °C), high pressures (25-60 bar) and large capacities (>100MW).

Due to the advantages with entrained beds, many demo and commercial scale entrained flow reactors for biofuel production are developed in Europe.
[Girard p et al, p.32]

Slagging and non-slagging gasification

‘Slagging ‘and ‘non-slagging’ modes refer to molten ash or dry ash production respectively. If oxygen is used, for example as in the case with the Carbo-V process the gasifiers will operate at high temperatures in slagging mode . The calorific value of the producer gas will be higher due to absence of nitrogen in the product gas. The gas will also be rich in CO as there is almost no need for steam (<20%) Advantage with slagging mode is an increase in specific capacity. Due to costs with production of oxygen however, slagging gasification is more suitable for large scale applications. The gasifiers have to be changed for the process and expensive membrane walls have to be used. [Knoef et al., p.33, 2005]

Inventory Tables

