LIFE CYCLE ASSESSMENT OF BTL-FUELS, CONVERSION CONCEPTS AND COMPARISON WITH FOSSIL FUELS

Jungbluth, N., Tuchschmid, M. Frischknecht, R.
ESU-services Ltd.
Kanzleistrasse 4, CH-8610 Uster, T. +41 44 940 6132, jungbluth@esu-services.ch

Different types of process designs for BTL (biomass-to-liquid) are developed in the moment by different companies and research institutes. Also the biomass input might be quite variable ranging from agricultural residues like straw over forest wood to energy crops like miscanthus. Several such conversion concepts and biomass inputs have been compared from an environmental point of view in a life cycle assessment (LCA). This takes into account not only greenhouse gas emissions or energy uses, but all types of environmental problems caused in the life cycle, e.g. eutrophication or land occupation issues. Straw, Miscanthus and Short-rotation wood have been included as biomass inputs for the assessment. The LCA shows that the conversion efficiency and the type of biomass are quite important for such an assessment. The LCA gives hints for the further process improvements.

A second LCA confirms the findings of other biofuel-studies concerning the comparison with fossil fuels. The greenhouse gas emissions and fossil energy use can be reduced due to the use of BTL, but on the other side there are higher environmental impacts for environmental problems caused by the agricultural production (acidification, eutrophication, pesticide use, land occupation, etc.). Thus only BTL-fuels from wastes and forest wood have lower total environmental impacts than fossil fuels. There is no general better performance of BTL compared to other types of biofuels.

The reports of the LCA for different conversion concepts and the life cycle inventory data are public available. Thus they can be used also for follow-up studies.

Keywords: life cycle assessment (LCA), liquid biofuels, synthetic biofuels

1 INTRODUCTION

Life cycle assessment (LCA) has proved to be a powerful tool for the environmental improvement of production processes in the agri-food sector. The aim of two projects was to investigate data for biomass production, compare different types of conversion processes to biomass-to-liquid (BTL) fuels and investigate the use of BTL for transport services.

The life cycle assessment (LCA) of producing BTL-fuels has been elaborated within the RENEW project[1] (Renewable Fuels for Advanced Powertrains). The project investigated different production routes for so called biomass-to-liquid (BTL) automotive fuels made from biomass. The study is described in detail in a series of reports [1-5]. The description in this article is mainly based on the summary of this study [5].

A second study investigated the use of BTL-fuels and compared it with fossil fuels [6]. This comparison was a follow up study for a Swiss project investigating several types of biofuels [7, 8].

Here we summarize the main results of the two LCA studies.

2 LIFE CYCLE ASSESSMENT OF PRODUCING BTL-FUEL

2.1 Methodology

The goal and scope report [1] provides an introduction into the methodology of life cycle assessment (LCA). The LCA method aims to investigate and compare environmental impacts of products or services that occur from cradle to grave. All environmental impacts caused by a product, e.g. 1 litre of biofuel, are assessed in a standardized way. It includes all the stages during the life cycle: the production of pesticides and fertilizers, the necessary transports, the conversion of the biomass to fuel and all emissions in the life cycle are investigated in the LCA. The method has been standardized by the International Organization for Standardization (ISO) [9].

2.2 Goal and Scope of the study

2.2.1 Production routes developed in the RENEW project

Within the RENEW project, different production routes for BTL-fuels, which are produced by gasification of biomass followed by a synthesis process, were further developed. These are:

- production of Fischer-Tropsch-fuel (FT) by two-stage gasification (pyrolytic decomposition and entrained flow gasification) of wood, gas treatment and synthesis;
- production of FT-fuel by two-stage gasification (flash pyrolysis and entrained flow gasification) of wood, straw and energy plants as well as CFB-gasification (circulating fluidized bed), gas treatment and synthesis;
- BTL-DME (dimethylether) and methanol production by entrained flow gasification of black liquor from a kraft pulp mill, gas treatment and synthesis. Biomass is added to the mill to compensate for the withdrawal of black liquor energy;
- bioethanol production in different processes using different feedstock.

2.2.2 Goal of the LCA

The goal of the LCA is to compare different production routes of BTL-fuels (FT-diesel and BTL-DME) from an environmental point of view. The two production routes for ethanol are excluded from the LCA because of lack of sufficient data. The assessment includes all process stages from well-to-tank (WTT) of BTL-fuels. The following questions are addressed in the LCA study:

- Which production route for BTL-fuels, investigated within the RENEW project, is the one with the lowest environmental impacts?

---

[1] www.renew-fuel.com

- If there is a choice between different biomass inputs, which one leads to the lowest overall environmental impacts?
- What are the relative shares of contribution to the environmental impacts in different stages of production of the investigated fuels?
- Where are the potentials for improvement?
- How does the environmental profile of a certain fuel change if the scenario is changed (e.g. different efficiency in fuel production process; different external energy supply)?

The answers to these questions should support the decision on the most promising production routes for BTL-fuels that should be supported by politics and automobile manufacturers in the future.

It is important to note that several questions are out of the scope of the LCA in the RENEW project and that it is not possible to answer these questions with data nor analysis made during this LCA study. Such questions are for example:

- What are the environmental impacts of using the fuels investigated in this study (well-to-wheel - WTW)? (See next chapter).
- Are there better possible uses for the biomass, e.g. as a material or a fuel in power plants and heating devices?
- Does it make sense to produce the BTL-fuels investigated in this study and to support this in agricultural policy or would it be better to use the available land resources for other purposes?
- Are there better options to reduce greenhouse gas emissions or environmental impacts caused by road traffic?
- What are social and economic impacts of the investigated production chains?
- Are BTL-fuels sustainable?

2.2.3 Stakeholders and audience

The LCA study is elaborated for all people involved in the development of conversion processes for BTL-fuels. The results of the LCA can be used to improve the BTL-fuel production from an environmental point of view. Further parties, which might be interested in the results, are producers of biomass resources and distributors of BTL-fuels, politicians and decision makers in the automotive industry.

2.2.4 Reference flow and functional unit

The reference flow describes in a physical unit the final product or service delivered by the investigated product systems. It is the appropriate unit for analysing different products or production routes.

The function of interest in this study is the supply of chemically bound energy to powertrains. The reference flow used in the comparison of BTL-fuel production routes is defined as the energy content expressed as the “lower heating value of the fuel delivered to the tank”.

2.2.5 Product system

The LCA within the RENEW project investigates the life cycle from biomass provision to the tank and excludes the actual use of the fuel in the powertrain (well-to-tank). Figure 1 shows the major stages of the product system, which are investigated as unit processes. The conversion processes are divided into different sub-processes (e.g. gasification, gas treatment, synthesis, etc.) and are modelled in separate unit processes.

Inputs of materials, energy carriers, resource uses, etc. to the shown unit processes are followed up as far as possible. To achieve this, the recursively modelled background data of the ecoinvent database v1.3 are used [10, 11]. There are no fixed cut-off criteria in terms of a specific percentage of mass or energy inputs to the system. Relevant data gaps due to lack of data are filled as far as possible with approximations. The product system is modelled in a way that all inputs and outputs at its boundaries are elementary flows.

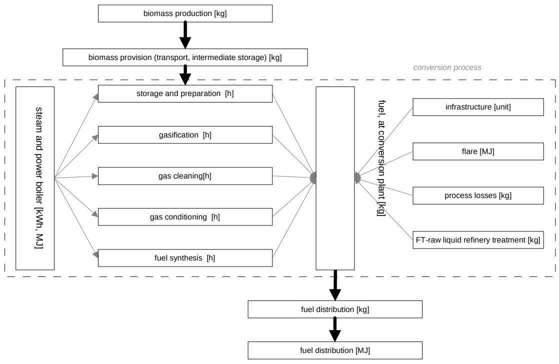

Figure 1 Flowchart of the product system of BTL-fuel with individual unit processes. The conversion process is described with nine sub-processes

2.2.6 Modelling principle attributional LCA

The LCA assigns the environmental impacts of foreseen production chains to the produced products. The attributional approach is used in the RENEW project. The attributional methodology aims at describing the environmentally relevant actual physical flows to and from a life cycle and its subsystems. Thus it considers only environmental impacts of the running processes and not the impacts caused by a change from one technology to another. Results are stable over time and resistant to changes in other parts of economy. This type of analysis does not reflect that, due to a decision supported by the LCA, production patterns might be changed.

2.2.7 Multi-output process modelling

There is no standardized way or best solution how to solve problems of by-products and further functions in life cycle inventory modelling. The ISO standard leaves different choices for the problem. Depending on the solution chosen, the results of an LCA might be quite different.

In this study, multi-output processes are divided into subsystems (where possible). If this is not possible, the approach of allocation based on different relationship principles is used as far as possible. The allocation between wheat straw and wheat grains is based on prices. The allocation between heat and electricity in the conversion power plant is based on the exergy content. Irrespective of the allocation approach chosen, it is intended that mass balances are correct in all cases.

The biomass input to the conversion process is fully allocated to fuel production. No part of the biomass is allocated to the generation of heat and electricity which might be produced as a by-product.

2.2.8 Scenarios

Two different scenarios are considered in the modelling of the process chains. They are described in a separate document [12].

Starting point calculation

The so-called “starting point calculation” addresses the possible production route in the near future. Average data representing agricultural and harvesting technology of today are used for these production systems. Farms with very small production volumes, which are not supplied to the market, are not considered in the assessment. The inventory of the conversion processes is based on the actual development state of the different technologies. In a nutshell this means “assuming we would erect such a plant today, what would the plant look like?” In this scenario the operation of the biomass to biofuel plant is self-sufficient, which means that biomass is the only energy source the plant relies on. Thus, no external electricity or other non-renewable energy supply to the conversion plant is considered in the process models.

Scenario 1

In scenario 1 a modelling of a maximized fuel production is made. The supply chain is supposed to be as efficient as possible regarding biofuel production. One of the most important criteria of the evaluation is the ratio of biofuel production to needed agricultural land. The use of hydrogen improves the carbon/hydrogen-ratio and thus leads to a higher conversion rate of biomass to fuel. External electricity input into the production system is used in most of the conversion concepts for providing the necessary hydrogen.

A quite crucial point in scenario 1 is the assumption on the hydrogen supply to the biomass conversion. The way the electricity for the water electrolysis is produced has important consequences on the costs and the environmental performance of the conversion concept. Here we assume that the external electricity is provided with wind power plants. The project team considers this one option for a maximized fuel production based on renewable energy.

Although it is not realistic to get such a renewable electricity supply until 2020 for more than a small number of conversion plants, this scenario describes a direction that might be worth going. Only if there is the possibility in 2020 to produce hydrogen with wind power, the conversion rate biomass to fuel could be increased in the way modelled here. Due to the limited production capacity until 2020, this scenario does not describe a general improvement option, but an option for special locations. The influence of using the average electricity supply mix of Europe is shown in a sensitivity analysis.

For biomass production, it is assumed that inputs of fertilizers and pesticides are higher in 2000 than for today. In addition, the yields are higher than today.

2.3 Life cycle inventory analysis

The second report describes the life cycle inventory analysis (LCI) for the LCA study [2]. In this step of the study, data are collected for all inputs and outputs in different stages of the life cycle of BTL-fuels.

2.3.1 Biomass production

Three types of biomass inputs are used in the conversion to BTL-fuels. These are short rotation wood (willow-salix or poplar), miscanthus and wheat straw. The life cycle inventory data of biomass production are based on regional information investigated for Northern, Eastern, Southern and Western Europe. The data were collected by regional partners from the RENEW project. The main assumptions about the intermediate storage of biomass are harmonized with partners of the RENEW project.

Table 1 shows some key figures from the life cycle inventory analysis of biomass products and intermediate storage. A critical issue in the inventory of wheat straw is the allocation between wheat straw and wheat grains. In the base case, this allocation is made with today market prices. This gives an allocation factor of about 10% to the produced straw (on a per kg basis). A sensitivity analysis is calculated based on the energy content, which leads to an allocation factor of 43% to the produced straw.

Several influencing factors are taken into account when modelling scenario 1. These are e.g. intensified agriculture in Eastern Europe, improvements in plant species and agricultural technology, achievements of maximized yields by higher inputs of fertilizers and pesticides. The different requirements give not one direction of development. Scenario 1 neither gives a clear picture of the average biomass production in the year 2020 compared to the situation today in the starting point calculation.

Table 1 Key figures of the life cycle inventory of biomass production; allocation between wheat straw and grains based on today market price

		bundles, short-rotation wood	bundles, short-rotation wood	miscanthus-bales	miscanthus-bales	wheat straw, bales	wheat straw, bales
		starting point	scenario 1	starting point	scenario 1	starting point	scenario 1
N-fertilizer	g/kg DS	5.2	6.3	4.0	5.6	2.2	1.8
P2O5-fertilizer	g/kg DS	4.0	3.5	3.1	2.8	1.1	0.8
K2O-fertilizer	g/kg DS	6.4	5.4	5.1	4.3	0.9	1.5
Lime	g/kg DS	6.5	5.9	3.6	2.4	4.4	2.8
diesel use	g/kg DS	5.1	4.9	4.3	3.3	2.3	1.4
yield, bioenergy resource	kg DS/ha/a	10'537	12'630	14'970	20'504	3'718	4'428
yield, wheat grains	kg DS/ha/a	-	-	-	-	4'900	6'719
energy content of biomass	MJ/kg DS	18.4	18.4	18.8	18.8	17.2	17.2
losses during storage	%	7%	4%	6%	3%	6%	3%

DS : dry substance

2.3.2 Data collection for conversion processes

Data of the conversion processes were provided by the different plant developers in the RENEW project. The data are mainly based on technical modelling of such plants, which is based on experiences and knowledge gained from the research work done in the RENEW project. The data are crosschecked as far as possible with project partners doing the technical assessment of the conversion concepts. Further details about the data quality check can be found in the WP5.4-reports.

Where so far no reliable first-hand information is available (e.g. emission profiles of power plants, concentration of pollutants in effluents or the use of catalysts) assumptions are based on literature data. Thus, sometimes it is difficult to distinguish between different process routes because differences could not be investigated. Table 2 provides an overview on the data provided by different partners and the generic assumptions used for modelling of the conversion processes.

We like to emphasise that the different conversion processes investigated in this study, have different development degrees. Thus, data presented in the report represent the current development status of the respective technology. A lot of effort was put to produce LCI data as accurate as possible.

All conversion concepts are based on their optimal technology. Four concepts are investigated on a scale of 500 MW biomass input and one was investigated based on 50 MW biomass input. Some conversion concepts might be improved by increasing the plant size to up to 5 GW. This has not been considered in this study.

The products produced by the different process chains are not 100% identical with regard to their physical and chemical specifications. Therefore, a possible further use of the data in other studies or investigations has to be reflected under these circumstances. Interpretations and especially comparisons based on the data developed in this study must consider the herewith-linked technology background.

Table 2 Overview on data provided by different conversion plant developers

Concept	Centralized Entrained Flow Gasification	Centralized Autothermal Circulating Fluidized Bed Gasification	Decentralized Entrained Flow Gasification	Allothermal Circulating Fluidized Bed Gasification	Entrained Flow Gasification of Black Liquor for DME-production
Abbreviation	cEF-D	CFB-D	dEF-D	ICFB-D	BLEF-DME
Developer	UET	CUTEC	FZK	TUV	CHEMREC
Biomass input	Amount and type	Amount and type	Amount and type	Amount and type	Amount and type
Biomass type	Wood, straw	Wood, straw	Straw	Wood, miscanthus	Wood, black liquor
Heat and electricity use	Provided	Provided	Provided and own assumptions	Provided	Provided
Auxiliary materials	Hydrogen, Fe(OH)2	Filter ceramic, rape methyl ether, silica sand, quicklime, iron chelate	Nitrogen, silica sand	Nitrogen, rape methyl ether, quicklime, silica sand	No auxiliaries reported
Catalysts	Literature	Literature	Literature	Amount of zinc catalyst	Literature
Emission profile	Literature for gas firing and plant data for CO	Literature for gas firing	Literature for gas firing, plant data for H2S and own calculations	Literature for gas firing and plant data for CO, CH4, NMVOC	Literature for wood firing and plant data for CO, H2S, CH4
Amount of air emissions	Calculated with emission profile and CO2 emissions	Calculated with emission profile and CO2 emissions	Calculated with emission profile and own assumptions on CO2.	Calculated with emission profile and CO2 emissions	Calculated with emission profile and CO2 emissions
Effluents	Amount and concentrations	Only amount. Rough assumption on pollutants	Only amount. Rough assumption on pollutants	Only amount. Rough assumption on pollutants	Amount and TOC concentration. Rough assumption on pollutants
Wastes	Amount and composition	Only amount	Only amount	Only amount	Only amount
Fuel upgrading	Included in process data	Standard RENEW model for upgrading	Standard RENEW model for upgrading	Standard RENEW model for upgrading	Included in process data
Products	BTL-FT, electricity	FT-raw product, electricity	FT-raw product, electricity	FT-raw product, electricity	BTL-DME

2.3.3 Key figures for starting point calculation

Key figures on the starting point calculation are summarized in Table 3. Here we show the conversion rate from biomass to fuel in terms of energy, the plant capacity and the production volume per hour. The BLEF-DME process has the highest conversion rate followed by the cEF-D process. The ICFB-D process has a rather low conversion rate (biomass to fuel) because it produces large amounts of electricity as a by-product. The electricity is only burdened with the direct air emissions from the power plant, but not with the production of biomass. This is a worst-case assumption for the BTL-fuel and reflects the project idea of mainly producing fuel.

Table 3 Starting point calculation. Key figures of conversion processes: conversion rate between biomass input and BTL-fuel output in terms of energy

	Biomass	Wood	Straw	Wood	Straw	Straw	Wood	Miscanthus	Wood
	Process	Centralized Entrained Flow Gasification	Centralized Entrained Flow Gasification	Centralized Autothermal Circulating Fluidized Bed Gasification	Centralized Autothermal Circulating Fluidized Bed Gasification	Decentralized Entrained Flow Gasification	Allothermal Circulating Fluidized Bed Gasification	Allothermal Circulating Fluidized Bed Gasification	Entrained Flow Gasification of Black Liquor for DME-production
	Product	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-DME
	Code	cEF-D	cEF-D	CFB-D	CFB-D	dEF-D	ICFB-D	ICFB-D	BLEF-DME
	Developer	UET	UET	CUTEC	CUTEC	FZK	TUV	TUV	CHEMREC
conversion rate (biomass to all liquids)	energy	53%	57%	40%	38%	45%	26%	26%	69%
capacity biomass input (MW)	power	499	462	485	463	455	52	50	500
all liquid products (diesel, naphtha, DME)	toe/h	22.5	22.3	16.6	15.0	17.5	1.1	1.1	29.0

Toe: tonnes oil equivalent with 42.6 MJ/kg

2.3.4 Key figures for scenario 1

The idea of scenario 1 is to maximize the biomass conversion rates. Due to external inputs of electricity, it is even possible to achieve biomass to fuel conversion rates higher than 100%. We summarize the key figures for scenario 1 in Table 4.

The conversion rates vary quite a lot between the different processes. The conversion rate of the ICFB-D process (55%) is in the range of the figures presented by other plant operators for the starting point calculation. There is no external hydrogen input for this conversion process.

According to the data provided and used, the cEF-D process has the highest conversion rate (108%). The process CFB-D has a similar conversion rate like the ICFB-D process, but with quite higher amount of hydrogen input. The differences and reasons for the technical differences are further analysed in WP5.4 of the RENEW project.

The demand on external electricity ranges between 135 and 515 MW. With an installed capacity of 1.5 MW per wind power plant, a wind park with 100 to 400 units of wind power plants is required to cover the demand of one conversion plant. The production of biofuels would be quite dependent on the actual electricity supply situation. The dEF-D process is strictly speaking not producing a fuel from biomass, but from wind energy (WtL) because more than half of the energy input is electricity.

Table 4 Scenario 1. Key figures of conversion processes. Ratio biomass input to fuel output in terms of energy and hydrogen input

	Biomass	Wood	Wood	Straw	Straw	Wood	Miscanthus
	Process	Centralized Entrained Flow Gasification	Centralized Autothermal Circulating Fluidized Bed Gasification	Centralized Autothermal Circulating Fluidized Bed Gasification	Decentralized Entrained Flow Gasification	Allothermal Circulating Fluidized Bed Gasification	Allothermal Circulating Fluidized Bed Gasification
	Product	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-FT
	Code	cEF-D	CFB-D	CFB-D	dEF-D	ICFB-D	ICFB-D
	Developer	UET	CUTEC	CUTEC	FZK	TUV	TUV
conversion rate (biomass to all liquids)	energy	108%	57%	56%	91%	55%	57%
capacity biomass input (MW)	power	499	485	464	455	518	498
external electricity, including H2 production	MW	489	135	149	515	-	-
hydrogen input conversion	kg/kg product	0.24	0.13	0.13	0.34	-	-
all liquid products (diesel, naphtha, DME)	toe/h	45.6	23.4	21.9	34.9	24.1	24.0

toe tonnes oil equivalent with 42.6 MJ/kg

2.3.5 Sensitivity analysis

A sensitivity analysis within the life cycle inventory analysis covers the following most important issues:

- Wheat grains and wheat straw are produced together. In the base case, we assume an allocation of all inputs and outputs based on todays market price. This attributes only a small part (10%) of the mass and energy flows to the production of straw. A sensitivity analysis is performed with an allocation based on the energy content, which is similar to the amount of dry matter of straw and grains harvested.
- The ICFB-D process has a plant layout designed for the cogeneration of electricity and heat together with BTL-FT production. In the base-case, all environmental impacts of biomass provision are allocated to the fuel production. A sensitivity analysis is performed that takes into account that biomass is also a necessary input for the electricity delivered to the grid.
- A crucial point in scenario 1 is the provision of electricity for the production of hydrogen. In the scenario 1 base case, a supply from wind power plants is assumed. This is not realistic for a large-scale production in Europe due to capacity limitations. Thus, a sensitivity analysis is performed taking into account the average central European electricity mix.

2.3.6 Electronic data format and background data

All inventory data investigated in this report are recorded in the EcoSpold data format. The format follows the ISO-TS 14048 recommendations for data documentation and exchange formats. It can be used with all major LCA software products [3].

All background data, e.g. on fertilizer production or agricultural machinery are based on the ecoinvent database v1.3 [10]. They were investigated according to the same methodological rules as used in this study. The quality of background data and foreground data is on a comparable and consistent level and all data are fully transparent.

2.4 Life cycle impact assessment and interpretation

The third report elaborates on the life cycle impact assessment (LCIA) and the interpretation of the life cycle assessment [4]. The data describing emissions and resource uses are calculated over the full life cycle. In a second step, they are aggregated to the list of category indicators described in Table 5. The category indicator results are interpreted in view of the questions addressed in this study.

2.4.1 Category indicators in life cycle impact assessment

The elementary flows from the life cycle inventory analysis are characterised according to commonly accepted methodologies. The life cycle impact assessment (LCIA) covers several impact category indicators. These indicators characterise and summarise the contribution of individual emissions or resource uses to a specific environmental problem. The higher the figure, the higher is the potential environmental impact resulting from emissions and resource uses over the life cycle of the investigated product. There is no weighting used across the category indicators.

The inclusion or exclusion of category indicators was discussed within the project team. The main criteria for the choice of category indicators were the reliability and the acceptance of the existing LCIA methods by all partners.

This life cycle impact assessment evaluates the use of primary energy resources, the emission of greenhouse gases and the potential contribution of elementary flows to photochemical oxidant formation, acidification and eutrophication. Besides the LCIA results, two cumulative results of elementary flows are presented. The water use sums up all demands of water in the life cycle including rainwater but excluding turbine water. For land competition, all surface land uses are summed up as square metre used over one year.

Table 5 Category indicators investigated in this study [13, 14]

Category indicator	**Abbreviation**	**Description of the problem and relevance for the processes investigated**
Cumulative energy demand	CED	The cumulative energy demand of biomass, other renewable, fossil and nuclear energy resources is characterised and summed up with the reference unit MJ-eq (mega joule equivalents).
Abiotic depletion	ADP	Important is the use of non-renewable energy resources. The depletion of other abiotic resources is included in this indicator as well. The use of uranium for electricity generation is included with a smaller characterisation factor compared to the CED.
Global warming	GWP	Contribution to the problem of climate change evaluated with the global warming potential. Main reason for promotion of BTL-fuels.
Photo-chemical oxidation, non-biogenic	POCP, non biogenic	Evaluation of potential contribution to the formation of summer smog. The production processes and agriculture have some relevance. It has to be noted that only a small part of NMVOC gets a characterisation factor according to the CML methodology. All unspecified NMVOC are not assessed. Here we do not evaluate biogenic emissions from plant growing, but other biogenic emission, e.g. CO from biomass burning.
Acidification	AP	Emission of acid substances contributing to the formation of acid rain. Relevant are air emissions from agriculture and fuel combustion in transport processes.
Eutrophi-cation	EP	Overfertilization of rivers and lakes due to human-made emissions. High relevance for the use of fertilizers in agricultural processes.
		Inventory results
Water use		Water is a scare resource especially in Southern European countries. The indicator includes all types of water use including rainfall on the agricultural area, irrigation water and direct uses of water in conversion processes.
Land competition		Fertile land area is the most important resource for production of biomass and there are differences between different biomass types. It is recorded in m2a (square metre occupied for one year).

2.4.2 Analysis of category indicators results in the starting point calculation

The main drivers regarding all environmental category indicators are analysed in the study. Here we explain the results for the more realistic starting point calculation. Detailed results related to the scenario 1 can be found in the full report [4].

The major elementary flow regarding the cumulative energy demand is the energy bound in harvested biomass. Thus, the biomass production process accounts for 80%-90% of the cumulative energy demand in the starting point calculation.

Crude oil (50%-60%) and natural gas use are the major contributions to abiotic depletion. The use of uranium has only a small contribution within this category indicator. The resource extraction takes place in many different unit processes of the life cycle.

Fossil carbon dioxide (50%-70%) and dinitrogen monoxide (20%-40%) are the major elementary flows with respect to climate change. Methane from off-gases and emissions of the internal power plant in the conversion plant accounts for up to 15% of the total greenhouse gas emissions.

A range of different substances is important with regard to the photochemical oxidation. The most important ones are sulphur dioxide, carbon monoxide and different NMVOC. Dimethylether emissions are relevant in the distribution of BTL-DME.

Acidification is caused by ammonia, sulphur dioxide and nitrogen oxides in about equal shares. The emissions of acidifying substances can be attributed to the biomass production, direct air emissions of these conversion processes that release off-gases and emissions from the internal power plant. The operation of transport devices and tractors is also an important source of such emissions.

Eutrophication is caused by nitrates, phosphates, ammonia and nitrogen oxides. A share of more than 50%

of the release of eutrophication emissions can be attributed in most cases directly to the agricultural production process. Other important sources of emissions are the direct air emissions from the conversion process and power plant. The production of fertilizers contributes in smaller amounts.

The water use is fully dominated by rainwater used in agriculture. Other water uses e.g. in the conversion plant or for irrigation are not very important.

The results for land competition are dominated by the agricultural biomass production, which accounts for about 90% of all land uses. For the conversion routes based on straw, this share is reduced to 80%. Because of the allocation procedure, only a small part of the land used for wheat cultivating is attributed to straw. Several wood-consuming background processes, e.g. storage facilities, get a share of up to 20% in the land occupation of straw-conversion routes.

2.4.3 Comparison of concepts in the starting point calculation

In the following, the category indicator results of different conversion concepts are compared from well to tank.

The ranking of the different processes is visualized in Table 6. The process with the lowest environmental impacts is set to 100% in this evaluation (per impact category). The table shows the environmental impacts of all processes in comparison to the process with the lowest impacts. In addition, processes with just 15% higher environmental impacts are ranked “lowest”. Processes with up to 16% to 50% higher impacts than the “lowest” are ranked as “low impacts” processes. Different colours help to identify these levels.

Many category indicators like acidification, eutrophication, water use and land competition show an absolutely dominating influence of the agricultural production of biomass. Thus, the type of biomass and the conversion rate are important in the comparison.

The conversion rate plays a major role in the formation of air emissions from the conversion plant. It is assumed that the higher the conversion rate, the lower is the share of biogenic carbon dioxide and thus also other pollutants which are released to the ambient air. Therefore, the improvement of the conversion rates and the reduction of the environmental burdens of the biomass production itself are the main drivers for further environmental improvements of the BtL-chains, within the same scenario.

The conversion processes cEF-D and BLEF-DME have the lowest environmental impacts in the assessment with regard to the environmental indicators cumulative energy demand, global warming, photochemical oxidation, acidification, eutrophication and abiotic resource depletion. They are followed by CFB-D and dEF-D process. The ICFB-D process shows the highest environmental impacts due to a process design with a considerably high amount of electricity production and thus a lower biomass to fuel conversion rate.

In the case of the conversion of wood, the cEF-D process has between 15% and 30% higher impacts than the production of dimethylether with regard to the category indicators cumulative energy demand, abiotic depletion, global warming, eutrophication, water and land use. This can mainly be explained with the higher conversion rate of the BLEF-DME process. However, the cEF-D process has 35% lower impacts in the category indicator photochemical oxidation, because the emissions in the dimethylether distribution are higher. CFB-D has more than 65% higher impacts than cEF-D and BLEF-DME. The ICFB-D process has a rather low conversion rate and thus has higher impacts in all category indicators except photochemical oxidation, which does not include biogenic emissions.

The comparison of processes based on wood or straw depends not only on the type of biomass, but also on the difference in the conversion rate. The CFB-D process based on wood performs slightly better than processes based on straw regarding the category indicators cumulative energy demand, abiotic depletion, global warming potential and eutrophication potential. For the cEF-D concept, the process with straw has lower environmental impacts than the conversion of wood.

In the case of straw conversion, the cEF-D process has the lowest impacts fin all category indicators followed by the dEF-D and the CFB-D process. There is only one conversion process using miscanthus (ICFB-D). Thus, a direct comparison with other conversion concepts is not possible.

Table 6 Starting point calculation. Ranking of the different conversion concepts with respect to the category indicators based on the energy content of the fuel delivered to the tank

	Biomass	Miscanthus	Straw	Straw	Straw	Wood	Wood	Wood	Wood
	Process	Allothermal Circulating Fluidized Bed Gasification	Centralized Autothermal Circulating Fluidized Bed Gasification	Decentralized Entrained Flow Gasification	Centralized Entrained Flow Gasification	Centralized Autothermal Circulating Fluidized Bed Gasification	Allothermal Circulating Fluidized Bed Gasification	Centralized Entrained Flow Gasification	Entrained Flow Gasification of Black Liquor for DME-production
	Code	ICFB-D	CFB-D	dEF-D	cEF-D	CFB-D	ICFB-D	cEF-D	BLEF-DME
	Company	TUV	CUTEC	FZK	UET	CUTEC	TUV	UET	CHEMREC
Category indicator	Product	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-DME
cumulative energy demand	MJ-Eq	*252%*	*186%*	147%	115%	*169%*	*263%*	128%	100%
abiotic depletion	kg Sb eq	*255%*	*260%*	*155%*	121%	*165%*	*257%*	128%	100%
global warming (GWP100)	kg CO2 eq	*226%*	*252%*	128%	104%	*171%*	*224%*	116%	100%
photochemical oxidation, non-b	kg C2H4	*244%*	*361%*	*258%*	100%	*292%*	*245%*	104%	141%
acidification	kg SO2 eq	*256%*	*192%*	*190%*	100%	*181%*	*289%*	130%	133%
eutrophication	kg PO4--- eq	*453%*	*207%*	*162%*	106%	*176%*	*300%*	117%	100%
water use	m3	*780%*	*151%*	127%	100%	*672%*	*1034%*	*508%*	*396%*
land competition	m2a	*631%*	*155%*	139%	100%	*610%*	*959%*	*458%*	*358%*

	Min	Max
Lowest impacts	100%	115%
Low impact	116%	150%
High impact	*151%*	*250%*
Highest impacts	*251%*	

The data of biomass conversion have been investigated in detail for different sub-processes of the process. The aim was to compare also different sub-processes and to see the relative share of sub-processes in relation to the total environmental impacts.

In general, many category indicators results of the sub-processes of the conversion process are quite dependent on the biomass input. The share of biomass production and provision is in most cases higher than 90% with respect to the cumulative energy demand, water use and land competition. The second most important factor are the air emissions with off-gases or due to the energy production in the on-site power plant. This is especially important for the release of substances contributing to photochemical oxidation. Thus, the sub-processes using more heat and electricity contribute more to the total environmental impacts.

The detailed analysis shows that it is difficult to compare different conversion concepts based on the detailed results of single process stages, because the allocation of environmentally relevant streams within the plant might be quite different. Thus, the importance of the different sub-processes might be distinctly different even if the overall results are quite similar.

2.4.4 Sensitivity analysis

The allocation criterion between straw and wheat grains has an important influence on the total impacts of all processes that use straw as an input. Allocation by energy content results in up to three times higher environmental impacts per MJ of fuel produced from straw as compared to allocation by actual market prices.

A sensitivity analysis of the ICFB-D process was made. Heat and electricity produced simultaneously are accounted for as equal products to liquid fuels according to their exergy content. The results of different category indicators are reduced by 10% to 30%, if the wood input for the ICFB-D process is reduced by about 30% according to the exergy shares of fuel, heat and electricity production.

2.4.5 Fuel yields per hectare

The fuel yield per hectare is an important yardstick for comparing different types of biomass and different process routes. The calculation includes the full life cycle from seed to tank, e.g. also biomass losses during storage and land occupation for processes other than biomass production. All land uses (not only the agricultural land area) are included in this calculation.

The fuel yield of energy crops per hectare is between 860 to 2300 kg oil equivalents. Processes based on straw show a fuel yield of up to 8200 kg oil equivalents per hectare, if the agricultural land is allocated to the straw based on its share of the today revenue of wheat production. The yield of processes based on straw is only 1300 to 1900 kg oil equivalents per hectare if the allocation is based on the energy content of grains and straw.

These fuel yield figures highlight that it is preferable to use by-products, such as straw or wastes, for biofuel production. Nevertheless, it has to be taken into account that their potential is limited and that a rising demand will lead to higher prices, and, because of the allocation criterion (revenue), also to higher environmental impacts.

2.4.6 Comparison of concepts in scenario 1

The main idea of scenario 1 is an increase of the fuel yield per hectare. The use of hydrogen produced by electrolysis is considered an interesting option for the conversion process. Two out of six conversion concepts use electric energy in the same amount like the direct biomass input. CHEMREC did not provide data for BLEF-DME in scenario 1.

All processes show a considerable increase of the fuel yields per hectare of between 60% and 200% if hydrogen is used in the process. A fuel yield between 2100 and 4100 kg oil equivalent per hectare is possible when using miscanthus and wood.

In scenario 1, the importance of process steps is influenced largely by the external electricity input. The process stage, which uses hydrogen produced with external electricity, is more important concerning the environmental indicators that are influenced by the electricity production, e.g. cumulative energy demand. The biomass input stage is relevant for those category indicators, like land use, which are dominated by impacts from agriculture.

The cEF-D process using wood has the lowest impacts of all investigated concepts with respect to several category indicators except the cumulative energy demand, water use and land competition (Table 7). This can be explained with the highest conversion rate of all processes. Because of the lower environmental impacts of straw production in water use and land competition, the dEF-D process has a lower impact on these category indicators. The ICFB-D concept is modelled without an input of external energy. Thus, it has the lowest cumulative energy demand, because the supply of wind electricity involves a rather low conversion efficiency of the primary energy. The dEF-D process with straw has the lowest impacts with respect to eutrophication potential, water use and land competition.

Comparing straw based processes, the process of FZK (dEF-D) shows the lowest impacts except cumulative energy demand, which is highest. These low impacts can be explained mainly by the higher conversion rate of the dEF-D process compared with the CFB-D concept.

Comparing wood based processes, the cEF-D of UET shows the lowest impacts except cumulative energy demand, where the ICFB-D process of TUV has a lower impact because it does not use external electricity.

A clear overall ranking with regard to the use of different biomass resources cannot be made. In addition, a clear ranking of the different conversion processes is not possible, because results show trade offs between the different category indicators. A formal weighting between category indicators, which would bridge these trade-offs, must not be used in comparative LCA studies according to the ISO standards.

Table 7 Scenario 1 with wind power used in hydrogen production. Ranking of the different conversion concepts with respect to the category indicators based on the energy content of the fuel delivered to the tank

	Biomass	Miscanthus	Straw	Straw	Wood	Wood	Wood
	Process	Allothermal Circulating Fluidized Bed Gasification	Centralized Autothermal Circulating Fluidized Bed Gasification	Decentralized Entrained Flow Gasification	Centralized Autothermal Circulating Fluidized Bed Gasification	Allothermal Circulating Fluidized Bed Gasification	Centralized Entrained Flow Gasification
	Code	ICFB-D	CFB-D	dEF-D	CFB-D	ICFB-D	cEF-D
	Company	TUV	CUTEC	FZK	CUTEC	TUV	UET
Category indicator	Product	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-FT
cumulative energy demand	MJ-Eq	100%	*219%*	*292%*	*207%*	112%	*218%*
abiotic depletion	kg Sb eq	101%	*257%*	*160%*	*257%*	134%	100%
global warming (GWP100)	kg CO2 eq	119%	*261%*	133%	*254%*	*151%*	100%
photochemical oxidation, non-b	kg C2H4	139%	*238%*	*170%*	*226%*	*155%*	100%
acidification	kg SO2 eq	125%	*163%*	118%	*209%*	*175%*	100%
eutrophication	kg PO4--- eq	*336%*	*212%*	100%	*237%*	*212%*	102%
water use	m3	*573%*	*163%*	100%	*929%*	*959%*	*489%*
land competition	m2a	*331%*	147%	100%	*611%*	*622%*	*319%*

	Min	Max
Lowest impacts	100%	115%
Low impact	116%	150%
High impact	*151%*	*250%*
Highest impacts	*251%*	

A sensitivity analysis was performed for the use of average European electricity mix instead of wind power. The ICFB-D process (by TUV) does not use an external hydrogen production and thus no electricity from the grid. Thus, it shows a better performance in this analysis than the other processes with regard to the global warming potential, cumulative energy demand and photochemical oxidation. On the other side, it has higher impacts on the category indicators directly related to biomass production (eutrophication, water and land use).

The CFB-D process (by CUTEC) using straw has lower or about the same results as the process of dEF-D (by FZK) for the category indicators cumulative energy demand, abiotic depletion, global warming potential, POCP and AP. For eutrophication, land and water use, it has slightly higher impacts. So there is no clear overall ranking among the conversion concepts.

Among the two processes converting wood and using hydrogen (cEF-D and CFB-D process), the cEF-D process (by UET) has slightly higher impacts on the electricity dominated indicators abiotic depletion, global warming, POCP and AP due to the higher external electricity demand of the cEF-D process. The CFB-D concept (by CUTEC) has slightly higher impacts for category indicators related to biomass production (cumulative energy demand and eutrophication).

The electricity mix changes some of the results of the comparison quite significantly. The ranking according to the cumulative energy demand, photochemical oxidation, eutrophication, water and land competition remains about the same. Regarding abiotic depletion and global warming, the differences between the process routes get more significant.

Producing hydrogen with electricity will only make sense if renewable energy, e.g. wind power, is available in very large capacities and with a secure supply. Generally, the use of hydrogen produced via electrolysis and using the today electricity mix would be a clear disadvantage regarding most of the evaluated category indicators. Because the necessary capacities of wind power will not be available at many conversion plant locations, this scenario does not describe the average nor an achievable situation of BTL-production in the year 2020.

2.4.7 Improvement options

Different improvement options are identified from an environmental point of view. The most important one is the increase of the biofuel yield from a given amount of biomass. This reduces the input of biomass and decreases the losses. e.g. in form of air pollutants or effluents.[2]

Another conclusion is to improve the environmental profile of the biomass production itself, because this analysis shows that the biomass production has a dominating influence on most of the environmental indicators. Using wastes and by-products is therefore preferable with respect to some category indicators, but not always possible. Possibilities for such an improvement have not been evaluated in detail. Detailed studies of agricultural production show that improvements are not easy to achieve. Different influencing factors like e.g. fertilizer and pesticide use, diesel consumption and level of yields have to be balanced out to find an optimum solution. Also the use of wood from forests, produced without using fertilizers and pesticides, might be a viable option for the provision of biomass not yet investigated.

The use of after treatment technologies to reduce the emissions to air has not been studied in detail. It is assumed that all conversion plants have to meet the legal emissions limits, but do not further reduce the emissions. Such an after treatment might reduce the direct emissions, but might lead to higher indirect impacts e.g. due to surplus energy use or necessary auxiliary materials and certainty to higher costs, not considered in the economic assessment. Further research would be necessary to identify the optimum solutions.

For some processes, auxiliary inputs, e.g. quicklime, are found to be an important contribution to some category indicators. Thus, further focus should be put on reducing the necessary input. In addition, a separate refinery treatment of Fischer-Tropsch raw products can increase the environmental impacts slightly.

Nutrients, which are bound in the biomass, such as phosphorous, are lost with the disposal of ashes, sludge, slag or effluents. Recovering these nutrients and

---

[2] A linear relationship between carbon losses and following emissions to air accompanying the biogenic CO_2 emissions is assumed.

recycling them for a use in agriculture might be another option to improve the overall performance.

All conversion concepts are investigated on a scale of 500 MW biomass input. Some conversion concepts might be improved by increasing the plant size to up to 5 GW. This has not been considered in this study.

2.5 Conclusions

In general, this study confirms the knowledge already gained in several LCA studies of biofuels. The type of biomass input and the conversion rate to the final fuel are quite important with respect to the environmental evaluation of all types of biofuels. Direct emissions of the conversion plant and transport issues are less relevant as long as legal limits are maintained and biomass is not transported over very large distances.

2.6 Limitations of the study

Environmental impacts due to the use of pesticides and the emissions of heavy metals in agricultural production are not assessed with the category indicators used in this study. These substances have toxicological effects on animals, plants and human beings.

With regard to the category indicators of toxicological effects there was no consensus in the project group whether or not the requirements of ISO 14044, 4.4.2.2.3 are fulfilled by LCIA methods assessing such impacts. Toxicology indicators are not included in the study and the importance of this decision with respect to the comparison of the conversion routes has not been evaluated in the final report.

The exclusion of certain category indicators might be quite important regarding the ranking of different conversion processes. The authors of this study consider the exclusion of toxicity impacts as a major shortcoming of this study. Such effects should be taken into account especially if it comes to a comparison between fuels made from agricultural biomass and fossil fuels. Further research on the definition of reliability within the ISO standards and a consensus finding process for the best available methodologies for toxicological effects is necessary and currently ongoing.

2.7 Outlook

This life cycle assessment study compares different concepts of BTL-fuel production based on the status of technology development in the year 2006. Further improvements can be expected in all technologies. Thus, this study is only valid for today and it might be possible that the ranking of different conversion concepts must be revised in future. The results of the study should be reconsidered as soon as updated data are available or first commercial plants are in operation.

The starting point calculation highlights the differences in environmental impacts caused by different conversion concepts and of different types of biomass inputs. It can serve as a first basis for the comparison of different conversion concepts. Scenario 1 can be used to evaluate the possible maximized fuel yields, if large quantities of surplus electricity are available to produce hydrogen for the process. Several improvement options have been identified in the study.

3 LIFE CYCLE ASSESSMENT OF USING BTL-FUELS

3.1 Introduction

A second study elaborates a life cycle assessment of using of BTL-fuels [6]. The study has been elaborated as a follow-up study of a recent investigation on several types of biofuels [7, 8]. In that study the environmental impacts of several biofuel options like biogas, plant oil methyl ethers, ethanol and methanol have been investigated from a Swiss market perspective. The study investigated mainly renewable fuels, which are directly produced from a biomass resource by a physical, chemical or biological process like oil pressing, chemical reaction, fermentation or anaerobic digestion. The study concludes that with many biofuels it would be possible to reduce the emissions of greenhouse gases. But, on the other side there are severe disadvantages regarding several other environmental problems if biofuels are compared with fossil fuels.

This type of study forms the basis to develop criteria for the tax exemption on biofuels in Switzerland [15]. At present it is planned to cut the tax on those fuels which are made from residues or which achieve a substantial reduction of greenhouse gas emissions (-40%) without harming the environment more than fossil gasoline.

3.2 Goal

We investigate the transport service provided by passenger cars and compare this with the fossil reference. This includes the necessary infrastructure for roads and its maintenance and the production, maintenance and disposal of cars. Thus, this is the evaluation of the full life cycle of transport services, which is also commonly referred to as “cradle to grave”.

3.3 Life cycle inventory analysis

The inventory for fuel production is based on the RENEW study and ecoinvent data v2.0 [2, 16]. The inventory of the fuel use emissions is based on information published by automobile manufacturers on reductions due to the use of BTL-fuels. Passenger cars fulfilling the EURO3 emission standards are the basis for the comparison.

3.4 Life cycle impact assessment

The Swiss study [8] compared the environmental impacts of several biofuels with using fossil fuels in conventional cars. The authors used two single score impact assessment methods for their evaluation, namely the Eco-indicator 99 (H,A) and the ecological scarcity 2006 method [17, 18] as well as the cumulative energy use and the global warming potential [14]. With these methods also impacts of toxic substances like pesticides are taken into account.

3.5 Comparison of BTL-fuels with fossil fuels

Figure 2 shows a comparison of transports with passenger cars operated with BTL-fuel and fossil fuel. The comparison is presented for the use of non-renewable energy resources. The ranking of the different types of fuels is the same as already discussed on the basis of one MJ of fuel delivered to the tank [2].

Of interest is the difference between the transport with cars operated on BTL-fuel and the reference cars operated with petrol. The inventory of a EURO 3 passenger car is taken as the baseline. The use of non-renewable energy resources can be reduced by 37% to 61% due to the use of the investigated BTL-fuels.

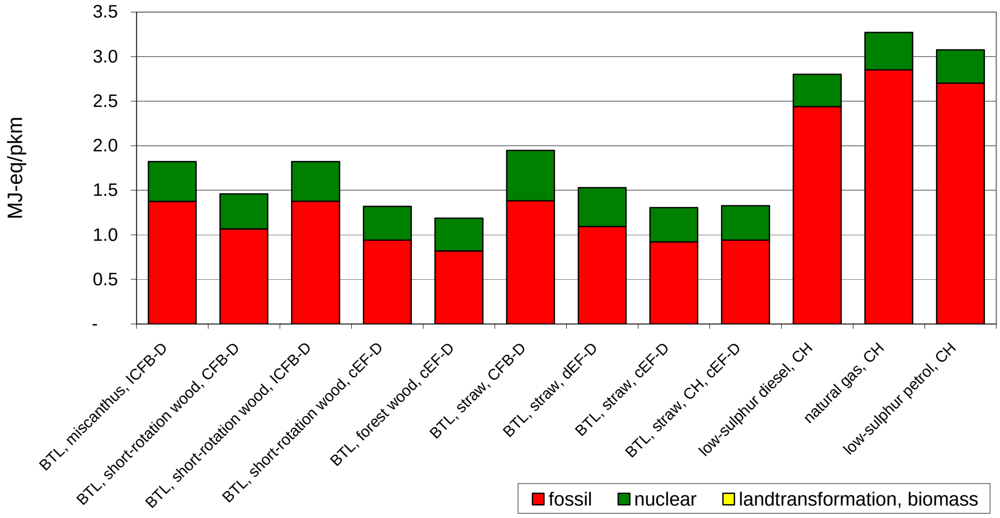

Figure 2 Non-renewable cumulative energy demand of the transport service (MJ-eq/pkm)

Figure 3 compares the emission of greenhouse gases in the life cycle of BTL-fuels and fossil fuels. The emission of greenhouse gases is reduced between 28% and 69% compared to the petrol car if BTL-fuels are used. Thus, most BTL-fuels investigated here would meet the present criteria of 40% GWP reduction as foreseen for the Swiss tax exemption [15].

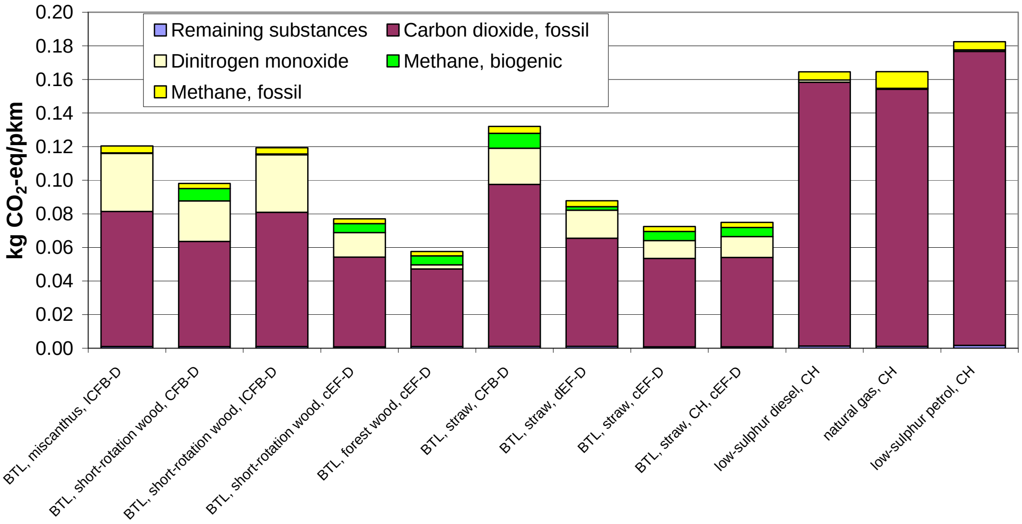

Figure 3 Global warming potential of transport services (kg CO_2-eq per pkm) over a time horizon of 100 years

Figure 4 shows the Eco-indicator 99 (H,A) scores of the different alternatives. Most BTL-fuels have higher impacts than the fossil reference. The most important impact is the land use. For energy crops like short-rotation wood not only the land occupation has a negative effect. Also the transformation of set-aside land to highly intensive agricultural area makes an important contribution of about 20% to the total impacts.

BTL-fuels based on straw show environmental impacts not much higher than the reference. In this case the land occupation is considerably lower because the major part is allocated to the produced wheat grains.

If land use would be excluded from the assessment (as proposed in a sensitivity analysis by Zah *et al.*) most BTL fuels would achieve results comparable to the fossil reference.

The BTL-fuel made in the most efficient process from forest wood, has lower impacts than the fossil reference. This can be explained by the lower negative impacts of forests on biodiversity compared to agricultural land. This fuel would achieve the criterion for tax reduction, which is not to have higher environmental impacts than fossil petrol [15]. The use of forest residues, which is not investigated here, would be even more favorable.

The impacts caused by for carcinogenic emissions are negative in Figure 4 for the BTL from short-rotation wood because the uptake of certain heavy metals from soil during biomass growing is assessed higher than the emissions in the life cycle.

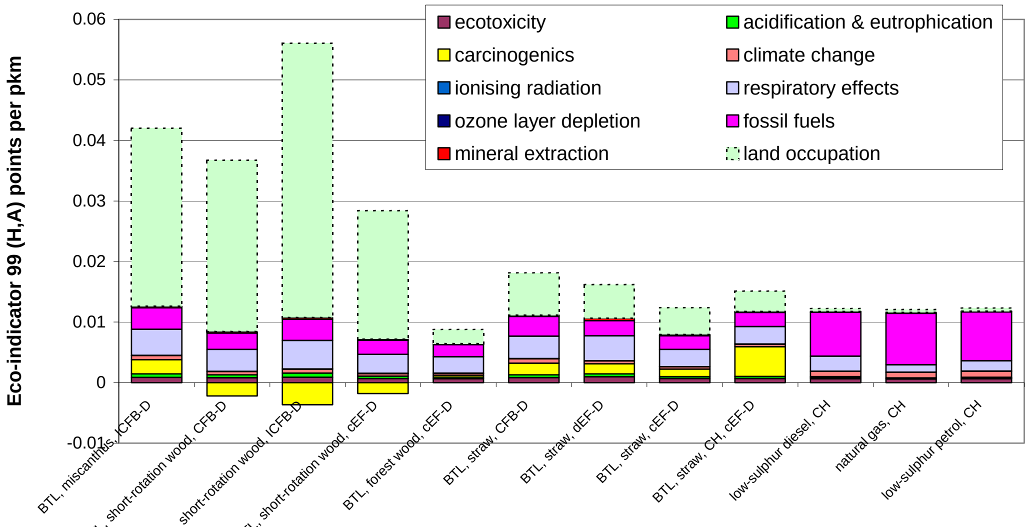

Figure 4 Eco-indicator 99 (H,A) score of the transport service (points/pkm)}

Figure 5 shows the results with the method ecological scarcity 2006 [18, 19]. Also here some heavy metals are removed from the agricultural soil during plant growing and thus results in the category emissions into topsoil are negative. All BTL-fuels made from agricultural biomass have higher environmental impacts than the fossil reference. The emissions of nitrate are comparably higher for miscanthus. This is the reason for the relatively higher contribution from emissions into groundwater.

For some fuels environmental impacts due to waste management are quite important. This is due to the disposal of ashes and slag from the conversion process. It might be possible to further improve the disposal or even to reuse the remaining as fertilizers in biomass production. So far such options have not been considered in the modeling of the conversion plants.

The total environmental impacts of the best option using forest wood are about the same as for the fossil reference. Thus, it is possible to produce BTL-fuels competitive to fossil fuel.

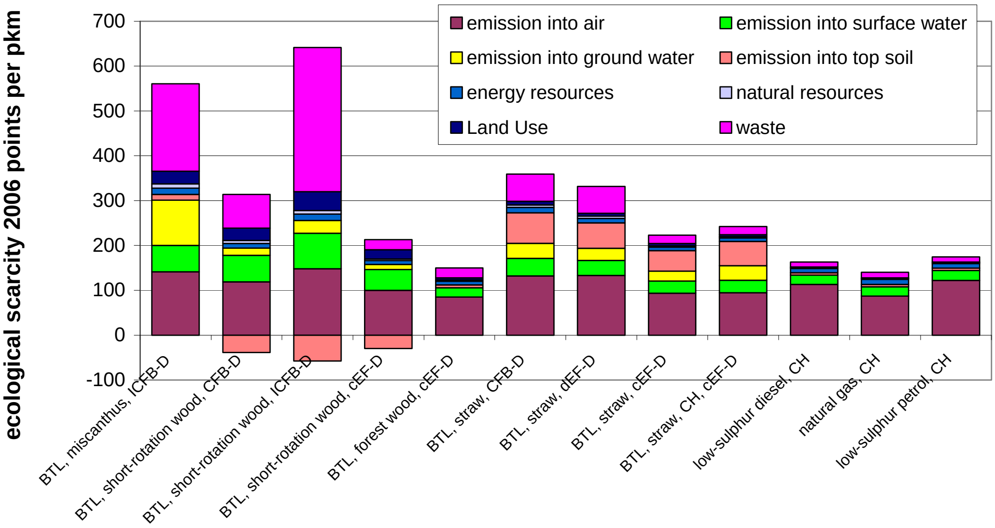

Figure 5 Ecological scarcity (2006) score of the transport service (points/pkm)

3.6 Comparison with other biofuels

A comparison with other biofuels is possible based on the data investigated before [7, 8]. Figure 6 shows a comparison with the fuels evaluated in those studies. All BTL-fuels from agricultural biomass have higher environmental impacts than the fossil reference. Some BTL-fuels from agricultural biomass have only slightly higher environmental impacts than the reference. BTL-fuel from forest wood is a good possibility concerning reduction of greenhouse gas emissions and protection of the environment. This shows that it is possible to produce BTL-fuels, which are competitive to fossil fuels from an environmental point of view. But, it also shows that the use of agricultural biomass needs further improvements in order to achieve this goal with BTL.

In comparison to other already available biofuels like e.g. rape methyl ether the results are in the same order of magnitude. These results confirm the findings of the Swiss LCA [8]. Many biofuels derived from agricultural biomass are not preferable from an environmental point of view if the full life cycle is taken into account. But, BTL-processes may also use wood from forestry or biomass residues. In comparison to short-rotation wood or other energy crops, this would substantially reduce the environmental impacts.

It is not possible to draw general conclusions for the comparison of synthetic BTL-fuels with e.g. plant oils, ethanol or methyl ethers. For all types of renewable fuels the used biomass type is an important factor for the environmental impacts. Thus, better and worse fuels exist in each category. A general advantage of BTL-fuels compared to other biofuels, as claimed in some publications, is not confirmed by our study, nor a general disadvantage.

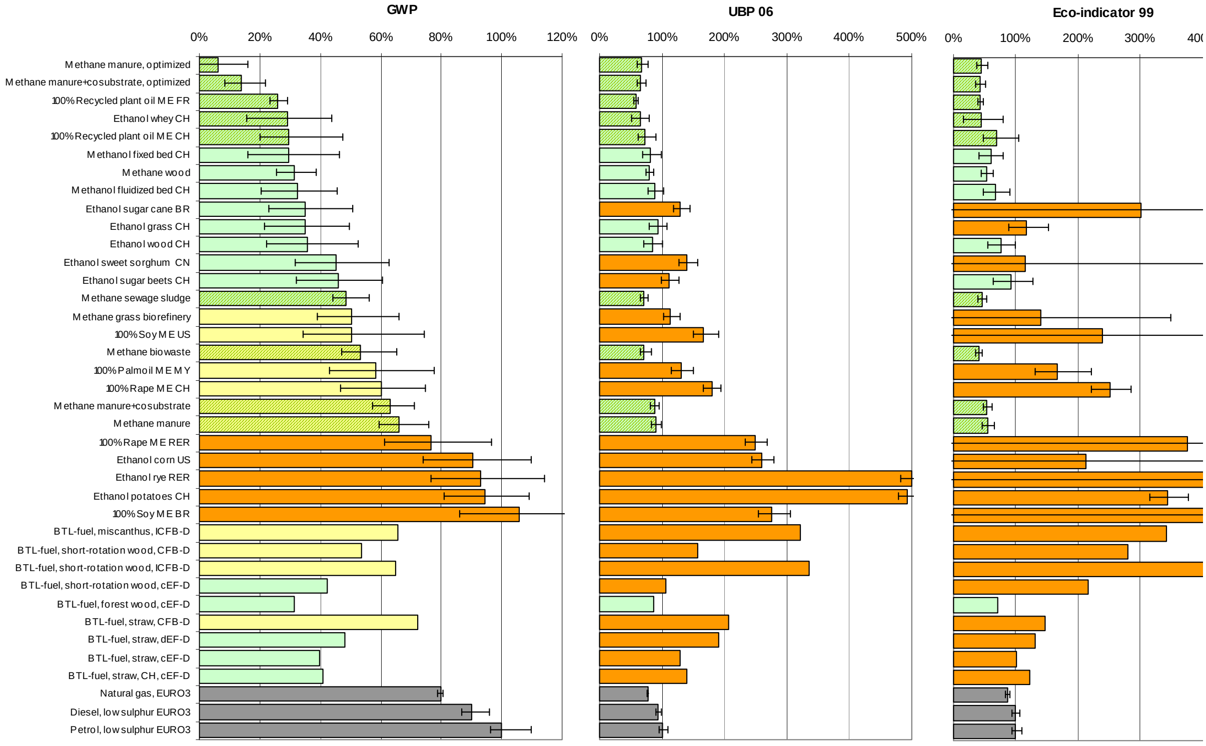

Figure 6 Relative comparison of passenger transports using different category indicators (basis pkm of transport). Reference for all fuels is the use of an EURO 3 petrol car. Life cycle impact assessment with global warming potential, Eco-indicator 99 (H,A) and ecological scarcity 2006 (Pt – points)

The best BTL process achieves fuel yields, which allow driving about 50’000 km from the short-rotation wood grown on one hectare. This is about the same as for sweet sorghum and in the upper range of the biofuels investigated [8]. On the other side also greenhouse gas emissions per hectare are relatively high compared to the renewable fuels investigated in a previous study. The best option is again forest wood, but this fuel achieves slightly lower mileage per hectare than short-rotation wood.

Concerning fuel yields per hectare there is no general advantage or disadvantage compared to other types of biofuels. Again type of biomass and the large range of efficiencies lead to a wide range of possible results.

4 DISCUSSION AND CONCLUSIONS

The use of biofuels is mainly promoted for the reason of reducing greenhouse gas emissions and the use of scarce non-renewable resources e.g. crude oil. The possible implementation of BTL-fuel production processes would help to achieve this goal. The emissions of greenhouse gases due to transport services can be reduced by about 60% with the best BTL-processes using short-rotation wood or straw as a biomass input. This is comparable to other types of biofuels made from agricultural biomass resources. With forest wood, reductions up to 69% are possible.

On the other side, there are severe disadvantages from an environmental point of view if fuels are produced from agricultural biomass. The introduction of BTL-fuels made from energy crops would further increase environmental problems mainly caused due to today’s agricultural practice. Emissions of substances contributing to eutrophication and acidification are much higher than these of transport services based on fossil fuels. Only one BTL-fuel shows about the same acidification potentials as the fossil fuel car, while all others have higher emissions. Further process improvements are necessary in order to overcome the disadvantage at least regarding acidification. But, the pressure on land and water resource is increased considerable due to the increased production of all BTL-fuels. This would be especially relevant if set-aside land is transformed to intensively used agricultural area. Until now many BTL-fuels produced from energy crops would have higher overall environmental impacts than fossil fuels.

The use of BTL-fuels is more preferable from an environmental point if wood residues can be used [20] or if wood stems from forestry instead of short-rotation plantations.

These findings are in line with several former life cycle assessment studies on biofuels [8, 21, 22]. Differences compared to so-called well-to-wheel studies can mainly be explained by data gaps and different assumptions on the biomass production.

The BTL concepts investigated in this study are modelled for self-sufficient energy supply of the conversion plant and the aim to achieve high fuel yields per hectare. There might be several other ways of development, which are not considered in detail. One possible line of development is the co-production of BTL-fuels together with electricity, heat and feedstock for the petrochemical industry. With such a concept the achievable fuel yields would be lower, but the overall energetic efficiency could be higher. It would also be possible to use other energy carriers than biomass in the conversion plant. One such concept is the use of hydrogen produced e.g. from renewable electricity. This would allow higher fuel yields but therefore considerable supplies of clean electricity would be necessary.

So far all data for the conversion processes are based on modelling and not on commercial plants. The environmental impacts of BTL-fuels must be reevaluated if BTL-fuels are introduced to the market. To quantify the real environmental impacts it is necessary to know the type of biomass used and key figures of the conversion plant, in particular the conversion efficiency, amount and revenues of by-products, emissions and wastes.

Due to the variety of conversion concepts and possible biomass resources it is not possible to make generally valid statements concerning the overall environmental impacts of BTL-fuels compared to other types of renewable or fossil fuels.

Some aspects are not covered in the modeling of this LCA. An important aspect is the impact of land transformation on the carbon stock in soils. First publications claim that such land use changes might be well relevant in the assessment of greenhouse gas emissions. Another aspect is the release of N_2O emissions due to the use of fertilizers in agriculture. New research work claims that these emissions might be higher than modeled until today.

5 LITERATURE

1. Jungbluth N, Frischknecht R, Faist Emmenegger M, & Tuchschmid M, *Life Cycle Assessment of BTL-fuel production: Goal and Scope Definition (revised)*. 2007, RENEW - Renewable Fuels for Advanced Powertrains, Sixth Framework Programme: Sustainable Energy Systems, Deliverable: D 5.2.2, ESU-services Ltd.: Uster. Retrieved from www.esu-services.ch.
2. Jungbluth N, Frischknecht R, Faist Emmenegger M, Steiner R, et al., *Life Cycle Assessment of BTL-fuel production: Inventory Analysis*. 2007, RENEW - Renewable Fuels for Advanced Powertrains, Sixth Framework Programme: Sustainable Energy Systems, Deliverable: D 5.2.7., ESU-services: Uster. Retrieved from www.esu-services.ch/renew.htm.
3. Jungbluth N & Schmutz S, *Inventory dataset: EcoSpold/Gabi/Excel*. 2007, RENEW - Renewable Fuels for Advanced Powertrains, Sixth Framework Programme: Sustainable Energy Systems, Deliverable: D 5.2.9, ESU-services Ltd.: Uster. Retrieved from www.esu-services.ch.
4. Jungbluth N, Frischknecht R, Faist Emmenegger M, Steiner R, et al., *Life Cycle Assessment of BTL-fuel production: Life Cycle Impact Assessment and Interpretation*. 2007, RENEW - Renewable Fuels for Advanced Powertrains, Sixth Framework Programme: Sustainable Energy Systems, Deliverable: D 5.2.10., ESU-services: Uster. Retrieved from www.esu-services.ch.
5. Jungbluth N, Frischknecht R, Faist Emmenegger M, Steiner R, et al., *Life Cycle Assessment of BTL-fuel production: Final Report*. 2007, RENEW - Renewable Fuels for Advanced Powertrains, Sixth Framework Programme: Sustainable Energy Systems, Deliverable: D 5.2.15., ESU-services: Uster. Retrieved from www.esu-services.ch/renew.htm.
6. Jungbluth N, Büsser S, Frischknecht R, & Tuchschmid M, *Ökobilanz von Energieprodukten: Life Cycle Assessment of biomass-to-liquid fuels*. 2008, Programm Biomasse, 280006, ESU-services Ltd. im Auftrag des Bundesamt für Energie, Bundesamt für Umwelt und Bundesamt für Landwirtschaft: Berne, CH. Retrieved from http://www.esu-services.ch/btl.
7. Jungbluth N, Chudacoff M, Dauriat A, Dinkel F, et al., *Life Cycle Inventories of Bioenergy*. 2007, ecoinvent report No. 17, v2.0, ESU-services: Uster, CH. Retrieved from www.ecoinvent.org.
8. Zah R, Böni H, Gauch M, Hischier R, et al., *Ökobilanz von Energieprodukten: Ökologische Bewertung von Biotreibstoffen*. 2007, Schlussbericht, Abteilung Technologie und Gesellschaft, Empa im Auftrag des Bundesamtes für Energie, des Bundesamtes für Umwelt und des Bundesamtes für Landwirtschaft: Bern. Retrieved from http://www.bfe.admin.ch/energie/00588/00589/00644/index.html?lang=de&msg-id=12653.
9. International Organization for Standardization (ISO), *Environmental management - Life cycle assessment - Principles and framework*. 2006, ISO 14040:2006; Second Edition 2006-06: Geneva.
10. ecoinvent Centre, *ecoinvent data v1.3, Final ecoinvent reports No. 1-16*. 2006, CD-ROM, ISBN 3-905594-38-2, Swiss Centre for Life Cycle Inventories: Duebendorf, Switzerland. Retrieved from www.ecoinvent.org.
11. PRé Consultants, *SimaPro 7.1*. 2007: Amersfoort, NL. www.simapro.com.
12. SP5-Partners, *Definition of the scenarios and boundary conditions used to investigate the different biofuel production pathways - well to tank - Revision 2007*. 2007, RENEW - Renewable Fuels for Advanced Powertrains, Sixth Framework Programme: Sustainable Energy Systems, Europäisches Zentrum für erneuerbare Energie: Güssing.
13. Guinée JB, (final editor), Gorrée M, Heijungs R, Huppes G, et al., *Life cycle assessment; An operational guide to the ISO standards; Parts 1 and 2*. 2001, Ministry of Housing, Spatial Planning and Environment (VROM) and Centre of Environmental Science (CML): Den Haag and Leiden, The Netherlands. Retrieved from http://www.leidenuniv.nl/cml/ssp/projects/lca2/lca2.html.

14. Frischknecht R, Jungbluth N, Althaus H-J, Bauer C, et al., *Implementation of Life Cycle Impact Assessment Methods*. 2007, CD-ROM, ecoinvent report No. 3, v2.0, Swiss Centre for Life Cycle Inventories: Dübendorf, CH. Retrieved from www.ecoinvent.org.
15. MinöStV, *Mineralölsteuerverordnung: Änderung vom 30. Januar 2008 (Vorabdruck)*, in *Schweizer Bundesrat*. 2008: Switzerland. http://www.news-service.admin.ch/NSBSubscriber/message/attachments/10941.pdf.
16. ecoinvent Centre, *ecoinvent data v2.01, ecoinvent reports No. 1-25*. 2007, CD-ROM, Swiss Centre for Life Cycle Inventories: Duebendorf, Switzerland. Retrieved from www.ecoinvent.org.
17. Goedkoop M & Spriensma R, *The Eco-indicator 99: A damage oriented method for life cycle impact assessment*. 2000, Methodology Report, 2nd revised ed., PRé Consultants: Amersfoort, The Netherlands. Retrieved from www.pre.nl/eco-indicator99/.
18. Frischknecht R, Steiner R, & Jungbluth N, *Methode der ökologischen Knappheit - Ökofaktoren 2006*. 2008, Öbu SR, 28/2008, Bundesamt für Umwelt (BAFU), ÖBU Schweizerische Vereinigung für ökologisch bewusste Unternehmungsführung: Zürich und Bern. Retrieved from www.esu-services.ch/ubp06.
19. Frischknecht R, Steiner R, Braunschweig A, Egli N, et al. *Swiss Ecological Scarcity Method: The New Version 2006*. in *The Seventh International Conference on EcoBalance, Nov 14-16, 2006*. 2006, Tsukuba, Japan. Retrieved from www.esu-services.ch/ubp06.
20. Baitz M, Binder M, Degen W, Deimling S, et al., *Kurzfassung: Vergleichende Ökobilanz von SunDiesel (Choren-Verfahren) und konventionellem Dieselkraftstoff*. 2004, PE Europe GmbH im Auftrag von Volkswagen AG und DaimlerChrysler AG: Stuttgart, DE. http://www.choren.com/de/choren_industries/informationen_presse/info_downloads/.
21. Jungbluth N, Frischknecht R, & Faist Emmenegger M, *Review of LCA case studies for BTL-fuel production*. 2004, RENEW - Renewable Fuels for Advanced Powertrains, Sixth Framework Programme: Sustainable Energy Systems, Deliverable: D 5.2.1, ESU-services: Uster.
22. Reinhardt G, Gärtner S, Patyk A, & Rettenmaier N, *Ökobilanzen zu BTL: Eine ökologische Einschätzung*. 2006, IFEU im Auftrag der Fachagentur Nachwachsende Rohstoffe e.V.: Heidelberg. Retrieved from www.fnr-server.de.