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Johann Heinrich von Thünen-Institut

IEA Bioenergy Task 38 - Case Study

Environmental Assessment of Liquid Biofuel from Woody Biomass

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by

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List of Abbreviations

AP	Acidification Potential
C_2H_4	Ethylene
CML 2001	Life cycle assessment method developed at the Institute of Environmental Science, University Leiden 2001
CO	Carbon monoxide
CO_2	Carbon dioxide
DBH	Diameter at breast height
DLUC	Direct land-use change
EP	Eutrophication potential
EU	European Union
fert.	With fertilizer application
FT	Fischer-Tropsch
GHG	Greenhouse gas
GWP	Global warming potential
ha	Hectar
HC	Hydrocarbons
hr	Hour
ILCD	International reference life cycle data system
ILUC	Indirect land-use change
IPCC	Intergovernmental Panel on Climate Change
kW	Kilowatt
kWh	Kilowatt hour
LCA	Life cycle assessment
LHV	Lower heating value
MJ	Mega joule
N_2O	Nitrous oxide
NH_3	Ammonia
NMVOC	Non-methane volatile organic compounds
NO_3	Nitrate
NO_x	Mono-nitrogen oxides
O_2	Oxygen
odt	Oven-dry tonne
PNV	Potential natural vegetation
PO_4	Phosphate
POCP	Photochemical ozone creation potential
SO_2	Sulfur dioxide
SOC	Soil organic carbon
SOM	Soil organic matter
SRC	Short rotation coppice
VOC	Volatile organic compound
w/o fert.	Without fertilizer application
yr	Year

1 Introduction

In view of climate change the objective of securing mobility without loading the atmosphere with additional carbon dioxide emissions is increasingly being regarded. In this context liquid biofuels from renewable resources became more and more popular in recent years. It is feared that first-generation biofuels from rapeseed, wheat or oil palm may cause worse environmental impacts than their fossil reference and may lead to an increase in food prices (Blanco-Fonseca et al. 2010). To avoid additional environmental burdens and occupancy of agricultural fields, the interest in so-called second-generation biofuels, produced from wastes, residues or non-food cellulosic material, arise. Fischer-Tropsch (FT) diesel as one of these second generation biofuels, made from cellulosic biomass, may prospectively gain in importance (Eisentraut 2010).

In 2009, the European Union set sustainability criteria for biofuels to be eligible for support (Directive 2009/28/EC). The European Commission has to provide updated default greenhouse gas impact values for future biofuels like FT diesel until the end of 2012. This illustrates the growing importance of second-generation biofuels and the need for assessing their environmental impacts.

2 Scope

2.1 Objectives

The EU directive sets up a 10 % minimum target for the share of biofuels in the overall road transport fuel consumption by the year 2020. To be accounted to this target the biofuels GHG emissions have to be at least 35% lower compared to its fossil alternative. The assessment of GHG savings has to comprise the whole life cycle of the biofuel, including biomass cultivation and transport, its processing into biofuel as well as the biofuels use phase.

This study examines the environmental impacts of the production chain of FT diesel via Choren-process based on different woody resources. There are two alternative processing routes studied. In Chapter 4.1.4 the two versions will be explained in detail. The considered base materials are: wood from short rotation coppice (SRC), pulpwood from conventional forestry, wood residues from forest operations and untreated post-consumer waste wood. The overall target of the study is to compare these woody based biofuel production chains with fossil diesel in terms of total GHG emissions and further environmental impacts which are eutrophication, acidification and photochemical ozone formation.

2.2 Method

For this study life cycle assessment method according to ISO 14040 and 14044 (DIN 2006) is used. The method is often used for assessing environmental impacts of a product or product system over its entire life cycle. A balance sheet of the major in- and outputs of the product system is prepared, which subsequently is used to assess the environmental impacts of the product system. In this study the so called CML 2001 method by Guinée (2002) has been adopted for impact assessment. IEA Task 38 focuses on the assessment of greenhouse gas emissions from biofuels and their impact on global warming. Therefore the major part of this LCA study is greenhouse gas impact assessment. The CML 2001 method calculates greenhouse gas impact using the global warming potential calculated according to IPCC definition (Solomon 2007) over a time horizon of 100 years. In addition, three other impact categories have been analysed:

- eutrophication potential (EP)
- acidification potential (AP)
- photo-oxidant creation potential (POCP)

2.2.1 Carbon accounting

According to the Task 38 assessment methodology (Horne and Matthews 2004) and the IPCC reporting guidelines (IPCC 2006) carbon dioxide[1] emissions from combustion of sustainably produced biomass are not accounted in this study. It is assumed that the same amount of CO_2 emitted during combustion is sequestered as the biomass is regrown (IPCC 1996)[2]. In comparison, the fossil energy system releases additional CO_2 into the atmosphere during production and utilization. Nevertheless the bioenergy system is not free of CO_2 emissions. Accountable emissions occur due to fossil fuel combustion along the biomass supply chain, during fuel processing and distribution. Only CO_2 emissions originating from the additional inputs of fossil energy or other consumables are included into the calculation of greenhouse gas emissions. CO_2 emissions from the converted biomass occurring during FT diesel processing are not considered.

3 System boundaries and functional unit

3.1 System boundaries of the biofuel chains

The environmental impacts of FT diesel production based on four different raw materials and its use are assessed in this study. The considered raw materials are wood

1 Other GHGs beside CO_2 have been accounted

2 This is a conventional approach, but it is ignoring the potential impact on global warming that can arise as a result of the timing of emissions and removals

from short rotation coppice, pulpwood, harvesting residues from forestry and untreated post-consumer waste wood.

System boundaries of FT diesel production from the "fresh" resources like short rotation wood, pulpwood and forest residues comprise the different steps of biomass cultivation and processing up to FT diesel production, its distribution and utilization. Harvesting residues from forestry operations are considered as a co-product of pulpwood production. Therefore system boundaries are the same as that of pulpwood and comprise additionally collecting and processing of the residues. The four biomass supply chains considered, which are displayed in Figure 1, are described briefly below.

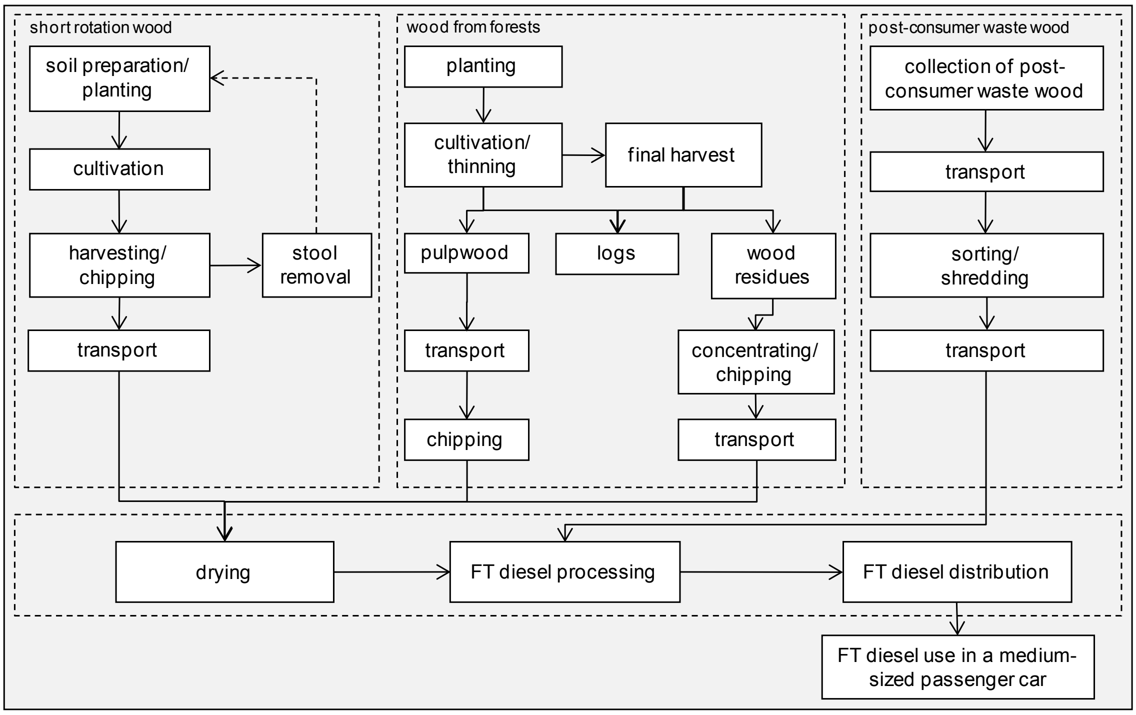


Figure 1 Biomass supply chains for FT diesel production considered within the study

The first chain is FT diesel production from short rotation poplar chips. The assessment comprises all relevant biomass production steps starting with soil preparation of a fallow agricultural site.

The second chain is FT diesel production based on pulpwood. Since the rise in prices of fuel wood in Germany there are no big differences between pulpwood and fuel wood prices. From this point of view also pulpwood is a potential base material for FT diesel production and was included into the assessment. The chain starts with the planting of seedlings in a forest stand. Pulpwood is received from thinnings as well as from final fellings. Also harvesting residues are a potential base material for FT diesel processing, and are the third chain considered. The system boundaries are similar to the pulpwood chain but additionally comprise collection, concentration and chipping.

A further woody resource for FT diesel production, the fourth chain considered, is untreated post-consumer waste wood. Since waste wood arises through another product system, the wood recycling includes processes shared with the new product: as illustrated in Figure 2, consumables and burdens of gathering, transportation and shredding of the post-consumer wood is only partly accounted within the assessment. The applied allocation will be described in chapter (5.2).

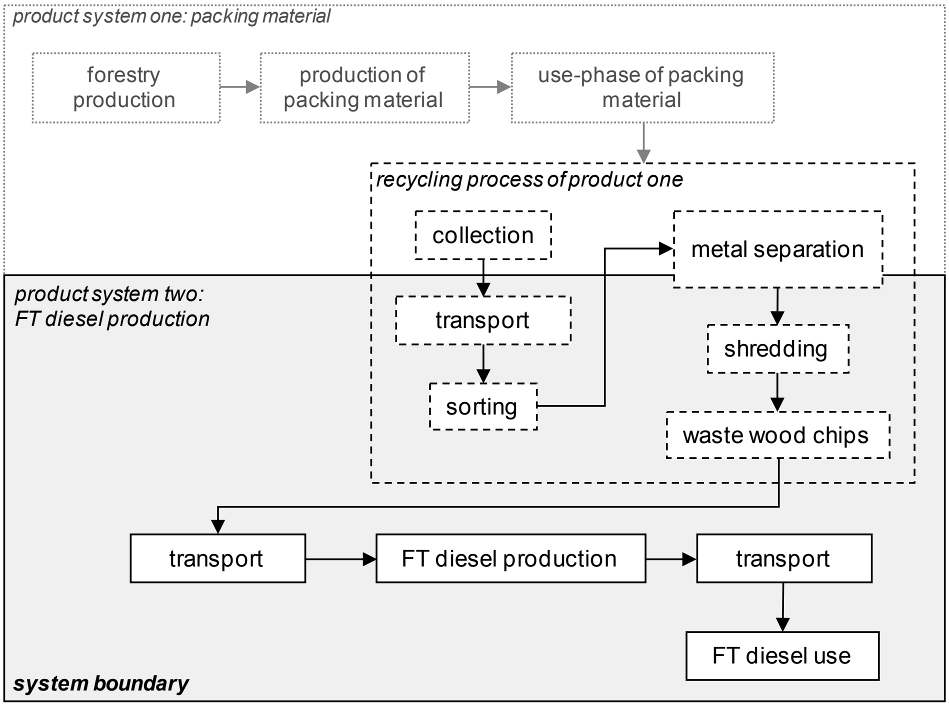


Figure 2 System boundaries for FT diesel production from post-consumer waste wood, using packing material as example

For all four chains, after transportation of wood chips to the FT diesel production plant the chips have to be dried until the required moisture content is reached. Also the distribution of the finished product to the petrol station and its use in a medium sized passenger car is considered within the system boundaries of the study.

Chapter 4 further describes the data used and allocation procedures.

The construction of buildings and machinery is not part of the assessment.

3.2 Functional unit

This study is divided into two parts. The first part focuses on the production, processing and distribution of the different woody biomass resources for FT diesel production. Within this part the functional unit "oven-dry tonne (odt)" is chosen. It should be mentioned that the displayed results for the functional unit "oven-dry tonne" do not imply the production of one oven-dry tonne in reality. This is just a theoretical reference unit. Depending on their type, the produced woody biomass resources still contain different amounts of water.

Secondly the FT diesel production process is analysed by using the functional unit "kg FT diesel". Finally, the whole FT diesel production and utilization chain is analysed by adopting the functional unit "100 km travelled distance". Like Gnansounou et al.

(2009) emphasize, it is important to include the use phase into the assessment when comparing biofuels and fossil fuels. Carbon dioxide released during vehicle operation does not load the atmosphere additionally because it was fixed before during tree growth. Hence carbon dioxide emissions of FT diesel consumption are not factored into the greenhouse gas impact of the biofuel. Additionally there are differences in the lower heating values of the fuels. That is why the "well-to-wheel" approach is applied here, where the functional unit represents a given service.

3.3 Reference systems

3.3.1 Fossil reference chain

It is assumed that FT diesel substitutes crude oil based diesel. The assessment of the reference chain comprises all steps of diesel production from extraction of crude oil, crude oil refining, distribution and use in a comparable medium sized diesel car on a distance of 100 km.

Figure 3 illustrates the differences between the bioenergy system and its fossil reference according to the Task 38 methodology (Horne and Matthews 2004).

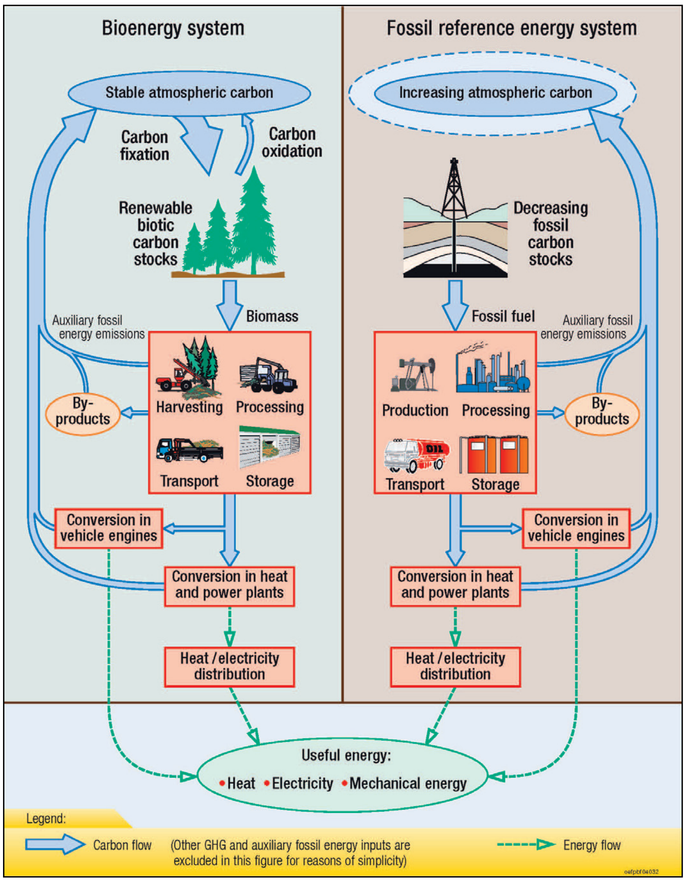


Figure 3 Task 38 standard system boundaries for the comparison of GHG balances of bioenergy chains and their fossil reference (source: Horne and Matthews 2004)

3.3.2 Reference land use

Energy use and the environmental impacts are calculated using the method of attributional life cycle assessment (LCA). Which means the balance describes the environmental properties of a life cycle, but does not account for consequences of changes in adjacent systems (Curran 2006). It is not the aim of this study to include credits or debits of the reference uses into the balances of the examined biofuel chains.

But since this study views the use of a limited source for achieving savings of energy and greenhouse gas emissions, the environmental consequences of land use change should be considered. Thus a reference land use scenario is set. The environmental impacts of the studied biofuel chains will be calculated based on this reference.

Table 1 shows the studied biofuel chains with their respective reference biomass use and reference land uses.

Table 1 Analyzed biofuel production chains and their reference biomass and land use

Biomass chain	Fossil reference	Reference biomass use and land use
Short rotation poplar to FT-diesel	Diesel refined from crude oil	Agricultural fallow land
Pulpwood to FT-diesel	Diesel refined from crude oil	Pulpwood production for paper, particle or fibre board
Wood residues from forestry to FT-diesel	Diesel refined from crude oil	Decay of residues in the forest
Post-consumer waste wood to FT-diesel	Diesel refined from crude oil	Burning of waste wood with energy recovery

For each biomass chain GHG emissions from land use change are calculated considering soil carbon changes and emissions from maintenance of the reference crop.

For the biofuel chains considered within this study a real land use change only occurs in the case of cultivating short rotation coppice on fallow agricultural land. As it will be discussed in chapter 6.1.6 soil carbon pools might change, but also greenhouse gas emissions from the mowing and maintenance of the fallow land will be avoided.

In the case of pulpwood from forests it is assumed that no impact on land use change is occurring. There is just a different use of the regularly harvested wood from commercial forests assumed, but not an increase in the harvested amount of wood. Maintenance of forest area and the sustainable use of forest resources are protected by law in Germany (BWaldG 2010). If harvested wood formerly used for pulp and paper production is increasingly used for FT diesel production the prices will rise and pulpwood will be imported from other countries (Bringezu et al. 2009). This might increase the pressure on forests there, and may result in “indirect land use change” (ILUC). It is difficult to quantify indirect land use changes which might be induced by the increased demand of pulpwood. Possible scenarios might be intensification of forestry, depletion of forest resources, but also afforestation or the establishment of plantations, if pulpwood is used for energy generation instead of paper production. At the moment no approved methodology to calculate ILUC exists. Recent proposed methodologies concentrate mainly on biofuels from agricultural crops and do not consider ligno-cellulosic based fuels. Croezen et al. (2010) evaluated available model predictions of emissions from ILUC but did not find any factors for so called second generation biofuels, amongst which is FT diesel. Laborde (2011) reported to the EU commission on land use changes induced by the European Renewable Energy Directive but also concentrated on first generation biofuels from agricultural crops. He found that 80% of land use changes due to increasing European biofuel demand are taking place within managed land. This means forests are less affected by a growing demand on agricultural feed stock.

Forest residues are increasingly used for energy production. But nevertheless not the total amount of forest residues that accumulate are extractable and usable (Mantau 2009). This means, that a part of these residues remains in the forests and secures the nutrient supply to the ecosystem. Therefore in this study it is assumed that only 50% of the total mass of forest residues is extracted which neither causes considerable intensification of biomass use nor land use changes. If the residues would not be used for energy they would decay in the forests, therefore the reference case assumes the residues decay in the forest.

4 Data and allocations

4.1 Data and parameter assumption

For modelling the software GaBi 4.0 was used (PE, LBP 2009). This tool additionally provides a database, which contains in- and outputs of the provision of various raw and auxiliary materials. General data on standard grid electricity production, fuel and lubricant oil extraction, processing and distribution, fossil energy supply chains and data on the supply chain of further consumables have been derived from the database (PE, LBP 2009).

The complete data on the fossil reference diesel chain was adopted from GaBi databases (PE, LBP 2009). It considers the country specific crude oil imports, transport distances and transport modes, as well as the properties of the national refinery facilities (cf. Table 2).

Table 2 Greenhouse gas emissions from fossil diesel and electricity supply chain in kg CO_2 eq per MJ energy content

Emission [kg CO_2 eq MJ^{-1}]	Fossil diesel	Electricity (grid Germany)
Carbon dioxide	6.93E-03	1.87E-01
Nitrous oxide	3.92E-05	2.00E-03
Sulphur hexafluoride	6.46E-10	4.86E-08
NMVOC	1.33E-06	3.13E-04
Methane	2.16E-03	7.97E-03
VOC (unspecific)	1.04E-07	1.33E-07

Information about the in- and outputs of the FT synthesis (cf. Table 3) is taken from the study of Baitz et al. (2004). The assessment of short rotation coppice cultivation used both, literature data and data generated during the joint research project AGROWOOD (Bemmann and Knust 2008). The underlying databases and assumptions for the LCA of short rotation wood production are presented more detailed in Roedl (2008).

Table 3 Inputs into the two processing routes (closed and partial open processing) of FT diesel production (after Baitz et al. 2004)

Input per kg FT diesel	Closed processing	Partial open processing
Wood chips [kg]	6.03	4.90
Natural gas [kg]	7.44E-03	6.03E-03
Sodium hydroxide	2.60E-02	2.11E-02
Hexamethylendiamine (HMDA) [kg]	1.02E-04	1.02E-04
Methyl isobutyl ketone [kg]	9.90E-05	9.90E-05
Naphtha [kg]	9.90E-05	9.90E-05
Oxygen [kg]		2.70
Nitrogen [kg]		1.52E-01
Electricity [MJ]		2.60
Water [kg]		1.35E-02

4.1.1 Biomass from short rotation coppice

It is assumed that the short rotation coppice is established on an abandoned agricultural site. Around 10.000 poplar cuttings per hectare are planted by planting machine after the soil was prepared by plough and disc harrow. The production of cuttings in a nursery was modelled after Kaltschmitt and Reinhardt (1997). Additionally the spraying of a glyphosate herbicide was considered to inhibit the growth of competing vegetation. Within the first year also a mechanical weeding is considered. Every four years the plantation is cut by forage harvester with a wood cutting attachment. We assume that 5% of the harvested biomass is lost during harvest operations.

Some studies have shown that the nutrient content of most agricultural soils in Germany is adequate to ensure stable increment of short rotation poplar without fertilizing (Kauter et al. 2001; Knust 2007), but in some cases fertiliser might be necessary. Therefore this study assesses SRC cultivation with and without fertilizer application. Where fertilizer application is considered, nitrogen (N), potassium (K) fertilizer and lime (Ca) are applied after every harvest. The required amount of fertilizer is compensating nutrients which have been removed by harvesting (Roehricht and Ruscher 2004). Table 4 shows the assumed amounts of the three spread fertilizer components after each harvest every four years.

Table 4 Amount of nutrients assumed to be applied to the SRC after each rotation

Nutrient	Spread amount [kg ha^{-1}]
Nitrogen (N)	147.9
Potassium (K)	103.4
Calcium (Ca)	96.1

The yield of the non-fertilized plantation amounts to 8 t ha^{-1} yr^{-1}. In the fertilized case the yield is assumed to increase to 9 t ha^{-1} yr^{-1}, which is a conservative assumption. Colman et al. (2006) found yield increases due to fertilizing of poplar plantations of 43-82%. In contrast other studies could not find any explicit increases in yield due to fertilization for short rotation poplar (Scholz et al. 2004; Rehfuess 1995). Because of these uncertainties the yield is assumed to increase by a modest 12.5%.

The plantation is removed after 20 years and reconverted into arable land with a mulcher, which removes the upper parts of the stumps, followed by a rotary tiller, which removes the roots. After harvesting the poplar chips are transported by lorry, with payload of 27 tonnes, from the field to the FT diesel plant, an assumed average distance of 50 km. The wood moisture (u) after harvest and during transportation is assumed to be 100%.

The following table (Table 5) provides an overview of the applied machinery and their fossil fuel consumption. Background data on fossil fuel supply chains, chemicals and fertilizer production and data on the production of further auxiliaries were taken from GaBi 4.0 database (PE, LBP 2009). Transport processes from this database have been adapted in terms of transport distance, load and driving share of different road categories. The production of the herbicide was modelled after Audsley et al. (1997). Diesel fuel consumption and operating times for field preparation, weed control and fertilizer application have been taken from the agricultural database KTBL (2006). For planting, harvesting and reconversion of the field, data were provided from field trials in Eastern Germany (Bemmann und Knust 2008). Emission factors of fossil diesel combustion have been taken from Rinaldi et al. (2005) and Kaltschmitt and Reinhardt (1997).

Table 5 Fuel consumption and used machinery in each sub-process of short rotation coppice cultivation and processing

Operation	Machinery	Fuel consumption [$l\ ha^{-1}$]	Annotation
Soil preparation	120 kW tractor with plough 120 kW tractor with harrow	25.0 9.0	
Herbicide spraying	45 kW tractor with sprayer	1.0	Glyphosate: 4 l ha^{-1} Water: 200 l/ha^{-1}
Planting	45 kW tractor with planting machine	16.6	10.458 cuttings per ha
Fertilizing	54 kW loader 67 kW tractor with drawn dry spreader	1.5	Fuel consumption in each case of N, K and Ca application
Weed control	54 kW tractor with hoe machine	5.0	
Harvesting	333 kW forage harvester 78 kW tractor with trailer	56.0 8.0	With wood cutting attachment
Stool removal	224 kW tractor with bush-hog 224 kW tractor with rotary tiller	137.0 325.0	
Transport to FT diesel plant	lorry (27 t payload)	4.9	50 km one-way

The application of nitrogen fertilizer might cause emissions in air and ground water. The most important of them are the release of ammonia (NH_3) and nitrous oxide (N_2O) as well as the leaching of nitrate (NO_3).

According to Bentrup et al. (2000) 1% of the applied amount of nitrogen is released as ammonia (NH_3).

Nitrous oxide (N_2O) emissions are directly caused by the production and application of nitrogen fertilizer. Indirectly N_2O is released following the volatilisation and leaching from managed soils and fossil fuel combustion (De Klein et al. 2006). Within the present model the emission factor from the IPCC was adopted, which assumes direct N_2O emission from the soil of 1% of the applied amount of nitrogen (De Klein et al. 2006). The indirect emissions consist of 1% from volatilised fraction and 0.75% of the leached fraction of the nitrogen applied. Concerning the emission factor of N_2O release from fertilizer production and application Crutzen et al. (2008) started a discussion. They estimate that 3-5% of the nitrogen applied nitrogen fertilizer is released as N_2O, which would have a considerable influence on the assessment results. But this estimate is also disputed by others. The release of direct N_2O emissions is influenced locally by climate and soil properties (Dechow et al. 2011). For croplands in Germany, Dechow et al. (2011) found a mean emission factor of 0.91% direct N_2O release due to nitrogen fertilizer application. This modelled emission factor supports the IPCC factor of 1% from 2006 (De Klein et al. 2006).

Nitrate leaching occurs if there is a surplus of nitrogen which cannot be absorbed by the crop. Aronsson and Bergström (2001) showed that 160-190 kg nitrogen fertilizer can be applied per hectare without any significant leaching of NO_3. In the modelled case the applied nitrogen amount is adjusted to the nutrient loss. Therefore in the present model no losses of nitrogen to the ground water are considered, since nitrogen addition is limited to the replacement of nutrient removed.

4.1.2 Biomass from conventional forestry

In general the production of roundwood includes the following production steps: planting of seedlings, pre-commercial thinning, regular thinnings, weed and pest control, liming, construction of forestry roads and final harvesting. In Central Europe it takes about 100 to 200 years until a forest stand is fully regenerated by a new generation of trees.

Forestry in Germany produces different roundwood qualities mainly as raw materials for the forest based sector. In this study it is distinguished between two products. On the one hand logs for industrial purposes like the manufacturing of pulp and paper or wood-based panels are termed hereafter, according to the FAO nomenclature (FAO 2010), “pulpwood”. And on the other hand logs for sawnwood or veneer sheet production are hereafter called “logs”.

All harvestable forest products could be potentially used for FT diesel production. At this point of time it seems feasible that also pulpwood is used for FT diesel production, because its prices are quite similar to the ones of fuel wood. Below, the production of wood in forests in general will be described. Further elaborations on the adopted allocation methods will be given in the corresponding chapter 5.1.

The sub-process modules of the forestry model namely planting, release treatment, which includes cleaning and liberation cuttings[3], pre-commercial thinning, weed and pest control, liming and construction of forestry roads are taken from the study of Schweinle (2000). The following table (Table 6) provides an overview on the machinery and their fuel consumption for the named sub-processes. The model and the data are mainly taken from Schweinle (2000) with slight changes and up-dated data on fuel consumption of modern machinery.

[3] Cleaning: Release treatment made in forest stands in which the vegetation size is not past the sapling to free the favored trees from less desirable individuals that overtop them or are likely to do so

Liberation cuttings: Removal of poor quality or un-merchantable trees to favor the growth of desirable trees. Both are realized in earlier stages than pre-commercial thinnings

Table 6 Fossil fuel consumption of the used machinery (Source: slightly updated after Schweinle 2000)

Operation	Machinery	Fuel consumption [$l\ ha^{-1}$]	Type of fuel
Planting	3000 seedlings per hectare by 60 kW tractor with planting machine	46.8	Diesel fuel
Release treatment	Cleaning and liberation cuttings by clearing saw 2.1 kW	72.0	Two-stroke mixture
Pre-commercial thinnings	Light chain saws Tractor with bush-hog	36.0 18.0	Two stroke mixture Diesel fuel
Road building	Tractor with special attachment	2.0	Diesel fuel
Liming	Helicopter	38.0	Kerosene

Stand establishment

Within the model planting of seedlings is assumed to be carried out by planting machine, although, nowadays natural regeneration is the most common form of forest regeneration. Only 20% of the stands up to a height of 4 meters have been regenerated artificially (BMELV 2009). Therefore the present model is a very conservative assumption. In the first years of forest establishment usually cleanings and liberation cuttings have to be carried out. In Table 6 both activities are summarized by the term "release treatments". Normally both measures are carried out with a clearing saw with an average fossil fuel consumption of 2.4 l per machine hour. The assumed working time for the all release treatment measures is 30 hours (Schweinle 2000).

Forest management

Pre-commercial thinnings are carried out in young stands with light chainsaws with 2.1 to 2.6 kW rated power. They are powered by two-stroke mixture and consume on average 2.4 l per machine hour. For schematic thinnings the use of a tractor with an attachment bush-hog is assumed. Three machine hours are assumed for hogging with a diesel consumption of 6 l per machine hour. Road building is assumed to be in terms of figures 54 m per hectare, see details in Schweinle (2000). Liming is sometimes necessary to prevent acidification of forest soils due to air pollutants. Liming measures were declining in the last few years. That's why liming measures are subsidized by the EU and the German government. Usually it should be repeated every 8 to 12 years to maintain the buffer effect. Nevertheless only one liming is assumed during the life span of the forest stand within the model.

Thinning and final harvesting

The sub-processes thinning and final harvesting of the model from Schweinle (2000) has been up-dated. The fossil fuel consumption of the used machinery and the amount and structure of the harvested wood product categories have been revised. Usually thinning operations start when the diameter at breast height (DBH) has reached approx. 10 cm. Thinning is the removal of trees to improve the quality and growth of the remaining trees. Final harvesting in the model is defined in accordance to yield tables (Schober 1987) and varies between the tree species. Final harvesting of spruce is drawn out in the age of 100 years, pine in the age of 120 years, beech at 150 and oak at 200 years.

To simplify the model the existence of pure forest stands was assumed. Three quarter of the German forest area consist mainly of four tree species: spruce (*Picea abies*) 28%, pine (*Pinus sylvestris*) 24%, beech (*Fagus sylvatica*) 15% and oak (*Quercus robur* and *Quercus petraea*) 10%. In many regions pure forests are still dominant. Although forestry tried over the last decades to switch from pure forests to more stable, nature-oriented forests and enforced the establishment of mixed forests. At present the share of mixed stands amounts to 39% of all forests. These proportions are considered within the model to cover the differences of forest management by a general model. Detailed information on the applied allocations will be given in chapter 5.1.

When trees are cut they have different ages and dimensions. Some trees are taken from the forest during thinning measures and others by final harvesting. The technical equipment for harvesting differs due to the dimensions of the removed trees. Therefore working times and fuel demand are varying. For the thinning of coniferous stands the use of harvesters is assumed. 30% of final harvesting in coniferous stands is carried out by harvesters. For the thinning of beech stands half of the removed wood is considered to be harvested by harvesters and the other half manually by chainsaws. Oak stands are considered to be thinned manually by chainsaws only. For final harvest of deciduous stands only manual harvesting by chainsaws is considered.

After felling, the harvested stems have to be moved from the stand to the landing. Small dimensioned coniferous and deciduous stems cut by harvesters are assumed to be extracted by forwarder. Wood from stands, which were harvested by chainsaws, is assumed to be extracted by cable skidder.

Following table shows the required equipment for the treatment of the different tree species (Table 7).

Table 7 Machinery and their fossil fuel consumption used for thinning, final harvesting and forest transport

Tree species	**Operation**	**Machinery**	**Fuel consumption** [$l\ hr^{-1}$]
Spruce	Thinning	Medium harvester and forwarder	9.0 9.0
	Final harvesting	30% with big harvester and forwarder	9.0 9.0
		70% with 2 chain saws cable skidder	4.8 6.5
Pine	Thinning	Medium harvester and forwarder	9.0 9.0
	Final harvesting	30% with big harvester and forwarder	9.0 9.0
		70% with 2 chain saws and cable skidder	4.8 6.5
Beech	Thinning	50% with big harvester and forwarder	9.0 9.0
	Final harvesting	50% with 2 chain saws and cable skidder	4.8 6.5
		2 chain saws and cable skidder	4.8 6.5
Oak	Thinning	2 chain saws and cable skidder	4.8 6.5
	Final harvesting	2 chain saws and cable skidder	4.8 6.5

Harvesters can be grouped according to their rated power (Forbrig and Klugmann 2001). There are the following categories: small harvesters up to 70 kW, medium sized from 70 to 140 kW and big harvesters with over 140 kW. The same categorisation is applied to forwarders. Within the present study the employment of medium sized harvesters and forwarders is assumed.

For manually harvesting and thinning professional chainsaws with rated powers from 4 to 5 kW are assumed, with an average petrol consumption of 2.4 l per machine hour (Ruppert 2009). The labour productivity of manual harvesting taken from KWF (2004) corresponds to the standard harvesting procedure by chainsaws with two persons; therefore fuel consumption of two chainsaws is displayed in Table 7. Skidding after manual harvesting is considered to be carried out by medium sized cable skidders (80-120 kW).

Data on labour productivity of thinning, harvesting and wood extraction were taken from a database of the German Agency of Forest Technology KWF (KWF 2004).

Data on the proportion of timber from thinnings and final harvests have been derived from the German Forest Accountancy Network (BMELV 2007). On average 65% of the total roundwood stems from thinnings and 35% from final harvests. The in general extracted proportion of pulpwood was determined by means of yield and assortment tables from Schöpfer and Dauber (1989) (see section 5.1).

The harvested and extracted wood has to be transported from the forest site to the wood-using facility. Within this study pulpwood is assumed to be transported by lorry over 70 km to the FT diesel plant.

For FT diesel processing the roundwood sections have to be chipped. It is possible to do this already in the forest or later on in the FT diesel plant. Within this study it is assumed that the logs are chipped in the FT diesel production plant by a stationary chipper with 260 kW (Kanzian 2005). A dry matter loss during chipping of 1% is assumed (Betz et al. 2002). Emissions of chipping have been estimated by means of emission factors from Kaltschmitt and Reinhardt (1997).

Fresh wood from forest has average moisture content (u) of 100% on an oven-dry basis. During processing, temporary storage and hauling the wood moisture decreases to about 90%. For the FT diesel synthesis wood moisture content (u) of max 25% is required. Therefore the fresh wood has to be dried. It is assumed that drying is done in the FT diesel plant with the help of waste heat from the process (see chapter 4.1.4).

Forest residues

With every thinning or harvest operation residues like branches or other residues are derived as co-products. These harvest residues consist of needles or leaves, limbs, stumps, roots, undersized stems and brush. Usually these residues are left in the forest after logging. Sometimes they are collected by private persons for fuel wood. In recent years the extraction of forest residues became also more important for operating companies in the energy sector and they are also a reasonable resource for FT diesel production.

After logging forest residues are scattered all over the stand and have to be gathered, concentrated and chipped. It is assumed that the residues are collected in the stand and transported to the forest road by a forwarder. Forwarder productivity was taken from KWF database (KWF 2004). On average a productivity of 5 oven-dry tonnes per working hour was assumed for all tree species. After moving the residues to the landing they are left for drying. During summer wood moisture (u) can be reduced from 100% to 43% within a few months. Therefore the moisture content of the delivered chips was assumed to be 43%. After pre-drying the material is chipped by a portable chipper mounted on a truck (ca. 300 kW). Kaltschmitt et al. (2009) gave a range of fuel consumption of chippers from 0.7 to 1.7 l per tonne of wet material. After chipping it is assumed that the chips are transported 70 km by lorry (40 t operating weight) to the FT production facility. As stated before, max moisture content (u) of 25% is required for input material to the FT diesel production process. To reach this moisture the delivered chips are dried in the FT diesel plant with the help of waste heat from the process.

4.1.3 Post-consumer waste wood

A further raw material base for FT synthesis is untreated post-consumer waste wood, hereafter called “waste wood”. It is assigned to category A1 of the German post-consumer waste wood classification system. Waste wood is collected via a recycling system since it is regulated by law (§4 Abs. 1 KrW-/AbfG) that prohibits the disposal of waste with organic compounds to landfill. Waste wood belonging to category A1 mainly consists of wooden packing materials like pallets, cable drums, crates, packing cases and untreated construction timber or untreated solid wood. Wooden packing materials are mostly made of softwood and only partly of hardwood. An inventory of wood species of marketable waste wood chips (Lang 2004) showed a proportion of 83% softwood and 17% hardwood chips. Usually the waste wood is collected, transported to the recycling plant, sorted, separated from metals and shredded. Within this study it is assumed that the waste wood is collected and transported to the recycling plant within a radius of 50 km. Information on the average productivity and the energy demand of a standard recycling plant in Germany is provided by Wollf (2005). He found a productivity of 15 t waste wood per hour. Considering average moisture content (u) of 15% on a dry basis (d.b.) (see Trübswetter 2009) it can be calculated that about 13 oven-dry tonnes (odt) waste wood are treated per hour. For the whole treatment process from pre-shredding to chipping Wolff (2005) assumes an electricity demand of 21.5 kWh per tonne moist waste wood. Translated into oven-dry wood this means 25 kWh odt^{-1} are used. In contrast Jungbluth et al. (2002) report an electricity consumption of 9 kWh per cubic meters bulk volume. Translated by a converting factor of 5.2 CUM odt^{-1} (FAO 2004) it amounts an electricity demand for the whole recycling process on about 47 kWh per oven-dry tonne waste wood. A big waste shredder additionally uses 36 MJ of fossil diesel for shredding of one oven-dry tonne of post-consumer waste wood. Rivela et al. (2006) found also an electricity consumption of more than twice the number of Wollf (2005) for a Spanish waste wood recovery centre. Table 8 summarizes the figures of productivity and energy consumption given by the authors named. In the recent study the more conservative data by Jungbluth et al. (2002) were assumed.

The applied allocations concerning the recycling process will be described in the corresponding chapter (5.2).

Table 8 Productivity and electricity demand of sorting, metal separation, pre-shredding, conveying and chipping of post-consumer waste wood (calculated after Wolff 2005)

Source	Productivity	Power consumption	Fossil diesel consumption
Wollf (2004)	13 odt hr^{-1}	25 kWh odt^{-1}	
Jungbluth et al. (2002)		47 kWh odt^{-1}	36 MJ odt^{-1}
Rivela et al. (2006)		55 kWh odt^{-1}	

Within this study it is assumed, that the waste wood chips are transported to the FT production facility after their processing. The analysis of raw material supply of the Choren pilot plant showed, that the facility very much depends on imports of waste wood from abroad (Freytag 2009). Therefore in this study a transport distance of treated waste wood to the FT facility of 200 km is assumed.

4.1.4 Fischer-Tropsch diesel production process

The study examines the FT diesel production via Choren-process. The process consists of the gasification of biomass and the subsequent Fischer-Tropsch synthesis. The gasification step requires pressure and high temperatures. Via Fischer-Tropsch synthesis the received gas from the gasification step is converted into liquid hydrocarbons. With the help of additives a high cetane diesel fuel is produced. Oxygen, nitrogen, hydrogen and catalysts are required as auxiliary substances for the process. Figure 4 gives a schematic overview of the process steps and consumables of FT diesel synthesis.

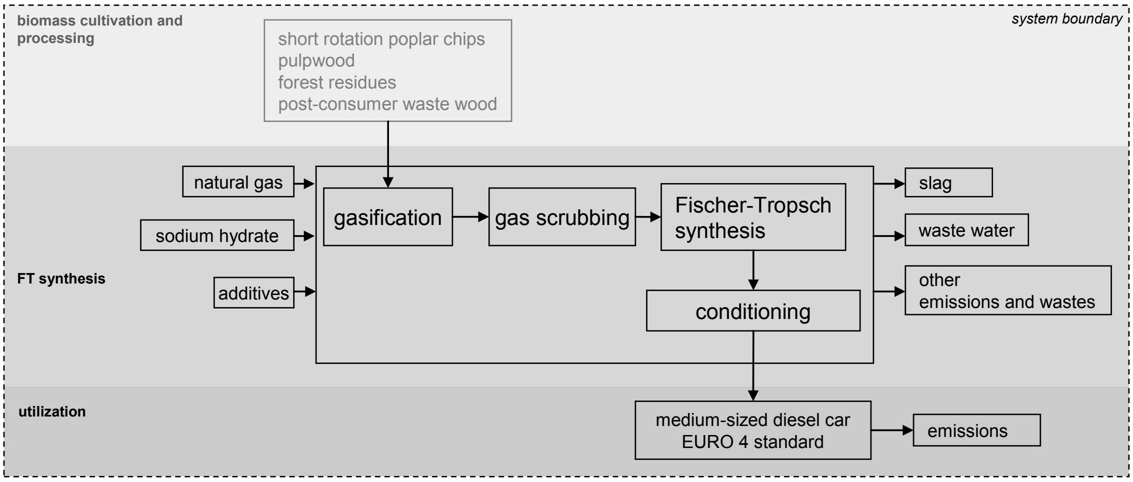


Figure 4 System boundaries and process steps of Fischer-Tropsch diesel synthesis

The FT diesel synthesis process is still in the pilot phase. Two alternative process routes are possible at this time. They differ in terms of additionally required input of chemicals and energy. For the first version, hereafter called “closed processing”, the required consumables are mostly obtained from the woody biomass during the process. These are oxygen, hydrogen, heat and power. Only some consumables like natural gas, sodium hydrate and several additives have to be added to the system from outside. Therefore this process version is characterized by a quite wide input-output ratio. 6 kg (od) wood is consumed per kg FT diesel produced.

In the second case, hereafter called “partial open processing”, electricity, nitrogen, hydrogen, oxygen natural gas, sodium hydrate and additives are added from outside.

Thus the input-output ratio from wood input (kg od) to diesel (kg) output amounts to 4.9:1.

The process requires the input of wood chips with a moisture content (u) of 25%. Chips from SRC, pulpwood or forest residues have to be pre-dried before gasification. It is assumed that the chips are dried with a belt drier that requires electrical power and heat input (Kneip and Minette 2008). The heat demand is covered by waste heat from the synthesis process in all cases and the electrical power is provided from the grid in both processing routes.

The necessary background data of extraction and processing of the named consumables is taken from GaBi 4 database. Data on process parameters and material and energy flows were derived from Baitz et al. (2004) and Choren (2009).

4.1.5 Use phase of Fischer-Tropsch diesel

The utilization phase of the FT diesel is included into the assessment. This is essential for the comparison of biofuel to its fossil reference (see chapter 3.3.1). Fossil fuels and biofuels differ in terms of CO_2 emissions from their use phase. CO_2 emissions from biofuel combustion are not contributing to the global warming. They are considered to be “neutral”, because the carbon dioxide has been fixed before during plant growth.

The finished FT diesel is distributed to the petrol stations. For that within this study the delivery of FT diesel by lorry (40 tonnes) within a radius of 100 km is assumed. Consumption and emission factors for road transport have been taken from the GaBi 4 database (PE, LBP 2009). For its use the transport distance, load and driving share of different road categories have been adjusted to the assumptions, mentioned before.

Subsequently the utilization of the FT fuel in a medium sized diesel car is assumed. The calculation of the resulting emissions is based on the EURO 4 emission standard. The fuel consumption on a given distance depends on the lower heating value (LHV) of the fuel. FT diesel has a slightly higher LHV than fossil diesel (Table 9). Fuel consumption of a medium sized car was averaged over all street categories. The data on fuel consumption and emissions were taken from the database on emission factors for road transport in the German speaking countries Germany, Austria and Switzerland (Keller et al. 2004). For car operation by FT diesel these emission factors of fossil diesel have been adjusted according to Baitz et al. (2004). Hydrocarbon, carbon monoxide and particle emissions are lower for FT diesel use, while the emissions of nitrogen oxides (NO_x) remain constant. There are no sulphur dioxide emissions arising from FT diesel use. The following table (Table 9) summarizes heating values, fuel consumption per kilometre and emission factors of FT diesel and fossil diesel.

Table 9 Comparison of lower heating values, fuel consumptions per km and emission factors of fossil diesel and Fischer-Tropsch diesel

		Fossil diesel	FT diesel
Lower heating value	[MJ kg^{-1}]	42.96	43.81
Fuel consumption	[g km^{-1}]	48.27	46.82
CO_2	[g km^{-1}]	152.06	145.62
CO	[g km^{-1}]	0.0798	0.0040
NO_x	[g km^{-1}]	0.3061	0.3061
Particle	[g km^{-1}]	0.0149	0.0089
HC	[g km^{-1}]	0.0188	0.0009
SO_2	[g km^{-1}]	0.0048	-

4.2 Fossil reference system

The fossil reference fuel chain was adopted from the database GaBi 4 by PE, LBP (2009). Within their model of crude oil refinery they apply a combination of allocation by net calorific value and mass.

5 Allocation

Within this study different cases of biomass production are assessed. Some of them produce multiple outputs. For this study an attributional approach of life cycle assessment modelling was chosen. Emissions and resource consumption are allocated between the different co-products. Allocation was necessary in several biomass production processes except wood production in short rotation coppice, where poplar chips are the only product. Biomass resources production in forests and waste wood distribution require an allocation procedure, which will be described in the following section.

5.1 Pulpwood and forest residues

As described in chapter 4.1.2 forestry produces two main products which are logs and pulpwood and forest residues as a co-product respectively. Due to growing demand on fuel wood, forest residues have a positive economic value, thus burdens of the wood production chain are also attributed to the forest residues. It is assumed that only half of the totally accruing amount of the residual wood from felling, limbing and bucking operations is used for energy purposes. The other part is, for environmental and logistical reasons, considered to remain in the forest stands. The extracted portion of the total residual wood will be hereafter named “fuel wood”.

Which wood product categories can be obtained from a forest stand, depends on the stands diameter distribution (DBH-diameter at breast height). With the help of yield tables (Schober 1987) the average diameters of the harvested trees during thinnings and final harvesting have been identified. To determine the resulting wood product categories an “assortment table” (Schöpfer and Dauber 1989) was employed. Assortment tables display only the merchantable wood categories and the non-usable parts of the tree which are thicker than 7 cm. Latter denote residues remaining after limbing and bucking of the trees. In order to determine the total amount of harvested biomass expansion factors have been used. These biomass expansion factors were calculated from extracts of the Second German National Forest Inventory (BMELV 2004b). By subtracting the merchantable timber biomass volume from the total biomass volume the amount of available slash was calculated. The following figure visualizes the different parts of a tree and their attribution to the product groups.

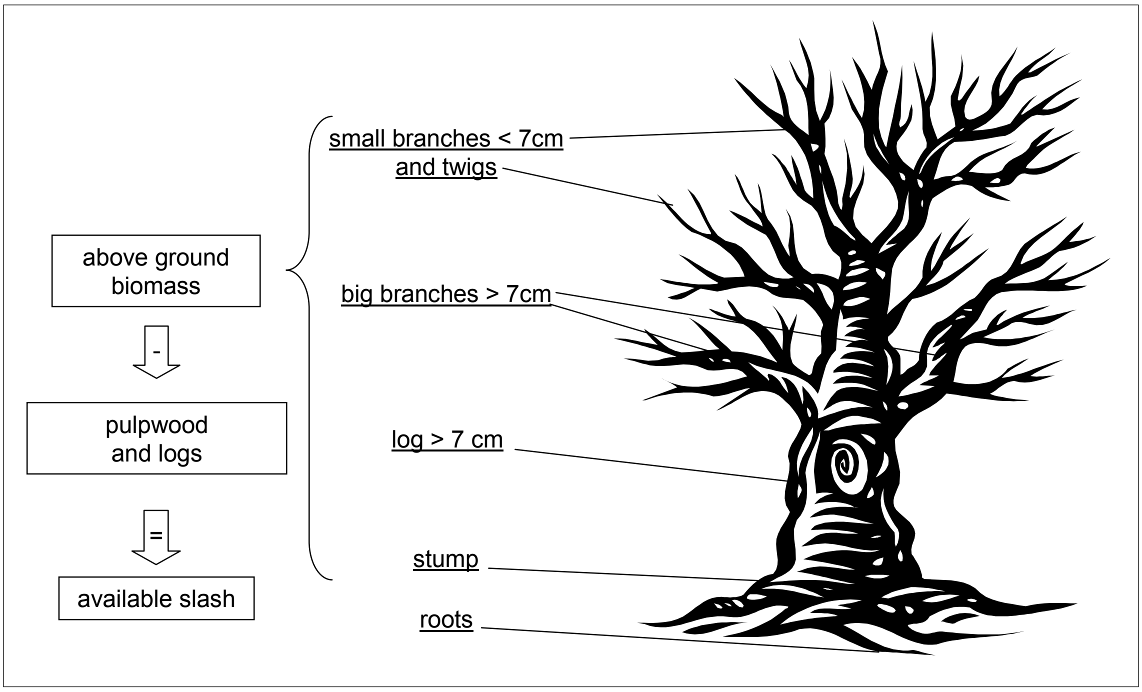


Figure 5 Compartments of forest biomass and composition of wood residues

Since it is assumed that only half of the total amount of slash in a stand is used for fuel wood, it appears that there are in fact 4 products from forest operations. These are namely logs, pulpwood, fuel wood and remaining residues. Within the model it is assumed that harvesting operations during thinnings and final felling always produce each of these four products in a certain proportion. The proportion of residual wood on the total biomass of a tree depends on the tree species. Deciduous trees have a bigger crown and therefore a higher percentage of non-usable biomass.

Data on the species composition of the totally harvested wood in Germany was required to determine the share of each tree species in the potential available mix of harvest residues. Their percentage of the totally harvested amount of wood in the period of

2008 to 2012 (Table 10) was derived from the German National Forest Inventory database (BMELV 2004 a-c).

The proportion of the tree species in each harvested wood category differs from that of the total amount of harvested wood. Beech for example has the biggest share of the harvested pulpwood. This has been taken also under consideration within the model.

Table 10 Tree species composition of the totally harvested wood in Germany 2008-2012 (WEHAM)

Tree species group	Share of the totally harvested wood (all categories)
Oak	8%
Beech	31%
Spruce	42%
Pine	19%

Resource consumption and emissions of the employed machinery for planting, cleaning, liberation cutting and pre-commercial thinning are allocated to the products according to their share and weighted by their economic value. Also any further upstream resource consumption and environmental burdens from planting are allocated to products according to their economic value. The timber and fuel wood prices at forest road have been derived from EUWID (2009 a-d).

Table 11 Wood products derived during thinnings and final felling ordered by tree species, their market prices and applied allocation factor, for each wood category

Harvest operation	Species group	Category	Share	Price [EUR odt-1]	Allocation
Thinning	Spruce	Logs	41%	174	68%
		Pulpwood	34%	87	28%
		Fuel wood	12%	37	4%
		Remaining residues	12%	0	0%
	Pine	Logs	33%	104	47%
		Pulpwood	46%	78	49%
		Fuel wood	11%	33	5%
		Remaining residues	11%	0	0%
	Beech	Logs	26%	95	36%
		Pulpwood	51%	75	56%
		Fuel wood	11%	52	8%
		Remaining residues	11%	0	0%
	Oak	Logs	38%	205	74%
		Pulpwood	29%	65	18%
		Fuel wood	17%	51	8%
		Remaining residues	17%	0	0%

To be continued next page

Table 11 continued

Harvest operation	Species group	Category	Share	Price [EUR odt^{-1}]	Allocation
Final Felling	Spruce	Logs	81%	195	97%
		Pulpwood	2%	87	1%
		Fuel wood	9%	37	2%
		Remaining residues	9%	0	0%
	Pine	Logs	78%	142	94%
		Pulpwood	6%	78	4%
		Fuel wood	8%	33	2%
		Remaining residues	8%	0	0%
	Beech	Logs	60%	138	81%
		Pulpwood	19%	75	14%
		Fuel wood	10%	52	5%
		Remaining residues	10%	0	0%
	Oak	Logs	57%	377	93%
		Pulpwood	10%	65	3%
		Fuel wood	16%	51	4%
		Remaining residues	16%	0	0%

5.2 Post-consumer waste wood

The post-consumer waste wood is not directly generated in a primary production process but stems from a recycling process. The wood which is primarily produced in forests is used in a first product system e.g. for pallet production or constructions. At the end of its life it is treated and can be used in a secondary product system. In the case of waste wood utilization for biofuel production the recycling is considered to be an open-loop recycling situation, because the material is not reused in the same product system. The recycling process is on the one hand the end-of-life processing of the first product system and at the same time the extraction process of the second system. Resource consumption and emissions of the recycling process are therefore shared between the first and the second product system. For allocation the economic values of the products are applied. The ILCD handbook (EC JRC 2010) suggests the following allocation procedure: Wood waste has a negative market price; one has to pay for waste wood disposal. But during the recycling process a product with a positive market value is produced. For that reason all emissions of the waste treatment process are attributed only to the first production system until the product crosses the market value of zero. All consumptions and emissions resulting from the production of a valuable product are allocated to the second product system.

Within the allocation applied prices of waste wood disposal were taken from price lists of waste disposal sites throughout Germany. On average there is a fee of 50 EUR for the acceptance of one tonne untreated waste wood by a recycling facility (see Annex 1 Table

16). The prices of class A1 waste wood chips in the year 2009 have been averaged over all regions and quarters (see Annex 2 Table 17). One tonne of chipped untreated waste wood was offered on an average price of 30 EUR in 2009.

Thus 62% of emission and consumables from the recycling process are allocated to the first product system for post-consumer waste wood treatment. Therefore the second product system carries only 38% of consumables and emissions from the recycling process.

Due to the landfill prohibition law it is considered in this study that 100% of post-consumer waste wood from the first product system is recycled.

6 Results

In the following, the assessment of environmental impacts of FT diesel production and use are organized in three parts. Along the production chain energy consumption, emissions and environmental impacts are assessed. The first part's focus is on the impacts of production and processing of the different biomass resources. Afterwards the differences in energy consumption between the two processing routes of FT diesel production will be analysed. In the following part the full production chains from biomass production to FT diesel consumption will be compared in terms of their environmental impacts. The result chapter will highlight some aspects from the life cycle inventory which are non-renewable energy consumption (6.1.1) and carbon dioxide emissions (6.1.2). Finally the different impact assessment results will be presented.

6.1 Impacts of biomass production and distribution

Four different woody biomass resources for FT diesel production have been assessed. These resources can be divided into two groups. On one side there is fresh, on purpose grown biomass, like wood from short rotation plantations or pulpwood from forests. And on the other side there are by-products or wastes, like post-consumer waste wood or forest residues. Due to differences in production, processing and wood properties, the production of every wood resource features its typical energy consumption pattern. This will result in varying emissions and environmental impacts of each biomass resource.

6.1.1 Use of fossil energy

The following figure (Figure 6) displays the consumption of non-renewable energy for biomass production, processing and its transport to the conversion facility.

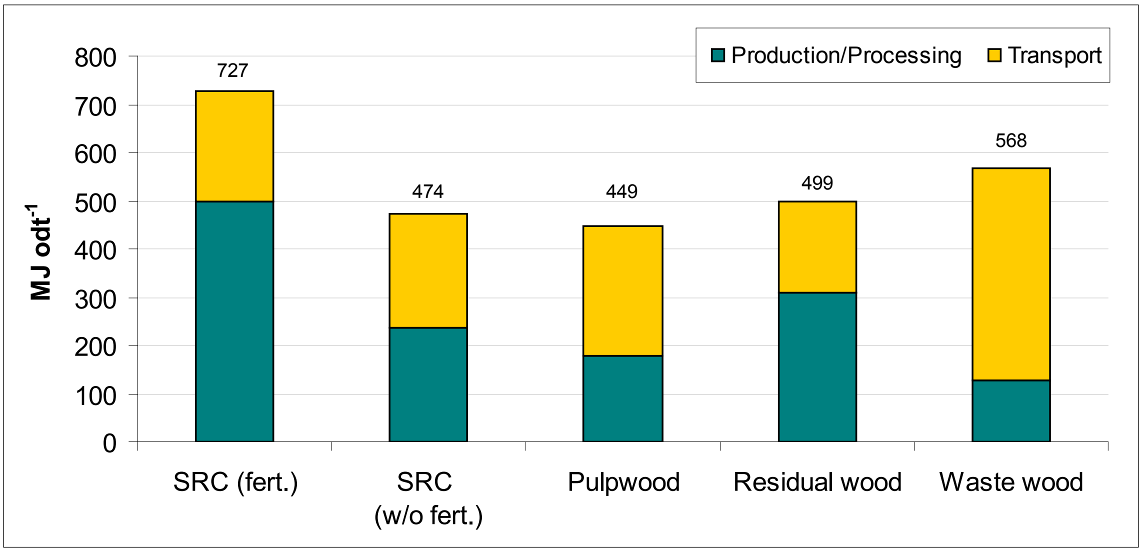


Figure 6 Consumption of non-renewable energy due to biomass production, processing and transport; per 1 oven-dry tonne (odt)

The production of wood in fertilized short rotation coppice requires the highest non-renewable energy input of all studied resources. This is mainly attributed to site preparation, application of chemicals and fertilizer and also to short harvest cycles. The whole supply chain of wood from fertilized SRC requires 727 MJ odt^{-1}. Whereas the non-renewable energy input could be reduced to 474 MJ odt^{-1} if the short rotation plantation is grown without fertilizer application.

The applied quantity of fertilizer considered here is very low and is applied just once every four years. Short rotation poplar coppice does not necessarily need to be fertilized. Studies found that it is also possible to do without fertilizer application (Knust 2007; Kauter et al. 2001; Boelke 2006). Without fertilizing consumption of non-renewable energy for short rotation coppice production could be halved (52%). The consumption of non-renewable energy could be reduced from 497 to 237 MJ per oven-dry tonne (Figure 6).

The production of one tonne pulpwood demands in contrast the lowest non-renewable energy input of all compared resources (449 MJ odt^{-1}). This is due to longer production periods in the forests, effective harvesting and hauling procedures and stationary chipping of the logs. But also the economic allocation procedure leads to relatively low emissions, due to the low price of pulpwood. Besides a relatively high proportion of beech wood is considered, whose production demands fewer non-renewable energy than those of other tree species. This is mainly due to higher wood density and long rotation periods.

The non-renewable energy consumption for processing and transport of residual wood is rather high. 499 MJ odt^{-1} of non-renewable energy are required, although forest residues are a co-product of roundwood production. This is due to the energy cost of gathering and extraction of the residues from the forest stands and their chipping in the forest.

The processing of waste wood has the lowest non-renewable energy demand. But the non-renewable energy use for the transport of waste wood to the FT production plant is higher than for the other biomass resources. This is due to the assumption that the sufficient provision of waste wood to the conversion plant could only be ensured by importing waste wood from abroad (see chapter 4.1.3).

On average an oven-dry tonne (odt) of wood embodies 18,500 MJ of energy. The output-input ratio to processing and transporting one oven-dry tonne of the different biomass resources varies between 41:1 and 25:1. Highest ratios indicate a low non-renewable energy input.

6.1.2 Carbon dioxide emissions

The following figure (Figure 7) displays the carbon dioxide emissions which occur during the production, processing and transportation of the four studied biomass resources. The emissions are displayed per oven-dry tonne of biomass.

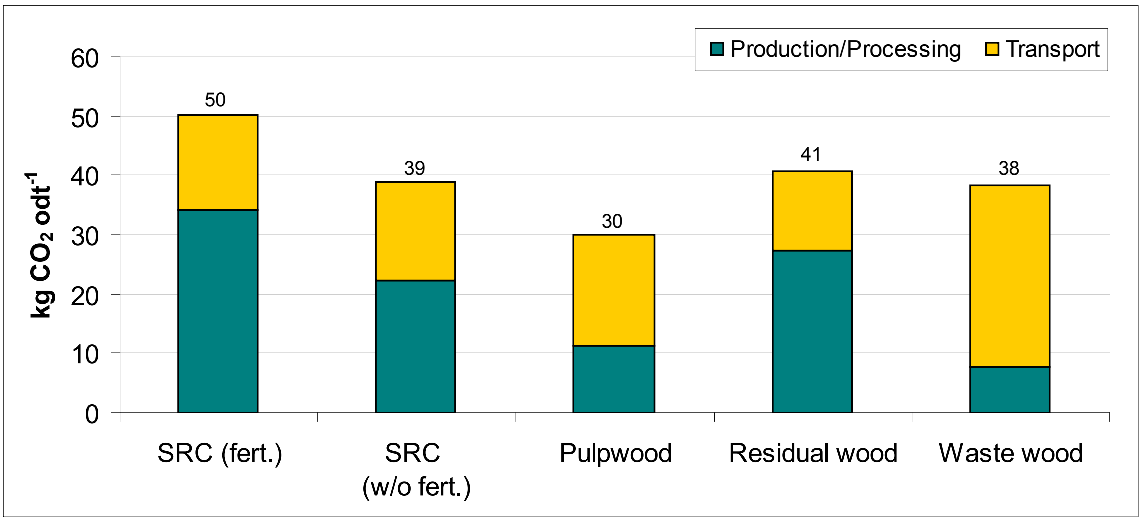


Figure 7 Carbon dioxide emissions due to biomass production, processing and transport; per 1 oven-dry tonne (odt)

The carbon dioxide emissions follow basically the pattern of the non-renewable energy consumption. The cultivation of wood in short rotation plantations causes the highest carbon dioxide emissions of all studied resources. If fertilizer application is avoided, carbon dioxide emissions from short rotation production could be decreased by 35% from 34 to 22 kg CO_2 per oven-dry tonne (Figure 7).

The production and transportation of one tonne (odt) pulpwood causes the lowest carbon dioxide emissions (30 kg odt^{-1}) of the compared resources due to a low non-renewable energy input, which has been discussed the previous chapter (6.1.1). Due to high energy input for gathering, extraction and chipping the processing of forest residues causes higher CO_2 emissions (41 kg odt^{-1}) than the provision of pulpwood. The processing of post-consumer waste wood causes the lowest CO_2 emissions of all compared resources (8 kg odt^{-1}), but long-haul carriage of post-consumer waste wood exceeds the CO_2 emissions from the transport of the other resources (30 kg odt^{-1}).

6.1.3 Greenhouse gas emissions

Carbon dioxide emissions and further greenhouse gases add up to the greenhouse gas impact. Figure 8 illustrates the greenhouse gas emissions from the provision of the assessed biomass resources

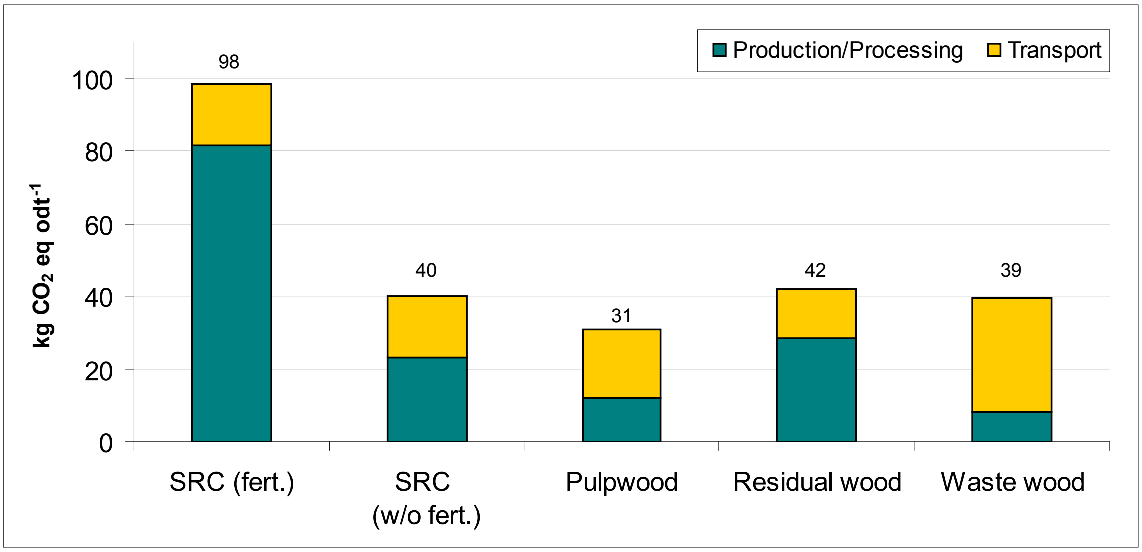


Figure 8 Greenhouse gas emissions due to biomass production, processing and transport; per 1 oven-dry tonne (odt)

The high GHG emissions (98 kg CO_2 eq odt^{-1}) from the production of short rotation wood on fertilized fields is due to greenhouse gas emissions from nitrogen fertilizer, which are emitted in addition to CO_2 emissions from fossil energy combustion. The GHG emissions from the non-fertilized production are 72% lower (40 kg CO_2 eq odt^{-1}). Like shown for carbon dioxide emissions, the provision of pulpwood has also the lowest GHG emissions (31 kg CO_2 eq odt^{-1}). The GHG emissions of wood from non-fertilized SRC, residual wood and waste wood are almost equal, although emissions of their production and processing differ.

6.1.4 Eutrophication potential (EP), acidification potential (AP) and photochemical ozone creation potential (POCP)

The eutrophication potential of the production of almost all biomass resources are low (Figure 9), except the production of short rotation coppice on fertilized fields. The impacts of its production and transport add up to 0.1 kg PO_4 eq odt^{-1}, which is almost twice the EP of the other woody resources, ranging from 0.04 to 0.05 kg PO_4 eq odt^{-1}. The high eutrophying emissions in the case of fertilized SRC, like nitrous oxide (N_2O), nitrogen oxides (NO_x) and ammonia (NH_3) occur from the application of nitrogen fertilizer and its supply chain. The combustion of fossil diesel fuel in harvesting machinery or transport vehicles causes nitrogen oxides which additionally contribute to the eutrophication potential.

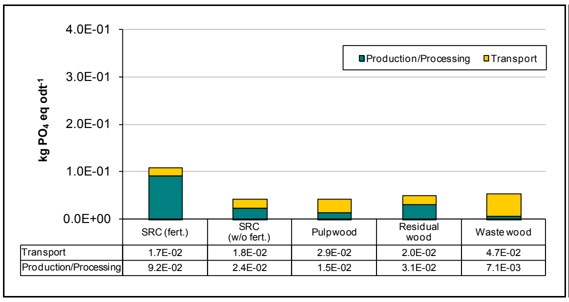


Figure 9 Eutrophication potential (EP) of biomass production, processing and transport per odt biomass

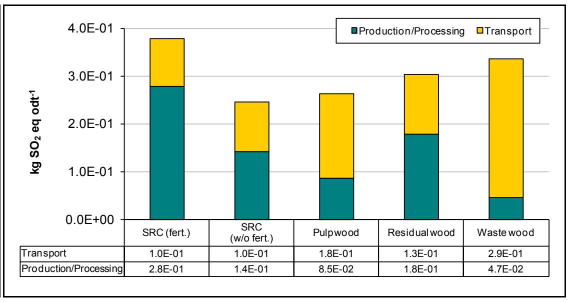


Figure 10 Acidification potential (AP) of biomass production, processing and transport per odt biomass

The acidification potential shows the same pattern as the EP but on a higher level (Figure 10). Nitrogen oxides which originate from diesel fuel combustion account for the biggest proportion of the acidification potential. That's why most of the acidification impact is caused by processes with a high level of machine employment, such as harvesting, recultivation of SRC field, transport and extraction and chipping of residual wood. The combustion of fossil diesel fuel causes sulphur dioxide emissions which is also contributing to a small fraction of the acidification potential. The highest acidification potential was found for the production of short rotation coppice when fertilizer is used. Together with the transport to the FT diesel production facility the AP is adding up to 0.38 kg SO_2 eq odt^{-1}. Ammonia and nitric oxide, which also contribute to the acidification potential, mainly occur during the supply chain of nitrogen fertilizer and its application. Therefore the AP of biomass cultivation and processing could be reduced by almost 50% to 1.4 kg SO_2 eq odt^{-1}, when short rotation coppice is cultivated without fertilizer.

The pattern of the photochemical ozone creation potential (POCP) of the different woody resources is deviating from the before analysed impact categories. The POCP is a value for the likely formation of so called "summer-smog". This means the creation of ground-level ozone from emissions of fossil fuel combustion, like nitrogen oxides (NO_x) and carbon monoxide (CO), through the exposure to solar radiation. This process mostly occurs in summer time, due to the higher intensity of solar radiation.

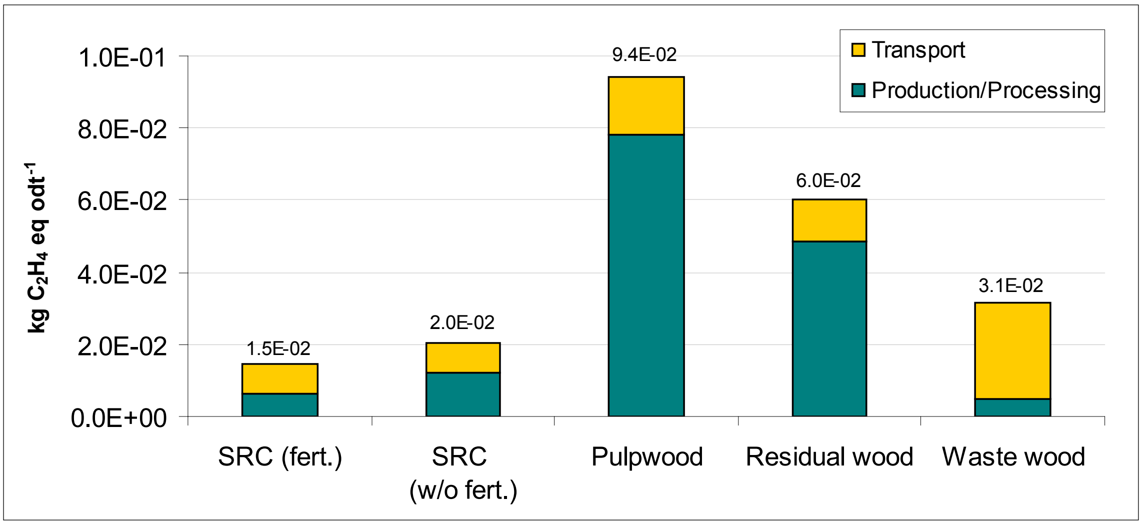


Figure 11 Photochemical ozone creation potential (POCP) of biomass production, processing and transport per odt biomass

The highest POCP was found for the production of pulpwood (9.4 kg C_2H_4 eq odt^{-1}). This is due to the high share of chainsaw employment, which releases carbon monoxide (CO) due to the combustion of two-stroke mixture. Additionally the combustion of fossil diesel in harvesting and hauling machinery contributes to the POCP due to the emission of nitrogen oxides (NO_x). Therefore the POCP of the production of pulpwood and residual wood are exceeding the POCP of the other biomass resources production. Further, the non-fertilized short rotation coppice has a higher POCP than the fertilized SRC production, which contrasts the before discussed impact category results. This is arising from the fact of higher nitric oxide (NO) emissions from the fertilized field. During fertilizer production and its application nitric oxide is released, which counteracts the creation of ozone by forming nitrogen dioxide (NO_2) and oxygen (O_2). This diminishes the POCP of the fertilized cultivation of short rotation coppice.

6.1.5 Normalization

The normalization of impact indicator results allows the comparison of impacts across the different categories. Normalization helps to better understand the relative importance and magnitude of the category results (Guinée 2002). The normalization applied in this study refers to the total environmental impact of each category in Germany in the year 2006. The above calculated impact indicator results are put into relation to these total values, which have been adopted from the GaBi database (PE, LBP 2009).

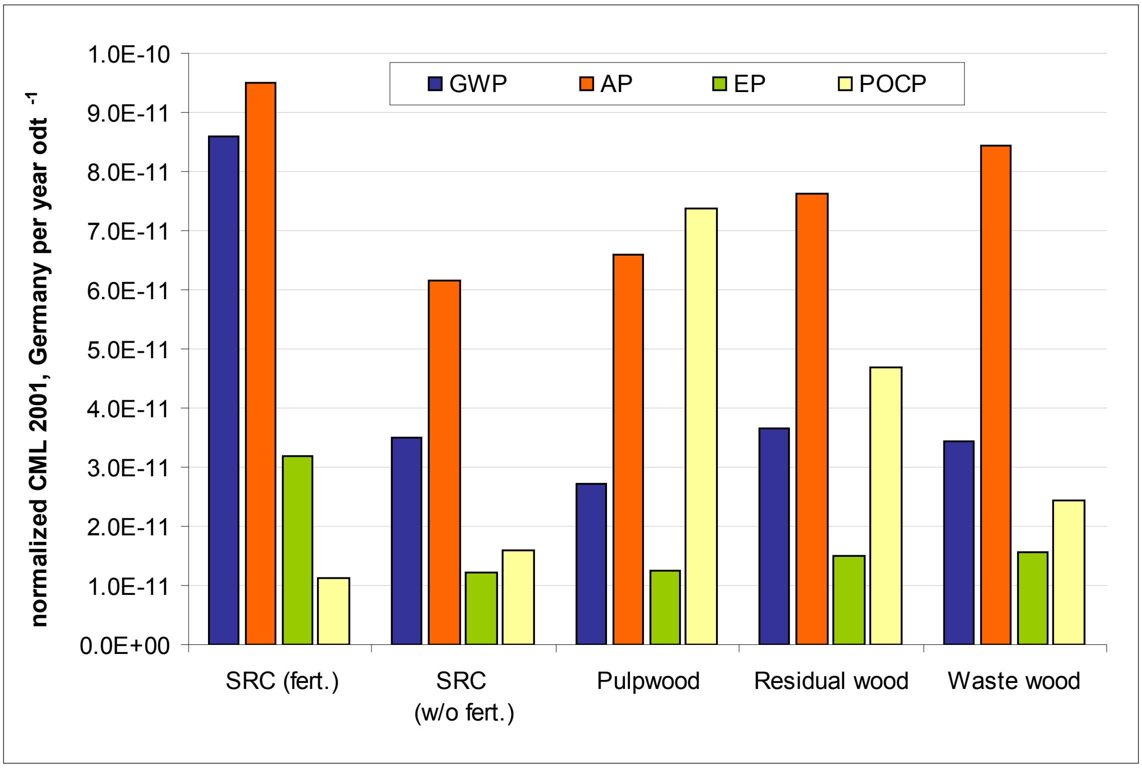


Figure 12 Normalized impact indicator values for biomass production and transport per odt biomass

The normalization in Figure 12 points out that acidification (AP) is beside greenhouse gas impact (GWP) the most important impact category for the provision of almost all biomass resources. Photochemical ozone creation (POCP) is an important impact of the provision of pulpwood and residual wood, but not so far for the other woody resources. The lowest POCP occurs during the provision of short rotation biomass from fertilized fields. Pulpwood production causes the lowest greenhouse gas impact of all assessed resources. All resources have a relatively low EP. Favourable is the biomass provision from non-fertilized short rotation coppice, which has relatively low impact values in all categories. It becomes apparent that, focusing different impact categories produces diverse results and divergent recommendations.

6.1.6 Impacts on soil carbon

If environmental impacts of fuels from biomass are assessed, also the impacts from land use itself have to be considered. The use of land for crop cultivation influences soil properties, nutrient cycle, water balance and the fauna of this acreage. Some methodological LCA studies suggested using the soil organic carbon content (SOC) as an operational indicator of land-use impacts (Milà i Canals et al. 2007; Brandao et al. 2010; Müller-Wenk et al. 2010). The SOC influences the soil fertility, the local water balance and plays a vital role in the carbon and nutrient cycle.

The release or sequestration of carbon dioxide resulting from soil carbon changes have not been included in the results presented in earlier sections. Therefore these aspects are analysed separately in this chapter. The following analysis of land-use impacts mainly focuses on the investigation of soil carbon stock changes resulting from biomass production. Furthermore impacts on the nutrient cycle will be highlighted.

Soil organic carbon (SOC) is a part of soil organic matter (SOM) in the mineral soil, which consists of decomposed plant and animal materials. It can be released from the soil during tillage, harvests or burnings due to decreased litter input or an increased decomposition rate (Saurette 2008; Grandy and Robertson 2007; Lal 2005). As a consequence especially land-use changes lead to the release of CO_2. Especially the conversion of high carbon biomes, like forests or grasslands, are causing major concerns about lots of greenhouse gas emissions which might counteract the GHG savings due to biofuel use (Searchinger 2008, Fargione 2008, Gibbs 2008, Fritsche 2009, Lapola 2010). There might be impacts from direct or indirect land-use changes. According to a definition of the European Commission (Edwards et al. 2010), direct land-use changes (DLUC) occur if the biomass is grown on uncultivated land. If biomass is grown on arable land and if there is an unchanged demand, food and feed crops have to be produced somewhere else, which might lead to indirect land use changes (ILUC). In the case of SRC cultivation at this point of time mainly marginal or abandoned lands are used. Therefore the risk of shifts in the agricultural production is considered to be low. In the case of timber production in forests it might be also very unlikely. Where biomass for energy is obtained from forests, there is also a risk that land use change or change in land management could deplete carbon stocks. If harvested wood formerly used for pulpwood is used for FT diesel production the pulpwood has to be imported from elsewhere (Bringezu et al. 2009). While the risk that this will directly result in deforestation elsewhere is considered to be low, there might be intensification of harvest (Ovando and Caparrós 2009). This could lead to a depletion of forest resources or degradation of forested lands, but it is also possible that forest area will be expanded due to the cultivation of plantations on agricultural land (Bringezu 2012; UNECE 2011).

Among the investigated cases of wood production in this study, the biggest changes in land use occur when agricultural fields are converted into short rotation coppice. In this case the land use is switched from annual crop production into a perennial system. In the case of harvest residues removal, the land use is intensified. In the case of pulpwood utilization the land use forestry remains constant. And in the case of waste wood utilization the forest production and with it all aspects of land use belong to the previous product sphere and is not part of the system boundaries. Below, some effects of land-use change or land-use intensification will be elaborated.

Cultivation of short rotation coppice

Land-use changes from an annual to a perennial cropping system are in general associated with carbon stock increases in soil and vegetation (Cherubini et al. 2009;

Lasch et al. 2010; Hillier et al. 2009; Cacho et al. 2008; Milà I Canals et al. 2007; Freibauer et al. 2004; Smith et al. 2000). Studies which assessed soil carbon changes after tree plantation establishment on croplands found increases in carbon contents of the organic soil (Guo and Gifford 2002; Deckmyn 2004). The mineral soil tends to lose carbon after conversion (Paul et al. 2002), but these losses are later overcompensated by increased carbon sequestration (Hansen 1993; Paul et al. 2002; Saurette 2008; Grigal and Berguson 1998). Long term poplar cultivation of more than 6-12 years on croplands was found to sequester significant quantities of soil carbon, in addition to carbon sequestration in the vegetation (Hansen 1993). In contrast, Dowell et al. (2009) found decreasing soil carbon contents after the establishment of short-rotation plantations on former pasture land, in agreement with Guo and Gifford (2002).

A recent study simulated a carbon increase of 0.81 t C per ha and year after the planting of aspen in eastern Germany (Lasch 2009). This region corresponds to the region investigated within this study. Another study of soil property changes under short rotation poplar and willow in eastern Germany found carbon gains between 0.5 and 0.8 t C ha^{-1} yr^{-1} (Kahle 2007). Other studies report smaller increases in SOC after SRC establishment. Freibauer et al. (2004) and Mila I Canals et al. (2007) found 0.6 t C ha^{-1} $year^{-1}$ with an uncertainty of 50%. Brandão et al. (2011) use for their calculations 0.09-0.18 t C ha^{-1} yr^{-1} for willow SRC, based on literature data. Hansen (1993) found a carbon sequestration rate under middle aged hybrid poplars of 1.63 t C ha^{-1} yr^{-1}.

Some further simple considerations might help to assume at least the magnitude of soil carbon stock changes due to the conversion of arable land into poplar plantations for the here assessed case.

The starting point is the initial carbon content of the arable land on which the plantation is established. Smith et al. (1998) use for their calculations an initial SOC stock of arable land in the EU of 53 t C ha^{-1}. If no SRC would be planted, two reference scenarios were possible. Either, the land would remain abandoned over the whole period or the land would instead be used for arable crop production. According to Freibauer et al. (2004) abandoned fields sequesters less than 0.4 t C ha^{-1} yr^{-1} and arable lands lose on average 0.83 t C ha^{-1} yr^{-1} (-2.93 to +0.31 t C ha^{-1} yr^{-1}). According to the above stated studies, SRC cultivation leads to SOC stocks increases of 0.5 to 0.8 t C per hectare and year. In comparison with an abandoned field, SRC cultivation would cause a net increase of carbon stock by 0.1 to 0.4 t C ha^{-1} yr^{-1}. Referred to arable crop cultivation, carbon net gains would summarize to 1.33-1.63 t C per hectare and year. Within the 20 years of the assumed plantation cultivation in total net gains of 2-8 t C per ha, referred to the abandoned field and of 26.6-32.6 t C per hectare referred to arable crop production could be achieved. Within these 20 years the non-fertilized SRC plantation would produce 160 odt of biomass per hectare. This would mean a net carbon pool increase of 12.5-50 kg C per odt of biomass compared to the fallow field. Translated to carbon dioxide (CO_2), this would mean an increase of approximately 46-183 kg CO_2 per oven-dry tonne of biomass.

Starting from the reference land use, avoided emissions from maintenance of the fallow site also have to be considered. Regularly mowing would release 41 kg CO_2 eq per hectare and year. Referring to the produced amount of wood and a timeframe of 20 years about 5 kg per odt of SRC wood would be saved.

As summarized in Table 12, the credits diminish the net GHG emission of SRC biomass production. So they approximate in the fertilized case the net GHG emissions of residual wood supply (42 kg odt^{-1}). In the case of non-fertilized SRC production soil carbon storage and avoided emissions from the reference land use would exceed the emissions of production, processing and transport.

Table 12 Decrease of net GHG emissions from fertilized and non-fertilized SRC by soil carbon storage and avoided GHG emissions due cessation of maintenance of the fallow site

Process [kg CO_2 eq odt^{-1}]	**SRC (fert.)**	**SRC (w/o fert.)**
Biomass production, processing and transport	98	40
Indirect CO_2 emissions avoided from maintenance	-5	-5
Soil carbon change (min.)	-46	-46
Total	47	-11

Removal of forest residues

In general, thinnings and harvests have an influence on the carbon cycle of the forest. The soils are disturbed and the litter fall is decreased. This is accompanied by changes of microclimate and increased soil respiration, which might lead to alterations of the nutrient and carbon cycle. The effects of final harvesting, especially of clear cutting, are stronger than the impacts of thinning or selective harvesting. The additional removal of harvest residues might enforce soil carbon decrease (Jandl et al. 2007). The intensified utilization of forest residues decreases the litter and slash input into the forest soil. Several studies found that soil carbon stock (SOC) decreases due to slash removal (Eriksson et al. 2007; Palosuo 2001; Olsson 1996; Jones 2008, Smolander 2008; Johnson 2010), although SOC contents in the mineral soil respond very slowly on forest management practices (Olsson 1996; Mund and Schulze 2006). For Finnish forest soils Palosuo et al. 2001 calculated, that 3% of the original carbon amount from harvest residues is stored in the soil within a period of 100 years. This means, if slash is removed from the forest sites this amount of carbon is not available for the build-up of soil carbon stock, which decreases carbon storage (Palosuo 2001, Mund and Schulze 2006). Coniferous forest soils are more vulnerable to residue removal than deciduous forest soils because of the reduced litter input. It seems to be obvious that the normally presumed SOC increase between 0.3-0.6 t C ha^{-1} yr^{-1} (Brandao 2011; Kribitzsch 2005; Freibauer et al. 2004) in forest soils would not continue if harvest residues are removed completely and permanently. But in this study it is assumed that only 50% of the available amount of harvesting residues is removed from the forest. Also the stumps remain in the forests, because their extraction is not a common practice of biomass production in Germany. In addition large clear cutting is increasingly avoided in German forestry, also because of certain legal regulations (BNatSchG 2009; LWaldG of the different federal states). In the above cited studies in most cases complete removal of residues was assumed (Palosuo 2001; Jones 2008; Smolander 2008; Olsson 1996). And in addition the stand was assumed to be clear cut, which has a stronger influence on the soil carbon stock than variation in residues removal (Olsson 1996).

Therefore it can be assumed for this study that soil carbon storage is not reduced because of thinnings, harvests and the extraction of harvesting residues.

The carbon storage in the soil develops slowly over a long period. From biomass inputs finally only a small amount of the initial carbon remains in the soil. Calculations with the soil carbon model YASSO (Liski et al. 2005) showed that within the first 10 years after harvest around 40% of the carbon contained in the residues is released to the atmosphere, 60% after 20 years. In a timeframe of 100 years 96% of the contained carbon will be released and only 4% will be stored in the soil. The results correspond to findings of Palosuo et al. (2001). For the model calculation soil and litter fractions as well as average decomposition and fractionation rates for deciduous and conifer trees have been adopted from Karjalainen et al. (2002). The amount and composition of the woody debris have been derived from yield and assortment tables (Schöpfer and Dauber 1989) at the time of thinning and final harvesting as described in chapter 4.1.2 and 5.1. Foliage and needles have been assumed to be left on site and there was no stump extraction considered. Just branches, twigs and coarse woody debris have been included in the modelling. The used parameter and data are furthermore presented in Annex 3.

Repo et al. (2011) argue that in greenhouse gas balances of bioenergy indirect emissions from the utilisation of forest residues have to be considered, which would not occur if the residues had decayed slowly in the forest. Within a time span of 100 years indirect or additional emissions to the atmosphere from using harvesting residues are equal to the amount of carbon which will not be stored in the soil (4%). All other carbon is released over the time due to decomposition anyway. Related to the extraction of one oven-dry tonne of residues about 62 kg CO_2 are released additionally according to the reference scenario (Table 13). These indirect emissions exceed the emissions of biomass production and distribution. The total GHG emissions of FT diesel production from forest residues then also exceed all other assessed woody biomass resources.

Table 13 GHG emissions per oven-dry tonne (odt) residual wood including indirect carbon dioxide emissions from lost soil carbon

	GHG emissions [kg CO_2 odt^{-1}]
Biomass production, processing and transport	42
Indirect CO_2 emissions (100 years)	62
Total	104

Not only carbon pools are affected but also the cycle of other macronutrients. Studies showed big impacts of residues removal on sites with poor and medium nutrient supply (Stüber et al. 2008). Especially in spruce and pine stands the phosphorus supply tends to decrease, which is not the case for beech stands. Due to residues removal the replenishment of mobile phosphorus in the soil is disturbed (Rumpf et al. 2008). Also the supply of micronutrients like potassium, calcium and magnesium could be reduced due to residues removal. Especially spruce and beech stands with acid soils are vulnerable. In particular the removal of needles, leafs, small twigs and brush wood leads to losses of potassium, calcium and magnesium (Dammann et al. 2008). Within the present study it is assumed that just half of the available residual biomass is removed from the forest. This would diminish carbon and nutrient loss.

Until this point these estimations are just a part of the life cycle inventory, without any impact assessment. Meanwhile some methods for assessing carbon emissions from soil pools within life cycle assessment studies have been suggested (Mila I Canals et al. 2007, Brandao et al. 2011, Kendall 2009, Müller-Wenk and Brandao 2010). They are based on the assumption, that the actual land use is postponing the natural succession of the area. Therefore the potential natural vegetation (PNV) is considered as reference system. The authors propose to half or to weight carbon emissions from soils before they are added to carbon emissions from fossil sources. It is assumed that the released carbon from soil and vegetation after land conversion is not staying in the atmosphere for the same period like carbon from fossil origin. But due to some remaining uncertainty, these suggested methods will not be adapted to the present case of SRC cultivation on arable land.

6.2 Biomass conversion into Fischer-Tropsch diesel

After the analysis of the different options of woody biomass production, in the following chapter the conversion process of biomass into FT diesel will be assessed. For that the functional unit "1 kg FT diesel" will be employed. Like described in chapter 4.1.4, two routes of FT diesel processing -"closed" and "partial open"- are assessed.

Figure 13 compares the non-renewable energy consumption of the two processing routes only for the production of 1 kg FT diesel. Non-renewable energy consumption of biomass cultivation and for its processing and transport are not included in the figure.

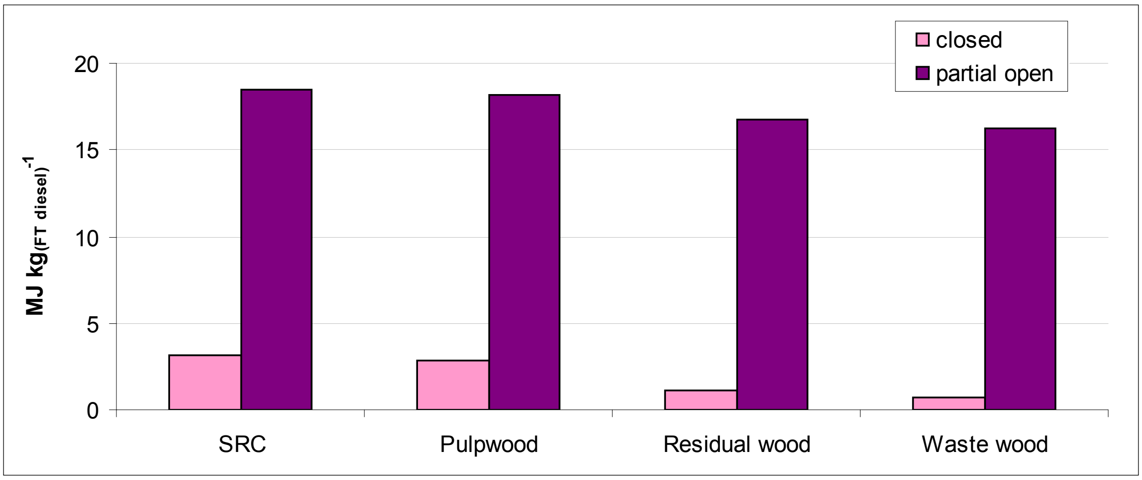


Figure 13 Use of non-renewable energy for the two processing routes of Fischer-Tropsch diesel production from different woody biomass resources

The partial open FT processing requires the input of several auxiliary materials and energy sources. Therefore the non-renewable energy input is 6 to 24 times higher than for the closed processing, depending on the used biomass resource. Non-renewable energy use for the closed processing version ranges from 0.7 to 3.2 MJ per kilogram FT diesel and from 16 to 19 MJ kg FT diesel^{-1} for the partial open processing.

The energy consumption of the closed processing version mostly originates from the supply chain of the employed few auxiliaries (natural gas, additives, sodium hydroxide). The slight differences between different biomass inputs are attributable to differences in moisture content of the raw material. Within both processing versions additional electricity input is needed for pre-drying, when the initial moisture content of the employed biomass is high. The production of FT diesel from short rotation wood requires the highest additional electricity input in both processing routs. Waste wood already features the right moisture content and doesn't need to be dried. For this reason the non-renewable energy consumption for its conversion into FT diesel is lowest.

The GHG impact follows the pattern of the non-renewable energy consumption. As apparent from Figure 14 the issues discussed above are applicable to the results of GHG impact as well. The GHG emissions of the closed and the partial open processing differ enormously. The partial open processing releases 6 to 26 times more greenhouse gases than the closed processing. The GHG emissions of the closed processing range between 0.04 and 0.2 kg CO_2 eq per kg FT diesel. GHG emissions from the partial open processing lie between 1.0 and 1.2 kg CO_2 eq per kg^{-1}. The highest values can be found in either case in combination with FT diesel production from short rotation wood.

The indicator values of acidification potential (AP; Figure 15) differ like the GHG effect considerably between both FT diesel processing routes. GHG effect and AP are both influenced by the consumption of non-renewable energy. On the contrary eutrophication potential (EP; Figure 16) and photochemical ozone creation potential (POCP; Figure 17) do not show any significant differences between the two FT diesel processing routes.

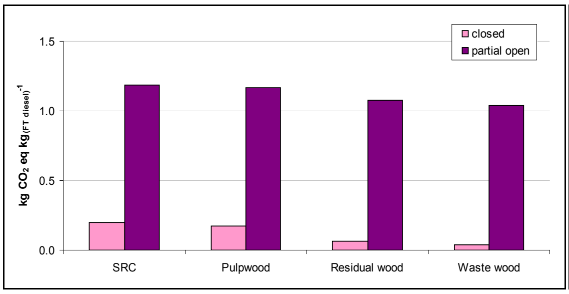


Figure 14 GHG emissions of the two Fischer-Tropsch diesel processing routes

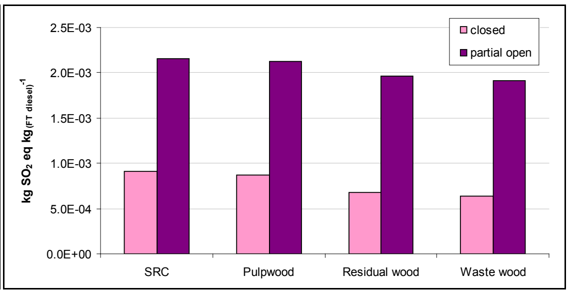


Figure 15 Acidification potential (AP) of the two Fischer-Tropsch diesel processing routes

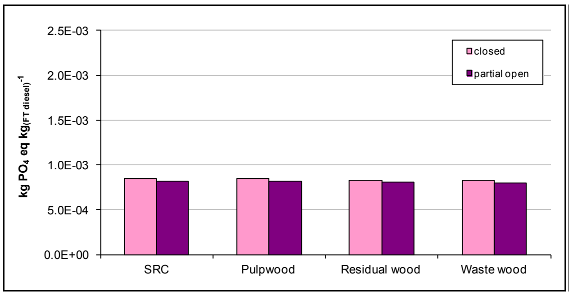


Figure 16 Eutrophication potential (EP) of the two Fischer-Tropsch diesel processing routes

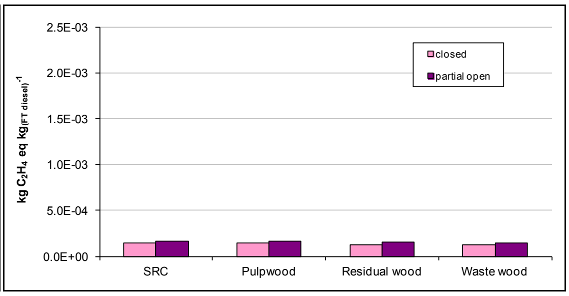


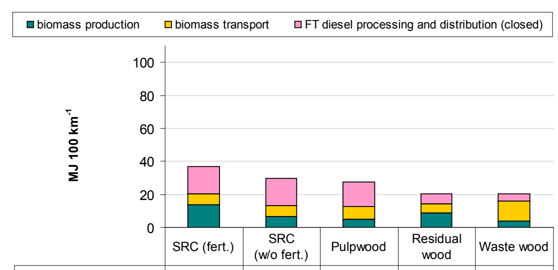
Figure 17 Photochemical ozone creation potential (POCP) of the two Fischer-Tropsch diesel processing routes

6.3 Biomass conversion and Fischer-Tropsch diesel utilization

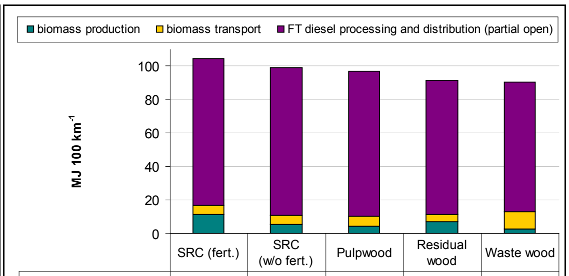
Finally, in the following chapter the above described parts of the assessment will be summarized in the analysis of the whole chain of FT fuel production and utilization. The non-renewable energy consumption and the environmental impacts are shown per travelled distance 100 km in a FT diesel-fuelled car. Finally the different versions of FT diesel production are compared to the impacts of ordinary fossil diesel.

6.3.1 Consumption of non-renewable energy

After looking separately on both parts of the FT diesel production process, FT diesel consumption will be included in the assessment. Therefore the functional unit “100 km driven” is employed. The following figures (Figure 18 and Figure 19) display only the demand of non-renewable energy for FT diesel production and use. This means that the renewable energy, which is inherent in the FT fuel and consumed during car operation, is not included in the diagrams. During 100 km driven by car 205 MJ renewable energy inherent in FT diesel are consumed.



	SRC (fert.)	SRC (w/o fert.)	Pulpwood	Residual wood	Waste wood
FT diesel processing and distribution (closed)	16.3	16.3	14.6	6.4	4.6
biomass transport	6.5	6.7	7.6	5.4	12.4
biomass production	14.0	6.7	5.1	8.7	3.6



	SRC (fert.)	SRC (w/o fert.)	Pulpwood	Residual wood	Waste wood
FT diesel processing and distribution (partial open)	88.0	88.0	86.6	80.0	77.5
biomass transport	5.3	5.4	6.2	4.4	10.1
biomass production	11.4	5.4	4.2	7.1	2.9

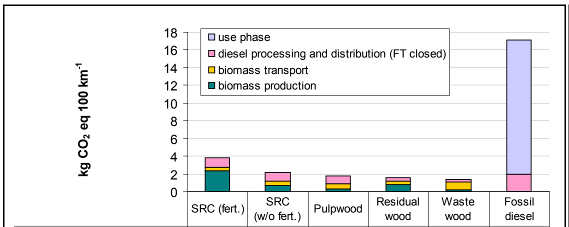
Figure 18 **Figure 19**

Use of non-renewable energy for production and distribution of Fischer-Tropsch diesel per 100 vehicle-kilometres, except energy stored in the fuel. Compared are the Fischer-Tropsch diesel production in the closed processing (Figure 18) and the partial open processing (Figure 19)

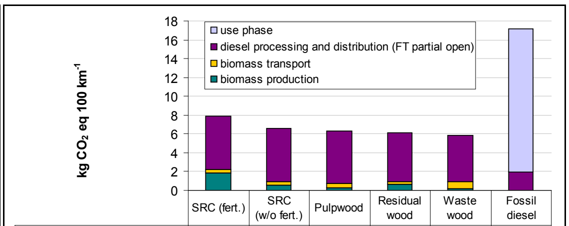
Non-renewable energy consumption for FT diesel production varies between almost 21 and 105 MJ 100 km^{-1}. The highest value was found for FT diesel produced from fertilized SRC via partial open synthesis and the lowest for FT diesel from residual wood via closed processing. If the renewable energy consumption in the form of FT diesel is included, life cycle primary energy consumption adds up to 226 and 310 MJ per 100 km respectively. In comparison, fossil diesel refining uses 35 MJ of fossil energy, related to the functional unit of 100 km travelled. Furthermore the energy inherent in the fossil diesel fuel amounts to 207 MJ per 100 km. This amounts to a total fossil energy use of 242 MJ per 100 km in the conventional case. The refining process of conventional diesel from crude oil needs slightly less fossil energy than the FT diesel production from fertilized SRC. But if the resource consumption inherent in the fuel is considered the non-renewable energy use for fossil diesel production and utilization exceeds the one for FT production from fertilized SRC by a factor of 2.3.

For the whole biofuel production chain (“well-to-tank”) energy ratios range between 5.6:1 and 10.0:1 for the closed FT processing and between 2.0:1 and 2.3:1 for the partial open processing has been found. This means depending on the used resources and conversion process 2 to 10 mega joules of FT diesel can be produced from one mega joule of fossil diesel.

6.3.2 Greenhouse gas (GHG) effect



	SRC (fert.)	SRC (w/o fert.)	Pulpwood	Residual wood	Waste wood	Fossil diesel
use phase						15.21
diesel processing and distribution (FT closed)	1.03	1.03	0.92	0.40	0.28	1.94
biomass transport	0.46	0.48	0.54	0.38	0.88	
biomass production	2.31	0.65	0.33	0.80	0.23	



	SRC (fert.)	SRC (w/o fert.)	Pulpwood	Residual wood	Waste wood	Fossil diesel
use phase						15.21
diesel processing and distribution (FT partial open)	5.64	5.64	5.55	5.13	4.96	1.94
biomass transport	0.38	0.39	0.44	0.31	0.72	
biomass production	1.88	0.53	0.27	0.65	0.19	

Figure 20 **Figure 21**

GHG emissions of production and distribution of Fischer-Tropsch diesel per 100 vehicle-kilometres, except GHG emissions from Fischer-Tropsch diesel combustion during car operation. Compared are the Fischer-Tropsch diesel production in the closed processing (Figure 20) and the partial open processing (Figure 21)

The GHG emissions follow the shape of the fossil energy use. The partial open FT diesel processing has higher greenhouse gases emissions than the closed processing. FT diesel produced via the closed processing releases GHG emissions in the range of 1.4 to 3.8 kg CO_2 eq 100 km^{-1} and FT diesel from the partial open processing produces GHG emissions in the range of 5.9 to 7.9 kg CO_2 eq 100 km^{-1}.

FT diesel production from fertilized short rotation coppice causes the highest GHG emissions of all biofuel scenarios. This results from fertilizer production and application on the one hand. On the other hand FT diesel production from short rotation wood requires more pre-drying due to the comparatively high moisture content of the wood.

But compared to the GHG emissions of fossil diesel (17.1 kg CO_2 eq 100 km^{-1}) every processing route of FT diesel has only low GHG emissions. This is due to the emission of carbon dioxide (CO_2) caused during the use phase of fossil diesel, whereas the CO_2 emissions of the use phase of FT diesel are not accounted for, because they are resulting from biomass combustion.

But also if the biomass CO_2 emissions from the use phase would be accounted for, all FT diesel versions beside FT diesel from fertilized SRC would show slightly lower GHG emissions than fossil diesel.

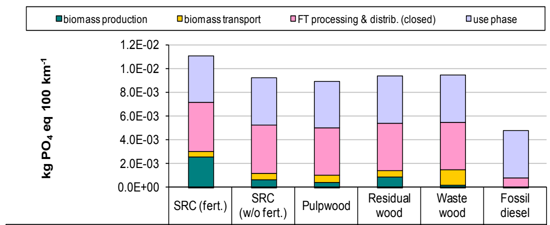
The presented net GHG emissions results do not include emissions or removals from soil carbon changes nor avoided emissions from the reference land use. Including these would result in different GHG emissions which will be discussed in chapter 8.4.

6.3.3 Eutrophication potential (EP), acidification potential (AP) and photochemical ozone creation potential (POCP)

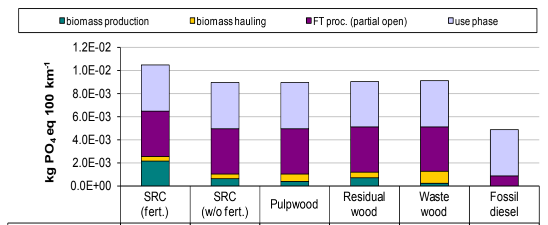
Further environmental impacts of FT diesel production and utilization are assessed in the following with the help of three impact categories.

Eutrophication is affecting terrestrial or aquatic ecosystems due to an oversupply of macronutrients, which leads to enhanced plant growth and potentially to a shortage of oxygen due to increased biomass decomposition. Acidification has impacts on soil, groundwater and other aquatic ecosystems, but also on the man-made environment; on buildings etc. Acidifying processes are caused by an accumulation of hydrogen cations in water or soil, which abates their pH. The creation of photochemical ozone, as explained in chapter 6.1.4, is formed from volatile organic compounds (VOC), carbon monoxide (CO) and nitrogen oxides (NO_x) under the presence of sunlight. Photochemical ozone is affecting the natural environment and human health.

The present assessment of eutrophication, acidification and summer smog potential include the use phase emissions of FT diesel. The following figures (Figure 22 and Figure 23) compare the eutrophication potential of FT diesel production and use from different resources for the two processing routes related to 100 km of vehicle operation. Additionally the impact indicator results are compared to fossil diesel production and use.



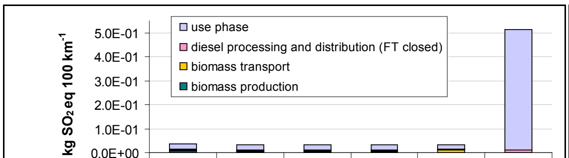
	SRC (fert.)	SRC (w/o fert.)	Pulpwood	Residual wood	Waste wood	Fossil diesel
use phase	4.0E-03	4.0E-03	4.0E-03	4.0E-03	4.0E-03	4.0E-03
FT processing & distrib. (closed)	4.1E-03	4.1E-03	4.0E-03	4.0E-03	4.0E-03	8.5E-04
biomass transport	4.9E-04	5.1E-04	6.1E-04	5.7E-04	1.3E-03	
biomass production	2.6E-03	6.8E-04	4.1E-04	8.6E-04	2.0E-04	



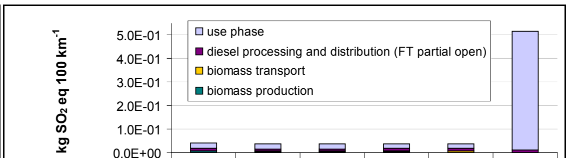
	SRC (fert.)	SRC (w/o fert.)	Pulpwood	Residual wood	Waste wood	Fossil diesel
use phase	4.0E-03	4.0E-03	4.0E-03	4.0E-03	4.0E-03	4.0E-03
FT proc. (partial open)	3.9E-03	3.9E-03	3.9E-03	3.9E-03	3.9E-03	8.5E-04
biomass hauling	4.0E-04	4.1E-04	6.6E-04	4.7E-04	1.1E-03	
biomass production	2.1E-03	5.6E-04	3.3E-04	7.0E-04	1.6E-04	

Figure 22 **Figure 23**
Eutrophication potential (EP) of the production and distribution of Fischer-Tropsch diesel per 100 vehicle-kilometres. Compared are the Fischer-Tropsch diesel production in the closed processing (Figure 22) and the partial open processing (Figure 23) each with the fossil reference fossil diesel.

The eutrophication potential (EP) of FT diesel from all woody resources is higher than the EP of fossil diesel. FT diesel EP ranges from 0.009 to 0.01 kg PO_4 eq per 100 km^{-1}. Use phase emissions are the same for all FT diesel versions and fossil diesel (0.004 kg PO_4 eq 100 km^{-1}). Variations of the eutrophication potential are due to varying impacts of biomass production and its distribution. Alone the impacts of biomass provision and the impacts of FT diesel production add up to higher EP values than the EP of fossil diesel use chain. As already shown in chapter 6.1.4 biomass production in fertilized short rotation plantations has the highest eutrophication potential. Therefore FT diesel made from short rotation wood from fertilized fields has the highest eutrophication potential related to 100 km of car operation.



	SRC (fert.)	SRC (w/o fert.)	Pulpwood	Residual wood	Waste wood	Fossil diesel
use phase	2.1E-02	2.1E-02	2.1E-02	2.1E-02	2.1E-02	5.0E-01
diesel processing and distribution (FT closed)	4.9E-03	4.9E-03	3.8E-03	3.8E-03	3.6E-03	1.1E-02
biomass transport	2.8E-03	2.9E-03	3.8E-03	3.6E-03	8.2E-03	
biomass production	7.9E-03	4.0E-03	2.4E-03	5.0E-03	1.3E-03	



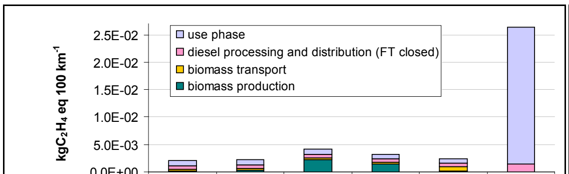
	SRC (fert.)	SRC (w/o fert.)	Pulpwood	Residual wood	Waste wood	Fossil diesel
use phase	2.1E-02	2.1E-02	2.1E-02	2.1E-02	2.1E-02	5.0E-01
diesel processing and distribution (FT partial open)	1.1E-02	1.1E-02	1.1E-02	9.8E-03	9.5E-03	1.1E-02
biomass transport	2.3E-03	2.4E-03	4.1E-03	2.9E-03	6.7E-03	
biomass production	6.4E-03	3.2E-03	2.0E-03	4.1E-03	1.1E-03	

Figure 24 **Figure 25**

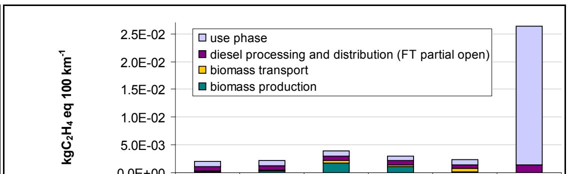
Acidification potential (AP) of the production and distribution of Fischer-Tropsch diesel per 100 vehicle-kilometres. Compared are the Fischer-Tropsch diesel production in the closed processing (Figure 24) and the partial open processing (Figure 25), each compared to the fossil reference

The acidification potentials (AP) of the whole well-to-wheel chain of FT diesel from different woody resources for both synthesis versions are shown in Figure 24 and Figure 25. The AP of FT diesel from all resources and both synthesis versions is lower than the AP of fossil diesel. The AP of biomass supply and FT diesel production in all assessed cases are very low compared to the use phase acidification potential of FT diesel use. But in comparison to acidifying emissions from the use phase of fossil diesel (0.52 kg SO_2 eq 100 km^{-1}), the burdens of wood based FT diesel are low. In contrast to fossil diesel, FT diesel does not contain sulphur compounds, which result in sulphur dioxide emissions during combustion. The AP of FT diesel use ranges from 0.031 to 0.041 kg SO_2 eq per 100 km.

The comparison of the photochemical ozone creation potential (POCP) between FT diesel production from different woody resources via both processing routes and fossil diesel are displayed in Figure 26 and Figure 27.



	SRC (fert.)	SRC (w/o fert.)	Pulpwood	Residual wood	Waste wood	Fossil diesel
use phase	9.0E-04	9.0E-04	9.0E-04	9.0E-04	9.0E-04	2.5E-02
diesel processing and distribution (FT closed)	7.2E-04	7.2E-04	6.5E-04	6.5E-04	6.4E-04	1.5E-03
biomass transport	2.3E-04	2.4E-04	3.5E-04	3.3E-04	7.5E-04	
biomass production	1.8E-04	3.4E-04	2.2E-03	1.4E-03	1.3E-04	



	SRC (fert.)	SRC (w/o fert.)	Pulpwood	Residual wood	Waste wood	Fossil diesel
use phase	9.0E-04	9.0E-04	9.0E-04	9.0E-04	9.0E-04	2.5E-02
diesel processing and distribution (FT partial open)	8.2E-04	8.2E-04	8.1E-04	7.6E-04	7.4E-04	1.5E-03
biomass transport	1.8E-04	1.9E-04	3.7E-04	2.7E-04	6.1E-04	
biomass production	1.5E-04	2.8E-04	1.8E-03	1.1E-03	1.1E-04	

Figure 26 **Figure 27**

Photochemical ozone creation potential (POCP) of the production and distribution of Fischer-Tropsch diesel per 100 vehicle-kilometres. Compared are the Fischer-Tropsch diesel production in the closed processing (Figure 26) and the partial open processing (Figure 27) each compared to the fossil reference

The POCP resulting from the use phase of fossil diesel exceeds the photochemical ozone causing emissions from FT diesel production and use. POCP of FT diesel use ranges from 0.002 to 0.004 kg C_2H_4 eq per 100 km and 100 km travelled by fossil diesel car cause a POCP of 0.0264 kg C_2H_4 eq.

As shown before (6.1.4) the photochemical ozone creation potential of FT diesel use from pulpwood and residual wood are higher than of FT diesel use, which was produced from the other woody resources. This is due to harvesting and processing pulpwood by chainsaws, which are operated by two-stroke mixture mainly due to NMVOC (non methane volatile organic compounds) emissions and partly because of carbon monoxide from fuel combustion in two-stroke engines. But anyhow the POCP of fossil diesel use exceeds the POCP of all FT diesel use from all resources and process steering. This is due to higher emissions of carbon monoxide, sulphur dioxide and NMVOC from the combustion of fossil diesel.

7 Comparison to other studies

Within this study at first the environmental impacts of production, processing and transport of different woody resources have been explored. In terms of non-renewable energy consumption output-input energy ratios ranging from 41:1 to 25:1 have been found in this study. Which means 25 to 41 MJ inherent in the woody biomass can be produced by the use of one MJ of fossil energy. The production of 1 tonne short rotation wood on fertilized fields and its transport to the FT production facility requires the highest non-renewable energy input of all assessed resources (727 MJ odt^{-1}). If short rotation coppices are not fertilized, their non-renewable energy use for wood production and transport is quite similar (474 MJ odt^{-1}) to pulpwood or residual wood (499 MJ odt^{-1}) production. Dubuisson and Sintzoff (1998) found for SRC production on fertilized fields ratios between 22:1 and 28:1, which correspond to the values found in this study. According to several studies fertilizer use for poplar cultivation is not essential (q.v. chapter 4.1.1). At this point of time there is no clear evidence of the benefits of fertilizing poplar SRC. Therefore, from an environmental point of view, SRC could be a big potential of assuring sustainable wood supply from outside forests, without causing too many additional environmental burdens. Field trials have to proof whether a sufficient production without fertilization can be assured over a long period of time.

The least non-renewable energy input for biomass production is required for pulpwood production (449 MJ odt^{-1}), at which the larger proportion is used to transport the wood to the FT diesel production facility. For comparison there are some other studies available, which assess energy use and greenhouse gas emissions of conventional roundwood production in forests. Berg and Lindholm (2005) examined the timber production in Sweden and found energy output-input ratios between 52:1 and 38:1, which are corresponding to the findings of the present study (41:1). They also found largest energy requirements for secondary haulage. A recent study by Gonzáles-García et al. (2009) compared the environmental impacts of pulpwood production in Spain and Sweden and found much lower output-input ratios of 28:1 and 20:1. The comparatively high non-renewable energy use in their study is due the considered silvicultural practices in these countries with soil scarification, fertilizer and pesticide application.

The assessment results of residual wood processing from forest can be compared to results of Zimmer (2010). Zimmer (2010) calculated for several methods of residual wood processing in Germany energy ratios between 67:1 and 22:1. Within this wide frame the here found ratio of 37:1 for residual wood processing and transport fits very well. The distribution of residual wood uses more non-renewable energy than the roundwood production. This is due to additional machinery input for gathering, processing and primary extraction in addition to harvesting and previous forest management.

A further result is the comparable high non-renewable energy input to provide a FT diesel production plant with post-consumer waste wood. If only the processing of post-consumer waste wood is analysed, the lowest non-renewable energy input of all biomass resource provision chains can be found (128 MJ odt^{-1}). This is because post-consumer wood is a waste material that results from another product system and is therefore not carrying any burdens from its primer production. The recovery process consumptions and emissions are shared between first and second product system, therefore burdens accounted in the second product system are comparatively low. But if the whole provision chain, including the transport of waste wood to the FT production facility is assessed, non-renewable energy use for waste wood distribution is higher than for pulpwood or residual wood provision. If waste wood has to be imported and transported over long distances to feed the fuel production plant, the advantages of using a waste material are shrinking and for the whole chain 568 MJ non-renewable energy per odt are used. The transport of waste wood requires three times the energy input of its processing and causes accordingly higher CO_2 emissions. Jungbluth et al. (2002) calculated for the processing and distribution of waste wood an energy use of 349 MJ per odt but they just assumed a transport distance of 50 km. It is quite a realistic scenario to import post-consumer waste wood from abroad, because nearly the whole German waste wood resources are already in use in incineration plants (Ebrecht 2009). Therefore, the usage of this initially advantageous resource does not really seem to be a favourable option.

The analysis of the whole FT diesel production chain found smaller output-input energy ratios than only for the provision of biomass. The present study found energy output-input ratios for the closed FT diesel processing between 10:1 and 5.6:1 and for the partial open processing between 2.3:1 and 2.0:1. This means, depending on the processing route, 1 MJ non-renewable energy produces 2 to 10 MJ inherent in the FT diesel fuel, which can be used for car operation. This well-to-tank analysis does not include the car operation; it is just referring to the usable energy inherent in the FT diesel in the vehicle tank.

Cherubini et al. (2009) report ratios between 2.5:1 and 6.7:1 for FT diesel from biomass. Sandilands et al. (2008) found a ratio of 3.9:1 for FT diesel production from forest residues. The found non-renewable energy use for the partial open FT diesel processing calculated in the present study exceeds slightly the amount calculated in other studies. As already stated, the results depend a lot on assumptions of transport distances and on the modelling of the FT diesel production process itself. These modelling assumptions can vary between the different studies, because the FT diesel production is still in a test stage. But nevertheless the comparison of the energy ratios of the biomass resource and the finished product shows a big loss of usable energy during the conversion process. The closed processing saves energy from fossil origin but wastes the usable energy inherent in the biomass. Like shown in Roedl (2010) it might be better in terms of saving GHG emissions and natural resources to use the biomass for heat or power generation instead of producing FT diesel.

The pattern of CO_2 and GHG emission assessment shows similar results to the fossil energy use, because CO_2 emissions are closely correlated to the non-renewable energy use. The differences between wood production in fertilized SRC and the other woody resources become more apparent if the GHG impact is analysed. This is due to N_2O emissions during fertilizer production and application.

The GHG emissions calculated in the present study for the whole chain reaches from 1.4 to 3.8 kg CO_2 eq 100 km^{-1} for the closed processing and from 5.9 to 7.9 kg CO_2 eq 100 km^{-1} for partial open processing. In order to compare these results to the findings of other studies, the results have to be translated into other functional units. For example Sandilands et al. (2008) use the energy content in the FT fuel in MJ as a functional unit. The translation of the here found GHG emissions to this functional unit, result in 6.8-18.5 g CO_2 eq MJ^{-1} and 28.8-38.5 g CO_2 eq MJ^{-1}. Sandilands et al. (2008) found GHG emissions of FT diesel production within this range of 14.3 g CO_2 eq MJ^{-1}. Although this result does not include the delivery of FT diesel to the petrol stations and the use phase. Edwards et al. (2007) calculated average GHG emissions for the production of FT diesel and its delivery to the market of 6.9 g CO_2 eq MJ^{-1} within a range of 5.4 to 18.8 g CO_2 MJ^{-1}. These results correspond to the range of GHG emissions for the closed FT diesel processing found in this study. But they exceed the results found by other studies results for the partial open FT diesel processing.

If the results of the present study are translated to the functional unit passenger kilometre (pkm) with a passenger load of 1.59 persons per run, they result in values between 9 and 50 g CO_2 eq pkm^{-1}. But Jungbluth et al. (2008) found higher GHG emissions per passenger kilometre of 90 g CO_2 eq pkm^{-1}. This might be because Jungbluth et al. (2008) took fertilizer and pesticide application into account as well as the production of machinery and infrastructure.

The further comparison of other impact category results is difficult, because most studies just assess energy consumption and greenhouse gas emissions or they use different characterisation methods (Berg and Lindholm 2005; Gonzáles-García et al. 2009). Further they sometimes present their results just in normalized figures like Reinhardt et al. (2006), which makes it difficult to compare.

8 Sensitivity analysis and discussion

The results on environmental impacts of FT diesel production and use presented in the previous chapters are determined by the underlying system boundaries, accounting methods and parameter assumptions. Following the most sensitive points of the model are discussed and analyzed.

8.1 System boundaries

The system boundaries chosen in this study comprise in the majority of cases the complete production chain of the biomass resource and of the biofuel. Special cases are the utilization of post-consumer waste wood and harvesting residues, where waste material is used for FT diesel production.

The chosen system boundaries for FT diesel production from post-consumer waste wood partly include the waste wood treatment in the primary product system. Considering waste wood fully as waste, without accounting separation and shredding the GHG emissions for FT diesel from waste wood would be reduced by 17% for the closed processing and by 3% for the partial open processing. But in any case, with or without accounting for recycling, FT diesel from waste wood has the lowest global warming impact.

In the case of FT diesel production from harvesting residues the system boundaries include parts of the burdens from forest management. If forest residues were considered as a waste, without burdens from the forestry production this would be equal to choosing the allocation factor zero. The resulting GHG emissions of FT diesel from harvest residues would be lowered by 51% (closed processing) and 11% (partial open processing) respectively. Compared to the other FT diesel production chains FT diesel from harvesting residues would create least GHG emissions per 100 km.

Particularly if a waste material is used the setting of system boundaries has a big influence on the impact indicator results. Harvesting residues can be considered as a by-product of logs and pulpwood production wood also because they have received a market price for some time. Therefore they carry burdens from the forestry production which have to be included into the assessment.

Re-use of post-consumer waste wood requires some kind of reprocessing which belongs to the new product sphere. The here applied accounting method follows recommendations of the ILCD handbook (EC JRC 2010) to draw the boundary at the point where market price turns from negative to positive. Attributing the complete burdens of recycling to the first product system would not properly reflect the life cycles of the two products because if there wasn't any re-use, burdens of reprocessing would not occur.

8.2 Allocation

The choice of the allocation method is an essential part of the assessment, because it has in almost all cases strong effects like some studies (Luo et al. 2009; Werner et al. 2007; Reijnders 2003) already showed and which has been also confirmed during the present study. It is obvious that only from the choice of the allocation method very different percentages of the overall consumables and emissions are allocated to the particular product. In the present study economic allocation was chosen for the biomass production chain of pulpwood and harvesting residues as well as for post-consumer waste wood treatment to divide the consumables and environmental burdens between the product systems.

Application of economic allocation in the case of forest products reflects appropriately their weighting because products of higher quality have higher values and therefore receive a greater weight than lower quality products. Allocation according to mass would result in higher allocation to the biofuel and thus in higher impact indicator values. If the allocation procedure for forestry wood production was based on the produced mass instead of their market value, impact indicator results would increase strongly. The impact indicator results of pulpwood production would increase by 20% each. GHG effect, AP and EP of residual wood production would also increase by approximately 13%, energy use by approx 20% and POCP even by 99%. In this case impacts of pulp and residual wood provision would even exceed the impacts of SRC wood production. But applying a mass based allocation would be misleading, because the co-products with a bigger mass would receive higher proportions of the overall burdens than the main product. In the case of wood production a little more than half of the whole produced biomass is normally extracted from forests as roundwood. The other portion (25-45%) of tree biomass is left on site (Megalos 2008), which is considered as residues. Via allocation based on the market value these residues are charged less burdens, which corresponds better to their status of being a residual material.

In the case of post-consumer waste wood treatment the prices reflect properly the border between the first and the second product system. Negative prices indicate the end of life processing in the first system and positive prices the preparation of the raw material in the secondary system. Therefore it seems reasonable to allocate also the burdens of the treatment to the first product sphere according to these costs. The other part of the burdens is attributed to the second product system, according to the expenses of producing a valuable product (EC JRC 2010). By adopting this allocation method it is taken into consideration that there is an intentional enhancement of the waste material compared to the pure disposal and therefore some of the burdens of the recycling process have to be allocated to the second product sphere. The main proportion of the overall burdens of waste wood disposal is attributed to the first product sphere and the remaining part is allocated to the valuable product.

Furthermore, to avoid double counting a convention on the allocation procedure is needed. If a study like the present is only interested in the second product system but includes burdens from the first product system, this should be taken into consideration for studies of the first product system, where these burdens should be deducted.

8.3 Parameter variation

Some variations of key parameters are already included in the main part of the study. There is the variation of FT production process with the varying share of additional inputs assessed by the “closed” and the “partial open” processing. Further there is the variation of SRC cultivation with and without application of fertilizer. Both strongly influence the indicator results. GHG emissions of the closed processing of FT diesel amount to only 4% of the GHG emissions of the partial open processing. Greenhouse gas emissions of the non-fertilized SRC cultivation only amount to around 30% of the GHG emissions of the fertilized cultivation.

Other parameter like transport distances of the raw material or the FT fuel do not have such a strong influence on the indicator results of the whole FT diesel. If the transport distance of pulpwood, forest residues or SRC wood is increased to 200 km instead of 70 km or 50 km, the GHG emissions only would increase by around 3%. Also transport weight, which is mainly influenced by wood moisture, affects the results only slightly. In the case of forest residues, for example, assuming that wood moisture (u) is 100%, like freshly harvested wood instead of before taken wood moisture (u) = 43% of pre-dried wood, would increase the GHG emissions only by 1.5%.

8.4 Soil carbon changes and reference land use

Another point of uncertainty is the inclusion of soil carbon pool changes into the assessment. The above presented results do not consider emissions from soil carbon changes, but they have been calculated separately in the supplementary analysis in section 6.1.6.

As shown in chapter 6.1.6 the effects of land use change from annual agricultural crops to perennial cropping, as well as the effects of forest residues removal are very uncertain. Several studies report quite a high carbon sequestration rate following the establishment of SRC on former arable or abandoned fields. Adopting the average literature values (chapter 6.1.6) results in a net increase of the soil carbon pool by 46-183 kg CO_2 per oven-dry tonne of biomass. In the case of the non-fertilized cultivation of SRC on an abandoned field, this would mean that more carbon is sequestered in the soil than emitted during the whole biomass production and transport chain. In the case of fertilized SRC production the overall global warming impact would be almost halved by soil sequestration. For FT diesel utilization produced from short rotation wood via the closed processing route a credit between 0.28 and 1.10 kg CO_2 eq referred to the functional unit 100 vehicle km could be given. GHG emissions from FT diesel use produced in the partial open processing route would be reduced by between 0.23 and 0.90 kg CO_2 eq per 100 km (see Table 14). But it should be noticed that these figures have a huge uncertainty and can vary due to numerous site specific conditions.

The question is whether the uptake of carbon could be fully attributed to the harvested wood, because the soil carbon pool is unstable and might be released during harvesting and reconversion of the acreage. Furthermore it is very unsure how much carbon is really fixed, because some studies showed also losses within the first years.

The magnitude of carbon sequestration depends also on the considered reference land use which is based on assumptions of future land use in the area. If fallow land is considered during the entire time frame, credits from avoided emissions of maintenance will be lower than if the cultivation of agricultural crops is considered during this time. But if a time frame of e.g. 100 years is assumed it is not possible to predict future land use. Therefore the indicator results can just be a model, visualizing the possible frame of environmental impacts.

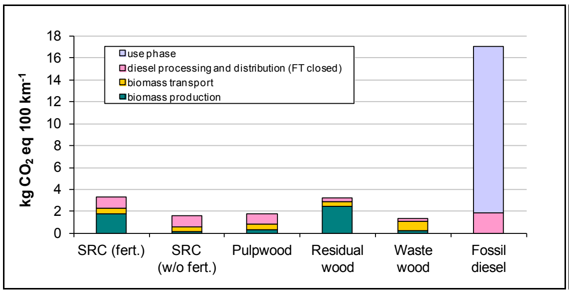
Additionally, depending on the processing route 0.2 and 0.12 kg CO_2 per 100 km respectively, could be saved by replacing the reference land use fallow land. If agricultural land is replaced by SRC plantations even more GHG emissions would be avoided, but this examination goes beyond the scope of this study. If agricultural crops are replaced by SRC they would have to be produced anywhere else, where again GHG emissions are released, which also have to be offset. But this kind of life cycle assessment would follow the consequential method, which is not applied for this study.

Table 14 Changes of net greenhouse gas emissions due to changes of the soil carbon pool as presented in chapter 6.1.6

Type of FT diesel processing and used biomass resource	Alteration of net GHG [per kg CO_2 eq 100 km^{-1}]	
	min	max
Closed FT diesel processing		
SRC soil carbon change	-0.28	-1.10
SRC indirect emissions (100 years)	-0.20	
Residual wood, indirect emissions	+1.70	
Partial open FT diesel processing		
SRC	-0.23	-0.90
SRC indirect emissions (100 years)	-0.12	
Residual wood, indirect emissions	+1.40	

In chapter 6.1.6 it was also shown that the inclusion of soil carbon losses due to the removal of harvesting residues increases the indicator value of greenhouse gas emissions. Table 14 also displays the resulting changes in net greenhouse gas emissions if the lost soil carbon accumulation is taken into account. The values shown result from model calculations and therefore include large uncertainty. Liski et al. (2005) report large uncertainties in the model especially for parameter values on humification and decomposition rates. For the sample calculation in this study average values for deciduous and conifer trees data from Karjalainen et al. (2002) have been adopted. For the required amount of forest residues for FT diesel production within this study this would mean about 0.4 kg CO_2 (closed) and 0.3 kg CO_2 kg FT diesel^{-1} (partial open) respectively are released additionally according to the reference scenario. This would mean in relation to the functional unit indirect carbon emissions of 1.7 kg CO_2 and 1.4 kg CO_2 per 100 km respectively, have to be added to the GHG values. These indirect emissions would exceed the emissions of biomass production and distribution. The total GHG emissions of FT diesel production from forest residues then also would exceed emissions of FT diesel production from all assed biomass resources besides that from fertilized SRC.

Figure 28 and Figure 29 display the changes in global warming indicators if soil carbon changes due to land use change, biomass removal and avoided reference land use are considered. GHG emissions from SRC cultivation slightly decrease but net emissions from harvesting residues utilization increase. Overall GHG emissions of FT diesel production and use are lower than that from fossil diesel production and use.



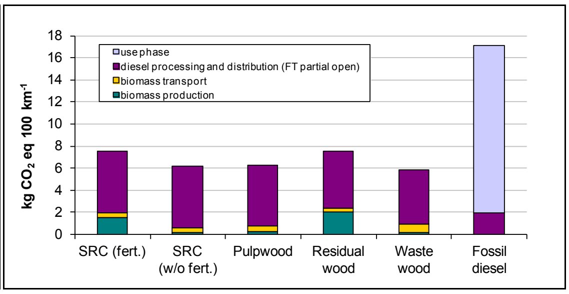


Figure 28 **Figure 29**
GHG emissions of production and distribution of Fischer-Tropsch diesel per 100 vehicle-kilometres, except GHG emissions from Fischer-Tropsch diesel combustion during car operation. Including soil carbon storage and avoided reference land use. Closed (Figure 28) and partial open (Figure 29) FT diesel processing.

8.5 Discussion

The GHG emissions of FT diesel utilization calculated within this study are lower than that of fossil diesel. This also applies in the case of residual wood utilization if soil carbon changes due to their removal are considered. The GHG emissions savings are calculated with the assumption that the released biogenic CO_2 is not included in the calculation of GHG emissions. This accounting method implies that the carbon inherent in the used amount of wood will again be absorbed by the regrowth. But this accounting method is also highly controversial (see Pingoud et al. 2010). Carbon emissions from biomass combustion could not all the time be considered as climate neutral because carbon re-absorption by growing trees takes longer than its release. By application of the climate neutral method an incentive for the energetic use of biomass is provided which might lead to forest clearings or other land-use changes, which reduces the global carbon pools and increases carbon emissions (Searchinger et al. 2009). This accounting problem is an issue which has to be discussed and needs further research.

In this study at least effects on climate impact from land use change were estimated. One result is that in the long run the utilization of residual wood saves GHG emission compared to fossil fuels. Compared to the reference case where they decay slowly in forest the combustion of wood residues releases the total stored amount of carbon at once. Initially more GHG emissions are released by the use of the biomass than from the fossil reference. Using fossil diesel would then be favourable to using FT diesel. But according to modelled results from YASSO (Liski et al. 2001) this relation will reverse within 10 years when the decaying wood has released more carbon than the fossil reference (see Repo et al. 2011). Within the following years more and more carbon dioxide from wood decay is released in addition to greenhouse gases from fossil energy use which turns the preferences towards the use of bioenergy.

In the case of SRC wood utilization emissions will be sequestered within the following rotation period. Therefore its climate impact is not very large, which was also found by Cherubini et al. (2011).

If carbon dioxide emissions from the use phase of FT diesel were fully accounted the GHG emissions of FT diesel from pulpwood, converted in the partial open processing, would exceed the GHG emissions of fossil diesel use by 21%. The GHG emissions of FT diesel from pulpwood converted in the closed processing would be 5% lower than that of fossil diesel use. This means, if biogenic carbon dioxide were included in the accounting FT diesel use would not meet the required 35% greenhouse gas emission savings required by the European Renewable Energy Directive (Directive 2009/28/EC). This implies that the found advantage of FT diesel use in terms of GHG emission savings results in some cases just from the accounting method.

Several studies have currently assessed this accounting problem from different perspectives (Cherubini 2011, Searchinger 2009, Palosuo 2001, Repo 2011).

Cherubini et al. (2011) discuss this problem and present a method for measuring the climate impact of biogenic carbon. They propose to use a factor between 0 and 1 to account for global warming impact according to rotation lengths, forest management and other pre-conditions. This means the climate impact of biomass use is more than zero but less than fossil energy use. Within their work they found that short rotation biomass has a lower climate impact than long rotation biomass. But they also state that mitigation of climate change by utilizing bioenergy is more effective with a long time horizon.

9 Conclusions

In this study environmental impacts of FT diesel production from different woody biomass resources have been assessed. A big part of the study focused on the provision of different woody biomasses. Many aspects of the FT diesel production process are uncertain because it is a quite new technique, still under development and there is little information publicly available. Meanwhile the company is undergoing a restructuring and at the moment it is unclear when FT diesel will be produced in a large scale and how the process will then look like. Nevertheless two possible processing routes have been studied.

With the help of the normalized view of the impact indicator results in Figure 30 it is possible to compare their relative importance and magnitude. The normalization procedure relates every impact value to its total reference. In the present case, total German indicator category values for the year 2006 are considered (Table 15).

Table 15 CML 2001 normalization factors for Germany (PE, LBP 2009) used in this analysis

Impact category	Unit	Normalization factors
Eutrophication potential	kg PO_4 eq	3.58E-10
Photochemical ozone creation potential	kg C_2H_4 eq	6.88E-10
Global warming	kg CO_2 eq	8.21E-13
Acidification potential	kg SO_2 eq	2.00E-10

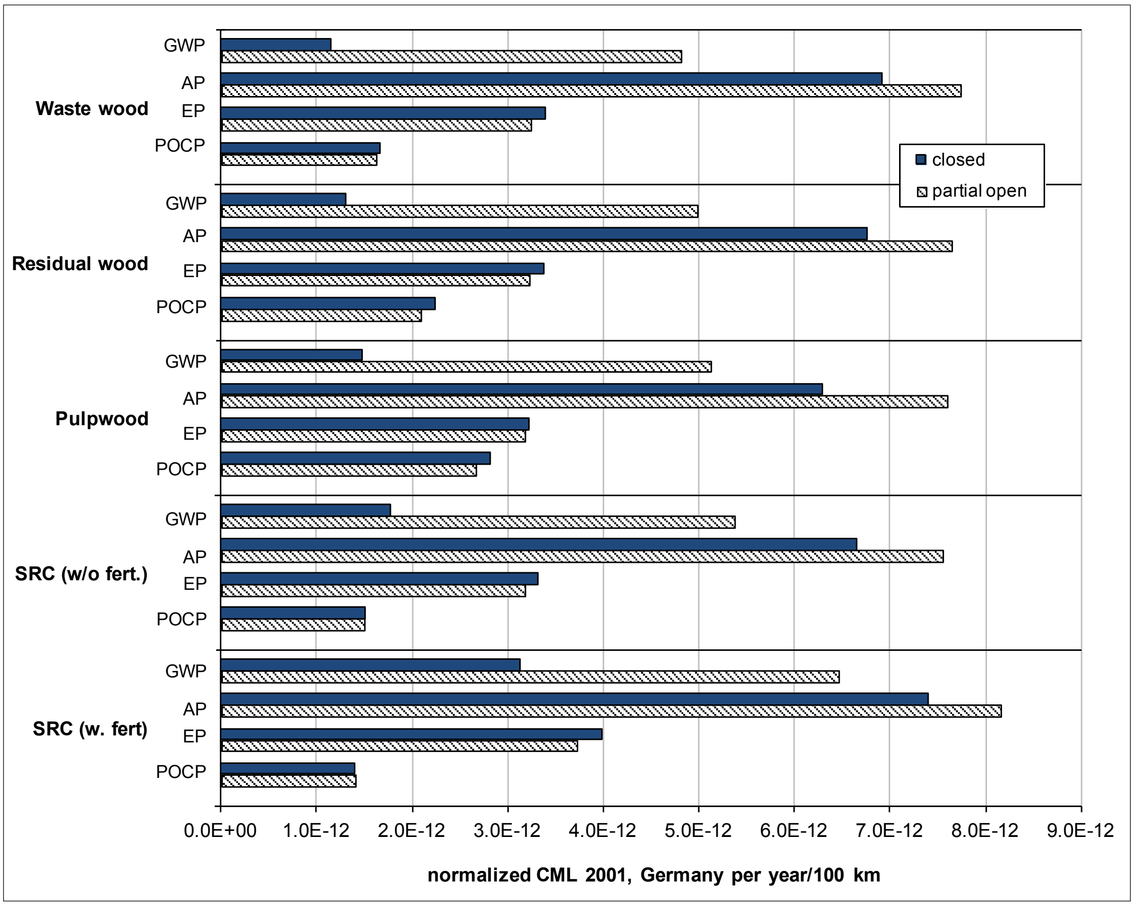


Figure 30 Normalized impact indicator values of vehicle operation (100 km) based on FT diesel from different biomass resources

After normalization it becomes apparent that the differences found between the impacts of biomass provision are almost levelled out when the use phase of FT diesel is integrated in the assessment. Nevertheless the acidification potential (AP) remains the most important impact category and in most cases the eutrophication potential (EP) becomes the second important impact category. Also the photochemical ozone creation potential (POCP) exceeds for three biomass resources the importance of the global warming impact, when the closed FT processing is considered. For the partial open FT processing global warming (GWP) is the second important impact category beside the acidification potential (AP).

Depending on the focused impact category there would be divergent recommendations which biomass resource and FT diesel processing route should be favoured. Task 38 mainly focuses on greenhouse gas emissions to evaluate the impact of biofuels. If only the global warming is of concern, then waste wood should be used for FT diesel production irrespective of the process steering. If the acidification potential (AP) or the eutrophication potential (EP) are the categories of interest, then pulpwood should be used in the closed FT synthesis process and SRC from non-fertilized fields in the partial open synthesis process. But the importance of impact categories also changes between the FT diesel processing alternatives. If the partial open production of FT diesel is assumed, global warming plays a major role beside AP. From these results it can be inferred that it is appropriate to consider more impacts than global warming when evaluating biofuel utilization.

Anyway, compared to the impacts of fossil diesel use, the impacts of vehicle operation by FT diesel produced from all assessed biomass resources are lower (Figure 31).

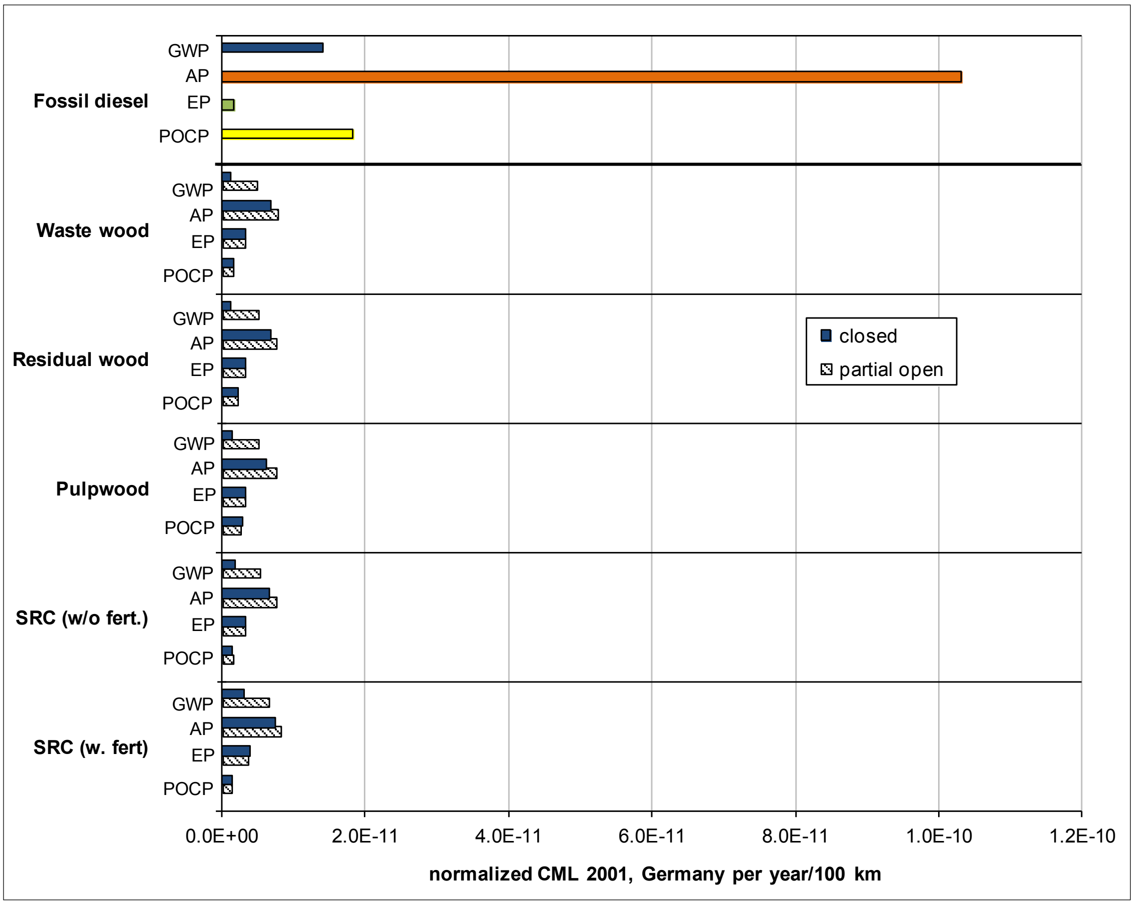


Figure 31 Comparison between normalized impact indicator results per 100 km of fossil diesel use and Fischer-Tropsch diesel from different woody resources

As Cherubini et al. (2009) found in their study, biofuel production and use often causes higher environmental burdens than fossil fuels in impact categories other than global warming. In the following figure the effects of substituting fossil diesel by FT diesel are visualized more clearly (Figure 32).

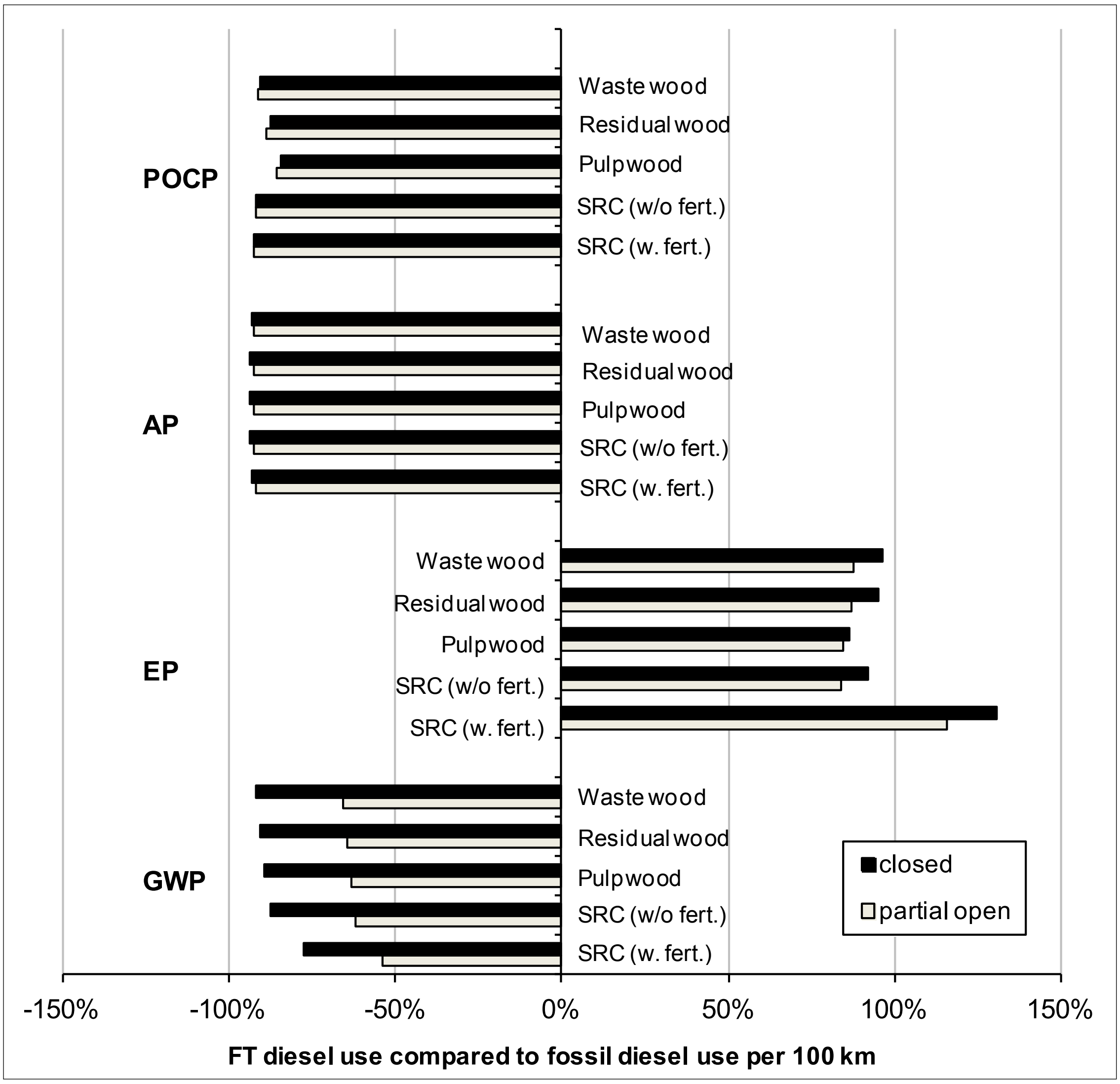


Figure 32 Relative differences of impact indicator results from Fischer-Tropsch diesel and fossil diesel use per 100 km

It becomes apparent that life cycle impacts of fossil diesel use exceed the impacts of FT diesel use in terms of photochemical ozone creation potential (POCP), acidification potential (AP) and global warming (GWP). But it is also evident that FT diesel use has a higher eutrophication potential (EP) than fossil diesel use regardless of which woody resource is used or which processing route is chosen. The highest increase in eutrophying emissions occurs if FT diesel processed from fertilized short rotation wood is used instead of fossil diesel. At the same time also the biggest savings of POCP can be achieved by using FT diesel made from fertilized SRC. On the other hand, the lowest savings of greenhouse gas emissions can be achieved by using FT diesel from fertilized SRC. Nevertheless these savings would be still sufficient to meet the reduction targets for biofuels under the European Renewable Energy Directive (Directive 2009/28/EC), which requires GHG emission savings of at least 35%. These findings could differ if a different carbon accounting method is adopted, as discussed in Section 8.5.

The AP and POCP values do not differ between the two processing routes, whereas EP and global warming values are influenced by the choice of processing route. In terms of greenhouse gas emission savings there is a huge difference between the two alternative processing routes of FT diesel production. By using FT diesel, produced within the closed processing, higher savings compared to fossil diesel can be achieved, than by using FT diesel from the partial open processing. Besides, some attention should be paid on sustainable production of biomass to avoid possible negative impacts caused by soil carbon and nutrient cycle changes. Since the FT diesel production process is very energy intensive, it should not be operated by additional energy from fossil origin.

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11 Annex 1

Table 16 Average price of the disposal of post-consumer waste wood in different German regions

Category	Region	Fees for acceptance [EUR t^{-1}] (ex. VAT)	Reference
A1	Buchholz	79.13	http://www.buhck.de/heinz-husen/onlinebestellung/annahmepreisliste-husen/index.php
A1	Ennigerloh	11.90	http://www.awg-kreis-waf.de/.../Recyclinghof_Ennigerloh_Preisliste_2009_03.pdf
n.s.	Gotha	29.18	http://www.landkreis-gotha.de/index.php?id=46
A1-A3	Göttingen	95.59	http://www.stadtentwaesserung.goettingen.de/html/index.php?id=56
A1-A3	Heidenheim	35.00	http://www.abfallwirtschaft-heidenheim.de/HOMEPAGE/ez_gebuehren.html
A1	Illerrieden	41.56	http://www.illerrieden.de/servlet/PB/menu/1298806_l1/index.html
A1-A3	Langen	83.12	http://www.langen.de/leseobjekte.pdf?id=3398o
A1-A3	Lüchow-Dannenberg	40.00	http://www.luechow-dannenberg.de/desktopdefault.aspx/tabid-1076/4129_read-21857/
A1-A3	Ludwigsburg	65.09	http://www.avl-ludwigsburg.de/main.php?SID=&set_id_menue=246
A1-A3	Münster	30.00	http://www.muenster.de/stadt/awm/gewberatung.html
n.s.	Oder-Spree Landkreis	34.08	http://www.landkreis-oder-spree.de/media/custom/1300_102_1.PDF
A1-A3	Oldenburg	50.00	http://www.oldenburg-kreis.de/715.html
A1	Salzgitter	40.72	http://www.entsorgungszentrum.de/Preise/Gewerbe/Verwertung.php
n.s.	Schwäbisch-Hall	100.00	http://www.landkreis-schwaebisch-hall.de/2282_DEU_WWW.php
A1	Schweinfurt	35.70	http://www.ihr-umweltpartner.de/PreislisteFirmen.html
A1	Taunus/Rheingau	32.70	http://www.kopp-umwelt.de/con/index.php?id=20
A1-A3	Vechta	66.64	http://www.awvonline.de/main/index
A1	Siegen	41.65	http://www.baustoffaufbereitung.de/leistungen_preise.html
	Durchschnitt	**50.67**	

12 Annex 2

Table 17 Quarterly average prices of untreated waste wood chips in 2009

Waste Wood Category	Quality	Region	Price [EUR t^{-1}]								
			January		April		July		October		**Mean**
			Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	
A I	Chips (0-150 mm), untreated, clean	Northeast	26	36	25	34	25	36	25	38	
		Northwest	24	35	24	32	24	35	24	38	
		South	24	35	24	33	24	35	25	35	
		Mean all regions	**30**		**29**		**30**		**31**		**30**
		Source:	EUWID (2009a)		EUWID (2009b)		EUWID (2009c)		EUWID (2009d)		

13 Annex 3

Table 18 Derivation of input data on residual wood compartments for the modeling of soil carbon storage in YASSO (Liski et al. 2005)

FT diesel processing	Input residual wood [kg od*kg FT diesel^{-1}]	CO_2 content [kg CO_2*kg FT diesel^{-1}]
closed	6.0	11.1
partial open	4.9	9.0

		Coars woody litter	Fine woody litter	
Spruce	Thinning	33%	67%	
	Final harvest	15%	85%	
Pine	Thinning	32%	68%	
	Final harvest	22%	78%	
Beech	Thinning	30%	70%	
	Final harvest	29%	71%	
Oak	Thinning	31%	69%	
	Final harvest	35%	65%	
				Total share[4]
Average	Thinning	31%	69%	65%
	Final harvest	25%	75%	35%
Total share from thinning and final harvest; weighted		29%	71%	

	Model Input		Model results	
	Coars woody litter	Fine woody litter	Stored in soil after 100 years	
	[kg CO_2 kg FT diesel^{-1}]	[kg CO_2 kg FT diesel^{-1}]	[kg CO_2 kg FT diesel^{-1}]	[kg CO_2 100 km^{-1}]
Closed processing	3.2	7.8	0.4	1.7
Partial open processing	2.6	6.4	0.3	1.4

[4] Share between thinnings and final harvest derived from the German Forest Accountancy Network (reference see 4.1.2)

Table 19 Parameters for modeling of soil carbon changes induced by residual wood decay with the model YASSO (Liski et al. 2005), adopted from Palosuo et al. (2001) and Karjalainen et al. (2002)

a = fractionation rate per year; c = litter composition; k = decomposition rate per year; p = transfer proportion from the litter fraction; fwl = fine woody litter; cwl = coarse woody litter; nwl = non woody litter; ext = soluble compounds; cel = holocellulose; lig = lignin like compounds

Parameter	value
a_fwl	0.5
a_cwl	0.05
c_fwl_ext	0.03
c_fwl_cel	0.65
c_fwl_lig	0.32
c_cwl_ext	0.03
c_cwl_cel	0.72
c_cwl_lig	0.25
c_nwl_ext	0.325
c_nwl_cel	0.435
c_nwl_lig	0.24
k_ext	0.65
k_cel	0.3
k_lig	0.15
k_hum1	0.013
k_hum2	0.0012
p_ext	0.15
p_cel	0.15
p_lig	0.18
p_hum	0.18