REPORT

Life cycle assessment of climate impact of Fischer-Tropsch diesel based on peat and biomass

Kristina Holmgren Linus Hagberg

B1833
February 2009

This report approved
2009-02-10

Peringe Grennfelt
Scientific Director

IVL Swedish Environmental Research Institute

Organization

IVL Swedish Environmental Research Institute Ltd.

Address

P.O. Box 21060
SE-100 31 Stockholm

Telephone

+46 (0)8-598 563 00

Report Summary

Project title

Project sponsor

Vapo Oy

Authors

Kristina Holmgren, Linus Hagberg

Title and subtitle of the report

Life cycle assessment of climate impact of Fischer-Tropsch diesel based on peat and biomass

Summary

By combining biomass gasification and Fischer-Tropsch synthesis it is possible to produce biodiesel. Vapo is investigating the possibilities for a plant where a mixture of different biomass fractions and peat would be used as raw material. In this study the climate impact of such synthetic diesel is calculated in terms of radiative forcing. The calculations show that the following parameters have large impact on the results:

- the emission factors associated with external power demand (purchased electricity)
- the use of carbon capture and storage
- the time perspective used in the analysis
- the raw material mix (amount of peat vs. amount of forest residues)
- the reference scenario for the peat production (type of peatland)

All the FT-diesel scenarios with a peat input of 90% will have higher climate impact than fossil diesel after 100 years, except when CCS is applied and Swedish electricity mix is assumed for the external power demand. In order to have lower climate impact than conventional diesel after 100 years, the peat input must be significantly lower than the biomass input.

Substantial reductions of the climate impact can be achieved by applying CCS. With CCS, all peat based FT-diesel scenarios (except the ones based on 90% peat) result in lower climate impact than fossil diesel after both 100 and 300 years. For scenarios with marginal electricity, the reductions are 50-84% after 100 years compared to conventional diesel. For scenarios with Swedish electricity mix the reductions are 100-135% (i.e. zero or negative radiative forcing).

The scenarios in this study are based on the assumption that the biodiesel refinery is located close to a harbour so that transportation of captured CO_2 to a storage site can be made by ship. An inland location would require truck transport or pipelines and the cost, infrastructure and logistics for this might not be feasible.

Keyword

Fischer-Tropsch diesel, gasification, biomass, peat, radiative forcing, climate impact

Bibliographic data

IVL Report B1833

The report can be ordered via

Homepage: www.ivl.se, e-mail: publicationservice@ivl.se, fax+46 (0)8-598 563 90, or via IVL, P.O. Box 21060, SE-100 31 Stockholm Sweden

Summary

By combining biomass gasification and Fischer-Tropsch synthesis it is possible to produce biodiesel. Vapo is investigating the possibilities for a plant where a mixture of different biomass fractions and peat would be used as raw material. This study was commissioned by Vapo and we have calculated the climate impact of synthetic diesel produced from a mixture of peat, forest residues and in some scenarios also reed canary grass. The climate impact is calculated in terms of radiative forcing (relative radiative forcing commitment) for the production and utilisation chains of the FT-diesel based on life cycle emissions. The calculations include emissions and uptake of greenhouse gases during the production of the raw material for the process (peat, forest residues and in some scenarios reed canary grass), from emissions from the diesel production plant (gasification, FT-synthesis, including production of auxiliary inputs and in some scenarios carbon capture and storage) and emissions from the end-use of the fuel.

The energy and carbon balance of the planned FT-diesel refinery is based on information given by Vapo. The estimates of emissions associated with the production of raw material (peat, forest residues and reed canary grass) are based on previous studies by IVL and other literature sources. The conditions for the production and utilisation are that the FT-refinery would be located in Sweden and the raw material would be produced within reasonable transportation distance. Calculations have been made for different production scenarios with different fractions of peat and biomass.

The calculations show that the following parameters have large impact on the results:

- the emission factors associated with external power demand (purchased electricity)
- the use of carbon capture and storage
- the time perspective used in the analysis
- the raw material mix (amount of peat vs. amount of forest residues)
- the reference scenario for the peat production (type of peatland)

All the peat and biomass based FT-diesel scenarios with a peat input of 90% will have higher climate impact than conventional fossil diesel after 100 years, except when CCS is applied and Swedish electricity mix is assumed for the external power demand. In order to have lower climate impact than conventional diesel after 100 years, the peat input must be significantly lower than the biomass input.

For production chains without CCS where peat input comes from forestry drained peatlands and is 23-33%, the biomass input is 67-77% and the Swedish electricity mix is assumed for the external power demand, the climate impacts are 6-25% lower than for fossil diesel after 100 years. The climate impacts of these scenarios are comparable to the climate impacts of synthetic diesel based on coal (CtL) and natural gas (GtL) with CCS. The corresponding scenarios where peat is cut at cultivated peatlands result in climate impacts 30-40% lower than the climate impact of fossil diesel.

Substantial reductions of the climate impact can be achieved by applying CCS (carbon capture and storage). With CCS, all peat based FT-diesel scenarios (except the ones based on 90% peat) result in lower climate impact than conventional diesel after both 100 and 300 years. For scenarios with marginal electricity, the reductions are 50-84% after 100 years compared to conventional diesel. For scenarios with Swedish electricity mix the reductions are 100-135% (i.e. zero or negative radiative forcing).

The methodology used for the calculations in this study takes into consideration all uptake and emissions that occur due to raw material production, diesel refining and utilisation compared to a reference case where the raw material is not produced. It also considers the dynamics of the fluxes. In general, biomass based carbon fluxes are set to zero as default in environmental assessments, resulting in

that the timing (dynamics) of those fluxes are not considered. We have also made calculations where the dynamics of the biomass based carbon fluxes are not considered. This has some impact on the results, making the climate impact for the peat and biomass based FT-diesel scenarios lower. The impact on the results is greater for scenarios with higher biomass based content (i.e. higher impact for scenarios with 67% forest residues than for scenarios with 10% forest residues).

In the FT-process CO_2 has to be cleaned from the synthesis gas, hence the extra energy demand for carbon capture is limited compared to for instance the energy demand for carbon capture at a power plant. However, the technical requirements and difficulties for storage of separated CO_2 are similar. The results in this study are based on the assumption that the biodiesel refinery is located close to a harbour so that transportation of captured CO_2 to a storage site (geological formation) can be made by ship. An inland location would require truck transport or pipelines and the cost, infrastructure and logistics for this might not be feasible.

Contents

1 Introduction

This study was commissioned by Vapo and the aim was to investigate the climate impact of peat and biomass based Fischer-Tropsch diesel production and utilisation chains, and compare to conventional fossil diesel. Vapo Oy is investigating the possibilities for producing Fischer-Tropsch diesel (FT-diesel) based on peat and biomass. The production method would be thermal gasification followed by Fischer-Tropsch synthesis and the peat would come from peatlands that already before the peat harvesting have been impacted by man by drainage and the biomass would come from forest residues or cropping of reed canary grass. A planned FT-diesel refinery could be located in Sweden and the raw material, i.e. peat and biomass would then be produced in the nearby area.

1.1 Background

According to the coming Directive no XXX/2009/EC[1] of the European Parliament and of the council on the promotion of the use of energy from renewable sources (European Parliament, 2008), hereafter referred to as the RES Directive, Sweden should increase its share of energy from renewable sources from 39.8% in 2005 to 49% by 2020. The RES Directive also defines certain sustainability criteria for biofuels and bioliquids which include a demand for reduction of greenhouse gas impact compared to conventional fossil alternatives by at least 35% from the introduction of the directive and by at least 50% (60%[2]) from 2017 and onwards. In addition to the RES Directive, Directive 2003/30/EC states that member states should ensure a certain amount of biofuels and other renewable fuels for the transport sector on a national level, being at least 5.75% in 2010. In order to fulfil the targets of the amount of renewable energy and also in order to fulfil the targets for greenhouse gas emissions it is important to find alternative low emission fuels for the transport sector.

The Fischer-Tropsch process is a commercial technology that is being used in industrial scale to produce liquid fuels. In theory the possibility of using different types of raw materials for the diesel synthesis is large. During the Second World War the technology was used to produce transport fuels based on coal in Germany and similarly in South-Africa coal has been and still is used as raw material. Vapo is investigating the possibilities for combining biomass gasification and the Fischer-Tropsch synthesis to produce diesel based on a raw material mixture of peat and biomass (forest residues). The suggested size of the refinery would need a significant amount of forest residues if that would be the sole raw material input, approximately 3.4-3.5 TWh, to be compared with the current total annual Swedish production of forest residues of 10 TWh. Hence it is necessary to also find other possible raw materials for the production. In this study we investigate the climate impact of synthetic diesel based on a mixture of peat, forest residues and in some scenarios also reed canary grass and compare it to the climate impact of fossil diesel. The results of the study will be used by Vapo as an input to the environmental impact assessment of a possible future plant.

1.2 Objectives

The objectives of this study were to determine the climate impact, in terms of radiative forcing, of life cycle chains for production and utilisation of peat and biomass based Fischer-Tropsch diesel. The scenarios are based on peat production from forestry drained or cultivated peatlands and the biomass input is forest residues or reed canary grass. Productivity and emission estimates in connection to the scenarios are made for Swedish conditions. As comparison, calculations have also

---

[1] The Directive has as of 30th January 2009 not yet been given a number.
[2] 60% is required if the production installation is taken into use after 2017.

been made for production and utilisation of conventional fossil diesel, coal based FT-diesel (CtL) and natural gas based FT-diesel (GtL).

2 Method

This study describes the climate impact of FT-diesel production and utilisation from a life cycle perspective. Emission estimates for the different parts of the production and utilisation chain are used for calculating the climate impact in terms of radiative forcing. The results are given in relative radiative forcing commitment (see next section for a description of this measure). The life cycle emissions of the raw material input are included in the calculations. This means that both direct and indirect emissions and impacts of the biomass systems are included. In the peat utilisation case a land use perspective is applied, where avoided emissions from the drained peatland and emissions and uptake at the after-treated cutaway are included.

The life cycle assessment methodology contains the following steps:

- goal and scope definition
- inventory analysis
- impact assessment and interpretation
- critical review and reporting

The results are heavily dependent on the conditions in the scenarios and on the set system boundaries. The key question is what happens if the particular bioenergy chain is implemented or not. The reference land use and system boundaries should be defined carefully responding to this question.

2.1 Goal and scope definition

2.1.1 Relative radiative forcing commitment of peat and biomass based FT-diesel

The climate impact of the fuel production and utilisation scenarios is expressed in relative radiative forcing commitment (RRFC) using radiative forcing modelling. The RRFC is a dimensionless ratio of the total energy absorbed into the Earth's thermodynamic system (atmosphere, surface and oceans) due to changes of greenhouse gas concentrations in the atmosphere caused by emissions and sinks from the fuel chain ($E_{absorbed}$) to the fuel energy produced in the fuel chain (E_{fuel}). The concept is described in further detail by Kirkinen et al., 2008 and the equations given below:

$$\mathrm{RRFC(T)} = \frac{E_{absorbed}(T)}{E_{fuel}}$$

$$E_{absorbed}(T) = \int_0^T RF(t)dt \cdot A$$

Where RF(t) is the radiative forcing at time t caused by the emissions and sinks of greenhouse gases due to the fuel production and utilisation chain, and A is the surface of the Earth.

The results show how the climate impact changes over time, and take into consideration the importance of the timing of the emissions. The radiative forcing calculations are made using the CIM model (Climate Impact Model) developed at IVL, based on the functions describing the relationship between atmospheric concentrations of greenhouse gases and radiative forcing given in IPCC, 2007.

All important emissions of the greenhouse gases carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) during the product's life cycle are included, from production of raw materials to refining and utilisation of the FT-diesel, including transports. Since peat and biomass production involves biological processes, which occur over longer time scales than the industrial processes, greenhouse gas fluxes between the atmosphere and the peat or biomass system are extended over time. This is taken into account in the calculations. All fluxes (emissions and uptake) of greenhouse gases that occur in the ecosystems due to the raw material production needed for the FT-diesel are included. Thus, changes in fluxes that are taken into account are:

- fluxes on the peat or biomass production site before, during and after harvesting
- fluxes during collection, transport of raw material and FT-diesel processing
- fluxes due to the utilisation of the FT-diesel

The total emissions associated with the FT-diesel production and utilisation chain is the sum of emissions from all stages of the production and utilisation chain minus the emissions of the reference scenario. The reference scenario is defined as business-as-usual, that is, no peat is harvested and no biomass is collected (the sites are left with their current land use) and no FT-diesel is produced. The chosen reference scenarios are further explained in section 7.3.

2.1.2 Description of the studied system

Figure 1 is a description of the FT-diesel production system in this study. Fluxes of greenhouse gases from the raw material production, from the FT-diesel production and utilisation are included. The input raw material to the plant is different mixes of energy peat, forest residues and reed canary grass. In addition the greenhouse gas emissions associated with the production of the auxiliary inputs to the FT-diesel refinery is included (i.e. power production and methanol production).

The greenhouse gas emissions associated with the utilisation of the co-products are not included. Instead energy allocation has been applied, which means that the emissions from the FT-diesel refinery has been allocated on the different products based on their energy content. Four different products are considered, i.e. FT-diesel, product gas, naphtha and district heating. However, in the default settings district heating is not considered as a product, but for the main scenarios calculations have also been made including district heating in the energy allocation. In addition to the four products residual gas (tail gas) and steam will be produced, but are mainly used within the process to produce electricity or for pre-drying. The internal electricity production only covers part of the power demand; the rest will be purchased from the grid (as indicated in the figure). The plant will have a net output of heat, in the form of district heating. The amount of district heating taken into consideration in the calculations is based on an estimate of how much that actually could be sold at the local site. See section 7.4 for a discussion on different allocation methodologies.

The system can be divided into three major sections:

- **Raw material production and transportation**
    - ***Peat production chain***

      Emissions and uptake of greenhouse gases due to peat harvesting, aftertreatment of the cutaway peatland and transport of peat to the FT-diesel refinery. The following equation is applied for calculating the LCA emissions from the peat production chain:

$E_{tot} = E_{harvesting} + E_{aftertreatment} – E_{reference}$ where

E_{tot} = total emissions from the peat production

$E_{harvesting}$ = emissions due to peat harvesting including emissions from harvesting area, stockpiles, harvesting equipment and transports. In most of the scenarios the conventional milling method is assumed, but there are also scenarios where the new biomass dryer method is assumed.

$E_{reference}$ = the emissions in the non-utilisation case, hence emissions that would have occurred if the peatland would not have been used for peat harvesting. We assume that the current land use continues throughout the studied period. By including the reference in this equation we get the land use change emissions. In this study the assumption is that peat is produced from peatlands that already today are impacted by man by drainage, either forestry drained peatlands or drained cultivated peatlands. Today the Swedish peat production is partly on pristine peatlands, and partly on already drained peatlands (sees also section 3.1.3 and 7.7 for the description of the assumptions made for the peat production chain).

- ***Forest biomass production chain***
  Emissions and uptake of greenhouse gases due to collection of forest residues and transportation to FT-plant. A similar approach to the peat scenario is applied. All emissions due to forest residue collection and utilisation relative to the emissions that would have occurred if the forest residues were left in the forest (reference case) are included. This includes an impact on the soil carbon pool. See also section 7.3 and 7.5 for the description of the assumptions made for the forest residues production.
  - ***Reed canary grass production chain***
    Emissions and uptake of greenhouse gases due to cultivation, harvesting, collection and transportation of reed canary grass to the FT-diesel production plant. Reed canary grass is only cultivated on a limited scale in Sweden today and hence we have assumed a factor for changes in management of the land used for reed canary grass cultivation. We assume that the reed canary grass is cultivated areas relatively close to the FT diesel plant (see also section 3.1.2 and section 7.7 for the description of the assumptions made for the reed canary grass utilisation case).
  - ***Methanol production chain***
    Emissions of greenhouse gases due to methanol production and transport to FT-diesel plant. Methanol is assumed to be produced from natural gas.
  - ***Power production chain***
    Emissions of greenhouse gases due to production of external auxiliary electricity needed in the FT-diesel plant. Two main scenarios are applied, either assuming Swedish electricity mix or a marginal electricity which is coal based production.
- **FT-diesel refining**
  - Net emissions of greenhouse gases from the FT-diesel production process (based on plant specific data provided by Vapo Oy).
  - Emissions of greenhouse gases from transport and storage of CO_2 in the case of CCS
- **End-product utilisation**
  - Emissions of greenhouse gases due to distribution and utilisation of FT-diesel.

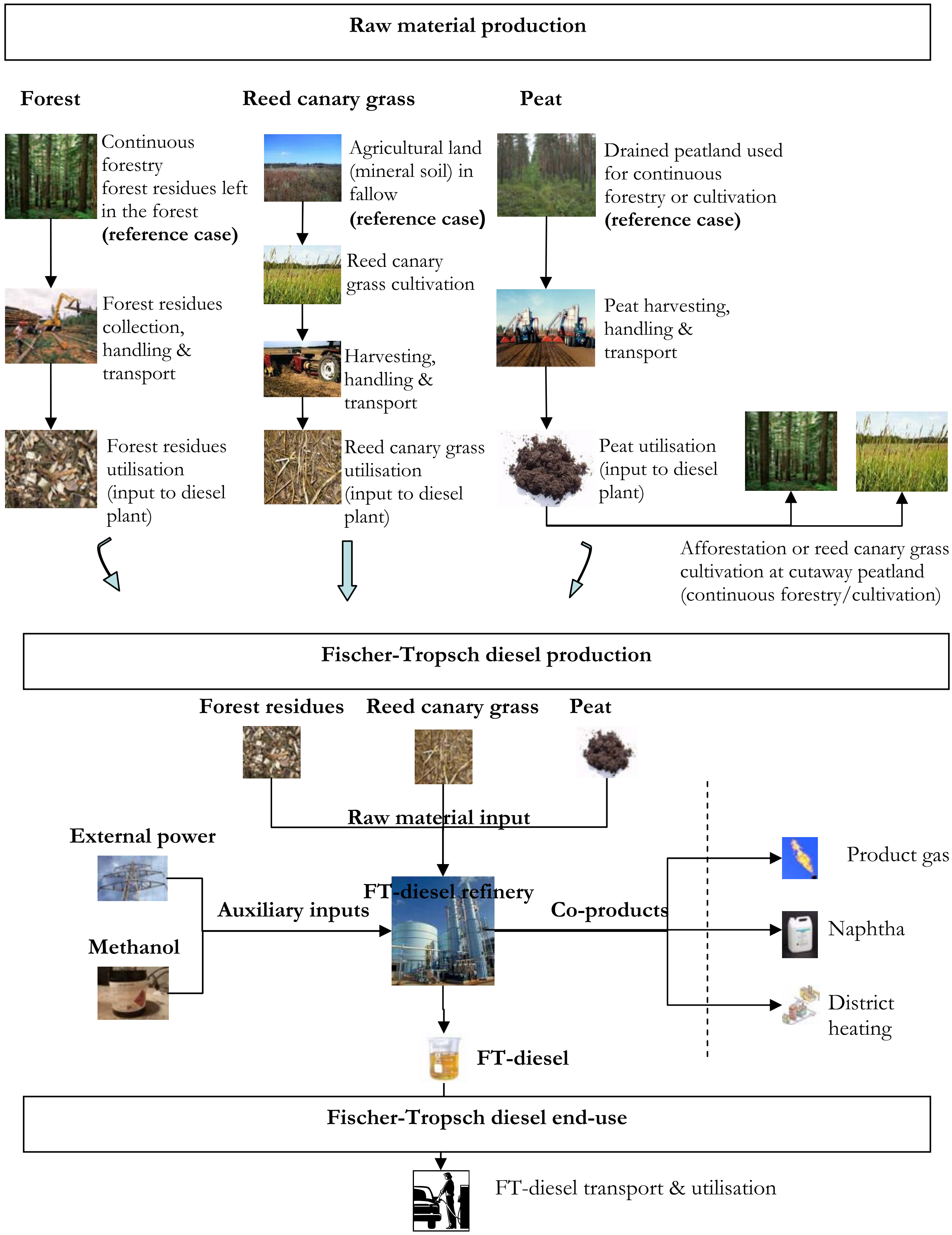

Figure 1 System description for FT-diesel production and utilisation chain used in this study

2.1.3 Limitations and uncertainties

Only the climate impact (in terms of relative radiative forcing commitment) is assessed, and only emissions of CO_2, N_2O and CH_4 are included in the assessment. Emissions associated with infrastructure, construction of harvesting and transport equipment or the construction of the FT-diesel plant are not included in the assessment. It should have only a limited effect on the results.

Note also that other aspects such as impacts on biological diversity or other values are not included.

There are many sources of uncertainties to our calculations. Among the most important ones are the assumption concerning the reference scenario for the peat production. As stated we assume that the reference is a non-utilisation case of the peat resource (hence the peat is not extracted from the peatland) and that the current land use would continue throughout the study period. We consider two different types of reference managements of peatlands; forestry (on forestry drained areas) and agriculture (on cultivated peatlands). Since our scenarios are calculated over 300 years this includes significant uncertainty, especially when looking at the results after longer time periods. Hence the uncertainty of the results increases with the time scale. The aftertreatment period considered in our scenarios is also extended over the entire scenario length. Assumptions of the greenhouse gas fluxes from the aftertreated area are therefore important. According to STPF, 2008 approximately 10 000 ha of peatlands are in active peat production in Sweden. Modern peat production started in Sweden during the early 1980ies and only now areas are starting to be ready for after treatment. According to the statistics from STPF (Swedish Peat Producers Association) 1650 ha has been completely harvested and are subject to aftertreatment. Since few aftertreated areas exist in Sweden, and thereby the greenhouse gas fluxes and productivity of these areas are relatively unknown, these assumptions are associated with significant uncertainty.

In addition also the emission estimates from the FT-diesel refining include uncertainties. We have based our calculations of the process completely on the process description provided by Vapo. The energy and mass balance of the installation have been provided by Vapo based on information from their technology provider. Figure 3 gives an overview of the proposed plant and in Table 12 the main properties for the production process in the different scenarios are given.

2.2 Fuel scenario descriptions

The climate impact of the FT-diesel production chain depends on a number of factors. Based on different assumptions on key factors, a number of scenarios were selected and evaluated. The scenarios are shown in Table 1 and are based on different assumptions on the following parameters:

- Input raw material mix of peat, forest residue and reed canary grass
- The type of peatland used for peat production
  - forestry drained peatland
  - cultivated peatland
- Harvesting method used in peat production
  - conventional milling
  - the new biomass dryer method (which is still under development)
- Aftertreatment alternative at the peatland after harvesting
  - afforestation
  - cultivation of reed canary grass
- FT-plant with or without carbon capture and storage (CCS)
- Emission factors for purchased electricity
  - Swedish power mix
  - marginal power from coal

Table 1. Studied fuel chains. The percentages in the column for primary energy source indicate the share of the total raw material input in terms of energy content. Hence for chain 1 there are two cases, one case with 33% peat and 67% forest residues and one with 90% peat and 10% forest residues.

Chain	Primary energy source	Production & utilisation	After-treatment	Reference situation for the different inputs
1	Peat (33%; 90%) (forestry drained peatland) Forest residues (67%; 10%)	Conventional peat production & FT-diesel refining (with & without CCS)	Afforestation	Peat: Non-utilisation of peat reserve, continuation of current land use. Forest residues: Residues left to decay in forest
2	Peat (23%) (forestry drained peatland) Forest residues (67%) Reed canary grass (10%)	Milled peat production & FT-diesel production (with & without CCS)	Cultivation of reed canary grass	Peat: Non-utilisation of peat reserve, continuation of current land use. Forest residues: Left to decay in forest Reed canary grass: Cropland under fallow
3	Peat (33%) (forestry drained peatland) Forest residues (67%)	New peat production method & FT-diesel (with & without CCS)	Afforestation	Peat: Non-utilisation of peat reserve, continuation of current land use. Forest residues: Left to decay in forest
4	Peat (33%)(cultivated peatland) Forest residues (67%)	Milled peat production & FT-diesel refining (with & without CCS)	Afforestation	Peat: Non-utilisation of peat reserve, continuation of current land use. Forest residues: Left to decay in forest
5	Peat (23%)(cultivated peatland Forest residues (67%) Reed canary grass (10%)	Milled peat production & FT-diesel refining (with & without CCS)	Cultivation of reed canary grass	Peat: Non-utilisation of peat reserve, continuation of current land use. Forest residues: Left to decay in forest Reed canary grass: Cropland under fallow
6	Forest residues (100%)	FT-diesel refining	-	Forest residues: Left to decay in forest
7	Crude oil (100%)	Conventional diesel refining	-	Crude oil: Non-utilisation of crude reserve
8	Coal (100%)	FT-diesel refining	-	Coal: Non-utilisation of coal reserve
9	Natural gas (100%)	FT-diesel refining	-	Natural gas: Non-utilisation of natural gas reserve

3 Emission inventory

3.1 Raw material production

3.1.1 Forest residues

If forest residues are not used for FT-diesel production it is assumed that they are left in the forest and slowly decays (see section 7.7 and 7.3). The decay functions are based on Ågren et al., 2007 assuming that the harvesting site is located at 60 degrees north and 25% are needles and 75% are branches. The characteristics of the forest residues are based on estimates from the literature and summarised in Table 2.

Table 2 Characteristics of forest residues

Characteristic	Value	Unit	Reference
Moisture content	51	%	Nilsson & Bernesson, 2008
Carbon content	50	%	Nilsson & Bernesson, 2008
Net calorific value	19.2	MJ kg dm^{-1}	Nilsson & Bernesson, 2008

According to several studies (Ågren et al., 2004; Wihersaari, 2005 and Eriksson et al., 2007) the soil carbon will also be impacted by the removal of forest residues. In this study the estimate given by Eriksson et al., 2007 have been applied, which corresponds to 7 g CO_2/MJ over 300 years. The CO_2 emissions associated with the recovery and transport of forest residues is based on data in the Well-to-tank study (CONCAWE, 2006), whereas the CH_4 and N_2O emissions are based on Uppenberg et al., 2001, see Table 3.

Table 3 Emissions associated with production and transportation of forest residues

Emission source	[g MJ^{-1}]			Reference
	CO_2	CH_4	N_2O	
Transport	2.7	1.15 *10^{-3}	0.225*10^{-3}	CONCAWE, 2006; Uppenberg et al., 2001
Collection and chipping	0.7	-	-	CONCAWE, 2006
Ash return	0.05	-	-	CONCAWE, 2006

3.1.2 Reed canary grass

Reed canary grass has been identified as a highly interesting energy crop for Swedish conditions (Thériault et al., 2003) but according to Nilsson & Bernesson, 2008 only 200 ha are currently cultivated with reed canary grass in Sweden. Some of the FT-diesel scenarios in this study are based on a raw material input of 10% reed canary grass. That input corresponds to 345 GWh of reed canary grass, which would require a cultivation area of almost 12 000 ha (based on the assumption that the yield is 6 ton dm/ha). Since the available cutaway peatland area in Sweden today is very limited (only a few thousand hectares have been completely cut and taken out of production for after-treatment so far), and since the cutaway peatlands are dispersed all over the country, it means that within a near future there will not be sufficient cutaway peatlands in order to supply the FT-diesel plant with sufficient reed canary grass. Other land areas must be used for the required reed canary grass input for the FT-diesel production.

It is assumed that agricultural land in fallow is used for the reed canary grass cultivation. Reed canary grass is a perennial crop; it is assumed that one establishment will last for ten years. There is a need for an establishment year when the crop is not harvested. During the second year when the first harvest is taken the yield of reed canary grass cultivation will be lower compared to the following years when the crop has been established properly. It is assumed that during the second (of ten) years the yield is 2/3 of the average yield during the coming years. The assumed average yield in the reed canary grass cultivation is 6 t dry matter ha^{-1} yr^{-1}, which corresponds to an energy content of 10.56 MJ m^{-2} yr^{-1} (105.6 GJ $ha^{-1}yr^{-1}$).

The characteristics used for reed canary grass are shown in Table 4.

Table 4 Characteristics of reed canary grass

Characteristic	Value	Unit	Reference	Comment
Moisture content	14	%	Nilsson & Bernesson, 2008	Spring harvest
Carbon content	46	%	Nilsson & Bernesson, 2008	Spring harvest
Net calorific value	17.6	MJ kg dm^{-1}	Nilsson & Bernesson, 2008	Spring harvest

3.1.2.1 Emissions from reed canary grass cultivation

The input data for the cultivation of reed canary grass for use as raw material in the FT-diesel plant is based on Nilsson & Bernesson, 2008 and is presented in Table 5 below. For a more detailed description of the assumptions on the inputs in the reed canary grass cultivation see Appendix 1. The estimated CO_2 emissions due to energy inputs in the production is 5.1 g $CO_2/MJ_{reed\ canary\ grass}$ produced over a ten-year period.

Table 5 CO_2 emissions associated with production of reed canary grass and assumed values of energy output (yield). These data are used for the cultivation of reed canary grass for use as raw material in the FT-diesel plant.

Cropping year	No of years	Emissions [kg CO_2/ha]	No of years	Output (yield) [MJ/ha]
Establishment, year 1	1	315	1	0
Year 2	8	484	1	69 000
Year 3-10	1	344	8	103 000
Annual average during production cycle		453		89 400

3.1.2.2 Below-ground CO_2 uptake and N_2O emissions

Agricultural areas will have to be used for the production of reed canary grass in the scenarios of this study where reed canary grass is used as raw material for the FT-diesel. It is assumed that mainly mineral soils will be used and that the net accumulation of soil C at these areas compared to the reference case will be 50 g C m-2yr-1 during 50 years. This is based on the assumption that agricultural areas which otherwise had been in fallow would be used for reed canary grass cultivation and the calculation method and default emission factors given in IPCC Good Practice Guidance for LULUCF. The estimate is similar to the estimate made by Börjesson, 1999.

According to Börjesson, 1999 the change from annual food crops to perennial energy crops at mineral soils would also save 0.04 tonne C-equivalents ha-1yr-1 by reducing soil N2O emissions (corresponds to 0.05 g N_2O $m^{-2}yr^{-1}$). However, since we assume that the land area used for reed canary grass cultivation probably would have been under fallow, which also reduces the N_2O emissions compared to annual cropping we assume that the reduction in N_2O emissions due to the cultivation of reed canary grass is negligible.

3.1.3 Peat

All life cycle emissions from energy peat production, utilisation (FT-refining) and after-treatment are included in the study. The emission estimates from the different stages of the peat production chain is mainly based on Hagberg & Holmgren, 2008. The emissions due to peat production and utilisation are described by Figure 2 and the equation given below:

Reference scenario
E.g. drained (forestry) peatland emissions of greenhouse gases, mainly CO_2 and N_2O.

Harvesting stage
Emissions from the cutting area, storage transports and working machines.

Utilisation stage
Great emissions of greenhouse gases.

Aftertreatment stage
E.g. afforestation (picture) or reed canary grass cultivation can result in carbon accumulating system.

Figure 2. Illustration of greenhouse gas fluxes due to peat production and utilisation (Hagberg & Holmgren, 2008)

Total emissions for peat utilisation scenario =
harvesting stage + utilisation stage + after-treatment stage – reference scenario

Where;

Harvesting stage	=	Peat cutting stage. All emissions from the drained harvesting area, stockpiles, working machines and transports are included. The amount of emissions depends on harvesting time and the production technology used.
Utilisation stage	=	The emissions due to utilisation (FT-refining, combustion) of peat are the largest source of emissions during the peat utilisation chain.
Aftertreatment stage	=	Emissions/uptake at the peatland after harvesting depends on the after-treatment of the cutaway. In this study two options for aftertreatment are included, afforestation and cultivation of reed canary grass.
Reference scenario	=	This is the non-utilisation scenario represented by the pre-harvesting conditions at the peatland. It is assumed that pre-harvesting land use would continue in the reference scenario. Emissions from this stage are considered to be avoided in the utilisation scenario (hence the subtraction in the equation).

In scenarios where conventional milling method is used, it is assumed that the peat production is 0.159 GJ_{peat} m^{-2} (which corresponds to 485 m^3 ha^{-1} yr^{-1}). In scenarios where the new production technology (biomass drier) is utilised, it is assumed that the peat production is 3.64 GJ_{peat} m^{-2}, which corresponds to 11 000 m^3 ha^{-1} yr^{-1}. Since the total input of peat in the FT-diesel production plant is approximately 4130 TJ (assuming one third peat and two thirds forest residues) this corresponds to a minimum need of production area of almost 2 600 ha in the case of conventional peat production. The assumed values for peat characteristics are presented in Table 6 below:

Table 6 Characteristics for Swedish energy peat.

Characteristic	Value	Unit	Reference
Moisture content	45	%-w/w[3]	Nilsson, 2004
Carbon content	53.7	%-w/w dry	Nilsson, 2004
Net calorific value	20.7	MJ/kg dry	Nilsson, 2004

3.1.3.1 Emissions before harvesting

Forestry drained peatlands

The emission estimates of forestry drained peatlands are based on Hagberg & Holmgren, 2008. Hagberg & Holmgren made different assumptions for areas of different fertility. In this study an average estimate has been used, assuming 50% being low fertility and 50% being high fertility land. The emission estimates used in this study for the forestry drained peatlands are shown in Table 7.

Table 7 Emissions from forestry drained peatlands used in this study.

Emission source	[g m^{-2} yr^{-1}]			Reference
	CO_2	N_2O	CH_4	
Soil emissions	638	0.28	0	Hagberg & Holmgren, 2008
Carbon sequestration in living biomass	-618[4]	0	0	Hagberg & Holmgren, 2008

Cultivated peatlands

Drained cultivated peatlands can be large sources of both CO_2 and N_2O. The emissions vary with land use, suggesting that soil management practices associated with different crops have a major influence on the emissions. For the purposes of this study, the estimates of the average emissions from cultivated peatlands in Sweden found in Hagberg & Holmgren, 2008 have been used. The estimates are based on average emissions measured from cultivated peatlands with different land use (Maljanen et al., 2007; Nilsson & Nilsson, 2004), that have been weighted by the actual land use in Sweden from the land use inventory made by Berglund & Berglund, 2008. The emission factors used in this study for cultivated peatlands are shown in Table 8.

Table 8 Emissions from cultivated peatlands used in this study.

Emission source	[g m^{-2} yr^{-1}]			Reference
	CO_2	N_2O	CH_4	
Weighted average emissions used in this study	1780	1.5	0	Hagberg & Holmgren, 2008

3.1.3.2 Emissions during peat harvesting

Emissions during the peat production stage include emissions from the drained extraction area, from stockpiles and from harvesting equipment and transports. It is assumed that peat is harvested and utilised for FT-diesel production during one year. With conventional peat harvesting, however, the harvesting is carried out layer for layer during approx. 20 years before the harvesting is completed plus approx. 2 years of pre-drainage for forestry drained peatlands before harvesting can start. In this study, the average annual emissions from the peat harvesting area (including both drainage-stage and harvesting stage) are therefore used. The emission estimates used to calculate the annual average emissions during peat harvesting are based on Hagberg & Holmgren, 2008, and are summarised in Table 9.

[3] Percentage by weight.

[4] Note that the corresponding amount is assumed to be emitted at cutting, 80% of sequestered carbon is assumed to be emitted directly and 20% during coming rotation period.

Table 9 Emissions during peat harvesting, based on Hagberg & Holmgren, 2008. From the emissions presented for conventional harvesting, annual average emissions are calculated, since only one year peat production is assumed in this study.

Emission source	**[g m^{-2} yr^{-1}]**		
	CO_2	**N_2O**	**CH_4**
Conventional harvesting method			
Harvesting area during drainage stage for forestry drained peatlands (2 years)	980	0.3	3.7
Harvesting area (20 years)	980	0.3	3.7
Stockpiles (20 years)	250	negligible	negligible
Harvesting equipment & transports	1 g MJ^{-1}	0.025 mg MJ^{-1}	0.7 mg MJ^{-1}
New harvesting method			
Harvesting area (1 year)	770	0.1	negligible
Stockpiles (1 year)	20	negligible	negligible
Harvesting equipment & transports	0.5 g MJ^{-1}	0.012 mg MJ^{-1}	0.35 mg MJ^{-1}

3.1.3.3 Emissions after harvesting

Afforestation
At the afforested cutaway peatland there are both emissions and uptakes of greenhouse gases. The emissions consist mainly of CO_2 emissions from decomposition of residual peat and various amounts of soil emissions of N_2O. At the same time CO_2 uptake in growing biomass occur both above and below ground. How large this uptake is depends mainly on the forest productivity of the cutaway peatland. It is also crucial how the uptake in the forest is considered. The emission estimates used for the afforested cutaway peatland are based on Hagberg & Holmgren, 2008 and are summarised in Table 10.

CO_2 emissions at the afforested cutaway peatland are assumed to decrease exponentially from 1100 g CO_2 m^{-2} yr^{-1} during the first rotation period, when 50% of the residual peat has been decomposed (Hagberg & Holmgren, 2008). Thereafter slow release during the rest of the simulation period. N_2O emissions are assumed to be 0.15 g N_2O m^{-2} yr^{-1} after afforestation and decrease linearly to 0.06 g N_2O m^{-2} yr^{-1} after 45 years, and are then assumed to stay on that level throughout the study period (Hagberg & Holmgren, 2008). The CH_4 emissions at afforested cutaway peatlands are assumed to be negligible.

For scenarios where peat harvesting is carried out with the new harvesting method, the CO_2 emissions from the afforested cutaway peatland are assumed to be 50% lower than the emissions with the milling method at the same stage, and the N_2O emissions 30% lower (Hagberg & Holmgren, 2008). This is mainly beacause the remaining peat layer after harvesting is thinner, and the microbial population is more disturbed.

In this study continuous forestry is considered. The CO_2 uptake in living biomass during forest growth is considered for each tree rotation period (85 years), and that the same amount of CO_2 is released each time the forest is cut down. 80% of the sequestered carbon is assumed to be released instantaneously at cutting (illustrating the removal of biomass from the land-area), whereas 20% is assumed to be left at the site and decompose during the coming rotation period. The annual forest productivity that can be reached at the cutaway peatland after afforestation is assumed to be 7.1 m^3 ha^{-1} (subject to fertilization or ash-application), which is the same as the average productivity at drained forested peatlands with high fertility in Sweden (Hagberg & Holmgren, 2008). With a rotation period of 85 years this corresponds to 820 g CO_2 m^{-2} yr^{-1}.[5] It means that for drained forested peatlands with low fertility, the forest productivity is assumed to increase by 3.5 m^3 ha^{-1} after afforestation at the cutaway. For drained forested peatlands with high fertility, the forest productivity is assumed to be sustained on the same level. It should be noted that this value is a best estimate for Sweden and is for instance to high for north of Sweden, whereas it could be higher in the south.

After the peat has been removed and the cutaway peatland is afforested, carbon accumulation in soil organic matter will start and continue until equilibrium between accumulation and decomposition is reached. In this study, carbon accumulation in humus is assumed to occur at a constant rate until 3.5 kg C m^{-2} is reached after one rotation period (Hagberg & Holmgren, 2008). With a rotation period of 85 years the annual uptake will be 150 g CO_2 m^{-2}.

Table 10 Emissions after harvesting at the afforested cutaway peatland (Hagberg & Holmgren, 2008).

Emission source	**[g m^{-2} yr^{-1}]**		
	CO_2	**N_2O**	**CH_4**
Soil emissions (conventional production method)	1100 exponential decrease during first rotation period when 50% of the residual peat has been decomposed. Thereafter slow release during rest of simulation period.	Linear decrease from 0.15 to 0.06 after 45 years.	0
Soil emissions (new production method)	550 exponential decrease during 45 years when 50% of residual peat has been decomposed. Thereafter slow release during rest of simulation period.	Linear decrease from 0.1 to 0.06 after 15 years.	0
Carbon sequestration in living biomass	-820 during each rotation period (7.1 m^3 ha^{-1} yr^{-1}), the corresponding amount of carbon is assumed to be emitted at each cutting, 80% directly and 20% during coming rotation period	-	-
Soil carbon sequestration	-150 during one rotation	-	-

Cultivation of reed canary grass

Below ground carbon accumulation

Perennial crops such as reed canary grass might increase the below-ground uptake of carbon in cultivated soils. Huttunen et al., 2004 made a theoretical carbon balance for reed canary grass cultivation on a cutaway peatland which indicated that the system might be a net sink or a net source of soil carbon. In any case it would be a smaller source than a peat extraction area. Shurpali et al., 2008 have made measurements of the ecosystem respiration from reed canary grass cultivation on a cutaway peatland and based on it can be seen that at least in the short term the system is most likely accumulating soil carbon and is definitely a smaller source than afforested and cultivated organic soils.

According to Huttunen et al., 2004 the net ecosystem exchange (NEE) is calculated by the following equation:

$$NEE = P_G – (R_{TOT} + W)$$

where
P_G = gross photosynthesis
R_{TOT} = total respiration
W = weathering (leaching)

[5] Based on the following assumptions: dry density of stem wood = 420 kg m^{-3}, carbon content in stem wood = 50 %, total standing biomass in thinnings and final cutting (inclusive stem, branches, needles, stump and roots) is 1,5 times the stem biomass. Total uptake [kg C ha^{-1} $year^{-1}$]= 1,5 * 420 * 0,5 * productivity

We used this formula and the results by Shurpali et al., 2008 in order to estimate the NEE for the reed canary grass cultivation system. Our estimate is that NEE is 80 g C $m^{-2}yr^{-1}$ during 50 years. Thereafter we assume that the net accumulation is zero (this corresponds to accumulated carbon storage of 4 kg C m^{-2}) and that the decomposition of residual peat is low (same magnitude as in afforested cutaway peatlands after corresponding time period).

Soil emissions of nitrous oxide

In the Swedish national inventory of greenhouse gas emissions the IPCC default emission factor is used for the estimate of soil emissions of nitrous oxide (N_2O) from cultivated organic soils. The emission factor is 8 kg N_2O-N ha^{-1} yr^{-1} which corresponds to 1.3 g N_2O $m^{-2}yr^{-1}$. The value for organic soils used in the Swedish inventory is 0.5 kg N_2O-N ha^{-1} yr^{-1} (which corresponds to 0.08 g N_2O $m^{-2}yr^{-1}$). Since the cutaway peatland is a mineral soil with a residual layer of peat (organic matter) a value somewhere in between these values was used in this study. Based on assumptions in previous studies the value 0.3 g N_2O $m^{-2}yr^{-1}$ was used.

Table 11 summarises the emissions and uptake of greenhouse gas emissions from the cutaway peatland aftertreated by cultivation of reed canary grass.

Table 11 Emissions from cutaway peatlands aftertreated by cultivation of reed canary grass.

Emission source	Emission estimates	References
Soil emissions, N_2O	0.3 g N_2O m^{-2} yr^{-1}	Hagberg & Holmgren, 2008
Soil emissions, CO_2, decomposition of residual peat	During first 50 years net accumulation of soil carbon. Thereafter emissions of CO_2 from decomposition of residual peat for rest of simulation period. The decomposition rate is assumed to be slow, same magnitude as in afforested cutaway peatlands after corresponding time period	Adjusted after Shurpali et al., 2008; Huttunen, 2004; Hagberg & Holmgren, 2008
Below ground carbon sequestration	-80 g C m^{-2} yr^{-1} during 50 years, thereafter 0	Adjusted after Shurpali et al., 2008; Huttunen, 2004
Emissions due to input in cropping system	4.8 g CO_2 MJ^{-1} (see further appendix 1 for more detailed information on assumptions)	Bullard & Metcalfe, 2001; Pahkala et al., 2003.

3.2 FT-diesel refining

A schematic description of the refining process is shown in Figure 3. Calculations are made for FT-refining with and without carbon capture and storage (CCS). Calculations are also made for different mixtures of raw material input, i.e. peat, forest residues and reed canary grass, and hence the figure on raw material input is only approximate. The total output of FT-diesel and co-products is the same in all scenarios.

The main properties of the process in terms of energy flows and emissions are summarised in Table 12. The figures are completely based on information given by Vapo, 2008. The methanol input is estimated based on Soimakallio et al., 2008.

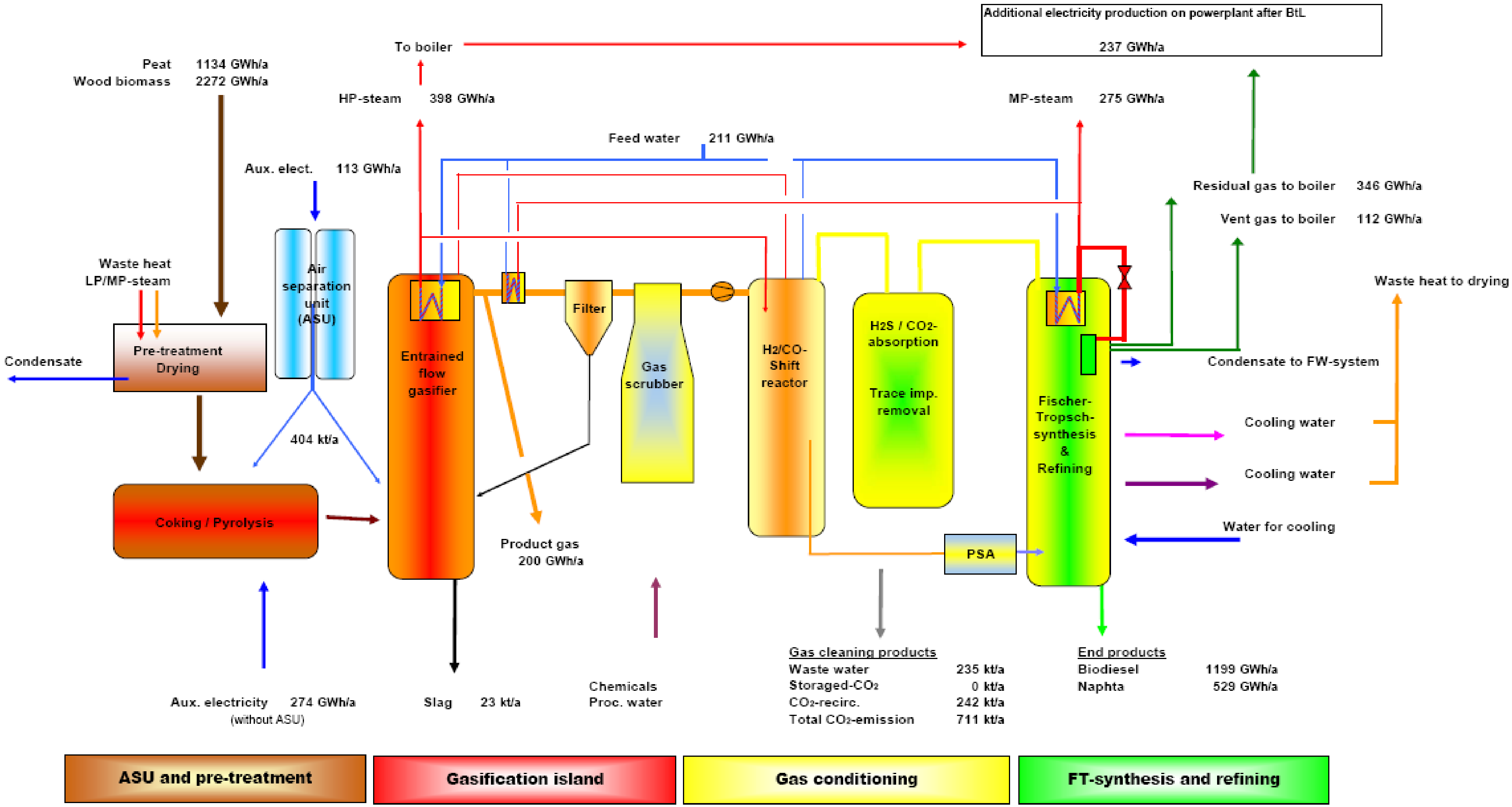

Figure 3 Schematic description of the FT-diesel refinery (Vapo, 2008).

Table 12 Main properties of the FT-plant (Vapo, 2008).

	Unit	Peat (33%) forest residues (67%)	Peat (23%) forest residues (67 %) reed canary grass (10%)	Peat (90%) forest residues (10%)
Operating hours	h/year	8000	8000	8000
Input				
Energy peat	GWh/a	1134	823	3151
Forest residues	GWh/a	2272	2272	354
Reed canary grass	GWh/a	0	338	0
Total peat & biomass input	GWh/a	3451	3433	3505
Methanol	kton/a	0.98	0.98	0.98
External electricity for main process	GWh/a	38	38	38
External electricity for oxygen plant	GWh/a	113	115	113
Total external power demand	GWh/a	151	153	152
Power for CO_2 liquefaction/transport to harbour	GWh/a	101	101	102
Total external power demand, with CCS	GWh/a	252	254	253
Output				
Product gas	GWh/a	200	200	200
FT-diesel	GWh/a	1199	1199	1199
Naphtha	GWh/a	529	529	529
District heating	GWh/a	130	130	130
CO_2 emissions				
From synthesis gas cleaning	kton/a	711	711	716
From synthesis gas cleaning with CCS	kton/a	71	71	72
Other process emissions	kton/a	77	77	77

Most of the carbon in the input raw material will be transferred into the end-products. The FT-diesel is assumed to be utilised within the same year, emitting its carbon content when combusted. The remaining carbon (which does not go into end products) will be emitted during the process or during internal energy production. In the case of CCS, some of the carbon will be captured and stored and therefore not emitted.

3.2.1 Carbon Capture and Storage (CCS)

The FT-diesel process in Figure 3 includes a scrubber unit where CO_2 is separated from the syngas before entering the FT-synthesis unit. The separated CO_2 can be captured and liquefied for transportation to some permanent underground storage. In the scenarios with CCS, it is assumed that 90% of the separated CO_2 can be captured (equals approximately 48% of total carbon input to the plant) The extra electricity demand for liquefaction and compression of captured CO_2 to 7 bar and -50ºC and transportation to harbour is estimated to 0.084 $MJ_{el}/MJ_{FT\text{-}disel}$.

The estimates of energy demand for the CCS are based on the assumption that the FT-plant is situated near a harbour in mid-Sweden or southern Finland. In the CCS scenarios, the captured CO_2 is liquefied and compressed to 7 bar and -50 ºC which is required for ship transport. The extra energy needed for liquefaction and compression is included in the energy balance of the FT-plant with CCS, as shown in Table 12. The liquefied CO_2 is temporarily stored in storage tanks in the harbour and then transported by ship approximately 1600 km to the North Sea for permanent storage in the Utsira aquifer. Storage in an aquifer requires CO_2 in supercritical condition, which means that further compression is needed at the platform before injection (139 bar and 30-40ºC is assumed in this study, to compensate for pressure drop during injection). The energy demand for compression to 139 bar has been roughly estimated to 65 kWh/ton CO_2 based on McCollum et al., 2006. The emissions due to compression depend on what electricity source that is assumed. Here, the electricity is assumed be generated from natural gas at the platform (the emission factor is shown in Table 14).

The emissions from CO_2 transport has been estimated based on IEAGHG, 2004. The estimates include return transport and are based on a ship with a capacity of 10 000 ton CO_2 with an average speed of 15 knots. The emissions are proportional to the transport distance and come from three different sources: CO_2 boil-off from the temporary storage tanks, boil-off during ship transport and emissions from the ship engine. The estimated emissions from CO_2 transport is presented in Table 13.

Table 13 Estimated emission levels from CO_2 transport (based on transport distance of 1600 km by ship).

	Unit	CO_2	N_2O	CH_4	Reference
Storage tanks (boil-off)	kg/ton CO_2	5	-	-	IEAGHG, 2004
Transport (boil-off)	kg/ton CO_2	8	-	-	IEAGHG, 2004
Transport (engine exhaust)	kg/ton CO_2	33	0	0.0002	IEAGHG, 2004; NTM, 2007

It should be noted that the calculations are based on ship transport of captured CO_2. If the plant is situated far from a harbour, additional land transport is necessary. The feasibility of a CCS application or the climate impact of the additional land transportation with an inland location was not analysed in this study (see also section 7.5).

3.2.2 Emissions related to external power demand

The electricity demand in the FT-plant is larger than what is internally generated from excess steam and tail gas. The emissions from the purchased electricity depend on how the environmental impact of electricity is valued. In this study two different scenarios are made: the purchased electricity is assumed to be Swedish power mix, with low emission factors, or marginal electricity from coal power, with high emission factors. These two scenarios will more or less represent the lower and upper limit of climate impact from electricity purchased in Scandinavia. In the scenarios with CCS, the power demand for compression of CO_2 to 139 bar at the storage site is assumed to be covered with power from natural gas at the platform. The emission factors used for electricity are shown in Table 14.

Table 14 Emission factors for electricity used in this study.

	Unit	CO_2	N_2O	CH_4	Reference
Swedish power mix	g gas/MJ_{el}	5.4	0.001	0.028	Uppenberg et al., 2001 & power mix in 2007
Coal power (η=35%)	g gas/MJ_{el}	269	0.004	3.1	Uppenberg et al., 2001

3.2.3 Emissions from methanol production and distribution

Methanol is used in the FT-synthesis as a solvent for carbon dioxide separation. The methanol is assumed to be produced from natural gas. The life cycle emissions of methanol production and distribution used in this study are based on CONCAWE, 2006. The emission factors are shown in Table 15.

Table 15 Emissions of methanol production and distribution used in this study.

Emissions	Unit	CO_2	CH_4	N_2O	Reference
Production and distribution (well-to-tank)	g/MJ_{fuel}	1.1	0	0	CONCAWE, 2006

3.3 End-use of FT-diesel

3.3.1 Emissions from FT-diesel distribution and utilisation

Emissions associated with distribution and utilisation of the produced FT-diesel based on CONCAWE, 2006 and CONCAWE, 2007 are included in the calculations. The emission factors for distribution and dispensing and utilisation of FT-diesel used in this study are shown in Table 16.

Table 16 Emission factors for distribution, dispensing and utilisation (combustion) of FT-diesel used in this study.

Emissions	Unit	CO_2	N_2O	CH_4	Reference
Distribution & dispensing	g/MJ_{fuel}	1.1	0	0	CONCAWE, 2006
Utilisation (combustion)	g/MJ_{fuel}	70.8	0.00055	0.071	CONCAWE, 2007

3.4 Fossil based diesel scenarios

The climate impact of the peat and biomass based FT-diesel scenarios are compared to conventional fossil diesel. Also the corresponding climate impact of synthetic diesel from coal (Coal to Liquid, CtL) and natural gas (Gas to Liquid, GtL) are presented, based on emission estimates given in literature.

3.4.1 Conventional diesel

The life cycle emissions of conventional fossil diesel production and utilisation used in this study are based on CONCAWE, 2006 and CONCAWE, 2007 and are summarised in Table 17.

Table 17 Life cycle emissions of conventional fossil diesel used in this study.

Emissions	Unit	CO_2	N_2O	CH_4	Reference
Crude oil extraction & processing	g/MJ_{fuel}	3.7	0	0	CONCAWE, 2006
Crude oil transport	g/MJ_{fuel}	0.9	0	0	CONCAWE, 2006
Refining	g/MJ_{fuel}	8.6	0	0	CONCAWE, 2006
Distribution & dispensing	g/MJ_{fuel}	1	0	0	CONCAWE, 2006
Utilisation (combustion)	g/MJ_{fuel}	73.54	0.00055	0.071	CONCAWE, 2007
Total	g/MJ_{fuel}	87.74	0.00055	0.071	

3.4.2 FT-diesel from coal (CtL) and natural gas (GtL)

A rough comparison with fossil pathways of FT-diesel production is also made in this study. The estimated life cycle emissions of FT-diesel from coal (Table 18) and natural gas (Table 19), with and without CCS, are based on CONCAWE, 2006 and CONCAWE, 2007. The CONCAWE figures are not completely comparable with the scenarios in this study, since there are differences in defined system. The figures for CtL and GtL FT-diesel include credits for any excess electricity and in the case of CCS, compression to 150 bar is included which is assumed to be sufficient for further transport in pipeline (100-150 km) and injection into a storage-site. In all the other CCS scenarios of this study the assumption is that transport is made by ship.

In all cases (both our scenarios and the CtL and GtL FT-diesel scenarios) physical energy allocation is applied, i.e. emissions are allocated on the main product and co-products (mainly naphtha and petroleum gases) with respect to their energy content, since all products directly or indirectly are assumed to substitute conventional diesel/gasoline.

Table 18 Life cycle emissions of FT-diesel from coal (CtL) used in this study.

Emissions	Unit	CO_2	N_2O	CH_4	Reference
Production and distribution (well-to-tank)	g/MJ_{fuel}	100.89	0	0	CONCAWE, 2006
Production and distribution with CCS (well-to-tank)	g/MJ_{fuel}	9.31	0	0	CONCAWE, 2006
Utilisation (combustion)	g/MJ_{fuel}	70.80	0.00055	0.071	CONCAWE, 2007

Table 19 Life cycle emissions of FT-diesel from natural gas (GtL) used in this study.

Emissions	Unit	CO_2	N_2O	CH_4	Reference
Production and distribution (well-to-tank)	g/MJ_{fuel}	16.47	0	0	CONCAWE, 2006
Production and distribution with CCS (well-to-tank)	g/MJ_{fuel}	4.17	0	0	CONCAWE, 2006
Utilisation (combustion)	g/MJ_{fuel}	70.80	0.00055	0.071	CONCAWE, 2007

4 Results – climate impact assessment

4.1 Climate impact of the main scenarios for the FT-diesel production chains of the Vapo-plant

The climate impacts, in terms of relative radiative forcing commitment after 100 years, of the main FT-diesel scenarios for the Vapo-plant, are presented in Figure 4. The results are given in a 100 year perspective, i.e. showing how much energy that has been absorbed in the atmosphere after 100 years due to the emissions of greenhouse gases caused by the production and utilisation of one GJ diesel. The FT-diesel in these scenarios are produced from a raw material mix of either 90% peat/10% forest residues or 33% peat/67% forest residues (based on input energy content). Peat is produced from forestry drained peatlands using the conventional milling method, and the cutaway peatland is aftertreated by afforestation. In the main scenarios the emissions associated with the purchased electricity are calculated based on a Swedish electricity mix. For comparison, scenarios made with 100% forest residues as raw material input in the FT-diesel plant as well as fossil diesel comparators, i.e. conventional diesel from crude oil and synthetic diesel from coal (CtL) and natural gas (GtL) are presented. Calculations based on marginal electricity, and scenarios based on other raw material mixes are presented in section 4.2.

As discussed in section 7.1 the time perspective is of importance when assessing the climate impact of the various fuel chains. In Figure 5 and Figure 6 the time development from year 0 - 300 of the scenarios presented in Figure 4 are shown. In these figures the reader can chose another time perspective than 100 years if that is needed or found more appropriate for any purpose. Raw material production, diesel refining and utilisation occur during one year.

- The results for the 100-year perspective show that FT-diesel from 90% peat/10% forest residues without CCS will have significantly higher climate impact than conventional fossil diesel (comparable to coal-based synthetic diesel, CtL). With CCS, the climate impact is about 7% lower than conventional diesel and comparable with CtL with CCS.
- For FT-diesel based on 33% peat/67% forest residues the climate impact without CCS is 6% lower than conventional diesel in a 100-year perspective. However, with CCS the radiative forcing will be zero in a 100 year perspective. The difference between including, and not including, district heating in the energy allocation is small, due to the small amount of district heating that is possible to sell on the local market.
- FT-diesel based on 100% forest residues, without CCS, has according to our results 60% lower climate impact than conventional diesel. With CCS the climate impact of the 100% forest residue scenario is more than 150% lower than conventional diesel.

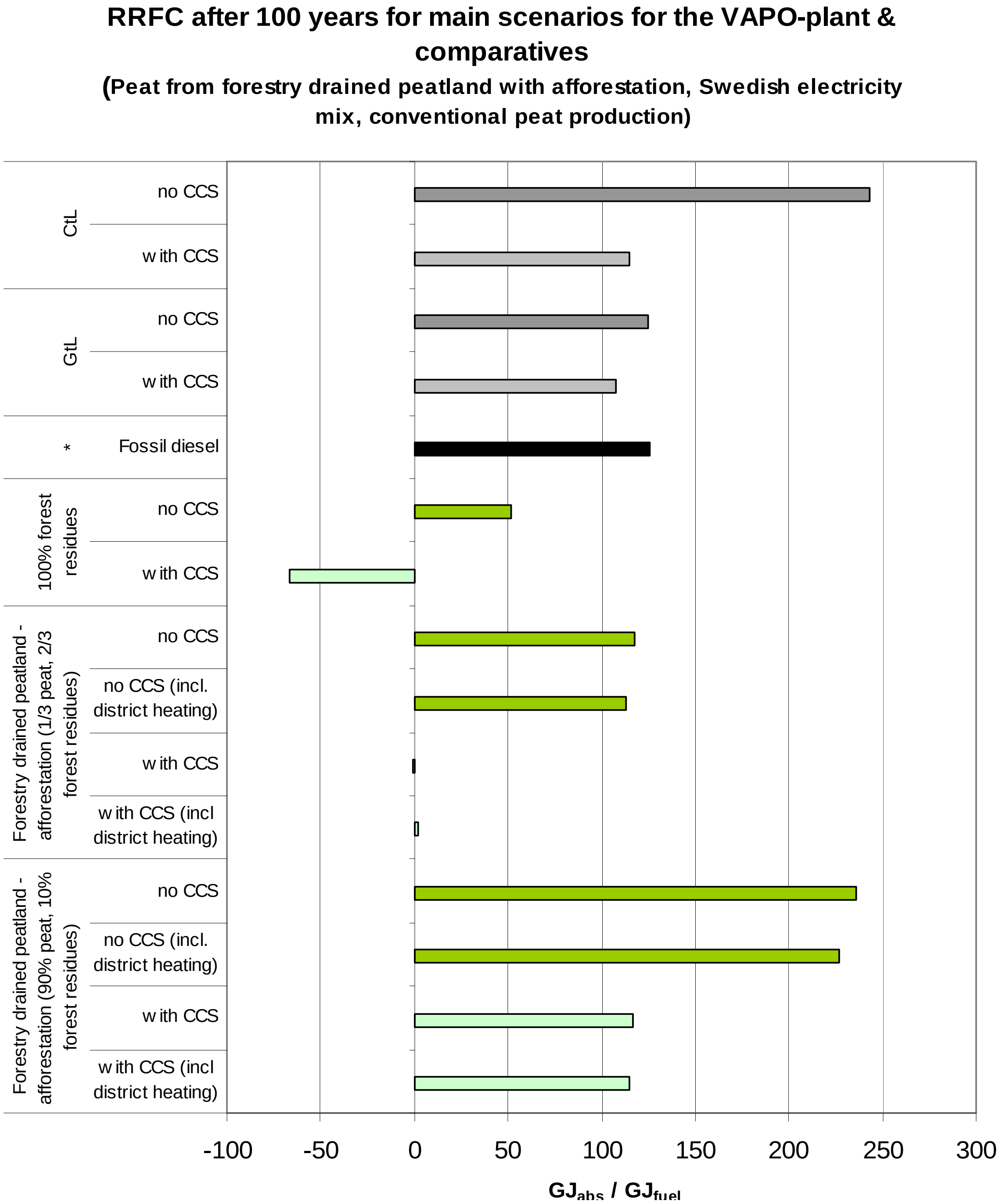

Figure 4 Relative radiative forcing commitment (RRFC) after 100 years of the main scenarios for the Vapo-plant, compared with fossil fuel chains and a 100% forest residue scenario. The main scenarios assume peat input from forestry drained peatlands followed by afforestation, conventional peat production and Swedish electricity mix. For all chains energy allocation of emissions has been applied, i.e. allocation of emissions between main product (diesel) and co-products (naphtha and product gas) based on the energy content of the products. When indicated, also district heating was considered as a co-product.

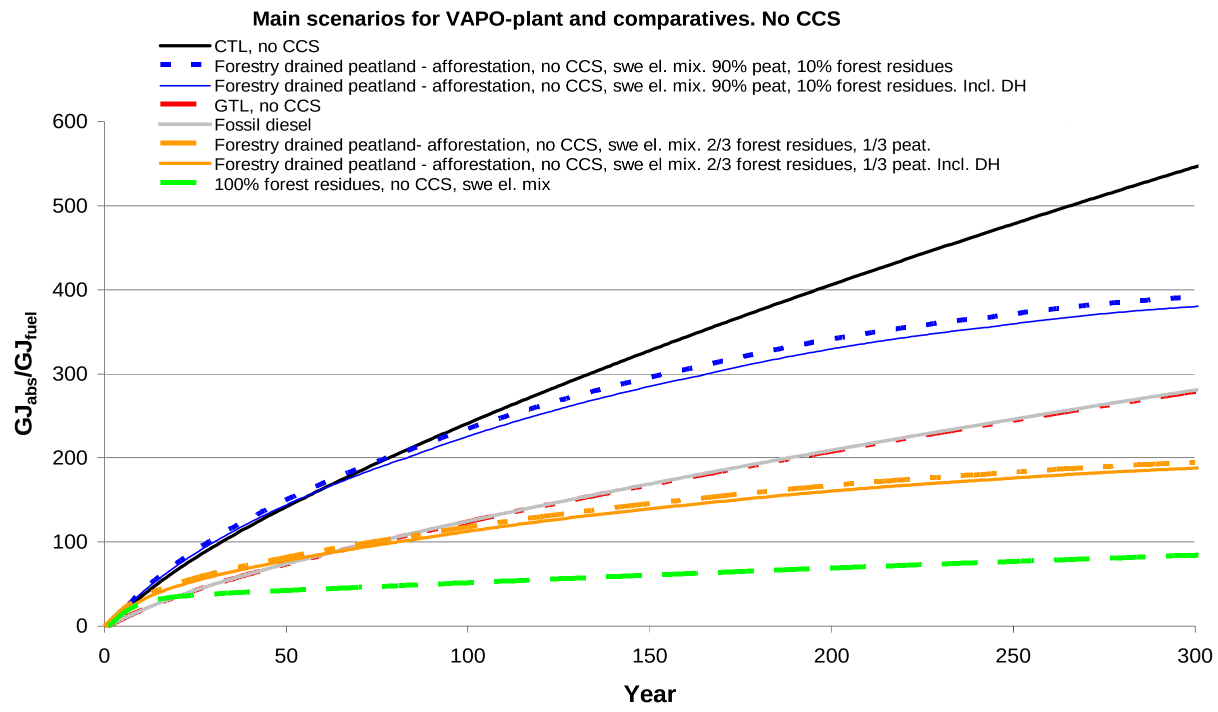

Figure 5 This figure shows the time development from year 0 - 300 of the scenarios without CCS in Figure 4.

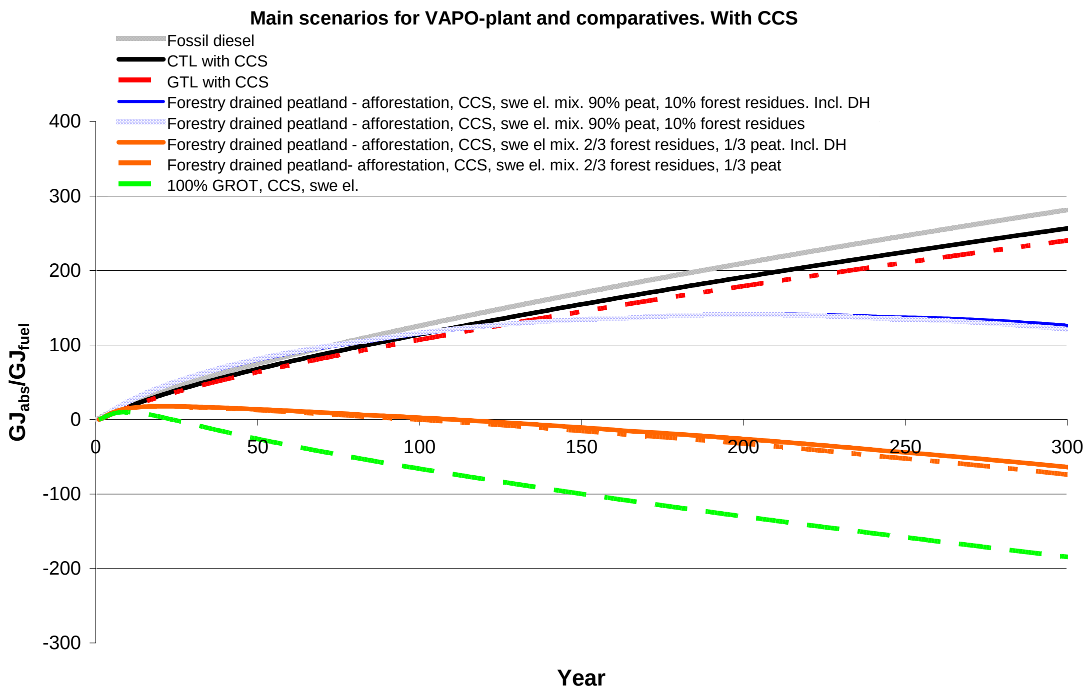

Figure 6 This figure shows the time development from year 0 - 300 of the scenarios with CCS in Figure 4.

4.2 Climate impact of all studied scenarios

The climate impact, in terms of relative radiative forcing commitment, of all the different production scenarios is shown in Figure 7. The results are given both in a 100 years perspective and a 300 years perspective, i.e. how much energy is absorbed in the thermodynamic system of the Earth due to the production and utilisation of one GJ diesel after 100 and 300 years respectively. FT-diesel scenarios based on peat and biomass in the Vapo-plant are compared with diesel production from crude oil (conventional fossil diesel), coal (Coal-to-Liquid, CtL) and natural gas (Gas-to-Liquid, GtL). The climate impact of FT-diesel production in the Vapo-plant based on 100% forest residues is also calculated as a comparison.

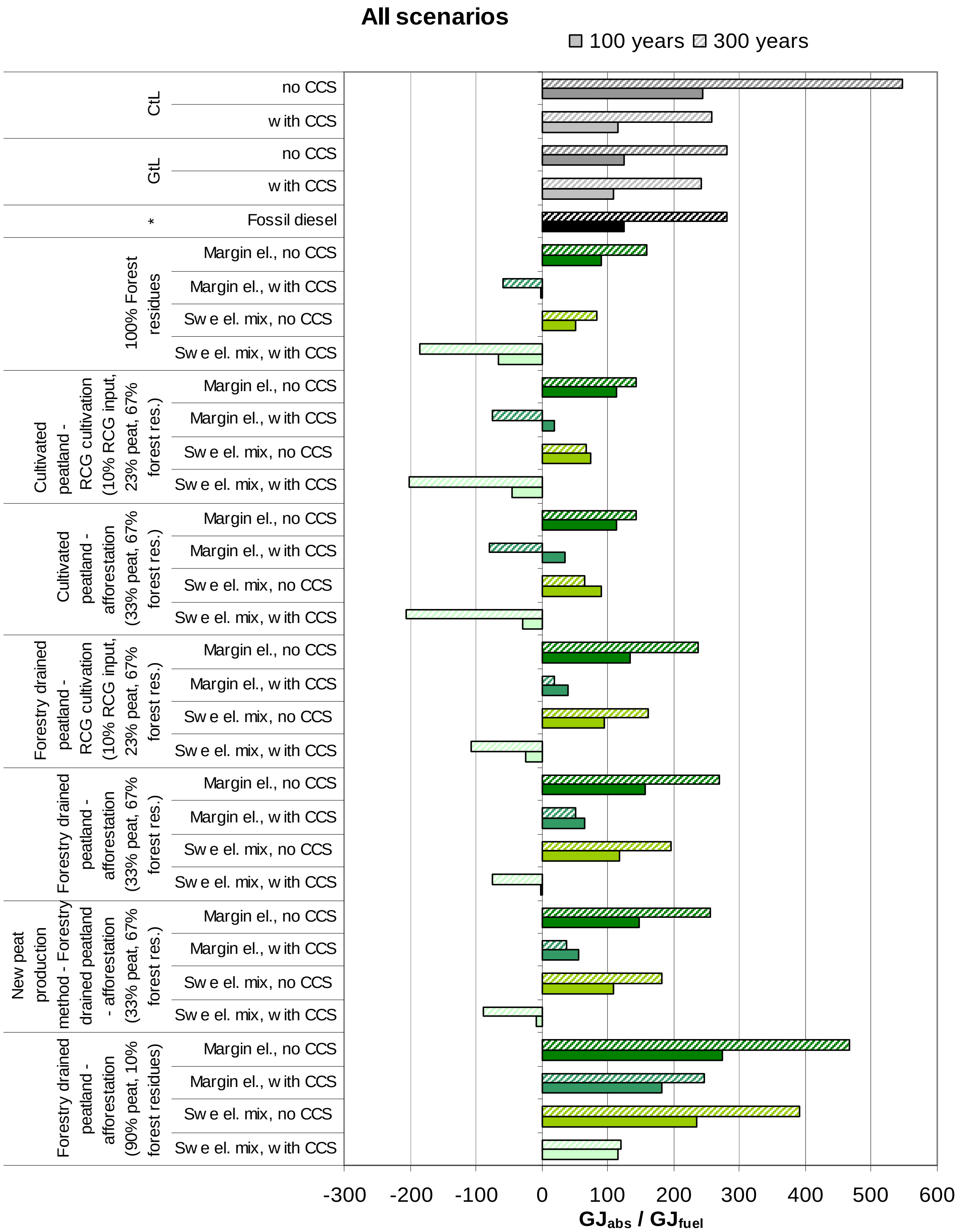

Figure 7. Relative radiative forcing commitment (RRFC) of fuel chains. For all chains energy allocation of emissions has been applied, i.e. allocation of emissions based on energy content of products. In these scenarios district heating was not considered as a product and not included in the energy allocation. Solid columns show RRFC for 100 years whereas striped columns show RRFC for 300 years.

5 Conclusions

5.1 FT-diesel scenarios compared to fossil alternatives

Based on the results of the calculations of the relative radiative forcing commitment of the FT-diesel scenarios we draw the following conclusions (see Figure 7):

- All the FT-diesel scenarios based on 90% peat and 10% forest residues have significantly higher climate impacts than conventional diesel after 100 years, except the scenario with CCS and where Swedish electricity mix is assumed for the external power demand. For both scenarios with Swedish electricity mix, the climate impacts are comparable to coal based synthetic diesel (CtL) after 100 years (CtL with CCS is approximately 5-10% lower than conventional diesel and without CCS it is approximately 90% higher than conventional diesel after 100 years).
- In order to result in lower climate impact than conventional fossil diesel after 100 years, FT-diesel scenarios without CCS where the peat input comes from forestry drained peatlands must have a peat input significantly lower than the biomass input.
- With CCS, all peat based FT-diesel scenarios (except the ones based on 90% peat) will have lower climate impact than conventional diesel after both 100 years and 300 years. If marginal electricity is assumed, the reduction is 50-84% after 100 years compared to conventional diesel, and if Swedish electricity mix is assumed the reduction is 100-135% (i.e. zero or negative radiative forcing).
- For scenarios with 23-33% peat input from forestry drained peatlands, without CCS and assuming Swedish electricity mix for external power, the climate impact is 6-25% lower than for conventional diesel after 100 years. In the very long time perspective of 300 years the climate impacts of these scenarios are 30-40% lower than the climate impact for conventional diesel. However, the long time perspective increases the uncertainty of the results (see section 7.1). With CCS the same scenarios have negative radiative forcing both after 100 years and 300 years.
- 10% reed canary grass input lead to lower climate impact than corresponding scenarios without reed canary grass input, mainly since the peat input is reduced.
- FT-diesel production chains based on 100% forest residues, closely followed by cultivated peatland scenarios, have the lowest climate impact after 100 years. In a 300 years perspective the FT-diesel scenarios based on 33% peat and 67% forest residues, where the peat is produced from cultivated peatlands have a climate impact even lower than the FT-diesel scenario based on 100% forest residues. However, the long time perspective increases the uncertainty of the results and drawing conclusions based on a 300 years perspective should be made very carefully (see section 7.1).
- The climate impacts of synthetic diesel from coal (CtL) and natural gas (GtL) with CCS are comparable to the climate impact of FT-diesel scenarios (33% peat and 67% forest residues) without CCS, with Swedish electricity mix assumed for the external power demand and where the peat input comes from forestry drained peatlands scenarios.
- In the scenarios where marginal electricity is assumed, the climate impacts are much higher than if Swedish electricity mix is assumed (see 5.2 for conclusions on how important parameters are impacting the results).

5.2 Important parameters impacting the results

We conclude that the climate impact of the FT-diesel scenarios based on peat is strongly dependent on the following parameters:

- ***The emission factors associated with purchased electricity***
  If the external power demand is assumed to come from production in low-effective coal power plants (marginal electricity) the climate impact is much higher than if Swedish electricity mix is assumed. The climate impact relative to conventional diesel is approximately 30% higher for scenarios where marginal electricity is assumed compared to scenarios where Swedish electricity mix is assumed. For instance, scenarios where FT-diesel is based on 33% peat from forestry drained peatlands, where CCS is not considered and where Swedish electricity mix is assumed for the external power demand, the climate impact is 6% lower than conventional diesel. The climate impact for the same scenario but with marginal electricity assumed for the external power demand is 25% higher than that of conventional diesel.

- ***The use of carbon capture and storage, CCS***
  CCS reduces the climate impact of the FT-diesel chains significantly. Scenarios based on 33% peat and 67% forest residues where Swedish electricity mix is assumed and CCS is applied result in zero or negative radiative forcing (a negative radiative forcing tends to cool the atmosphere). This is explained by the fact that more carbon is captured by CCS than what is put in to the refinery in terms of peat (in scenarios with 33% peat or less).
  An important factor is hence the amount of carbon that actually will be possible to capture. This will be dependent on the specific process set up and could vary from installation to installation. In addition, the possibility of storage of the separated CO_2 is dependent on location. Our results are based on the assumption that the installation is located at a harbour, making transportation to storage site by ship possible. An inland location in Sweden where transportation by truck or pipeline is necessary would either reduce the efficiency significantly (truck), or might be difficult due to lack of infrastructure (pipeline) or logistics (truck).

- ***The time perspective***
  The climate impact for some of the FT-diesel scenarios tend to decline after hundreds of years compared to conventional diesel, due to avoided emissions from greenhouse gas leaking peatlands. This effect is especially notable for the scenarios where peat is harvested from cultivated peatlands, since the reference scenario of these peatlands includes high emissions of greenhouse gases. How the climate impact develops over time is visualized in Figure 5 & Figure 6 and Figure 9 & Figure 10.

- ***The raw material mix for the FT-diesel production***
  FT-diesel produced from 33% peat and 67% forest residues has lower climate impact than the FT-diesel produced from 90% peat and 10% forest residues. In scenarios where reed canary grass is included, part of the peat (10% of total raw material input) is substituted, and hence these scenarios have lower climate impact than the corresponding scenarios without reed canary grass input. FT-diesel from 100% forest residues (i.e. 100% biomass) has the lowest climate impact in the 100 year perspective.

- ***The reference scenario of the peat production area***
  Peat harvested from cultivated peatlands result in lower climate impact than peat from forestry drained peatlands. The difference increases with increasing time horizon since the impact of the reference scenario increases over time, and the cultivated peatlands have higher emissions of greenhouse gases in the reference scenario.

There are also other factors of minor importance such as:

- ***Peat production technology***
  If the peat is harvested using the new production technology (which still is under development and not commercial) the climate impact can be somewhat reduced compared to the conventional milling method.
- ***Products considered in energy allocation***
  The total greenhouse gas emissions associated with refining at the FT-diesel plant are divided on the main product, FT-diesel, and the co-products, naphtha and product gas, based on the energy content of the products. This is called energy allocation. The impact of including district heating in the energy allocation is limited since the estimated amount of district heating with an economic value is small compared to the other products. However, if the amount with an economic value is higher this parameter could be of more significant importance. In addition, if energy allocation would not have been applied and all emissions would have been accounted to the FT-diesel chains, the results would be significantly different.
- ***Considering the biomass based carbon emissions and uptake***
  The methodology in this study takes into consideration all uptake and emissions that occur due to raw material production, diesel refining and utilisation compared to a reference case where this raw material is not produced. It also considers the dynamics of the fluxes. In general, biomass based carbon fluxes are set to zero as default in environmental assessments resulting in that the timing (dynamics) of those fluxes are not considered. In Chapter 6 calculations the scenarios are made where the dynamics of the biomass based carbon fluxes are not considered. This has some impact on the results, making the climate impact for the peat and biomass based FT-diesel lower. The impact on the results is greater for scenarios with higher biomass based content (i.e. higher impact for scenarios with 67% forest residues than for scenarios with 10% forest residues).

6 The impact of not considering the timing of biomass based carbon emissions – alternative calculation methodology

In this chapter we present the results of calculations of the climate impact of the FT-diesel scenarios but where the effect of timing of the biomass based carbon emissions from the forest residues is not considered. These calculations have been made mainly since the timing of biomass based carbon emissions usually not are taken into consideration in environmental assessments.

6.1 Climate impact for main scenarios – timing of biomass carbon emissions not considered

In Figure 8 the timing of emissions of biomass based carbon is not considered, i.e. the CO_2 emissions from utilisation (e.g. combustion) or decomposition of forest residues are set to zero. The resulting climate impact after 100 years of the FT-diesel chains will be somewhat lower (Figure 8), compared to if the effect of timing of the biomass based CO_2 emissions is considered (see Figure 4).

- FT-diesel based on 33% peat and 67% forest residues, without CCS, will have approximately 20% lower climate impact than conventional diesel. The same scenarios with CCS will have 115% lower climate impact than conventional diesel. This can be compared with 6% or 100% lower climate impact if the timing of biomass carbon emissions is considered (Figure 4).
- The effect of not accounting for the timing of biomass based emissions is largest in the 100% forest residue scenario. The resulting climate impact after 100 years for FT-diesel based on 100% forest residues (without CCS) is 80% lower than conventional diesel, compared to 60% lower if the timing of biomass carbon emissions are considered (Figure 4).

In Figure 9 and Figure 10 the time developments from year 0-300 of the scenarios in Figure 8 are given. For further discussion on accounting for the timing of biomass based carbon emissions, see section 7.3.

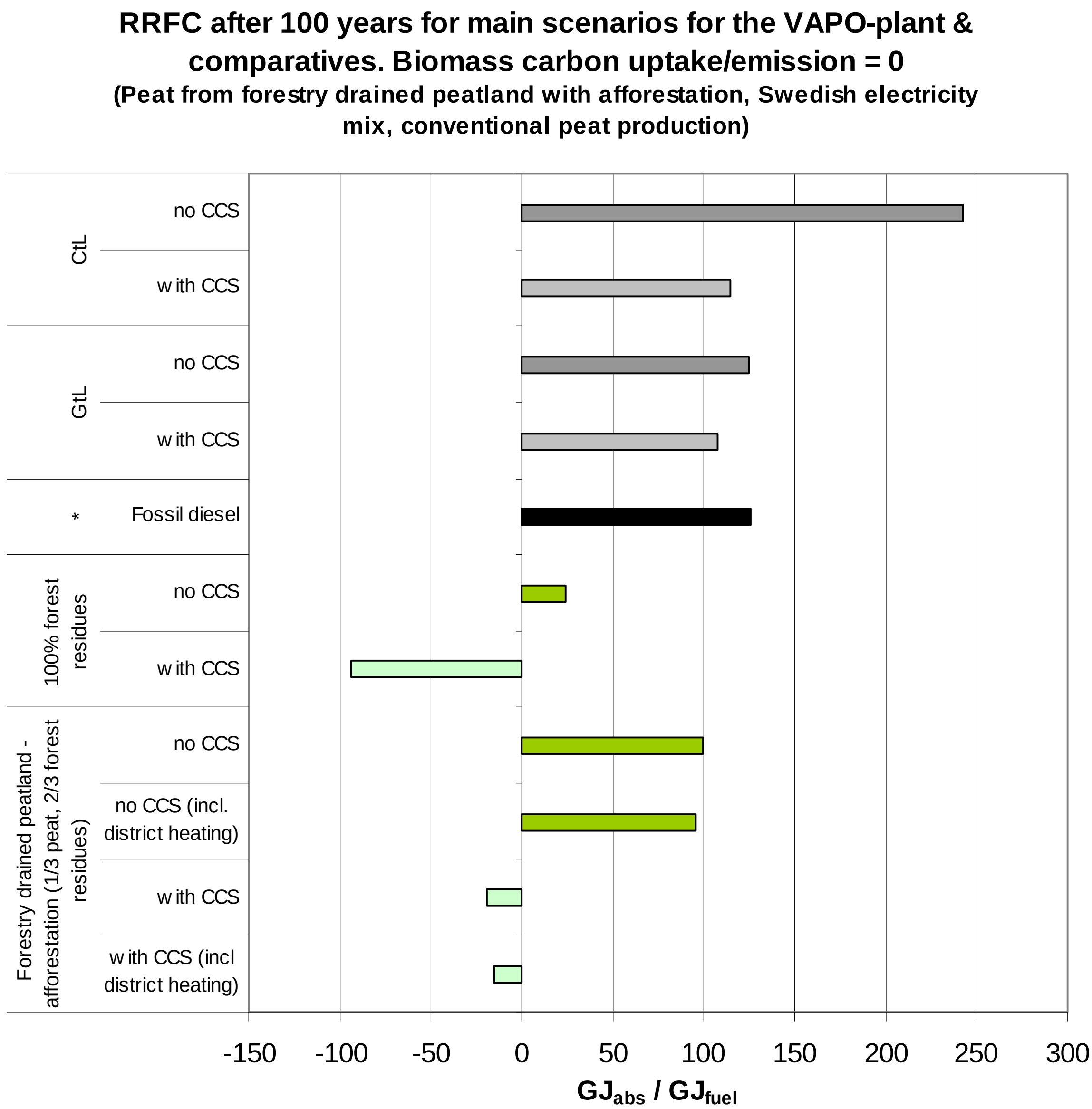

Figure 8. Relative radiative forcing commitment (RRFC) after 100 years of the main scenarios for the Vapo-plant, compared to fossil fuel chains. In these scenarios CO_2 emissions from utilisation (combustion) or decomposition of forest residues are set to zero, i.e. the timing of biomass based CO_2 emission and uptake is not considered. Peat input from forestry drained peatlands followed by afforestation, conventional peat production and Swedish electricity mix is assumed. For all chains energy allocation of emissions has been applied, i.e. allocation of emissions between main product (FT-diesel) and co-products (naphtha and product gas) based on the energy content. Where indicated also district heating has been considered a co-product.

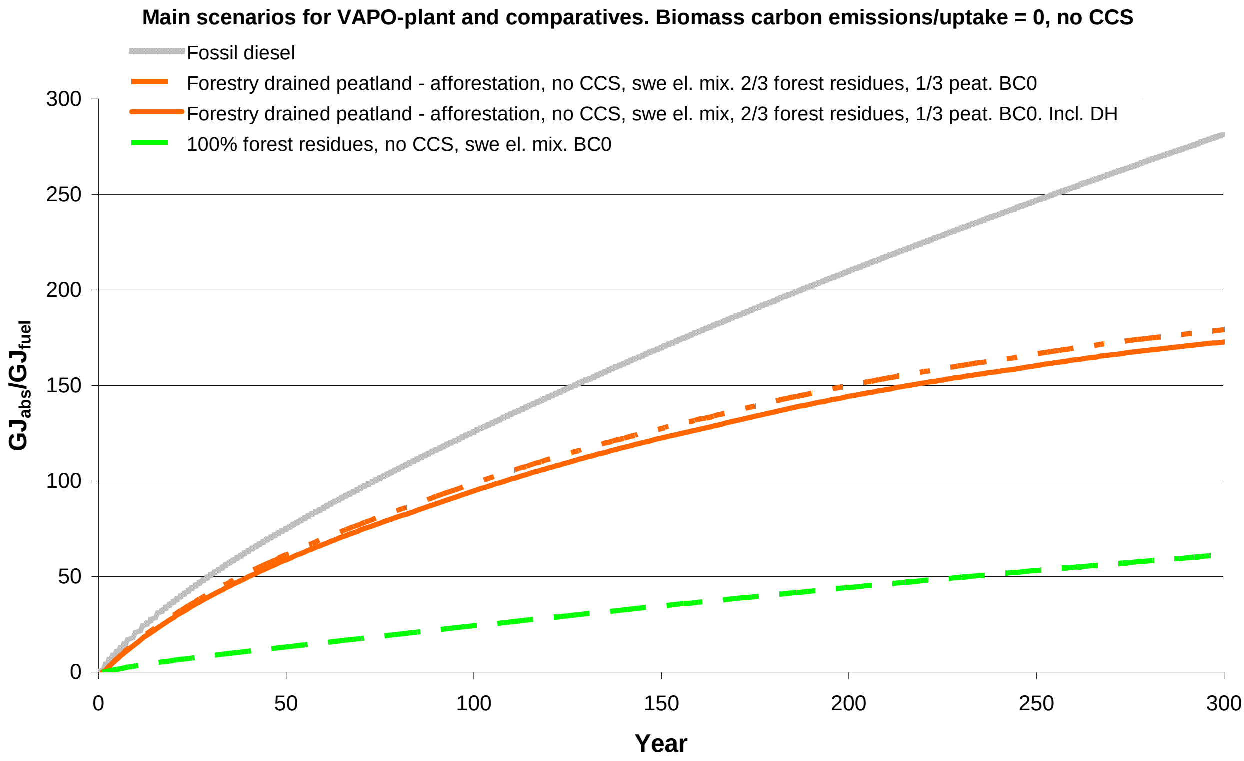

Figure 9 The figure shows the time development from year 0 - 300 of the scenarios without CCS in Figure 8.

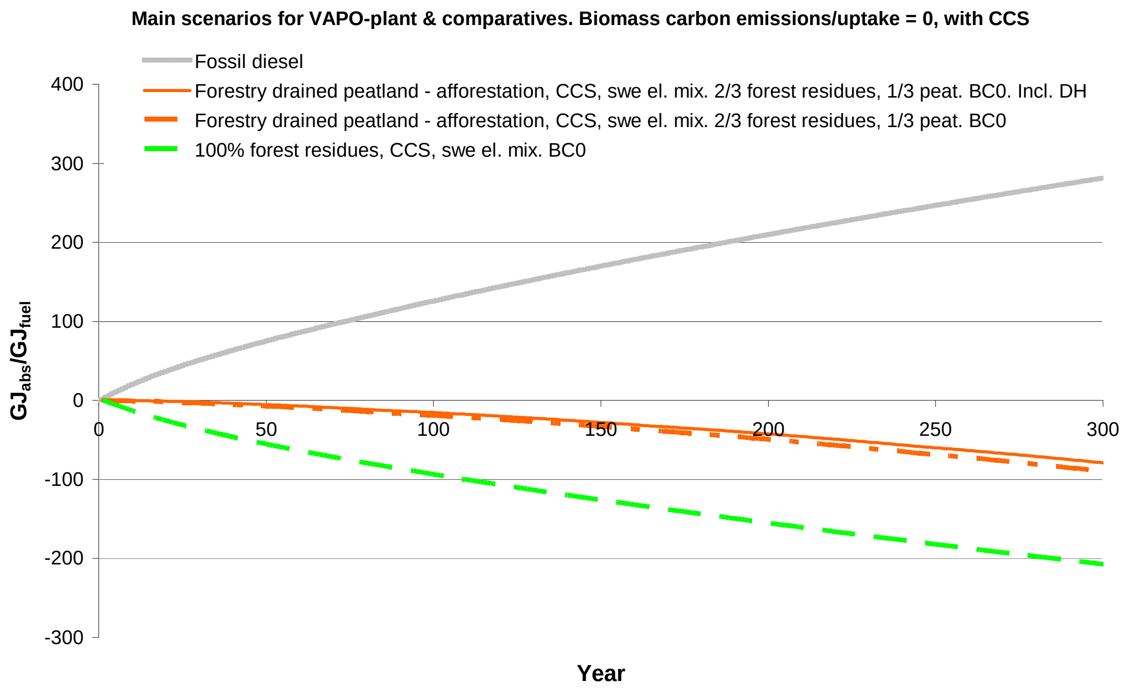

Figure 10 The figure shows time development from year 0 - 300 of the scenarios with CCS in Figure 8.

6.2 Climate impact for all scenarios – timing of biomass based carbon emissions not considered

Figure 11 show the corresponding climate impact for the fuel chains in Figure 7, but where the timing of the emissions from biomass is not considered, i.e. the CO_2 emissions from forest residues (both emissions from utilisation and decomposition in reference scenario) are set to zero.

According to Figure 11, the climate impacts of FT-diesel scenarios are somewhat lower if biomass emissions are set to zero, than if the timing of biomass emissions is considered (Figure 7).

- For the scenarios with 67% forest residues and 33% peat and/or reed canary grass the difference between considering the impact of timing of biomass based carbon emissions will be 15% lower climate impact after 100 years in the case not considering the timing (compare Figure 7 and Figure 11). For instance, the scenario "forestry drained peatland, Swedish electricity mix & no CCS" have 21% lower climate impact (Figure 11) than conventional diesel compared to 6% lower climate impact when the timing of biomass based carbon emissions are considered (Figure 7).
- The effect of considering the timing or not is larger for the 100% forest residues scenarios. In the case without CCS, the 100% forest residue scenario will have 60% lower climate impact than conventional diesel when the timing of biomass based carbon emissions is considered (Figure 7), compared to 80% lower climate impact than conventional diesel when the timing is not considered (Figure 11). The effect of not considering the timing of biomass based emissions will, however, decline with time. After 300 years, the difference between calculations made with the two methodologies will be smaller.

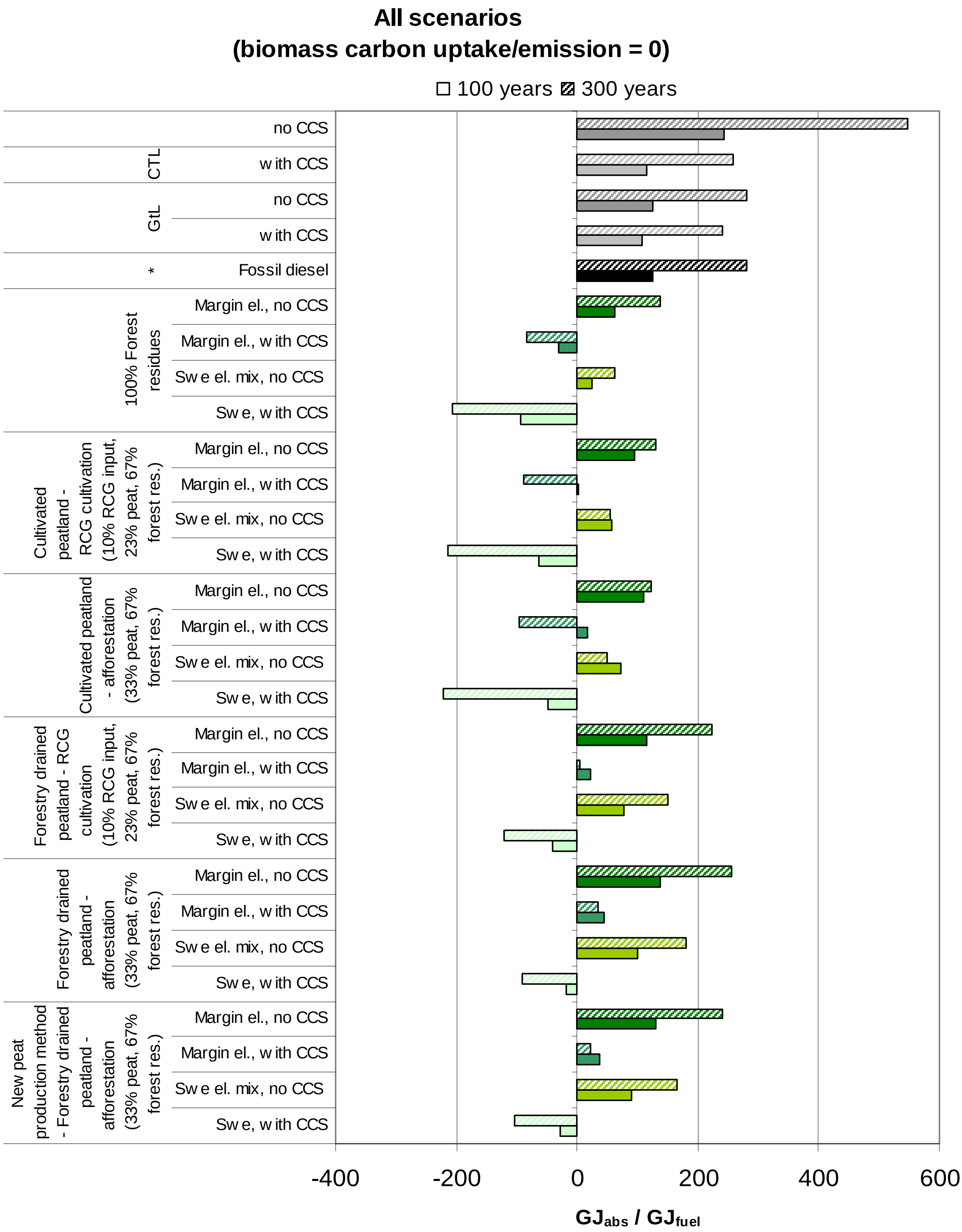

Figure 11. Relative radiative forcing commitment of fuel chains. In these scenarios carbon emissions from utilisation (combustion) and decomposition of biomass are set to zero, i.e. the timing of the biomass based emissions and uptake of CO_2 are not considered. Energy allocation excluding district heating was used in these scenarios. Solid columns show RRFC for 100 years whereas striped columns show RRFC for 300 years.

7 Discussion

7.1 Comparison to other methods of assessing climate impact of fuels

We have chosen to assess the climate impact of the fuel production and utilisation scenarios in terms of radiative forcing. A more common way to compare the impact of different fuels or activities is life cycle assessment of emissions. That is for instance what is suggested in the calculation methodology for renewable biofuels and bioliquids given in the RES directive (European Parliament, 2008). When considering for instance soil carbon changes in an emission based assessment, simplification of the dynamics is usually applied. In the RES directive it is suggested that soil carbon changes shall be annualised over a 20 year period. With our methodology, where the timing of emissions is considered, dynamics with longer time perspectives can also be included in a more accurate way. It enables us to show long term effects of slow changes in biological systems (such as the decomposition of the peat in drained peatlands). However, long time perspectives also introduce more uncertainty, and results for time perspectives of several hundreds of years should be considered as indicative. Our methodology enables us to look at different time perspectives and not just the 100 year time perspective, which is fixed in emission assessment where the GWP_{100} -values is used.

The method of using radiative forcing for determining the climate impact of fuels from a life cycle perspective has previously been used mainly for peat based fuel chains (Zetterberg et al. 2004, Nilsson & Nilsson, 2004; Kirkinen et al., 2007) but also for biofuels and fossil fuels (Savolainen et al., 1994; Holmgren et al., 2007; Kirkinen et al., 2008).

7.1.1 The consideration of timing of biomass based carbon emissions

The reason why we consider the timing of biomass based carbon emissions (i.e. in this report the carbon emissions of forest residues) is that we thereby treat all carbon emissions, independent of origin (biomass, peat or fossil source) in the same way. Normally, biomass based carbon emissions are assumed to be zero, thereby ignoring the impact of timing whereas for peat based and fossil carbon the actual emissions are included. Since our method includes avoided peat based soil carbon emissions the impact of timing becomes important.

7.2 The time perspective

We present the radiative forcing of different FT-diesel production chains both at fixed time horizons, 100 and 300 years respectively, and continuously from 0 to 300 years. We want to emphasize that we by no means favour a 300-year time perspective. The scenarios have been made for a 300-year period in order to show long-term effects especially for the slow development of peatlands. The reader can, in the result figures showing the time development of the climate impact of the production chains, choose time perspective and thereby draw his/her own conclusions. What time perspective that is to prefer depends on what one would like to achieve, how fast and maybe also what alternatives that are available. The IPCC has not given definite instructions on what time perspective that should be applied for the purpose of mitigating climate change, but they have stressed that there is a need for immediate action. In the Kyoto Protocol and the weighting of different greenhouse gas emissions, a 100-year perspective has been chosen.

7.3 Impact of timing of biomass based carbon emissions

In most LCA studies carbon emissions due to the combustion of biomass is set to zero although the combustion actually results in CO_2 emissions. The corresponding amount of CO_2 was captured by the living biomass from the atmosphere during growth, and if the biomass production is continuous the re-growth will also capture CO_2 from the atmosphere. If the biomass production is not continuous, i.e. if the biomass comes from an area under deforestation there will be no compensation. However, also the case where the combustion emissions will be compensated for by the re-growth of new biomass, there is an impact by the CO_2 emissions from the combustion due to the fact that emissions will occur faster/earlier compared to the compensation by re-growth.

Greenhouse gases have an impact on the radiative balance of the Earth by capturing infrared outgoing radiation and thereby increasing the temperature of the surface and the atmosphere. Since carbon dioxide have a long atmospheric lifetime, it is important when emissions occur (compare with putting money in the bank where the capital generates interest). 30 years after the emission of one unit of CO_2, 50% has been removed, whereas after 200 years still 30% remains in the atmosphere. As long as the CO_2 is in the atmosphere the molecules will capture infrared outgoing radiation, and thereby increase the temperature.

In the sub-system describing the production of forest residues we assume that the reference is that the forest residues are left to decay in the forest. During the decay process CO_2 will be released to the atmosphere. In the scenarios of this study the forest residues are used for the production of FT-diesel, and during the production and utilisation of the FT-diesel the corresponding amount of CO_2 will be released to the atmosphere (based on the assumption that 100% of the residues will be decomposed in the reference case). However, in the FT-diesel case, emissions will occur during one year whereas in the reference case emissions will occur during a few decades. This timing of the emissions will have an impact on the radiative balance.

The calculations in this study for the utilisation of forest residues takes the timing of the biomass based CO_2 emissions into account. However, we have also made alternative calculations of the scenarios, indicated with "biomass carbon uptake/emissions = 0" (BC0), presented in chapter 6, where we exclude this effect and hence assume that the CO_2 emissions from decomposition or utilisation (combustion) of forest residues are zero. The latter is the conventional way of considering biomass based CO_2 emissions. Note that this has an impact only on the production of forest residues, where the decay in the reference case would take approx 15 years to release 80% of the carbon. In the case of reed canary grass the reference is fallow or cultivation of other crops and hence the same reasoning is not applicable.

Figure 12 shows how much CO_2 that remains in the atmosphere after the combustion of one unit of forest residues and after the decomposition of one unit of forest residues respectively. The curves take into consideration the atmospheric life time of CO_2. As can be seen there is a difference in the amount of CO_2 in the atmosphere which is significant during the first couple of decades. Since the amount of CO_2 in the atmosphere has a direct impact on the radiative balance, these two scenarios will have different impact on the climate. The combustion scenario will have a higher impact on the radiative balance, hence warming the atmosphere more.

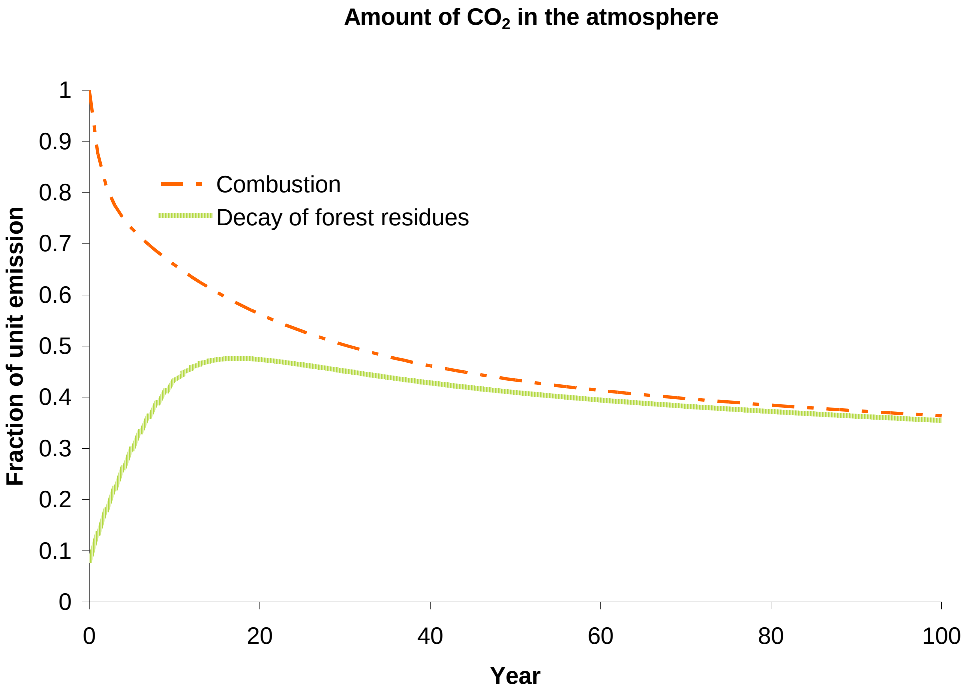

Figure 12 CO_2 remaining in atmosphere due to either combustion or decomposition of forest residues. Combustion is assumed to occur in the first year, whereas the decomposition occurs over many years.

7.4 Allocation methodologies

In life cycle assessments of products it is preferable to use system expansion to include the emissions of the most likely alternative for the co-products. The emissions associated with the production and utilisation of the alternative product should then be credited to the main product as avoided emissions. Another method is to use energy allocation (or physical allocation), which means that the total emissions of the production chain is divided between the different end-products based on their energy content. The energy allocation method is suggested in the proposed EU directive on the promotion of the use of energy from renewable sources (KOM, 2008; European Parliament 2008). A third method is to allocate the emissions between the end-products based on their economic value.

In this study energy allocation is applied, which mean that the emissions are allocated between the FT-diesel, naphtha, product gas and in some cases also district heating based on energy content. The reasons for using the energy allocation method are;

i) it is the most transparent and safest method based on the data available in this study
ii) it is the suggested method in the coming EU RES Directive (European Commission 2008) and
iii) the co-products naphtha and product gas are normally used to replace diesel/gasoline/oil and thereby has similar substitute as the main product FT-diesel.

To define what should be considered as a co-product is not trivial. In this study we include a certain amount of district heating as a co-product based on the assumption that it is a commercial product. However, the demand for district heating is very site specific and the assumption that district heating actually can be sold is somewhat uncertain. Our default settings were therefore that district heating is not a product but we also made calculations where district heating was considered as a co-product and thereby included in the energy allocation. As discussed earlier, including district heating or not in the energy allocation had limited effect on the results.

7.5 Is CCS likely to be applied at a real plant?

The chemistry of the Fischer –Tropsch synthesis result in a stream of CO_2, which has to be separated from the diesel product independently of whether or not the gas can be stored in a geological formation or just be emitted to the atmosphere. This is in contrast to post combustion separation which is the case for CCS in carbon fired power plants. The post combustion separation means separation of CO_2 at much lower concentrations and requires significant amount of extra energy and thereby reduces the efficiency of the installation. Further the post combustion separation is not a commercial technology but is still under development. The separation at a Fischer-Tropsch plant does not require as much additional energy. However, it should be noted that since the end-products in a FT-diesel refinery are hydrocarbons, only part of the total carbon can be separated during production and stored underground (about 48% in our case). The rest will be emitted during utilisation of FT-diesel and the co-products. In post combustion separation at power plants most of the carbon content of the fuel can be removed (80-90%).

However, the storage and transportation to storage parts of the CCS are the uncertain parts. The scenarios including CCS in this study are based on the assumption that the plant is located so that transportation by ship to the Utsira field under the North Sea is possible. If this is the case, both storage and transportation to the storage could probably be solved. However, if the plant is located in the inland without proximity to waterways or harbour it will be very difficult. Today there is no known storage site under land in Sweden and there is no infrastructure for transportation by pipeline. Transportation by truck would probably be difficult to solve logistically due to the large amounts of separated CO_2. Hence an inland location without proximity to shipping possibilities would make scenarios with CCS unlikely in the near future.

7.6 Emissions associated with external power demand

In this study two different sets of assumptions of the greenhouse gas emission factors for external power demand (electricity) have been applied. The first assumption is that emission factors for marginal electricity are used and that marginal electricity is produced in coal condensing power plants with low efficiency. The assumption of coal-based marginal production represents a worst case. The other assumption is that emission factors for Swedish electricity mix are used. This would probably be the suggested assumption for the calculations of the greenhouse gas emissions according to the RES Directive since regional power mixes should be used. The Swedish electricity mix is associated with very low greenhouse gas emissions and could therefore represent a best case. There are a number of additional different possible assumptions for the marginal electricity or other assumptions for the external electricity demand for the FT-diesel refinery that could be applied. Depending on the purpose of the calculations, time perspectives etc. different assumptions could be considered as most feasible. We have chosen to only make these two assumptions which in a way show best and worst case.

7.7 Reference scenarios

Peatland management
For the peat production scenarios we assume that the reference scenario is that current management (land use) will continue throughout the study period. This assumption is associated with significant uncertainty, especially for longer time horizons, see section 2.1.3. Other possible reference scenarios would be to assume some other kind of land use change. However, that would also include uncertainties, and in order to be able to compare different scenarios with each other it is important to have one common reference scenario. The assumption of continuation of current management is a simple reference scenario. Other assumptions might increase the complexity.

Forest residues
For the production of forest residues we assume that the reference scenario is that the forest residues will be left to decay in the forest. Today that is not a likely scenario in the southern parts of Sweden. Almost everywhere forest residues are recovered. Only a decade ago this was not the case, and in the northern parts of Sweden it is still not applied at every cutting, depending on for instance transportation costs etc. Another possible reference would therefore be to assume that the forest residues would be used in a combined heat and power plant. However, since the FT-diesel refinery for which we have made the calculations in this study needs an significant amount of forest residues (especially in the scenarios where 2/3 of the raw material input is assumed to forest residues), we make the assumption that such an installation would increase the demand for forest residues, making extraction also in today unutilised areas profitable.

Reed canary grass cultivation
We assume that reed canary grass would be cultivated at land that currently is, or otherwise would have been, under fallow. We thereby assume that different types of soils will be used. The assumption that fallow land will be used for the cultivation of reed canary grass is uncertain. The amount of land under fallow has varied greatly during the last couple of years depending on prices of corn and changed rules in the CAP (EU Common Agriculture Policy). Some areas has been under fallow due to the compensation system in CAP, whereas others might be under fallow due to other reasons such as low productivity, and might therefore not be suitable for cultivation of reed canary grass. However, since fallow means low input (chemicals, energy and fertilisers) and low tillage practices the assumption of this type as reference is a conservative assumption in terms of emission reductions. In addition, the basic assumption that it is possible to find reed canary grass in an amount corresponding to 10% input in the suggested FT-diesel plant is an assumption associated with great uncertainty. This since the high costs for transportation would require that the reed canary grass is produced in the same region as the FT-diesel plant, which means that the Swedish area cultivated with reed canary grass would have to increase from 200 to approximately 12 000 ha, and most of it would have to be close to the FT-diesel refinery.

7.8 Raw material supply - importance of location

The starting point of this study is a possible future plant for biomass and peat gasification and Fischer-Tropsch synthesis located in Sweden. The emission estimates are also based on the assumption that the raw material supply (peat and biomass input) could be managed by producers located in the same region as the refinery. The scenarios are based on input of peat, forest residues and reed canary grass, but also other biomass fractions, such as for instance bark could be used in order to manage the raw material supply. Further, for the CCS scenarios our calculations rest on the assumption that the installation is located at a harbour. Such location also opens up for import of biomass where the transport emissions could be kept low due to shipping possibilities compared to similar transport distances by truck. We have made no analysis of a specific location or the actual raw material supply possibilities, but this should be taken into consideration if our results are to be used for a specific case.

8 Literature

Ågren, G. & Hyvönen, R. 2003. Changes in carbon stores in Swedish forest soils due to increase biomass harvest and increased temperatures analysed with a semi-empirical model. Forest Ecology and Management, 174:25-37.

Ågren, G., Hyvönen, R. & Nilsson, T. 2007. Are Swedish forest soils sinks or sources for CO_2? – Model analyses based on forest inventory data. Biogeochemistry 82: 217-227.

Berglund Ö. & Berglund K. 2008. Odlad organogen jord i Sverige 2003. Areal och grödfördelning uppskattad med hjälp av digitaliserade databaser. Rapport 7, Swedish University of Agricultural Sciences, Department of soil Sciences, Division of Hydrotechnics, Uppsala, ISSN 1653-6797

Bullard M. & Metcalfe, P. 2001. Estimating the Energy Requirements and CO_2 emissions from production of the perennial Grasses Mischanthus, Switchgrass and Reed Canary Grass. ETSU B/U1/00645/Rep. DTI/Pub URN 01/797.

Burvall J. 1997. Rörflen som bränsleråvara. Fakta Teknik nr. 1, 1997. Sveriges Lantbruksuniversitet (In Swedish).

Börjesson, P. 1999. Environmental effects of energy crop cultivation in Sweden – I: Identification and quantification. Biomass & Bioenergy, 16 pp 137-154.

CONCAWE, EUCAR, JRC/IES, 2006. Well-to-Wheels analysis of future automotive fuels and powertrains in the European context, WELL-TO-TANK Report, Version 2b, May 2006.

CONCAWE, EUCAR, JRC/IES, 2007. Well-to-Wheels analysis of future automotive fuels and powertrains in the European context, TANK-to-WHEELS Report; Version 2c, March 2007.

Eriksson E., Gillspie, A., Gustavsson, L., Langvall, O., Olsson M., Sathre, R. & Stendahl, J. 2007. Integrated carbon analysis of forest management practices and wood substitution. Canadian Journal of Forest Research vol. 37, pp 671-681.

EU Directive 2003/30/EC of the European Parliament and of the Council of 8 May 2003 on the promotion of the use of biofuels or other renewable fuels for transport

European Parliament 2008. PA_TA-PROV(2008)0609 Directive XXX/2009/EC on the promotion of the use of energy from renewable sources. In "Text adopted at the sitting of Wednesday 17 December 2008. PA_TA-PROV(2008)12-17".

Hagberg, L., & Holmgren K. 2008. The climate impact of future energy peat production. IVL B-report 1796. www.ivl.se

Holmgren, K., Eriksson, E., Olsson, O., Olsson, M., Hillring, B. & Parikka, M. 2007. Biofuels and climate neutrality – system analysis of production and utilisation. Elforsk report no 07:35. www.elforsk.se

Huttunen, J. T., Nykänen, H., Martikainen, P. J. & Shurpali, N. J. 2004. Reed Canary Grass Cultivation on Cut-away peatlands and the ecosystem carbon balance. In Proceedings of the 12th International Peat Congress, Tampere Finland, 6-11th June. Vol. 2, pp 977-982.

IPCC 2007. Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, , J. Nganga, R.. Prinn, G. Raga, M. Schulz and R. Van Dorland, 2007: Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M- Marquie, K-B-Averyt, M. Tignoer and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York , NY, USA.

IEAGHG 2004; Ship Transport of CO_2, IEA Greenhouse Gas Research and Development Programme, Report no PH4/30, July 2004.

Kirkinen, J., Palosuo, T., Holmgren K. & Savolainen, I. 2008. Greenhouse Impact due to the use of combustible fuels: Life cycle viewpoint and relative radiative forcing commitment. Environmental Management, 42 pp 458-469.

Kirkinen, J., Minkkinen, K., Penttilä, T., Kojola, S., Sievänen, R., Alm, J., Saarnio, S., Silvan, N., Laine, J. & Savolainen, I. 2007. Greenhouse impact due to different peat fuel utilisation chains in Finland – a life-cycle approach. Boreal Environmental Research 12:211-223.

KOM 2008. Förslag till EUROPAPARLAMENTETS OCH RÅDETS DIREKTIV om främjande av användningen av förnybar energi, KOM (2008) 19 slutlig, Bryssel den 23.1.2008.

Maljanen, M., Hytönen, J., Mäkiranta, P., Alm, J., Minkkinen, K., Laine, J., & Martikainen, P.J. 2007. Greenhouse gas emissions from cultivated and abandoned organic croplands in Finland. Bor. Env. Res. 12:133-140.

McCollum, D.L., & Ogden, J.M. 2006. Techno-Economic Models for Carbon Dioxide Compression, Transport, and Storage & Correlations for Estimating Carbon Dioxide Density and Viscosity, Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-06-14

Nilsson D. & Bernesson S. 2008. Pelletering och brikettering av jordbruksråvaror – en systemstudie. Processing biofuels from farm raw materials – A systems study. Department of energy and technology, SLU Rapport no 001. ISSN 1654-9406. Uppsala

Nilsson K., 2004. The carbon dioxide emission factor for combustion of Swedish peat. IVL B-report no 1595, Stockholm.

Nilsson K. & Nilsson M. 2004. The climate impact of energy peat utilisation in Sweden – the effect of former land use and aftertreatment. IVL B-report 1606. www.ivl.se

NTM, 2007. Environmental data for international cargo sea transport, Version 2007-09-07. Network for Transport and the Environment, www.ntm.a.se

Savolainen, I., Hillebrand, K., Nousianinen, I., & Sinisalo, J. 1994. Greenhouse gas impacts of the use of peat and wood for energy. VTT Research Notes no 1559, Espoo, Finland.

Shurpali, N. J., Hyvönen, N. P., Huttunen, J.T., Biasi, C., Nykänen, H., Pekkarinen, N. & Martikainen P. J. 2008. Bare soil and reed canary grass ecosystem respiration in peat extraction sites in Eastern Finland. Tellus 60B, pp 200-209.

Soimakallio, S., Mäkinen, T., Ekholm T., Pahkala, K., Mikkola, H. & Paappanen T. 2008. Greenhouse gas balances of transportation biofuels, electricity and heat generation in Finland – dealing with uncertainties. (Manuscript).

Pahkala, K. Partala, A., Suokannas, A., Klemola, E., Kalliomäki, T., Kirkkari, A-M., Sahramaa, M., Isolahti, M., Lindh, T. & Flyktman, M. 2003. Odling och skörd av rörflen för energiproduktion. MTT. Forskningscentralen för jordbruk och livsmedelsekonomi. ISBN 951-729-744-0.

STPF 2008. Torvåret 2007, Statistik över Sveriges Torvproduktion 2007. Sammanställd av Svenska Torvproducentföreningen. STPF-rapport.

Thériault, F., Javorská, H., Cásová, K., Tucker, M. & Gullholm-Hansen T. 2003. The Potential for Perennial Grasses as energy Crops in Organic Agriculture. Ecological Agriculture I, Socrates European Common Curriculum (05 85 00).

Vapo Oy, 2008. Information provided by Mika Timonen.

Uppenberg S., Zetterberg, L. & Åhman, M. 2001. Climate Impact from Peat Utilisation in Sweden. IVL B-report 1423. www.ivl.se

Wihersaari, M. 2005. Greenhouse gas emissions from final harvest fuel chip production in Finland. Biomass & Bioenergy, 28: 435-443.

Zetterberg, L., Uppenberg, S. & Åhman, M. 2004. Climate impact from peat utilisation in Sweden. Mitigation and Adaptation Strategies for Global Climate Change. No 9 pp 37-76.

Appendix 1

Table 20 Energy input and CO_2 emissions in production and transportation of reed canary grass. Based Nilsson & Bernesson, 2008. These data are used for the cultivation of reed canary grass for input in the FT-diesel plant.

	Establishment (year 1) MJ ha^{-1}	Establishment (year 1) kg C ha^{-1}	Year 2-9 MJ ha^{-1}	Year 2-9 kg C ha^{-1}	Year 10 MJ ha^{-1}	Year 10 kg C ha^{-1}
Seed	52	1.0	0	0	0	0
N	1 612	33.1	4 030	82.8	2 015	41.4
P2O5	111	4.3	111	4.3	39	1.5
K2O	277	8.4	443	13.5	111	3.4
Mn/Lime	0	0	0	0	0	0
Pesticide	0	0	0	0	0	0
Cultivation	562	11.4	0	0	787	15.9
Drill	0	0	0	0	0	
Fertiliser application	28	0.6	28	0.6	28	0.6
Chemical application	0	0	0		0	0
Harvest & Storage	953	19.3	953	19.3	953	19.3
Transport	387	7.8	581	11.8	581	11.8
TOTAL	**3 983**	**86**	**6 146**	**132**	**4 514**	**94**

Table 21 Energy input and CO_2 emissions in production and transportation of reed canary grass. Based on Bullard & Metcalfe, 2001 and Pahkala et al., 2003. These data are used for the cultivation of reed canary grass at cutaway peatlands

	Establishment (year 1) MJ ha^{-1}	Establishment (year 1) kg C ha^{-1}	Year 2-9 MJ ha^{-1}	Year 2-9 kg C ha^{-1}	Year 10 MJ ha^{-1}	Year 10 kg C ha^{-1}
Seed	120	2.3				
N	1 964	33.1	2 946	49.7	2 946	49.7
P2O5	708	12.2	531	9.1	531	9.1
K2O	840	13.5	840	13.5	840	13.5
Pesticide	1 953	16	0	0	1816	15
Cultivation	3 054	62	0	0	0	0
Drill	621	12	0	0	0	0
Fertiliser application	100	2	100	2	100	2.0
Chemical application	145	2.2	0	0	145	2.2
Harvest	451	9.1	676	13.7	676	13.7
Storage	95	1.9	143	3	143	3
Transport	390	7.8	581	11.8	581	11.8
Handler	237	3.8	356	5.7	356	5.7
TOTAL	**10 675**	**177.5**	**6 173**	**108**	**8 134**	**125**