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Johanna Kirkinen

Greenhouse impact assessment of some combustible fuels with a dynamic life cycle approach

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Keywords greenhouse gas, emission, greenhouse impact, fuel, energy, carbon dioxide, methane, nitrous oxide, radiative forcing, global warming potential, life cycle

Abstract

Climate change mitigation requires steep reductions in greenhouse gas emissions. New sustainable solutions to provide low-carbon energy production will be needed. In this thesis the greenhouse impacts of some combustible fuels were comprehensively assessed using Life Cycle Assessment. A dynamic analysis method called Relative Radiative Forcing Commitment was developed in order to provide clear, unambiguous data to inform effective climate change mitigation strategies. RRFC gives a dynamic approach to greenhouse impacts and demonstrates their significance.

The greenhouse impacts of a variety of fuels were assessed: peat, coal, forest residues and reed canary grass, together with different diesels – Fischer-Tropsch (from peat and forest residues), Jatropha and fossil crude oil. Biomass-derived fuels are considered as one way to decrease greenhouse gas emissions. In the past, they were often held to be carbon-neutral fuels. However, all biogenic fuels considered in this thesis have a warming impact on the climate, as their production requires fossil fuel inputs, and in addition, land use emissions from changing carbon pools may have large effect on the total greenhouse impact. If raw materials for fuel are produced by cultivation, the manufacture and use of fertilisers may be of great importance.

If global warming is to be halted at the level of 2 to 3 °C degrees Celsius, deep emission reductions will have to occur during the next decades. The RRFC of coal is about 180 over 100 years, thus if 1 MJ of coal is used for energy, the energy absorbed into the global atmosphere-surface system warms the globe by 180 MJ. Warming occurs due to the radiative forcing caused by concentration increases due to greenhouse gas emissions. The use of forest residues and reed canary grass for energy has one of the lowest greenhouse impacts, causing only about a tenth of the impact of coal. Natural gas has a greenhouse impact nearly one third lower than coal. The greenhouse impact of using peat for energy depends strongly on the type of peatland used of peat production, resulting in a lower or higher greenhouse impact than coal.

Johanna Kirkinen. Greenhouse impact assessment of some combustible fuels with a dynamic life cycle approach [Värdering av drivhuseffekten av vissa bränslen enligt den dynamiska livscykelsmetoden]. Espoo 2010. VTT Publications 733. 63 s. + bil. 58 s.

Nyckelord greenhouse gas, emission, greenhouse impact, fuel, energy, carbon dioxide, methane, nitrous oxide, radiative forcing, global warming potential, life cycle

Sammanfattning

Att mildra klimatförändringen kräver kraftiga minskningar i utsläppen av växthusgaser. Det behövs nya lösningar i enlighet med hållbar utveckling för att erbjuda kolfattig energiproduktion. Drivhuseffekten av vissa bränslen undersöktes omfattande med hjälp av livscykelvärdering i denna avhandling. Den dynamiska analysmetoden Relative Radiative Forcing Commitment utvecklades för att erbjuda tydlig och entydig information om effektiva strategier för att mildra klimatförändringen. RRFC möjliggör ett dynamiskt synsätt på växthuseffekter och påvisar signifikansen av dem.

Drivhuseffekten för olika bränslen värderades: torv, stenkol, hyggesrester, samt rörflen, och också olika dieselsorter – Fischer-Tropsch (torv och hyggesrester), Jatropha och fossil mineralolja. Bränslen som härstammar från biomassa anses vara ett sätt att minska på emissionen av växthusgaser. Tidigare ansågs dessa vara kolneutrala bränslen. Alla i denna avhandling undersökta biogena bränslen har dock en värmande effekt på klimatet eftersom deras produktion kräver fossila bränsleinput och dessutom kan utsläpp från sönderfall av kolreservoarer ha en stor effekt på hela drivhusverkan. Ifall råmaterialen för bränsle härstammar från odlingar kan tillverkningen och bruket av gödsel vara mycket betydande.

Vill man stanna av den globala uppvärmningen på 2–3 °C måste man skära ner utsläppen radikalt under de kommande decennierna. Stenkolens RRFC är ca. 180 över 100 år, så om 1 MJ stenkol används för energi, värmer den i det globala atmosfär-ytsystemet absorberade energin jordklotet med 180 MJ. Värmningen uppstår pga. radiative forcing som orsakas av koncentrationssökningar till följd av utsläpp av växthusgaser. Energibruket av hyggesrester och rörflen har av de lägsta drivhuseffekterna, endast ca. en tiondedel jämfört med verkan av stenkolförbrukningen. Verkan av bruket av naturgas är nästan en tredjedel mindre än av stenkolförbrukningen. Drivhuseffekten av energibruket av torv beror mycket på vilken typ av torvmossa som används för torvproduktionen – slutresultatet kan vara antingen en lägre eller en högre drivhuseffekt än vad stenkolförbrukningen har.

Preface

This study was carried out while working at VTT Technical Research Centre during years 2005–2009. I acknowledge the main funder of my work, the Academy of Finland, for the finance (project no. 117842 IFEE–Indicator Framework for Eco-Efficiency in the KETJU Research Consortium). I also thank Jenny and Antti Wihuri Foundation for a grant that gave me the opportunity to fully concentrate on finishing my thesis.

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I greatly thank all my colleagues from VTT Technical Research Centre and especially my Climate Change Mitigation -team for their assistance, valuable consultation and continued support as well as for excellent “team spirit”. I would like to warmly thank all people from our Energy Systems -research area and especially the joyful coffee breaks and bets (my greatest achievement was third place). I also thank all the other colleagues contributed to my work and articles: Kari Minkkinen, Tomi Penttilä, Soili Kojola, Risto Sievänen, Jukka Alm, Sanna Saarnio, Jukka Laine, Taru Palosuo, Kristina Holmgren, Sampo Soimakallio and Tuula Mäkinen.

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Finally, I express my love and gratitude to my family and friends for their support and encouragement.

In Helsinki, April 2010

Johanna Kirkinen

List of original articles

This thesis consists of the following original publications, which are referred to in the summary part. The author’s contribution is described in more detail below.

I **Kirkinen, J.**, Minkkinen, K., Penttilä, T., Kojola, S., Sievänen, R., Alm, J., Saarnio, S., Laine, J., Savolainen, I. Greenhouse Impact Due to Different Peat Fuel Utilisation Chains in Finland – A Life-Cycle Approach. *Boreal Environment Research* (2007) 12, pp. 211–223.

II **Kirkinen, J.**, Palosuo, T., Holmgren, K., Savolainen, I. Greenhouse Impact Due to the Use of Combustible Fuels: Life Cycle Viewpoint and Relative Radiative Forcing Commitment. *Environmental Management* (2008) 42, pp. 458–469. DOI: 10.1007/s00267-008-9145-z.

III **Kirkinen, J.**, Sahay, A., Savolainen, I. Greenhouse Impact of Fossil, Forest Residues and Jatropha Diesel: A Static and Dynamic Assessment. *Progress in Industrial Ecology – An International Journal* (2009) 6(2), pp. 185–206. DOI:10.1504/PIE.2009.029082.

IV **Kirkinen, J.**, Soimakallio, S., Mäkinen, T., Savolainen, I. Greenhouse Impact Assessment of Peat-Based Fischer-Tropsch Diesel Life-Cycle. *Energy Policy* (2010) 38, pp. 301–311. DOI:10.1016/j.enpol.2009.09.019.

Author’s contribution

The author is the responsible author of all the publications I–IV. For all the publications, the author was responsible for the writing and calculations, and Savolainen acted as the supervisor. In paper I, the author was responsible for the calculations, writing and interpretation. Information on the greenhouse gas sinks and sources was provided by Minkkinen, Penttilä, Kojola, Sievänen, Alm, Saarnio and Laine. In paper II, the author was responsible for all data collection other than forest residues (Palosuo) and natural gas (Holmgren). In papers III and IV the author was responsible for the calculations, writing and interpretation of the results.

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Units and abbreviations

AGGI	Annual Greenhouse Gas Index
CCS	Carbon Capture and Storage
CFC	Chlorine-Fluorine-Carbon
CH_4	Methane
CO_2	Carbon Dioxide
CO_2-eq.	Carbon Dioxide Equivalent
COP	Conference of Parties
EC	European Commission
EU	European Union
FT	Fischer-Tropsch
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GTP	Global Temperature Potential
GWP	Global Warming Potential
HFC	Hydrofluorocarbon
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standard Organisation
LCA	Life Cycle Assessment

LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LULUCF	Land Use, Land Use Change and Forestry
N_2O	Nitrous Oxide
OECD	Organisation for Economic Co-operation and Development
PFC	Perfluorocarbon
ppb	Parts per billion
ppm	Parts per million
RF	Radiative Forcing
RRFC	Relative Radiative Forcing Commitment
SF_6	Sulfur Hexafluoride
SRES	Special Report on Emissions Scenarios
UNFCCC	United Nation Framework Convention on Climate Change

1. Introduction

1.1 Climate change

Climate change is a topic widely discussed in scientific fields as well as political ones. It is a fact that anthropogenic carbon dioxide concentration in the atmosphere is increasing and causing increase in global temperature. Information is available on the changes in the greenhouse gas concentrations: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and halocarbons, e.g. CFCs, HFCs, PFCs and SF_6. From a pre-industrial (arbitrarily chosen as the year 1750) value of about 280 parts per million (ppm) of $CO_{2,}$ the concentration has increased to 386 ppm CO_2 in the year 2008, while the annual growth rate has been on average 2 ppm during previous years 2000–2008 (NOAA 2009). The current concentrations exceed by far the natural range which can be detected over 650,000 years (180 to 300 ppm) as determined from ice cores. The level of global CH_4 concentration has increased from a pre-industrial value of about 715 part per billion (ppb) to approximately 1790 ppb. The level of global N_2O concentration has increased from a pre-industrial value of about 270 ppb to 322 ppb (IPCC 2007a). The global radiative forcing (RF) of all long-lived greenhouse gases equals 2.7 W/m^2 in 2008, of which CO_2 contributed 64% (NOAA 2009).

The largest contributor to the increased CO_2 emissions is the energy sector and especially fossil fuel use. The level of energy-related CO_2 emissions has increased about 60% (from 18 Gt to 29 Gt) from 1970 to 2007 (IEA 2009). The emissions of CH_4 and N_2O occur primarily due to agriculture, but also due to fuel production and combustion, waste sector as well as industry. The current growth rate of CO_2 emissions have been accelerating on a global scale, increasing from 1% for 1990–1999 to more than 3% for 2000–2007. The emission growth rate since 2000 has been higher than for the most fossil-fuel intensive emission scenario of the Special Report on Emissions Scenarios (SRES) by the

Intergovernmental Panel on Climate Change (IPCC 2000) developed in the late 1990s (Raupach et al. 2007). The current economic recession is expected to cause a temporary decline of some per cent in the global emissions. However, a strong increase in emissions can be expected in the years to come. If global fossil fuel use continues to drive up energy-related CO_2 emissions, i.e. business as usual, an increase of 40% is predicted (from 29 Gt in 2007 to 40 Gt in 2030), leading us on a path to a global average temperature increase of up to 6°C (IEA 2009).

The impacts of global warming can be considerable, so strict climate change mitigation targets are needed. According to observations from all continents and most oceans, regional climate change affects natural systems. In particular, rising temperatures lead to changes in the hydrological system, snow, ice and permafrost as well as terrestrial, marine and freshwater biological systems (IPCC 2007b). Altered frequencies and intensities of extreme weather, climate and sea-level events lead to changing impacts. Impacts of climate change will differ regionally, but they are very likely to cause net annual costs which will increase over time as global temperatures increase (IPCC 2007b). Costs of mitigating climate change will increase if no action is taken. The overall costs and risks of climate change will be equivalent to losing at least 5% of global GDP each year (Stern 2006). The estimates of damage could rise to 20% of GDP or more if a wider range of risks and impacts are considered (Stern 2006).

1.2 Climate change mitigation

Without mitigation, the global GHG emissions are projected to increase strongly (IPCC 2000, IEA 2009). However, there is substantial economic potential to reduce emissions in the short and medium term (until 2030). Those measures could reduce emissions or offset the assessed growth of global emissions (IPCC 2007c). There are numerous ways to reduce emissions in different sectors. In the energy sector, which is mainly responsible for the anthropogenic emissions, there is a wide range of mitigation technologies and practices currently commercially available, e.g. improved supply and distribution efficiency; fuel switching from coal to gas; nuclear power; renewable heat and power (hydropower, bioenergy, wind, geothermal and solar); combined heat and power; early applications of Carbon Capture and Storage (CCS, e.g. storage of removed CO_2 from flue gases of coal and natural gas combustion) (Haszeldine 2009). Technologies and practices available before 2030 include CCS for gas, biomass and coal-fired electricity generating facilities; advanced nuclear power; advanced renewable energy, including tidal and wave energy, concentrating solar, and solar photovoltaic (IPCC 2007c). In particular, increasing end-use energy efficiency in different sectors reduces GHG emissions cost-effectively (IEA 2009, McKinsey & Company 2009). Also the emissions of land-use and agriculture as well as carbon sequestration in forests and soils of the biosphere can be covered as a means of mitigation practices related to e.g. biofuels. However, the definite goal of climate change mitigation can be seen as the low-carbon society, where goods and services are produced with low or no GHG emissions, and temperature increase can be halted despite growing human population and economic well-being.

Technological or practical means enhance and enable climate change mitigation, but significant political decisions also need to take place in order to prevent global warming from reaching dangerous levels. Concern about the need for climate change mitigation at the international level led to the establishment of the United Nation Framework Convention on Climate Change (UNFCCC). The Convention text was adopted in Rio Janeiro in 1992 and entered into force on 21st March 1994. The objective of this treaty is to set an overall framework for intergovernmental efforts to tackle the challenges posed by climate change (UNFCCC 1992). As an addition to the treaty, an international and legally binding target to reduce GHG emissions worldwide was approved by 37 industrialized countries and the European Union. This addition is called the Kyoto Protocol, which was adopted in Kyoto in 1997 and entered into force on 16 February 2005. The main feature of the Kyoto Protocol is to reduce total GHG emissions on average 5% from 1990 levels over the period 2008–2012 (Kyoto Protocol 1997). The major difference between the Convention and the Protocol is that while the former encourages industrialized countries to stabilize GHG concentrations, the latter commits them to reduce GHG emissions. However, before the first commitment period of the Protocol ends, a new international framework and the next emission reduction targets need to be negotiated. This new international climate change deal was under discussion at the United Nations Climate Change Conference (COP 15, Conference of Parties) in Copenhagen, 7–18 December 2009. The Copenhagen Accord states that the global warming should be limited to two degrees compared to pre-industrial times and further, both developed and developing countries should contribute to the emissions reductions (UNFCCC 2009a).

The 2°C target requires strong cuts in global greenhouse gas emissions. According to IPCC (2007c), the GHG emissions need to be reduced by 50 to 85% by 2050 from the 2000 level. The emissions need to peak and decline during the period 2000–2015. The EU has set a precise binding unilateral target to reduce GHG emissions by 20% by 2020 compared to the level of 1990, or even 30% if other developed countries make comparable efforts (EU 2008, 2009). Another key target of this agreement (March 2007) by the European Council is to increase the share of the renewables in the energy consumption of the EU to 20% by 2020. The renewable target also included a 10% binding target for the share of energy from renewable sources in transport by 2020.

There are important aspects when considering time periods in climate change mitigation. The lifetime of different GHGs and their removal from the atmosphere need to be taken into account. CO_2 does not have a specific lifetime due to the carbon cycle; it is continuously cycled between the atmosphere, oceans and land biosphere and its net removal from the atmosphere involves a range of processes with different time scales. If a pulse of CO_2 is emitted to the atmosphere, almost 40% of the emitted CO_2 is still effectively in the atmosphere after 100 years (IPCC 2007a). The lifetimes of CH_4 and N_2O are somewhat more than 10 and 100 years, respectively. The changes in the RF due to the concentration changes occur slowly. Very strong and rapid emission cuts are needed to stop the concentration increases, the growth of RF, and global average temperature increases due to the inertia of the global warming process. The thermal capacity of the oceans slows down the warming rate. However, even if emissions were to peak and decline in coming decades, the stabilisation of CO_2 concentration would take 100 to 300 years, stabilisation of temperature would take a few centuries and sea-level rise would continue at a stable growth rate for centuries to several millenia due to thermal expansion of water and ice melting (IPCC 2007b). Also the inertia of world's energy system slows down the speed of change towards low and zero-emissions due to long investment life-times and the capital-intensive character of the industry. The utilisation of some carbon stocks and fuel reserves causes long-lasting changes in the reserves and their emissions or sinks, e.g. the utilisation of forest and peat, which are considered in this thesis.

Finding new ways of producing energy with lower emissions needs to be introduced. Assessing the greenhouse effect due to various energy generation technologies and fuels is important for effective mitigation strategies. Information on the sustainability of different fuels is needed in order to plan investments, measures and policies for the mitigation of climate change. Therefore the metrics of the greenhouse impact assessment as well as the definition of sustainability need to be developed and applied, especially when the share of biomass-derived fuels will increase.

1.3 Greenhouse impact assessment and emissions reporting

For the greenhouse impact assessment two different approaches are generally used: Radiative Forcing (RF) and Global Warming Potential (GWP). RF describes the deviation of the radiation energy balance of the Earth and can be accessed on the basis of the calculated changes in the concentration levels of GHGs (e.g. CO_2, CH_4 and N_2O) caused by the emissions and sinks. On the global scale the present RF can be calculated on the basis of measured concentrations from the atmosphere. RF takes into account time-dependency of the occurred emissions or sinks and slow removal of the GHGs from the atmosphere. In some cases, long-term changes in the carbon storages of the ecosystem take place in the utilisation life cycle of the assessed fuel. Thus, in order to provide decision-makers and policymakers with appropriate information on climate change mitigation measures, it is important to consider the climate impact of energy sources at appropriate time horizons linked to the goal of climate change mitigation policies. If the objective of the policy is to halt the warming rapidly (e.g. in 50 years) relatively short time horizons should be considered. If the objective is to stabilize warming in the long term, long time horizons are needed. However, long time horizons alone are not necessarily very effective in halting the temperature rise rapidly (IPCC 2009).

GWP is a simple application of RF to give relative weights for various GHGs in relation to CO_2. Countries are required to make an inventory of their greenhouse gas emissions and to report to the UNFCCC (2006). GWPs are used in this reporting. The inventory includes actual anthropogenic GHG emissions and sinks during the reporting year as accurately as possible. This enables the monitoring of actual levels and trends in GHG emissions and an assessment of meeting the commitments under the Kyoto Protocol or under possible future emission control protocols.

Life Cycle Assessment (LCA) differs from emission inventory as an assessment approach. LCA provides information on the environmental impacts “from the cradle to the grave”. The life cycle perspective aims at estimating all the environmental impacts of a function or product (ISO 14044 2006). In greenhouse impact assessment all the significant emissions and sinks caused by the function or product during the whole life cycle are included. In the case of utility articles, all emissions occur within a short time period; during a few months or at most within a few years. The emissions occurring in different years are added up, and no particular attention is paid to the time span. In the case of some biogenic fuels, e.g. peat fuel, emissions or sink processes may last up to hundreds of years, and therefore it makes sense to introduce a time dimension to the study and to the way in which the results are presented. Potential emissions and sinks occurring in the future highlight the fact that the results of LCA are not compatible with the inventory approach, which only takes into account the emissions and sinks of the reporting year. Also, the greenhouse gas inventory reports emissions by sector and by emission class as well as by geographic region, whereas in the LCA of a single function or product, emissions are split up among several classes (e.g. in the case of peat fuel emissions are split into Energy, Agriculture, Land Use, Land Use Change and Forestry (LULUCF) (Lapveteläinen et al. 2007)).

1.4 Biogenic fuels and climate change

Biomass-derived fuels are considered to be “carbon-neutral” and are seen as one option for mitigating climate change. However, their sustainability and greenhouse gas savings compared to fossil fuels need to be clearly shown from the life cycle perspective. The European Union has set a target to increase the share of energy from renewables in transport by 10%. The savings in greenhouse gas emissions from the use of biofuels and bioliquids compared with fossil fuel need to be at least 35% and thus clearly proven. The required savings will increase over time; the savings need to be at least 50% after 2017 (EU 2009).The saving targets can be seen as political choices. The objective is to improve the environmental efficiency of transport fuels.

The term biogenic fuel is used in this thesis in order to include peat, which has its own category ‘Peat’ in the IPCC reporting guidelines (IPCC 2006) and is thus not considered renewable or fossil. However, fossil fuels are also biogenic fuels, although millions of years old. The role of carbon stock changes from the atmospheric viewpoint is important, and needs to be included in the assessment as accurately as possible.

The greenhouse impact of different bio-based fuels has been studied abroad and in Finland, e.g. by UNEP (2009), Soimakallio et al. (2009), Hill et al. (2006), Holmgren et al. (2006), Nilsson & Nilsson (2004), Edwards et al. (2003), Savolainen et al. (1994). Next chapters give short introductions to these studies. UNEP (2009) assessed biofuels comprehensively and concluded about their greenhouse gas balances, that net GHG savings compared to fossil fuels depend on the feedstock and conversion technology, but also on other factors, such as methodological assumptions. High savings in greenhouse gas emissions depend on high yields. Increased emissions may result in particular when production takes place in converted land and the associated mobilization of carbon stocks is accounted for. High greenhouse gas savings are recorded especially in the case of utilizing forest residues and wood.

Soimakallio et al. (2009) assessed the energy and greenhouse gas balances of transportation biofuels and agrobiomass in Finland. The study included assessment of both commercial technologies i.e. ethanol from barley and rapeseed methyl ester (RME) from turnip rape, as well as technologies under development i.e. synthetic fuels using logging residues or reed canary grass as raw material. The results were that greenhouse gas emissions from production and use of barley-based ethanol or biodiesel from turnip rape are very probably higher compared to fossil fuels. Second generation biofuels produced using forestry residues or reed canary grass as raw materials seem to be more favourable in reducing greenhouse gas emissions. However, there were significant uncertainties involved in the results mainly due to the uncertainty in N_2O emissions from fertilization, emissions from the production of the electricity consumed, as well as the price of raw material and reference fuels.

Hill et al. (2006) estimated the environmental, economic, and energetic costs and benefits of soybean biodiesel and corn grain ethanol. The criteria included that if biofuels were a viable alternative, they should provide a net energy gain, have environmental benefits, be economically competitive, and be producible in large quantities without reducing food supplies. According to Hill et al. greenhouse gas emissions are reduced 12% by the production and combustion of ethanol and 41% by biodiesel compared to displaced fossil fuels.

Holmgren et al. (2006) studied and compared earlier studies made of peat fuel greenhouse impact assessments made in Sweden and in Finland. The results indicated that scientific approach and calculation methodology was very similar. Some differences occurred in the definitions and system boundaries. The main reason for the differences in results between the two studies was differences in greenhouse gas emission and sink estimates for the after-treatment phase and the non-utilisation chain (i.e. reference scenario). Both Swedish and Finnish studies suggested that the use of cultivated peatland for energy peat utilisation results in lower climate impact than using coal. The climate impact of peat utilisation chains where fens and forestry-drained peatlands are used for peat production differs between the Finnish and the Swedish study.

Nilsson & Nilsson (2004) studied the potential climate impact of four different peatland types (pristine mires, organic agricultural soils, drained forests and abandoned harvesting area subjected to previous peat extraction). They also included two different after-treatments in the scenarios: rewetting and afforestation. Their conclusion was that the current Swedish use of energy peat gives smaller climate impact than the use of coal but larger impact than the use of natural gas.

Edwards et al. (2003) have performed an evaluation of the Well-to-Wheels energy use and greenhouse gas emissions for a wide range of potential future fuels and powertrain options. First version was published in 2003. An exact and detailed analysis is available for a variety of fuels.

Savolainen et al. (1994) studied radiative forcing impacts of using peat and wood for energy already more than 15 years ago. The results were that the smallest radiative forcing during 100 year was caused by the use of wood waste, forest residues, wood from first thinning and, in the long run, wood from regeneration felling possibly wood from coppices cultivated for energy use. Next group in the extent of radiative forcing consisted of natural coppices, peat from cultivated peatlands, natural gas and oil. The largest radiative forcing was caused by coal and peat from virgin and forestry-drained peatlands.

Growing doubts about the environmental sustainability of bio-derived fuels and concern over the impacts on food prices have led to a rethink about the biofuels targets in many countries (IEA 2009). Especially the impact of the emissions from land use, land use changes and forestry (e.g. changes in carbon stock, biomass for energy is harvested or grown) on the total greenhouse impact of bio-based fuels has been recently discussed by e.g. Melillo et al. (2009), Searchinger et al. (2009) and Fargione et al. (2008).

Melillo et al. (2009) raises up the question about indirect effects related to bioenergy production i.e. indirect emissions occur when biofuel production on agricultural land displaces agricultural production and causes additional land-use change that leads to an increase in net greenhouse gas emissions. Substantially more carbon loss is predicted to be caused by indirect land use. However, predicted increases in fertilizer use causing N_2O emissions will be more important than carbon losses. Best practices for nitrogen fertilizer use can dramatically reduce emissions associated with biofuel production. Searchinger et al. (2009) concluded that corn-based ethanol doubles greenhouse gas emissions over 30 years and increases greenhouse gases for about 170 years instead of resulting savings in greenhouse gas emissions, which has been the prevailing assumption. The results were based on a worldwide agricultural model taking into account e.g. that farmers convert forest and grassland to new cropland to replace the grain (or cropland) diverted to biofuels. Fargione et al. (2008) also pointed out that the greenhouse gas savings relates how biofuels are produced. Converting rainforests, peatlands, savannas, or grasslands to produce food crop–based biofuels creates a carbon debt. However, biofuels made from waste biomass or from biomass grown on degraded and abandoned agricultural lands planted with perennials incur little or no carbon debt and can offer immediate and sustained GHG advantages.

1.5 The objective of the thesis

The objective of this thesis is to assess the greenhouse impact of different fuels and to evaluate their climatic sustainability while providing an accessible tool for interpreting the results. The different fuels whose climatic sustainability were compared and evaluated were peat, coal, natural gas, forest residues, and reed canary grass as well as different diesels: Fischer-Tropsch diesels based on peat and forest residues, Jatropha diesel and fossil diesel (Table 1).

In this thesis, climatic sustainability means that the actions taken today will not endanger the possibilities of future generations to fulfil their needs from the climate point of view. In practice, this means that the greenhouse impact of the actions considered should be low (applied from IUCN 1980). These sustainability targets by EU (2009) can be seen as political choices.

It is interesting to note that the sustainability of e.g. the use of peat as well as the role of the time spans were first considered hundreds of years ago. Already in the 18th century Swedish natural scientist Carl von Linne brought up in his book called Skånska resa (1749) the following thoughts: “To burn a peat moss does twenty times as much damage, as a forest can twenty times grow up before a new and equally good peat moss matures. – It may seem to be a good invention to use the fens for fuel and thus spare the wood; but a forest can grow several times in a seculum, whereas a fen is not filled with peat in several secula.” The radiative forcing of the Northern peatlands have been studied e.g. by Frolking and Roulet (2007). The amount of carbon in the peat layers of the Finnish peatlands is decreasing, however, if the carbon in increasing forests on the drained peatlands is also accounted, the total amount of carbon is increasing (Turunen 2008, Statistics Finland 2008). In this thesis, new measurement data from the Research Programme about Greenhouse Impacts of the Use of Peat and Peatlands in Finland were used in order to assess the greenhouse impact of peat fuel use (Ministry of Agriculture and Forestry 2007).

Table 1. Studied energy chains and the main phases of their life cycle

Energy chain	Production reserve	Production and utilisation	After-treatment	Utilisation of after-treatment	Emissions and sinks from the reference case	Source
1a	Pristine fen	Peat production and combustion	Restoration	-	Normal development of pristine fen	Paper I
2a	Pristine fen	Peat production and combustion	Afforestation	-	Normal development of pristine fen	Paper I
3a	Forestry-drained peatland	Peat production and combustion	Afforestation	-	Normal development of forestry-drained peatland	Paper I
4a	Cultivated peatland	Peat production and combustion	Afforestation	-	Normal development of cultivated peatland	Paper I
5a	Forestry-drained peatland	Advanced peat production and combustion	Afforestation	-	Normal development of forestry-drained peatland	Paper I
6a	Cultivated peatland	Advanced peat production and combustion	Afforestation	-	Normal development of cultivated peatland	Paper I
1b	Reed canary grass	Fertilization, harvesting	-	-	-	Paper II
2b	Forest residues	Harvesting	-	-	Decomposition of forest residues	Paper II
3b	Peat from forestry-drained peatland	Milled peat production method	Afforestation	-	Normal development of forestry-drained peatland	Paper II
4b	Peat from cultivated peatland	New peat production method	Afforestation	Energy use of the produced wood biomass	Normal development of cultivated peatland	Paper II
5b	Natural gas	Produced in the North Sea, combusted in Sweden	-	-	-	Paper II
6b	Coal	Produced in Poland, combusted in Finland	-	-	-	Paper II
1c	Crude oil	Production, diesel refining, supply, and utilisation (Europe)	-	-	-	Paper III
2c	Forest residues	Collection, crushing, transportation and FT diesel refining (Finland)	-	-	Decomposition of forest residues	Paper III

3c	Jatropha seeds	Production and transesterification, supply and utilisation (India)	-	-	-	Paper III
1d	Crude oil	Production, diesel refining, supply, and utilisation (Europe)	-	-	-	Paper IV
2d	Forest residues	Collection, crushing, transportation and FT diesel refining (Finland)	-	-	Decomposition of forest residues	Paper IV
3d	Reed Canary Grass	Cultivation, harvesting, crushing, transportation and FT diesel refining	-	-	-	Paper IV
4d	Forestry-drained peatland	Peat production with milled peat technique, storage, transportation and FT diesel refining	Afforestation	-	Normal development of forestry-drained peatland	Paper IV
5d	Forestry-drained peatland	Peat production with milled peat technique, storage, transportation and FT diesel refining	Paludification		Normal development of forestry-drained peatland	Paper IV
6d	Forestry-drained peatland	Peat production with milled peat technique, storage, transportation and FT diesel refining	Cultivation of Reed Canary Grass	Reed Canary Grass is refined into FT diesel	Normal development of forestry-drained peatland	Paper IV
7d	Forestry-drained peatland	Peat production with milled peat technique, storage, transportation and FT diesel refining	Afforestation	Wood biomass is refined into FT diesel	Normal development of forestry-drained peatland	Paper IV
8d	Forestry-drained peatland	Peat production with a new technique, storage, transportation and FT diesel refining	Afforestation	Wood biomass is refined into FT diesel	Normal development of forestry-drained peatland	Paper IV
9d	Cultivated peatland	Peat production with a new technique, storage, transportation and FT diesel refining	Afforestation	-	Normal development of cultivated peatland	Paper IV
10d	Cultivated peatland	Peat production with a new technique, storage, transportation and FT diesel refining	Afforestation	Wood biomass is refined into FT diesel	Normal development of cultivated peatland	Paper IV
11d	Forestry-drained peatland	Peat production with a new technique, storage, transportation and FT diesel refining	Cultivation of Reed Canary Grass	Reed Canary Grass is refined into FT diesel	Normal development of forestry-drained peatland	Paper IV

Another objective of the thesis is to provide an accessible tool for interpreting the results. The metrics of greenhouse impact currently used, GWP and RF, are compared and used in this thesis. In order to provide a greenhouse impact assessment metric which is transparent and replicable, besides maintaining the accessibility of the study, a new assessment approach to the interpretation of RF results was developed. The approach is called relative radiative forcing commitment (RRFC). RRFC provides a simple dimensionless tool to illustrate the greenhouse impact of different energy sources alternatives, including the dynamic perspective about the impact on climate.

LCA is an essential part of the thesis. LCA was used in order to provide comprehensive and up-to-date information on the assessed fuels. The greenhouse impact not only consists of the combustion emissions but also emissions from the production of fuel and the impacted ecosystem carbon storages. Especially peat fuel and peat-based Fischer-Tropsch diesel provide a good example of the complexity of the comprehensive greenhouse impact assessment and the role of different stages of the life cycle. Also, long time scales need to be considered due to the fact that utilisation of forest or peat-based fuels induce long-lasting changes in the emissions of fuel reserves and utilised ecosystems. The timing of greenhouse gas emissions caused by changes in land use has been noted and different approaches suggested, e.g. a time correction factor (Kendall et al. 2009).

2. Methods

The next chapters present the methods used in this thesis. Firstly, the principles on which the greenhouse impact is most often calculated are introduced. Life Cycle Assessment, Radiative Forcing and Global Warming Potential are discussed further. In addition, methodology applied in the thesis is introduced.

2.1 Life cycle assessment

Life cycle assessment is a well-known standard methodology broadly used in environmental science. It is a tool to assess the environmental impacts and resources used throughout the life cycle of a product or a function (ISO 14040 1997, ISO 14044 2006). It takes account of all the inputs and outputs of the system during the whole life cycle, providing a comprehensive assessment and considering all attributes or aspects of the environment and resources. The phases of LCA have been divided into four elements, as follows:

- definition of goal and scope
- inventory analysis
- impact assessment
- interpretation.

Critical review and reporting are also a part of the assessment process. It is important to define the comparative assertion and the functional unit used in the assessment (ISO 14040 1997, ISO 14044 2006). Transparency and replicability are important aspects of LCA so that the study can be conducted by any other party. The framework of the LCA is presented in Figure 1.

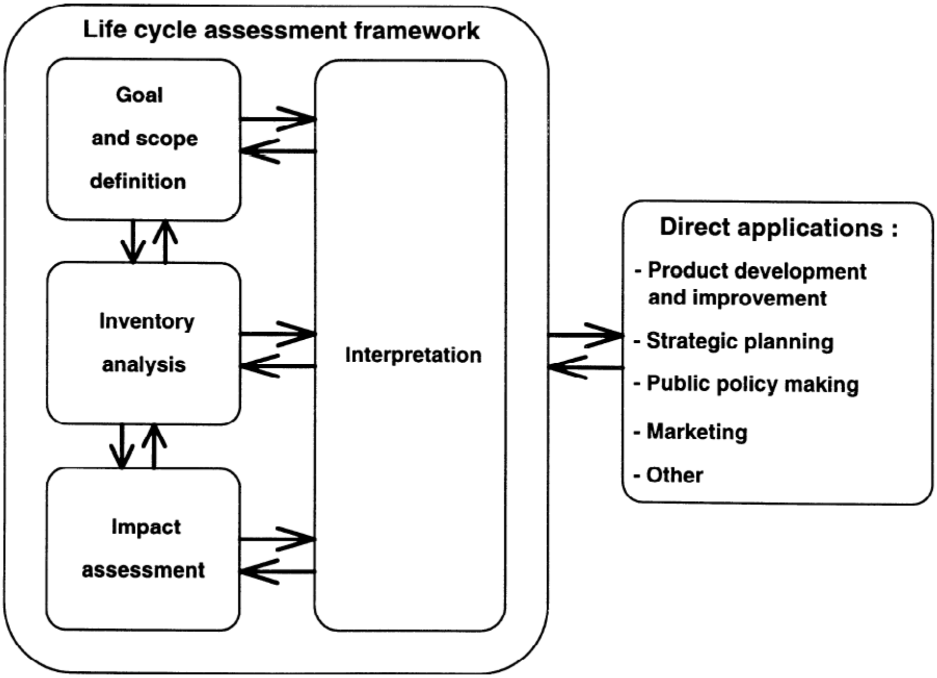

Figure 1. Phases of life cycle assessment according to ISO 14040 (1997). There are four phases in an LCA study: the goal and scope definition phase, the inventory analysis phase, the impact assessment phase, and the interpretation phase. LCA addresses the environmental aspects and potential environmental impacts. It can be used for decision-making related to e.g. product development and improvement, strategic and public policy planning as well as marketing.

The scope includes definition of system boundaries and level of detail. The life cycle inventory analysis phase (LCI phase) is the second phase of LCA, which includes listing of the input and output data. The life cycle impact assessment phase (LCIA) is the third phase of the LCA, where the results are developed in order to provide understandable information about the impacts. Life cycle interpretation is the final phase, in which the results are summarized and discussed as a basis for conclusions, recommendations and decision-making in accordance with the goal and scope definition (ISO 14044 2006).

2.2 Calculation of the greenhouse impact

When calculating the greenhouse impact for an energy chain, only the impact due to human activities has been considered according to UNFCCC. The natural greenhouse impact has not be seen as a perturbation, as it belongs to the natural system. Impact is calculated on the basis of the emissions from the energy chains under consideration. All CO_2, CH_4 and N_2O gas fluxes from all the different stages of the life cycle of the energy chain considered were taken into account. The net greenhouse impact I is calculated as

$$I = I_U - I_R \tag{1}$$

where I_U is the impact of the utilisation (e.g. impact from the production of raw material, transportation, working machines, end use (combustion) and after-treatment). I_R is the impact from the reference situation, i.e. the normal development of the utilised resource during the studied time period. For example, in the case of peat and peat-based FT diesel, this means the greenhouse impact of the peatland occurring naturally as a function of time, if not used for peat production. In the case of forest residues and FT diesel based on forest residues, this means the greenhouse impact of the decomposition of the logging residues if they are not harvested and used for FT diesel production. It should be noted that in the case of fossil fuels, I_R equals zero. In the future, when more reliable information about the emissions of land use is available, the role of the reference situation may be emphasised in the assessment of biogenic fuels.

2.3 Radiative forcing

Radiative Forcing describes the perturbation of the radiation energy balance of the Earth. It can be interpreted to represent the heating power of the atmosphere-surface system. Positive RFs lead to a global mean surface warming, and negative RFs to a global mean surface cooling. RF is produced by the increased amount of greenhouse gases in the atmosphere, which is dependent on the GHG emissions and sinks as well as by the reflection of incoming solar radiation. The latter is described by the reflection factor, albedo. Changes in the Earth’s albedo are caused by changes on the surface, e.g. changes in vegetation, and by changes in particulate emissions. The particulates in the air increase the reflection of solar radiation and also contribute to increased clouds, which increase reflection. Radiative forcing is usually expressed in watts per square meter (W/m^2) (IPCC 2007a). The current levels of GHG concentrations equate with a radiative forcing level of 2.7 W/m^2. However, due to cooling impacts like e.g. the increased amount of particulates, the net RF is about 1.6 W/m^2. If the CO_2 concentrations were doubled, the outgoing radiation would decrease approximately 4 W/m^2, which warms the atmosphere in order to reach the equilibrium of incoming and outgoing energy fluxes. Figure 2 presents the warming and cooling RF components and ranges with their geographical extent and level of understanding.

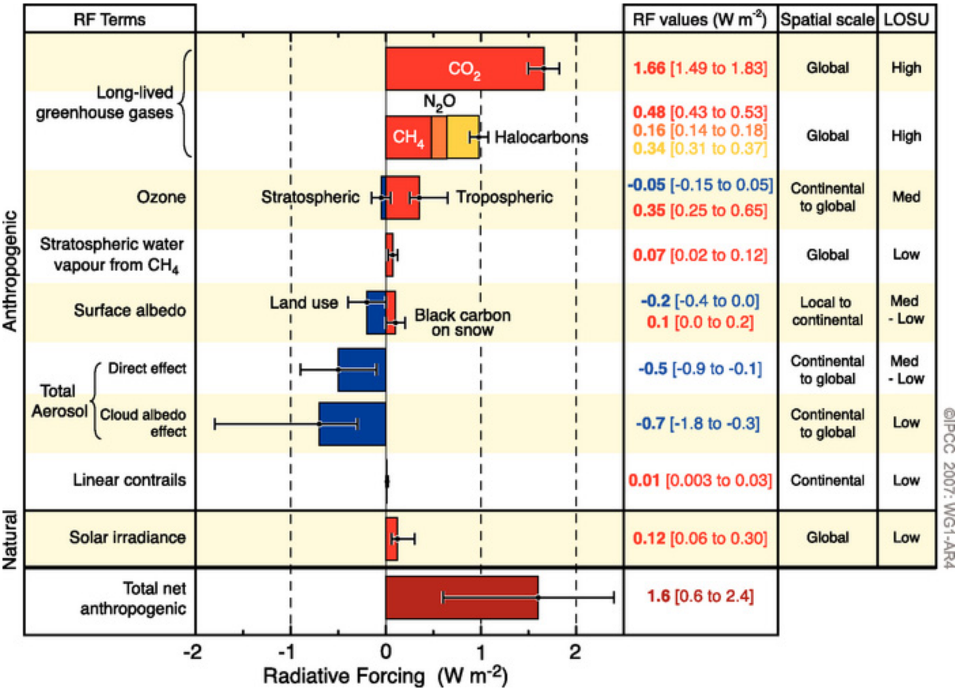

Figure 2. Global average radiative forcing (RF) components and ranges for CO_2, CH_4, N_2O and other important agents and mechanisms, together with the spatial scale of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its uncertainty range are also shown (IPCC 2007a).

The statistics and measures of greenhouse gas concentrations are maintained by NOAA (2009). They provide an Annual Greenhouse Gas Index (AGGI) (Figure 3), which has been defined as the ratio of the total radiative forcing due to long-lived greenhouse gases for any year for which adequate global measurements exist to that which was present in 1990 (NOAA 2009). AGGI is a measure of radiative forcing of climate, and was designed to enhance the connection between scientists and society by providing a normalized standard that can be easily understood and followed by policymakers, educators and the general public. This index shows annual changes in conditions that have impact on CO_2, CH_4 and N_2O emission sources and sinks as well as the decline in the atmospheric abundance of ozone-depleting chemicals related to the Montreal Protocol (NOAA 2009). For the year 2008, the AGGI was 1.26, showing an increase of 26% since 1990. Most of this is caused by CO_2, the forcing of which increased 35% since 1990. Also N_2O concentration is continuing to increase at a constant rate. While the radiative forcing of the long-lived, well-mixed greenhouse gases increased about 26% from 1990 to 2008 (app. 0.57 W/m^2), CO_2 has accounted for nearly 80% of this increase (app. 0.45 W/m^2) (NOAA 2009).

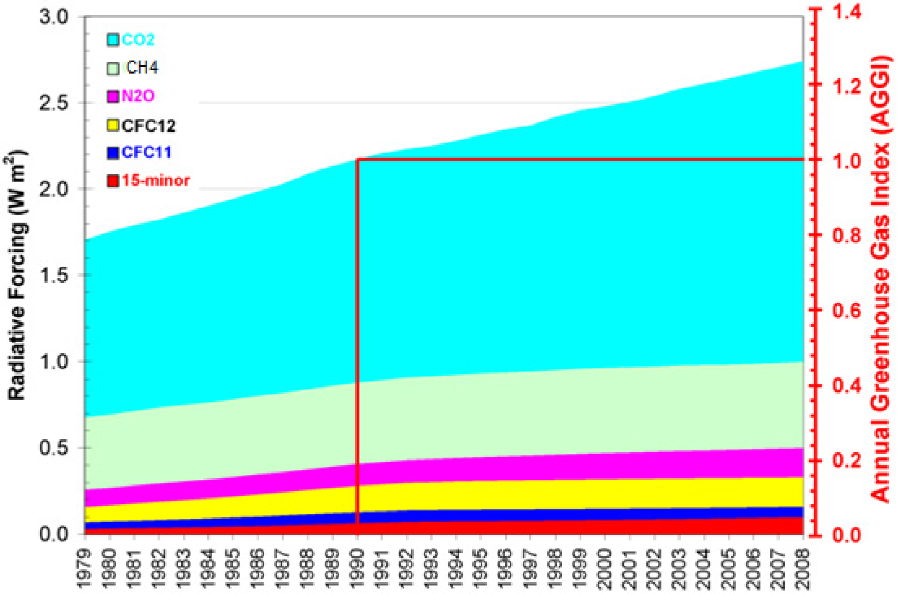

Figure 3. The Annual Greenhouse Gas Index (AGGI) shows the annual changes of radiative forcing due to greenhouse gas emission sources and sinks. AGGI shows the relatively large contribution of CO2 to the total RF. 15-minor refers to a set of 15 minor long-lived halogenated gases including CFC-113, CCl4, CH3CCl3, HCFCs 22, 141b and 142b, HFCs 134a, 152a, 23, 143a, and 125, SF6, and halons 1211, 1301 and 2402 (NOAA 2009).

The greenhouse impact of the considered energy chains is assumed to be a linear function of the net emissions (emissions minus sinks by gas) because the emissions considered are a very small fraction of the global greenhouse gas emissions and sinks. The greenhouse impact is described as radiative forcing (Korhonen et al. 1993, Savolainen et al. 1994, Monni et al. 2003). Radiative forcing takes account of emission histories and slow removal of greenhouse gases from the atmosphere, providing a time-dependent view of the greenhouse impact. The emissions are calculated as a function of time:

$$E_i(t) = E_{i,U}(t) - E_{i,R}(t) \tag{2}$$

where $E_i(t)$ is the net emission (net emissions meaning here emissions and sinks) of gas i (CO_2, CH_4, N_2O) at time t caused by the activity considered. $E_{i,U}(t)$ are the emissions of gas i in the case of the utilisation of the fuel resource, and $E_{i,R}(t)$ in the reference case of non-utilisation.

In the calculation of atmospheric concentrations and radiative forcing due to the atmospheric concentration, the REFUGE model was used (see e.g. Monni et al. 2003). In the calculation of the greenhouse gas i concentration $C_i(T)$ at the instantaneous time T due to the emissions of the gas i, REFUGE uses a convolution integral:

$$C_i(T) = \int_0^T E_i(t) f_i(T-t)dt + C_{0,i}(T) \tag{3}$$

where f_i is the pulse-response function given by Maier-Reimer and Hasselmann (1987) and $C_{0,i}$ is the background concentration which can be time dependent due to other sources of emissions in the case of CO_2. CH_4 and N_2O concentrations are described with a one-exponential life-time model. The radiative forcing is calculated in REFUGE on the basis of additional concentrations caused by the considered activity. The total radiative forcing I_{RF} due to the three gases considered is roughly a sum of the radiative forcings of the different gases:

$$I_{RF}(T) = RF\left[C_{CO_2}(T), C_{CH_4}(T), C_{N_2O}(T)\right] \tag{4}$$

However, the overlapping of the infrared radiation absorption bands of CH_4 and N_2O is also accounted for in Eq. 4, as given by IPCC (2001). The radiative forcing due to CH_4 includes the forcing due to water vapour input to the stratosphere due to the decay of CH_4.

2.4 Relative Radiative Forcing Commitment (RRFC)

In this study, a new interpretation method called Relative Radiative Forcing Commitment (RRFC) is used instead of RF expressed in W/m^2 (Paper II), as an indicator of the greenhouse impact. RRFC describes the ratio of the energy absorbed E_{abs} into the global atmosphere-surface system to the fuel energy E_f produced in the fuel chain under consideration. RRFC is calculated by integrating radiative forcing over the total surface A of the Earth and accumulating it over a given time horizon TH.

$$RRFC(TH) = \frac{E_{abs}(TH)}{E_f} = \frac{1}{E_f}\int_0^{TH} RF(t)dt * A \qquad (5)$$

RRFC takes account of the radiative forcing caused by concentration changes due to emissions of GHGs, but it does not consider climatic feedbacks such as the increasing content of water vapour in the atmosphere due to warming. RRFC is related to the Absolute Global Warming Potential (AGWP) described by IPCC (1996). RRFC equals the AGWP integrated over the surface area of the earth divided by the fuel energy produced in the fuel chain considered. RRFC can be used to compare the warming impacts or warming commitments caused by the use of various fuels or other energy sources.

RRFC expresses the results illustratively, as it gives the ratio of the energy heating the globe to the energy produced in the fuel chain. RRFC can also be expressed as a function of time in order to provide a dynamic cumulative picture of the caused effect. Varying time horizons can be studied separately, for example when studying the effects of different climate policies in varying time scales. The greenhouse impact is assessed for the 20, 100 and 300 year time horizons *TH* (Paper II). If global emission reduction policies are considered, where the rise of the global average temperature should be limited to 2–3 degrees °C above the pre-industrial level, the emissions should be limited to a small fraction of the present level within this century (IPCC 2007b). Therefore, the time horizon of 100 years or even shorter can be seen as relevant for decision-making on emission reduction measures and appropriate energy sources. The longer time horizon of 300 years is, in this respect, of theoretical or academic interest only.

RRFC also easily allows the use of possible albedo changes, which can be relevant in the case of some biogenic fuels. E.g. Betts (2000) and Lohila et al. (submitted) have studied forestation and its impact on albedo, which can be considerable.

2.5 Global warming potential

Global Warming Potential (GWP) is defined by IPCC (2007a) as follows: “An index, based upon radiative properties of well-mixed greenhouse gases, measuring the radiative forcing of a unit mass of a given well-mixed greenhouse gas in the present-day atmosphere integrated over a chosen time horizon, relative to that of carbon dioxide. The GWP represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing thermal infrared radiation.”

GWP is widely used due to its simplicity. The Kyoto Protocol uses GWPs over a 100-year time frame. This means that the emissions of methane and nitrous oxide are given by multiplying by GWPs of 21 and 310, respectively, the values given by IPCC (1996). Newer values however, are provided by IPCC (2007a), which are 25 for CH_4 and 298 for N_2O for the time horizon of 100 years and 7.6 for CH_4 and 153 for N_2O for 500 years. The formula for calculating GWPs is presented below:

$$GWP_i = \frac{\int_0^{TH} a_i * \left[C_i(t)\right] dt}{\int_0^{TH} a_{CO_2} * \left[C_{CO_2}(t)\right] dt} \tag{6}$$

where: *TH* is the time horizon over the calculation period (depending on climate mitigation policies and other factors), a_i is the radiative efficiency (W/m^2 kg), $C_i(t)$ refers to the time-dependent decay of abundance after the instantaneous release of one unit of gas *i*. The corresponding quantities for the reference gas (CO_2) are in the denominator. The numerator and denominator are called the absolute global warming potential (AGWP) of gas *i* and CO_2, respectively.

$$AGWP = \int_0^{TH} RF(t)dt \tag{7}$$

The GWP values are used to give the weights of different gases in relation to CO_2. On the basis of the GWP weights, e.g. the estimate of the greenhouse impact of a studied diesel chain is expressed in Carbon Dioxide Emission Equivalents (CO_2-eq.). The uncertainties of GWPs are assessed to be ±35% for the 5 to 95% (90%) confidence range (IPCC 2007a).

2.6 Comparison of the greenhouse impact assessment methods

Greenhouse impact assessment methods RF and GWP, previously introduced, are compared to each other. The advantage of RF is the dynamic presentation of the results, especially when the time horizon is long and the policy decision on climate change mitigation needs to be made. The RRFC method assesses the ratio of the energy absorbed into the Earth system due to the atmospheric concentration changes caused by the emissions of the considered fuel chain to the fuel energy produced in the chain. The GWP method assesses the greenhouse gas emissions of the considered fuel chain in terms of carbon dioxide equivalents.

The method based on GWP coefficients is very easy to use. Therefore, it is also very widely used. However, the present way to use GWPs does not give a dynamic picture of the greenhouse impact itself. At most it provides a dynamic picture of greenhouse gas emissions expressed in carbon dioxide equivalents. However, RRFC directly provides the cumulative greenhouse impact as a function of the cumulation time in relation to the fuel energy produced. RRFC also suits the situation where the emissions change over a relatively long time horizon of some tens of years or even longer. RRFC can also be quite easily extended to consider the energy balance of the changes due to changing albedo as a result of surface cover changes due to biomass raw material production. Furthermore, the new modelling work done for the IPCC new assessment report uses Radiative Forcing to describe various scenarios.

The following Figure 4 and Table 2 show a comparative analysis performed with GWP and RRFC. In Figure 4, the greenhouse impact of Jatropha diesel is studied. The time horizons are 100 and 300 years. The relative greenhouse impact is dependent on the assessment method used, but the differences are rather minor. The changes probably occur due to different parameter values in the atmospheric carbon removal models applied (IPCC 2007a, Monni et al. 2003). The largest difference between the RRFC and GWP results is in the share of CH_4. The surprisingly small differences between the results of these methods may be explained by the fact that both methods use Radiative Forcing, although in different ways.

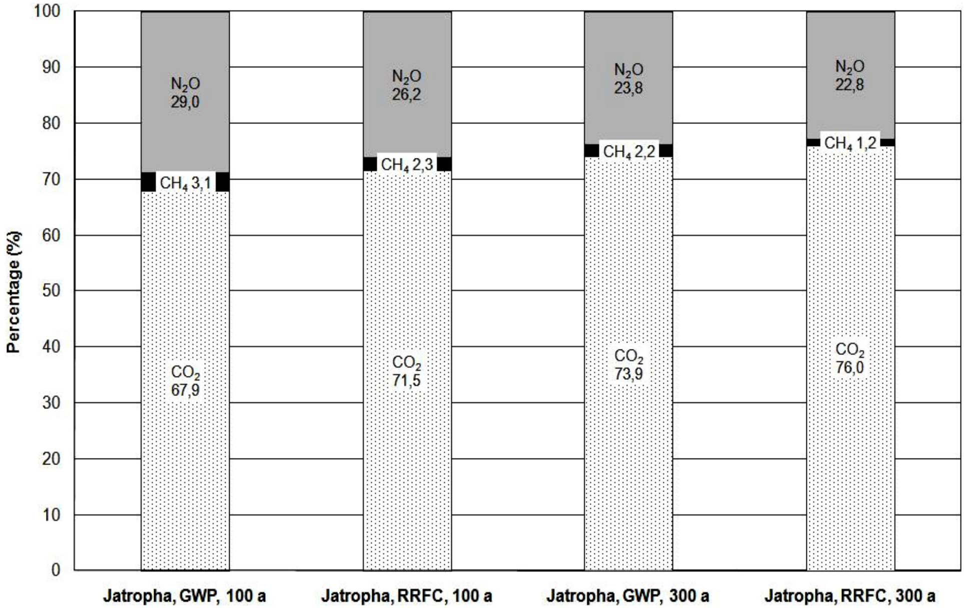

Figure 4. Example of the greenhouse impact by relative gas contribution due to Jatropha biodiesel assessed by GWP and RF on the basis of 100-year and 300-year time horizons (Paper III).

In Table 2 the results of RRFC and the GWP of different diesels were compared to each other, while fossil diesel acted as the reference base (100%), which allows the comparison of the impacts of Jatropha and biodiesels based on forest residues side by side from 100-year and 300-year time horizons. The GWP factors for the 300-year time horizon are linearly interpolated on the basis of the values for 100 and 500 years provided by IPCC. The main result is that in the case of biodiesel based on forest residues, the greenhouse impact assessed with GWP gives lower values than RRFC, both in the 100-year and 300-year time horizons. This is due to the simplified calculation with GWP which assumes carbon neutrality for forest residues, which is the prevailing practice. In the RRFC calculation, the more exact assessment of the emissions in burning and decomposing forest residues in the reference situation has been taken into account. In theory this can be done with GWP calculation by assuming the degree of carbon pooling of the logging residues. In the case of Jatropha-based biodiesel, GWP gives higher values of the greenhouse impact than RRFC (Paper III).

Table 2. The relative greenhouse impact of forest residues and Jatropha-based diesel compared to fossil diesel (100%) presented on the basis of 100-year and 300-year time horizons (Paper III).

	100 years	**300 years**
Forest residues, GWP	62%	61%
Forest residues, RRFC	74%	65%
Jatropha, GWP	70%	65%
Jatropha, RRFC	67%	63%

2.7 Methodology applied in the thesis

The overall goal of this thesis was to assess the greenhouse impact of different fuels. In this thesis, only the greenhouse impact is assessed; no other environmental impacts have been considered. LCA is used in order to provide a framework for the assessment and to help perform a systematic research. LCA has been used extensively for the greenhouse impact assessment of biogenic fuel production and use (e.g. Soimakallio et al. 2009, Edwards et al. 2003, Sokka et al. 2005, Savolainen et al. 1994). Cherubini et al. (2009) raises some key issues concerning the greenhouse gas-based LCA of biofuels and bioenergy systems. Even though similar bioenergy systems are compared, there may be differences in the results due to several reasons: type and management of raw materials, conversion technologies, end-use technologies, system boundaries and reference energy system with which the bioenergy chain is compared. These uncertainties concerning LCAs are discussed in chapter 3.3.

The goal and scope of the thesis was stated in the introduction chapter: assessing the climatic sustainability of different fuels as well as presenting a new approach to interpret the greenhouse impact (RRFC). The inventory analysis is the next stage of performing the LCA of a product or function. In the greenhouse impact assessment, inventory analysis includes the listing of all GHG emission sources and sinks according to the life cycle phase and parameter. The results of the greenhouse impact of assessed fuels are compared to each other and especially to fossil fuels to be able to see the saving in greenhouse gases. The LCA performed in this thesis can be seen as one kind of simplification of LCA. Streamlined LCA focuses on the key elements of the assessment while identifying the elements that can be omitted or using generic data without significantly affecting the accuracy of the results. Thus, the purpose of the simplified LCA and how it is conducted needs to be clearly stated in the goal and scope definition process (Weitz and Sharma 2006). A comprehensive LCA of biogenic fuels and assessment of non-climate impacts (e.g. impacts on ecosystem quality and resources) has been conducted e.g. by UNEP (2009).

Recent developments in LCA have been studied by Finnveden et al. (2009). Finnveden et al. emphasize that even though improvements have been made in several areas in LCA methodology, there are also many areas in which further development would be useful. One area recognised is the method for assessing impacts on the ecosystem from land use. Currently, there is no agreement on how these impacts should be included in an LCA. In this thesis the impacts of land use and land use changes due to human activities have been included due to the special character of fuel production reserve. Especially in land areas where the impact on the atmosphere is strong, e.g. peatlands, the impact of land use need to be included in order to determine the realistic impact on the atmosphere.

A simplified example of the stages of the life cycle of peat-based Fischer-Tropsch diesel is presented in Figure 5. This example shows the complexity of the LCA. Definition of the system boundaries is a difficult task, since the life cycle may be very complex and there are several critical issues influencing the product life cycle. In the example case of peat-based FT diesel, introduced in Fig 5, the utilisation chain including the production and use of peat diesel is quite straightforward. Including after-treatment of the utilised peatland makes the assessment more difficult, as does the inclusion of the reference situation I_R (non-utilisation case, where peat layer decays and produces greenhouse gas emissions), when longer time periods considered in the assessment increases the uncertainty range. These are discussed more deeply in the following chapters.

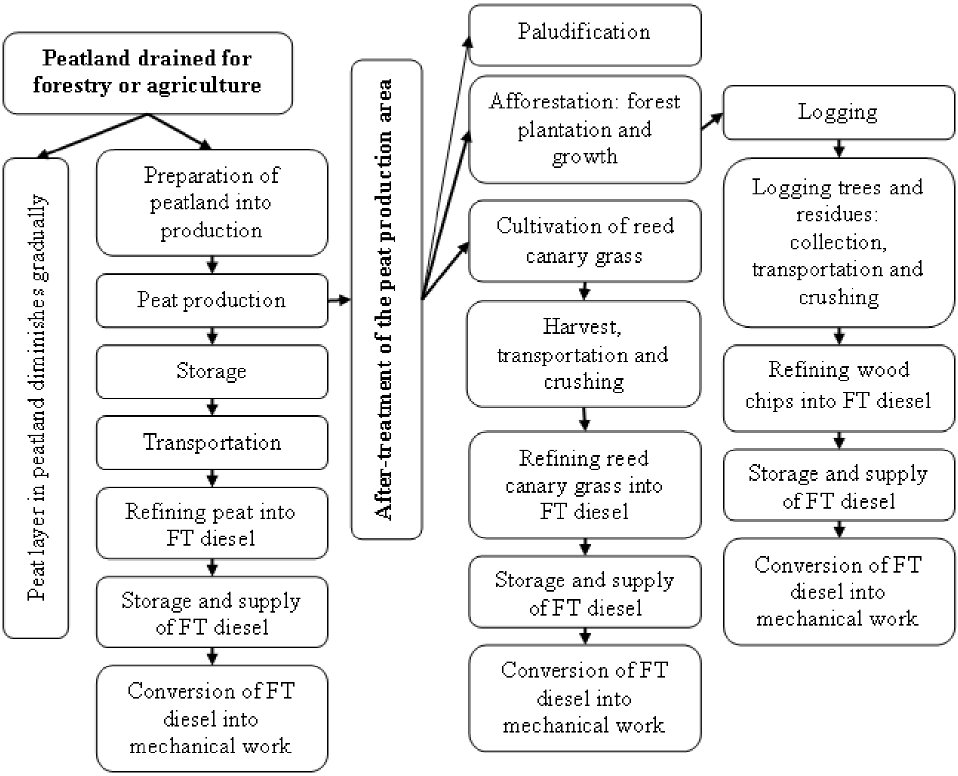

Figure 5. Example of the simplified life cycle stages of peat-based FT diesel. The assessment can be complicated, since it can include different after-treatment alternatives for the utilised land (e.g. in this example there are three different alternative life cycles) and also the impact of not utilising the resource. In addition, it is important to define the system boundaries (Paper IV).

3. Main results of greenhouse impact assessment related to combustible fuels

This chapter introduces main results of the greenhouse impact assessment of biogenic fuels. Greenhouse impact assessment was mainly implemented by using radiative forcing together with life cycle assessment. Some results are shown in chapter 3.1 in order to provide an understanding of the methodology. The role of the different stages of the greenhouse impact assessment is discussed due to the contribution of these stages, which may differ largely. The role of the uncertainty analysis is introduced and examples of the uncertainty analysis made are presented. Two examples of the calculations are provided in order to give a deeper understanding of the concrete assessment.

3.1 Radiative forcing in the greenhouse impact assessment

Radiative forcing enables a dynamic assessment of the greenhouse impact. An example of instantaneous impact assessment is presented in Figure 6. The life cycle of e.g. peat fuels includes many stages, depending on the system boundaries. During the first 20 years, most of the emissions occur (peat fuel production and combustion), which can be seen as a peak in the instantaneous greenhouse impact (chains 1–4). After peat utilisation, the bottom of the peatland is after-treated by e.g. restoration or afforestation. The decrease in the instantaneous radiative forcing is due to the carbon cycle: carbon transfer from the atmosphere to the oceans and sequestration into growing biomass. If the assumptions are changed, for example in the chains 5–6, where the combustion of peat occurs in the first year among others due to more efficient peat production methods, the instantaneous impact is by far the largest in the beginning, but starts to decrease at a faster rate than in the other chains.

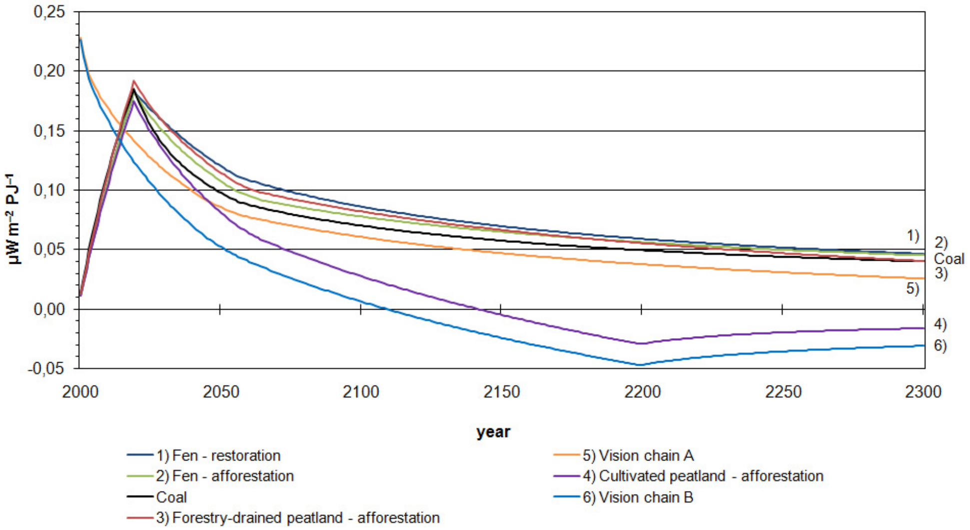

Figure 6. Example of the instantaneous radiative forcing of different peat fuel chains as a function of time. Coal chain produces the comparative perspective (Paper I).

The instantaneous radiative forcing helps in understanding the nature of the assessment and the time scale of the occurring emissions. However, the cumulative impact shows the integrated impact over a certain time period, e.g. the overall impact 100 years since the beginning of production and utilisation of the peat fuel (Figure 7). In the long time periods it represents the most illustrative presentation, since the total impact is dependent on the time period considered. Radiative forcing enables the dynamic presentation of greenhouse impact as a function of time. Especially in cases where land use and land use changes are taken into account, the emissions occur over long time periods. The cumulative presentation of greenhouse impact can be used in interpreting the greenhouse impact of different climate policies related to different time horizons. Clear visualization of the phenomenon helps one to understand the impact, while comparison with the other fuels is provided in order to understand the relative difference. For example, Figure 7 introduces the cumulative greenhouse impact of some peat fuel chains as well as coal. During the first 100 years, which is a relevant time horizon, if global warming is to be halted at 2 or 3 °C, the impact of peat is roughly the same magnitude as the greenhouse impact of coal (except chains 4 and 6, where different peatland is used).

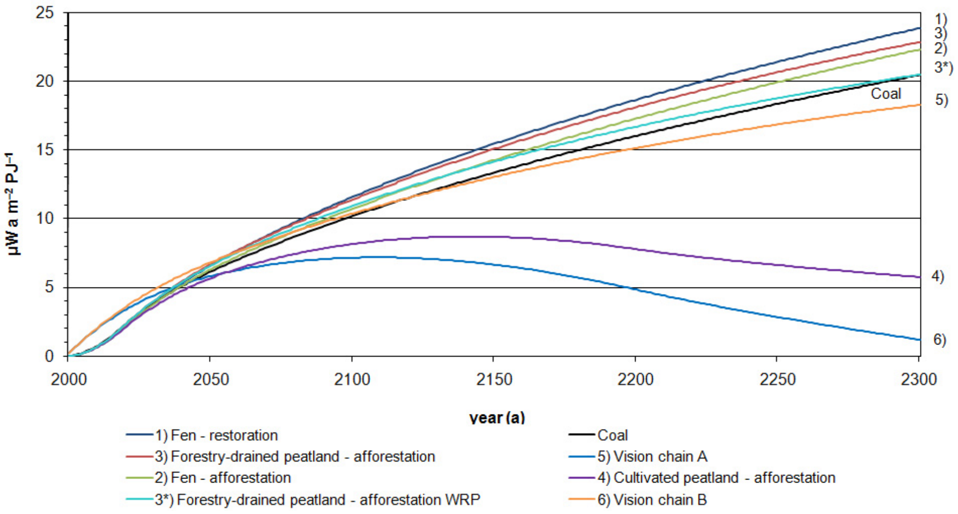

Figure 7. Example of the cumulative radiative forcing of different peat fuel and coal chains. The results show the integrated forcing impact over the assessed time period as a function of time (Paper I).

3.2 The role of the different life cycle stages of the greenhouse impact assessment

The greenhouse impacts of different fuels should be studied from the life cycle perspective since there are stages other than just combustion, which may make a relevant contribution to the total greenhouse impact, especially in the case of biomass-based and non-fossil fuels. When the greenhouse impact of forest residues and peat were studied, the contribution of parts of the life-cycle other than combustion can be as much as 90%, either adding to or decreasing the total impact.

The greenhouse impact assessment of fossil fuels (natural gas, coal and fossil diesel were assessed in this thesis) is rather simple due to the fact that emissions in the reference situation are zero ($I_R = 0$). The uncertainty of the assessment of fossil fuels is relatively low compared to the uncertainty of biomass-based fuels, where the assessment is more complicated and may include factors not as well known (e.g. the N_2O emissions from the manufacture and use of fertilizers). The role of the different stages of the life cycle is especially emphasized when the fuels are refined further (e.g. Fischer-Tropsch diesel), where many input flows have to be taken into account. Also, the emissions and sinks of land use and land use changes need to be taken into account. According to Searchinger et al.

(2009), the accounting of bioenergy for the Kyoto protocol is erroneous. The current accounting treats bioenergy as carbon neutral even thought there can be emissions when biomass is harvested or grown. Thus the potential of bioenergy to reduce emissions strongly depends on the source of the biomass and its net land-use impacts. The impacts of the land use have been included and discussed in the thesis.

An example of the peat-based Fischer-Tropsch diesel greenhouse impact assessment is presented in Figure 8. The impacts of different stages are shown. The time horizon of the impacts is 100 years. The largest contributor to the impact is due to production, refinement, and utilization of peat diesel. This phase includes peat production (e.g. harvesting machines, storage), refinement, storage and supply of peat diesel, end-use (direct emissions from peat diesel use) and losses in the process. In particular, refinement has a large greenhouse impact since it is an energy-intensive phase. Changes in land use also have a large impact. In this example the avoided greenhouse impact of the utilized peatland (in this case agricultural peatland, which has strong emissions) reduces the total impact by about one fifth over the 100-year time horizon. In this example also the after-treatment of the utilized peatland has been taken into account. However, while afforestation is considered to be the after-treatment of choice, the impact is in fact neutral. The emissions from producing and using diesel based on logging residues neutralize the cooling impact of the carbon sequestration in the wood biomass. It should also be noticed that since this example shows the greenhouse impact from the land-use perspective, taking into account the energy production from a certain area, the total greenhouse impact is assessed, including diesel based on both peat and wood biomass produced on the site over 100 years (the share of peat diesel is 90% and share of wood biomass diesel is 10%) (Paper IV).

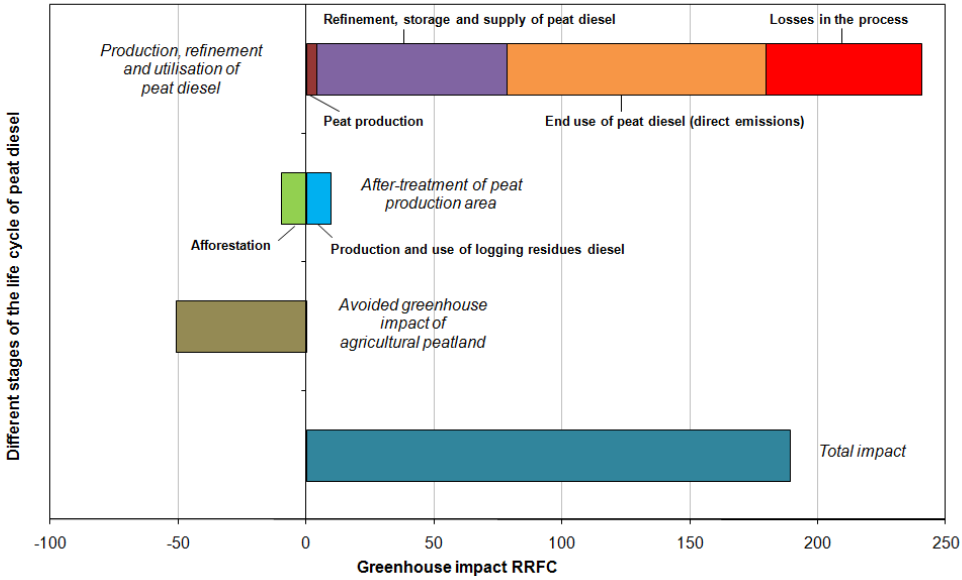

Figure 8. Example of the different stages of the life cycle of peat-based FT diesel. The contribution of different steps other than just the direct emissions from peat diesel use have a large impact. Also the impact caused by land use and land use changes has been taken into account (Paper IV).

3.3 Uncertainties in the greenhouse impact assessment

Uncertainties may exist in the greenhouse impact assessment for many different reasons. Huijbregts (2001) has studied the uncertainty and variability assessments of LCAs comprehensively. Huijbregts presents a framework for addressing the uncertainty and variability, of which the following types of are recognized: uncertainty related to parameter, model, uncertainty due to choices, spatial, temporal and variability in objects/sources. Recognizing the type of the uncertainty and/or variability enables one to use the best tools for dealing with them.

In the examples calculated in this thesis, the functional unit was chosen to be the energy unit (J), which was the same as in the assessment of different fuels in order to preserve comparability. The largest uncertainties arose from the greenhouse emissions and sinks in different stages of the life cycle. This is recognized in the inventory phase. The system boundaries are one important aspect causing sensitivity in the results. Alternative boundary selection was used in this thesis to show the importance of different alternatives. Different system boundaries were applied in the example cases in the thesis, e.g. for after-treatment of the bottom of peatland in the case of peat fuel and peat-based diesel. Also, the emissions of electricity production have been considered in two different ways in the assessment of FT diesel refinement.

There is uncertainty in the calculation models, which is discussed in the chapters dealing with the models (chapters 2.2 and 2.3). However, when all the same calculation models (either RF or GWP) are used in the assessment, the uncertainty of the models does not necessarily have any effect, since all the results may have the same bias. There is also uncertainty due to the temporal variability e.g. of greenhouse gas fluxes from managed or unmanaged ecosystems like peatlands or agricultural lands. The greenhouse impact has been assessed for long time periods and for different time horizons. The uncertainty increases over longer time horizons. The continuance of the reference situation I_R over 300 years is rather theoretical. The assessment of greenhouse impact for fossil fuels is done without complicated analysis since the impact of the reference situation is zero ($I_R = 0$). Since the climate change mitigation targets aim at reducing emissions, which mainly occur from fossil fuel use, the calculation of the alternative fuels also needs to be more accurate and clear. Therefore, more information is needed, especially from the land use emissions and sinks, in order to reduce the overall uncertainty.

Two examples are presented where the parameter uncertainty has been assessed (Paper IV, Paper II). In Figure 9 the uncertainty is presented for different stages of six different chains. In Figure 10 the uncertainty is presented for these same chains, however, now paying attention to the uncertainties of the impacts over different time horizons. The uncertainties of the different stages of fossil fuels are the lowest due to e.g. the combustion emissions factor. Also, the impact of the reference stage is zero ($I_R = 0$), which then does not have an impact on the total result. The largest uncertainties are related to land use. The emissions from the peatlands are not accurately known. Also, the impact of the production phase has some uncertainties, especially when cultivation occurs (in the case of reed canary grass, chain 1).

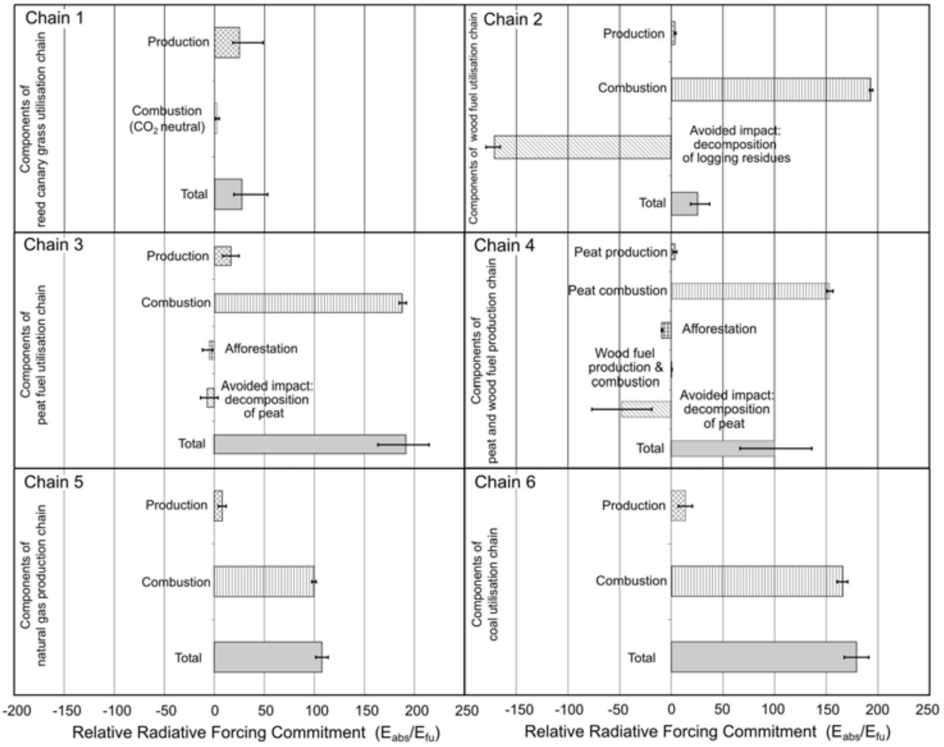

Figure 9. Example of the contribution of different stages in greenhouse impact assessed with RRFC over a 100-year time horizon. The largest contribution is due to combustion in most cases (except chain 1; considered as carbon-neutral due to short rotation time of carbon). The combustion phase has the lowest uncertainty due to the well-known combustion emission factors. The largest uncertainties are related to land use and forestry, especially avoided impacts of peatland use as well as the production phase (especially in the cultivation of reed canary grass, chain 1). In chain 3 peat is produced from forestry-drained peatland, which is a modest source of GHG emissions. In chain 4 peat is produced from cultivated peatland, which is a significant source of GHG emissions, so the avoided impact lowers the total impact of the chain (Paper IV).

Uncertainty also exists due to the long calculation horizons. Figure 10 presents the uncertainty of different fuels chains over 20, 100 and 300 years. It can be noticed that the uncertainty increases with time. It should also be emphasized that the continuance of the emissions from land use for such a long time as 300 years is rather theoretical. The assessment is more accurate when shorter time periods are considered. The reed canary grass, forest residues and peat fuel chains have the largest uncertainties, while coal and natural gas have the lowest uncertainties. Relatively largest uncertainties compared to the total impact are from the reed canary grass forest residues over 20 and 100 years. However, the impact of the peat fuel produced from cultivated peatland has the largest uncertainty over long time horizon due to the uncertainties in the reference situation, as can be seen from Figure 9.

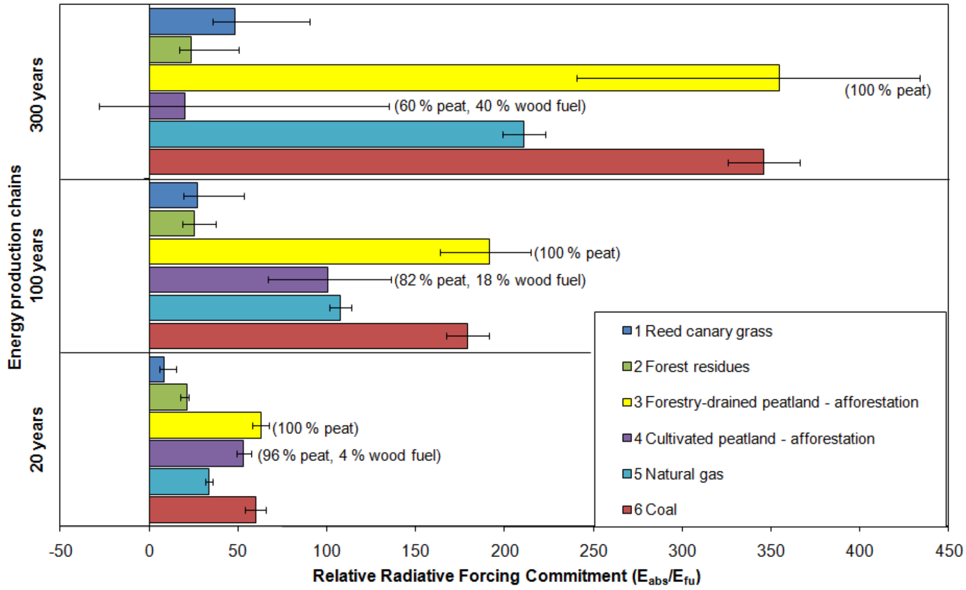

Figure 10. Example of greenhouse impacts of different fuels over 20, 100 and 300 years (theoretical). The vertical lines represent the uncertainty of the impact. The uncertainties grow over time (Paper II).

3.4 Examples of the calculation

In this chapter two examples of the greenhouse impact calculation are presented in order to bring up the issues considered in the thesis. Some of the key issues are the dynamic assessment of the greenhouse impact, the contribution of life cycle stages other than those causing direct emissions, and showing the results by using the new interpretation method RRFC.

3.4.1 Peat-based Fischer-Tropsch diesel

Peat has been used for energy purposes for at least 2000 years. It has been used for cooking and heating especially in the temperate and boreal regions of Europe (Strack 2008). In Finland the use of peat in energy production in recent years has been approximately 6% (Statistics Finland 2009). It has also been considered as a new raw material for diesel production by gasification and Fischer-Tropsch (FT) synthesis. In this example the peat is produced either from forestry-drained or cultivated peatlands, since these areas are both sources of greenhouse gases (forestry-drained peatland is a moderate source of CO_2 and N_2O emissions, cultivated peatland is a significant source of CO_2 and N_2O emissions and modest of CH_4). The peat raw material is assumed to be produced from the site in one year. Peat production also causes emissions from working machines. Peat also decays in peat production fields and storage, causing emissions. Peat is assumed to be produced either by traditional milled peat production or by using the new peat production technique (biomass dryer) which is based on a more efficient process that produces less emissions (Silvan et al. 2008). The advantages of using new technology are: less GHG and dust emissions, the possibility of after-treating the excavated area immediately, and utilisation of all the peat according to the shapes of the bottom soil of the peatland.

After the peat is produced, it is stored and transported to refineries, where it is processed initially as FT primary liquids and subsequently as FT diesel. Refining peat into diesel and the end use of peat diesel also cause emissions, especially through the consumption of electricity. In those areas of the FT diesel production process where the use of electricity is intensive (crushing and refining), it has been assumed that the total electricity consumption increases in Finland due to the new operation. Increased electricity consumption is assumed to be met by using more marginal electricity. This means electricity which is produced by the power plants in the electricity system that are used to meet additional demand. In the Nordic electricity network marginal electricity is produced by coal-fired condensing plants most of the time (Soimakallio et al. 2009).

The after-treatment of utilised peatland also has an impact on the results. Different after-treatment options are introduced: afforestation, cultivation of reed canary grass and paludification. In some cases (chains 6–8, 10–11), it was assumed that the peatland is after-treated following peat production and the produced biomass used for the production of FT diesel. In chains 4 and 9 only the production of peat has been considered and the carbon stock changes due to the after-treatment is accounted for (e.g. increase in carbon stock due to forest growth over long time horizons due to sequestration of carbon into growing biomass and accumulation of surface and underground biomass). The stages of LCA were presented earlier in Figure 5. Also, the greenhouse impacts of fossil diesel and FT diesels based on forest residues and reed canary grass are provided for comparison and in order to be able to assess the relative greenhouse impact. More detailed information about the emissions is presented in Paper IV.

The results are presented in Figure 11 by using RRFC. If peat is used for a raw material for FT diesel, it has an approximate greenhouse impact ranging from 190 to 300 RRFC over 100 years, depending on the production site, production technology and after-treatment boundaries. This means that the energy produced from the use of peat diesel will warm the globe by 190 to 300 times compared to the energy gained from the fuel use. Diesels based on forest residues and reed canary grass cause the lowest greenhouse impact over the 100-year time horizon resulting in around 120 RRFC. Fossil diesel causes a RRFC of about 150. If theoretical time horizons (until 300 years) are considered, the greenhouse impact of peat and wood diesel produced from cultivated peatland with new peat production technology (NP) (chain 10) would start to decrease after 140 years and would have an even lower impact than diesels based on forest residues and reed canary grass.

The results for the long time horizon have less relevance, because the climate change mitigation targets pertain to time horizons of 100 years and less, and the reductions in greenhouse gas emissions need to occur relative soon. However, it is also important to acknowledge that there are very long term impacts. Results from 300-year time horizon illustrate the long-term behaviour of the phenomena. They can be highly uncertain, but they are not just theoretical (Solomon et al. 2009, Archer and Brovkin 2008). These raise important long-term intergenerational ethical issues, and ultimately should play a role in policy decisions; Figure 11 points towards this with the different trajectories by years 250–300 in the dynamic cumulative greenhouse impact.

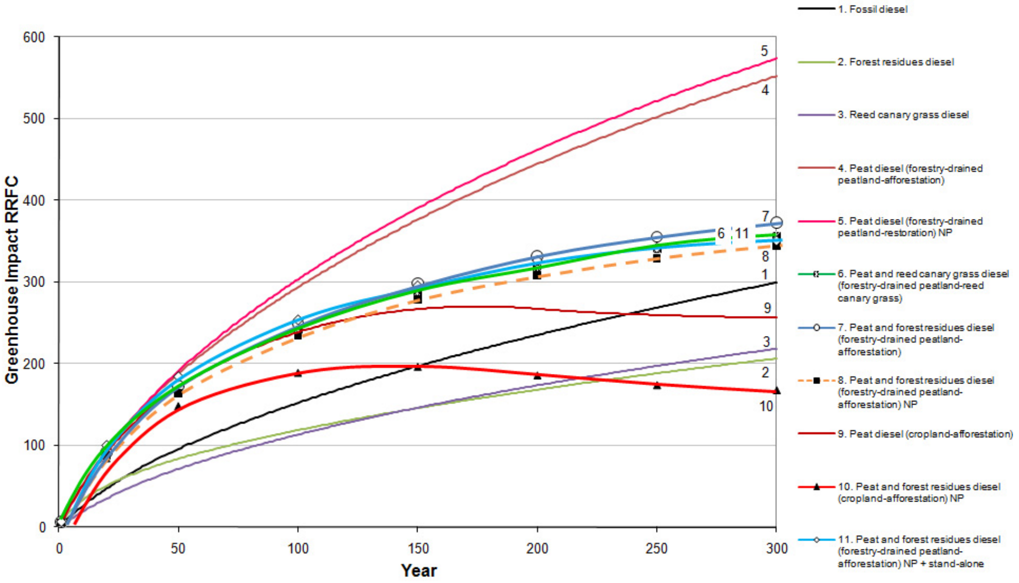

Figure 11. The dynamic cumulative greenhouse impact of different transportation fuels assessed in the study for a time horizon up to 300 years. The electricity used in the fuel processing is assumed to be marginal (generated by power plants in a marginal position in the Nordic electricity system), which has a major impact on the total greenhouse impact. In chains 6–8 and 10–11 the share of peat produced in the chain decreases as a function of time, since the longer time of after-treatment leads to larger production of renewable biomass (Paper IV).

3.4.2 Forest residues

The energy use of forest residues is increasing due to the rising price of oil and policies aimed at reducing GHG emissions. Forest residues are an ideal potential source of energy since that biomass is not otherwise utilized. In 2007, wood-based fuels accounted for one fifth (295 PJ) of total energy consumption in Finland, including industrial waste liquors (mainly black liquor produced by pulp industries) and solid wood fuels. Solid wood fuels are further divided into wood fuels consumed by heating and power plants and fuel wood consumed by small-sized dwellings for heating. A total of 137 PJ (19.2 million m^3) of solid wood fuels were consumed, with heat and power plants accounting for 89 PJ (13 million m^3) of the total (Finnish Forest Research Institute 2008). The total potential for producing forest residues in Finland in the year 2010 is assessed to be about 86 PJ (includes forest residues, stumps and small firewood) (Mäkinen et al. 2006).

Forest residues are usually collected from the final fellings, and recently the collection of stumps for energy has also increased. The stages of the forest residue fuel chain are bundling of logging residues (to lower transportation costs), transportation from the forest, chipping, long-distance transportation, transportation of work machines, and crushing. These stages are sources of emissions either directly or indirectly (e.g., crushing needs electricity, so the emissions of electricity production have been evaluated). Forest residues (also called logging residues) have also been recognized as a suitable raw material for Fischer-Tropsch diesel. The advantages of using forest residues as a raw material are that they do not affect the use of cultivation land and do not take land away from food production.

When using forest residues for energy, it results in CO_2 emissions earlier compared to the reference case (I_R), which is the decay of the forest residues on the forest floor, resulting in CO_2 emissions as a function of time. The decay of the forest residues has been calculated using a soil carbon model called YASSO (Liski et al. 2005). The decay of the residues is presented in Figure 12. The remaining carbon stock is presented as a function of time. Logging residues decay very quickly during the first 20 years. Later on the decay process slows down, with some non-decayed material possibly remaining still after 300 years (Paper II). Using RF in the assessment, the time-dependant factors of the greenhouse impact calculations (such as decay of the residues if not utilized) can be taken into account and the total impact can be presented as it would occur. The total impact of fuel based on forest residues is presented in Figure 13 in the next section. If the residues are collected and used for energy, the avoided impact of the decayed residues is nearly offset.

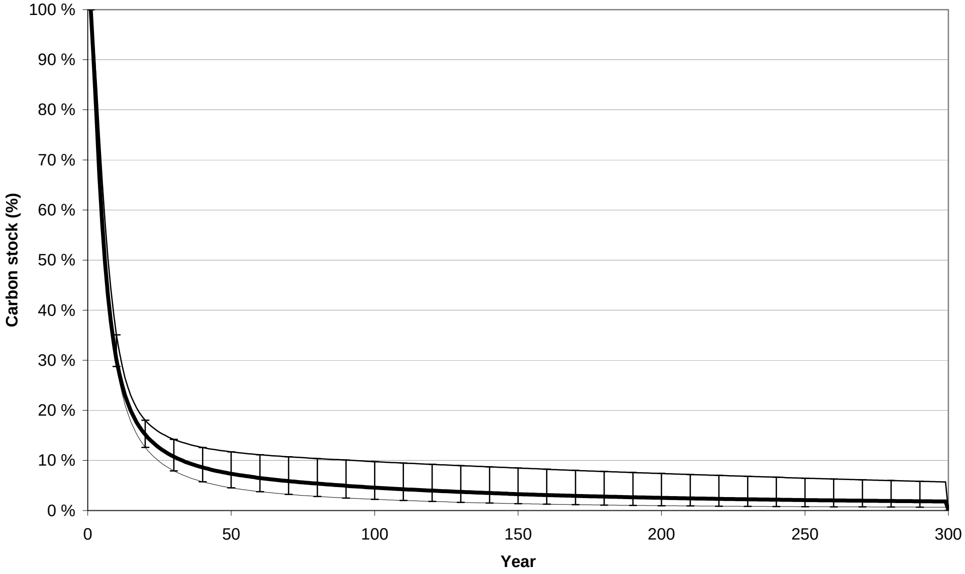

Figure 12. The remaining carbon stock of forest residues as a function of time in Finland (reference situation (I_R) for forest residues FT diesel case) (Paper II).

3.4.3 Overview of the greenhouse impact of some combustible fuels

This chapter presents the results of the greenhouse impact and climatic sustainability of some assessed fuels compared to each other (Figure 13). The fuels considered are forest residues, reed canary grass, natural gas, coal, and peat (produced from forestry-drained peatland or peatland in agricultural use; in both cases the after-treatment is afforestation). The uncertainty of the impact is represented by the vertical lines. The lowest greenhouse impact is from the use of forest residues: the assessed RRFC varies between 20 to 40 in 100 years, causing a warming impact which is 20–40 times the energy produced in the fuel chain. Reed canary grass has a slightly higher greenhouse impact than forest residues. The CO_2 emissions from the combustion have been assumed to be zero due to rapid sequestration of carbon in the new yield, although CH_4 and N_2O emissions from combustion remain. In the case of reed canary grass the production phase has the largest impact compared to the impact of the production phase of other fuels. This is due to fossil energy use in fertilizer manufacture and agriculture, as well the N_2O emissions from fertilizer manufacture and use of fertilizer in agriculture. The RRFC of reed canary grass varies between 20 to 50 in 100 years.

The uncertainty for reed canary grass is higher due to the poorly known N_2O emissions from the manufacture and use of fertilizers.

The RRFC of fossil fuels were assessed for natural gas and coal. The RRFC of natural gas was assessed for the natural gas use in Sweden, since no reliable data for natural gas transported and produced from Russia, from where natural gas is delivered to Finland, was available. The RRFC for coal was assessed based on the information in Sokka et al. (2005) for Polish coal use in Finland. The RRFC for natural gas is approximately 100–110. The CO_2 emission factor of the combustion of coal (94.6 g CO_2/MJ) is remarkably higher than that of natural gas (56.5 g CO_2 /MJ). Thus, the RRFC of coal is about 170–190. The highest greenhouse impact of the presented fuels in Figure 13 is from the use of peat, which is produced from forestry-drained peatlands and the utilised area is after-treated by afforestation. The CO_2 combustion factor of peat is relatively high (105.9 g CO_2/MJ) compared to other fuels. The avoided greenhouse impact of the reference situation (forestry-drained peatland) somewhat reduces the total impact. However, the decomposition of peat in the forestry-drained peatlands is slow and over 100 years it reduces the total impact of 190 RRFC (160–220) by only less than 10 units. Also, the production and after-treatment have some impact on the total RRFC. See more detailed figures in Figure 9, chain 3.

The use of peat fuel harvested from agricultural peatland causes somewhat a lower greenhouse impact than peat from forestry-drained peatland. The RRFC of peat produced is approximately 130 (uncertainty of 100–160). The uncertainty in the case of agricultural peatland is large due to the variability of the reference case emissions. The present peat fuel production has practically no contribution from agricultural peatland. Most of the peat fuel (ca. 75%) is produced from forestry-drained peatlands (Selin 1999). The greenhouse impact of peat fuel from natural peatlands (especially fens) is about the same or larger than that from forestry-drained peatlands (Paper I).

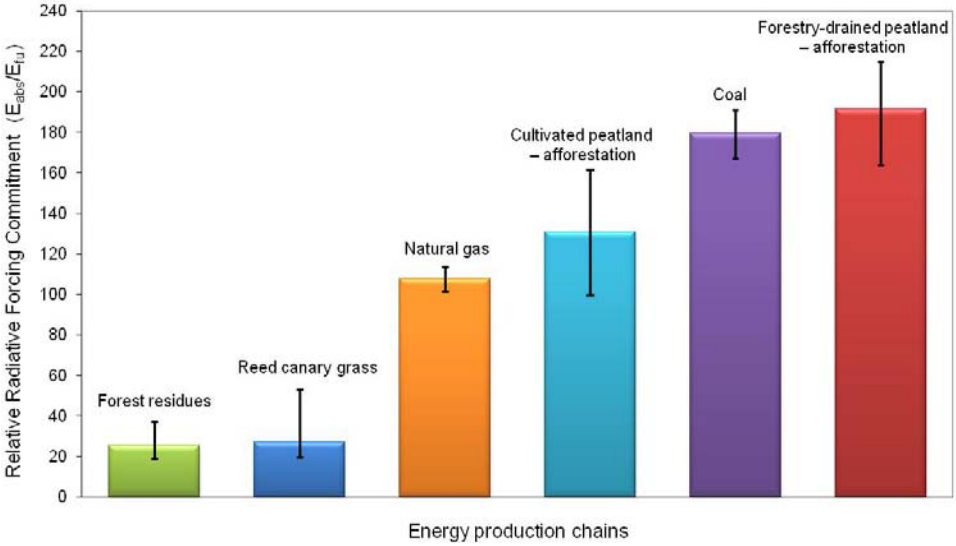

Figure 13. Greenhouse impact of different biogenic fuels assessed for the 100-year time horizon. The lines represent the uncertainty of the total impact. Fossil fuels, natural gas and coal have the lowest uncertainty due to the well-known combustion factor. The relative uncertainties of forest residues and reed canary grass are the largest. The uncertainties for peat chains are also considerable, especially in the case where peat is produced from cultivated peatland.

4. Discussion and conclusions

The discussion and evaluation of the results presented in this study are divided under four topics: evaluation of the used methods, discussion over biogenic fuels and climate change, contribution of the study and conclusions. The conclusions are based on the results and the aims pursued in this thesis.

4.1 Evaluation of the used methods

The RF assessment method is suitable for a greenhouse impact assessment in which the emissions and sinks occur over some period of time. Especially in the case of the fuels where the assessment includes emissions from land use or land use changes, a clear and transparent assessment can be achieved by using radiative forcing. GWP is a simplified metric to assess the greenhouse impact in the case where emissions and sinks take place over a relatively short time period and the dynamics of the greenhouse impact are not of interest. This is often the case for many goods and services. Thus, the GWP method does not give a dynamic picture and the uncertainty can be relatively high compared to RF. RRFC is a dimensionless ratio that assesses the greenhouse impact and absorbed energy in the thermodynamic system of Earth versus the produced energy. RRFC is a new interpretation tool, developed in this study, which allows the development of the results to be illustrated in dimensionless units. RRFC can also be used for addressing possible albedo changes, which can be relevant in some biogenic fuels cases. The time dependency of the climate impacts as well as the extent of the impacts is possible to present with radiative forcing. This can be important information for different future greenhouse gas reduction pathways if exceeding 2 °C global warming is not allowed during certain time periods (e.g. until 2100).

Also another new interpretation method has been proposed. GWP is widely used due to its simplicity; however, it has been criticised for not showing the real contribution to climate change (UNFCCC 2009b). A new metric called Global Temperature Potential (GTP) is further discussed to replacing or augmenting GWP (IPCC 2009, UNFCCC 2009b, Shine et al. 2005, Meira Filho and Gonzalez Miguez 2000). However, definitions and calculation formulae have not yet been finally accepted and also the benefits of GTP are still uncertain. The metric is planned to be assessed in the IPCC 5th Assessment Report to be published in 2013.

The role of metrics is increasing since greenhouse gas reductions need to be clearly shown in the most comprehensive and accessible way. The metrics need to be simple, but they must also be comparable and sensitive to changing parameters. The metrics need to be clear and they must illustrate the relevance of the impact. The role of different metrics is also increasing since the monitoring and reporting of the emissions of different products and services are getting more common. Not only at the national level but also in business, estimation of the carbon footprint has become an important tool of companies and organizations in assessing the greenhouse impact of their products or services.

LCA was used in order to provide a framework for the assessment. LCA is a widely used and well-known tool. However, it does not give detailed guidelines on how the greenhouse impact assessment should be made. LCA is a tool providing only a common level of instructions. Thus the LCA needs to be clearly documented to maintain transparency and replicability of the assessment. Normally, when the greenhouse impact of a product or service is assessed, the emissions occur in a relatively short time period and the distribution of emissions and sinks within that short time period is not interesting. The considered time horizons in this thesis are 20, 100 and 300 years. However, the 300-year time horizon is rather theoretical and for scientific purposes only. If global warming is to be halted at 2°C, the emissions need to peak and start to decline during 2000–2015 and need to be reduced by 50–85% by 2050 (IPCC 2007c), which suggests a relatively short time horizon for decision-making purposes. The goals of climate change mitigation are decided by policymakers, who need tools to assess the climatic sustainability of energy alternatives for effective mitigation strategies. If longer time horizons are considered, the question of how much warming is allowed must be asked.

4.2 Discussion over biogenic fuels and climate change

The potential role of biogenic fuels in climate change mitigation is large (e.g. IPCC 2007c) and therefore the assessment of their sustainability has a major role. This thesis presents some issues concerning the greenhouse impact assessment of the discussed fuels. The fuels assessed were peat, coal, forest residues, reed canary grass and different diesel: Fischer-Tropsch diesels based on peat and forest residues, Jatropha diesel and fossil diesel. As stated earlier, biomass-derived fuels are often considered to be “carbon-neutral” and are seen as one option for mitigating climate change. This has prompted a lot of discussion on whether it is a false term and whether biogenic fuels should be considered neutral in terms of their greenhouse impact, since there are emissions from production as well as e.g. changes in the carbon stock of land use (Fargione et al. 2008, Melillo et al. 2009, Kendall et al. 2009, Johnson 2009). This thesis shows the impacts of different fuels and all of them have a positive greenhouse impact of different magnitudes.

When, then, should biomass-derived fuels be considered sustainable? The sustainability criteria of the European Union are currently the following: the savings of the greenhouse gas emissions from the use of biofuels and bioliquids need to be at least 35% and at least 50% after 2017 compared to fossil fuels (EU 2009). The savings need to be clearly and transparently proven. Time horizons were discussed in the previous chapter. The saving in greenhouse impact, however, depends on the time horizon. If the 100-year time horizon is considered, only forest residues and reed canary grass fulfil the required GHG emission savings compared to coal, although the EU criteria are meant for liquid transportation biofuels.

The role of the reference situation in the final results is large in the peat fuel chains. Recent published studies of biomass-based fuels have underlined the need to develop the assessment of the greenhouse impact of biofuels. Changes in land use should be considered as well as the emissions. In some cases of increased demand for land (e.g. Jatropha), the emissions from the utilized land specify all the emissions and sinks (Melillo et al. 2009) to a large extent.

While moving towards the low-carbon society and using less fossil fuels, the assessment of the greenhouse impact of different energy sources will be even more important. System boundaries and the recommendations of the calculations will be even more relevant than today. Depending on the assumptions made, the outcome may be quite different. For example, when electricity is used for the refining process as in FT diesel, the emissions from electricity production should be considered by taking into account the behaviour of the electricity production system, including the operation of electricity markets. System boundaries were one of the key elements when assessing the sustainability of different fuels. The uncertainty and sensitivity of the results has been discussed in chapter 3.3, where the most relevant sources of uncertainty in this study were considered. In practice, however, simplifications need to be made. Also the changing climate may change the parameter values used in the papers of the thesis.

4.3 Contribution of the study

The new scientific contribution of this thesis, and the four papers included into it, is a new dynamic assessment method called Relative Radiative Forcing Commitment (RRFC) for the greenhouse impact and its application to some combustible fuels. The greenhouse impact assessments using the LCA approach in this thesis are exceptional, since the dynamics of the impact are considered. The consideration of land use reference is also new and exceptional. An important result is also that the greenhouse impact of slowly renewing biogenic fuels is shown to be considerable. This thesis adds to the knowledge of some not widely known fuels, e.g. peat fuel and peat-based Fischer-Tropsch diesel.

However, science is never ready. New theories, approaches, measurements and falsifications of theories advance the science (Popper 1959). This thesis shed light on the latest information on the emissions and sinks related to the life cycle of biogenic fuels, applying the greenhouse impact assessment methods currently considered most appropriate for the purpose on the basis of best knowledge. However, the greenhouse impact assessment should be made again, when new information is available.

4.4 Conclusions

Climate change mitigation requires strong cuts in global greenhouse gas emissions over a short time horizon. This thesis assesses the greenhouse impact of different combustible fuels and considers their climatic sustainability. This thesis also provided a new accessible tool for illustrating the results called Relative Radiative Forcing Commitment (RRFC). The greenhouse impact was assessed by using radiative forcing, and a comparative assessment was made by using global warming potentials, which are the simple way to assess the greenhouse impact. However, in order to be able to calculate the warming impact as a function of time, and if the emissions occur over a long time period, greenhouse impact assessment methods based on the use of RF give more accurate time-dependent results.

If global warming is to be halted at 2 to 3 degrees Celsius, deep emission reductions will be needed in the coming decades and the use of fossil fuels must be replaced to a large extent by energy sources with a lower greenhouse impact. The lowest greenhouse impact of the combustible fuels considered in this study is from the use of forest residues: the RRFC assessed over the 100-year time horizon varies between 20 to 40, causing a warming impact which is 20–40 times the energy produced in the fuel chain. In the scenarios in the Foresight Report on Long-term Climate and Energy Policy by the Government of Finland, forest energy remains clearly the most important source of renewable energy (Prime Minister's office 2009). Increase in the use of forest residues is justified based on the results of this study. Reed canary grass has a slightly higher greenhouse impact than forest residues (between 20 to 50). The RRFC of fossil fuels were also assessed for natural gas and coal. The RRFC for natural gas is approximately 100–110. Thus, the RRFC of coal is about 170–190. The highest greenhouse impact of the presented fuels is from the present way of peat fuel use, based on utilisation of peat from forestry-drained peatlands, resulting in a total impact of 190 RRFC (160–220). However, if cultivated peatland is used for peat production, the impact is somewhat lower due to large emissions in the reference case. Important factors contributing to the results and their uncertainty are the system boundaries and the models used in the studied cases, as well as the time horizon and greenhouse gas emissions from the reference case, i.e. emissions if the fuel resource is not utilised.

From the findings of this study it is evident that there are needs for a thorough and comprehensive evaluation of the greenhouse impact of biogenic fuels. In particular the land-use emissions must be factored into the calculations. It is also clear that uncertainties in emission data inevitably give rise to uncertainties in any final impact assessment. In order to improve the quality and understanding of the greenhouse impact, the assessments of biogenic fuels must be carried out as and when new information becomes available. In addition, the methods introduced here should undergo further scrutiny with a view of a wider adoption of the methodology. This would help in developing the assessments of greenhouse impacts of biogenic fuels in even more intelligible and comprehensive ways.

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PAPER III

Greenhouse Impact of Fossil, Forest Residues and Jatropha Diesel

A Static and Dynamic Assessment

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Greenhouse impact of fossil, forest residues and jatropha diesel: a static and dynamic assessment

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Abstract: Biofuels have been recognised as one option for mitigating climate change. However, in order to show the sustainability of biomass-based fuels, an assessment of the savings in Greenhouse Gas (GHG) emissions compared to fossil fuels needs to be clearly shown. There are two ways to measure the greenhouse impact of an activity. It can be done statically or dynamically, by using Global Warming Potential (GWP) or Radiative Forcing (RF) respectively. This article compares these two methods for assessing the greenhouse impact and introduces two more rarely discussed and lesser-known raw materials for biodiesel production, forest residues in Finland and jatropha in India, as well as their greenhouse impact compared to fossil fuel from a life cycle perspective.

The analyses made with GWP and RF show some differences. Using a time horizon of 100 and 300 years, the magnitude of the greenhouse impact of jatropha biodiesel assessed with GWP and RF differs by only a few percent. When the greenhouse impact of forest residue-based Fischer-Tropsch (FT) diesel was assessed, the difference between the GWP and RF assessment was larger, up to 10%. This is also a reflection of the more accurate calculation possibility of the greenhouse impact with RF in which the exponential and time dependent decay of forest residues can be taken into account. Compared to fossil diesel, the greenhouse impact of jatropha and forest residue-based biodiesel was approximately one-third less, irrespective of the assessment method. This, however, may not be enough to fulfil the requirements of the European Union (EU) on the sustainability of biofuels.

Keywords: greenhouse impact; global warming potentials; GWP; radiative forcing; biofuel; forest residues; jatropha; fossil diesel.

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1 Introduction

The rise of global temperatures is very likely due to the increase in anthropogenic Greenhouse Gas (GHG) emissions. The primary source of increased atmospheric concentration of carbon dioxide, the most important anthropogenic GHG, is the use of fossil fuels (IPCC, 2007b). The mitigation of global warming to a relatively low temperature rise of 2°C to 3°C compared to the pre-industrial era requires strong cuts in rising global GHG emissions. Limiting the global mean temperature rise for 2° requires cutting the global CO_2 emissions by 50% to 85% by 2050 compared to their 2000 level (IPCC, 2007a). In order to cut GHG emissions, a wide array of measures are needed. In the transportation sector, biofuels have been seen as one way of reducing GHG emissions. The European Union (EU) has proposed a binding target to increase the share of transportation biofuels to 5.75% by 2010 and to 10% by 2020. Biofuels also need to provide at least a 35% saving in GHG emissions compared to fossil fuels (EC, 2003; 2008a–b) and, after 2016, at least a 50% saving in the case of old installations, and at least 60% in the case of new installations. The targets, however, have been under strong debate due to increasing food prices and questions over the sustainability of biofuel production.

This study analyses the greenhouse impact of two lesser-known raw materials for biodiesel production, jatropha (India) and forest residues (Finland). The objective is to study the greenhouse impact using two different methods of greenhouse impact assessment: Global Warming Potential (GWP) and Radiative Forcing (RF). GWP is a simple static method for assessing greenhouse impact, but RF is more accurate and it also takes into account the time dependency, which is important in the case of forest residues (the forest residues decay slowly if they are not utilised). The greenhouse impact is studied by using Life Cycle Assessment (LCA). Jatropha and forest residue-based diesels are further compared to the greenhouse impact of fossil fuel. Also, the external energy consumption of assessed diesels has been given. However, this study has been limited to only discussing those sustainability issues concerning GHG emissions and energy consumption. The other aspects (costs, security of supply, and impact on biodiversity) have not been taken into consideration.

Jatropha and forest residues have been chosen for this study to represent raw materials that do not affect food production. Jatropha is a non-edible oil-seed plant with high oil content. It is suitable for cultivation in low-productivity areas (wastelands) not considered suitable for food production. Forest residues in Finland are collected and used for energy production. Both these raw materials are suitable for biodiesel production; jatropha by transesterification, and forest residues by gasification and the Fischer-Tropsch (FT) method. The transportation fuels under study were chosen to be diesels, since according to earlier studies biodiesel is more climate-friendly than bioethanol or other bio-based transportation fuel products (Hill *et al.*, 2006). Hill *et al.* also stated that energy invested in the production of bioethanol yields 25% more energy, whereas biodiesel yields 93% more. This study assesses the use of jatropha for biodiesel production in India and the use of forest residues in Finland. The input data is mainly from the literature.

Also, both jatropha and forest residues have been tested and have raised interest in Finland’s biggest refining and marketing company, Neste Oil (2008). Neste Oil Corporation is focused on transportation fuels and is building the world’s biggest biodiesel production plant in Singapore (due to be completed by the end of 2010). It is currently using palm oil, rapeseed oil, and animal fats for its Next Generation Biomass to Liquid (NExBTL) biodiesel production but, according to press releases, it is interested in both forest residues and jatropha (Neste Oil, 2008).

There are a large number of studies about the greenhouse impact of transportation fuels. However, the greenhouse impact of the use of jatropha and forest residues as raw materials for biofuels have been considered only in a few studies (Reinhardt *et al.*, 2007; Mäkinen *et al.*, 2006) and have not been compared to each other earlier. This is noteworthy, especially in the case where food prices increase; the attention is given to raw materials, which do not take away land from food production. However, the sustainability of biofuels needs to be clearly and transparently stated, which can be done by using LCA and other assessment methods.

2 Climate change mitigation in the transportation sector

The transportation sector plays an important role in climate change mitigation. According to the Intergovernmental Panel on Climate Change (IPCC), the transportation sector was responsible for 23% (6.3 Gt CO2 emissions) of world energy-related GHG emissions in 2004 (Kahn *et al.*, 2007). Road vehicles are mainly responsible for emissions in the transportation sector. GHG emissions from the transportation sector are also increasing rapidly. Over the past decades, these emissions have increased faster than in any other energy-related sector. This increase will continue in the future, since there are still many people without access to personal vehicles or even motorised transport (Kahn *et al.*, 2007).

The International Energy Agency (IEA, 2007) has especially pointed out the roles of India and China, which are the key players when talking about increasing energy demand. The projected global oil demand is growing 1.3% per year. The transportation sector is the main driver behind oil demand in most regions (globally, the share of the transportation sector in oil use was 47% in 2005 and will be 52% in 2030). In Asia the increase in oil demand is very high. About 42% of the increase in total oil demand in the world from 2006–2030 will come from China and India. India’s yearly demand (3.9%) is growing slightly faster than Chinese demand (3.6%). However, in absolute terms, Chinese oil demand has the largest share of all the countries and regions. In the EU, oil demand has been assessed to stay the same during 2006–2030 (IEA, 2007). The increasing number of vehicles also affects the need for transportation fuels. Today there are about 900 million vehicles on the world’s roads (excluding two-wheelers). According to IEA (2007), this number will pass 2.1 billion by 2030; most of these new vehicles are destined for Asia.

The role of biofuels has been raised in a considerable number of different studies. However, the IEA (2007) has assessed that, although biofuels are taking an increasing share of the markets for road-transportation fuels, oil-based fuels still continue to dominate the markets. By IEA projections, the share of oil-based fuels will decrease from 94% to 92% during the period 2006–2030. Despite the fact that oil-based fuels will dominate in the near future, biofuels have been seen as important means for reducing GHG emissions in the transportation sector. Biofuels can also be viewed as an energy security issue by reducing the reliance on foreign oil due to increasing fuel prices. Pacala and Socolow (2004) have brought up a portfolio of different options to solve the climate problem during the next half-century and for stabilising the atmospheric CO_2 concentration. Regarding the transportation sector, these options are more efficient vehicles, the reduced use of vehicles and the use of biofuels. To be able to reduce one ‘wedge’ of emissions (relative to 14 GtC/year BAU-scenario) by 2054, Pacala and Socolow (2004) suggest that biofuel production needs to be multiplied. In the case of bioethanol, current production needs to be increased a hundred-fold through the use of $250 * 10^6$ ha of land (one-sixth of the world’s croplands).

Biofuels are also included in many GHG mitigation actions as a means to reduce emissions. In the EU, the main action has been the setting up of Directive 2003/30/EC on the use of renewable energy (EC, 2003), which aims at promoting the use of biofuels and sets down a target of 5.75% for all transportation fuels to be replaced by biofuels by 2010. With reference to India and Finland, the two countries being assessed with respect to biodiesel production, actions in Finland are adhered to quite strictly as per the actions of the EU. Finland has also stated its own obligations with respect to the use of biofuels. Biofuel's share needs to be 2%, 4% and 5.75% for 2008, 2009 and 2010, respectively (Ministry of Trade and Industry of Finland, 2006).

In India, the need for reducing the dependency on imported oil is among the reasons to promote the production and use of biofuels. India is one of the largest consumers of energy in the world and the need for energy is rising rapidly due to their having one of the fastest growing economies. The rising cost of fuel, together with rising consumption, has given cause for great concern. Biofuels are required not only to satisfy energy needs, but also to satisfy environmental requirements, which will tighten in the future. However, India has a high priority for securing its food supply, which affects those raw materials that are suitable for food or areas of cultivation that are suitable for food production. Thus, India cannot afford to allocate large areas of land for biofuels. The Government of India has had different policies regarding the use of biofuels. When talking about bioethanol, the government's policy in 2006 mandating 5% blending of ethanol with petrol has been partially successful. Biodiesel, however, and despite the efforts of the government, has not caught on. The government's Planning Commission has set a target of 11.2 million hectares to be planted with jatropha by 2012 in order to produce a biodiesel blend of 20% with diesel as per a so-called national biodiesel programme. Indian Railways, too, has projects on its books for the planting and use of jatropha (Singh, 2007).

However, there are critics of the policies and targets for biofuels. For example, biofuel use, if extended widely, can be controversial as an energy source because of the competition for land use. The land used to produce energy crops for biofuel may not be available for other purposes, *e.g.*, food production or the conservation of biodiversity (Haberl *et al.*, 2007; Krausmann *et al.*, 2008). The European Environment Agency (EEA, 2008) has commented on the biofuel targets. It suggests suspending the EU's targets. Rising food prices have also made policy makers begin withdrawing the implementation of biofuel targets. However, is it too soon to give up on all biofuel targets? As suggested by Arvizu (2008), more comprehensive studies should be made before giving up totally on biofuel targets. Jatropha, however, can be cultivated on lands which are not suitable for food production. The system boundaries and assumptions may have a large effect on the results, which makes it reasonable to provide more transparent information on the saved GHGs, while using biofuels instead of fossil fuels. Biofuels were also called 'climate-neutral fuels', which according to the knowledge we have today, was proved to be a mistake (Holmgren *et al.*, 2007).

3 Methodology

Greenhouse impact was assessed by using a LCA, which took into account all the GHG emissions and sinks during the whole life cycle. LCA is presented in the following chapter. Greenhouse impact was assessed by using GWP and RF. GWP and RF were compared in order to assess the differences in the methods used.

3.1 Life Cycle Assessment (LCA)

LCA is a standard used by the International Organization for Standardization (ISO 14040, 1997). It is a tool widely used in environmental impact assessment. It takes into account all the inputs and outputs of the system during the whole life cycle, taking into account the impact of assessed products/services from ‘cradle to grave’. LCA has been widely used for analysing the greenhouse impact of different products. It has also been used extensively for the greenhouse impact assessment of the production and use of biofuels (*e.g.*, Edwards *et al.*, 2003; Soimakallio *et al.*, 2009; JRC, 2007).

The phases of LCA have been divided into four elements, as follows:

1. definition of goal and scope
2. inventory analysis
3. impact assessment
4. interpretation.

Critical review and reporting are also a part of the assessment process. It is important to define the comparative assertion (in this study it is a comparison to fossil diesel) and the functional unit used in the study (1 MJ of diesel).

The goal and scope of the study have been brought up Section 1 (assessment of greenhouse impact of two different biodiesels from an LCA point of view using two different methods for analysing climate the impact). Inventory analysis is performed in Section 5 (GHG emission: input data), where all the studied GHGs (CO_2, CH_4 and N_2O) have been listed during the assessed diesel life cycle. Impact assessment is carried out by using GWP and RF methods for assessing greenhouse impact comparatively. The results of the greenhouse impact of assessed biodiesels will be compared to each other and especially to fossil diesel to be able to see the saving in GHGs. Transparency is one of the important aspects of LCA; all the data used in the calculations have been presented in the study, so that the study can be conducted by any other party.

3.2 Radiative Forcing (RF)

The definition of RF according to the IPCC (2007a) is:

> “the change in the net vertical irradiance (expressed in Watts per square meter: Wm^{-2}) at the tropopause due to an internal change or a change in the external forcing of the climate system, such as a change in the concentration of carbon dioxide or in the output of the sun.”

RF can be used to describe the greenhouse impact due to atmospheric concentration changes caused by the emissions and sinks associated with an anthropogenic activity. It can be interpreted to present the heating power of the atmosphere-surface system. RF is a more specific method than GWP in greenhouse impact assessment, especially when the emissions/ sinks last for long time horizons, such as the decaying of forest residues. RF explicitly takes into account the concentration changes that are due to the removal of CO_2, CH_4 and N_2O from the atmosphere and also dynamic changes in the emissions and sinks as a function of time. In the calculation of RF, the model REduction of FUture Greenhouse gas Emissions (REFUGE) was used (Monni *et al.*, 2003). The model calculates, on the basis of emissions and sinks, the GHG concentrations and RF they cause. Assessment of the greenhouse impact by using radiative forcing has been used in some studies, especially in those where the time horizon of emissions needed to be taken into account (*e.g.*, Kirkinen *et al.*, 2008).

RF is typically expressed in Watts per square meter (Wm^{-2}) (IPCC, 2007b). In this study, a new concept, Relative Radiative Forcing Commitment (RRFC) is used as an indicator for greenhouse impact instead of RF and also expressed in Wm^{-2} (Kirkinen *et al.*, 2008). RRFC describes the ratio of the energy absorbed (E_{abs}) into the global atmosphere-surface system to the fuel energy (E_{fu}) produced in the fuel chain under consideration. RRFC is calculated by integrating the RF over the total surface (A) of Earth (Kirkinen *et al.*, 2008) and accumulating it over a given time horizon (TH).

$$RRFC(TH) = \frac{E_{abs}(TH)}{E_{fu}}, \tag{1}$$

$$E_{abs}(TH) = \int_0^{TH} RF(t)dt * A. \tag{2}$$

3.3 Global Warming Potential (GWP)

The GWP is defined by IPCC (2007a) as follows:

> "An index, based upon radiative properties of well-mixed greenhouse gases, measuring the radiative forcing of a unit mass of a given well-mixed greenhouse gas in the present-day atmosphere integrated over a chosen time horizon, relative to that of carbon dioxide. The GWP represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing thermal infrared radiation."

GWP is widely used due to its simplicity. The Kyoto Protocol uses GWPs over a 100-year time frame. This means that the emissions of methane and nitrous oxide are given by multiplying by 21 and 310, respectively, the values given by IPCC (1996). In this study, newer values provided by IPCC (2007a) are used, which are 25 for CH_4 and 298 for N_2O for the time horizon of 100 years and 7.6 for CH_4 and 153 for N_2O for 500 years. The formula for calculating GWPs is as follows:

$$GWP_i = \frac{\int_0^{TH} a_i * [C_i(t)]dt}{\int_0^{TH} a_{CO_2} * [C_{CO_2}(t)]dt}. \tag{3}$$

where:

TH = the time horizon over the calculation period (depending on, *e.g.*, climate mitigation policies)

a_i = the radiative efficiency (Wm^{-2} kg)

$C_i(t)$ = the time-dependent decay of abundance after the instantaneous release of one unit of gas (i).

The corresponding quantities for the reference gas (CO_2) are in the denominator. The numerator and denominator are called the Absolute Global Warming Potential (AGWP) of gas i and of CO_2, respectively.

$$AGWP = \int_0^{TH} RF(t)dt. \tag{4}$$

The GWP values are used to give the weights of different gases in relation to CO_2. On the basis of the GWP weights, the estimate of the greenhouse impact of a studied diesel chain is expressed in Carbon Dioxide Emission Equivalents.

3.4 Calculation of the total greenhouse impact

Greenhouse impact was calculated on the basis of the emissions from the energy production chains under consideration. All CO_2, CH_4 and N_2O gas fluxes from all the different phases of the life cycle were taken into account in the calculation of greenhouse impact. In the calculation of greenhouse impact, only the impact due to human activities was assessed. The greenhouse impact of transportation fuels was calculated in principle using the following equation:

$$I = I_U - I_R \tag{5}$$

where I_U equals the impact from the production and utilisation of the studied fuel chain (*e.g.*, impact from the production of raw material, working machines, transportation, end use and after-treatment). I_R equals the impact from the reference situation. The reference situation refers to the normal development of the utilised land resource during the studied time horizon. For example, in the case of forest residue FT diesel chains, this means the greenhouse impact of the decomposition of the residues after logging, in case they are not harvested and used for FT diesel production (Kirkinen *et al.*, 2008).

In this study, however, specific information on I_R is available only for fossil diesel (I_R is zero) and for forest residues. In the future, when more reliable information about the emissions of land-use is available, the reference situation of the use of land for jatropha cultivation can and should be added. Thus, in this study we assumed that the carbon storage of the jatropha plantation is as large as in the reference case, where the land is not used for jatropha cultivation. In principle, deviations from this assumption can be in both directions. In the case of jatropha, it was assumed that the rotation time of oil is so short that no dynamics should be accounted for, *i.e.*, jatropha oil is carbon neutral. In the case of the calculations based on GWP, this was assumed also for forest residues.

In this study, the greenhouse impact was assessed; no other environmental impacts were considered. RRFC expressed the results illustratively as it gives the ratio of the energy, which is heating the globe, to the energy produced in the fuel chain. RRFC can also be expressed as a function of time in order to provide a dynamic cumulative picture of the caused effect. Varying time horizons can be studied separately, for example when studying the effects of different climate policies in varying time scales. Greenhouse impact was assessed for the 100- and 300-year TH in this study. If we consider global emission reduction policies, where the rise of the global average temperature should be limited to 2°C or 3°C above the pre-industrial level, the emissions should be limited to a small fraction of the present level within this century (IPCC, 2007a). Therefore, the time horizon of 100 years can be seen as relevant for decision making on emission reduction measures and appropriate energy sources. The longer time horizon of 300 years is, in this respect, of theoretical/academic interest only.

4 Assessed diesel chains

The greenhouse impact of different diesels was calculated from a life cycle point of view. The assessed diesel chains are presented in Table 1, in which the different phases of the life cycle are given. Chain 1 represents fossil diesel, where the starting point of the diesel chain is crude oil. After producing crude oil, it is further refined to diesel, which is further supplied to the customers and utilised. Chain 2 is forest residue-based FT diesel, where the starting point of the diesel chain is forest residues, which are collected and crushed. Woodchips are then transported to the processing plant, where material is further refined into diesel using the gasification (FT) method. If forest residues are not collected and utilised, they will decompose in the forest and produce CO_2. Chain 3 stands for the use of jatropha for diesel production. The chain starts with the production of jatropha seeds, their transesterification for diesel, which is then supplied to customers and utilised. In this study only forest residue-based FT diesel is included in the reference case (I_R). In chain 3, the utilisation of jatropha, the reference situation of the land use has been excluded, since the data from earlier land use, as well as the emission data, are not available and need to be extensively assessed.

Table 1 The life cycle phases of the assessed transportation diesel chains

Chain	*Starting point*	*Production and utilisation*	*Reference case*
1	Crude oil	Production, diesel refining, supply and utilisation (Europe)	–
2	Forest residues	Collection, crushing, transportation and FT diesel refining (Finland)	Decomposition of logging residues
3	Jatropha seeds	Production and transesterification, supply and utilisation (India)	–

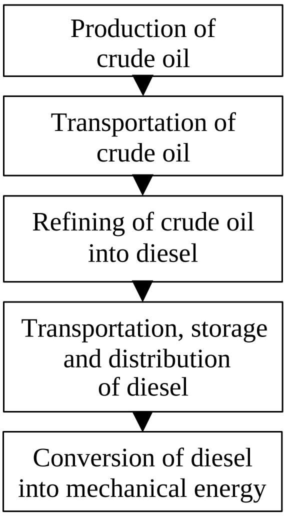
5 GHG emission: input data

The next subsections present the data and assumptions behind greenhouse impact calculations. In the calculation of greenhouse impact, emissions of the different phases of the life cycle needed to be clearly distinguished. While using the RF calculation method, it was assumed that 1 GJ (0.28 TWh) of diesel fuel energy is produced and utilised to enable the calculations. However, when using the RRFC method, the amount of energy produced is not significant when the results of warming impacts are interpreted to be energy per energy (dimensionless).

5.1 Fossil diesel

The assessment of the greenhouse impact of fossil diesel was based on a study by Mäkinen *et al.* (2006), which mainly used the values from the study of Erwards *et al.* (2003). Diesel oil is a crude oil refinement product, which needs to be cleaned in oil refineries for distribution and use. Starting values for the GHG emission balances were calculated based on the situation in 2010, when only a limited share of traditional refinements is assessed to be substituted with biomass-based fuels. Emissions from fuel transportation were calculated by taking into account the typical share of different transportation modes in Europe. Crude oil is usually transported first by pipelines into harbours, where crude oil is then shipped to refineries. Most of the fossil fuels used in Europe are also refined in Europe. Refineries in Europe consume about 6% of the crude oil purchased in the process. In addition they also buy electricity and gas. The allocation of emissions to the assessed fuels is difficult, especially in the case where the shares of different products from the refineries change. However, in the study by Edwards *et al.* (2003), the assumptions are clearly and transparently indicated. The life cycle of the fossil diesel is introduced in Figure 1. After crude oil is produced it is transported to the refinery, where after refining the crude oil into diesel, it is transported and supplied to customers. The end use of diesel is also taken into account in the assessment of greenhouse impact. The values used in the calculation of the greenhouse impact of fossil diesel are presented in Table 2.

Figure 1 The life cycle of fossil diesel utilisation



Source: Applied from Mäkinen *et al.* (2006)

Table 2 Emissions of the different phases of the life cycle of fossil diesel

Life cycle phases	*CO_2 (g/MJ)*	*CH_4 (g/MJ)*	*N_2O (g/MJ)*
Production of crude oil	3.33	0	0
Transportation of crude oil	0.81	0	0
Refinement of crude oil	8.60	0	0
Transportation of diesel oil	0.23	0.0001	0
Storage of diesel oil	0.10	0.0002	0
Distribution and dosage of diesel oil	0.72	0.001	0
Use of diesel oil in engine	73.3	[1]	[1]

Notes: [1] Emissions are dependent on what kind of engine and under what conditions fuel is combusted. When different fuels are compared in the same consumption target, CH4 and N2O emissions do not in practice have differences between the fuels being compared.

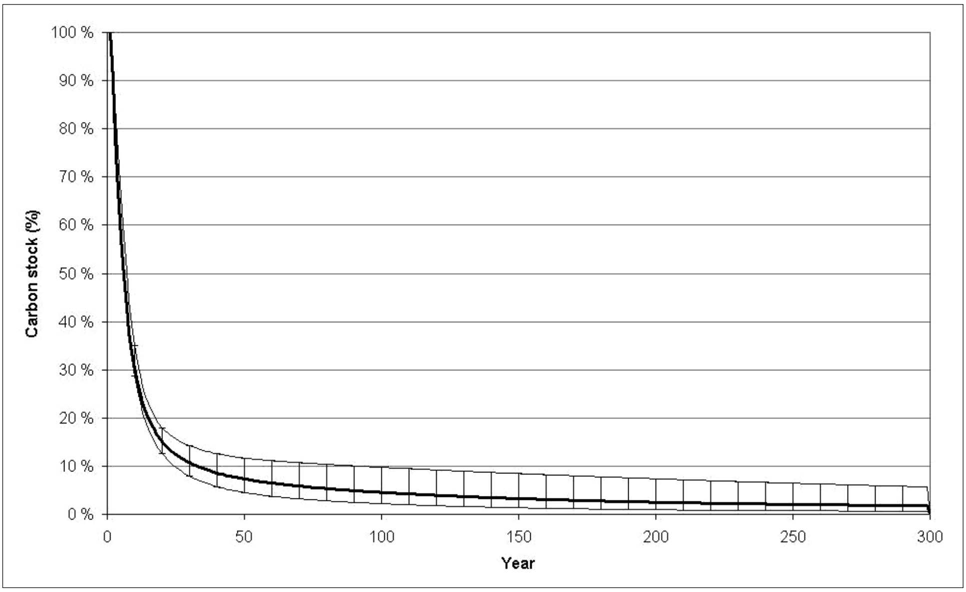
Source: Mäkinen *et al.* (2006)

5.2 Forest residues FT diesel

Forest residues (also called logging residues) have been recognised as a raw material for FT diesel. Forest residues are also suitable for biodiesel production, since they do not affect the use of cultivation land and do not take land away from food production. The total potential for producing forest residues in Finland in the year 2010 is about 23.8 TWh, including forest residues, stumps and small firewood (Mäkinen *et al.*, 2006). When using forest residues as a raw material for FT diesel, it results in CO_2 emissions earlier (in the FT diesel process) compared to the reference case (I_R), which is the decay of the forest residues causing CO_2 emissions as a function of time. Decaying of the forest residues has been calculated using the soil carbon model called YASSO (Liski *et al.*, 2005). Decaying of the residues is presented in Figure 2. The remaining carbon stock is presented as a function of time. Logging residues decay very fast during the first 20 years, after which decaying slows, with some non-decayed material possibly remaining after 300 years (Kirkinen *et al.*, 2008).

The production of logging residue-based FT diesel (the collection of logging residues, baling, chipping, crushing) causes emissions through the use of working machines and transportation. Emissions are also caused in the refining, storage and distribution stages. The GHG balance of logging residue-based FT diesel was studied by Mäkinen *et al.* (2006). These values are used in this assessment as well. Emission data from the production and utilisation of logging residue-based FT diesel are been presented in Table 3. However, Mäkinen *et al.* (2006) studied the GHG balances of the forest residues FT diesel using GWP. RF assessment is more accurate for forest residues, which allows the time-dependent factors of greenhouse impact calculations to be taken into account (see, *e.g.*, Kirkinen *et al.*, 2008). In those areas of the forest residues FT diesel production process where the use of electricity is intensive (crushing and refining), it was assumed that the total electricity consumption increases in Finland due to the new operation. Increased electricity consumption was assumed to be met by using more marginal electricity (mainly coal). It is also notable that, while forest residues are generated during the logging process, the environmental impact and energy use of the forest plantations, fertilisers and logging actions were not allocated to forest residues since they were generated irrespective of the need for them. This means that logging is based on the need for timber wood, not by the need for forest residues. Forest residues are produced whether or not they are utilised.

Figure 2 The remaining carbon stock of forest residues as a function of time in Finland (reference situation I_R for the forest residues FT diesel case)



Source: Kirkinen *et al.* (2008)

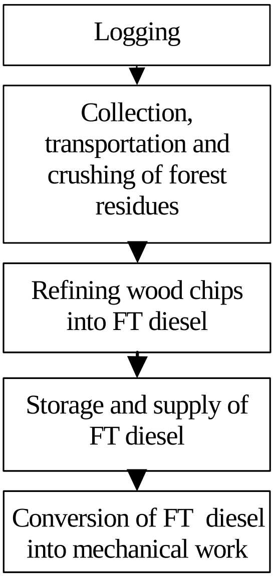
Table 3 Emission data per MJ of FT diesel produced in the different phases of the life cycle of logging residue-based FT diesel (Finland)

Different phases of the utilisation of logging residue FT diesel	*CO_2 (g/MJ)*	*CH_4 (g/MJ)*	*N_2O (g/MJ)*
Bailing, forest transportation, chipping, long distance transportation, transfers (emissions caused by the use of diesel oil)	1.84	0.0001	0.0007
Crushing (marginal electricity)	0.21	$5.6 * 10^{-5}$	$1.2 * 10^{-5}$
Refining (marginal electricity)	48.07	0.0134	0.0027
Storage and distribution	0.82	0.0012	0
Process emissions	39.7	–	–
Direct emissions from end use	70.7	[1]	[1]

Notes: [1] Emissions are dependent on what kind of engine and under what conditions fuel is combusted. When different fuels are compared in the same consumption target, CH4 and N2O emissions do not in practice have differences between the fuels being compared.

The life cycle of forest residue-based FT diesel is presented illustratively in Figure 2. Residues are left in the forest after logging, where they are collected. They are then transported to the processing plant and crushed. Chips are refined into FT diesel, which is then stored and supplied to consumers, who use the fuel.

Figure 3 The life cycle of forest residue-based FT diesel production and utilisation



Source: Mäkinen *et al.* (2006)

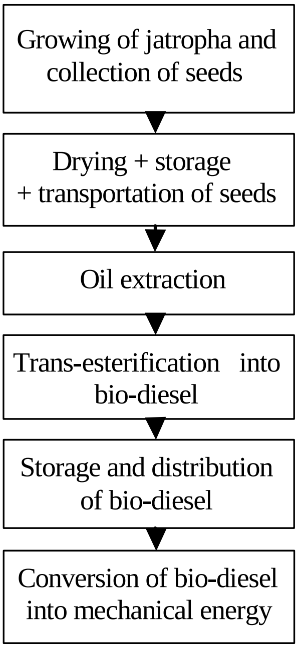
5.3 Jatropha diesel

Jatropha (Jatropha curcas) is a non-edible oil plant, which can exist under adverse conditions. Jatropha was originally from Mexico and Central America. It is a drought-resistant, perennial plant, living up to 50 years and has the capability to grow in marginal soils. Trees reach a height of up to 6 m. It requires very little irrigation and grows in all types of soils. Jatropha can be grown in wastelands, of which India has nearly 63 million hectares, 33 million hectares of which has been allotted for tree planting. The production of jatropha seeds is about 0.8 kg per sq m per year. Seeds are light (2000 seeds/kg). The oil content of jatropha seed ranges from 35% to 40% by weight, but due to the toxins, the oil is not edible. Plants live for 35–40 years and produce throughout their lifetime (TERI, 2006). Figure 4 shows a jatropha plantation and seeds.

The life cycle of jatropha-based biodiesel is presented in Figure 5. The life cycle of jatropha-based diesel starts with the production of jatropha seeds. The plantation phase of LCA involves identifying the complete GHG flows during plantation and harvesting of the crop. This includes the chemicals used in the farm (fertilisers, pesticides, limestone, *etc.*) and their associated emissions (*e.g.*, production and transportation of fertilisers). Mature seeds are collected and harvested. Seeds are then dried and stored. Seeds are transported to crushers, followed by crude oil extraction from the crushed seeds. Crude oil is transported to a diesel refinery. The crude oil is converted into biodiesel using transesterification. Biodiesel is then transported to distribution stations. The last phase of the life cycle is the utilisation of the biodiesel and conversion of the diesel into mechanical energy (TERI, 2006). The direct emissions and the use of electricity in the process are taken into account.

Figure 4 Jatropha plantations in the state of Rajasthan in India (left) and the seeds of the jatropha tree (right)

Figure 5 The life cycle of jatropha-based biodiesel production and utilisation



Sources: Adapted from TERI (2006); Reinhardt *et al.* (2007)

There are only a few studies that have analysed the GHG emissions during the life cycle of jatropha. Reidhardt *et al.* (2007) have studied the GHG emissions extensively and distinctively. According to Reinhardt *et al.*, jatropha requires a lot of inputs, especially in the first years of cultivation. From a GHG emission perspective, jatropha requires irrigation water (for the first three years), diesel fuel (for tractors and irrigation pumps) and mineral fertilisers. There are three different scenarios for the yields and the need for fertilisers. The three scenarios presented were ‘today’, ‘optimised’ and ‘best’. The scenario ‘today’ reflects the current yields of jatropha, whereas ‘optimised’ assumes higher yields due to future optimisations of agricultural practices. The third scenario ‘best’ is even more optimised, where further improved agricultural practices are applied resulting in a higher seed-to-husk ratio. This study presents the optimised scenario. Earlier land use has not been taken into account due to the lack of data. Table 4 shows the GHG emissions from the different phases and sources of the jatropha biodiesel chain. The main emissions are caused by transesterification.

Table 4 Emission data related to the different phases of the life cycle of jatropha biodiesel

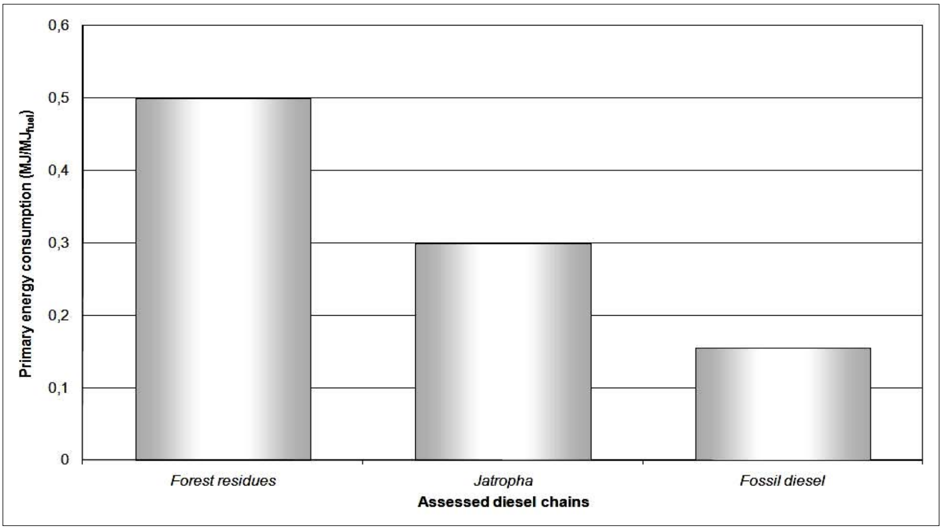
Different emission sources from the production and utilisation of jatropha biodiesel	*CO_2 (g/MJ)*	*CH_4 (g/MJ)*	*N_2O (g/MJ)*
Tractor	7.08	0.01	0.00
Biomass field emissions	0.00	0.00	0.03
Production steam and hexane	3.75	0.00	0.00
Usage	0.00	0.00	0.01
Fertilisers	6.66	0.02	0.02
Production electricity	7.50	0.02	0.00
Transesterification	15.83	0.03	0.00
Others	0.83	0.00	0.00

Source: Based mainly on Reinhardt *et al.* (2007)

6 Comparison of energy balances of the different diesel types

The primary energy consumption per energy content of the assessed fuel is presented in Figure 6. The energy input in every assessed fuel chain is higher than the output, where the energy of the fuel is accounted for. The production of biodiesel from jatropha or forest residues is more energy intensive than from fossil diesel; therefore, the needs related to energy input are higher. This means that, when fossil diesel is substituted with biodiesel, the need for primary energy increases. The manufacture of fossil crude oil into diesel requires some energy in the refining process. The energy requirement for jatropha diesel (Reinhardt *et al.* 2007) comes from machinery on the plantation, the production of fertilisers and the energy used in the refining phase (steam, electricity). In the case of forest residues, electricity is especially needed in the FT process used as a basis for this study (Mäkinen *et al.* 2006).

Figure 6 The primary energy consumption of assessed transportation diesel chains for production of 1 MJ of diesel fuel



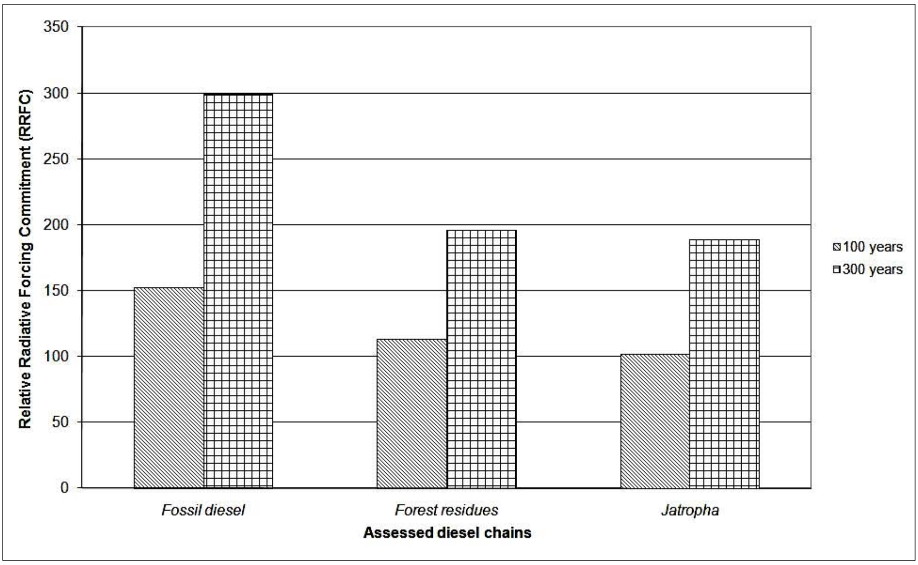
7 Results

The greenhouse impact of the fuel chains under review is presented in Figures 7–10. Figure 7 shows the total greenhouse impact of the studied diesel fuels for 100-year (left column) and 300-year (right column) time horizons using the RRFC method. During the 100-year time horizon, fossil diesel causes a warming impact of 150 times compared to the energy of the fuel. The impact of forest residues biodiesel is about 20% lower than the impact of fossil diesel. Jatropha biodiesel has the lowest impact during the 100-year time horizon. The impact is about 30% lower than the impact of fossil diesel, resulting in a warming effect of about 100 times compared to the fuel energy.

During the 300-year time horizon, fossil diesel has a warming impact of 300 times compared to the energy of the fuel, which is double compared to the impact of the 100-year time horizon. The greenhouse impact of forest residues biodiesel during 300 years is about one-third lower than the impact of fossil diesel. Also, jatropha biodiesel causes more than a one-third lower greenhouse impact compared to fossil diesel (Figure 7).

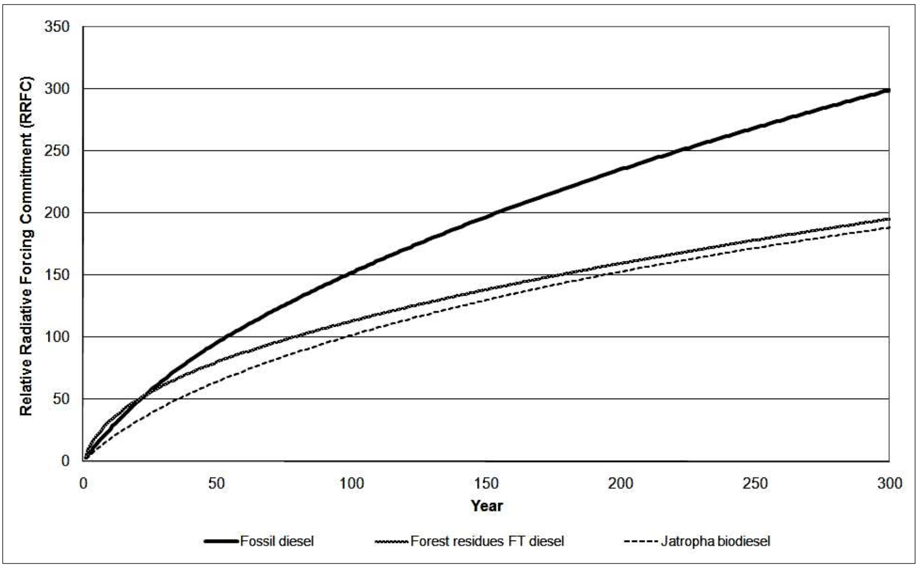
Greenhouse impact, when calculated using the RF method, can be presented as a function of time. In Figure 8, the cumulative greenhouse impact of the studied diesel is shown over a 300-year time horizon. At the beginning of the time horizon, forest residues-based diesel actually causes a slightly higher greenhouse impact than fossil or jatropha-based diesels, but ends up having a clearly lower greenhouse impact than fossil diesel. This is due to the high emissions of the forest residues FT diesel production process due to the large requirement for electricity and the oxidation of carbon in raw material in the FT diesel process. However, the decomposition of the forest residues has a strong impact causing the relative lowering of the total greenhouse impact (I_R in Formula 5). A cumulative greenhouse impact figure is also useful when interpreting the greenhouse impact for different climate policies, according to different time horizons, and needs to be clearly stated.

Figure 7 The greenhouse impact of assessed diesel chains (fossil diesel, forest residues based FT diesel and jatropha biodiesel) from 100- and 300-year time horizons using radiative forcing



Notes: Results are expressed by RRFC providinginformation on the extent of the greenhouse impact compared to the amount of energy in the diesel fuel. RRFC is the energy absorbed in Earth's system divided by the energy in the produced fuel.

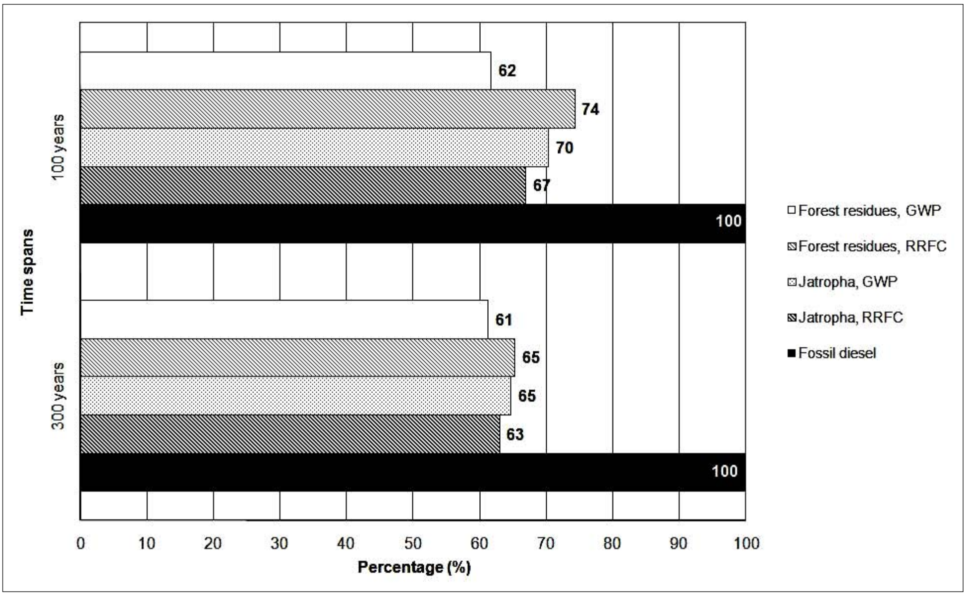
Figure 8 The cumulative greenhouse impact of assessed diesel chains (fossil diesel, forest residues-based FT diesel and jatropha biodiesel) as a function of time using radiative forcing



Note: Results are expressed by RRFC which provides information as to the extent of the greenhouse impact compared to the amount of energy used.

The greenhouse impact of different diesels was assessed in this study by using two different methods, GWP and RF. By choosing one of the diesels as a reference base (in this case, fossil diesel), the impacts of jatropha and forest residues-based biodiesels can be assessed side by side from 100- and 300-year time horizons, when calculated using these two different methods. The GWP factors for the 300-year time horizon are linearly interpolated on the basis of the values for 100 and 500 years provided by the IPCC. The main result is that in the case of forest residue-based biodiesel, the greenhouse impact assessed with GWP gives lower values than RRFC, both in 100- and 300-year time horizons. This is due to the simplified calculation, which assumes carbon neutrality for forest residues (prevailing practice). In the RRFC calculation, the exact assessment of the decomposing forest residues in the reference situation has been taken into account. In the case of jatropha-based biodiesel, GWP gives higher values of greenhouse impact than RRFC.

Figure 9 The relative greenhouse impact of forest residues and jatropha-based diesel compared to fossil diesel presented on the basis of 100- and 300-year time horizons

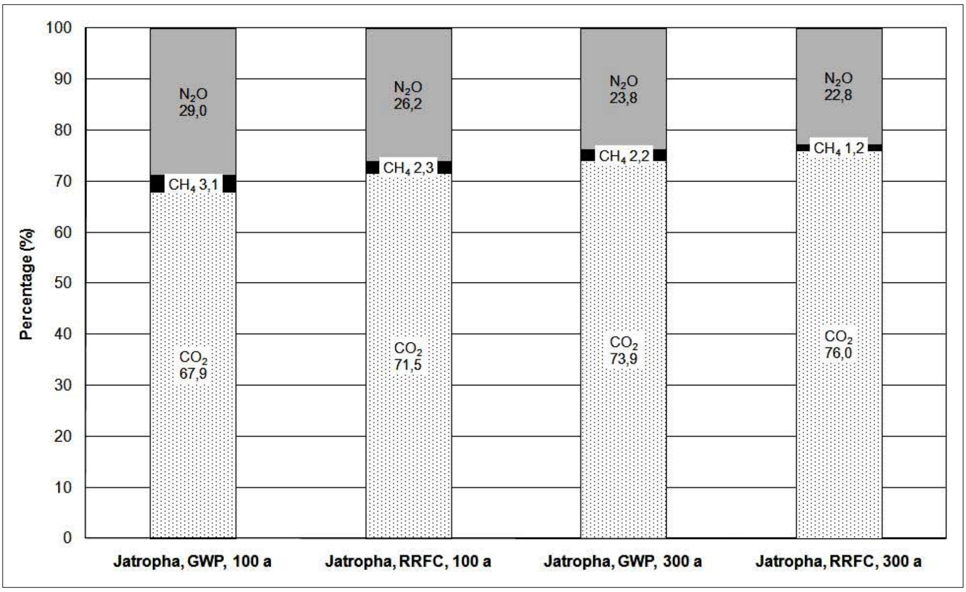


Notes: The Greenhouse impact assessed with RF and GWP is presented. Fossil fuel is set as a comparison target; the greenhouse impact due to fossil diesel production and use represents 100% greenhouse impact.

Figure 10 presents the relative shares of the GHGs, causing the total impact of jatropha-based biodiesel. The GHGs CO_2, CH_4 and N_2O have been taken into the GHG assessment (the jatropha oil itself is assumed to be carbon neutral; CO_2 is from the fossil fuels needed in the production chain). Since the GHG emissions are the same for both the GWP and RRFC assessment methods, the main differences occur due to the differences in the methods. In the case of the longer time horizon of 300 years, the share of CO_2 seems to be somewhat higher than in the case of 100 years. On the other hand, the RRFC method seems to produce a slightly higher share for CO_2 than the GWP method.

This might be due to different parameter values in the carbon removal models applied (IPCC, 2007b; Monni *et al.*, 2003). The largest relative difference is in the share of methane between the GWP and RRFC results.

Figure 10 The greenhouse impact of jatropha biodiesel assessed by GWP and RF on the basis of 100- and 300-year time horizons



Note: The relative greenhouse impact of different gases (CO_2, CH_4 and N_2O) is dependent on the assessment method used; however, the differences are minor.

8 Discussion

This paper considers the greenhouse impact of three different diesel fuels using two different calculation methods. In the relative results between different diesels, the calculation methods gave quite similar results. The RRFC method assesses the ratio of the energy absorbed into Earth's system due to the atmospheric concentration changes caused by the emissions of the considered diesel fuel chain to the diesel fuel energy produced in the chain. The GWP method assesses the GHG emissions of the considered diesel fuel chain in terms of carbon dioxide equivalents. The surprisingly small differences between the results of these methods may be explained by the fact that both methods use RF, although in different ways.

The method based on GWP coefficients is very easy to use. Therefore, it is also very widely used. However, the present way to use GWPs does not give a dynamic picture of the greenhouse impact itself. At most it provides a dynamic picture of GHG emissions expressed in carbon dioxide equivalents. However, RRFC directly provides the cumulative greenhouse impact as a function of cumulation time in relation to the fuel energy produced. RRFC also fits into the situation where the emissions change over a relatively long time horizon of some tens of years or even longer. RRFC can also be quite easily extended to consider the energy balance of the changes due to changing albedo as a result of surface cover changes due, for example, to biomass raw material production. Further, the new modelling work done for the IPCC's new assessment report uses RF to describe various scenarios (IPCC, 2008).

The input parameter values for the assessment with respect to fossil diesel are relatively well known. However, in the case of diesel based on forest residues, the input values are not so well known and the FT process utilised in the production of diesel fuel can be implemented in many ways related to the need for the raw material and the amount of external energy used. Typically, there is a trade-off between the amount of raw material and the amount of external energy needed (Mäkinen *et al.*, 2006). Further, the harvesting of forest residues can be arranged in several ways, and the decay of the forest residues in the reference case also includes uncertainty (Figure 3).

In the case of jatropha, the uncertainty concerning input values increases further. Jatropha oil can be produced in many kinds of environments related to plantation and harvesting. Diesel production can also be implemented in many ways. Literature available for selecting the studied case and the values needed in the calculation of greenhouse impact is still limited. It is therefore difficult to estimate the reliability of the input values and the calculation results.

9 Conclusion

The greenhouse impact of two different biomass-based transportation fuels were analysed using two different methods. Fossil diesel was included in the study as a comparative reference. Both methods seem to produce quite similar results. The GWP method is simple to use, but it does not provide a dynamic picture of the greenhouse impact, whereas the RRFC method does. In principle, the RRFC can be extended to also cover the albedo change effect.

According to the results, the life cycle of both biomass-based diesels seems to cause a 30% to 40% lower greenhouse impact than the life cycle of fossil diesel in the cases under review. However, this may not be enough to fulfil the requirement of the EU biofuels directive (EC, 2008b). The greenhouse impact of fossil diesel can be assessed with relatively small uncertainty, but the uncertainties of the results relating to the biomass-based diesels is very large due to variability in the production processes and the emissions data. However, despite many uncertainties, the external primary energy needs per unit of diesel fuel produced seemed to be higher in the cases of forest residue-based diesel and jatropha diesel compared to fossil diesel in the cases under review. The RRFC method reveals an interesting detail in the case of forest residue diesel. The greenhouse impact of the forest residue-based diesel initially increases even more rapidly than that of fossil diesel, and only after some decades will it become lower than that of fossil diesel.

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PAPER IV

Greenhouse Impact Assessment of Peat-Based Fischer-Tropsch Diesel Life-Cycle

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Greenhouse impact assessment of peat-based Fischer–Tropsch diesel life-cycle

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ABSTRACT

New raw materials for transportation fuels need to be introduced, in order to fight against climate change and also to cope with increasing risks of availability and price of oil. Peat has been recognised suitable raw material option for diesel produced by gasification and Fischer–Tropsch (FT) synthesis. The energy content of Finnish peat reserves is remarkable. In this study, the greenhouse impact of peat-based FT diesel production and utilisation in Finland was assessed from the life-cycle point of view. In 100 year's time horizon the greenhouse impact of peat-based FT diesel is likely larger than the impact of fossil diesel. The impact can somewhat be lowered by producing peat from the agricultural peatland (strong greenhouse gas emissions from the decaying peatlayer are avoided) with new peat production technique, and utilising the produced biomass from the after-treatment area for diesel also. If diesel production is integrated with pulp and paper mill to achieve energy efficiency benefits and if the electricity demand can be covered by zero emission electricity, the greenhouse impact of peat-based FT diesel reduces to the level of fossil diesel when agricultural peatland is used, and is somewhat higher when forestry-drained peatland is used as raw material source.

1. Introduction

The mitigation of global warming to a relatively low temperature rise level of 2–3 °C, compared to the pre-industrial era – requires strong cuts in the rising global greenhouse gas emissions (IPCC, 2007). The European Union has proposed that the global temperature rise should be limited to 2 °C compared to pre-industrial level. According to this requirement, the EU strives to limit the emissions from industrialised countries by 60–80% of the 1990 level by 2050. As an intermediate goal, the EU has set a binding unilateral target to reduce her emissions by 20% by 2020 compared to the level of 1990; the production and use of biofuels has been seen as one of the ways to reduce the EU's emissions by this deadline. Biofuels have also been considered interesting not only into climate change mitigation, but also due to rising fuel prices and energy security issues. The European Union has set a 10% binding target for the share of energy from renewable sources in transport in 2020 (EU, 2009).

Greenhouse gas balances of biofuels presented in different studies may vary significantly from each other depending on the one hand on raw materials, case specific conditions and technologies, and on the other hand on system boundaries, approaches, assumptions, and indicators used. Consequently, it is important to understand the scope and goal of the studies when interpreting and especially applying the results for certain purposes, e.g. political decisions.

A number of recent studies (e.g. Doornbosch and Steenblik, 2007; Edwards et al., 2008) have concluded that the production of biofuels may cause significant environmental and social problems. Firstly, greenhouse benefits from substituting fossil fuels by biofuels may be questionable due to auxiliary material and energy inputs required, direct land-use impacts and, in particular, due to indirect system impacts, e.g. deforestation. Secondly, the other environmental impacts, such as nutrient losses, may also be significant and are not well known. Thirdly, production of biofuels from raw materials also suitable for food production have partly been found to increase food prices and cause thus social problems. Consequently, research and development of biofuels is more and more focusing on raw materials not directly competing with food production. In addition, a number of initiatives (e.g. Cramer et al., 2006; EU, 2009; Fritsche et al., 2006) on sustainability criteria for biofuels have been announced by various institutions aiming to ensure that the production of biofuels does not cause serious harm for the environment and society.

Peat is an interesting raw material for transportation fuel since it is suitable from a technical viewpoint and does not compete with food production. The peat resources in Finland are considerable. It has been assessed that from the original amount of about 10 million ha of natural peatlands in Finland, approx. 5.7 million ha have been drained for forestry (55%) and 85,000 ha (0.8%) are used for agriculture and about 38% (4.0 million ha) were undisturbed (pristine peatlands), and the rest were under water

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reservoirs, in peat harvesting or under roads in the year 2000. The carbon content of the Finnish peatlands (peat layer and tree stand) was estimated at 6000 Tg, of which 5300 Tg as peat similarly in the year 2000 (Turunen, 2008). The use of peat for energy covers about 0.6% of the use of peatlands in Finland. The annual use of peat fuel for energy, electricity and heat, is about 17–27 TWh (6–11 $MtCO_2$ in terms of emissions from combustion) depending on the harvesting conditions, which comprises 6–7% of total energy use. The total energy content in peat in Finland is estimated to be about 13,000 TWh (46,800 PJ, 1 100 million toe) (Virtanen et al., 2003). For comparison, the share of energy consumption in the transport sector during 2006 was about 197 PJ in Finland (Statistics Finland, 2007).

The carbon pool in the peat layers of the natural peatlands in Finland has been assessed to have grown about 1.3 Mt per year (5 Mt/year in terms of CO_2) during the recent 50 years on the average (Turunen, 2008). On the other hand, according to Statistics Finland (2008), the agricultural peatlands and forestry-drained peatlands emitted about 5 and 7 $MtCO_2$ in 2006, due to the decay of the soil peat layer.

FT diesel fuel can be produced from peat through gasification and so-called Fischer–Tropsch (FT) synthesis. Soimakallio et al. (2009) has assessed stochastic greenhouse gas balances for a few various FT diesel concepts using logging residues and reed canary grass as raw materials. The greenhouse impact for FT diesel based on peat has not yet been assessed. However, the greenhouse impact of the use of peat for energy production has been assessed in some studies (e.g. Kirkinen et al., 2007a, 2007b; Nilsson and Nilsson, 2004; Savolainen et al., 1994).

The objective of this study is to assess the greenhouse impacts of FT diesel technology under development based on using peat as the raw material in Finland. For comparison, the greenhouse impacts of FT diesel based on logging residues and reed canary grass (RCG) as well as of fossil diesel are studied. Different peat production alternatives, FT diesel processing concepts and land-use options of peat production areas are studied in order to find out which would be the most suitable way from a climatic point of view to produce peat-based FT diesel (later in this study peat diesel). Other environmental impacts are not considered.

2. Description of FT diesel production

Fischer–Tropsch diesel (FT) technology using coal and natural gas as raw material is commercially used but biomass-based FT production process is under development and the first commercial-scale plant is expected to be in operation in 2012–2015 (IEA Bioenergy, 2008).

The Fischer–Tropsch diesel process using solid raw material like woody biomass, reed canary grass or peat consists of the following process steps: drying of raw material, gasification, gas cleaning and conditioning, FT synthesis and final upgrading of FT liquids. Cleaned and processed synthesis gas is predominately a mixture of hydrogen and carbon monoxide. The synthesis gas can be then converted into a number of products. Products which can be used as transportation fuels include methanol, dimethyl ether, Fischer–Tropsch (FT) hydrocarbons, methane and hydrogen. In the overall synthesis-gas route to transportation biofuels, both the gasification and synthesis steps yield significant amounts of by-product energy in the form of either steam or fuel gas. Application of the conversion process at the pulp mill site will be highly favourable if the by-product energy of the conversion process can be fully utilised in the mill (McKeough and Kurkela, 2007; Saviharju and McKeough, 2007).

In this study, two production concepts of FT diesel have been assessed. The main emphasis is on the production of biomass diesel integrated into pulp and paper mill (Fig. 1). The fundamental idea in the integrated concept is that bark-based CHP plant of the pulp and paper mill is replaced by FT synthesis and the lost electricity production is purchased from the grid or some other power plant. The electricity output lost in the replacement is relatively large and therefore the emission per diesel fuel unit is high. Another option is a stand-alone FT diesel production plant with lower conversion efficiency but also lower requirement for purchased electricity per FT diesel produced compared to the integrated concept (Fig. 2). In both Figs. 1 and 2 the incremental energy flows are expressed in terms of lower heating value (LHV).

3. Methods of calculating of greenhouse impact

3.1. Approaches and system boundaries

Greenhouse impacts were assessed in this study by using Life-Cycle Assessment (LCA), described at principal level in ISO standards 14040–14043 (ISO 14040, 1997). LCA takes into account the environmental impacts all the emissions and sinks "from cradle to grave" inside the defined system boundary. LCA consists of four different stages: goal and scope definition, inventory analysis, impact assessment and interpretation. In this study, the LCA is used as an assessment method of greenhouse impact only. In the application of LCA on a biofuel product system, the functional unit offers a reference unit for which the inventory and impact assessment results will be presented, making it possible to compare the results with the results of reference products.

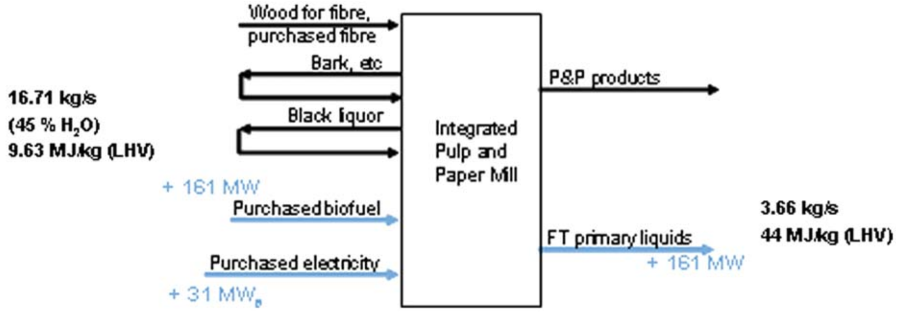

Fig. 1. The integrated production of Fischer–Tropsch diesel in the context of plant in forest industry (e.g. pulp and/or paper plant) changes the mass and energy balances of the plant. It has been assumed that the amount of purchased biomass-based raw material has been minimised in relation to the output of FT primary liquids. The purchased electricity replaces the electricity produced within the reference pulp plant without integration to the FT diesel plant (the fuel use of the gasification process is 267 MW_{fuel}) (Saviharju and McKeough, 2007).

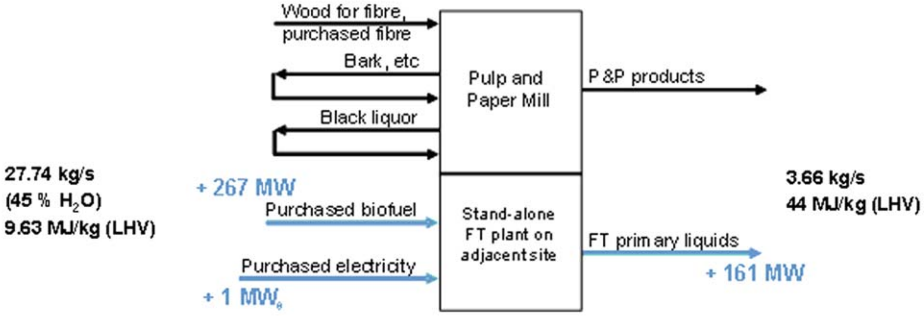

Fig. 2. Stand-alone production of Fischer–Tropsch diesel. The share of purchased biofuel is much greater compared to purchased electricity than in the integrated production of FT diesel (see Fig. 1). FT primary liquids production from solid biomass residues (267 MW_{fuel}) (Saviharju and McKeough, 2007).

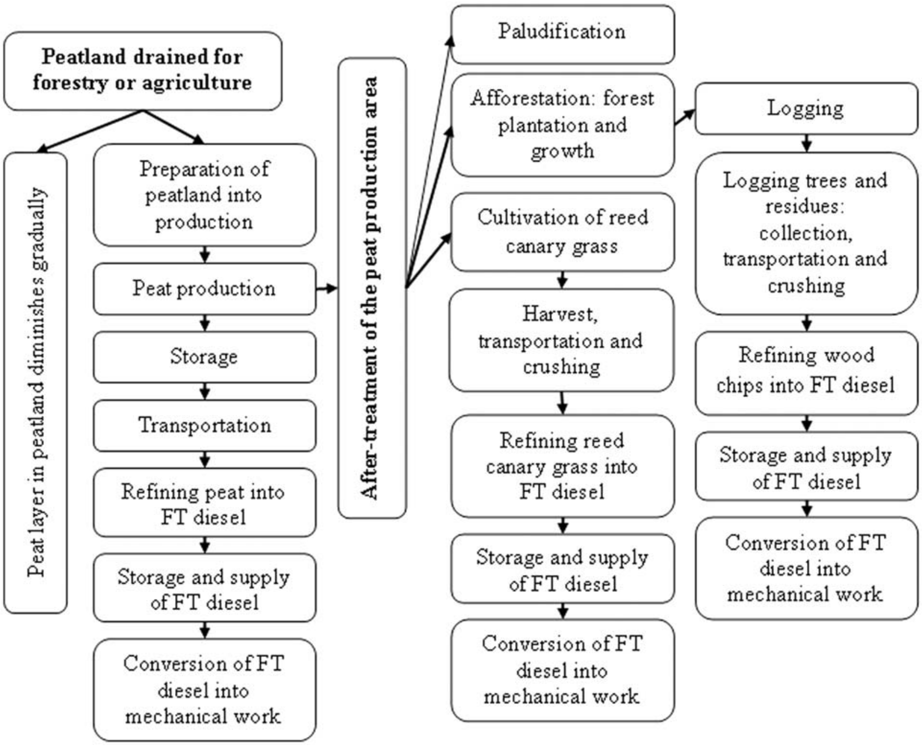

Fig. 3. Different phases of the life-cycle of studied peat diesel chains. If peat is not utilised, the peat layer in the soil will decay gradually from the drained peatland, causing greenhouse gas emissions. There are three different after-treatment choices considered in this study: paludification, afforestation and cultivation of reed canary grass (RCG). Wood biomass or RCG cultivated in the decommissioned peatland are assumed to be used as raw materials of FT diesel.

In LCA, goal and scope setting is a very crucial stage, ending up with the definition of the spatial and time-related system boundary and reference system, and selection of allocation methods. The goal may be set for very different perspectives, e.g. for global (e.g. overall climatic impacts), national/regional (e.g. country-specific emission targets, energy security issues, national/regional economy and other issues), actor (e.g. raw material or fuel producer) or consumer (e.g. guidance for more sustainable consuming) point of view. The convenience of allocating greenhouse impacts from various unit processes related to the system may be significantly different depending on the selected goal. Here, the considered fuel chains are assessed mainly from a climate change mitigation point of view. The economic and other possible barriers related to the feasibility of the particular fuel chains as well as indirect impacts caused from various market mechanisms were excluded in the assessment procedure used in this paper. The production of machinery, plants and infrastructure were excluded from all of the fuel chains considered due to lack of reliable data, as they are typically considered to be of minor importance (e.g. Fu et al., 2003; Bernesson et al., 2004; Börjesson, 1996), and as they compensate to some extent each other when fossil fuels are replaced by biofuels.

Inventory analysis is performed by collecting the information about greenhouse gas emissions and sinks during different phases of analysed diesel chains, from raw material production to the end-use of the processed fuels. The greenhouse impact of fuel chains have been analysed by using the radiative forcing method. Interpretation is done by using relative radiative forcing commitment (RRFC, Kirkinen et al., 2008) and comparing the impact of the peat diesel to other diesels (fossil, wood and reed canary grass) in order to perceive the relative extent of the impact, which is explained in more detail in the following section.

The studied life-cycle of peat-based FT diesel is presented simply in Fig. 3. Peatlands used as a raw material for diesel production in this study are drained peatlands for forestry and agriculture (organic soils). If these peatlands are not taken for energy peat production, then the peat layer gradually diminishes over time, causing greenhouse gas emissions and warming the climate; organic agricultural soils are remarkably more powerful in this respect than forestry-drained ones (Kirkinen et al., 2007b).

First the peatland is prepared for peat production. After peat production the peat is stored and transported to the refinery, where peat is processed into diesel, stored and supplied further. The last phase of the peat diesel chain is the conversion of peat diesel into mechanical power in vehicles.

The peatlands can be used for diesel production comprehensively, i.e. first the peat is extracted from the peatland and used for diesel production, and after that the bottom of the peatland can be used for the production of biomass. There are different alternatives for how the bottom of the peatland can be utilised after peat production. The options studied here are afforestation and cultivation of RCG which are assumed to be used as raw materials for FT diesel. As a comparison, after-treatment only including the long-term accumulation of the carbon storage in case of afforestation without utilisation of produced biomass is considered as an option. In addition, paludification was also considered as an after-treatment option.

3.2. *Greenhouse impact assessment*

Greenhouse impacts are measured by radiative forcing (RF), as RF is a rather more specific method for assessing a greenhouse impact compared to static GWP method (Kirkinen et al., 2008), especially in cases where emissions extend and change over long time horizons as in the case of peat. The commonly used GWP method takes the sums of the emissions by gases over a certain period considered and sums the gases together using GWP weights. The GWP and RF methods were compared by Kirkinen et al. (2009) and it can be concluded that within relatively short consideration periods the relative results of the two methods do not differ considerably but over longer time periods of interest the RF method gives more realistic picture on the greenhouse impact. Most studies concerning the greenhouse impact of peat utilisation have therefore used the RF method (e.g. Nilsson and Nilsson, 2004; Holmgren et al., 2006; Kirkinen et al., 2007a, 2007b, 2008; Hagberg and Holmgren, 2008).

Unlike the GWP method, RF takes into account dynamic changes in the emissions and sinks and also the direct removal of CO_2, CH_4 and N_2O from the atmosphere as functions of time. In the calculation of RF, the REFUGE model was used (e.g. Monni et al., 2003). The greenhouse impact of peat energy has earlier been assessed from the life-cycle point of view using radiative forcing as an indicator of greenhouse impact by Kirkinen et al. (2007a, 2007b) and by other authors (Holmgren et al., 2006; Savolainen et al., 1994).

Radiative forcing (RF) is typically expressed in Watts per square meter ($\mathrm{W\,m^{-2}}$) (IPCC, 2007). In this study the concept of relative radiative forcing commitment (RRFC) is used as an indicator for the greenhouse impact instead of RF expressed in $\mathrm{W\,m^{-2}}$ (Kirkinen et al., 2008). RRFC describes the ratio of the energy absorbed into the global atmosphere–surface system to the fuel energy produced in the considered fuel chain.

In the calculation of greenhouse impact, only the impact due to human activities has been assessed. The greenhouse impact of transportation fuels have been calculated with the following equation

$$I = I_U - I_R, \tag{1}$$

where I_U equals the impact from the production and utilisation of the studied fuel chain (i.e. impact from production of raw material, working machines, transportation, end-use, after-treatment). I_R equals the impact from the reference situation. Reference situation means normal development of the utilised resource during the studied time horizon. In the peat FT diesel chains this means the greenhouse impact of the peatland, in case it is not used for peat production.

RRFC express the results illustratively as it gives the proportion of the energy which is heating the globe to the energy produced in the fuel chain. RRFC can also be expressed as a function of integration time in order to give a dynamic cumulative picture of the caused effect. Varying time horizons can be studied separately, e.g. when studying the effects of different climate policies at varying time scales. The greenhouse impact is mainly assessed for the 100-year time horizons in this study but also for longer time scales.

4. Diesel fuel chains considered

The greenhouse impact of different fuel chains was assessed in this study. The studied transportation fuels include fossil diesel and FT diesel based on logging residues, RCG and various peat production chains. The main phases of the life-cycle of studied fuels with the reference case for the raw materials have been introduced in Table 1. As the reference use of raw materials was not considered in this paper, the reference case for crude oil-based diesel and reed canary grass-based FT diesel were non-extraction and non-cultivation, respectively. If logging residues were not collected for FT diesel, they were assumed to decompose in the terrain, releasing the carbon into the atmosphere.

Peat was produced by either using the normal milled peat production or the new peat production technique, which causes fewer greenhouse gas emissions during the production phase and is more efficient than the normal production technique. The same amount of peat can be produced in a much shorter time horizon and after-treatment can be started immediately after the area is cleared of peat (Silvan et al., 2008).

More than half of the peatlands in Finland are drained for forestry. In Southern and Eastern Finland 88–90% is drained (Turunen, 2008). Therefore, due to conservation of natural peatlands, it is recommended, also by the industry (Association of Finnish Peat Industries, 2009) that new peat extraction areas will not be opened in pristine peatlands. In Chains 4–8 and 11 peat is produced from forestry-drained peatland, and in Chains 9–10 peat is produced from cultivated peatland (Table 1). Kirkinen et al. (2007b) reported, however, that the greenhouse impact from combustion of peat fuel extracted from natural peatland is somewhat higher than that of peat extracted from forestry-drained peatlands if considered from the life-cycle viewpoint.

5. Parameter assumptions

5.1. *General*

In order to enable the calculation of the greenhouse impact of the fuel chains, values for the parameters of various phases inside the defined system boundary should be assumed. In all the calculation chains 1 GJ (0.28 TWh) of fuel is produced and utilised in the light-duty vehicle. The energy content of peat per hectare is assumed to be 33.840 $\mathrm{TJ\,ha^{-1}}$ (9400 $\mathrm{MWh\,ha^{-1}}$) in accordance with Leinonen and Hillebrand (2000). When biomass is produced in the after-treatment of the bottom of the peat production area, the area needed to produce 1 GJ of fuel reduces over time. Annual productivity of forest growth is assumed to be about 51,000 $\mathrm{MJ\,ha^{-1}}$ (Aro and Kaunisto, 2003; Kirkinen et al., 2007b) and of RCG about 100,800 $\mathrm{MJ\,ha^{-1}}$ (28 $\mathrm{MWh\,ha^{-1}}$) (Mäkinen et al., 2006).

Table 1
Studied transportation diesel chains and the main phases of their life-cycle

Chain	Starting point	Production and utilisation	After-treatment	Utilisation of after-treatment	Reference case
1	Crude oil	Production and FT diesel refining	–	–	–
2	Logging residues	Collection, crushing, transportation and FT diesel refining	–	–	Decomposition of logging residues
3	Reed Canary Grass	Cultivation, harvesting, crushing, transportation and FT diesel refining	–	–	–
4	Forestry-drained peatland	Peat production with milled peat technique, storage, transportation and FT diesel refining	Afforestation	–	Normal development of forestry-drained peatland
5	Forestry-drained peatland	Peat production with milled peat technique, storage, transportation and FT diesel refining	Paludification	–	Normal development of forestry-drained peatland
6	Forestry-drained peatland	Peat production with milled peat technique, storage, transportation and FT diesel refining	Cultivation of RCG	RCG is refined into FT diesel	Normal development of forestry-drained peatland
7	Forestry-drained peatland	Peat production with milled peat technique, storage, transportation and FT diesel refining	Afforestation	Wood biomass is refined into FT diesel	Normal development of forestry-drained peatland
8	Forestry-drained peatland	Peat production with new technique, storage, transportation and FT diesel refining	Afforestation	Wood biomass is refined into FT diesel	Normal development of forestry-drained peatland
9	Cultivated peatland	Peat production with new technique, storage, transportation and FT diesel refining	Afforestation	–	Normal development of cultivated peatland
10	Cultivated peatland	Peat production with new technique, storage, transportation and FT diesel refining	Afforestation	Wood biomass is refined into FT diesel	Normal development of cultivated peatland
11	Forestry-drained peatland	Peat production with new technique, storage, transportation and FT diesel refining in stand-alone process	Cultivation of RCG	RCG is refined into FT diesel	Normal development of forestry-drained peatland

Greenhouse gas emissions of the fuel chains considered are caused as soil-based emissions and by production of the auxiliary energy and chemical inputs required. The system boundaries and emission assumptions for fossil diesel are those presented by Edwards et al. (2003) and Mäkinen et al. (2006), and for FT diesel chains based on logging residues and reed canary grass those presented by Mäkinen et al. (2006), with a few exceptions. Firstly, the emissions from electricity production are assessed in accordance with Soimakallio et al. (2009). Secondly, the dynamics of logging residue decay are taken into account and assumed to be in accordance with Liski et al. (2005) and Kirkinen et al. (2008). Thirdly, the emissions given in terms of CO_2-eq. only by Mäkinen et al. (2006) or Soimakallio et al. (2009) are separated here as CO_2, CH_4 and N_2O based on the expert assessment of the authors. The emission data for the main phases of fossil diesel and FT diesel based on reed canary grass and logging residues are presented in Appendix A (Tables A1–A3 respectively).

The greenhouse gas emissions due to the used electricity shall be assessed, too. However, an unambiguous assessment of emissions from production of electricity required for a certain purpose is difficult as it significantly depends on which technology the electricity is produced. The issue gets even more difficult as it is very difficult to define what kind of technology or technology mix is used just for the particular purpose under consideration. When grid-based electricity is used, which is the typical case, system impacts on the electricity market should not be excluded.

According to Soimakallio et al. (2009), system impacts of consuming grid-based electricity in certain processes should be considered in accordance with marginal electricity production. However, the consumer may also invest in some particular electricity production form (e.g. low-emitting wind power or bioenergy) and thus increase its share in the electricity generation mix. In that case, the system considered would no longer only deal with the F-T diesel process, but also with general electricity production. Generally the consumer, however, has the possibility to cause system impacts diverging from the marginal side. Soimakallio et al. (2009) defined a wide stochastic range of 0–900 g CO_2-eq./kWh_e for emissions from electricity consumption in Nordic countries by taking into account the above-mentioned methodological issues. The lower and upper limits of that range were considered as deterministic figures in this paper.

Biomass-based CO_2 emissions are considered as emissions in this paper, as the carbon sequestration is considered separately in the method. The decay of the logging residues have been calculated by a model called YASSO (Liski et al., 2005, Fig. 1 in Kirkinen et al., 2008). The remaining carbon stock has been presented as a function of time. Logging residues decay very fast during the first 20 years, but after that the decay slows down and there might be some of the material left after 300 years which has not yet decayed. For FT diesel based on reed canary grass, however, it was assumed that there are no CO_2 emissions, because the carbon sequestration into RCG is fast (only 1 year) (see Appendix A, Table A3).

5.2. *Peat-based Fischer–Tropsch (FT) diesel*

Calculation of the greenhouse impact peat diesel chains was simplified by assuming that the peat is produced from site in 1 year. Peat is produced either from forestry-drained or cultivated peatlands. These sites are both sources of greenhouse gases. Peat is assumed to be produced either by traditional milled peat production or by using the new peat production technique (biomass dryer) which is based on a more efficient and less emitting way to produce peat (Silvan et al., 2008). Refining peat into diesel and the end-use of peat diesel also causes emissions, e.g. through the consumption of electricity. The after-treatment of utilised peatland also has an impact on the results.

Forestry-drained peatland is a moderate source of emission regarding CO_2 and sometimes also N_2O. When the peatland has been ditched and the water level has been lowered, peat has come into contact with oxygen and started to decay. Cultivated peatland is a remarkable source of emissions regarding CO_2 and N_2O and a

Table 2
Emission data of different phases of the peat diesel life-cycle.

	CO_2	CH_4	N_2O
Average emission data of peatlands considered in this study (Kirkinen et al., 2007a, 2007b).			
Forestry-drained peatland	224 (g/m^2/a)	0 (g/m^2/a)	0.1 (g/m^2/a)
Cropland	1.760 (g/m^2/a)	$-$0.147 (g/m^2/a)	1.297 (g/m^2/a)
Peat production techniques (Kirkinen et al., 2007a, 2007b).			
Milled peat technique	9.32 (g/MJ)	0.0046 (g/MJ)	–
New peat production technique (biomass dryer)	2.45 (g/MJ)	0.0007 (g/MJ)	–
Refining and use of peat-based FT diesel (Kirkinen et al., 2007c).			
Emissions from electricity requirement in integrated plant (marginal electricity 900 g CO_2/kWh)	50.46 (g/MJ$_{FT}$)	0.014 (g/MJ$_{FT}$)	0.003 (g/MJ$_{FT}$)
Emissions from electricity requirement in stand-alone plant (marginal electricity)	1.79 (g/MJ$_{FT}$)	0.001 (g/MJ$_{FT}$)	g/MJ$_{FT}$
Emissions from electricity requirement in integrated plant (zero emission electricity)	0.08 (g/MJ$_{FT}$)	g/MJ$_{FT}$	–
Storage and distribution	0.82 (g/MJ$_{FT}$)	0.0012 (g/MJ$_{FT}$)	0 (g/MJ$_{FT}$)
Emissions from process due to CO_2-loss (integrated plant)	42.7 (g/MJ$_{FT}$)	g/MJ$_{FT}$	–
Emissions from process due to CO_2-loss (stand-alone plant)	117.9 (g/MJ$_{FT}$)	g/MJ$_{FT}$	–
Direct emissions from end use	70.7 (g/MJ$_{FT}$)	[a]	[a]
Afforestation in the after-treatment phase of peatland utilisation (Kirkinen et al., 2007b).			
Sequestration of carbon into growing biomass[b]	$-$448 (g/m^2/a)	–	–
Accumulation of aboveground forest litter[b]	$-$147 (g/m^2/a)	–	–
Accumulation of belowground forest litter	$-$15 (g/m^2/a)	–	–
Production and utilisation of logging residue FT diesel from after-treatment phase (Mäkinen et al., 2006).			
Production and utilisation of logging residue FT diesel (marginal electricity)	50.95 (g/MJ$_{FT}$)	0.015 (g/MJ$_{FT}$)	0.003 (g/MJ$_{FT}$)
Production and utilisation of logging residue FT diesel (zero emission electricity)	2.74 (g/MJ$_{FT}$)	0.002 (g/MJ$_{FT}$)	0.001 (g/MJ$_{FT}$)
Restoration (Kirkinen et al., 2007b).			
Paludification	$-$121.6 (g/m^2/a)	22.66 (g/m^2/a)	0 (g/m^2/a)

[a] Emissions are dependent on what kind of engine is used and under what conditions fuel is combusted. When different fuels are compared in the same consumption target, CH_4 and N_2O emissions do not in practice have differences among the compared fuels.

[b] During long time phases (e.g. 100 years) it is assumed that carbon sequestered into forest achieves the averaged maximum carbon storage over rotation period in 45 years.

modest source of methane. The decay of peat is very fast in cultivated peatlands and the utilisation of these areas for energy peat production would be quite desirable, but in practise it is minimal (Kirkinen et al., 2007a, 2007b). The average emissions of forestry-drained and cultivated peatlands are presented in Table 2.

Peat decays in peat production fields and storage, causing emissions. Peat production causes emissions also through working machines. Usually peat is produced by milling the peat from the surface of the peatland. The milled peat is dried in the sun and during this it is harrowed and turned few times to fasten the drying process. When peat has reached approximately 40% moisture content, the peat is collected and transported, e.g. to a power plant.

A new peat production technique has also been considered in this study (Silvan et al., 2008). It has been developed by VTT Technical Research Centre and the largest Finnish peat production company, Vapo Ltd. In the new technique, only a small fraction of the peat production area is open for the production at the time, which differs from the traditional technique, where the whole area is open for a long time, up to 15 years. The area under production is emptied of peat down to the bottom, all at once. Peat is pumped into an asphalted drying field, where it dries faster and more efficiently than in the traditional field and it is also less vulnerable to weather changes. Other advantages of the new technique are the decrease of dust emissions and the possibility of after-treating the excavated area, immediately after production. Also, with the traditional milling technique it was not possible to utilise all the peat according to the shapes of the bottom soil of the peatland, and some amount of residual peat was left in the area, which started to decay, causing greenhouse gas emissions. With the new technique it is possible to collect practically all the peat from the production area so that no residual peat is left to decay and therefore causing emissions. Greenhouse gas emission data of peat production techniques is presented in Table 2, in which the emissions due to the use of e.g. working machines, emissions from peat production area and storing are included.

When peat diesel is produced, it is stored and transported to refineries, where it is processed initially as FT primary liquids and subsequently as FT diesel. The yield of processing FT diesel from FT primary liquids in the integrated process has been assumed to be 93% from in terms of energy content and 56% in the stand-alone process, respectively (Kirkinen et al., 2007c). Emission factors for peat-based FT diesel processes considered are given in Table 2.

In this study, different options for the after-treatment of the bottom of the peat production area were assessed: namely afforestation, cultivation of RCG and paludification. It was also assumed that in some chains (6–8, 10–11) the peatland is after-treated following peat production and the produced biomass used for the production of FT diesel. In Chains 4 and 9 the calculations only included the average carbon storage of the forest biomass developed over long time horizons (including sequestration of carbon into growing biomass and accumulation of above- and belowground biomass, see Table 2), and utilisation of the biomass was excluded. In the chains where produced biomass in the after-treatment phase are utilised into FT diesel production, the emissions from the production and utilisation of biomass were taken equally into account.

When the wood biomass from afforestation is utilised further as FT diesel, the emissions of the production and refining of diesel also need to be taken into account. In the after-treatment phase it is assumed in order to enable calculations that wood biomass is carbon neutral (no emissions from process or end-use). The approach used in the calculation of the greenhouse impact of solely forest residues-based FT diesel is different (see Appendix A, Table A2), due to more detailed information available about the decay of logging residues. Greenhouse gas emissions and sinks from afforestation and utilisation of wood biomass are presented in Table 2.

If peatland is restored back into a functioning peatland after peat excavation, the emission data is similar to the emissions from the pristine peatland (in this study assumed to be fen) (Kirkinen et al., 2007b). The emissions related to restoration are presented in Table 2. Production and utilisation of RCG is also a suitable option of after-treatment for the peatland. The emissions of cultivation and handling of RCG as well as production and refining of RCG diesel are presented in Appendix A (Table A3).

6. Results

The greenhouse impacts of different peat diesel chains are presented in Figs. 4–6. Results are presented as stated in the section of calculation methods as dimensionless units in terms of Relative Radiative Forcing Commitment (RRFC), which expresses the absorbed energy in the global atmosphere–surface system due to the production and utilisation of energy as the ratio of the absorbed energy to the energy content of the produced fuel. The results are first shown by components in Fig. 4, where the impacts of different phases of production and utilisation of peat diesel can be identified. The greenhouse impact of peat diesel (produced from cropland, after-treatment choice is afforestation) is shown over a 100-year time horizon. The total impact is the sum of the positive (warming) impact of peat production, refining, end-use and losses and negative (cooling) impact, which shows the extent of impact of peatland emissions, which will not release into the atmosphere, since the peat is excavated from the area for diesel production. After-treatment has also taken into account when the use of the bottom of peatland and the utilisation (produced biomass is further refined into diesel) of that is taken into account. Fig. 4 shows that the largest greenhouse impacts are due to the refinement, storage and supply of peat diesel, end-use and losses in the process. During 100 years' time horizon the avoided greenhouse impact from the utilised peatland decreases the total impact by about one fifth. The impact of afforestation is neutral since the emissions from producing and using logging residue-based diesel neutralises the cooling impact of the carbon sequestration in the wood biomass. However, in this chain the total greenhouse impact is assessed including both peat and wood biomass-based diesel produced on the site during 100 years, where the share of peat diesel is 90% and share of wood biomass diesel is 10%.

In Fig. 5 the greenhouse impact of different transportation fuels has been shown dynamically over the 300-year time horizon. The greenhouse impact describes the cumulative impact over the chosen time horizon. The electricity used in the process is assumed to be marginal electricity (generated in Nordic electricity markets), which has a major impact on the total greenhouse impact. In Chains 6–8 and 10–11 the share of peat and biomass produced in the after-treatment changes over time. The most significant greenhouse impact is caused when forestry-drained peatlands are used for peat diesel production only (Chains 4–5). If peat is produced from cropland, the greenhouse impact is lower than for fossil diesel after about 240 years from original peat excavation. The use of peatland for the production of biomass during the after-treatment phase leads to lower greenhouse impact than utilising only peat because the biomass produced in the chain is considered carbon neutral, apart from the emissions from refining the biomass into diesel. The greenhouse impact of peat-based FT diesel is much higher in the beginning when compared to reference fuels considered due to the higher need for energy and raw material input to the process. Also in the peat-fired process product yields are lower than those of the wood-fired process due to the lower extent of carbon conversion during

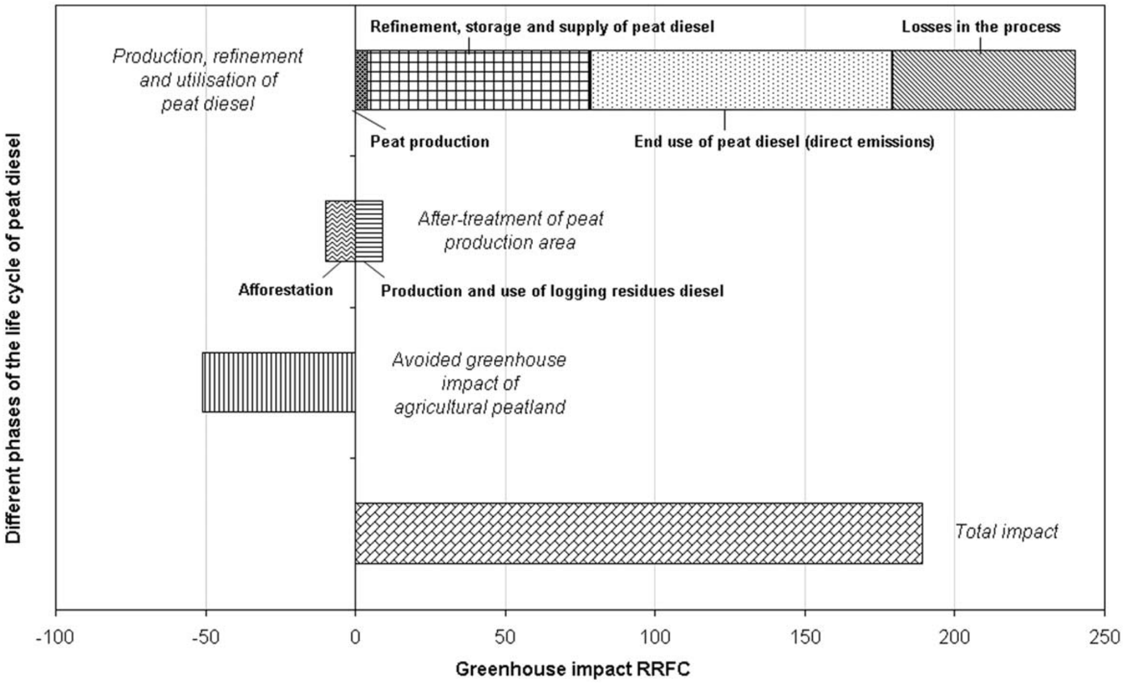

Fig. 4. The greenhouse impact of peat diesel chain from a 100-year time horizon divided into different phases. Peat is produced from cropland and refined into FT diesel. After peat production the area is forested. The produced biomass is further used for FT diesel production. Electricity used in the FT process is assumed to be marginal (generated by power plants in a marginal position in the Nordic electricity system), which has major impact on the total greenhouse effect. The share of peat diesel produced in the chain is 90% and wood biomass diesel 10%.

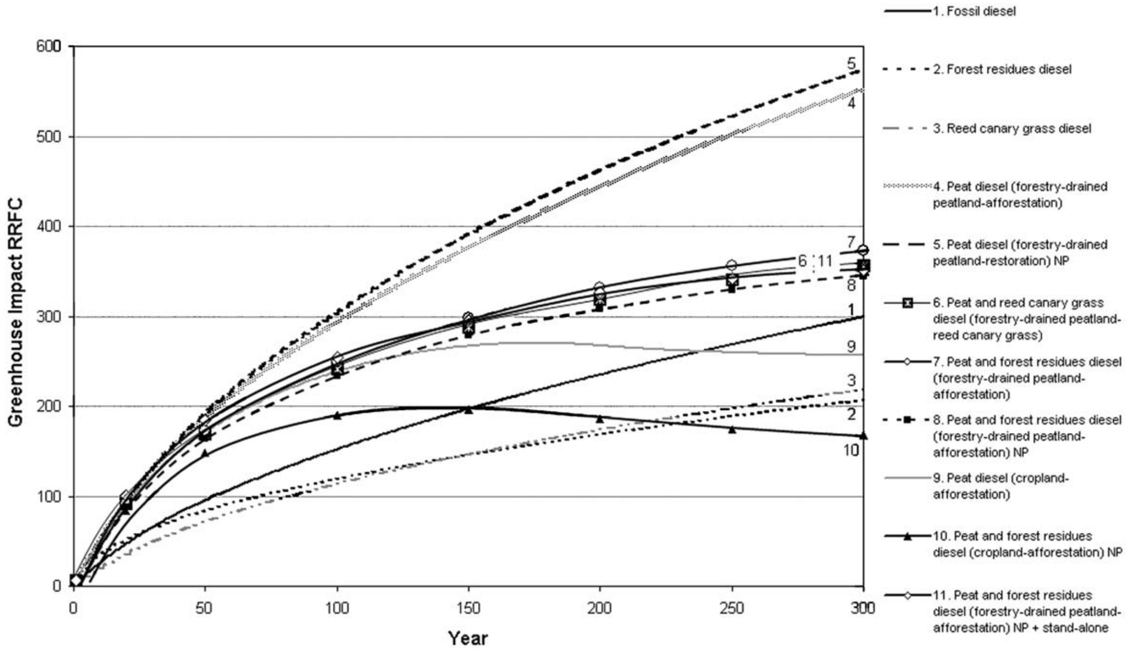

Fig. 5. The dynamic cumulative greenhouse impact of different transportation fuels assessed in the study during 300 years. Electricity used in the FT process is assumed to be marginal (generated by power plants in a marginal position in the Nordic electricity system), which has a major impact on the total greenhouse impact. In Chains 6–8 and 10–11 the share of peat produced in the chain decreases as a function of time, since the longer time of after-treatment leads to larger production of renewable biomass.

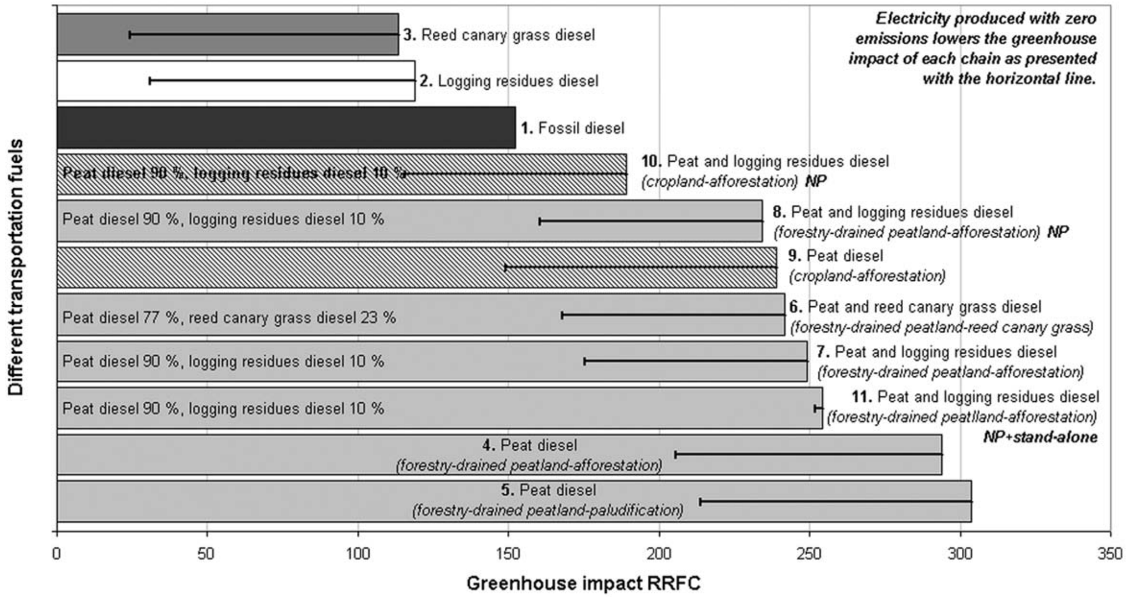

Fig. 6. Greenhouse impact of different transportation fuels integrated over a 100-year time horizon presented with RRFC. The left end of the thin horizontal line in the each FT diesel bar indicates the greenhouse impact, when the electricity used in the FT diesel process corresponds to zero emissions. NP equals new peat production (harvesting) technique. The share of peat diesel and logging residue or reed canary grass diesel is shown under each chain, where both have been produced. Example of reading the values of the figure: In the case of fossil diesel (Chain 1) about 150 times more energy is absorbed to the atmosphere–surface system within the time horizon of 100 years due to the emissions from the production and use of the fuel than bound in the produced diesel fuel in the fuel production chain.

gasification. The greenhouse gas emissions from the peat-based FT diesel processing are about 6 times higher of those of the fossil diesel.

The greenhouse impacts of studied fuel chains for a 100-year time horizon are presented in Fig. 6. The minimum of the horizontal thin lines presented in each of the FT diesel chain in Fig. 6 indicate the greenhouse impact, if the electricity used in the refining process corresponds to electricity without causing any emissions (with zero emission electricity). During the 100-year time horizon, FT diesel produced from RCG or logging residues results in a lower greenhouse impact than using fossil diesel or peat as a source of FT diesel. If marginal electricity is used in the diesel production process, the peat-based FT diesel has a higher greenhouse impact during a 100-year time horizon than fossil diesel. The emissions from electricity production have a large impact on the results and if zero emission electricity is used in the process, the greenhouse impact of peat diesel produced from croplands has, to some extent, a lower greenhouse impact than fossil diesel during 100 years.

The differences in the greenhouse impacts of various peat-based FT diesel chains are due to peat production site, peat production technique used, and after-treatment option implemented. When peat is produced from croplands, the greenhouse impact is the lowest of all peat production options considered due to avoiding the relatively fast decay of peat in agricultural sites in the reference case. When peat is produced by using the new peat production technique (Chains 8 and 10), the impact is slightly lower compared to the conventional production technique. If the produced biomass in the after-treatment has been taken into account in the total impact, the impact is remarkably lower compared to the assessment where only peat has been taken into account (Chains 4 and 7). This is due to the fact that a fraction of emission-intensive peat raw material is replaced with renewable biomass. If the after-treatment is the cultivation of RCG and utilising it into FT diesel, this causes a slightly lower greenhouse impact than if the after-treatment is afforestation. The production of FT diesel in integrated plants results in a lower greenhouse impact than production in a stand-alone plant, due to better overall energy and raw material use efficiency. This can be seen by comparing the Chains 8 and 11.

7. Discussion

The use of peat as a raw material for diesel fuel decreases the dependency on mineral oil which all is imported to Finland. Renewable biomass like forest residues can also be used as a raw material for diesel production. However, the demand for forest residues would be very high if a remarkable share of diesel fuel consumed in Finland were produced. Nonetheless, the demand for forest residues will grow strongly due to their increasing use in combined electricity and district heat production. Hence, a possible use of peat instead of forest residues as raw material for diesel would help in fulfilling the fuel demand for electricity and heat. Further, FT diesel production units would be relatively large ones whose raw material demand is difficult to fulfil with sparsely available forest residues.

The greenhouse impact of peat diesel has been assessed by using RRFC, which describes the absorbed energy in the global atmosphere–surface system as a ratio to fuel energy. RRFC is a suitable method for calculation in the cases where dynamic evaluation is of interest (e.g. when greenhouse gas emissions/sinks extend over a considerable time or it is wanted to describe the impact of the different lifetimes of greenhouse gases exactly as functions of time). The greenhouse impact of the use of peat for energy has been assessed in Sweden by using similar RF-based methodology as in this study (e.g. Nilsson and Nilsson, 2004; Holmgren et al., 2006; Hagberg and Holmgren, 2008).

The length of the time horizon of interest is related to the objectives of the climate policy. The international and EU level goals in the mitigation of climate change gives a framework for the time horizons in which measures to cut emissions need to be made. At the moment the EU proposal for the world's climate mitigation policy is to halt global warming so that the global average temperature rise would not exceed 2 °C. According to IPCC (2007) this would mean that global greenhouse gas emissions would already need to be cut by 50–85% by 2050. This means that significant actions to reduce greenhouse gas emissions need to be carried out during relative short time horizons, i.e. the next few decades. Consequently, it is reasonable to use the time horizon of 100 years or even less in the assessment of the greenhouse impact of various actions. The 300-year time horizon calculated in this study in Fig. 5 is rather theoretical and should only be used in the relation to where the emission reduction measures can be carried out at a slow pace and the target of the global temperature rise may be exceeding 3 °C or more.

The technology to produce FT diesel from biomass or peat is not yet fully commercially available. Gas cleaning and catalysts in particular require some development work. Furthermore, the energy use and greenhouse gas emissions from the last phase in the FT diesel production – upgrading of the FT primary liquids to diesel fuel – have not yet been assessed in detail.

Carbon capture and storage (CCS) can be one option for lowering the greenhouse impact of the production of peat diesel, since in the FT process the main share of CO_2 is removed from the synthesis gas before the FT synthesis due to technical reasons, as CO_2 as inert gas inhibits desired reactions in the FT synthesis. In the FT process it is possible to capture the majority (about 70%) of the carbon losses in the refining process. This has a reducing impact on the total greenhouse impact of peat diesel. CCS also has an impact on the total assessment and comparison between FT diesels and fossil diesel, since CCS cannot capture emissions from fossil fuel refining process to the same extent that the emissions can be captured from the FT diesel production process, because the CO_2 emissions in the refining of fossil diesel are much lower than in the refining of FT diesel. However, there are many issues to be considered in relation to the utilisation of CCS, such as technological issues, costs and a regulatory CO_2 storage framework which does not yet exist.

The assumptions and system boundaries used in the study have considerable impact on the results. The most important ones are those related to the definition of the diesel production chains, especially considering reference use of peat reserves utilised, land use during after-treatment, and those related to the integration of the FT process in pulp and paper mill and the impacts of the additional electricity production needed. Also, the purposes of the assessment have an impact on the system boundaries and relevant assumptions, meaning whether the assessment is made for climate change mitigation for seeking alternatives for fossil transportation fuels, for defining the most reasonable use of peatlands emitting greenhouse gases, or for considering the energy security issues.

In the after-treatment of some of the assessed peat diesel chains there are two different approaches: in some chains, the produced biomass has been included in the evaluation as raw material for diesel production and some take into account only peat. The approach where the produced renewable biomass (wood and reed canary grass) is utilised is justified from the land use perspective to see the most reasonable after-treatment choices from a climate and productivity point of view. However, the calculation chains where only peat as a raw material for FT diesel has been taken into account gives a picture of the greenhouse impact of the peat diesel itself.

Integrated production differs from the stand-alone production due to the lower need of raw material and the need of electricity to replace the lost electricity production of the pulp mill. In this study most of the peat diesel chains have been assessed to be produced in integral process, where the need of peat raw material has been minimised. One example of the stand-alone production of peat diesel has been introduced. The need for raw material is thus much higher, which has an impact on the loss of carbon in the process. The loss of carbon in the process is nearly three times more than in the integrated process, but then the need for electricity is minor.

The information related to peat production techniques, carbon content of peat and FT diesel and refining is relatively accurate, whereas the greatest uncertainties are related to the information about the emissions of peatlands in reference cases. There are eleven different chains assessed in this study which gives a relatively broad picture on the impact of different parameters and assumptions on the results. However, the parameter uncertainty was only considered for emissions from electricity production which have a large impact on the results. The sensitivity of the calculation parameters are, to large extent, covered by different assumptions in the calculation chains like different emission rates of the forestry-drained peatlands and the cultivated peatlands. Uncertainties due to peatland reference emission rates in the case of peat-based energy production are considered by Kirkinen et al. (2007a, 2007b). The emission data of the drained peatland is higher in Sweden, which may be due to different land-use history of peatlands, more Southern location or partly due to different measurement and assessment methods.

8. Conclusion

The greenhouse impact of the peat diesel fuel depends very much on possible integration of the diesel plant to an energy-consuming plant, e.g. a pulp and paper plant. In stand-alone diesel plants, the greenhouse impact is much larger than in the case of integration.

In the integrated plant the greenhouse impact mainly consists of three components: the impact of additional electricity needed, the end-use of peat diesel, and carbon losses in the FT process. The type of peatland used for peat production also has a notable impact on the results. The net greenhouse impact is considerably reduced if agricultural peatlands are used for peat production; those peatlands produce high greenhouse gas emissions anyway. In the cases where the greenhouse impact of the peat diesel is studied for optimal planning of the used area of peatland, the benefit of being able to produce biomass at the bottom of the peatland after peat production has been taken into account, which has a decreasing impact on the total net greenhouse impact. The greenhouse impact of the peat diesel is, however, in most cases higher than the impact of fossil diesel when marginal electricity is used in the process. Also, the time horizon of the assessments has a large impact on the results. The choice of time horizon is dependent on the climate change mitigation policy. In this study the time horizon used is mainly 100 years. The climate mitigation target of EU is not to exceed the global temperature rise over 2 °C, which means that the emissions need to peak already in the next decades; the focus should even be targeted on time horizons of less than 100 years.

If peat is produced from peatlands, which are significant emission sources (especially those lands drained for agriculture), the total impact can be lower due to avoided emissions from the utilised peatland. Also, if the after-treatment of the bottom of the peatland is taken into account, the impact is lower compared to the impact where only peat has been taken into account. The greenhouse impact can also be lowered by installing electricity production based on sources with low specific greenhouse gas emissions to supply the electricity demand of the system. However, the assessment of this assumption includes complicated considerations on the behaviour of the electricity production network which may not support the assumption.

The use of peat as a raw material for diesel fuel decreases the dependency on mineral oil which all is imported to Finland. Peat is suitable for the FT diesel process from a technological point of view, but the production and utilisation of peat-based FT diesel needs to be considered with caution from a climate perspective; thus, the possibilities to mitigate climate change by using peat diesel are quite limited when the whole life cycle is considered.

Table A1
Emission data of different phases in fossil diesel life-cycle (Edwards et al., 2003; Mäkinen et al., 2006).

Phases of life cycle	CO_2 (g/MJ)	CH_4 (g/MJ)	N_2O (g/MJ)
Production of crude oil	3.33	0	0
Transportation of crude oil	0.81	0	0
Refinement of crude oil	8.60	0	0
Transportation of diesel oil	0.23	0.0001	0
Storage of diesel oil	0.10	0.0002	0
Distribution and dosage of diesel oil	0.72	0.001	0
Use of diesel oil in engine	73.3	[a]	[a]

[a] Emissions are dependent on what kind of engine is used and under what conditions fuel is combusted. When different fuels are compared in the same consumption target, CH_4 and N_2O emissions do not in practice have differences among the compared fuels.

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Appendix A

Detailed greenhouse gas information on the greenhouse impact assessment of comparative fuels: fossil diesel, reed canary and forest residues-based Fischer–Tropsch diesels (Tables A1–A3).

Table A2
Emission data of different phases in logging residue diesel (Mäkinen et al., 2006).

Different phases of the utilisation of logging residue FT diesel	CO_2 (g/$MJ_{FT\ diesel}$)	CH_4 (g/$MJ_{FT\ diesel}$)	N_2O (g/$MJ_{FT\ diesel}$)
Baling, forest transportation, chipping, long distance transportation, transfers (emissions caused by the use of diesel oil)	1.84	0.0001	0.0007
Crushing (marginal electricity)	0.21	–	–
Refining (marginal electricity)	48.07	0.01	0.003
Refining (zero emission electricity)	0.08	0.0007	–
Storage and distribution	0.82	0.001	0
Emissions from process	39.7	–	–
Direct emissions from end use	70.7	[a]	[a]

[a] Emissions are dependent on what kind of engine is used and under what conditions fuel is combusted. When different fuels are compared in the same consumption target, CH_4 and N_2O emissions do not in practice have differences among the compared fuels.

Table A3
Emission data of the different phases in reed canary grass diesel life-cycle (Mäkinen et al., 2006).

Different phases of the utilisation of RCG diesel	CO_2 ($g/MJ_{FT\ diesel}$)	CH_4 ($g/MJ_{FT\ diesel}$)	N_2O ($g/MJ_{FT\ diesel}$)
Energy used in the machines during cultivation, cutting and harvesting	0.55	–	0.0002
Baling, crushing of bales	0.35	–	0.0001
Long distance transportation	1.53	–	0.000
Production and transportation of limestone	0.30	0	0
Production and transportation of fertilizers	1.51	0.0005	0.006
Refining (marginal electricity)	50	0.014	0.003
Refining (zero emission electricity)	0.1	0.001	–
Storage and distribution of FT diesel	0.82	0.0012	0
CO_2 emission of soil from lime stoning	3.21	0	0
CO_2 emission of soil from fertilizing	0	0	0.015

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Greenhouse impact assessment of some combustible fuels with a dynamic life cycle approach

Abstract

Climate change mitigation requires steep reductions in greenhouse gas emissions. New sustainable solutions to provide low-carbon energy production will be needed. In this thesis the greenhouse impacts of some combustible fuels were comprehensively assessed using Life Cycle Assessment. A dynamic analysis method called Relative Radiative Forcing Commitment was developed in order to provide clear, unambiguous data to inform effective climate change mitigation strategies. RRFC gives a dynamic approach to greenhouse impacts and demonstrates their significance.

The greenhouse impacts of a variety of fuels were assessed: peat, coal, forest residues and reed canary grass, together with different diesels – Fischer-Tropsch (from peat and forest residues), Jatropha and fossil crude oil. Biomass-derived fuels are considered as one way to decrease greenhouse gas emissions. In the past, they were often held to be carbon-neutral fuels. However, all biogenic fuels considered in this thesis have a warming impact on the climate, as their production requires fossil fuel inputs, and in addition, land use emissions from changing carbon pools may have large effect on the total greenhouse impact. If raw materials for fuel are produced by cultivation, the manufacture and use of fertilisers may be of great importance.

If global warming is to be halted at the level of 2 to 3 °C degrees Celsius, deep emission reductions will have to occur during the next decades. The RRFC of coal is about 180 over 100 years, thus if 1 MJ of coal is used for energy, the energy absorbed into the global atmosphere-surface system warms the globe by 180 MJ. Warming occurs due to the radiative forcing caused by concentration increases due to greenhouse gas emissions. The use of forest residues and reed canary grass for energy has one of the lowest greenhouse impacts, causing only about a tenth of the impact of coal. Natural gas has a greenhouse impact nearly one third lower than coal. The greenhouse impact of using peat for energy depends strongly on the type of peatland used of peat production, resulting in a lower or higher greenhouse impact than coal.

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Författarna
Johanna Kirkinen

Namn

Värdering av drivhuseffekten av vissa bränslen enligt den dynamiska livscykelsmetoden

Referat

Att mildra klimatförändringen kräver kraftiga minskningar i utsläppen av växthusgaser. Det behövs nya lösningar i enlighet med hållbar utveckling för att erbjuda kolfattig energiproduktion. Drivhuseffekten av vissa bränslen undersöktes omfattande med hjälp av livscykelvärdering i denna avhandling. Den dynamiska analysmetoden Relative Radiative Forcing Commitment utvecklades för att erbjuda tydlig och entydig information om effektiva strategier för att mildra klimatförändringen. RRFC möjliggör ett dynamiskt synsätt på växthuseffekter och påvisar signifikansen av dem.

Drivhuseffekten för olika bränslen värderades: torv, stenkol, hyggesrester, samt rörflen, och också olika dieselsorter – Fischer-Tropsch (torv och hyggesrester), Jatropha och fossil mineralolja. Bränslen som här-stammar från biomassa anses vara ett sätt att minska på emissionen av växthusgaser. Tidigare ansågs dessa vara kolneutrala bränslen. Alla i denna avhandling undersökta biogena bränslen har dock en värmande effekt på klimatet eftersom deras produktion kräver fossila bränsleinput och dessutom kan utsläpp från sönderfall av kolreservoarer ha en stor effekt på hela drivhusverkan. Ifall råmaterialen för bränsle härstammar från odlingar kan tillverkningen och bruket av gödsel vara mycket betydande.

Vill man stanna av den globala uppvärmningen på 2–3 °C måste man skära ner utsläppen radikalt under de kommande decennierna. Stenkolens RRFC är ca. 180 över 100 år, så om 1 MJ stenkol används för energi, värmer den i det globala atmosfär-ytsystemet absorberade energin jordklotet med 180 MJ. Värmningen uppstår pga. radiative forcing som orsakas av koncentrationssökningar till följd av utsläpp av växthusgaser. Energibruket av hyggesrester och rörflen har av de lägsta drivhuseffekterna, endast ca. en tiondedel jämfört med verkan av stenkolförbrukningen. Verkan av bruket av naturgas är nästan en tredjedel mindre än av stenkolförbrukningen. Drivhuseffekten av energibruket av torv beror mycket på vilken typ av torvmossa som används för torvproduktionen – slutresultatet kan vara antingen en lägre eller en högre drivhuseffekt än vad stenkolförbrukningen har.

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