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Aspects on bioenergy as a technical measure to reduce energy related greenhouse gas emissions

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Abstract

Greenhouse gas emission assessments of energy supply systems have traditionally included the CO_2 emissions produced as the fuel is burned. A lot of models and calculations for evaluating greenhouse gas emission savings by using bioenergy have been introduced. The approaches often cover a major part or sometimes even the whole energy system. The biofuel production process itself is one piece that is normally covered very briefly or considered insignificant. Unfortunately, this means that the significance of some affecting factors might not have been estimated.

The object of the thesis was to study the greenhouse gas balances in connection with the harvesting and production of biofuels and, based on this, evaluate in what situations there is a need to re-evaluate the potentials of greenhouse gas emission savings when using bioenergy for substituting fossil fuels.

Different methodologies were used in the separate evaluations: the philosophy and methodology of industrial ecology was used to analyse the sustainability and material flows of the Finnish forest industry. A simple calculation model was developed for analysing the energy consumption and greenhouse gas emissions for biomass production chains, upgrading of biofuels and production of solid recovered fuels. Emission risks from long-time storage of biofuel and biodegradable material were evaluated as well as changes in forest soil carbon due to harvesting of forest residues.

The examination of the biofuel production chains showed that in a favourable situation as much as 97–98% of greenhouse gas emissions for a fossil fuel could be avoided by substituting it with a biofuel. On the other hand the investigation also pointed out that e.g. increasing fuel storage and upgrading activities for biofuels are likely to decrease this percentage remarkably. The main conclusion of the thesis was that the neutrality of greenhouse gas emissions when producing bioenergy should be re-evaluated. The author further suggests that tools and stimulants for keeping the greenhouse gas emission levels in fuel production chains as low as possible should be developed.

Preface

The main part of the research work of this thesis was carried out as part of VTT research projects in the SIHTI Programme and the PUUENERGIA Programme of Tekes, the National Technology Agency of Finland, during the years 1995–2001. Professor Dan Asplund was the first one to encourage me to work in the field of biofuels and environment. During these years of working with projects and articles now leading to this thesis, Professor Ilkka Savolainen and D.Sc. (Tech.) Riitta Pipatti have been the persons providing the most important encouragement and guidance. I express my sincere gratitude to them for this.

I want to thank colleagues through the years, especially M.Sc. Taru Palosuo, Ph.D. Jari Liski, Professor Jouni Korhonen and M.Sc. (Tech) Sampo Soimakallio for fruitful co-operation in the research project leading to this thesis. Furthermore, I would like to acknowledge the pre-reviewers of my last two articles and the early draft of my thesis, Professor Ilkka Savolainen, D.Sc. (Tech.) Riitta Pipatti and Ph.D. Timo Nyrönen.

I am grateful to my supervisor Professor Carl-Johan Fogelholm and my instructor Professor Ilkka Savolainen for their patience and valuable comments. I would also like to express my gratitude to the official pre-examiners of my thesis, Professor Antti Asikainen and Professor Leif Gustavsson, for their comments.

The writing of this thesis was made possible by acknowledged support of VTT Processes and the Academy of Finland.

Last but not least, finishing this thesis has also been a family project – with my children Karri and Irina helping me with computer and language skills, Olga and Hugo providing background support and my husband Juha tenderly pushing me to sit down and "do it". All of this was done during our "mission" in Hungary – during a time when there would have been lots of more pleasant things to do.

List of original publications

This thesis is based on the following publications and some additional studies referred to and reported in the summary part:

I. Korhonen, J., Wihersaari, M. and Savolainen, I. Industrial ecology of the Finnish forest industry. *Ecological Economics* 39 (2001), pp. 145–161. Elsevier Science Ltd.

II. Wihersaari, M. Energy consumption and greenhouse gas emissions from biomass production chains. *Energy Conversation Mgmt* (1996), Nos 6–8, pp. 1217–1221. Elsevier Science Ltd.

III. Wihersaari, M. Greenhouse gas emissions from final harvest fuel chip production in Finland. *Biomass and Bioenergy* 28 (2005), pp. 435–443. Elsevier Science Ltd.

IV. Wihersaari, M. Evaluation of greenhouse gas emission risks from storage of wood residue. *Biomass and Bioenergy* 28 (2005), pp. 444–453. Elsevier Science Ltd.

V. Palosuo, T., Wihersaari, M. and Liski, J. Net greenhouse gas emissions due to energy use of forest residues – Impact of soil carbon balance. EFI Proceedings No. 39 (2001); Wood Biomass as an Energy Source Challenge in Europe. European Forest Institute, Joensuu. Pp. 115–130.

VI. Pipatti, R. and Wihersaari, M. 1998. Cost-effectiveness of alternative strategies in mitigating the greenhouse impact of waste management in three communities of different size. *Mitigation and Adaptation Strategies for Global Change* (1998), Vol. 2, No. 4, pp. 337–358. Kluwer Academic Publishers.

In Paper I Margareta Wihersaari made the calculations of the used data. The studies, which resulted in Paper II and IV, were conducted independently by her. She was the main researcher in the case study presented in Paper VI. In Paper III and V she had a central role in the formulation of the research objectives and in the treatment of the calculated results. The model applied in Paper V was constructed by Jari Liski.

Contents

Appendices

Papers I–VI

Appendices of this publication are not included in the PDF version. Please order the printed version to get the complete publication (http://www.vtt.fi/inf/pdf/)

Units and abbreviations

BC	base cations
CH_4	methane
C	carbon
CO_2	carbon dioxide
CO_2eq	carbon dioxide equivalent
dOC	degradable organic carbon
GHG	greenhouse gas
GWP	global warming potential
IPCC	Intergovernmental Panel on Climate Change
kg CO_2eq	kilogram of CO_2 equivalents
loose m^3	loose cubic metre
N	nitrogen
NO_x	nitrogen oxide
MJ	mega joule
MSW	municipal solid waste
MWh	mega watt hour
N_2O	nitrous oxide
pH	acidity
ppm, ppm(v)	part per million (volume)
m^3, solid m^3	solid cubic metre
SRF	solid recovered fuel
t	tonne
t_{dm}	tonne dry matter

1. Introduction

1.1 Global warming and energy related greenhouse gas emissions

Although the existence of an ongoing global warming process is disputed on[1] every now and then, some facts cannot be contradicted. The carbon dioxide level in the atmosphere is growing[2] and the changes in the concentration during the last hundred years have been estimated to mainly depend on human activity; changes in land use and utilisation of fossil fuels. The changes in the concentration of the greenhouse gases (GHG) in the atmosphere are calculated to affect the heat balance of the Earth; because of this, the mean temperature is expected to grow with 1.4–5.8°C during this century (IPCC 2001a). As the changes are relatively rapid compared with more natural cycles of the Earth, they are suspected to cause severe environmental disturbances such as rise of sea level, changes in precipitation, changes in the course of ocean currents, hurricanes, changes in biodiversity, losses in food production etc.

At the 1992 UN Conference on Environment and Development (UNCED) held in Rio de Janeiro, a Convention on Climate Change was signed. Its purpose is to stabilise greenhouse gas concentration levels in the atmosphere. The stabilisation of atmospheric concentration will take at least 100 years due to rapid growth of global population and consumption, slow change in economies and energy technologies and slow removal of greenhouse gases from the atmosphere. To start the mitigation of climate change, in the Kyoto Protocol (1997), more practical reductions and limitations of the GHG emissions were specified for the first commitment period (2008–2012). For Finland, this means that the emissions during this period have to be at the same level as in 1990, for EU15[3] a reduction of 8% has to be performed. There are still many open questions concerning this agreement, but the trend is clear: this is only the first step in the

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[1] It is difficult to detect statistically significant long-term trends in climat change over e.g. northern Europe because of the high inter-annual variability of climate (Kuusisto et al. 1996).

[2] The pre-industrial level of carbon dioxide in the atmosphere was about 280 ppm(v). In the year 2000 the level was 368 ppm, annually growing with about 1.5 ppm.

[3] The 15 member countries before EU enlargement 2004.

work against climate change. Soon it is time to begin to draft the objectives for a second commitment period, which is likely to be tougher and cause more expenses than the present one. It will also be necessary to give e.g. the developing countries their own targets as their emission levels are rapidly growing and will soon be at the same level as that of the industrial countries.

1.2 Renewable energy – a technical measure to reduce the energy related greenhouse gas emissions?

The Intergovernmental Panel on Climate Change (IPCC) gives general options for reduction of fossil fuel CO_2 emissions (IPCC 1996a,b; IPCC 2001b) such as improvement of energy efficiency, switching to less carbon-intensive energy sources, replacing fossil fuels by renewable energy sources and disposal of CO_2 emissions. A large part of the options recommended are already in use in Finland; additional potentials for cost-effective measures are estimated to be limited (Lehtilä et al. 1997). Wood energy is still considered to be a potential source of new energy in Finland, although about 20% of the energy used already originates from biomass. Conventional biofuels are firewood, fuel chips and by-products from the forest industry, such as saw dust, bark and black liquor. New, growing biofuel rates are expected to come from e.g. forest residues[4].

A lot of models and calculations for evaluating GHG emission savings by using bioenergy have been introduced in literature. Schlamadinger & Schwaiger (1997) calculated GHG emission savings for some countries and sectors, Schlamadinger et al. (1997) outlined a standard methodology for comparing the greenhouse gas balances of bioenergy systems with those of fossil energy systems. Also life cycle approaches have been used for evaluating various systems (Kaltschmitt et al. 1997, Jungmeier et al. 1998, Forsberg 2000, Mälkki & Virtanen 2001). As the approaches often cover a major part or sometimes even the whole energy system – involving energy conversion methods, conversion efficiencies and energy use – they have to be quite rough and system boundaries have to be quite well fixed, which might result in ignoring some important

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[4] The goal is to annually use 5 million solid cubic metres (10 TWh) of fuel chips produced from residual forest biomass by 2010 (Tekes 2003).

pieces of information. Different allocation rules[5] for environmental burdens make comparisons with other studies complex (Jungmeier et al. 1998, Mälkki et al. 1999). Some of the studies include no other GHG emissions than CO_2 (e.g. Malinen 1997, Korpilahti 1998, Forsberg 2000). The biofuel production process itself is one piece that normally is covered very briefly (Schlamadinger & Schwaiger 1997, Mälkki & Virtanen 2001) or considered insignificant. Unfortunately, this means that the magnitude of some affecting factors might not have been evaluated.

The forest industry is a considerable user of both energy and bioenergy. When studying forest fuel production systems in Finland, the connections and system boundaries between the raw material flow and the bioenergy streams have to be identified. Since biofuel production has to be sustainable to fulfil the biofuel requirements, also the forest ecosystem, forest industry material flows and its by-products have to be considered sustainable. Forests play an important role in the sequestration of carbon dioxide and the storage of carbon. Most of the Finnish forests are today used for producing raw materials for the forest industry; forest biofuels are mostly by-products from the forest industry. The tree stand is usually cut at an age of 60–120 years, the stem wood is utilised, residues left on site, and a new tree stand established as soon as possible after the clear cutting. In order to maximise the growth and improve the quality of the wood material, some of the trees are cut during the growing process (thinning etc.). The Finnish forests considered as a carbon pool are probably still growing; this is valid at least for the above ground biomass (NIR 2003). As the forest residues have until now mainly been left on site to decay when the stem wood has been taken out, a change in carbon balance for forest soil is likely to appear if residues will be taken out of the forests and utilised for e.g. as fuel (Liski et al. 1998). Börjesson (2000) identified three major factors that could affect the soil carbon pool. Firstly, the reduction of biomass input to the forest soil. Secondly, as an indirect impact, logging residue recovery reduces carbon mineralisation due to less optimal conditions for decomposers. Thirdly, the tree growth of the following forest generation may be reduced due to the increased output of nutrients. Results from short-term field trials (15 years) often indicate insignificant changes in the soil carbon pool after logging residue recovery.

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[5] Energy, exergy, heat, electricity, price etc.

Long-term predictions suggest that the carbon pool may decrease by about 1–2 tonne C ha^{-1} during a rotation period (Lilliesköld & Nilsson 1997). Such a small change in the soil carbon pool could not be verified in field trials (Olsson et al. 1996). However, long-term predictions of changes in the soil carbon pool are hampered by lack of long-term field data and the limitations in extrapolation from available short-term observations. Börjesson (2000) used an evaluation of reduced accumulation of C in forest soil of 1.2 t C ha^{-1} during a rotation period which for Swedish circumstances account for about 18 kg CO_2 MWh_{chip}^{-1}.

Greenhouse gas emission assessments of energy supply systems have traditionally contained the CO_2 emissions produced as the fuel is burned. The next step has been to include also other GHG emissions such as CH_4, N_2O and NO_x. This approach means that different combustion techniques could be evaluated and improvements made to lower emissions. Parallel to this the efficiency in energy conversion and utilisation has been enhanced which also lowers emissions, since less primary energy is needed to produce the same amount of end-use energy. One direction to still make improvements is to concentrate on the fuel production chains. It is not unimportant how the fuel is produced and to what extent the production processes affect the "emission quality" or "emission profile" of the fuel.

The production of fuels practically means that an external energy source is needed – emissions will appear due to this. The production can be physically situated thousands of kilometres away from the consumer, which is normal for fossil fuels, or relatively close, maybe only 50–100 km away, which is more normal for biofuels. This means that the emissions along the production and transportation chain will vary and may appear in different countries than where the fuel will be used. Some countries are working harder to reduce their GHG emissions than others. These things complicate the control and guidance of how energy should be produced, transported and used for minimising GHG emissions globally. Here, an approach to add a quality certificate to the fuel (e.g. energy amounts needed and emission amounts used for producing it) could help to guide the users towards using the most optimal fuels.

Schwaiger & Schlamadinger (1998) argue that the high GHG emissions[6] for chip preparation in Finland are mainly caused by a rather long average transport distance (150 km). Transportation accounted for almost half of the emissions in their evaluations. Forsberg (2000) stated that a great proportion of the emissions from the bioenergy system originate in off-road forest operations and that the most cost-effective system design to reduce emissions would be to improve the performance of off-road operations. Furthermore, he calculated that in bioenergy systems the use of fuels and electricity for operating machines and transportation carriers requires a net energy input of typically 7–9% of delivered electrical energy from the system[7]. Another study (Brännström-Nordberg & Dethlefsen 1998) find the energy input to be small, about 4% for forest fuels and 6% for short rotation coppice[8]. Forsberg (2000) underlined that in a bioenergy system there is a flow of biomass and all emissions vary with the flow. The relevant value of energy content in the calculations is the value at combustion.

In order to be able to evaluate possible emission savings when replacing fossil fuels with biofuels, one has to investigate the emissions caused when producing the biofuel and compare it to the emission profile of the fossil fuel that it is going to replace. Furthermore, when upgrading a biofuel, its energy content (per mass or volume) will probably rise but at the same time lower the total energy amount available and the emissions for producing the biofuel will grow. Nevertheless, the most basic biofuels, e.g. firewood and forest chips, cannot always be used to replace fossil fuels. Through calculating the magnitude of greenhouse gas emission saving potentials, it can be assumed that bio-chip or sawdust could replace coal, but oil and gas cannot be substituted by solid biofuels without investing in new equipment and making changes in the combustion process. If such aspects are not included in the studies, oil should be compared to upgraded fuels like bio-oil and gas to bio- or syngas. In Finland, upgraded biofuels could be produced from e.g. wood wastes and wood

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[6] 2620 kg CO_2eq TJ_{fuel}^{-1}, equal to 9.3 kg CO_2eq MWh_{fuel}^{-1}.

[7] In Forsberg´s calculations, 44% of the fuel energy was transformed into electricity. This means, that 7–9% of energy input for electricity refer to 3–4% of energy input for the used biofuel.

[8] Also in this study the input energy was compared with the output of energy (heat and electricity) at a CHP plant. The efficiency used in the calculations was 91.9% which means that the energy input would be about 0.5% lower if comparing with the biofuel.

(Tuhkanen & Pipatti 1999). Practically, this means that they would be easier to transport, but they would also be useful as substitutes for a larger range of fossil fuels. When producing upgraded fuels, the energy input becomes higher than base biofuels'. For e.g. for rape seed oil methyl ester (RME) production, the literature gives amounts of energy needed of 29–56% (Cvengros & Povanzanek 1996, Arnäs et al. 1997, Hovelius & Hansson 1999).

One difficult task in the use of biomass is the management of the storage and avoiding material losses and health risks due to degradation (Nurmi 1999, Forsberg 2000). Sometimes the fuel chips have to be stored for several months (Kofman & Spinelli 1997a, Marttila & Leinonen 1999). The reasons for using storages may be the structure of the energy demand, the aim of guaranteeing an uninterrupted fuel delivery, and the fact that biofuel may be harvested only within a limited period of time (e.g. willow, Kofman & Spinelli 1997a). A lot of fuel chips storage research has been performed in Finland and Sweden. Upon these research results, it seems very typical that fuel chips from both fresh and naturally dried logging residues start to decay and that the temperature rises very rapidly due to this. In some extreme cases, self-ignition has even caused a fire in the fuel storage. To keep material losses moderate in long-time storage, the moisture content would have to be kept very low, under 20 w-%, which is not possible without artificial drying.

Studies from the waste-handling sector rise a concern of there being a lack of knowledge concerning GHG emissions from biofuel storage operations, since no such studies can be found. The objects of the concern are self-heating biofuel piles containing such nitrogen and moisture contents that allow rapid decomposition circumstances similar to those found in bio-waste composting. In addition, large wood residue stockpiles – practically meaning landfilled wood waste – may represent a potential source of the greenhouse gases in countries where wood waste is not yet used as a fuel. If such GHG gases are emitted, a project which would mitigate the generation and stockpiling of wood residues could be allowed to claim greenhouse gas emission reductions (BTG 2002).

Municipal solid waste (MSW) is often classified as a renewable fuel (e.g. Tuhkanen & Pipatti 1999). This can be argued because of the high content of carbon bound by agriculture or forestry from the atmosphere. However, MSW also contains plastics whose carbon is of fossil origin, mainly plastics. These plastics will not have any influence on the GHG balances if burying them in a landfill, but if used as a fuel, they will cause emissions similar with those of fossil fuels. As a recycled fuel or solid recovered fuel (SRF)[9] consists of both biologically recently bound and fossil carbon, this fuel cannot be considered GHG emission neutral when burned. On the other hand, not all the emissions can be calculated for. In the Environmental Impact Assessment made of the Action Plan for Renewable Energy Sources in Finland (Tuhkanen & Pipatti 1999), recycled fuel was given a preliminary CO_2 emission factor of 30 g CO_2 MJ_{SRF}^{-1}. Additionally, the recycled fuel was given GHG emission saving credits of 95 g CO_2 MJ_{SRF}^{-1} for avoiding landfill emissions. This means, that the used emission factor when burning SRF was calculated to be –65 g CO_2 MJ_{SRF}^{-1} or –234 kg CO_2 MWh_{SRF}^{-1}. No GHG emissions were evaluated for the production process; nor was the impact of differences in recycled fuel quality evaluated.

1.3 The contents and objectives of the thesis

The object of this thesis was to study the greenhouse gas balances in connection with the harvesting and production of biofuels and, based on this, evaluate in what situations there is a need to re-evaluate the potentials of GHG emission savings when using bioenergy for substituting fossil fuels. In other words, the objective was to accept or reject the generally assumed hypothesis that the utilisation of biofuels is nearly totally greenhouse gas neutral.

Some questions arising from the literature survey were, if energy efficiency is a good measure for evaluating GHG emissions from biofuel production chains and what is the implication when upgrading biofuels. Another arising issue was if storage, changes in forest carbon pool and other such factors could have any influence on the emission saving calculations. Furthermore, can municipal waste be considered a biofuel and how does a different base scenario affect the calculations. Also a thrilling idea of appending a quality certificate to the fuels – both biofuels and fossil fuels – appeared.

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[9] A fuel produced from e.g. municipal waste. Definition of SRF has been proposed by CEN standardisation committee TC 343.

To achieve the object of thesis, a series of studies were conducted, presented in Papers I–VI, Soimakallio & Wihersaari (2002) and Wihersaari (2003). In Paper I, the energy and material flows of the Finnish forest industry were studied. In Papers II and III, the energy efficiency and the GHG emissions from some basic forest fuel production chains were investigated. In Wihersaari (2003), the assortment of biofuels was broadened and the influence of processing the fuels was included. Paper IV and VI focus on the storage of biomass, mainly on the emission risks when storing a forest fuel before using it; they also consider some aspects on the problems that may appear if by-products consisting biodegradable material would not be used but dumped. Paper V evaluates the magnitude of the changes in C storage of forest soils that may appear if forest residues are taken out and estimates what this would mean if the changes were considered as an indirect emission related to the production of the biofuel. The work mainly focuses on wood-derived fuels, as they are the main source of bioenergy in Finland; some parts deal also with other biofuels.

Chapter 1 of the thesis introduces the problems related to the rising greenhouse gas concentration levels in the atmosphere and presents upon literature measures to reduce energy related GHG emissions. The objectives of the thesis are then constructed upon the general supposition about GHG neutrality of biofuels. Chapter 2 presents the unifying methods and materials used in Paper I–VI and Wihersaari (2003).

Chapter 3 of the thesis presents a summary of the results from Paper I–VI and Wihersaari (2003). The chapter is divided into seven parts. The first part shows how bioenergy in Finland is related to wood production for the forest industry. It also describes some aspects on sustainable forest fuel production. In the second part, calculations of energy efficiencies and GHG emission of biofuel production chains are evaluated and some aspects on calculating saving potentials when replacing fossil fuels are considered. Part three presents GHG emission risk evaluations of storing biofuels; part four displays calculations on how the outtake of forest residue may effect on the carbon pool in forest soil. In part five, some aspects on how MSW can be considered a biofuel are presented. Part six illustrates some thoughts on how the results of the calculations may completely change character if the base scenario includes landfilled biomass. Finally, in part seven, the uncertainties of the calculations are roughly evaluated.

In Chapter 4 and 5 the results of the research are discussed, conclusions about the GHG neutrality of biofuels are made and some thoughts of possible directions of further investigations are presented.

The thesis presents new calculation results of greenhouse gas emissions from biofuel production chains and evaluations of how the emissions affect the efforts to reduce energy related GHG emissions. Not many evaluations have been published in this research field, especially not this large, including the potential effects of biofuel storage and of changes in the forest carbon pool. The approach to convert the emissions to carbon dioxide equivalents per produced unit of biofuel is new and opens new possibilities to evaluate the quality of the fuel production chain.

2. Methods and materials

Paper I utilises the philosophy and methodology of Industrial Ecology to analyse the sustainability and material flows of the Finnish forest industry. An industrial ecosystem is an industrial system that uses the model of a natural ecosystem in terms of its main material and energy flows. The primary goal in the material and energy flow approach of Industrial Ecology is to adopt the economic subsystem to the flows of the natural ecosystem or decrease the disturbance caused by the economic system to a sustainable level. In this Paper, an industrial ecosystem with the flows of matter, nutrients, energy and carbon was constructed. The flow of nutrients was demonstrated as the base cation flow of calcium, magnesium, potassium and sodium expressed in calcium equivalents. The flows were calculated on the basis of typical base cation contents of parts of the trees, stem wood, bark, branches and foliage for three common tree species in Finland (Scots pine, Norway spruce, Birch).

The approach of this study differs from the other Papers in this thesis, but the presence of the Paper can be justified by anchoring the use of bioenergy in Finland – mainly relaying on wood derived fuels – to the flows of wood raw material. The calculations were mainly made upon official statistics from the Finnish Forest Research Institute, the Ministry of Trade and Industry, and using Environmental Reports published by the Finnish Forest Industries Federation.

Biofuels can be produced from native raw material, by-products or even from waste material, Fig. 1. The biomass in these may originate from forestry, agriculture or even from energy biomass cultivation. All of these biofuel production ways and types of biomasses are, not comprehensively but to some extent, studied in this thesis.

When studying energy efficiency and GHG emissions of biofuel production chains the production process was divided into different parts. The energy input and GHG emission profile was identified for each part. Fig. 2 shows a principled picture of studied elements of forest residue fuel production chains. The energy balance of biofuel production chains was in this thesis defined as the external energy input in ratio to the biofuel output, Fig. 3.

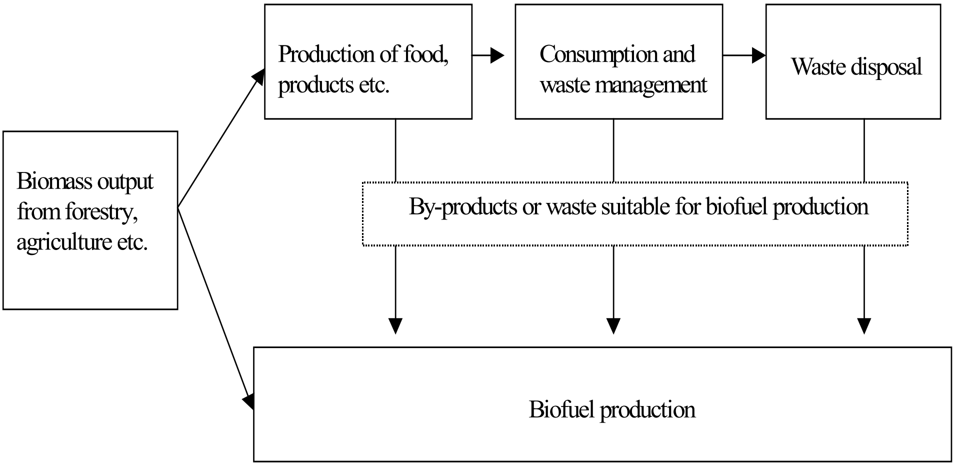

Figure 1. Different ways of generating biomass suitable for biofuel production.

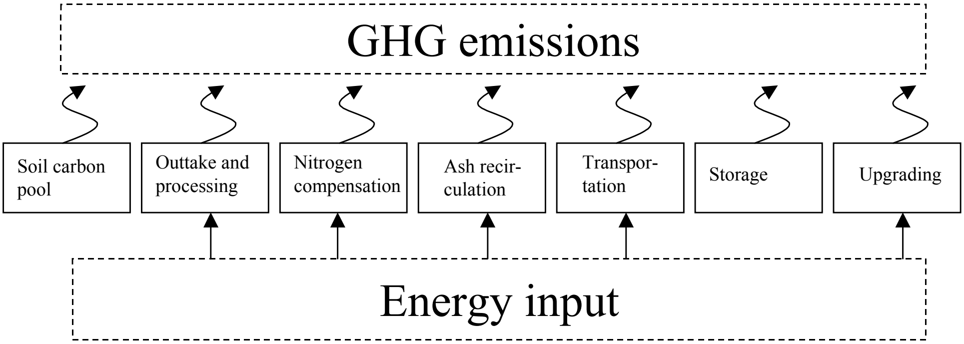

Figure 2. Some studied elements of the forest residue fuel production chains.

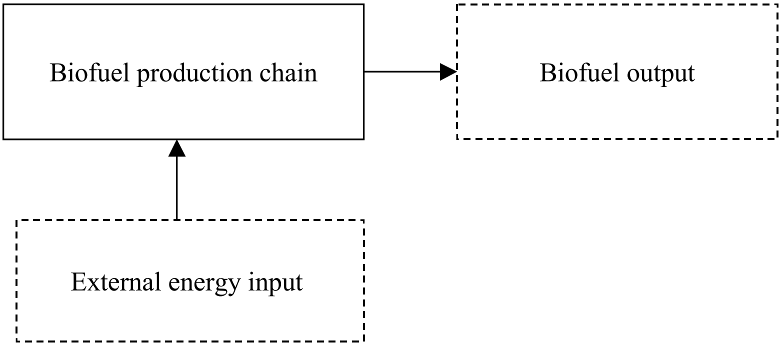

Figure 3. The expression "energy balance" used in this thesis refers to the external energy input in proportion to the biofuel output.

Paper II uses a simple model to evaluate energy consumption and GHG emissions for biomass production chains. In Paper III the same principles were further developed to construct a more complete model for evaluating the energy balances and GHG emissions of biofuel production chains. Model calculations for five different forest residue production chains were conducted. Energy balances for different parts of the chain can be evaluated in the model as well as the emissions of greenhouse gases: carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and carbon dioxide equivalents (CO_2eq). Emissions caused due to the production of fossil fuels (mainly diesel oil) needed in the biofuel production chains as well as manufacturing of machines, facilities and the building up of infrastructure were not included. In Wihersaari (2003) the calculation principles used in Paper III were applied on Hungarian circumstances including other biofuels than wood; the model was also used for studying the consequences of fuel upgrading.

System boundaries and input-output units for the initial forest residue model calculations[10] were carefully considered; the aim was to use units understood by forest fuel professionals. As forest fuel is produced as a by-product of stem wood production for the forest industry a natural starting point for the calculations was to evaluate the amount of forest residue based on stem wood

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[10] Input data used in the model calculations: $V_{timber,\ ha} =$200 $m^3\ ha^{-1}$, M_{res} = 150 kg per m^3, R_{site} =60%, L = 0–10%, H_{ar}= 40–55%, $Q_{net,d}$ = 19.6 MJ kg_{dm}^{-1}.

production amounts per hectare of forest land ($V_{timber,ha}$). The forest fuel output can then be expressed as:

$$W_{o\ bio,\ ha} = V_{timber,ha} \times M_{res} \times R_{site} \times (1 - L) \times Q_{net,ar} \times m_{ar}^{-1} \tag{1}$$

where $Q_{net,ar}$ is the energy content in the fuel received at the power plant.

$$Q_{net,ar} = Q_{net,d} \times (100 - m_{ar}) \times 10^{-2} - 0.02441\ m_{ar} \tag{2}$$

and where	$V_{timber,ha}$	Volume of timber as solid cubic metres per hectare of forest land
	M_{res}	Mass of dry forest residue per solid cubic metres of stem wood
	R_{site}	Recovery rate of forest residue from site
	L	Material losses during the production chain
	m_{ar}	Moisture content, air dry sample
	$Q_{net,d}$	Energy density in dry material.

The calculations (energy input/output and emissions) for every step was made for units produced per hectare of forest land. This approach was chosen because material losses and changes in the moisture content of the forest residue affect material amounts that have to be processed and transported and energy amounts received at the power plant.

Finally the different steps were added and converted to show energy input/output and emissions per MWh of biofuel received at the power plant. Referring to this unit and fixing the output system boundary here was reasonable because the users of the fuel normally pay for received energy amounts. The connection to other calculations made down-streams (e.g. for extending the calculation chains to study emissions for a produced amount of heat or electricity or upgrading the biomass) is also easy.

The GHG emissions from each step in the production chain (using machines, ash recirculation, nitrogen compensation etc.) was calculated on basis of production area and finally converted to show the emission amount per produced unit of biofuel:

$$GHG_{chain,\ MWh} = GHG_{chain,\ ha} \times W_{o\ bio,\ ha}^{-1} \tag{3}$$

where

$$GHG_{chain,\ ha} = \sum GHG_{mash,\ ha} + GHG_{ash\ res,\ ha} + GHG_{Ncomp,\ ha} + \sum GHG_{other,\ ha} \tag{4}$$

and where	$GHG_{chain,\ ha}$	GHG emissions from production chain, per hectare of forest land
	$GHG_{chain,\ MWh}$	GHG emissions from production chain, per MWh
	$GHG_{mash,\ ha}$	GHG emissions from mashinery, per hectare of forest land
	$GHG_{ash\ res,\ ha}$	GHG emissions from ash recirculation, per hectare of forest land
	$GHG_{Ncomp,\ ha}$	GHG emissions from nitrogen compensation, per hectare of forest land
	$GHG_{other,\ ha}$	Other GHG emissions from production chain, per hectare of forest land
	$W_{o\ bio,\ ha}$	Bioenergy output per hectare of forest land (MWh ha^{-1}).

The diesel engines were assumed to have a similar GHG emission profile and an average emission value of 2.74 kg CO_2eq l_{diesel}^{-1} was used in all of the calculations.[11]

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[11] This value contains 2.66 kg CO_2 l^{-1}, 0.1 g N_2O l^{-1}, 0.3 g CH_4 l^{-1} and an indirect N_2O emission of 0.15 g l^{-1} coming from the NO_x emission. The calculations were made upon an energy content in diesel oil of 9.794 kWh l_{diesel}^{-1} (Wihersaari & Palosuo 2000).

The energy balance (external energy input/biofuel output, $E_{i/o\ chain}$) of the fuel production was expressed as

$$E_{i/o\ chain} = W_{i\ f\ chain,\ ha} \times W_{o\ bio,\ ha}^{-1} \tag{5}$$

where the fossil energy input is

$$W_{i\ f\ chain,\ ha} = \sum W_{i\ f\ ,\ mash,ha} + W_{i\ f\ ,\ ash\ res,\ ha} + \ldots \tag{6}$$

and where	$W_{i\ f\ chain,\ ha}$	Fossil energy input in production chain producing a biofuel from one hectare
	$W_{i\ f\ ,\ mash,ha}$	Fossil energy needed by machines producing a biofuel from one hectare
	$W_{i\ f\ ,\ ash\ res,\ ha}$	Fossil energy needed for ash recirculation producing a biofuel from one hectare
	$W_{o\ bio,\ ha}$	Bioenergy output per hectare of forest land.

Analogical model calculations to those explained above were also performed for cultivated biomass. As straw and corn residues are very similar materials, an overall estimation[12] was made for both. The difference comes mainly from the hectare yields, but as the calculations are made upon material flows this does not have any remarkable influence on the results.

Biofuel cultivation was evaluated for Hungarian circumstances. The figures for biomass yields (16 t_{dm} ha^{-1} a^{-1}) were chosen from Hungarian trials (Marosvölgyi et al. 1999) with poplar (4 year cutting cycle, total cycle of 28 years) This yield might be too high for an average of commercial energy forestry. As energy forestry is practically very similar to growing Salix (same cutting cycles), the

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[12] The average input data used for the calculations: corn residue 10 t ha^{-1}, straw residue 3–4 t ha^{-1}, energy content 4.0 MWh t^{-1} (20% moisture content), collection: 10 kWh MWh^{-1}, transportation (20 km) 1,7 l diesel t^{-1}, nutrient compensation (N) calculated based on a nitrogen content of 0.5% in dry matter, assuming 50% losses (Wihersaari 2003).

values for energy input[13] were evaluated based upon Swedish figures taking in account that poplar in Hungary has about 80% higher yield per hectare of cultivated area than Salix in Sweden.

If upgrading a biofuel, its energy density (per mass or volume) will probably rise. At the same time the total energy amount available, produced from a certain land area, is likely to be reduced and both the (fossil) energy input needed and the emissions for producing the biofuel will grow. For evaluating upgraded fuels, steps from the base production chains were combined with the upgrading measures and the same calculation principles were applied:

GHG emissions per produced unit of upgraded biofuel:

$$GHG_{upgr,\ MWh} = (GHG_{chain,\ ha} + \sum GHG_{upgr,\ ha}) \times W_{o\ bio\ upgr,\ ha}^{-1} \qquad (7)$$

where	$GHG_{upgr,\ ha}$	GHG emissions from upgrading measures, per hectare of cultivated area
	$GHG_{upgr,\ MWh}$	GHG emissions from upgrading measures, per MWh
	$W_{o\ bio\ upgr,\ ha}$	Bioenergy output per hectare of cultivated area, upgraded.

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[13] Establishment 140 l_{diesel} ha^{-1} (28 a), maintenance 80 l_{diesel} ha^{-1} (4 a), harvesting and short-distance transport 755 l_{diesel} ha^{-1} (4 a), chipping 550 l_{diesel} (for 380 MWh), energy needed for preparating nutrients 2 MWh ha^{-1} a^{-1}, long-distance transportation 0.35 l_{diesel} per bulk m^3 (distance 50 km). (Wihersaari 2003).

The energy balance (external energy input/biofuel output) of the upgraded fuel production was expressed as:

$$E_{i/o,upgr} = (W_{i\ f\ upgr,\ ha} + W_{i\ f\ chain,\ ha}) \times W_{o\ bio\ upgr,\ ha}^{-1} \tag{8}$$

where	$E_{i/o\ upgr}$	Energy balance (input fossil/output upgraded biofuel)
	$W_{i\ f\ chain,\ ha}$	Fossil energy input in production chain producing a biofuel from one hectare
	$W_{i\ f\ upgr,\ ha}$	Fossil energy input needed to upgrade a biofuel produced from one hectare of land area.

In Paper IV phenomenon and material characteristics reported from biofuel storage and bio-waste compost research were compared and reported emission behaviour for compost was used to make a rough analysis of GHG emissions for storage of chipped forest fuels. The potential emissions from biofuel storage were calculated based on emission coefficients developed for biowaste composts and the magnitude of the results was checked by using conversion grades of initial amounts of carbon and nitrogen. To match earlier evaluations, the amounts of greenhouse gas emissions from storage of biomass produced per hectare of forest land was used and emission rates referring to the energy content of the produced biomass was calculated:

$$GHG_{stor,\ MWh} = GHG_{stor,\ ha} \times W_{o\ bio,\ ha}^{-1} \tag{9}$$

where	$GHG_{stor,\ ha}$	GHG emissions from storage of a biofuel, per hectare of forest land
	$GHG_{stor,\ MWh}$	GHG emissions from storage of a biofuel, per MWh
	$W_{o\ bio,\ ha}$	Bioenergy output per hectare of forest land (MWh ha^{-1}).

Notice that if the potential emissions from storage of biofuels are added to the chain, the total amount of bioenergy produced per hectare land area ($W_{o\ bio,\ ha}$) is reduced due to material losses which will affect also on the earlier calculations.

In Paper V, a dynamic model, which describes the carbon stocks and fluxes of decomposing organic matter in upland forest soils, was used for evaluating how the use of forest residue as a fuel affect the carbon pool in forest soils. The model used was developed at the European forest institute. A flow chart of the soil carbon model is presented in Fig. 4 and the parameter values used in the model calculations in Table 1. The parameters a_x indicate the exposure rates of litter to microbial decomposition and the parameters k_x indicate the microbial decomposition rates of compounds of soil organic matter. The parameters c_x tell how the material leaving the litter compartments is divided between the soluble, cellulose and lignin compartments; this division follows the actual concentrations of these compounds in the litter. The p_x fraction show what amount of the carbon is transferred to subsequent compartment and $(1-p_x)$ what amount leave the system as CO_2.

Table 1. Parameter values used in model calculations (Table 1 in Paper V).

Parameter	Value	Parameter	Value
a_{nwl}	1.0 a^{-1}	k_{sol}	0.5 a^{-1}
a_{fwl}	0.5 a^{-1}	K_{cel}	0.3 a^{-1}
a_{cwl}	0.05 a^{-1}	k_{lig}	0.15 a^{-1}
c_{nwlsol}	0.27	K_{hum1}	0.013 a^{-1}
c_{nwlcel}	0.51	K_{hum2}	0.0012 a^{-1}
c_{fwlsol}	0.03	p_{sol}	0.15
c_{fwlcel}	0.65	P_{cel}	0.15
c_{cwlsol}	0.03	P_{lig}	0.18
c_{cwlcel}	0.69	P_{hum1}	0.18

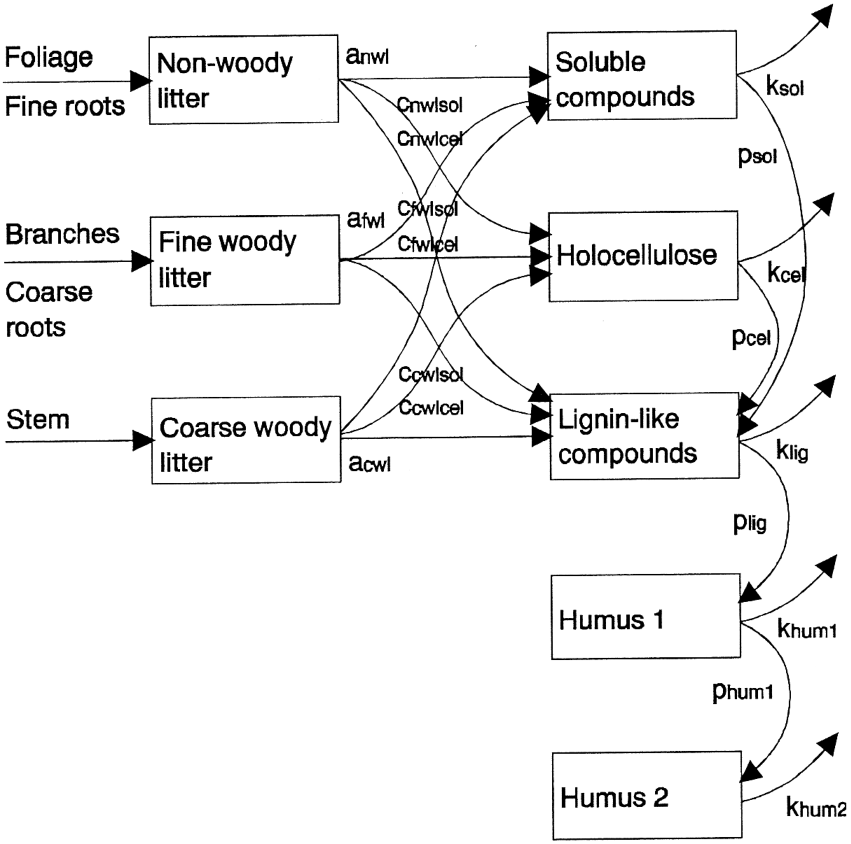

Figure 4. Flow chart of the soil carbon model. The boxes represent carbon compartments, the arrows carbon fluxes and the text by the arrows parameters controlling the fluxes. The values used for the parameters are shown in Table 1 (Fig. 1 in Paper V).

The changes in carbon stocks were quantified and considered as indirect GHG emissions that can be accounted as a burden taxing the emission saving potential of a forest residue fuel. The carbon content in the forest residue outtake from site (affecting on carbon balances in forest soil) can be expressed:

$$C_{\text{outtake, ha}} = C_{\text{residue site, ha}} \times R_{\text{site}} \qquad (10)$$

where

$$C_{\text{residue site, ha}} = V_{\text{timber, ha}} \times M_{\text{res}} \times C_{\text{dm}} \qquad (11)$$

and where	C_{dm}	Carbon content in dry matter of forest residue
	$C_{outtake, ha}$	Carbon outtake as forest residue from site
	$C_{residue\ site, ha}$	Carbon content in forest residue on site, per hectare of forest land
	M_{res}	Mass of dry forest residue per solid cube of stem wood
	R_{site}	Recovery rate of forest residue from site
	$V_{timber, ha}$	Volume of timber as solid cube per hectare of forest land.

The amount of indirect greenhouse gas emissions from reducing the carbon stock in forest soil are calculated referring to the energy content of the produced biomass:

$$GHG_{soil, MWh} = GHG_{soil, ha} \times W_{o\ bio, ha}^{-1} \qquad (12)$$

where	$GHG_{soil, ha}$	Indirect GHG emissions from reducing carbon storage in forest soil, per hectare of forest land
	$GHG_{soil, MWh}$	Indirect GHG emissions from reducing carbon storage in forest soil, per MWh
	$W_{o\ bio, ha}$	Bioenergy output per hectare of forest land (MWh ha^{-1}).

In Paper VI IPCC methodology estimating the potential future CH_4 emissions for a given amount of landfilled waste was used to evaluate GHG emission savings achieved by alternative waste treatment chains. Here biomass disposal was considered as business-as-usual or base scenario. For estimating the composition and carbon content of MSW, data published by the Advisory Board for Waste Management (1992) and IPCC Guidelines (IPCC 1997) was used.

The following principles for calculating the generated methane ($CH_{4\ gen}$), the recovered methane ($CH_{4\ rec}$) and the methane emitted ($CH_{4\ emi}$) for landfills was derived from the methodology given in the IPCC Guidelines (IPCC 1995, IPCC 1997):

$$CH_{4\ gen} = MSW_L \times dOC \times dOC_f \times MCF \times F \times 16/12 \qquad (13)$$

$$CH_{4\ rec} = CH_{4\ gen} \times R \qquad (14)$$

$$CH_{4\ emi} = (CH_{4\ gen} - CH_{4\ rec}) \times (1-OX) \qquad (15)$$

where	MSW_L	Amount of MSW landfilled
	dOC	Fraction of degradable organic C in MSW
	dOC_f	Fraction of dOC dissimilated
	MCF	Correction factor for dOC_F depending on the size and management of the landfill
	F	Fraction by volume of CH_4 in the landfill gas
	16/12	The molecular weight of CH_4 compared with C
	OX	Oxidation factor for CH_4 (oxidation in the surface layer of the landfill)
	R	Amount of recovered CH_4.

The calculations of methane fluxes were made using the following values:

Parameter	Value	Comment
dOC	0.20	[14]
dOC_F	0.50	
MCF	0.70	[15]
F	0.50	
OX	0.10	
R	0.40	

The used IPCC methodology gives an overall estimate of the potential future CH_4 emissions for a given amount of landfilled waste and is well suited for studies like this where the total emissions over time of different technologies are compared. In studies on annual emissions from landfilling methods time dependency of emissions must be used. It is recommended to validate the models with data from measurements.

The energy content of the recovered gas was assumed to be 50 MJ kg^{-1} of CH_4 and the CO_2 emissions from combustion were not considered as the CH_4 in landfill gas originates from renewable sources. Other GHG emissions from combustion of the landfill gas were assumed to be negligible. The GHG emissions from biological treatment of the biowaste fraction were estimated to be negligible as it was assumed that the bio-waste would be treated in modern, large scale composting units. The emissions from waste separation, transportation and treatment are included in the case studies in Paper VI but not in the overall comparison. The magnitude of such emissions is explained in Section 3.5. The net impact (Paper VI) was defined as the GHG emissions

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[14] The estimated waste composition was (weight-%): paper and cardboard 26%, textile 1%, plastic 6%, organic waste 46.5%, glass and metal 5.5%, other waste 15% (Table 1 Paper VI).

[15] Estimated, that half of the landfills in Finland has normal CH_4 generating potential (MCF=1) and half has low CH_4 generating potential (MCF=0.4).

subtracted with the emission savings that can be achieved by energy utilisation (substituting a fossil fuel) and C stored in landfills.

The total GHG emissions are expressed in carbon dioxide equivalents (CO_2eq) calculated from Global Warming Potential (GWP) values. The present recommended GWP_{100} values are 23 for CH_4 and 296 for N_2O (IPCC 2001a)[16]. As these recommended values have been changed a few times during the years the calculations in some of the Papers have been performed with a little bit different figures, but this do not have any remarkable influence on the results[17].

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[16] In the official national greenhouse gas emission inventories the GWP values in IPCC Good Practice Guidelines and Revised 1996 Guidelines are still used (NIR 2003).

[17] See also Chapter 3.7.

3. Aspects on greenhouse gas emissions related to using biofuels for substituting fossil fuels

The main object of the following studies was to investigate the GHG neutrality in connection with the harvesting and production of biofuels, and further to evaluate the impacts of the findings on GHG emission saving potentials when using bioenergy for substituting fossil fuels.

The first chapter (3.1) discusses how bioenergy in Finland is related to wood production of the forest industry. This study is needed to understand the interaction between raw material and forest fuel production and to briefly describe aspects on sustainable forest fuel production.

The second chapter (3.2) presents calculations of energy efficiencies and GHG emissions of biofuel production chains and evaluates saving potentials when replacing fossil fuels. The investigation aims at answering such questions as what is the level of GHG emissions produced in the biofuel production chain, is energy efficiency a good measure for evaluating GHG emissions from the production chains, and what is the implication when upgrading biofuels. This part of the study also strives to explain how the choice of a system boundary for fossil fuels may affect the calculations.

Issues studied in chapter 3.3 and 3.4 are if storage of biofuel and possible changes in forest carbon pool due to the outtake of forest residue might have an influence on emission savings. Chapter 3.5 deals with the problem whether MSW can be considered a biofuel and if the energy efficiency and GHG emission calculation model developed for forest fuels can be applied on waste fuel production chains. Finally, the study presented in chapter 3.6 deals with the issue of whether the results of the calculations might change character if the baseline includes landfilled biomass.

3.1 Forest fuels as a part of the utilisation of forest biomass

Wood derived fuels are the main source of biofuels in Finland today. The main production method is to utilise "waste" or by-products of the raw material handling process, Fig. 5.

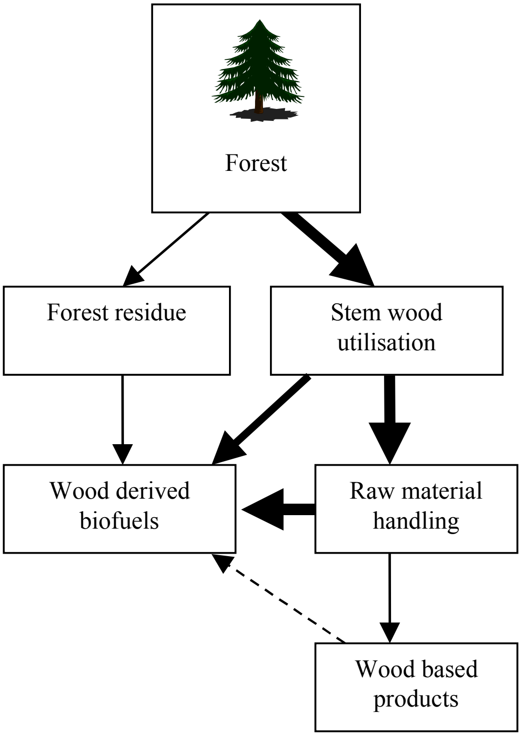

Figure 5. Various ways of producing wood derived fuels in Finland.

The second largest group of forest fuel products is represented by firewood used for heating up households and farms. This is also a type of stem wood utilisation. The third and newest group is utilisation of forest residue. Wood based products also, to some extent, end up as a fuel. This last group of biofuel is increasing as e.g. municipal waste incineration increases.

In Paper I, a forest industry Industrial Ecosystem is presented in the context of the national forest industry of Finland. The model is based on the analysis of the flows of matter (biomass), nutrients, energy and carbon in a forest ecosystem. Fig. 6 describes the main material flows (wood) of the Finnish forest industry 1997. The annual drain of stem wood (65.8 mill. m^3) was about 13% less than the annual growth. The domestic stem wood cuttings[18] used by the forest industry were 55.4 mill. m^3 and in addition, 8.7 mill. m^3 of stemwood was imported from Russia. 11.4 mill. m^3 wood waste (bark, sawdust etc.) from the wood products industry was used in the production of pulp as well as in the production of energy. Wastes from pulp mills (bark, black liquor) were incinerated as input in the forest industry energy supply system. 1.6 mill. m^3 industrial wood residue was used by energy producers outside the forest industry. Totally, about 59% of wooden material of the harvested stemwood ended up in products and 40% was used for energy. Less than 2% of the harvested wooden material ended up as wastes (waste fractions to landfill and water) (Finnish Statistical Yearbook of Forestry 1999, Sieppi 1999).

The forest ecosystem bounds atmospheric CO_2 and solar energy to wooden biomass. This biomass is utilised as raw material for products and as energy in the industry, and finally the carbon is released to the atmosphere as CO_2 from combustion processes or as landfill gas from the decay of products at landfills consisting of both CO_2 and CH_4. In Fig. 7 the forest industry activity is described by means of the carbon cycle of the forest ecosystem. The total amount of CO_2 bound annually into the forest biomass is about 48 mill. t C. The cuttings, non-industrial wood use and natural drain of stem wood in 1997 were about 65.8 mill. m^3 corresponding to a total carbon release from forest biomass of 42 mill. t C. The forest ecosystem served as a carbon sink of 6 mill. t C in 1997. Through harvesting carbon is transferred in wooden material to products or burnt during the industrial processes resulting in CO_2 emissions to the atmosphere. The lifetime of main paper products is on average quite short i.e. less than a one year (Pingoud et al. 1996). In addition, the major part of the sawn timber has a relatively short life time, from one year to some decades (Pingoud et al. 2000). About 60% of the carbon (13 mill. t C) inflow to the industry ends up to the products and will be to a large extent released back to the atmosphere either from incineration of used products or from landfills where the products decay.

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[18] To compare, the domestic stemwood cuttings 1998–2002 varied between 53.8 and 58.0 mill. m^3 (Finnish Statistical Yearbook of Forestry 2003).

About 40% of the carbon inflow ends up in combustion processes causing emissions of about 5.0 mill. t C. The fossil fuel use within the industry causes CO_2 emissions of about 1.5 mill. t C and the generation of electricity bought into the industry causes CO_2 emissions of about 1.0 mill. t C[19]. The CO_2 emissions from transportation activities due to forest industry can be estimated to be in order of 0.5 mill. t C (Pingoud et al. 1996). The used products lie in landfills in anaerobic conditions and emit landfill gas, which contains methane (CH_4) and carbon dioxide. The methane emissions from landfills are nowadays often collected. This is done, among other things, because CH_4 can be used as an energy source and because methane emissions enhance the greenhouse effect.

The flow of nutrient originating from the forests is described in Fig. 8. The base cations (BC) of calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+) and sodium (Na^+) follow a throughput direction, starting from forests and ending up as ash of combustion processes or as used wood based products at landfills. Because the waste wood fraction (e.g. bark) have higher nutrient content than pure stem wood fractions used in products, about 60% of the nutrients end up in ash of energy supply systems (Hakkila 1992, Wihersaari 1996). This part could, at least to some content, be recirculated. Base cations in a natural forest ecosystem have a renewable pool which is made up by weathering of minerals and, to some extent, also by atmospheric deposition, Fig. 9. Acidic deposition, on the other hand, can remove base cations from the pool and cause disturbance in the nutrient balance of the trees. Returning of ashes back to the ecosystem would increase buffering against acid rain.

The forest industry of Finland is arranged to a large extent as regional or local industrial systems or integrates, where a saw-mill, a pulp mill, a paper mill and a combined heat and power plant (CHP) are in close proximity to each other and engage in co-operation through waste material and energy utilisation. The power plants produce heat and electricity for pulp and paper mills as well for saw mills, which in turn provide the power plants with waste bark and waste liquor, and saw mill wastes for fuels. The use of waste pulping liquors as fuels also recovers the pulping chemicals back to the pulping process, and therefore, the need for

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[19] The CO_2 emissions from bought electricity are estimated on the basis of average CO_2 emissions per produced electricity (250 g CO_2/kWh) in Finland.

costly external chemical inputs and harmful outputs to ecosystems are reduced. In addition, fossil fuels and externally produced electricity are used. Fig. 10 presents the flows of energy and the structure of the forest industry energy supply system. About 70% of the fuels are industrial wood wastes and waste liquors. About 94% of the fuels are used in combined heat and power plants, where the waste heat from electricity production is used to produce process or space heat instead of dumping it into the ecosystem. This reduces the consumption of the external primary energy considerably, as about 30% of the electricity consumed by the forest industry is produced within the industry using waste fuels.

Discussion

Upon the presented study, the sustainability of the Finnish forest fuel production seems to be quite well in order, although questions like ash re-circulation and nutrient balances are still to be followed up. The strength of this kind of study is simplicity. Different flow parameters can be followed up by using the same model. On the other hand, the limited amount of studied parameters, too tight system boundaries etc. may reduced the quality of the result. One such issue not studied, that might affect sustainability in the long run, is biodiversity.

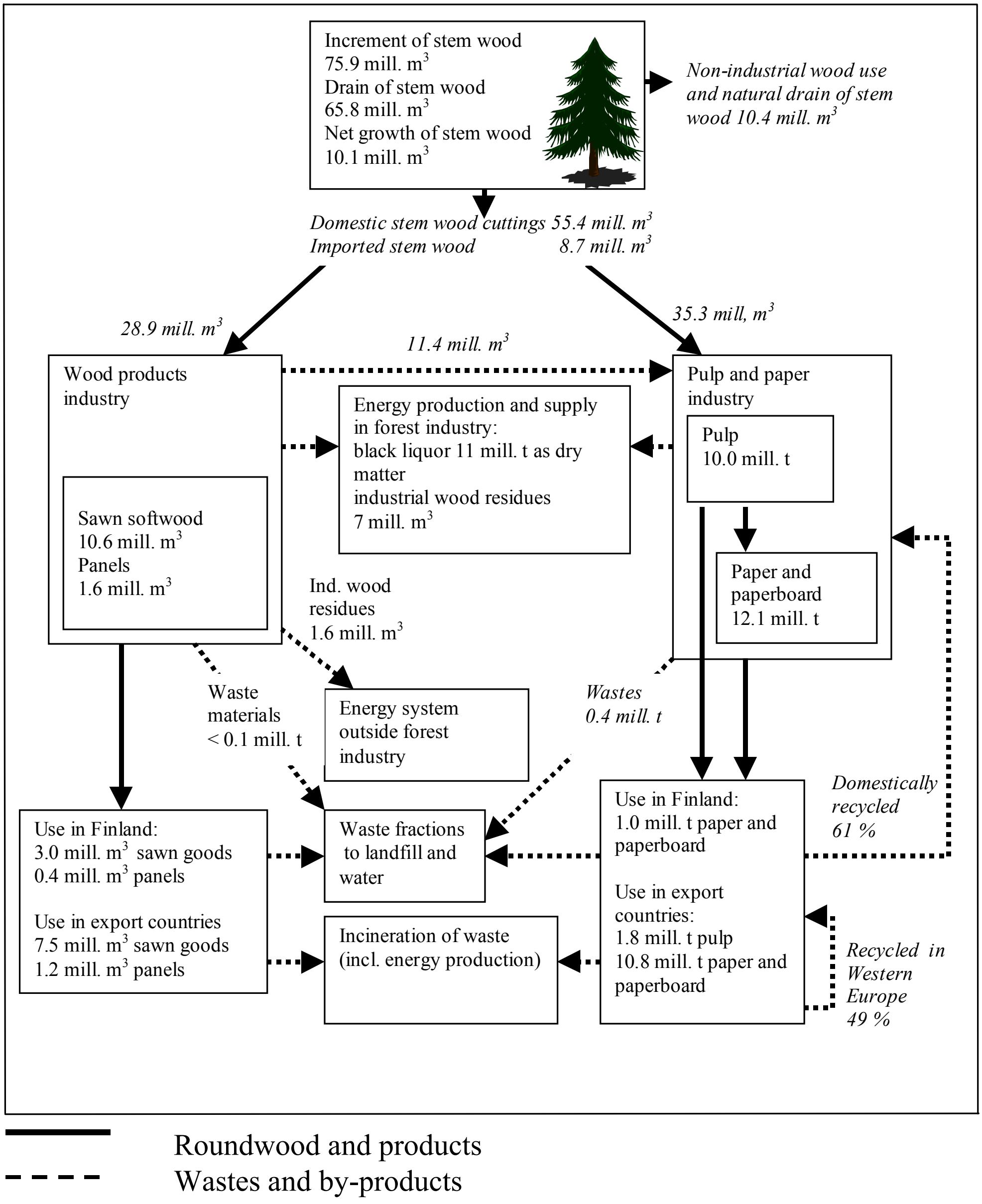

Figure 6. Flows of wooden materials in the Finnish forest industry in 1997 (Fig. 5, Paper I).

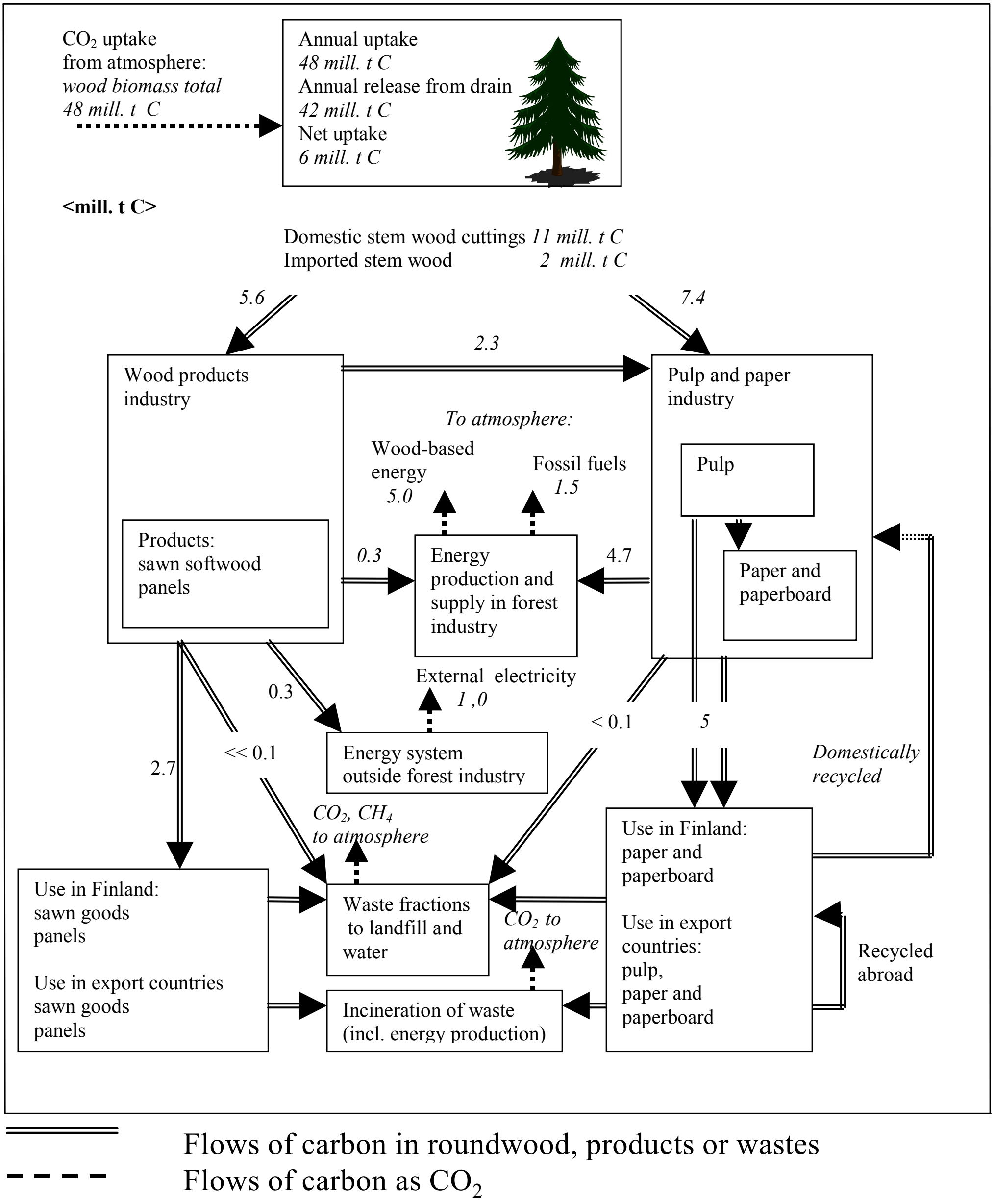

Figure 7. The carbon flows in Finnish forest industry in 1997 (Fig. 8 in Paper I).

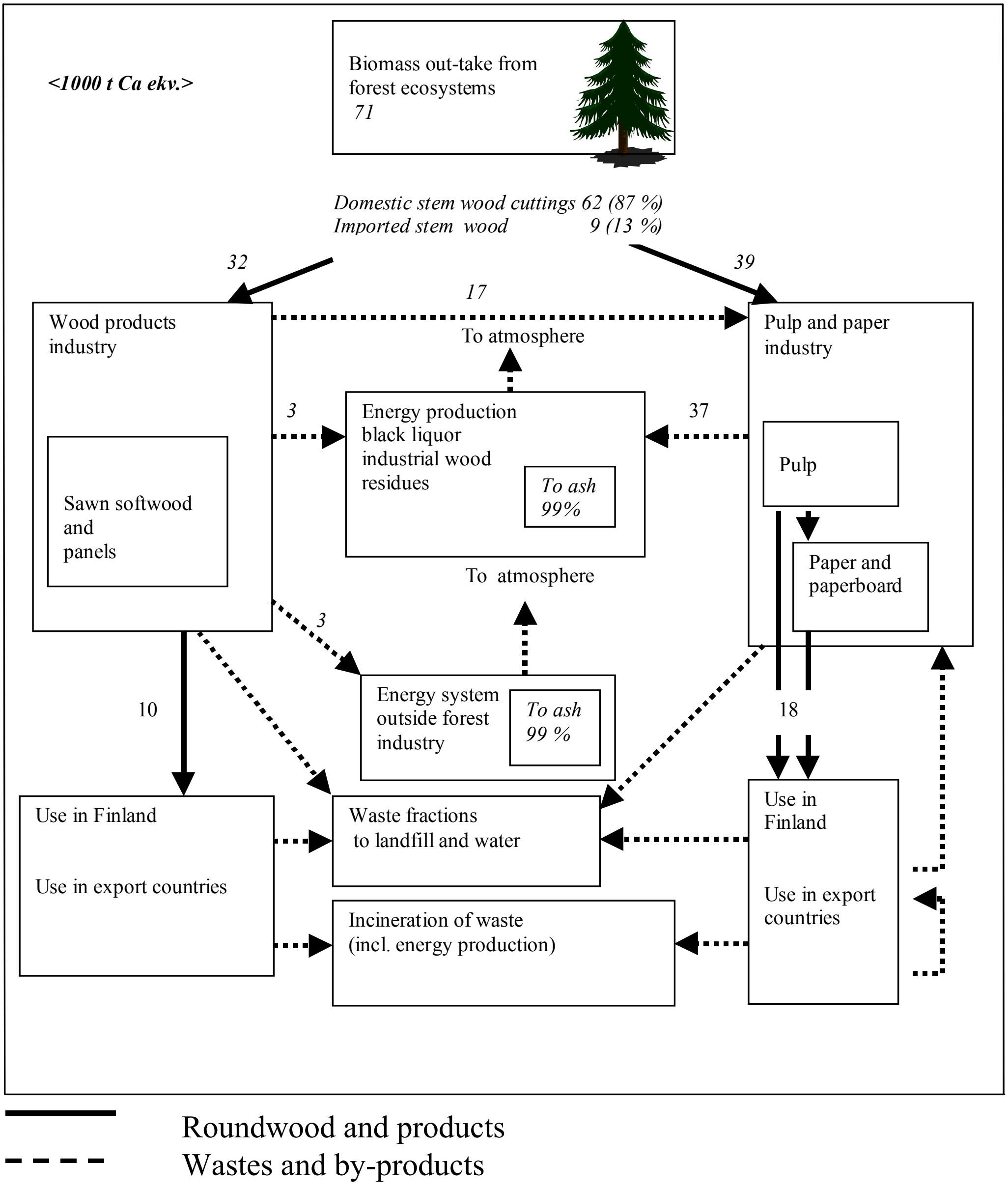

Figure 8. The flow of nutrients in the Finnish forest industry in 1997 (Fig. 6 in Paper I).

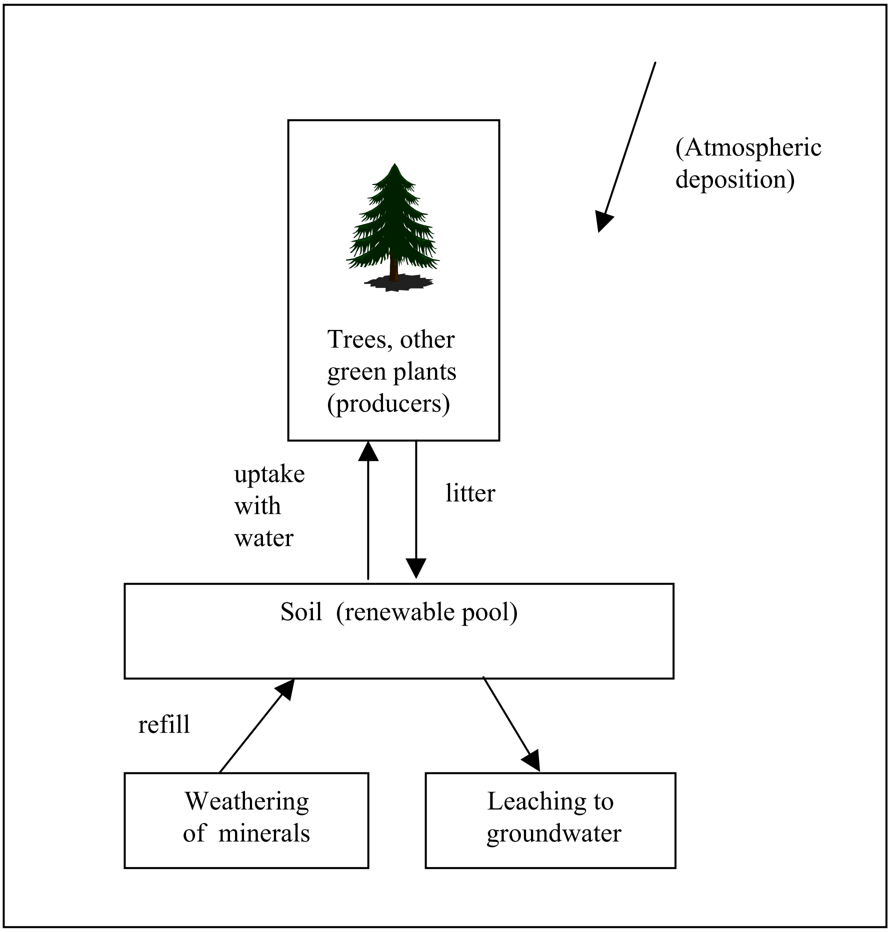

Figure 9. Flows of base cation nutrients in a forest ecosystem (Fig. 2 in Paper I).

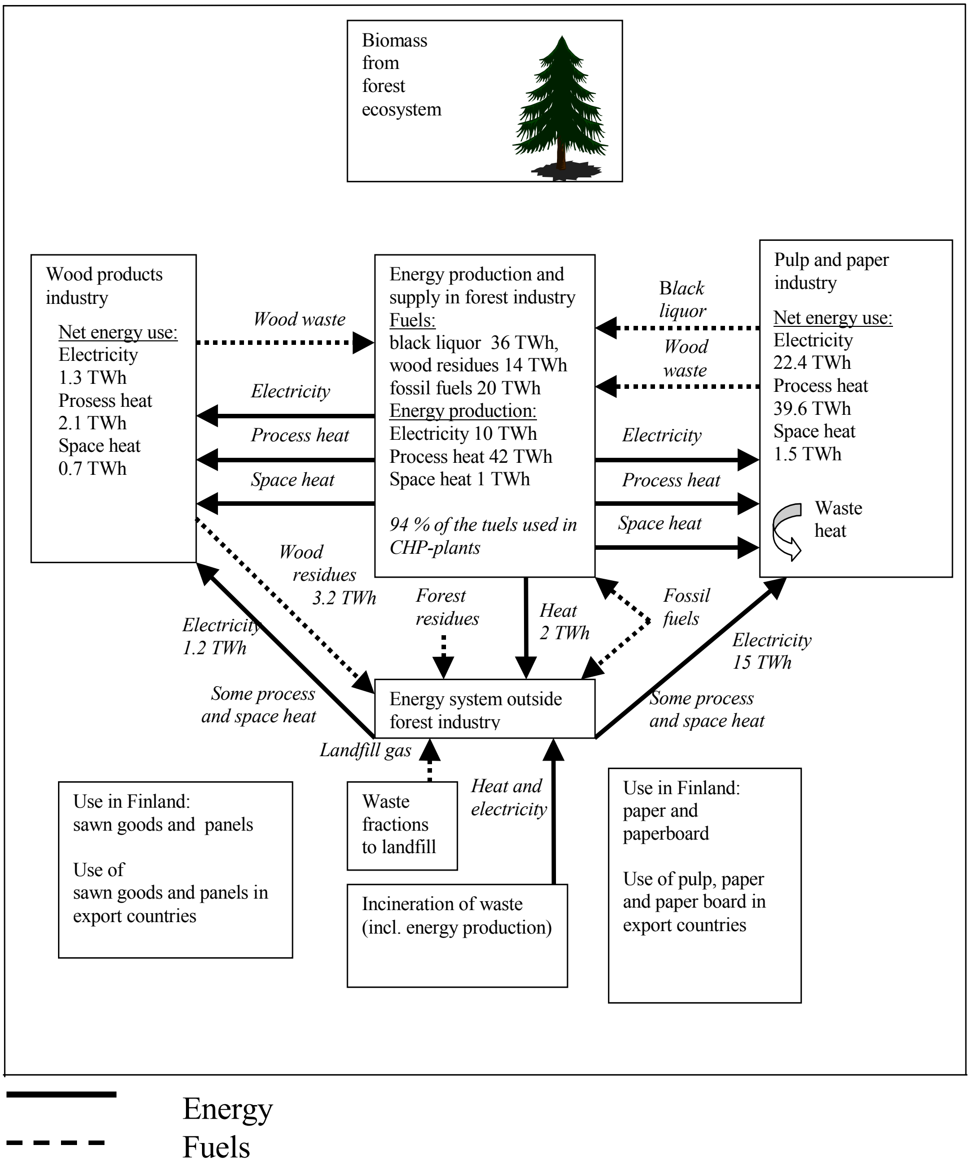

Figure 10. Fuels used and production of electricity, process heat and space heat in the Finnish forest industry in 1997 (Fig. 7 in Paper I).

3.2 Energy efficieny and greenhouse gas emissions of biofuel production chains

3.2.1 Forest residue

The studied fuel chip was produced from logging residue from final harvest. Five different fuel production chains were considered. The energy input (mainly diesel oil) for the biofuel production was calculated to be 1.9–2.6% of the energy content in the biofuel, Table 2. The GHG emissions from collecting, chipping and transporting the residues were calculated to be 4.3–7.5 kg CO_2eq MWh_{chip}^{-1}.

Ash recirculation and nitrogen fertilisation

Both traditional ash handling methods such as earth filling or dumping and more preferable methods such as ash recirculation by using e.g. pelleted ash was calculated to have a negligible effect on energy balances and greenhouse gas emissions. The energy input rate for the ash recirculation process was calculated to be less than 0.1% of the energy content of the produced wood chip and the emissions about 0.2 kg CO_2eq MWh_{chip}^{-1} (Paper III). As the outtake of nitrogen, however, cannot be compensated for by ash recirculation, because the fuel nitrogen ends up in the flue gases during combustion (Harju 2001), nutrient losses must probably, in the long run, be compensated for with fertilisation to keep the forest ecosystem in balance. If the whole nitrogen content of the biofuel outtake would be refunded[20] to the forest site by using an artificial fertiliser, this would cause emissions in the range of 7 kg CO_2eq MWh_{chip}^{-1} and the additional energy input rate was calculated to be quite high, about 1.4% (Paper III)[21].

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[20] Börjesson (2000) evaluate that about 5% of the nitrogen could theoretically be returned to the forest by atmospheric deposition of nitrogen oxides. As nitrogen deposition also is caused by e.g. burning fossil fuels a total refunding of the missing 95% is rarely needed.

[21] The energy input for the production of nitrogen fertilizer was in Paper III evaluated to be 13.9 kWh kg^{-1} (N). Scholz et al. (1998) reported the average figures for 1994 to be about 16.4 kWh in Germany and 20.8 kWh in the USA. The figures reported for 1970–1994 varied between 12 and 24 kWh kg^{-1}. Furthermore, there was a decreasing trend of the energy input for producing nitrogen fertilizers in Germany but not in the USA.

Table 2. Calculated energy input and GHG emissions for five wood chips production chains in Finland (Table 1, Paper III, modified). The outtake of forest residue is considered to be equal in all chains (100 loose m^3 ha^{-1}).

Input values and calculated results	Unit	Production chain				
		Terrain chipping	Roadside chipping	Terminal chipping	Chipping at end use Facility, transported: Loose	baled
Losses along the production chain	w-%	0	10	5	10	5
To combustion:						
fuel chips	loose m^3	100	90	95	90	95
moisture content	w-%	55	45	40	40	55
as energy	MWh per $ha_{forest\ land}$	83	79	85	81	79
Energy need along the production chain:						
production (diesel)	l per MWh_{chip}	1.6	1.9	2.3	0.8	1.5
long distance transportation (diesel)	l per MWh_{chip}	0.6	0.5	0.4	0.8	0.7
chipping (electricity)[a)]	kWh_{el} per MWh_{chip}	0	0	0	3.3	3.6
Energy input/output	%	2.1	2.3	2.6	1.9	2.6
Emissions from energy use during production chain	kg CO_2eq per kWh_{chip}	6.0	6.5	7.4	4.2	6.1
of which from electricity[a]					*0.04*	*0.04*

[a] Electricity is assumed to be produced from wood in a CHP plant having a total efficiency of 85%. Only large plants can afford this kind of stationary crushers. In early 2004, six Finnish CHP plants had a stationary crusher (Hakkila 2004).

These calculations do not include the greenhouse gas emissions of nitrous oxide emissions that accompanies N fertilizer application (IPCC 1997). A nitrous oxide emission rate of 1.25% (IPCC 1997, agricultural soils) of applied N would give an emission factor of the magnitude of about 6 kg CO_2eq MWh^{-1} when compensating for all the nitrogen outtake[22] due to forest residue utilisation However, as the conditions in Finnish forest soils that might need nitrogen compensation do probably not provide as ideal conditions for denitrification[23] processes as agricultural soil, the emissions are likely to be smaller. Furthermore, as the forest residue left on site would, when decaying, probably also have emitted N_2O to some extent, the N_2O emissions from fertilisation should probably only partly be accounted for.

Emissions from the full fuel chains

The magnitude of greenhouse gas emissions from a full fuel chip production and combustion chain is shown in Fig. 11. In most traditional analyses, only the production, meaning the use of machines and transport vehicles, and the combustion stages are considered, which means that quite important parts of the chains are left out. The emission rates due to fossil fuels used by machinery during production and transportation are of the same magnitude as the emissions from compensation of lost nitrogen by using fertilisation. The combustion stage is probably of minor importance, especially if the combustion technique and the control of it are in order, but might be of concern if not. The magnitude of the emissions due to ash recirculation are one tenth or less compared to other stages and could therefor be neglected in further calculations. Possible changes in carbon stocks in the forest soil (see Chapter 3.4) seem to be of significant relevance. The possible emissions from storage (see Chapter 3.3) should be further analysed as they together could be of the magnitude ten times as big as the emissions coming from rest of the chain.

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[22] Evaluated to be of the magnitude 1 kg N MWh^{-1}.

[23] Nitrous oxide (N_20) emission from soil is derived from denitrification and nitrification processes. The key process affecting nitrous oxide emission is denitrification, which is influenced by the level of oxygen present in soil, availability of nitrate and water–soluble organic C. Therefore, nutrient rich soils with abundant organic C under wet soil conditions would provide the most ideal conditions for denitrification to occur (Franzluebbers 2005).

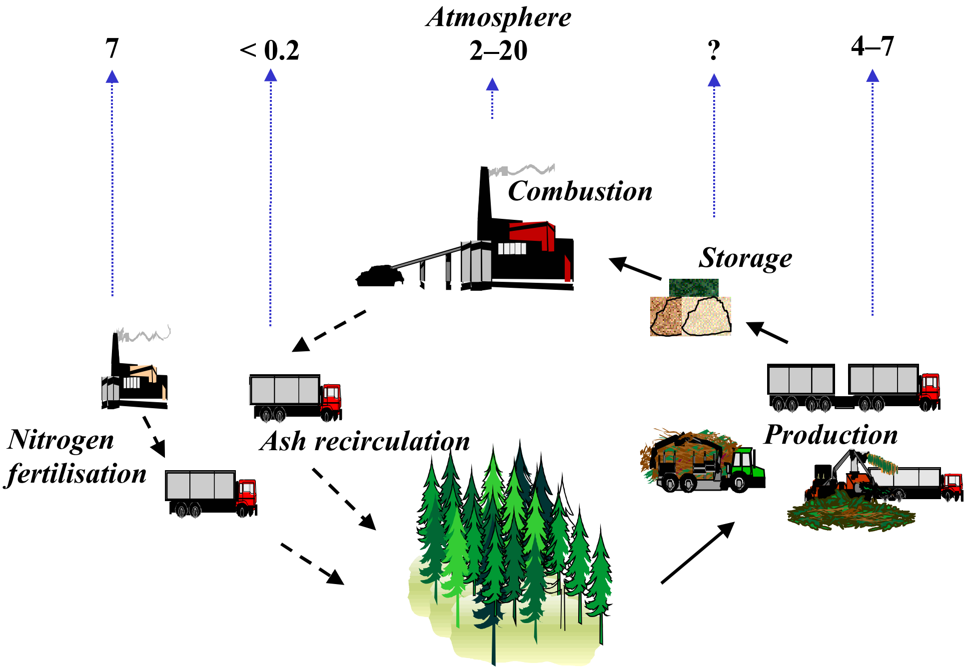

Figure 11. The magnitude of GHG emissions from a full fuel chip production and combustion chain (Fig. 2 in Paper III, modified).

3.2.2 By products

The same calculation principles as for forest residues were used for calculating energy input and GHG emissions for "wastes" or by-products from forest industry and agriculture. The evaluation (Wihersaari 2003) was made to briefly describe the beginning of the chain needed when upgrading biofuels. The results of the evaluation are shown in Table 3. Drawing the system boundaries for by products is not trouble-free due to e.g. choice of reference systems and allocation principles. This is discussed further in chapter 4.

Table 3. Evaluation of energy input and GHG emissions for agricultural by-products. The presented values were calculated for straw and corn in Hungary (Wihersaari 2003, modified).

	Energy input/output %	GHG emissions kg CO_2eq per $MWh_{biofuel}$
Collection	1	2.7
Transportation, distance 20 km	0.4	1.0
Fuel preparation[a] (chopping)	0–0.4	0–1.0
Nutrient compensation	0–3	0–15
Total	**1.4–4.8**	**3.7–19.7**

[a] fuel preparation is not needed if the fuel can be used as whole bales. Otherwise it was assumed that the energy input would be 3.5 kWh MWh^{-1}

A rough evaluation for chip as a by-product of the wood processing industry can be made upon the calculations for forest residue leaving out harvesting; if the chip comes from stem wood containing very little nitrogen, also the nutrient compensation is negligible.

3.2.3 Biofuel cultivation

Cultivating a biofuel, the biofuel is assumed to be the main product. This is the reason why establishment and maintenance is calculated to be part of the production chain. This evaluation (Wihersaari 2003) was also made to describe part of the chain needed for upgraded biofuels (see Chapter 3.2.4) and is only meant to demonstrate the magnitude of different production steps needed in biofuel cultivation. The result of the calculation, made using the example of cultivating poplar for biofuel purposes in Hungary, is shown in Table 4. The moisture content of the fuel chips was evaluated to be 30% and the energy content 4.2 MWh t^{-1} biofuel. These values give an energy yield of about 380 MWh ha^{-1} every fourth year.

Table 4. Evaluation of energy input and GHG emissions for energy forestry (poplar) in Hungary (Wihersaari 2003).

	Energy input/output %	GHG emissions kg CO_2eq MWh_{bio}^{-1}
Establishment, maintenance	0.3	0.7
Harvesting, transport on field	2.0	5.4
Chipping	1.4	4.0
Nutrient compensation	2.1	5.6
Transportation, distance 50 km	0.4	1.0
Total	**6.2**	**16.7**

3.2.4 Upgrading biofuels

The effect of biofuel upgrading on energy balances and GHG emissions was studied (Wihersaari 2003) by evaluating presumable, upgraded fuels from the three most potential bioenergy sources in Hungary; agricultural waste, traditional forestry and energy forestry. Interesting fuels for Hungarian circumstances were evaluated to be pellets, pyrolysis oil and syngas[24] production from biomass. Table 5 presents the evaluation of energy input and GHG emissions for producing these upgraded biofuels.

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[24] Syngas refer here to gas produced by thermal gasification of biomass. The expression biogas normally refer to gas produced from biomass by bacterical activity. This second method appears in this thesis only when producing landfill gas. The type of syngas studied here is not suitable for pipeline distribution but can be used e.g. to displace natural gas in combustion processes.

Table 5. Evaluation of energy input and greenhouse gas emission evaluations for producing upgraded biofuels in Hungary (Wihersaari 2003, modified).

Biofuel source	Upgraded biofuel	Energy input per energy output	GHG emissions
		%	kg CO_2eq $MWh_{biofuel}^{-1}$
Forestry	syngas	3–5	8–16
	pellet	~ 35	~ 75
	pyrolysis oil	~ 20	40–60
By-products of wood processing	pellet	5–33	13–69
By products of agricultural production	syngas	2–6	6–25
Energy forestry	syngas	8	21
	pellet	~ 39	~ 86

Syngas from forestry and agricultural by-products was calculated to be the most favourable upgraded biofuel, when considering the need of extern energy input and GHG emissions from the production chain. Syngas made from solid biofuels could in Hungary widely be used for substitution of natural gas. The fuel input of the gasification process was evaluated based on earlier presented results of base biofuels and a gas production efficiency of 0.8 was supposed.

Pellet production from dry by-products from wood processing industry was evaluated to have small energy input and emission factors but if the pellets are produced from a fresh material the factors multiply and are likely to reach values bigger than those of producing pyrolysis oil.

3.2.5 Aspects on substituting fossil fuels with a biofuel

When calculating GHG emission savings substituting a fossil fuel with a biofuel it is very common to only account for the avoided CO_2 emissions originating from the oxidation of carbon in the fossil fuel. As the carbon in biofuels originates from renewable sources, this CO_2 source is not accounted for, presuming that the biofuel is renewed in a sustainable way. This assumption is based on the reasoning that carbon stored in plants, which is released when burning the plant or parts of it as a biofuel, is taken up again by growing plants.

The combustion stage still causes other sources of GHG emissions, CH_4, N_2O and NO_x and these emissions are not considered neutral even for biofuels. In literature, GHG emissions from combustion of biofuels was found to be in the range of 3–20 kg CO_2eq MWh_{fuel}^{-1} or even more. To verify the greenhouse gas emission rates from modern combustion of forest residue chip, measurements were carried out at the Forssa Power Plant in Finland (Harju 2001). The sensitivity rate for the measurements of N_2O was 1 mg MJ_{fuel}^{-1} and the emission rate for wood chips was found to be lower than this value. The methane emissions varied between 0.4 and 0.8 mg MJ_{fuel}^{-1}. Based on these measurements, it can be assumed that combustion of wood chip in a modern CHP-plant produce a very low amount of greenhouse gases (N_2O, CH_4), about 2 kg CO_2eq MWh_{chip}^{-1} or even less. This means practically that if both the substituted fossil fuel and the substituting biofuel are combusted using modern combustion techniques with low emission rates, these emissions have little significance in the comparison of the greenhouse gas emissions from the different fuels.

When calculating emission savings, one step further is to calculate for all the emissions in the production chain. The magnitude of these emission rates when producing biofuels has been presented earlier. Being conscious of these emissions for biofuels in the evaluations, also the emissions from the production chains of fossil fuels have to be recognised. This causes some problems, though. As the main part of the fossil fuel production normally take place abroad, the emissions are not to well known and they are not accounted for in the national GHG emission evaluations. Table 6 shows an evaluation of the emission profile for fossil fuels used in Finland. Finland does not have any own domestic fossil fuel production, only oil refineries, and therefore the main amount of GHG emissions formed during the production and transportation chain are produced abroad.

Table 6. Emission profile of fossil fuels used in Finland (kg per MWh_{fuel}) (Wihersaari 2003).

	CO_2 from burning	CO_2eq from burning[a]	CO_2eq domestic	CO_2eq abroad	CO_2eq total	Production burning^{-1}
Coal	333.7	337.3	2.4	34.5	374	11%
Natural gas	200.9	204.5	15.4	43.4	263	29%
Fuel oil	275.8	279.4	16.5	16.5	312	12%

[a] The other GHG emissions than CO_2 from burning come from N_2O, CH_4 and NO_x and are assumed to be of the same magnitude for all fossil fuels (1 g CO_2eq per MJ).

The situation is somewhat different in Hungary where about 90% of the coal, 25% of the natural gas and 30% of the oil is produced domestically. Table 7 shows an evaluation of the emission profile for fossil fuels used in Hungary. Evaluated methane emissions are much higher for Hungarian coal mining than the values reported for coal imported to Finland. The main reason for this is that a big part of the coal production in Hungary is open-mining where CH_4 emissions are very difficult to control.

The emission factors estimated above can be compared to some figures estimated for Swedish circumstances: Gustavsson (1997) uses fuel cycle CO_2 emissions (compared with the combustion stage) of about 5% for heavy fuel oil, 22% for natural gas and 21%. Börjesson (1996b) uses 15%, 20% and 20%.

Table 7. Emission profile of the Hungarian fossil fuels (kg CO_2eq MWh_{fuel}^{-1} (Wihersaari 2003).

	Burning[a]	Production chain			$Production_{average}$
		Domestic	Average[b]	$Average_{dom}$[c]	$Burning^{-1}$
Coal	337.3[d]	98.4	92.2	88.8	27%
Natural gas	204.5	11.2	46.9	3.5	23%
Fuel oil	279.4	31	32.4	20.9	12%

[a] Other GHG emissions than CO_2 from burning (N_2O, CH_4 and NO_x) are assumed to be of the same magnitude for the fossil fuels (1 g CO_2eq/MJ) as for the substituting biofuels. This means, that in the emission saving calculations these other emissions will not be affecting on the results. Furthermore, when burning a biofuel the CO_2 emissions are assumed to be GHG-neutral.
[b] Assumed amount of domestic production: coal 90%, gas 25%, oil 30%.
[c] Only emissions produced domestically accounted for.
[d] Might be too small for Hungarian circumstances as the power plants are old.

In Wihersaari (2003) the GHG emissions presented earlier for biofuel production and upgrading chains are combined with the emission calculations of fossil fuels to evaluate the GHG saving potentials when using different kinds of biofuels. The calculations show that 180–420 kg CO_2eq MWh^{-1} of greenhouse gases can be saved in Hungary when substituting fossil fuels with biofuels, Fig. 12. The saving potentials[25] are biggest, 400–420 kg CO_2eq MWh^{-1}, when substituting coal with chipped biofuels. Using pellets instead of chip the potentials would decrease the potentials by 10–60 kg CO_2eq MWh^{-1} depending on the origin of the biofuel. By substituting fuel oil with bio-oil[26], the emission savings would be

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[25] The variation illustrates how big difference it makes depending on the choice of biofuel production chain and in what extence the emissions are included. For the smaller value, a biofuel production chain with higher emissions is used and the emissions abroad for fossil fuels are not included.

[26] Bio-oil is used to substitute oil in these calculations because e.g. bio-powder cannot be used for substitution without the fuel utiliser investing in new handling equipment, combustion technique etc.

in the range of 240–270 kg CO_2eq MWh^{-1}; for natural gas substituted with syngas, the range would be 180–240 kg CO_2eq MWh^{-1}. If replacing coal with chipped biofuels or oil with pyrolysis oil from wood, it is very insignificant if the emissions caused abroad in the fossil fuel production chain are accounted for or not. This will affect the calculated potentials by only 1–5%. For natural gas replaced by bio-gas, the chosen principle is of much more importance as the saving potentials will be 22–25% higher if the emissions abroad are included.

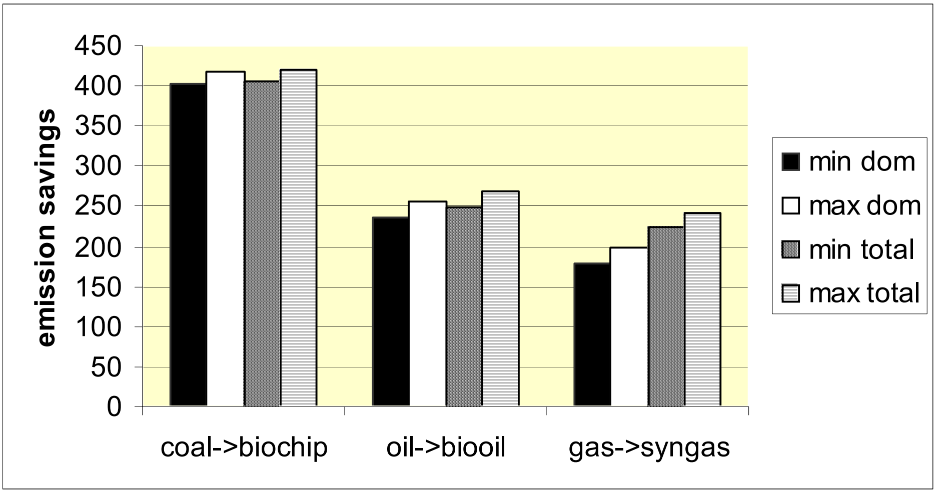

Figure 12. The magnitude of GHG emission savings in Hungary when replacing coal with bio-chip, oil with bio-oil and gas with bio-gas. For 'min dom' and 'max dom,' only the domestic emissions are calculated for, for 'min total' and 'max total,' also the emissions abroad are noticed. The unit is kg CO_2eq MWh_{fuel}^{-1} (Wihersaari 2003).

Discussion

The simple calculation model applied in the studies presented in chapter 3.2 to evaluate the magnitude of GHG emissions in different parts of the production chain seems to be very useful. Based on the calculations, energy-efficiency seems to be a good measure to evaluate GHG emissions from fuel production chains. The calculations show that same model can be applied on by-products, biofuel cultivation and upgraded biofuels and that segments studied for basic biofuels chains can be combined with the calculations of the upgrading process. Applying the calculation model on fossil fuel production chains gives us a tool to discuss the importance of the choice of system boundaries in the GHG emission saving calculations. Simple model calculations like this can easily be adjusted and kept transparent. New segments can be included and system boundaries can be changed. This kind of model calculations tells us the order of magnitude of the overall results and the role of different segments. Model calculations like this can also easily be applied on specific chains and the results can be understood by biofuel players. Expanding the system boundaries of the fossil fuel calculations to parts of the fuel production chain that are put into practice abroad will, in many cases, lead to situations where the accuracy of the results are much better for biofuels. Another issue to keep in mind in this kind of calculations is the importance of choice and documentation of allocation principles.

3.3 Potential greenhouse gas emissions from storage of biofuels

The production and use of wood derived fuels is a remarkable part of the forest industry material flow discussed in Chapter 3.1. Table 8 shows the amount of wood derived fuels used as energy in Finland in 2002. Bark, sawdust and chip are wood fuels stored as chopped material in some phase of the fuel production chain and these are, upon the findings of this thesis, estimated to be a potential risk of greenhouse gas emissions which increases with the length of storage time. Recent research projects (Marttila & Leinonen 1999, Kuoppamäki et al. 2003) indicate that there is a growing interest and need for wood fuel storage activity in Finland.

Table 8. Wood derived fuels used as energy in Finland 2002 (Statistics Finland 2003).

Wood derived fuel	Energy use in 2002, TWh
Black liquor	40.4
Industrial wood residues	
Bark	15.3
Sawdust	4.5
Chip from wood residue	1.6
Other wood fuels	0.8
Forest chip	3.3
Other small combustion of wood	13.0
Total	78.9

Table 9 shows annually utilised volumes, their typical moisture and energy content as well as a rough estimation of storage periods for bark, sawdust and fuel chip. Wood fuels, generated as by-products of the pulp and paper industry, are normally utilised as energy within a few days. Exceptions to this are e.g. maintenance periods or sporadic interruptions in the production, which may lead to storage times of typically 1–3 months. Wood fuels originating from sawmills that are not used on-site have to be stored, possibly dried and transported before utilisation. Among fuels originating from this branch it is more likely to find storages than in the pulp and paper industry. A sawmill survey indicated that 17% of sawmills have bark inventories older than 1 month and 10% have inventories older than 2 months (Kuoppamäki 2001). Bark with high moisture content produced e.g. in winter time may be stored (to dry up) over the summer months or to the next heating season. Contaminated (with e.g. stones, sand, soil, snow and ice) lots may be stored for even longer periods than estimated here.

If the forest fuel is used for municipal heat and/or electrical production, the length of the storage period depends to some extent on the fuel supply and demand situation. The longest storage periods (up to 12 months) appear where the fuel demand is big and storages are filled up during spring and summer time and dismounted until the end of the heating season.

Table 9. An evaluation of annually utilised volumes of bark, sawdust and fuel chip in Finland, their typical moisture and energy content and appearing length of storage time.

Wood fuel	Typical moisture content[27]	Typical energy content[28]	Estimated[29] volume used as fuel 2002	Rough estimation[30] of storage periods
	w-%	MWh per loose m^3	mill. loose m^3	months
Bark	40–65	0.6	25	0–12
Sawdust	45–60	0.6	8	0–12
Chip	45–55	0.8	5	0–6

Forest residue is normally stored on site and at roadside before chipping because of dewatering. To minimise material losses and maximise the energy content of the produced fuel, the ideal situation would be to prepare the fuel chip in July–August and to use the chopped material at once without intermediate storage. Nevertheless, as the fuel demand for producing heat and electricity (for municipal[31] use) is much higher during winter months (November–March), fuel suppliers have to include storages and/or to accept that the forest residue is re-wetted. The storage period of six months used for the calculations presented in Paper IV was chosen taking into account both the moments of optimal fuel preparation and maximal fuel demand.

To avoid misunderstandings, I want to underline that the calculations presented here are not an allegation that present biofuel storages in Finland produce remarkable amounts of GHG emissions but rather an evaluation of what magnitude the emissions might be if long-time storage activities are included in the production chains.

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[27] Alakangas et al. 1987, Impola 1998, Alakangas 2000.

[28] Alakangas 2000.

[29] Statistics Finland 2003, Metsätilastotiedote 2002.

[30] The estimation was made upon expert interviews in November–December 2004.

[31] The municipal energy supply sector is the main user of forest chip – only 26% was e.g. in 2001 used by the forest industry (Metsätilastotiedote 2002).

To investigate the impact of biofuel storage, biowaste-composting research was combined with information on forest fuel characteristics and knowledge of forest fuel storage behaviour (Paper IV). The C/N ratio and the moisture content of forest residue were found to be at a level, were fast decomposition may be expected. Temperature behaviour and the level of material losses also seemed to match between composting and biofuel storage.

Results from biofuel storage research point out that the decomposition behaviour differs depending on the moisture content of the fuel. Therefore, the emission mechanisms and rates known from different phases of composting were used for evaluating two different qualities of forest fuel chip: naturally dried forest residue with a moisture content of 40 w-% and fresh or re-wetted forest residue with a moisture content of 60 w-%.

In the calculations, the temperature of the two kinds of fuel heaps was assumed to rise to a level of over 40ºC within 1–2 weeks after the storage was established. The heap with lower moisture content was expected to cool down about 2 months later, whereas the other heap was assumed to keep a temperature over 40ºC for the whole storage period of six months, Fig. 13.

Similar decomposing and emission mechanisms that has been found during biowaste composting was assumed to take place:

- Organic material is assumed to decompose mainly to CO_2.
- The emitted N_2O is found to be either the end product of incomplete ammonium oxidation (aerobic conditions) or the end product of incomplete denitrification (anaerobic conditions).
- As nitrifying bacteria are sensitive to high temperatures (>40°C), no remarkable emissions of N_2O can be expected during the most intensive decomposing stage.
- CH_4 is known to be produced only during anaerobic conditions. Such conditions typically occur when the biological activity is high, or in other words, when the temperature and the CO_2 production are high.
- The formation of CH_4 is most intensive in the hot, anaerobic parts of the decomposing heap.

- Some of the formed methane is likely to be oxidised in aerobic parts of the material when the gas flows towards the surface, which means that the emissions will actually be lower than the amount of methane gas formed inside the heap.

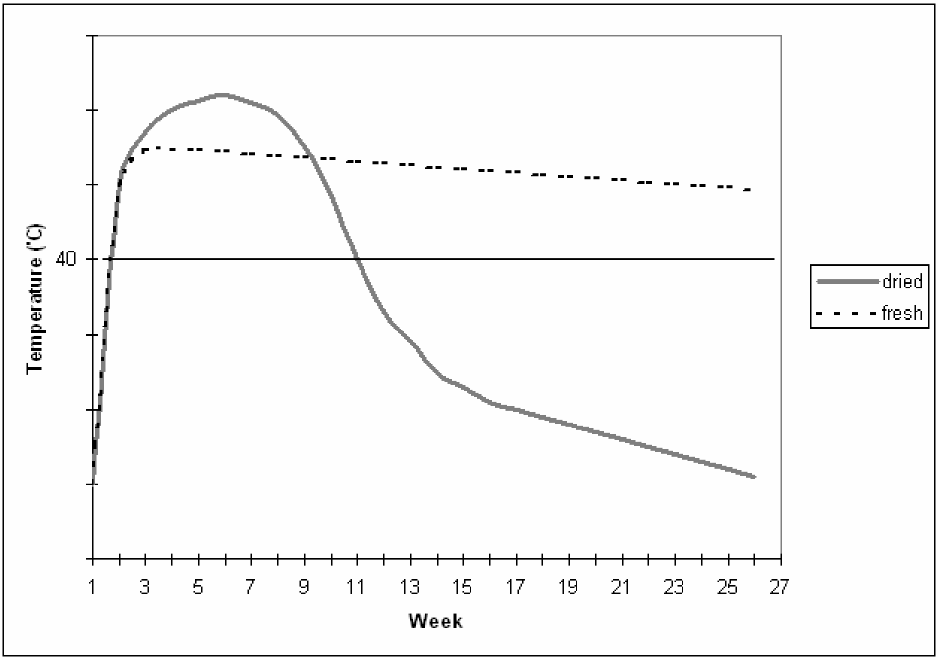

Figure 13. Simplified temperature behaviour assumed for two types of decomposing forest fuels (Fig. 2 in Paper IV).

Paper IV describes emission rates known from compost and initial proportions of carbon and nitrogen reported to form CH_4 and N_2O. Upon these, average values of 60 g CH_4 m^{-2} day^{-1} (reported variations 35–119 g CH_4 m^{-2} day^{-1}, Beck-Friis et al. 2000) and 1.2 g N_2O m^{-2} day^{-1} (reported variations 0.6–2.3 g N_2O m^{-2} day^{-1}, Beck-Friis et al. 2000) were chosen as emission values for the biofuel storage calculations. Fig. 14 shows the result as a principal estimation of the cumulative greenhouse gas emissions for long-time storage of two kinds of fuel chip, fresh forest residue and naturally dried forest residue.

The GHG emissions for a six months storage period described in Paper IV were calculated to be remarkable, 144 and 58 kg CO_2eq MWh^{-1}. To check the range of the results, the initial amounts of C and N needed to form the emitted gases was calculated and again, compared against values reported from compost research. The evaluated CH_4 emissions seemed to be quite well in line with figures from literature (1.3 and 4.4 w-% compared with literature values of 1–5 w-% of C forming CH_4) but the evaluated value of N_2O was found to be 2–4 times bigger (4.4 w-% compared with literature values of 1.0–2.6 w-% of N forming N_2O). The comparability for the calculated amount of N_2O with figures from literature is, however, difficult to estimate because the research periods in the consulted literature have probably been too short to account for all N_2O emissions that might be formed from compost heaps, already cooled down. Normal time-periods when investigating compost heaps are only 1–2 months, but Beck-Friis (2001) report "hotspots" with high N_2O concentrations in compost heaps aged 6 and 12 months. Furthermore, compost research is more concerned about ammonia (NH_3) emissions as they are the main source for unwanted nitrogen losses, and these emissions occur in a relatively early stage of the compost process.

Discussion

This study indicates that storage of biofuels may be an issue to keep eyes on because the emission risks seem to be remarkable. As the calculations leading to this conclusion are only a first attempt to evaluate GHG emission risks for biofuel storage and as the results have not been verified by measurements the uncertainty must be considered high (see Chapter 3.7). There are available proof of that storage heaps of forest fuel chip may produce CH_4 (Marttila & Leinonen 1999) but there are no such emission measurements available that could have been used as base for these calculations.

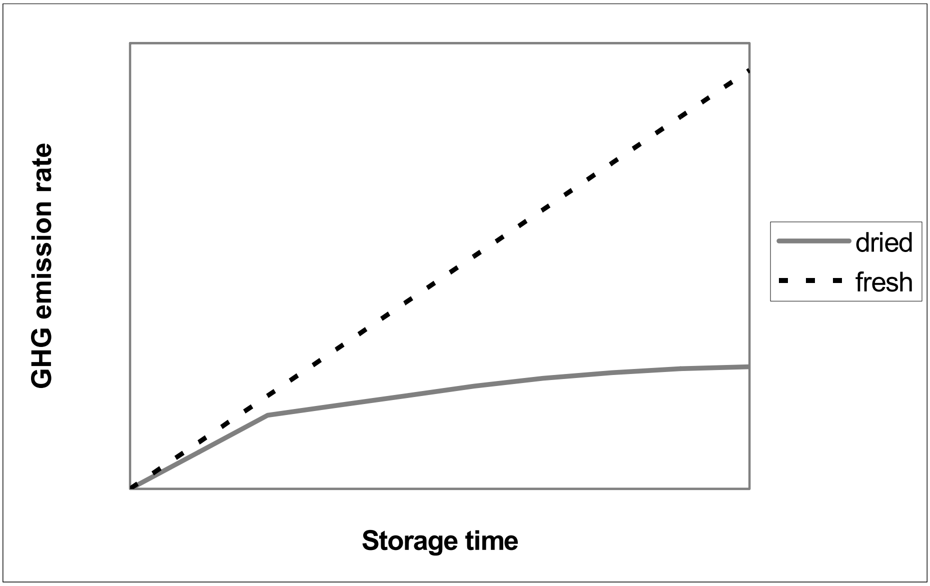

Figure 14. A principal estimation of cumulative greenhouse gas emissions for storage of two kinds of fuel chip with different decomposing behaviour. The assumed temperature level inside the storage heap is the same as shown in Fig. 13 (Fig. 3 in Paper IV, modified).

3.4 Utilisation of forest residues and the effect on the carbon pool in forest soil

In Paper V there is an attempt to quantify the impact of the collection of harvest residues to the carbon pool in forest soils. The decrease in forest soil carbon stock was estimated by simulating the decaying of the harvest residues at the forest site. The difference in soil carbon stocks between landscapes where residues are removed for e.g. biofuel production and where they are left to decay was considered as an indirect emission to the atmosphere. This time-dependent difference in carbon storage was then used to calculate an indirect CO_2 emission generated when using forest residues as a biofuel.

The difference in carbon stocks was calculated to be 11% of the total carbon amount in residues. For spruce stand with 200 m^3 ha^{-1} stemwood volume and 15 Mg C ha^{-1} of harvest residues (100% recovery), this means a carbon emission of

1.7 Mg C ha^{-1} or a CO_2 emission of about 6.1 Mg CO_2 ha^{-1}. Assuming that energy achieved would be 135 to 150 MWh ha^{-1} (depending on the moisture content[32] of the fuel chip) and a rotation length of 100 years, the calculated emission of CO_2 from the decreasing of soil carbon would be in the range of 40 to 45 kg CO_2 MWh_{chip}^{-1}. Using a lower recovery rate for harvest residues, e.g. 60%, will lower the carbon emissions calculated per hectare of forest land with the same range but this would not affect the emission amounts calculated per MWh_{chip} as the energy achieved would also decrease with the same rate.

Discussion

The model calculations show that the outtake of forest residue may have important effects on the soil carbon pool. Further, the calculations make it possible to compare the magnitude of the possible impact on GHG emission savings with other results presented in this thesis. But – there are many uncertainties in the study. First, these calculations were purely theoretical, not verified by any measurements. Secondly, the dynamic model calculations assumed that the forest carbon pool is in balance at the moment when the study begins. Furthermore, the impact of many factors such as changes in temperature and humidity conditions on the sites due to harvest residue removal was not evaluated.

3.5 Aspects on considering municipal waste as a biofuel

The main part of the carbon content of municipal waste comes from sources that can be considered renewable: paper, food, wood etc. The exception is plastic waste produced from fossil oil resources. As welfare increase, the share of plastics in municipal waste normally grows. In the beginning of the 1990's the carbon content of municipal waste in Finland was about 23%, of which about 20% originated from renewable sources and the rest from plastics (Paper VI). In calculations made about ten years later (Wihersaari 2000), the amount of biodegradable carbon was about the same, but the amount of carbon originating

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[32] Here used moisture values of 40 and 55 weight-% to evaluate the range of the emissions. The lower moisture value reffer to the lower emission rate.

from plastics had grown from 3 to about 8 per cent. Considering only the biodegradable part of municipal waste a biofuel, the emissions caused by plastics has to be counted for when evaluating the emission profile of solid recovered fuel (SRF).

Generally, the processing of waste to produce SRF can be examined in a similar way as producing biofuels (Wihersaari 2000). Fig. 15 shows the studied elements of the SRF production chain. Here, the simplest fuel having an energy content of about 2.8 MWh t^{-1} is represented by collected waste, transported to a mass incineration plant instead of dumping it. This "production chain" needs an energy input of about 2.2% and causes GHG emissions of about 6 kg CO_2eq MWh^{-1} (Wihersaari 2000). Assuming that 98% of the carbon content in the plastics oxidise during combustion, the emission originating from this is about 90 kg CO_2eq MWh_{SRF}^{-1}.

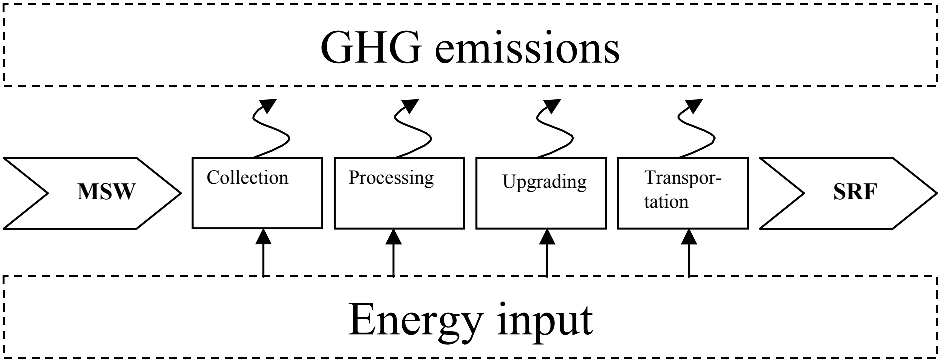

Figure 15. Studied elements of the SRF production chain.

In Finland, it is very common to sort municipal waste. Source separation of e.g. paper, biowaste, glass etc. is done everywhere to a certain extent. The so-called “dry fraction” is normally used as raw material for SRF but collection experiments with a source separated waste-fuel fraction have also been performed. Source separation means that the quality of the collected waste becomes higher while the total amount of available energy decreases. Calculated energy input rates for this kind of SRF was 2.0–3.2% when including central handling (without drying). Including a drying stage to lower the moisture content to a level of 10% increased the energy input to over 11%. The corresponding GHG emissions were 5.6–8.7 and about 30 kg CO_2eq MWh_{SRF}^{-1}

(Wihersaari 2000). The emission rates from combustion (because of plastics)[33] increase for these SRFs to 96–109 kg CO_2eq MWh_{SRF}^{-1}. Including the drying process the energy content in the fuel increase which means that the emissions from the combustion stage (from plastics) decrease with about 5 kg CO_2eq MWh_{SRF}^{-1}. This compensates only some of the additional emissions produced in the production chain.

Discussion

Applying the biofuel production model on MSW shows that the emission and energy efficiency profile of the production of SRF is very similar to that of biofuels. The same kind of model that was developed to study forest fuels can be used for studying SRF production. The fossil aspect coming mainly from the plastic content can be included as a fuel property for the produced SRF. Variations in the origin and quality of MSW though affect e.g. the plastic content, which probably will lead to a practise of using average figures for GHG emissions from combustion. System boundaries and allocation principles are issues that must be carefully considered and documented when studying SRF production.

3.6 Biomass or municipal waste disposal considered as a base scenario

When calculating the effects of forest residue outtake on the carbon pool in forest soil the case when the residues are left to decay in the forest is considered a baseline scenario. The following calculations where biomass and MSW disposal is considered a base scenario have a completely different starting point; here the baseline causes severe GHG emissions and different measures to avoid these emissions are studied. This kind of approaches make the definition of system boundaries and the calculations much more complicated but sometimes they have to be included to make the studies more complete.

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[33] For monitoring and reporting greenhouse gas emissions, Statistics Finland provide calculatory emission coefficients. The present CO_2 emission coefficient, that may be used within the scheme of greenhouse gas emission allowance trading, is for solid recovered fuels 31.8 t CO_2 TJ^{-1} (114.5 kg CO_2 MWh^{-1}). (Statistics Finland 2004).

Paper VI considers alternative strategies in mitigating greenhouse impact of waste management. The traditional waste handling method has been based on landfilling for decades in Finland. It is well known that landfill gas is formed when the organic matter degrades under the anaerobic conditions in the landfill. The values used for determining the emission factor for CH_4 (42 kg CH_4 per tonne waste or 214 kg CH_4 per tonne dOC) for landfills are explained in Paper VI.

The total GHG emissions from dumping 1 tonne of an average MSW in Finland was calculated to cause GHG emissions of about 880 kg CO_2eq (Table II, Paper VI). Taking in account that part of the biodegradable carbon will be stored, which means that the landfill will also act as a carbon pool, reduces the net impact of the landfill to about 400 kg CO_2eq t_{waste}^{-1}. The C in fossil waste like plastics was neither considered to contribute to the emissions from the landfills nor to the C sink.

Landfilling was calculated to clearly have the largest greenhouse impact. Landfill gas recovery and its combustion reduces the greenhouse gas emissions significantly. Landfill gas recovery (flaring) was calculated to decrease the net impact to about 50 kg CO_2eq t_{waste}^{-1} and if the recovered gas can be used for substituting a fossil fuel, the net impact would be zero (neutral) or even negative (reduce the greenhouse impact).

The alternative where the biological fraction was treated anaerobically or by composting and the rest of the waste was landfilled was calculated to produce greenhouse gas emissions comparable with landfilling combined with gas recovery. This result might not be accurate if basic outdoor compost methods are used.

Waste treatment alternatives including combustion were calculated to be most favourable for reduction of GHG emissions. Of the different, studied alternatives mass incineration was calculated to have the most favourable influence on the mitigation of greenhouse impact.

Furthermore, to be able to compare different emission saving methods with the costs of mitigating greenhouse impacts, alternative treatment scenarios were examined in Paper VI for the situation in the beginning of the 1990s for three different sizes of communities in Finland. Mass incineration was not included as an option in any of the studied cases. Landfill gas recovery from large landfills was estimated to be a very competitive way of reducing greenhouse gas emissions (0.01 FIM per kg CO_2eq ≈ 0.002 € per kg CO_2eq). Other treatment methods the greenhouse gas emission costs varied between 0.3 and 1.9 FIM per kg CO_2eq (0.05–0.32 €).

As wood residues from the forest industry are not normally landfilled in Finland, it is quite difficult to imagine that measures decreasing GHG emissions from such activities could possible claimed for emission reductions. Such attitudes exist – a good example is a recent World Bank project (BTG 2002) performed in Bulgaria, where the forest industry have been dumping wood wastes for decades. To evaluate CH_4 emissions from the dumped wood wastes (mainly bark but also saw dust), measurements from two areas with wood waste stockpiles was performed and model calculations were made to evaluate emissions from the present dumped material and the annual new wood waste rates. The size of the stockpiles was about 50 000 t dry matter each. It was estimated that the existing piles would emit methane in the range of 3.9 and 3.0 million m^3 during the next 10 years (64 and 49 kt CO_2eq or 1.3 and 1.0 kg CO_2eq $kg_{\text{dry biomass}}^{-1}$). New wood waste material was predicted to have a higher emission rate for the incoming ten years if dumping it, 1.3–1.7 kg CO_2eq $kg_{\text{dry biomass}}^{-1}$. A rough estimate that the new wood waste has a moisture content of about 50% and a lower heating value of 2.4 MWh t^{-1} gives us a huge emission coefficient of 270–350 kg CO_2eq per MWh of potential biofuel when dumping the wood waste. In other words, if using such a wood waste as a fuel instead of dumping it, substituting e.g. coal, the GHG savings would be in the range of 600–700 kg CO_2eq MWh^{-1}. No measurements nor model calculations of N_2O were performed in the project but upon findings in the literature survey of the project it was estimated[34], that accounting also the possible N_2O emissions, this could increase the GHG emission estimates with even 35%.

Discussion

The findings presented in this section show that the results of the calculations might completely change character if the baseline includes landfilled biomass. However, these kinds of enlargements of the studies make the analyses much

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[34] It was assumed that N_2O emissions from the biomass stockpiles are comparable to those of compost piles found in the literature survay. 50 000 tonnes of stockpiled biomass was evaluated to cause nitrous oxide emissions of 2.3 kton CO_2eq.

more complex and the level of uncertainty increases. Furthermore, the choice of baseline and calculation principles will have great effect on the results. In the future, the baseline of waste management systems is likely to change as the rules for waste disposal and properties of disposed waste change.

3.7 Uncertainties of the calculations

The overall uncertainty of the estimates made in the thesis cannot be calculated, because they were based on data with a very wide difference in reliability. Therefore, the magnitude of the uncertainty and the order of priority for the results are approximated by considering bigger groups of potential error sources. The overall estimate is presented in Table 10 and some of the given approximated levels are commented on below.

Table 10. An overall estimate of the uncertainty of the estimates made in the thesis.

Error source	Order of priority for the results	Uncertainty	
		Energy balance	GHG emission
Production of base biofuels	+	L	L
Upgrading biofuels	+++	L/M	L/M
SRF production	++	L/M	L/M
Ash recirculation	o	L	L
Nitrogen fertilisation	+	L	L
Forest soil carbon pool	+++	o	H
Storage	++++	H	H
Landfilling	++++	o	M

Scales: Negligible o, low +, medium ++, high +++, extremely high ++++, Low L, medium M, high H.

The calculations considering biofuel storage are considered the most uncertain part of these calculations. First of all, the chosen emission factors have not been verified by any measurements from biofuel storage. Further, the assumed temperature behaviour and the correlation between the temperature and the emitted GHG gases (N_2O and CH_4) from decaying biomass is not well known. To measure presentable emission rates for outdoor compost heaps is not easy, as the gases have very different relative density compared with air (CH_4=0,555, N_2O =1,530, CO_2=1,530) and this will probably affect the flow directions. Even decaying rates – or material losses – are difficult to exactly define in a storage heap. The calculated GHG emissions were checked against data upon how big amounts of the reacting C and N is known to form CH_4 and N_2O. This cross-checking improves the certainty of results as methane was calculated to be the main emission source and the cross-checked results for CH_4 were within a reasonable range.

The reliability of the model results for the changes in the forest carbon pool depends on both the validity of the model structure and accuracy of the model parameters. The sensitivity of the results to the model parameters has been studied in Palosuo & Wihersaari (2000). The uncertainties are further discussed in Paper V. The order of priority for the overall results and the uncertainty of the calculated emission factors must be considered to be high. This part of the calculations has no impact on the uncertainty of the calculations considering energy efficiencies.

Considering the calculations of the production chain of base biofuels, the accuracy of the data is estimated to be rather good and the calculations should include no remarkable uncertainties. There is a direct relation between energy efficiency and GHG emissions as the same emission factor has been used for all machines. As CO_2 represents about 97% of the GHG emissions (when studying emissions from machinery) measuring fuel consumption can simply follow them up. A sensitivity analysis of the fuel production chain can be found in Wihersaari & Palosuo (2000). The uncertainty of the calculations for ash recirculation is of the same type but smaller than for the biofuel chain. The order of priority for the results can be considered negligible as the energy input of this stage is only about 5% compared with the energy input of the base fuel chain.

The recommended (direct) GWP-values by IPCC, needed for evaluating the CO_2eq numbers in this thesis, have been estimated to be accurate within ±35% (IPCC 2001a). The recommended values have been changed a few times during the years and some calculations in the older Papers have been performed using different GWP-factors than in this thesis. The changes have been less than ±10%

for individual gases (CH_4 and N_2O) and they have been made in opposite directions. This means, that using updated GWP-values have had no remarkable effects on the calculated CO_2eq results in this thesis.

Despite of the large uncertainty of the overall results the order of magnitude in the estimates is adequate to give an understanding of the order of priority of the importance of further research and the importance of emission reduction measures for the different players.

4. General discussion

4.1 Discussion of the results

In this thesis some aspects on bioenergy as a technical measure to reduce energy related GHG emissions are presented. The calculations show that the present point of view that the production and use of biofuels is nearly totally GHG emission neutral is only part of the truth and that the real situation is somewhat more complicated.

There are five different methodologies used in the separate evaluations: Paper I utilises the philosophy and methodology of Industrial Ecology to analyse the sustainability and material flows of the Finnish forest industry. A simple calculation model was used for analysing the energy consumption and GHG emissions for biomass production chains, upgrading of biofuels and production of SRF. The model calculates the material flow, external energy input and GHG emissions for the different parts of the production chain. These are summed up and compared to the output of biofuel. Emission risks from long-time storage of biofuel were evaluated upon GHG emission rates known from decomposition of biowaste. To evaluate changes in forest soil carbon due to harvesting of forest residues, we used a dynamic model, which describes the carbon stocks and fluxes of decomposing organic matter. The fifth methodology was needed to estimate the potential future CH_4 emissions for a given amount of landfilled waste. The different papers all discuss greenhouse gas emissions and bioenergy. Furthermore they all aim to contribute to establish a calculation method that can be used for evaluating energy related greenhouse gas emission savings when using different kind of biofuels. As there has been no bigger changes in the GWP values recommended by IPCC, does the time of publishing not affect the overall results of this thesis although Paper II (published 1996) and Paper VI (published 1998) are quite old. The overall uncertainties of these calculations are evaluated to be large but the calculations still give a good base for understanding the order of priority of possible GHG emission reduction measures.

Biomass for energy is regarded as one of the most important renewable resources in future energy systems (European Commission 1997). The time window for renewability must though to be specified depending on in what context the word is used. In the work against climate change, the essential goal is to slow down (and stop) the mean temperature grow on Earth by stabilising the carbon dioxide level in the atmosphere within 100–200 years. This means, that the regeneration time of biomass considered as renewable (in this context) should to be shorter than the time window set for stabilisation. As the rotation period of forestry is normally 80–120 years in Finland forest fuels can be considered renewable in this context. Energy forestry and agricultural by-products do even have a shorter rotation time. Sustainability requirements must, of course, also be fulfilled.

Bioenergy in Finland is very strongly related to wood production for the forest industry. The primary goal in the energy and material flow approach of the Industrial Ecology system study (Chapter 3.1 and Paper I) was to investigate how the flows of the Finnish forest industry are adopted to the flows of the natural ecosystem, and to point out measures that could be taken to decrease the disturbance caused by the economic system, especially the forest fuel production modules, to a sustainable level. The cuttings of the forests in Finland are smaller than the annual growth. The positive consequence of this is that the annual binding of C in the Finnish forests presently exceeds the amount of C released from cuttings and natural drain, which decreases the amount of CO_2 in the atmosphere. This will, though, go towards a balance in the long run. Round wood and wood wastes are utilised in an advanced network of saw mills, pulp mills and energy plants that makes the recycling rate of both material and energy very high. Electricity and fossil fuels are still used to some extent and these could be partly replaced by e.g. forest residues. However, this would increase the problem with the poor recycling of nutrients (base cations). The base cations already follows a throughput direction, starting from forests and ending up as ash of combustion processes or as used wood based products at landfills. At the present situation about 60% of the base cations end up in ash. If the use of nutrient rich forest fuels increase, the importance of ash recirculation will grow. The recycling of nutrients is important for the growth of further tree generations and might effect on the binding of C in the new tree generation.

The examination of the biofuel production chains (Chapter 3.2, Paper II, III and Wihersaari 2003) showed that in a favourable situation as much as 97–98% of GHG emissions for a fossil fuel could be avoided by substituting it with a biofuel. Fig. 16 shows an evaluation of the magnitude of GHG emissions from different parts of the fuel chip production chain. The GHG emissions from collecting, chipping and transporting the forest residues were in this thesis calculated to be in the range of 4–7 kg CO_2eq MWh_{chip}^{-1}. Additionally, a complete ash and nitrogen refunding would account for less than 0.2 kg CO_2eq MWh_{chip}^{-1} and 7 kg CO_2eq MWh_{chip}^{-1} respectively. Börjesson (2000) calculated GHG emissions of 14 kg CO_2 MWh^{-1} for base forest fuels (including nitrogen and ash compensation) that are in line with the result presented in this thesis. Korpilahti (1998) evaluated the CO_2 emissions of wood fuel production (including harvesting, chipping and delivery) to vary from 5.6 to 7.8 kg.

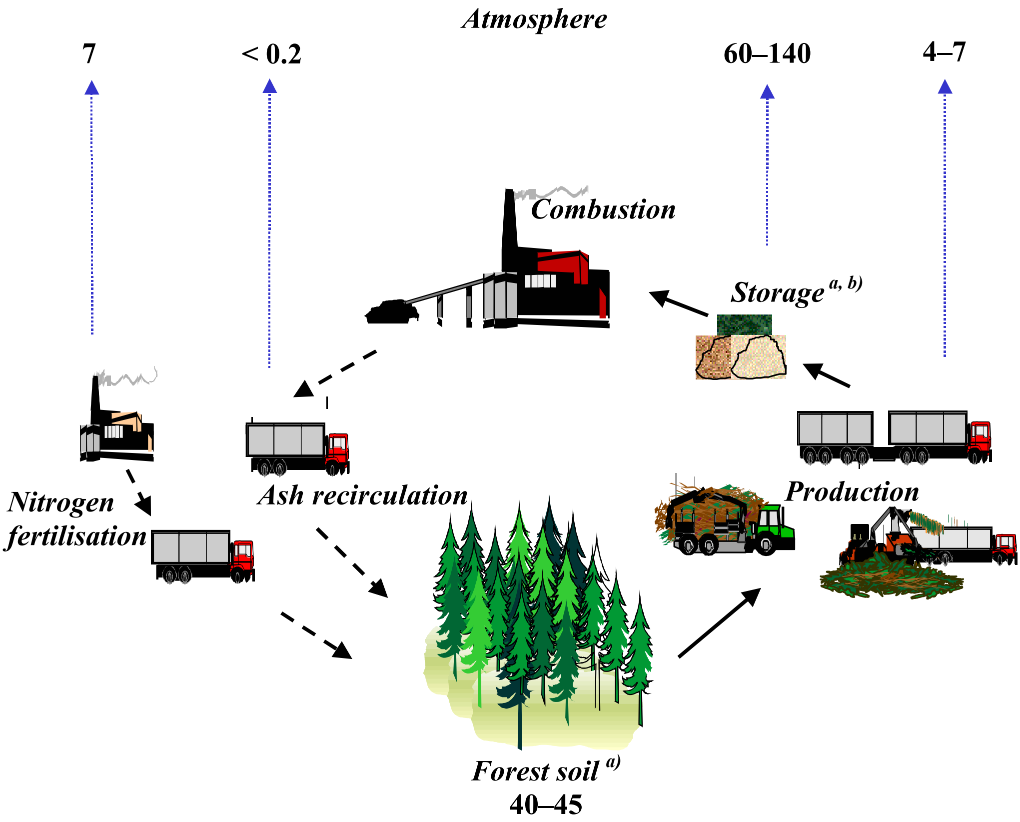

Figure 16. The magnitude of GHG emissions (kg CO_2eq MWh^{-1}) from different parts of a fuel chip production chain (a)The calculated magnitude of these emissions have to be considered more uncertain than the other. b) Evaluated for a six month storage of chip). (Fig. 2 in Paper III, modified).

A brief evaluation for some other biofuels was also performed, resulting in GHG emission figures of 4–20 kg CO_2eq MWh_{bio}^{-1} for agricultural and forest industry by-products (3 examples), 17 kg CO_2eq MWh_{bio}^{-1} for biofuel cultivation (only one calculated example) and 6–86 kg CO_2eq MWh_{bio}^{-1} for upgraded fuels (4 examples). These figures do not include the potential emissions from storage and forest soil, explained below.

The energy efficiency of the above mentioned biofuel production chains was also investigated. The external (fossil) energy input was compared with the energy content of the biofuel output. The production of forest residues was found to be very efficient with an energy input of 1.9–2.6%. Ash recirculation would increase this figure with less than 0.1% but the figure for refunding nitrogen was calculated to be quite high, about 1.4%. The corresponding figures for agricultural and forest industry by-products are 1−5%, for biofuel cultivation 6% and for upgraded fuels 2–40%.

Based on the results explained above, there seems to be a very good relation between energy efficiency and GHG emissions of biofuel production chains. This means, that the expected magnitude of GHG emissions can, in well-documented cases, simply be estimated by measuring the external energy consumption. Upgrading biofuels increase both GHG emissions and external energy input remarkably.

Some figures and results found in the literature are in line with the results presented in this thesis. Börjesson (1996a) calculated the energy input per unit of biomass produced to be 4–5% for some base biofuels such as straw, logging residues and Salix. Schwaiger & Schlamadinger (1998) calculated rather high GHG emissions for chip preparation in Finland, but the reason was the assumed long average transport distances (150 km) that accounted for almost half of the emissions in their evaluations. Forsberg (2000) calculated that in bioenergy systems the use of fuels and electricity for operating machines and transportation carriers requires a net energy input of typically 3–4%. Gustavsson & Karlsson (2002) used a primary energy input of 13% in an upgrading case (for pellet production from sawdust). Mälkki & Virtanen (2001) evaluated in a LCA analysis the energy input to be 2.3–3.2% for some forest chip production chains and the corresponding greenhouse gas emissions to be 7.5–10.0 kg CO_2eq MWh^{-1}. The boundaries and allocation principles that were applied in the study though differ from those used in this thesis. Another LCA analysis (Brännström-Nordberg & Dethlefsen 1998) found the energy input for producing forest chip to be about 3.5% compared with the fuel output. This figure include though the energy input for ash recirculation (0.01%) and flue gas cleaning (NO_x, 0,41%) so without these the energy input would been about 3%.

Some saving potentials when replacing fossil fuels were calculated for Hungarian circumstances. The calculations showed that 180–420 kg CO_2eq MWh^{-1} of GHG could be saved substituting fossil fuels with biofuels. The calculated saving potentials were biggest, 400–420 kg CO_2eq MWh^{-1}, when substituting coal with chipped biofuels. Using pellets instead of chip the potentials would decrease the potentials by 10–60 kg CO_2eq MWh^{-1}. By substituting fuel oil with bio-oil, the emission savings would be in the range of 240–270 kg CO_2eq MWh^{-1}. For natural gas substituted with syngas, the range would be 180–240 kg CO_2eq MWh^{-1}. As Hungary has also domestic production of fossil fuels some speculations on which fuel, the imported or the domestic was also possible to make. Further, the relevance of accounting the emissions abroad or not for fossil fuels was evaluated. If natural gas is replaced with syngas, the chosen principle is of big importance as the saving potentials will be 22–25% higher if the emissions abroad are included.

Here I once more underline that the numerical values above do not include the following figures of the potential effects of biofuel storage nor how the forest residue utilisation possible affects the forest carbon pool.

To evaluate the GHG emission risks of biofuel storage, the cumulative GHG emissions for a six month storage period of two kinds of fuel chip, fresh forest residue and naturally dried forest residue, were estimated. The GHG emissions for the whole six month period were calculated to be remarkable, about 140 and 60 kg CO_2eq MWh_{chip}^{-1}, Fig. 16. To check the range of the results, the initial amounts of C and N needed to form the emitted gases were calculated. The evaluated CH_4 emissions (1.3 and 4.4 w-% of C would form CH_4) seemed to be in line with figures from literature but the evaluated value of N_2O was found to be 2–4 times bigger. The comparability with figures from literature is not trouble-free as only data from biowaste composting research could be found and such emission investigation projects usually last for only 1–2 months. However, as 66–100% of the emitted GHG from a six-month storage was calculated to originate from CH_4 the quality of the overall calculation results can be considered more reliable than focusing only on N_2O.

When modelling the behaviour of carbon in forest soil, the carbon pool was assumed to behave like a dynamic system. The difference in soil carbon stocks between landscapes where residues are removed for forest fuel production and where they are left to decay was estimated by simulating the decaying of the harvest residues at the forest site. This time-dependent difference was considered as an indirect emission to the atmosphere, generated when using forest residues as a biofuel. The difference in carbon stocks was calculated to be 11% of the total carbon amount in residues. For a rotation length of 100 years, the calculations gave an emission rate of 40–45 kg CO_2 MWh_{chip}^{-1}, Fig 16.

When calculating avoided GHG emissions by substituting a fossil fuel with a biofuel the best results showed that as much as 97–98% of the GHG emissions could be avoided if coal[35] was substituted with a forest residue chip. This result is valid only for cases, where no fuel storage (as chip) is needed. If long-term storage is included, the percentage decrease to a level of 60–80%, using the storage emission figures explained above. If further, also accounting for possible impacts on the carbon stock in forest soil when utilising forest residues, the figure decrease even more, to a level of 50–70%. The figures will be even lower in cases where other fossil fuels are substituted and/or upgraded biofuels are used. These rough calculations show that the assumed GHG neutrality of using bioenergy should in many cases should be reconsidered.

During the period of fast degradation in biofuel storages, there are remarkable risks of emissions and energy losses, which can easily be detected through temperature measurements. Biofuel storage could be monitored with heat detectors, and depending on the follow-up data the decisions of in what order to dismount storages could be performed minimising emissions and material losses for the whole fuel supply system. To further decrease GHG emission risks from biofuel storages, investigations of the effects of measures known to affect

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[35] Gustavsson finds substitution of coal to be the most cost-effective reduction method of carbon-dioxide emissions (Gustavsson et al. 1995). He though assumed the biofuel production chains to be CO_2 neutral.

material losses such as compacting biofuel storages, coating methods of the stacks and cooling or even drying the biofuel by ventilation (Kofman & Spinelli 1997b) should be considered. Furthermore, the choice of chopping technique as well as methods used to stabilise biodegradable materials could be worth investigating.

The processing of waste to produce SRF was examined in a similar way as producing biofuels to evaluate GHG emissions and energy balances. For the plastic content, a certain emission factor for combustion was evaluated. The simplest fuel, MSW, was calculated to need an energy input of about 2.2% and causes GHG emissions of about 6 kg CO_2eq MWh^{-1} in the production chain. For the combustion stage, the GHG emission originating from plastics was evaluated to be 90 kg CO_2eq MWh_{SRF}^{-1}. The calculated energy input rates for SRF was 2–11% and the corresponding GHG emissions 6–30 kg CO_2eq MWh_{SRF}^{-1}. The emission rates from combustion were found to be higher than for MSW, about 100–110 kg CO_2eq MWh_{SRF}^{-1}.

The calculations show that the methods used for biofuels can be applied for evaluating the GHG emissions and energy efficiency of SRF production. Furthermore, the calculated range of energy input and GHG emissions is similar to that of biofuels. The emissions of the combustion differ due to the plastic content of the fuel. Usually knowing the plastic content quite well from SRF processing processes, the fuel specific fossil emission factor can be defined and thus the MSW derived fuel can be treated partly like a biofuel.

A different approach to study the utilisation or landfilling of biomass was made by assuming landfilling a base scenario causing severe GHG emissions. Different measures to avoid these emissions were studied. This approach introduced, by accident, to resent presented attitudes that activities decreasing GHG emissions from dumping of wood waste could possible claimed for GHG emission reduction credits. The GHG emission reduction methods and results would principally be rather similar for dumped wood waste as for MSW. The calculations showed that the total GHG emissions from dumping 1 tonne of an average MSW was calculated to cause GHG emissions of about 880 kg CO_2eq. The net impact, about 400 kg CO_2eq t_{waste}^{-1} was calculated by taking into account that part of the biodegradable carbon would be stored in the landfill. Landfill gas recovery (flaring) was calculated to decrease the net impact of a landfill to about

50 kg CO_2eq t_{waste}^{-1} and if the recovered gas can be used for substituting a fossil fuel, the net impact would be about zero (neutral). The alternative where the biological fraction was treated separately and the rest of the waste was landfilled was calculated to produce greenhouse gas emissions comparable with landfilling combined with gas recovery. Waste treatment alternatives including combustion were calculated to be most favourable for reduction of GHG emissions.

The costs are an effective guard on GHG emissions from e.g. transportation. Soimakallio & Wihersaari (2002) calculated, that a prolonging of the transport distance by 50 km increase the emissions by 1–2 kg CO_2eq $MWh_{biofuel}^{-1}$. This would, however, increase the fuel costs by about 1€ $MWh_{biofuel}^{-1}$. In practise this would mean that additional emissions of 1 t CO_2eq would cost the fuel producer about 500 €, in other words, the increase in costs limit the increase of GHG emissions from transport very efficiently. However, this is not the case for storage. Assuming a price of biofuel of 10 € MWh^{-1}, the losses of 6.6 w-% and 15.6 w-% (Chapter 3.3) would cost the storage-keeper 0.7–1.6 € per MWh sold fuel. Comparing the income losses with the GHG emissions gives us an estimate that at a cost level of 12 € t^{-1} emitted CO_2eq or more is the costs of the emissions higher than the costs of material losses. Estimated costs for CO_2 abatement will probably be much higher than this marginal cost during the next decades.

4.2 Further discussion and recommendations

The nitrogen flows between the forest, industrial systems and the atmosphere are quite complex. This thesis does not go deeply into questions connected to e.g. how changes in nitrogen flows might affect carbon balances.

Removal of timber and logging residue result in an immediate loss[36] of N from the forest ecosystem (Finér et al. 2003). If all nutrient rich logging residues are withdrawn from the forest, the amount of nutrients lost due to biomass harvest increase by a factor 1.5–5 compared with conventional forestry (Lundborg 1998).

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[36] According to Antikainen et al. (2004) the mean flow of nitrogen within wood raw material from Finnish forests was about 22 300 t a^{-1} during the period 1995–1999. Approximately 39% of this was estimated to be situated in bark and the main part of this wood fraction ends up as energy.

The nitrogen losses are partly balanced by anthropogenic nitrogen deposition but discounts in the nitrogen pool in forest soil might cause reductions in subsequent forest growth and due to this affect the forest carbon pool.

During combustion fuel nitrogen is released to the flue gases mostly as N_2 but also as oxides: NO, NO_2 and N_2O. Relative portions are dependent on combustion conditions and fuel properties. Air born nitrogen compounds are returned to the ground by atmospheric deposition.[37] The nitrogen deposition function to a certain level as a fertiliser activating the growth of trees. This is mainly the situation in Finland, as the Finnish forests typically have a shortage of nitrogen. In regions with low nitrogen deposition, it is possible to compensate for the losses (caused by e.g. outtake of logging residue) by fertilisation. If, on the other hand, the nitrogen load is too big, it will contribute to acidification and eutrophication. The influence of acidification can partly be cured by recirculating ash from wood combustion. Part of the nitrogen in the forest ecosystem is lost due to leaching and cause e.g. eutrophication of lakes.

During the 1990s many studies have indicated that it is possible to recover the wood-waste-based ash from forest industry power plants and return it to the forest ecosystem to serve as fertiliser (e.g. Ranta et al. 1996). In the year 2002 about 100 000 t a^{-1} of wood ash was produced in the forest industry and of that about 10% was recirculated to the forests (Vesterinen 2003). In this respect, the forest industry activity is beginning to participate into the cycle of nutrients. In the future, this effort should be increased to complete the natural-industrial nutrient cycle. The problem, though, may be the heavy metal content of the ash, e.g. cadmium. Also the ash should be conditioned into a form in which it can be easily stored, used and spread. Furthermore, the release rate of base cations from fertiliser should be appropriate in order to avoid rapid changes in the pH value of the soil. Because the base cation content is high in bark, branches, twists, and specially in needles, the efforts to increase the use of forest residues as an energy increase the base cation flow from the ecosystem. Therefore, the need for recycling of nutrients will increase. If the nutrient losses are not compensated for, there is a risk both in a short time window and in the long run that re-growth

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[37] The current nitrogen deposition is approximately 6 kg N ha^{-1} in southern Finland (Nordlund 1998).

of the biomass could be disturbed which would lead to a situation where the outtake of biomass could no longer be considered CO_2-neutral. Here one must weight the importance of substituting the fossil fuels with the use of forest residues as fuels against the importance and the above noted difficulties involved when the nutrient cycle of the forest ecosystem is concerned.

To start out the model calculations concerning the forest soil carbon pool, the system was considered to be in balance. It was assumed that due to the disturbance causing changes in carbon flow from living material, the system would seek for a new balance situation (Schlamadinger et al. 1997, Palosuo & Wihersaari 2000). The real situation is somewhat different. The carbon stock in Finnish forest soil has been growing from zero to the recent level since the glacial period about 7000 years ago. We still do not know for sure if the carbon stock in forest soil is in balance or still growing. In addition, forest cultivation methods improved in the 20th century leading to a growth of the amount of stem wood in the forests, especially after 1970. Furthermore, forest fires were very common in the past centuries. A coniferous forest area burned usually down with a 100–200 year's period. These regular forest fires decreased the carbon stock to a lower level (Liski et al. 1998). So, these calculations only give a picture of how big the changes might be compared with the present reference system where only stemwood is utilised. They do not evaluate the possible changes in the total carbon stock, which may be happening due to e.g. factors mentioned above.

The overall uncertainty of the estimates made in this thesis could not be calculated, but the magnitude of the uncertainty and the order of priority for the results were approximated by considering different groups of potential error sources. Using this evaluation method the calculations considering biofuel storage were evaluated to have an extremely high order of priority for the results but to be the most uncertain part of the results presented in this thesis. The uncertainty of the GHG calculations presented for forest carbon soil was also evaluated to be high. On the other hand, the results of the calculations dealing with the production of base biofuels and upgraded biofuels were estimated to have a low or low/medium level of uncertainty. The focus of further research should be on sectors such as upgrading biofuels, changes in forest soil carbon pool and storage of biomass, for which the order of priority for the results are evaluated to be high or extremely high.

An issue this thesis does not consider is allocation. Accounting forest industry wood residues as a waste it can be assumed that the "production chain" starts at the waste heap. Then it can even be argued that the utilising parties should be awarded with emission credits. On the other hand – if wood residue is considered a by-product it might be justified that the whole stem wood production chain – from the forest to the appearing of the by-product – should be investigated and that the energy efforts and emissions should be divided between the products. The same kind of discussion have been taking place every now and then for forest residue as this raw material also is a by-product – but in an earlier stage – from stem wood production. In this case we discuss whether the efforts put on cultivating should be divided and how.

The new EU emissions trading scheme (EU ETS)[38] is likely to have effects on where GHG emission savings are implemented and on new bioenergy projects. Many new EU countries are not using all of their emission allowances and will be able to trade with them in the future. Furthermore, through the Joint Implementation (JI) mechanism foreign countries are likely to develop emission reduction projects assuming that the emission credits can be converted into allowances under the EU emissions trading scheme.

Biofuel trading between countries already occurs. For the GHG balances this means, that the producing country score for all the emissions from the producing chain and that the importing country get a completely GHG free fuel. As the trading usually concentrate on upgraded fuels with high energy density (e.g. pellets) the GHG emissions to consider may be remarkable. In cases like this, quality declaration could help in guiding the energy systems into a more sustainable direction because the emissions from the production chain could be conveyed to score the consumer of the fuel. This should naturally also be the case for fossil fuels. A system like this would award clean and efficient fuel production.

Accepting the fact that bioenergy systems might not be as GHG emission neutral as we used to think, the next step should be to agree on how a reassessment concerning the GHG emission neutrality should be performed and find

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[38] The European Union Emission Trading Scheme (EU ETS). See e.g. http://europa.eu.int/comm/environment/climat/emission/press_en.htm.

stimulants for keeping the emission levels as low as possible. Anyhow, the assessment method should not be too complicated. Through elaborating the calculation method presented in this thesis, a tool to build up a GHG and energy efficiency quality certificate for biofuels, SRF and even fossil fuels could quite easily be developed. This would also be a step to ease GHG emission evaluations for many parties.

To avoid unpleasant surprises with new GHG emission sources in the future, I suggest that the focus of bioenergy research should be reconsidered. As a higher rate of biofuel utilisation will increase the need for using storage activities (Soimakallio & Wihersaari 2002), the GHG emissions from biofuel production will probably grow. Furthermore, the energy losses due to storage are likely to increase. Additionally, the effects of fuel upgrading should be carefully considered as the bioenergy amount available (for substituting fossil fuels) decreases and the GHG emissions from the production chain increases.

The sufficiency of biofuels was not considered in this thesis despite the fact that there are already areas in Finland where there is a lack of suitable biofuels (see e.g. Soimakallio & Wihersaari 2002). Sooner or later the use of limited biofuel resources will have to be optimised to maximise the GHG emission savings. In such calculations, GHG emission and energy efficiency data of biofuel production chains – similar to that presented in this thesis – will have to be clarified.

5. Summary

The object of this thesis was to study the greenhouse gas (GHG) balances in connection with the harvesting and production of biofuels and, based on this, evaluate in what situations there is a need to re-evaluate the potentials of GHG emission savings when using bioenergy for substituting fossil fuels. Briefly, the objective was to accept or reject the generally assumed hypothesis that the utilisation of biofuels is almost GHG neutral.

The questions arising from the literature survey included whether energy efficiency is a good measure for evaluating GHG emissions from biofuel production chains and what is the implication when upgrading biofuels. Another arising issue was if storage, changes in forest carbon pool, and other such factors could have any influence on the emission saving calculations. Furthermore, can municipal waste be considered a biofuel and how does the different base scenario affect the calculations. Last but not least – a thrilling idea of adopting a quality certificate to the fuels – both biofuels and fossil fuels – appeared.

Five different methodologies were used in the evaluation. The philosophy and methodology of Industrial Ecology was used to analyse the sustainability and material flows of the Finnish forest industry. A simple calculation model was developed for analysing the energy consumption and GHG emissions for biomass production chains, upgrading of biofuels and production of solid recovered fuels. The model calculates the material flow, external energy input and GHG emissions for the different parts of the production chain. These are summed up and compared to the energy content of the biofuel. Emission risks from long-time storage of biofuel were evaluated upon GHG emission rates known from decomposition of biowaste. To evaluate changes in forest soil carbon due to harvesting of forest residues, a dynamic model that describes the carbon stocks and fluxes of decomposing organic matter was used. The fifth methodology was needed to estimate the CH_4 emissions for a given amount of landfilled waste.

The overall uncertainties of the calculations were evaluated to be high but the calculations to still give a good base for understanding the order of priority of GHG emission reduction measures.

Bioenergy in Finland is very strongly related to wood production for the forest industry. Because of this, the energy and material flow of the Finnish forest industry was investigated. This study investigated how the flows have been adopted to the flows of the natural ecosystem and pointed out measures that could be taken to decrease the disturbance caused by the economic system, especially the forest fuel production modules, to a sustainable level. The calculations showed that the cuttings of the forests in Finland are smaller than the annual growth, and that this has a positive consequence on the annual binding of carbon in Finnish forests, presently exceeding the amount of carbon released from cuttings and natural drain. This will, though, go towards a balance in the long run. Round wood and wood wastes are utilised in an advanced network of saw mills, pulp mills and energy plants that make the recycling rate of both material and energy very high. Electricity and fossil fuels are still used to some extent and these could be partly replaced by e.g. forest residues. However, this would increase the problem with the poor recycling of nutrients. At the present situation about 60% of the base cations end up in ash from energy supply systems. If the use of nutrient rich forest fuels increased, the importance of ash recirculation would grow. The recycling of nutrients is important for the growth of further tree generations and might affect on the binding of carbon in the new tree generation.

The examination of the biofuel production chains showed that in a favourable situation as much as 97–98% of GHG emissions for a fossil fuel could be avoided by substituting it with a biofuel. The GHG emissions from collecting, chipping and transporting the forest residues were calculated to be in the range of 4–8 kg CO_2eq MWh_{chip}^{-1}. Additionally, a complete ash and nitrogen refunding would account for 0.2 kg CO_2eq MWh_{chip}^{-1} and 7 kg CO_2eq MWh_{chip}^{-1} respectively. A brief evaluation on some other biofuels were also performed, resulting in GHG emission figures of 4–20 kg CO_2eq MWh_{bio}^{-1} for agricultural and forest industry by-products, 17 kg CO_2eq MWh_{bio}^{-1} for biofuel cultivation and 6–86 kg CO_2eq MWh_{bio}^{-1} for upgraded fuels.

The energy efficiency of the above mentioned biofuel production chains was also investigated. The external (fossil) energy input was compared with the energy content of the biofuel output. The production of forest residues was found to be very efficient with an energy input of 1.9–2.6%. Ash recirculation would increase this figure with less than 0.1% but the figure for refunding nitrogen was calculated to be quite high, about 1.4%. The corresponding figures for agricultural and forest industry by-products are 1–5%, for biofuel cultivation 6% and for upgraded fuels 2–40%.

Based on the results, there seems to be a very good relation between energy efficiency and GHG emissions of biofuel production chains. This means, that the expected magnitude of GHG emission can in well-documented cases simply be estimated by measuring the external energy consumption. Upgrading biofuels increase both GHG emissions and external energy input remarkably.

The processing of waste to produce solid recovered fuel was examined in a similar way as producing biofuels to evaluate GHG emissions and energy balances. For the plastic content, a certain emission factor for combustion was evaluated. The simplest fuel (untreated municipal solid waste) was calculated to need an energy input of about 2.2% and to cause GHG emissions of about 6 kg CO_2eq MWh^{-1} in the production chain. For the combustion stage, the GHG emission originating from plastics was evaluated to be 90 kg CO_2eq MWh_{SRF}^{-1}. The calculated energy input rates for solid recovered fuels was 2–11% and the corresponding GHG emissions 6–30 kg CO_2eq MWh_{SRF}^{-1}. The emission rates from combustion of solid recovered fuels were found to be about 100–110 kg CO_2eq MWh_{SRF}^{-1}.

To evaluate the GHG emission risks of biofuel storage, the cumulative GHG emissions for a six month storage period of two kinds of fuel chip, fresh forest residue and naturally dried forest residue, were estimated. The GHG emissions for the whole six month period were calculated to be remarkable, about 140 and 60 kg CO_2eq MWh_{chip}^{-1}. To check the range of the results, the initial amounts of carbon and nitrogen needed to form the emitted gases were calculated. Due to this, the overall calculation results were considered more reliable than the calculations focusing on N_2O.

The behaviour of carbon in forest soil was examined by assuming that the carbon pool acts like a dynamic system. The difference in soil carbon stocks between landscapes where residues are removed for forest fuel production and where they are left to decay was estimated by simulating the decaying of the harvest residues at the forest site. This time-dependent difference was considered as an indirect emission to the atmosphere, generated when using forest residues as a biofuel. The difference in carbon stocks was calculated to be 11% of the total carbon amount in residues. For a rotation length of 100 years, the calculations gave an emission rate of 40–45 kg CO_2 MWh_{chip}^{-1}.

A different approach to study the utilisation or landfilling of biomass was made by assuming landfilling a base scenario causing severe GHG emissions. Different measures to avoid these emissions were studied. This approach introduced to resent presented attitudes that activities decreasing GHG emissions from dumping of wood waste could possible claimed for GHG emission reduction credits. The emission reduction methods and results would principally be rather similar for dumped wood waste as for municipal solid waste which means that the choice of base scenario may be important also for biofuel calculations. The results of the municipal solid municipal solid waste calculations showed that the total GHG emissions from dumping 1 tonne of an average municipal solid waste is about 880 kg CO_2eq. The net impact, about 400 kg CO_2eq t_{waste}^{-1} was calculated by taking into account that part of the biodegradable carbon would be stored in the landfill. Landfill gas recovery (flaring) was calculated to decrease the net impact of a landfill to about 50 kg CO_2eq t_{waste}^{-1} and if the recovered gas can be used for substituting a fossil fuel, the net impact would be about zero (neutral). Waste treatment alternatives including combustion were calculated to be most favourable for reduction of GHG emissions.

When calculating avoided GHG emissions by substituting a fossil fuel with a biofuel the best results showed that as much as 97–98% of the emissions could be avoided if substituting coal with a forest residue chip. This result is valid only for cases, where no fuel storage (as chip) is needed. If long-term storage is included, the percentage decrease to a level of 60–80%, using the storage emission figures explained above. If further, also accounting for possible affects on the carbon stock in forest soil when utilising forest residues, the figure decrease even more, to a level of 50–70%. The figures will be even lower in cases where other fossil fuels are substituted and/or upgraded biofuels are used. These rough calculations show that the assumed GHG neutrality of using bioenergy should in many cases should be reconsidered.

The calculations show that the same methods as used for biofuels can be applied for evaluating the GHG emissions and energy efficiency of solid recovered fuel production. Furthermore, the calculated range of energy input and GHG emissions are also similar to that of biofuels. The difference is the emissions of the combustion stage due to plastics. Usually knowing the plastic content quite well from the processing process of solid recovered fuel, a fossil emission factor can be defined and the municipal solid waste derived fuel treated partly like a biofuel.

Accepting the fact that bioenergy systems might not be as GHG emission neutral as we used to think, the next step should be to agree about how a reassessment concerning the GHG emission neutrality should be performed and find stimulants for keeping the emission levels as low as possible. Anyhow, the assessment method should not be too complicated. Elaborating the calculation method presented in this thesis a tool to build up a GHG and energy efficiency quality certificate for biofuels, solid recovered fuels and even fossil fuels could quite easily be developed. This would also be a step to ease GHG emission evaluations for many parties.

To avoid unpleasant surprises with new GHG emission sources in the future the focus of research should be reconsidered. A higher rate of biofuel utilisation will increase the need for using storage activities and this might increase the amount of GHG emissions along the production chain. Additionally, the energy losses due to storage should not be belittled. Also the effects of fuel upgrading should be carefully considered as the bioenergy amount available for substituting fossil fuels decreases and the GHG emissions increase.

The thesis presented new calculation results of GHG emissions from biofuel production chains and evaluations of how the emissions affect on the efforts to reduce energy related greenhouse gas emissions. The calculations made in the thesis showed that the generally assumed hypothesis, assuming that the production and use of biofuels is nearly totally GHG emission neutral, has to be rejected. The quantity and quality of GHG emissions along the fuel production chain have, in some way, to be taken into account.

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Aspects on bioenergy as a technical measure to reduce energy related greenhouse gas emissions

Abstract

Greenhouse gas emission assessments of energy supply systems have traditionally included the CO_2 emissions produced as the fuel is burned. A lot of models and calculations for evaluating greenhouse gas emission savings by using bioenergy have been introduced. The approaches often cover a major part or sometimes even the whole energy system. The biofuel production process itself is one piece that is normally covered very briefly or considered insignificant. Unfortunately, this means that the significance of some affecting factors might not have been estimated. The object of the thesis was to study the greenhouse gas balances in connection with the harvesting and production of biofuels and, based on this, evaluate in what situations there is a need to re-evaluate the potentials of greenhouse gas emission savings when using bioenergy for substituting fossil fuels.

Different methodologies were used in the separate evaluations: the philosophy and methodology of industrial ecology was used to analyse the sustainability and material flows of the Finnish forest industry. A simple calculation model was developed for analysing the energy consumption and greenhouse gas emissions for biomass production chains, upgrading of biofuels and production of solid recovered fuels. Emission risks from long-time storage of biofuel and biodegradable material were evaluated as well as changes in forest soil carbon due to harvesting of forest residues. The examination of the biofuel production chains showed that in a favourable situation as much as 97–98% of greenhouse gas emissions for a fossil fuel could be avoided by substituting it with a biofuel. On the other hand the investigation also pointed out that e.g. increasing fuel storage and upgrading activities for biofuels are likely to decrease this percentage remarkably. The main conclusion of the thesis was that the neutrality of greenhouse gas emissions when producing bioenergy should be re-evaluated. The author further suggest that tools and stimulants for keeping the greenhouse gas emission levels in fuel production chains as low as possible should be developed.

Keywords
greenhouse gases, emissions, energy supply systems, biofuels, bioenergy, biomass production, wood fuels, forest residues, municipal wastes, renewable energy sources

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