PAPER I

Greenhouse gas balances of transportation biofuels, electricity and heat generation in Finland

Dealing with the uncertainties

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Greenhouse gas balances of transportation biofuels, electricity and heat generation in Finland—Dealing with the uncertainties

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ABSTRACT

One way to reduce greenhouse gas emissions from the transportation sector is to replace fossil fuels by biofuels. However, production of biofuels also generates greenhouse gas emissions. Energy and greenhouse gas balances of transportation biofuels suitable for large-scale production in Finland have been assessed in this paper. In addition, the use of raw materials in electricity and/or heat production has been considered. The overall auxiliary energy input per energy content of fuel in biofuel production was 3–5-fold compared to that of fossil fuels. The results indicated that greenhouse gas emissions from the production and use of barley-based ethanol or biodiesel from turnip rape are very probably higher compared to fossil fuels. Second generation biofuels produced using forestry residues or reed canary grass as raw materials seem to be more favourable in reducing greenhouse gas emissions. However, the use of raw materials in electricity and/or heat production is even more favourable. Significant uncertainties are involved in the results mainly due to the uncertainty of N_2O emissions from fertilisation and emissions from the production of the electricity consumed or replaced.

1. Introduction

The promotion of renewable energy has a central position in the European Union's energy and environmental policy. The underlying target is to lower greenhouse gas emissions and mitigate the climate change. Targets have been set for different sectors, such as primary energy use, consumption of electricity and transportation fuels. The transportation sector covers a significant and further growing share of greenhouse gas emissions and it is highly dependent on fossil oil.

The Directive 2003/30/EC of the European Parliament and of the Council (EC, 2003) aims to promote the use of biofuels or other renewable fuels to replace diesel or petrol for transport purposes in each Member State, with a view to contribute objectives such as meeting the climate change commitments, securing an environmentally friendly energy supply and promoting the renewable energy sources. The Directive sets an indicative national target of 5.75% of all the petrol and diesel for road transport purposes placed on their markets by 2010 calculated on the basis of energy content.

In the "Green Paper—Towards a European Strategy for the Security of Energy Supply" (EC, 2000) the European Commission states that the European Union is consuming more and more energy and importing more and more energy products. The Community production is insufficient for the Union's energy requirements. As a result, the external dependence for energy is constantly increasing; in the next 20–30 years, if no measures are taken, from 50% to 70%. In the "Green Paper—A European Strategy for Sustainable, Competitive and Secure Energy" from the year 2006 the European Commission outlines suggestions and alternative courses of actions for the European energy future. It states that the European countries are well behind their target of 5.75% of transportation fuels.

The Commission of the European Union sets three main targets in its Strategy for Biofuels (EC, 2006). These targets are the promotion of biofuel in the EU and developing countries as well, the preparation for the large-scale use of biofuels by enhancing their competitiveness and increasing the research on second generation biofuels and the support of developing countries with a potential for economic growth from sustainable biomass production.

In the Communication from the Commission "An Energy Policy for Europe" (EC, 2007a) as part of the Strategic European Energy Review together with the Communication from the Commission "Renewable Energy Road Map" (EC, 2007b) and the Communication from the Commission "Biofuels Progress Report" (EC, 2007c), the European Commission proposes to set a binding minimum target for biofuels of 10% of vehicle fuel by 2020 and to ensure that the biofuels used are sustainable in nature, inside and outside the

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EU. The main drivers for this target are the mitigation of climate change, the reduction of oil-dependency and the improvement of security of supply. The particular target together with the demand to reduce greenhouse gas emissions by at least 35% compared to reference fuels to be replaced was published as a part of an integrated proposal for climate action of the European Commission (EC, 2008a–c). In addition, the demand for more comprehensive sustainability criteria was claimed.

At the end of 2005, the Ministry of Trade and Industry of Finland set up a task force to assess the promotion of biofuel use and production in the transport sector in Finland. The task force suggested that an obligation law should form the primary tool to promote the use of biofuels. On 9 June 2006, the working group set by the Ministry of Trade and Industry of Finland on climate and energy issues defined an indicative target of 5.75% for 2010. The Finnish Parliament passed the obligation law in February 2007, and it will be in force starting from the beginning of 2008. The biofuel shares set in the new Law are 2%, 4% and 5.75% for 2008, 2009 and 2010, respectively.

One of the means to achieve reductions in greenhouse gas emissions of transportation is to increase the use of biomass-based fuels. However, the determination of the potential to reduce greenhouse gas emissions is not a straightforward process as it heavily depends on the approach selected and the assumptions made in defining the system boundary. In addition, different raw materials and process options vary significantly in terms of auxiliary energy requirement and greenhouse gas emissions caused (see e.g., Edwards et al., 2003, 2008). Various recent studies have recognised changes in soil carbon balances, nitrous oxide emissions from soils and indirect land-use changes as major sources of uncertainty influencing greenhouse gas balances of biofuels (see e.g., Edwards et al., 2008; Crutzen et al., 2007; Searchinger et al., 2008; Fargione et al., 2008). That is why identifying auxiliary energy consumption and the environmental impact over the whole life cycle of biofuels is of importance when considering reductions in greenhouse gas emissions by replacing fossil fuels.

Finland is one of the northernmost countries in the world with a relatively cold climate and a short growing season. Carbon dioxide emissions from transportation have contributed to some 15–20% of the overall greenhouse gas emissions without emissions from land-use changes and forestry in Finland in recent years (Statistics Finland, 2008).

The objective of this paper was to assess energy and greenhouse gas balances for biomass-based fuels used in transportation as well as the greenhouse gas impact when reference fuels are replaced. Both commercial technologies and technologies under development were studied. Most suitable technologies for large-scale production in Finnish conditions were taken into consideration. For comparison, the greenhouse gas impact of using certain raw materials also in electricity and/or heat production was considered. Particular attention was paid to the variation of the results due to uncertainties and sensitivities involved. Consequently, the results provide a more general rather than case-specific picture of the issue.

2. Materials and methods

2.1. Approach

2.1.1. Reference land use

When assessing reductions in greenhouse gas emissions at least two conditions have to be confronted and compared to each other. The results depend fundamentally on the selections of conditions in comparisons and on system boundaries. The key question is what happens if the particular bioenergy chain is implemented or not. The reference land use and system boundaries should be defined by carefully responding to this question.

Bioenergy production chains may be implemented in fields already used for cultivation, uncultivated lands or in forests. In addition, different types of waste components may be used as raw materials. The possible impact of implementing a certain bioenergy chain on land use has to be taken into account when setting reference land use and system boundaries. If waste streams are used, no impact on land use typically takes place.

Here, the reference land use for agrobiomass-based bioenergy chains is assumed to be a set-aside as it would be the most likely option for bioenergy production in the short term. Therefore, the calculation of auxiliary energy inputs and emissions for agrobiomass chains begins from cultivation.

Forest residues are harvested after logging timber for industrial purposes. The current share of forest residues utilised in Finland (approximately 2 TWh) is small compared to the techno-economic potential corresponding to some 24 TWh (Electrowatt-Ekono, 2005). As forest industrial activities are not dependent on forest residue utilisation, no reference land use was assumed for forest-residue-based bioenergy chains. An assumption was made that more forest residues will be available than will be utilised for the studied bioenergy production chains. Therefore, if forest residues are not harvested they are left to decay, which is the basis for calculating auxiliary energy inputs and emissions.

2.1.2. System boundaries and allocation

Defining system boundaries and selection of the reference case are one of the most crucial phases of energy and greenhouse gas balance analysis. Allocation of energy inputs and emissions is a third important issue. These definitions have a significant impact on results and should be carefully considered.

There is no unique and unambiguous way for allocation procedures, and allocation should be avoided whenever possible. In this paper, allocation of different products was avoided by extending the system boundaries to also cover the use of products and by using the substitution method. Energy inputs and emissions as well as credits from the substitution of other products by co-generated products are then allocated to considered biofuels. This substitution method is often the most appropriate method.

Protein animal meal generated in the ethanol or biodiesel process was assumed to replace the use of soy protein imported from the USA. The credits in energy inputs and emission outputs of such a substitution are calculated in accordance with Edwards et al. (2003). Turnip rape-based glycerine produced in biodiesel (RME) production was assumed to be used for energy in heat production boilers to replace peat. Straw was not assumed to be harvested.

Certain issues are uniformly excluded in all fuel chains considered. For example, the energy input required and the emissions output caused by the construction of infrastructure, the production of facilities, machinery or other equipment required in overall fuel production chains were not considered. This exclusion was necessary as reliable data of such energy inputs and emissions outputs are not available. An assumption was made that the difference in the above-mentioned issues is not significant between biofuel and fossil fuel chains. In addition, the impact on emissions from ash recycling and biomass storing was not considered.

The functional unit for a transportation fuel was assumed to be one kilometre driven and for electricity (and heat) production one kilowatt hour produced. Emission reductions were calculated by replacing reference fuels with the biofuels considered.

2.1.3. Assessment of the greenhouse impact

Calculations for energy inputs and greenhouse gas emissions were carried out by following as uniform principles as possible for all the chains. Energy inputs were converted into primary energy by using certain factors depending on the form of energy required. Energy inputs include both fossil and renewable energy required in the fuel production chains, but not the energy which is transferred into fuel itself (i.e. only auxiliary energy inputs expressed as primary energy were considered).

Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) were considered when calculating greenhouse gas emissions. The greenhouse effect was studied by using the approach known as *Global Warming Potential* (GWP), and the emissions of CH_4 and N_2O were converted to carbon dioxide equivalents by using the time frame of 100 years and emission factors of 21 and 310, respectively (IPCC, 1996a).

According to Revised 1996 IPCC Guidelines (IPCC, 1996b), CO_2 emissions from biomass combustion are regarded as recycling atmospheric CO_2 if biomass is extracted from a sustainable (i.e. replenished) source. These CO_2 emissions are therefore excluded from net emission calculations.

2.2. Parameters for biofuel chains

2.2.1. Electricity

Electricity consumed within fuel production chains was assumed to be purchased from the electric grid. The Finnish electricity grid is connected to the Nordic electricity system containing various electricity production forms varying from very low emission (e.g. hydro power) to high emission (e.g. coal condensing power) sources. When aiming to mitigate climate change, the conservation of energy has been argued as one of the main emission reduction options by the EU (EC, 2008d). At the same time, there are plans to increase electricity consumption, e.g. by increasing the production of biofuels (EC, 2008c).

There is no generally accepted consensus on how the emissions from electricity production should be evaluated. These issues are discussed, e.g. by Curran et al. (2005). It is very typical that the greenhouse gas impact of electricity consumption for a certain purpose is assumed in accordance with the average production mix of a market area. The overall electricity consumption of a market area consists of numerous single consumption points and production forms at the same time. In principle, it is reasonable to consider that no consumption point can have just a certain kind of production but an average mix for all. However, this kind of approach is in conflict with the fundamental principle of the reference surface defined as it does not consider system impacts objectively.

When assessing the greenhouse gas impact of any electricity consuming process the reference surface should be considered as not implementing the particular process. If not implemented, the particular amount of electricity is conserved. In other words, the greenhouse gas impact of electricity consumption should be analogically valued as equal to the impact of conservation of that same amount of electricity. Decrease or increase in electricity consumption has a direct impact on the marginal side of electricity production constructed typically by high emission electricity production forms (see e.g., Kara et al., 2008; Holttinen and Tuhkanen 2004). Therefore, by valuing consumed electricity as the average mix of a market area, the impact on the greenhouse gas emissions of electricity conservation is underestimated.

It is also possible that the electricity required at the consumption point will increase the use of renewable energy sources that would have not otherwise taken place. For example, a consumer may generate the required electricity himself by using renewable energy sources or may buy some green certificates to ensure that the production of renewable energy sources will be increased by the amount consumed by the consumer. In these cases, it would be reasonable to assume that the electricity consumption would equal the particular production form instead of marginal electricity. However, if the particular consumption point reduces the amount of low emission electricity sold in the grid to replace marginal electricity, the electricity consumption should again be handled as marginal electricity.

According to the methodology defined above, in general, electricity consumed at a particular consumption point can be assumed to correspond to marginal electricity, some particular electricity production form (e.g. wind power or bioenergy) or anything in between. In addition, marginal electricity varies from year to year depending mainly on consumption, the availability of hydropower and the prices of fuels and emission allowances in the EU emission trading scheme (EU ETS). It is likely that marginal production will gradually move towards lower emission intensity, when tighter emission reductions will be required, but the change can be slow.

As a consequence of the very random nature of electricity consumed at certain general consumption points, a wide range of 0–900 g CO_2-eq./kWh_e was defined for emissions. The upper limit corresponds to typical current marginal electricity production in an average precipitation year in the Nordic electricity markets simulated by VTT (e.g. Kara et al., 2008). In addition, Holttinen and Tuhkanen (2004) concluded that wind power connected to the electric grid in the Nordic countries replaces mainly coal-fired power generation which is analogical with the given upper limit mentioned above.

The primary energy demand of electricity production was assessed according to calculation methods of Statistics Finland (2005) and by assuming that 10% additional primary energy is required to produce fuels used in electricity production. The primary energy factor for electricity consumption used was 2.35 kWh_{prim}/kWh_e with a variation of $\pm$20%.

2.2.2. Fossil fuels

The primary energy demand and the greenhouse gas emissions of diesel fuel, heavy fuel oil and natural gas required in machinery and equipment of fuel production chains were estimated in accordance with Edwards et al. (2003). As CH_4 and N_2O emissions from fuel combustion depend heavily on combustion technology and conditions, emissions for each type of machinery or boilers was assessed individually based on Statistics Finland (2006) and VTT (2006). Similarly, the specific fuel consumption and the greenhouse gas emissions of transport were estimated for each type of truck and assumed loading factors by using the LIPASTO (2006) calculation system of VTT (2006).

2.2.3. Fertilisers

The production of fertilisers, particularly nitrogen fertilisers, is energy intensive. In addition, nitrous oxide emissions during the production of nitric acid may be significant. Therefore, the energy input and the greenhouse gas emissions of fertilisers depend fundamentally on the nitrogen content. The primary energy input and the greenhouse gas emissions from fertiliser production (Table 1) were assessed in accordance with Kemira fertilisers (H. Hero, personal communication, October 2005).

Nitrous oxide emissions are also generated due to nitrification and denitrification processes caused by micro-organism activity in soil. Part of the nitrogen content of the fertiliser is converted directly to N_2O and part of it indirectly through nitrogen oxides (NO_x) and ammonium (NH_3) (Monni et al., 2007). The amount of these emissions is uncertain but may be significant. By using the

Table 1
Primary energy input and emissions from production and transportation of fertilisers as well as emissions from fertliser use (H. Hero, personal communication, October 2005; IPCC, 2006; Statistics Finland, 2006)

Fertiliser (Kemira)	Production and transportation				N_2O from soil			Total		
	Primary energy	Emissions (kg CO_2-eq./t)			Emissions (kg CO_2-eq./t)			Emissions (kg CO_2-eq./t)		
	GJ/t	Min	Def.	Max	Min	Def.	Max	Min	Def.	Max
Syysviljan Y1	7.8	636	736	938	163	1028	4507	798	1764	5444
Kevätviljan Y2	13.1	1097	1276	1632	288	1819	7973	1385	3095	9605
Kevätviljan Y3	11.9	977	1132	1442	250	1582	6933	1227	2713	8375

default values of IPCC (2006) and uncertainty boundaries given by Statistics Finland (2006) used for national greenhouse gas inventories it was assumed that the direct and indirect N_2O emissions from agricultural soils together are equal to 1.6235 kg N_2O-N/kg N-fertiliser and vary from 0.2566 to 7.116 kg N_2O-N/kg N-fertiliser. Crutzen et al. (2007) assessed that the global average of N_2O emissions from N fertilisers vary between some 3 and 5 kg N_2O-N/kg N fertiliser. The range given by Crutzen et al. (2007) is significantly higher compared to the default values given by IPCC (2006) but lower compared to the upper limit set in this paper based on field measurements and expert judgement (Monni et al., 2007).

Fertilisation of forest lands after removing forest residues may be necessary to compensate for nutrient loss due to outage of nitrogen. The loss may be compensated by nitrogen deposit or ash circulation. Wihersaari (2005) estimated that if compensation fertilisation of nitrogen would take place it would cause emissions of 7 kg CO_2-eq./MWh_{chip}. This was set as an upper limit for forest land fertilisation emissions considered in this paper with the lower limit of 0 kg CO_2-eq./MWh and the default value determined by given Weibull distribution (Table A1).

2.2.4. Limestone and pesticides

Different types of carbonate compounds are used to reduce the acidity of agricultural soil. Carbonate of limestone then reacts in soil and emits carbon dioxide into the atmosphere. The amount of carbon dioxide generated depends on the soil properties and the carbonate compound. The average emission factor for the use of limestone was defined according to Statistics Finland (2006) by taking into account the use of different types of carbonate compounds in Finland between 1990 and 2004, to equal 431 kg CO_2/t varying from 388 to 474 kg CO_2/t. In addition, the primary energy demand and the greenhouse gas emissions to produce and transport limestone were assessed to equal 0.5 GJ/t and 21 kg CO_2-eq./t, respectively.

According to Edwards et al. (2003), the primary energy input and the emissions from pesticide production vary significantly in different literature sources. However, the amount of pesticides used is relatively small, and therefore the impact on overall emissions is low. Default values given by Edwards et al. (2003) were used and equalled 267 GJ/t and 16 666 kg CO_2-eq./t. The range was from 175 to 516 GJ/t and from 10 642 to 31 379 kg CO_2-eq./t, respectively.

2.2.5. Soil carbon balances

A part of the carbon content of biomass is sequestered into soil if biomass is not harvested. Therefore, biomass harvesting decreases carbon content in soil. Part of the stored carbon may be released as methane, which is reduced by harvesting logging residues. However, as the amount of these emissions is not well-known, the possible compensating impact of the harvesting procedure is not considered in this paper.

If logging residues are harvested, soil carbon pools are decreased by 1–2% during the rotation of one tree generation (Palosuo et al., 2001). According to Yasso model calculations (Liski et al., 2005) approximately 2–10% of the original carbon content of logging residues would have been stored in soils during the first 100 years after felling, if not harvested. As this carbon content is released into the atmosphere during combustion, it can be seen as an indirect carbon emission over 100 years resulting from the harvesting and combustion of logging residues. Wihersaari (2005) estimated that this indirect emission compared to the energy content of logging residues may correspond to some 40–45 kg CO_2/MWh. In this paper, it was assumed that the upper value illustrates the upper boundary for indirect carbon emission, whereas the lower boundary is zero. The default value was set in the middle of the range.

When pristine land or virgin forest is converted to arable land, typically some amount of carbon stored in soils is released as carbon dioxide into the atmosphere. In addition, permanent harvesting and tillage result in a decline of soil carbon balance. This lowering will continue until a new balance between carbon input and output in the soil is achieved. Reduction or overall renunciation of tillage activity has been found to turn the soil carbon balance back into growth (e.g. Schjønning et al., 2007; Gregorich et al., 2005; Mikhailova et al., 2000) until a new balance between carbon input and output is achieved. Accumulation of soil carbon in mineral soils depends on the rate at which organic matter is added to the soil and the rate at which erosion and biological oxidation remove the organic matter from the soil (Reicosky et al., 1995). Similarly, the cultivation of viable perennial crops, such as reed canary grass, requires infrequent ploughing and therefore increases overall soil carbon stock until a balance is achieved. However, the quantitative changes in soil carbon balances are not well-known.

By using very rough factors given by IPCC (2006) intended for greenhouse gas inventories, it was assumed that the upper limit for annual change in soil carbon balance during 100 years is equal to −0.078 and 0.003 t C/ha for conventional tillage cultivation and the no-tillage option or cultivation of reed canary grass, respectively. The default values were set in the middle of the range.

2.2.6. Fuel processing chemicals

Small amounts of chemicals, for example sulphuric and phosphoric acid, smectite, caustic soda and hexane, are required and consumed in biofuel processing. Figures presented by Elsayed et al. (2003) were used for the energy input and emissions of the production and transportation of these chemicals.

2.3. Biofuel chains

2.3.1. Raw material production

Six different barley cultivation chains and five turnip rape chains were assessed. The production chains were formed by varying the method of soil tillage, the method of the seeding (seeding with a standard combined seed drill after tillage or direct drilling), the method of grain storage (hot air drying or storage of moist grains in an airtight silo) and the energy source for grain drying (oil or wood chips). The yield level of direct drilling was assumed to be 10% lower compared with the yield of the standard combined seed drill after tillage. Cultivation chains and the transportation of barley and turnip rape are presented in more detail by Mikkola and Pahkala (2008) and Mäkinen et al. (2006).

Reed canary grass represents the most yielding field energy plant in Finland, with a typical annual yield level varying from 4.5 to 8 t_{dm}/ha depending on soil type and fertilisation. Reed canary grass cultivation also represents a possible reuse option for decommissioned peatlands. According to Mäkinen et al. (2006), reed canary grass was assumed to be cultivated in set-aside agricultural lands and harvested either as loose material or baled bundles.

The harvesting, transportation and chipping of logging residues was assessed for three different commercial and established options: chipping at the end-use facility by harvesting as loose residue or as bundles or chipping at the roadside.

Cultivation or harvesting and transportation chains are presented with default values in Mäkinen et al. (2006). Those default figures with defined uncertainty ranges for the main parameters are presented in Appendix A. Ranges selected for yield levels represent the natural variation in Finland due to changes in climatic conditions and do not therefore correlate with the range assumed for fertilisation rates, which only indicate human errors.

2.3.2. Fuel processing, distribution and combustion

All liquid biofuels considered were assumed to be processed in industrial scale plants with an annual capacity of 28–47 and 79–105 kilotons biofuel produced for the technologies commercial and under development, respectively. Synthetic biofuel production (here F-T diesel) was assumed to be integrated into a modern pulp and paper mill or a paper mill, which provides significant advantages in overall energy efficiency.

The mass and energy balances of RME processing were assumed in accordance with Elsayed et al. (2003); for other fuels the expertise of the Technical Research Centre of Finland was used in setting default values (Mäkinen et al., 2006). The mass and energy balances with assumed uncertainty ranges are presented in Appendix B.

2.4. Reference chains

2.4.1. Diesel oil and gasoline

Fossil diesel oil and gasoline were used as reference fuels for liquid biofuels. In addition, diesel oil is required in the production of biofuels. For auxiliary energy requirements and greenhouse gas emissions from diesel oil and gasoline production chain (well-to-tank) figures given by Edwards et al. (2003) were used (Table 2).

Table 2
Energy input and greenhouse gas emissions from well to tank for diesel oil and gasoline (Edwards et al., 2003)

Fuel	Primary energy (MJ/kg)			Greenhouse gas emissions (g CO_2-eq./MJ)		
	Min	Def.	Max	Min	Def.	Max
Diesel oil	0.14	0.16	0.18	12.6	13.8	16.0
Gasoline	0.12	0.14	0.17	11.1	11.7	14.6

2.4.2. Replaced electricity and/or heat

For the comparison of the greenhouse gas impact of replacing fossil fuels in transportation the use of reed canary grass and logging residues in power and/or heat production was estimated. Direct fuel switching, e.g. replacing coal or peat by bioenergy in proportion to the effective heating value of the fuels in existing power and/or heating plants is a relatively straightforward way to estimate the greenhouse gas impact. However, fuel switching in existing power and/or heating plants is not always appropriate and not the only possible option to be considered.

Difficult methodological problems are encountered when considering new electricity and/or heating capacity based on bioenergy replacing something else. First, problems occur similar to those discussed in Section 2.2.1 to estimate the greenhouse gas emissions of marginal electricity. Second, there is not necessarily load for produced heat, which restricts the possibility to consider objectively CHP or stand-alone heating plants. Third, the production rates for heat and power may vary between technologies causing further methodological problems as the reference entity should be equal for the technologies in comparison (see e.g., Gustavsson and Karlsson, 2002).

The most probable options for defining reference fuels are direct fuel switching in existing power and/or heating plants and the replacement of certain fuels in foreseen plants, as well as the replacement of marginal electricity in stand-alone power plants. All these choices with independent uncertainties increase the sensitivity and stochastic nature of the greenhouse gas impact considered. However, the replacement of marginal electricity with its minimum and maximum values will very likely provide boundaries for calculating the credits of all above-mentioned choices.

The lower limit for marginal electricity was defined as 300 g CO_2-eq./kWh to correspond to possible foreseen marginal electricity in the future (gas-fired condensing power), whereas the upper limit equals 900 g CO_2-eq./kWh in accordance with Section 2.2.1. These values were selected to illustrate the variation in greenhouse gas emissions of replaced fuels, regardless of whether bioenergy is used in current or foreseen power and/or heating plants. It should be noted that the uncertainty is significantly lower if certain technology was replaced. Consequently, applying the above-mentioned range very likely exaggerates the overall uncertainty of replacing certain technology, but is more suitable to illustrate the likely variation of a range of technologies.

2.4.3. Substitution of soybean meal and peat

Soybean meal is the main protein-rich animal feed in the EU and most of it is imported from the USA. Protein fodder co-generated in the production of ethanol from barley or biodiesel from turnip rape can be used to some extent instead of soybean meal. As the protein content of those meals is not, however, as high as in soy bean meal, more barley or turnip rape-based animal meal has to be used to replace soy bean meal. 1 kg of soy bean meal was assumed to be replaced by 1.30 and 1.28 kg of turnip rape and barley meal, respectively.

Values for credits in primary energy input (2.7 kWh/kg) and greenhouse gas emissions (230 g CO_2-eq./kg) from the substitution of soybean meal were assumed in accordance with Edwards et al. (2003). The uncertainty for both energy and greenhouse gas emission credits was assumed to be ±30%.

Glycerine co-produced in RME biodiesel production was assumed to be used as energy in heating boilers, as the market for glycerine as a chemical is very limited. Peat was assumed as the reference fuel to be replaced in proportion to the effective heating value of the fuels. According to Kirkinen et al. (2007) and by using the GWP method, the greenhouse impact from peat production in forestry-drained peatland, peat combustion and the afforestation option during 100 years equals 107±12 g CO_2-eq./MJ. Those values for replaced peat were used in calculating credits for RME from glycerine use (assumed lower heating value (LHV), 16 MJ/kg).

2.5. Uncertainty analysis

The uncertainty analysis was conducted using the Monte Carlo method. In this method a suitable probability distribution is defined for each uncertain variable, and a large number of samples, in this case 15 000, are drawn from each distribution. For each set of samples from all distributions, the desired result variables are calculated, thus giving a set of frequency distributions for the result variables. The resulting frequency distributions represent the total effect of the variability of the assumptions on the result variable, and can be taken as empirical probability density distributions through normalising their area to a value of one.

Apart from one, all of the variables were represented with a three-parameter Weibull distribution due to its flexibility. Depending on the parameterisation, the distribution can vary from symmetric to skewed, thus giving the distribution the ability to imitate a large variety of probability distributions. An exclusion to this methodology was emissions for electricity, for which a uniform distribution was assigned. The variables were chosen so that there would be no correlations between them in the model.

The contribution of a single variable to the uncertainty of a result variable was measured using Spearman's rank correlations ρ between each of the uncertainty variables and the result values. The rank correlation has the advantage over common Pearson correlation in that it does not require the dependence between the quantities to be linear but only monotonic, which happens to be the case with all parameters and results in this study.

3. Results

3.1. Energy balances

Auxiliary energy is required in every step of biofuel chains from well to wheel. The difference in various cultivation or harvesting chains of particular raw materials was only minor. The exception was direct seeding in addition to air tight storage of grains resulting in approximately 25% lower energy consumption compared to other studied options for barley production (Mäkinen et al., 2006).

The major part of auxiliary energy is consumed within fuel processing, particularly ethanol and F-T diesel. The benefit from lower energy consumption in direct drilling of barley and turnip rape was almost compensated by the drawback from lower substitution credit due to a lower amount of animal meal produced compared to conventional tillage. Consequently, the variation between different cultivation chains in overall energy consumption per energy content of fuel produced was only minor.

Energy requirements were highest for the production of barley-based-ethanol and F-T diesel in the stand-alone concept (Fig. 1). These production chains consumed almost equally auxiliary energy as what is transferred to fuel itself. The lowest energy requirement was calculated for the RME and integrated F-T diesel concept minimising purchased electricity. The ranges were the widest for ethanol and RME, mainly due to uncertainties in credits from replacing soybean meal and in yield rates. All biofuel chains considered required significantly, approximately 3–5 times, more auxiliary energy compared to fossil diesel and gasoline chains from well to tank.

3.2. Greenhouse gas balances

Greenhouse gas balances of biofuel chains may vary significantly depending on many factors, e.g. raw material, possible land-use change effects, fertilisation, yield rates, auxiliary energy requirements and the sources of energy. As with auxiliary energy inputs, the difference in greenhouse gas balances in various cultivation or harvesting chains of particular raw material was also only minor (Mäkinen et al., 2006).

In order to enable comparisons of the impact of fuels on greenhouse gas emissions the use of the fuels should be taken into account. One kilometre driven was used as a reference entity on which the greenhouse gas impact was calculated. All biofuels were considered to be used in fraction of 5 vol% mixed to gasoline or diesel. The relative impact on greenhouse gas emissions when

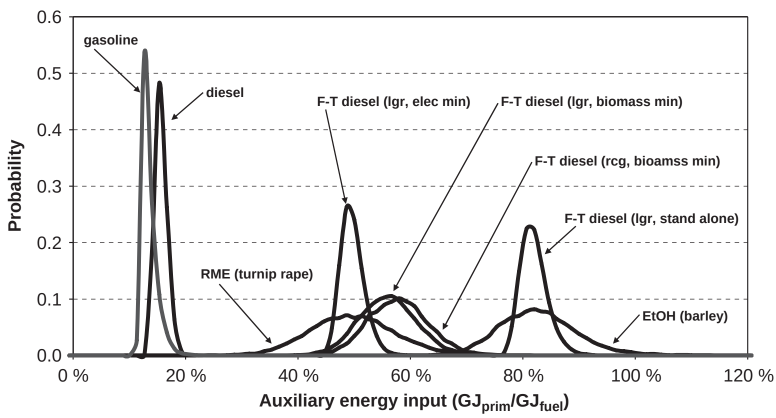

Fig. 1. Probability distributions for auxiliary energy input per fuel energy content for considered biofuels (lgr = logging residues, rcg = reed canary grass).

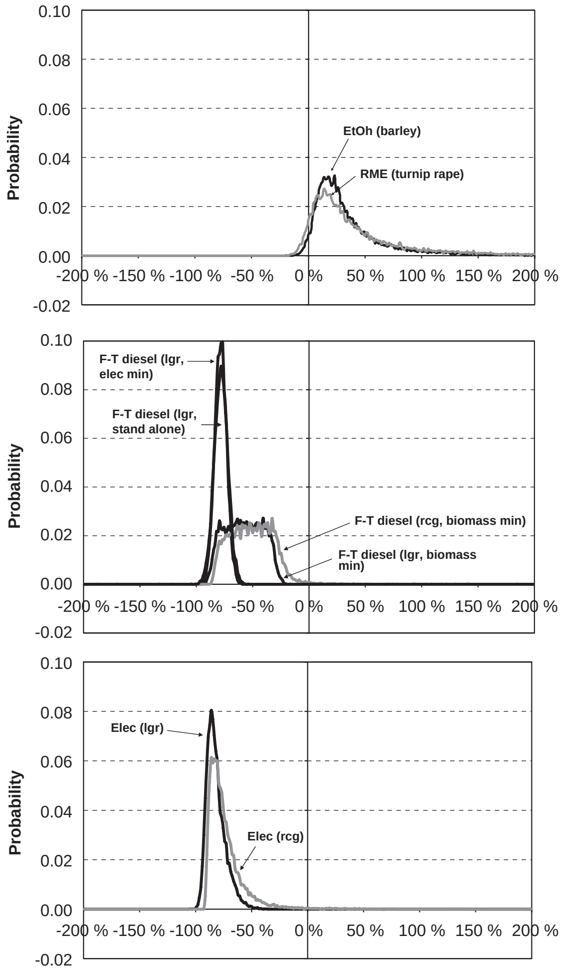

Fig. 2. (a)–(c) Probability distributions for the relative greenhouse gas impact when replacing reference fuels. For (a) and (b) Elec = electricity production, lgr = logging residues, rcg = reed canary grass. For (b) Elec min and biomass min refer to integrated F-T diesel processing cases with minimum purchased electricity and biomass, respectively.

substituting reference fuels was then calculated and it is illustrated in Fig. 2.

There is only a very low probability that greenhouse gas emissions from barley-based ethanol and turnip rape-based RME would be lower than those of gasoline and diesel (Fig. 2a). Instead, there is a moderate probability to get even 50–100% higher values. The wide uncertainty range, and particularly the high upper limit for ethanol from barley and RME from turnip rape, results mainly from a significant uncertainty in N_2O emissions from fertilisation. Yield rate, animal feed output and emissions from electricity production were the next dominant factors in the case of ethanol and RME.

Greenhouse gas emissions from producing F-T diesel depend significantly on the concept considered (Fig. 2b). If the biomass requirement is minimised, greenhouse gas emissions are highly dependent on emissions from production of electricity consumed in the process. For such concepts, the expected value of the relative greenhouse gas emission impact when replacing fossil diesel varies between −30% and −80%, depending mainly on emissions from electricity production. If the purchased electricity requirement is minimised and replaced by using more biomass, the uncertainty range is decreased significantly and the expected value for relative greenhouse gas emission impact when replacing fossil diesel is around −80%. Soil carbon losses and N_2O emissions from fertilisation added to the yield rate were the next dominant factors in the case of F-T diesel using logging residues and reed canary grass as raw materials, respectively.

The relative emission impact is probably higher when using logging residues or reed canary grass in electricity production to replace marginal electricity instead of producing biofuels of them to replace fossil diesel (Fig. 2b and c). It should be noted that the emission factor given for electricity has the opposite impact on the results in the case of replacing marginal electricity compared to electricity consumed in the case of transportation biofuels. Consequently, increase in the particular emission factor increases

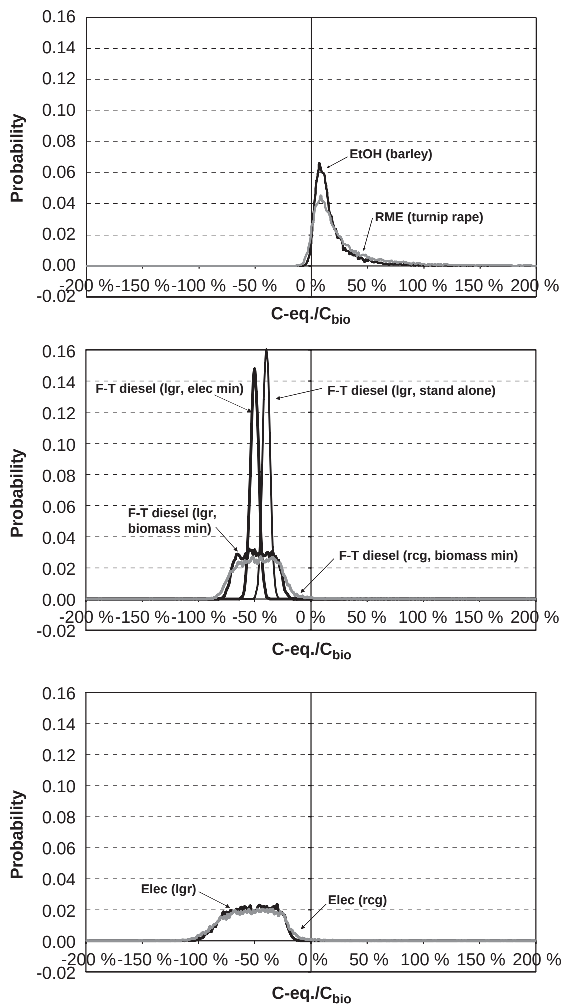

Fig. 3. (a)–(c) Probability distributions for reduced carbon equivalent emission per consumed biocarbon when replacing reference fuels. For (a) and (b) Elec = electricity production, lgr = logging residues, rcg = reed canary grass. For (b) Elec min and biomass min refer to integrated F-T diesel processing cases with minimum purchased electricity and biomass, respectively.

the relative emission impact of biofuels whereas decreases it of electricity production.

The relative greenhouse gas impact indicator gets the lower value from the higher the emissions from reference fuel replaced are, and from the lower amount of the biofuels produced, respectively (Fig. 2a–c). However, it does not indicate the effectiveness that a particular bioenergy chain has in reducing greenhouse gas emissions. In other words, a certain biofuel chain may look very favourable in terms of relative greenhouse gas emission impact, but at the same time consuming significant amount of biomass resulting in relatively low emission reduction in absolute terms. Consequently, it is necessary to consider how much greenhouse gas emissions can be reduced by consuming a certain amount of biomass (Fig. 3a–c). The most significant changes in Fig. 3 compared to Fig. 2 are the location of distributions for F-T diesel concepts based on a stand-alone solution and minimum purchased electricity use, as well as the form of probability distributions for electricity production from logging residues and reed canary grass. These changes are due to the relatively significant biomass requirement in the above-mentioned F-T diesel concepts and the more sensitive nature of this particular indicator compared to the relative emission impact against emission savings from replaced electricity.

If availability of land area is a limiting factor, it is important to consider greenhouse gas emission reduction that can be achieved from certain land areas producing biomass. This may be the case for agricultural biofuels as cultivated land area may be used for other purposes as well. This kind of indicator was not considered in this paper as it is not very well suitable for forest residue chains with no additional land requirement. However, according to the results presented in Fig. 3 it can be argued that the cultivation of reed canary grass for energy enables significantly more reductions in greenhouse gas emissions per land area than the cultivation of turnip rape or barley for energy. Similarly, more reductions per land area are very likely achieved by producing electricity and/or heat than F-T diesel from reed canary grass.

Nitrous oxide emissions, emissions from electricity production and emission savings from replaced electricity are the most significant parameters for ethanol and RME, F-T diesels, and electricity production, respectively. The uncertainties in other individual parameters have a clearly lower influence on the overall uncertainty of studied cases, but were all together not negligible (Table 3).

4. Conclusions and discussion

This paper assessed energy and greenhouse gas balances of biomass-based transportation fuels assumed to be the most suitable for large-scale production in Finland. Technologies that are both commercial and under development were considered. The results were compared to replaceable fossil fuels and also to the use of raw materials in electricity and/or heat production.

The auxiliary energy requirement in biofuel chains considered was approximately 3–5-fold compared to fossil reference fuel chains. However, all studied chains reduced the overall consumption of fossil fuels in substitution.

Significant uncertainties and sensitivities to parameter value selections are involved in the analysis, particularly concerning greenhouse gas emissions. Consequently, it was impossible to provide even nearly exact results on greenhouse gas emissions of biofuel production or on reductions in greenhouse gas emissions when replacing fossil reference fuels.

The results indicated that greenhouse gas emissions from the production and use of barley-based ethanol or biodiesel from turnip rape are very likely to be higher compared to the fossil reference fuels. The use of fertilisers is significant compared to the energy content of the barley and turnip rape yield in Finland mainly due to climatic conditions. The production and use of nitrogen fertilisers causes emissions of nitrous oxide, which are probably significant and may be very significant. The impact of various cultivation chains of barley and turnip rape on greenhouse gas emissions of ethanol and RME was only minor compared to the other uncertainties involved.

The cultivation of uncultivated or set-aside lands to produce barley-based ethanol or biodiesel from turnip rape will very likely increase the absolute emissions of greenhouse gases, regardless of the replacement of fossil fuels by the produced biofuels. Greenhouse gas emissions in absolute terms can to some extent be reduced by optimising cultivation to avoid surplus production.

Table 3
Impact of the 10 most important parameters on emission impact per biocarbon consumed for studied biofuel chains expressed as rank correlation

Parameter	EtOH	RME	F-T (lg, biom min)	F-T (lg, elec min)	F-T (lg, stand alone)	F-T (rcg, biom min)	Elec (lg)	Elec (rcg)
Emission from electricity production	0.27	0.07	**0.97**	0.36	0.09	**0.89**		
Electricity demand			0.06	0.02	0.01	0.04		
Yield rate of raw material	−0.26	−0.27				−0.16		−0.13
Carbon content in DM of raw material	−0.07					0.15	−0.01	0.12
LHV in DM of raw material			−0.04	−0.18	−0.15	−0.04	−0.04	−0.03
N_2O from soil (fertilization)	**0.84**	**0.88**	0.04	0.14	0.01	0.25	0.03	0.20
Fertiliser use	0.12	0.09				0.03		0.02
Emissions from fertiliser production	0.10	0.11						0.02
Ploughing								−0.02
Animal feed output		0.15						
Soil carbon losses	0.16	0.14	0.21	**0.84**	**0.94**		0.13	
Emission savings from replaced electricity							**−0.95**	**−0.89**
Efficiency of biofuelled power plant							−0.27	−0.26
Emissions of biofuelled power plant							0.02	
Output of produced fuel		−0.15	−0.05	−0.21	−0.19	−0.03		
Emission savings from replaced soybean meal	−0.06	−0.06						
Emissions from replaced reference fuel	−0.05		−0.06	−0.17	−0.15	−0.05		
Emissions from transportation			0.02	0.06	0.08	0.03	0.02	0.03
Emissions from forest haulage			0.01	0.02	0.02		0.01	
Emissions from chipping			0.01	0.01	0.02		−0.01	
CO_2 from liming	0.05							
Lime use		0.06						

A positive value indicates that an increase in the value of a particular parameter increases the value of the result. A negative value indicates the opposite effect. The most significant correlations (r values above 0.5) are highlighted.

The achievable emission reduction would probably be higher by reducing overproduction than by producing ethanol or biodiesel from barley and turnip rape, respectively. However, utilisation of straw to substitute fossil fuels and measures to increase the soil carbon balance and reduce nitrous oxide emissions could considerably decrease greenhouse gas emissions of the cereal crop chains. These options were not quantitatively considered in this paper due to the lack of practical solutions and information.

Second generation biofuels produced by using forestry residues or reed canary grass as raw materials seem to be more favourable in reducing greenhouse gas emissions. Lower emissions are mainly due to the significantly lower fertilisation demand per energy content of the particular raw materials compared to the cereal crops. However, the amount of biomass and purchased electricity used together with the large variation of greenhouse gas emissions from electricity production has a significant impact on the results. Consequently, the greenhouse gas impact per biocarbon consumed for F-T diesels is very likely between −30% and −70%.

The achievable emission reductions are likely higher by using the raw materials in electricity and/or heat production compared to producing liquid biofuels. This is true at least as long as there is a load for heat production or the greenhouse gas emissions from marginal electricity production which correspond approximately to the current level.

The relative greenhouse gas impact when replacing reference fuel related to greenhouse gas emissions from reference fuel does not objectively measure the effectiveness of biomass in reducing greenhouse gas emissions. Consequently, the indicator that takes into account the amount of biomass used or the area required to achieve a certain reduction in greenhouse gas emissions is more suitable for such purposes. These kinds of indicators are also suggested, e.g. by Pingoud et al. (2006) and Schlamadinger et al. (2005).

Several studies concerning greenhouse gas emissions of biofuels have been done in many contexts all over the world. The results may vary significantly between the studies due to many different reasons. First, methodological differences may occur in system boundaries, allocation procedures, as well as in reference land use, system or entity. Consideration of macro-effects such as land-use changes due to competition of raw materials is crucial but difficult to quantify and was excluded in this analysis. Figures for individual parameters may vary due to the above-mentioned issues. In addition, there may be a natural variation in parameters set due to differences in climatic conditions, cultivation or harvesting practices, fuel production processes and energy sources used, for example. All these factors make the objective comparison between different studies difficult without careful and detailed consideration of the causes for the results.

As the uncertainties associated with the greenhouse gas emissions of biofuels were found to be significant it is very difficult to define general default values that would be reliable and suitable for certain types of biofuels produced in various conditions. Therefore, the case-specific consideration of biofuels is required and cannot be excluded in policy-making. Attention should also be paid to research work aiming to reduce the uncertainty and significance of factors having remarkable impact on the results, such as nitrous oxide emissions from soils and soil carbon balances. However, the uncertainty involved in these processes may be very difficult to be reduced significantly due to lack of information, resulting in the need to accept the uncertainty associated with greenhouse gas emissions. In addition, system impacts on electricity production or land use caused by biofuel production should carefully be analysed as the implications on greenhouse gas emissions may be very significant. Consideration of these issues is crucial in the aim to prepare sustainable criteria for biofuels to avoid unwanted climatic implications.

Optimising the use of biomass is manifold and complicated as many vital and difficult issues other than mitigation of climate change are also involved. Consequently, the connection between energy-related and non-energy-related biomass cannot be cut. In addition, issues like employment, sufficient food supply, self-sufficiency and security in energy supply, famine and environmental issues other than those related to climate change are also of central importance. Typically, optimisation of one factor would not give an optimal solution for the others. Therefore, choices and compromise solutions have a significant impact on biomass production and utilisation, and furthermore on greenhouse gas emissions.

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Appendix A

Mass and energy balances with the given uncertainty ranges for raw material cultivation or harvesting and transportation (see Table A1).

Table A1

	Barley			Turnip rape			Reed canary grass			Logging residues		
	Min	Def	Max	Min	Def	Max	Min	Def	Max	Min	Def	Max
Yield level (t/ha, a)	2.975	3.5	4.025	1.36	1.6	1.84	4	8	10		51	
Moisture content (%)	12	13	14	8	9	10	18	20	22	39	43	47
LHV in dry matter (MJ/kg_{dm})	17.1	17.4	17.8	25.9	26.4	26.9	17.2	17.6	18.0	19.0	19.5	20.0
Start up fertilization at annual level (kg/ha, a)							27.0	30.0	33.0			
Start-up fertiliser N-P-K							13-7-13	13-7-13	13-7-13			
Annual fertilization (kg/ha, a)	360	400	440	392	435	479	150	300	325			
Annual fertiliser N-P-K (%)	20-3-8	20-3-8	20-3-8	23-3-5	23-3-5	23-3-5	20-3-8	20-3-8	20-3-8			
Emissions from forest fertilization (kg CO_2-eq./MWh)										0	1.90	7
Liming at annual level (t/ha, a)	720	800	880	720	800	880	720	800	880			
Pesticides (l/ha, a)	1.04	1.3	3.96	1.76	2.2	5.04						
Transportation distance (km)	50	100	150	35	70	105	35	70	105	30	60	120
Diesel fuel consumption in cultivation/harvesting (l/ha)	109	127	146	96	112	130	56	87	119	140	164	187
Diesel fuel consumption in transportation (l/MJ, km)[a]	1.4	1.5	1.7	1.4	1.5	1.7	6.6	7.4	8.1	4.0	4.4	4.9
Electricity consumption (kWh/ha)	57	63	70	29	32	36				110	122	135

[a] Uncertainty ranges given here do not take into account factors having an impact on overall energy content of raw materials.

Table B1

Product	EtOH	RME	F-T diesel (INT 1)	F-T diesel (INT 2)	F-T diesel (SA)	F-T diesel (INT 1)
Raw material	Barley	Turnip rape	Logging residues			Reed canary grass
Annual raw material input (t/a)	183 600	75 600	481 200	499 000	791 100	243 700
Raw material moisture (%)	13 (±10)	9 (±11)	45 (±10)	45 (±10)	45 (±10)	20 (±10)
Auxiliary energy demand						
Electricity (GWh/a)	19.7 (±2%)	4.1 (±5%)	247.6 (±5%)	24.0 (±5%)	7.8 (±5%)	191.7 (±5%)
Natural gas (TJ/a)	543.4 (±2%)	88.4 (±5%)				
Heavy fuel oil (TJ/a)		4.8 (±5%)				
Diesel oil (TJ/a)		8.6 (±5%)				
Co-produced animal meal (moisture 10%) (t/a)	36 100 (±2%)	52 960 (±5%)				
Co-produced animal meal (moisture 67%) (t/a)	42 200 (±2%)					
Co-produced glycerine (t/a)		3360 (±5%)				
Methanol demand (t/a)		3360	1030	810	1030	770
LHV of the fuel product (MJ/kg)	26.8	37.5	44.0	44.0	44.0	44.0
Annual fuel production (t/a)	47 400 (±2%)	27 600 (±5%)	103 100 (±5%)	81 200 (±5%)	103 100 (±5%)	76 900 (±5%)

INT1 = unit integrated into pulp and paper mill with minimised biomass demand.
INT2 = unit integrated into pulp and paper mill with minimised electricity demand.
SA = stand-alone unit.

Appendix B

Mass and energy balances with the given uncertainty ranges for ethanol, RME and F-T diesel processing (see Table B1).

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