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Greenhouse Impact Due to the Use of Combustible Fuels: Life Cycle Viewpoint and Relative Radiative Forcing Commitment

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Abstract Extensive information on the greenhouse impacts of various human actions is important in developing effective climate change mitigation strategies. The greenhouse impacts of combustible fuels consist not only of combustion emissions but also of emissions from the fuel production chain and possible effects on the ecosystem carbon storages. It is important to be able to assess the combined, total effect of these different emissions and to express the results in a comprehensive way. In this study, a new concept called relative radiative forcing commitment (RRFC) is presented and applied to depict the greenhouse impact of some combustible fuels currently used in Finland. RRFC is a ratio that accounts for the energy absorbed in the Earth system due to changes in greenhouse gas concentrations (production and combustion of fuel) compared to the energy released in the combustion of fuel. RRFC can also be expressed as a function of time in order to give a dynamic cumulative picture on the caused effect. Varying time horizons can be studied separately, as is the case when studying the effects of different climate policies on varying time scales. The RRFC for coal for 100 years is about 170, which means that in 100 years 170 times more energy is absorbed in the atmosphere due to the emissions of coal combustion activity than is released in combustion itself. RRFC values of the other studied fuel production chains varied from about 30 (forest residues fuel) to 190 (peat fuel) for the 100-year study period. The length of the studied time horizon had an impact on the RRFC values and, to some extent, on the relative positions of various fuels.

Keywords Greenhouse impact · Emission analysis · Radiative forcing · Energy sources · Fuels

Introduction

The energy sector is one of the greatest contributors to greenhouse gas (GHG) emissions and climate change (IPCC 2007a, b). When measures for the mitigation of climate change are planned, the greenhouse impacts of various combustible fuels and other energy sources should be considered. In addition to the emissions from combustion, other sources of GHG emissions are associated with fuel production and transportation, manufacture of energy production equipment, and raw material extraction. The production of fuels, such as wood and peat, also changes the carbon storages of the ecosystem. Fuels produced from biomass within the agricultural or forestry sector may also involve the use of fertilizers. Both the manufacture and the utilization of fertilizers cause emissions of nitrous oxide and other GHGs (IPCC 2006; Mäkinen and others 2006). The extraction of fuel peat changes the GHG emissions (especially methane emissions) from peatlands (Kirkinen and others 2007b). All the emission sources listed above provide grounds for considering the greenhouse impact of fuel production and utilization by means of life cycle analysis, which is a way to assess the total environmental impact during the life cycle of a product (e.g., ISO 14040

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1997; Schlamadinger and others 1997; Gustavsson and others 2000). These impacts of the other life cycle part can be significant, although combustion is often the greatest source of GHG emissions, especially in the case of fossil fuels (Kirkinen and others 2007b).

In some cases, long-term changes in the carbon storages of ecosystems take place through fuel production. Therefore, it would be interesting to know how long time horizons should be considered in order to give appropriate advice to the planners of climate change mitigation measures. The UN Framework Convention on Climate Change (UNFCCC) states the stabilization of GHG concentrations in the atmosphere at a safe level (UN 1992) as the ultimate objective. The UNFCCC does not, however, identify the safe levels of atmospheric GHG concentrations.

The EU has proposed that the global average temperature rise should be limited to 2°C compared to preindustrial levels. The 2°C temperature increase is estimated to occur at a concentration of carbon dioxide (CO_2) of 450 ppm or even lower (Meinshausen and others 2006; EU 2007; IPCC 2007a). The relationship between atmospheric GHG concentrations and temperature rise is, however, still not well known (IPCC 2007a) and includes delays. Currently, the atmospheric concentration of CO_2 is 380 ppm and growing at a rate of 2 ppm per year (NOAA 2006). In order to remain below the 450-ppm level, emissions should be reduced considerably within the next few decades. Global emission reductions within the next decade to half a century will have to be substantial (Den Elzen and Meinshausen 2004; Meinshausen and others 2006; IPCC 2007b). Also, Hansen and others (2000) have considered a 50-year time frame in the mitigation of greenhouse forcing. If the other GHGs, notably methane (CH_4) and nitrous oxide (N_2O), whose concentrations have also increased due to anthropogenic activities, are taken into account in the warming target, the stabilization level of CO_2 should be lowered and the time horizon made even shorter. If the mean global temperature rise were limited to about 3°C instead of 2°C, it would give us some additional decades to reduce emissions, but still the time horizon of interest for considerable emission reductions is a century or less (IPCC 2007b).

The time horizons above fit quite well with the 100-year time horizon used in global warming potentials (GWPs), which are commonly used in the reporting of GHG emissions as CO_2 equivalents. In the IPCC (2001) concentration stabilization scenarios, stabilization to a level near 1000 ppm is reached within 300 years. Such a scenario equals a mean temperature rise of about 6^o if the climate sensitivity is assumed to be about 3°C (IPCC 2007b). In this study, we chose to use the time spans of both 100 and 300 years to underline the dynamic nature of the greenhouse impact.

Usually the relative importance of various fuels in causing a greenhouse effect is calculated using GHG emissions and GWPs, which give the relative weights of other GHGs in relation to CO_2. If the GWP-weighted emissions are presented as a function of time, this kind of approach can be used to show the dynamics of emissions, but it does not give the dynamics of the greenhouse impact, which is contributed to by the slow removal of GHGs from the atmosphere. In order to show the dynamics of emissions, sinks, and slow removal of GHGs from the atmosphere explicitly, the changes in the atmospheric GHG concentrations due to the considered activities should be calculated. The total greenhouse effect of various gases can be shown if the changes in concentrations are converted to radiative forcing (RFs), which can be seen to be additive in the case of well-mixed gases (IPCC 2007a).

The objective of this study is to introduce a new concept to describe the greenhouse impact of fuel chains. The concept, called *relative radiative forcing commitment* (RRFC), is based on the ratio of the cumulative RF to the fuel energy. This new concept is used to assess the greenhouse impact as a function of time. Some typical fossil and biomass fuels in the case of Finland are used as illustrative examples. The emissions and sinks related to studied fuel chains are considered from a life cycle perspective. The studied fuels are reed canary grass, forest residues, peat, natural gas, and coal. These fuel chains were chosen in order to compare some of the combustible fuels discussed in climate policy in Finland (Kara and others 2004).

The greenhouse impact of forest residues, peat, natural gas, and coal has been assessed earlier by Savolainen and others (1994), Uppenberg and others (2001a), and Zetterberg and others (2004). These studies have assessed the greenhouse impact using RF, but without integration of the total energy absorbed in the Earth system.

Calculation Methodology

The net greenhouse impact I is calculated as

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

where I is the net greenhouse impact (disturbance caused by human activities), I_U is the greenhouse impact of the utilization (e.g., fuel production, transportation, and combustion) of fuel, and I_R is the greenhouse impact of the reference situation.

The greenhouse impact of different agents of climate change, e.g. changes in GHG emissions or changes in concentrations, is described with RF (IPCC 2007a; Monni and others 2003), which gives a concept for quantitatively comparing them. RF describes the perturbation of the radiation energy balance of the Earth. Positive RFs lead to a global mean surface warming, and negative RFs to a global mean surface cooling.

In this study a new way to use RF for assessing the greenhouse impact is presented. We define a dimensionless ratio called Relative Radiative Forcing Commitment (RRFC) using the following formulae (Eqs. 2 and 3):

$$RRFC(T) = E_{abs}(T)/E_{fu} \tag{2}$$

$$E_{abs}(T) = \int_0^T RF(t)dt * A \tag{3}$$

where E_{abs} is the total energy absorbed into Earth's thermodynamic system (atmosphere, surface, oceans) due to changes in concentrations in the atmosphere caused by emissions and sinks due to the life cycle of the energy production chain considered within a given time (T). E_{fu} is fuel energy produced in the energy production chain. $RF(t)$ is the RF due to the concentration changes caused by the energy production chain. RF is typically expressed in units of watts per square meter. The cumulative RF has been integrated over the surface (A) of the Earth.

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

In this article the word "commitment" is used analogously to radiation protection, where "dose commitment" means an accumulated radiation dose due to inhaled or ingested radionuclides. Emitted GHGs cause a RF accumulating over time.

Life cycle assessment (ISO 14040, 1997) was used to cover all the positive and negative environmental impacts during the life cycle of the fuels. This study, however, comprises only climatic impacts. No other environmental impacts have been assessed.

The atmospheric concentration changes of GHGs due to life cycle emissions and the caused RFs were calculated for this paper using the REFUGE model described by Monni and others (2003). REFUGE calculates additional concentrations of GHGs in the atmosphere due to given emission histories or scenarios and the consequent RF caused by increased concentrations. The application of REFUGE to fuel life cycle considerations were presented by Kirkinen and others (2007b). REFUGE uses the descriptions between concentrations and RFs given by IPCC (2001).

Fuel Chains

Six different energy utilization chains are studied in this work. The chains describe the conditions in Finland except for the utilization of natural gas. Since the emission data for natural gas in Finland were incomplete, natural gas data describe the conditions in Sweden. In the case of energy, peat emissions and sinks due to the aftertreatment of the cutaway peatland have also been taken into account. The studied fuel chains are listed in Table 1.

The reference situation (I_R) is zero in all studied energy production chains, except for forest residues and peat scenarios. If reed canary grass, natural gas, or coal is not used for energy, no emissions or sinks of GHGs will occur and we do not assume any alternative fuels to be used in their stead. On the contrary, if forest residues are not used for energy, they constitute a short-term carbon storage that decays slowly, releasing the carbon they hold as CO_2 to the atmosphere. In the case of peat, the GHG emissions and/or sinks of the peatland will continue if the peat is not used for peat fuel production. Forestry-drained and cultivated peatlands are both sources of GHGs. For example, the decay rate of the peat layer in cultivated peatlands has been observed to be so rapid that if no restorative actions are taken, the peat layer will be totally decayed in approximately 200 years (Kirkinen and others 2007b).

The assumed combustion technique for reed canary grass, forest residues, and peat is a bubbling fluidized bed, which is typical in Finnish conditions where these fuels are used in medium-size boilers for district heating. The new peat production method (Chain 4: cultivated peatland–afforestation) is a technique still in the pilot phase that cuts losses of carbon during peat harvesting by shortening the harvesting time. The reference situation for reed canary grass production can be any other agricultural production or land use, but the emissions associated with these activities are not considered due to the lack of representative data. Normal development of forestry-drained or cultivated peatland means managing the peatland for forestry or agriculture, respectively, and a continuous decay of the peat layer. The combustion technique pulverized combustion for coal is and gas turbines for gas.

One petajoule (PJ; 0.278 TWh) of energy is produced in 1 year in all energy production chains except Chain 4 (peat from cultivated peatland–afforestation). In this chain, energy is produced in two phases, first from peat and then from the wood biomass growing in the area. Also, in the case of this chain, the calculated impact is always scaled to correspond to the total energy output of 1 PJ, regardless of the time horizon.

Table 1 The studied energy production chains: the energy resource is utilized for fuel production

Chain	Energy resource	Emission sources of fuel production	Aftertreatment emissions	Emission source of reference case
1	Reed canary grass	Fertilization, harvesting	–	–
2	Forest residues	Harvesting	–	Forest residue decomposition in forest
3	Peat from forestry-drained peatland	Milled peat production method	Afforestation	Emissions from forestry-drained peatland
4	Peat from cultivated peatland	New peat production method	Afforestation & energy use of the produced wood biomass	Emissions from cultivated peatland
5	Natural gas	Produced in the North Sea, combusted in Sweden	–	–
6	Coal	Produced in Poland, combusted in Finland	–	–

Note: All fuel chains include transportation and combustion. Also, aftertreatment and the reference case were taken into account when appropriate

Life Cycle Emissions of the Considered Fuel Chains

Reed Canary Grass

The cultivation of reed canary grass for energy use in Finland has grown significantly and the increase is set to continue. The area of reed canary grass cultivation was 4500 ha in 2004 (the yield corresponds to 90 GWh), and there are forecasts that this area could reach 40,000 ha by 2015 (corresponds to 880–1200 GWh) (Flyktman and Paappanen 2005).

The advantage of reed canary grass cultivation is its high productivity. In Finland, the typical yield harvested annually is 4.5–8 tons of dry matter per hectare (22–38 MWh equals 79–137 GJ). Reed canary grass yields 10–12 years per planting. There are about 60 power plants in Finland where the use of reed canary grass is possible (combined heat and power [CHP] plants). According to Mäkinen and others (2006), the potential use of reed canary grass in Finland is about 3.9 TWh per year, assuming that about 200,000 ha of land is cultivated.

The GHG emission factors of reed canary grass fuel production are given in Table 2. The emission factors are defined as emission per fuel energy of the fuel chain considered. The main work phases are set up of the plantation, yearly fertilization, harvest, and transportation to the power plant. The production and use of fertilizers are responsible for the main part of GHG emissions during reed canary grass production.

The combustion of reed canary grass causes CO_2, CH_4, and N_2O emissions (Table 2). However, the CO_2 emissions are assumed here to be zero due to the quick sequestration of carbon dioxide from the atmosphere into the growing biomass. The CH_4 and N_2O emissions vary depending on the combustion technology employed (a CHP power plant is typically used).

Table 2 Emission factors of reed canary grass production and combustion, with uncertainty ranges

Emission factor	Average	Lower limit	Upper limit
Production (g MJ^{-1})			
CO_2	7.81	7.33	8.35
CH_4	0.001	0.001	0.001
N_2O	0.025	0.012	0.076
Combustion (g MJ^{-1})			
CO_2	0[a] (109.6)	–	–
CH_4	0.003	0.0012	0.0048
N_2O	0.005	0.0025	0.01

Note: Production includes manufacture and use of fertilizers as well as transportation (Mäkinen and others 2006)

[a] CO_2 emissions were assessed as zero due to rapid sequestration of carbon in the new yield

There are several ongoing studies related to the soil gas fluxes of reed canary grass. It is possible that the soil sequesters carbon (Martikainen 2006), but since the results are incomplete, the assumption has been made that there is neither carbon sequestration nor carbon emissions.

Forest Residues

The amount of roundwood harvested is almost as large as the growth of forests in Finland, and the primary use of roundwood is in the forest products industry. However, the energy use of forest biomass is increasing due to the rising price of oil and policies aimed at reducing GHG emissions. Forest residues are an ideal potential source of energy since that biomass is not otherwise utilized. The use of forest residues for energy in Finland has recently been increasing. The total use in 2004 was about 2.7 * 10^6 m^3 (Finnish Forest Research Institute 2005), which corresponds to about 5.3 TWh, or 1% of the total energy consumption in

Table 3 Emission factors of forest residue production and combustion, with uncertainty ranges (Mäkinen and others 2006)

Emission factor	Average	Lower limit	Upper limit
Production (g MJ^{-1})			
CO_2	1.81	1.54	2.31
CH_4	0.00010	0.000005	0.00015
N_2O	0.00072	0.00036	0.00108
Combustion (g MJ^{-1})			
CO_2	109.6	–	–
CH_4	0.002	0.001	0.003
N_2O	0.003	0.0009	0.0075

2004. Forest residues are usually collected from the final fellings, and lately the collection of stumps for energy has also increased (Hakkila 2004).

The phases of the forest residue fuel chain are bundling of logging residues, transportation from the forest, chipping, long-distance transportation, transportation of work machines, and crushing. These phases are sources of emissions either directly or indirectly (e.g., crushing needs electricity, so the emissions of electricity have been evaluated). In this study, logging residues are assumed to be bundled for transportation. This method has low transportation costs and will most likely become more widespread in the future. The CO_2, CH_4, and N_2O emissions and the uncertainty ranges used in this study are presented in Table 3.

Reference Situation: Decay of Forest Residues

The reference situation for the use of forest residues as energy—the decomposition of residues in forest—was estimated using the Yasso soil carbon and decomposition model (Liski and others 2005), which was developed as a simple but widely applicable soil model for forestry applications and has already been used in various forestry-related studies (e.g., Palosuo and others 2001; Thürig and others 2005; Liski and others 2006). It is also applied in the Finnish GHG inventory (Statistic Finland 2006). Yasso is a linear compartmental model that describes the decomposition process of carbon in organic matter, taking into account the quality of the material and climatic conditions. The decomposition was modeled for conditions typical of southern Finland, where the basic parameter set of the model was determined (Liski and others 2005). The forest residue material was assumed to be from the felling of a typical Finnish Norway spruce (Picea abies [L.] Karst.) site consisting of 80% branches and coarse roots and 20% stumps.

The uncertainty ranges for the modeled values were calculated based on 1000 Monte Carlo runs, where the basic parameters of the model were varied within their uncertainty ranges (see Table 1 of Liski and others 2005), assuming no correlations between the parameter values and assuming the parameter distributions within those uncertainty ranges to be uniform. The effects of the varying climatic conditions and varying material, such as different tree species and variable shares of biomass components, were excluded from the analysis. All these assumptions and limitations make the uncertainty estimates incomplete, covering only the parameter uncertainty of the model. The decomposition of forest residues is shown in Fig. 1.

Peat

Peat is used in Finland and in some other countries including Ireland, Sweden, Estonia, and Russia for energy production. The share of peat fuel is about 5% (2005) (69 PJ) of the total primary energy consumption in Finland (Statistics Finland 2007). Peat is a domestic fuel in Finland and its use increases energy security, and it acts as a long-term energy reserve. In addition, peat fuel production makes an important contribution to employment in rural areas (Kara and others 2004).

Peat fuel production in Finland is most common in forestry-drained peatlands. Approximately 75% of the peat fuel is harvested in peatlands drained to improve forest growth in Finland (Leinonen and Hillebrand 2000). The rest of peat fuel production takes place mainly on pristine peatlands. The amount of forestry-drained peatland is about 5.6 million ha in Finland. Forestry-drained peatlands are sources of CO_2 and modest sources of N_2O (see Table 4). The amount of peatland used as agricultural land (croplands) in Finland is 240,000 ha (Geological Survey of Finland 2003). Agricultural peatlands (cropland) are a relatively large source of GHG emissions due to the fast decomposition of the peat at these sites (Table 4). Due to the high emission levels, the utilization of these sites for

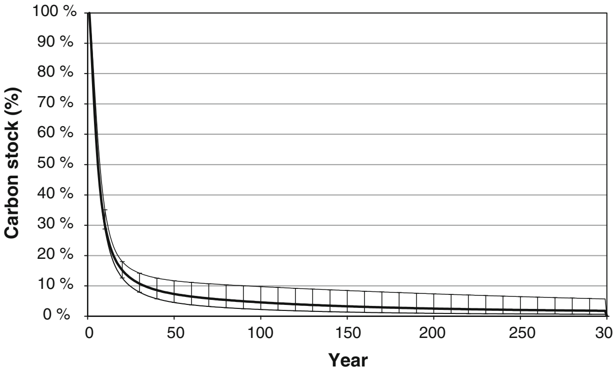


Fig. 1 Carbon storage in the forest residue pool as a function of time, Yasso soil carbon model (Liski and others 2005). Solid line: model results for the basic parameter set. Shaded area: estimated parameter uncertainty, excluding the simulated 5% of cases at both ends

Table 4 Emission factors for forestry-drained and agricultural peatlands (Kirkinen and others 2007b)

Emission factor	Average	Lower limit	Upper limit
Forestry-drained peatland (g m^{-2} a^{-1})			
CO_2	224	0	448
CH_4	–	–	–
N_2O	0.1	0.02	0.7
Agricultural peatland (cropland; g m^{-2} a^{-1})			
CO_2	1760	705	2820
CH_4	−0.15	−0.26	−0.031
N_2O	1.30	0.46	2.13

peat fuel production would be desirable but is not implemented in practice. The peat layer in the cultivated peatlands is estimated to decay at a rate of roughly 1 cm per year from the start of the cultivation (Kirkinen and others 2007b). Pristine mires have not been taken into account in this study because previous studies (e.g., Kirkinen and others 2007b) show that the greenhouse impact is highest when peat has been produced from pristine mires, compared with forestry-drained and agricultural peatlands (Kirkinen and others 2007b). In addition, the present environmental principles of the peat fuel industry will direct peat production into areas that have already been drained.

Production includes emissions from the peat production field, peat stockpiles, and working machines (Kirkinen and others 2007b). The normal production method is the milled peat method. The working phases of milled peat production are milling, harrowing, ridging, collection, and stockpiling (Leinonen and Hillebrand 2000). The dried milled layer is stockpiled. The drying is based on solar energy and takes about 1–4 days.

A new technology for peat production, called biomass dryer, has been developed by Vapo Ltd. and VTT Technical Research Centre of Finland, in which only a small part of the peatland area is in active production at one time (Kirkinen and others 2007a). The peat is excavated and pumped to a separate drying field, which is coated by asphalt. Under the drying field are finned (ribbed) tubes with hot water that heats the asphalt surface and accelerates the drying. The water is heated by solar panels surrounding the drying field. The new peat production method causes fewer emissions than the old one if calculated for produced fuel (Kirkinen and others 2007a). There are also many environmental benefits: GHG and dust emissions decrease and the aftertreatment of the peat production area can begin sooner than with traditional production methods. The emissions data for the combustion of peat are based on fluidized bed boiler combustion (Kirkinen and others 2007a).

The aftertreatment choice in this case is afforestation. Earlier studies have shown that if the area is rewetted for restoration of peatland, the greenhouse impact is higher than if it is utilized for growing biomass (Kirkinen and others 2007b). Another choice of aftertreatment could be the cultivation of energy grass (e.g., reed canary grass). The emission factors of production methods, combustion of peat, and afforestation are listed in Table 5.

Natural Gas

The use of natural gas in Finland is relatively common in power generation and in industry. The share of natural gas of the total primary energy consumption in Finland in 2005 was about 11% (149 PJ) (Statistics Finland 2007). The estimated emissions associated with utilization of natural gas in heat and power plants in this study are, however, based on the figures from Swedish production chains because there is no reliable information available on the emissions of transportation and production for the Russian natural gas used in Finland.

Currently the natural gas distribution net which covers the southwestern parts of Sweden is fed with gas from the Danish gas fields in the North Sea. The Swedish utilization of natural gas is approximately 10 TWh annually. Uppenberg and others (2001b) made an assessment of

Table 5 Emission factors of production methods, combustion of peat, and aftertreatment of the bottom of the peat production area (afforestation) (Kirkinen and others 2007b)

Emission factor	Average	Lower limit	Upper limit
Normal production (milled peat; g MJ^{-1})			
CO_2	9.32	4.66	14.00
CH_4	0.005	0.002	0.007
N_2O	0.00003	0.00001	0.00004
New peat production method (biomass dryer; g MJ^{-1})			
CO_2	2.45	1.23	3.68
CH_4	0.0007	0.0004	0.0011
N_2O	0.0003	0.0001	0.0004
Combustion (g MJ^{-1})			
CO_2	105.9	105.3	106.5
CH_4	0.0030	0.0015	0.0045
N_2O	0.005	0.0015	0.013
Aftertreatment afforestation (g m^{-2} a^{-1})			
CO_2^a	−448	−359	−505
CO_2^b	−147	−122	−155
CO_2^c	−15	0	−22

[a] Sequestration of carbon in growing forest

[b] Accumulation of aboveground forest litter

[c] Accumulation of belowground forest litter

Table 6 Emission factors of production, distribution, and combustion of Danish natural gas to Swedish utilities, with uncertainty boundaries

Emission factor	Average	Lower limit	Upper limit
Production and distribution (g MJ^{-1})			
CO_2	4.3	2.6	10.2
CH_4	0.012	0.0021	0.062
N_2O	0.000098	0.0000011	0.001
Combustion (g MJ^{-1})			
CO_2	56.5	55.37	57.63
CH_4	0.001	0.0008	0.0012
N_2O	0.002	0.0016	0.0024

different life cycle analyses of emissions for the production and distribution of different fuels, and the estimates in Table 6 are based on their recommendations. The emission estimates for combustion are based on the Swedish NIR (2007) and Boström and others (2004).

The uncertainty estimates for the combustion emissions are based on Boström and others (2004), whereas the uncertainty for the production and distribution are based on information given by SGC (2005) and Uppenberg and others (2001b).

Coal

The share of coal of the total primary energy consumption in Finland in 2005 was about 9% (129 PJ) (Statistics Finland 2007). The largest portion of the coal used in Finland is produced and imported from Russia; some coal from Poland is also used.

GHG emissions of the coal life cycle were studied in Finland by the Finnish Environment Institute (Sokka and others 2005). In that study, the coal was produced and imported from Poland and the emission data from this quite thorough study were used in this work. The emission factors for combustion of coal (Sokka and others 2005) are based on data from Statistics Finland and the IPCC. There is some information on the life cycle emissions of coal imported from Russia to Finland and these levels are quite close to those of coal imported from Poland (Kirkinen and others 2007a). The emission factors of the coal life cycle are listed in Table 7.

The fuel production phase includes emissions from coal mining and processing, external electricity and heat generation needed, transportation, raw material production, and recovered wastes, which are treated as by-products (Sokka and others 2005). The largest part of the CO_2 and N_2O emissions from coal production comes from electricity and heat generation in Poland. The greater part of the CH_4 emissions comes from mining.

Table 7 Emission factors of coal production and combustion, with uncertainty boundaries (Sokka and others 2005)

Emission factor	Average	Lower limit	Upper limit
Fuel production, transport, & processing (g MJ^{-1})			
CO_2	4.09	3.55	5.34
CH_4	0.21	0.18	0.30
N_2O	0.00002	–	–
Combustion (g MJ^{-1})			
CO_2	94.60	91.76	97.44
CH_4	0.0007	0.0002	0.0008
N_2O	0.0005	0.0003	0.0008

The combustion emissions result from pulverized fuel firing, which is the most common combustion technique for coal in Finland. The uncertainty estimates for combustion are based on Monni and Syri (2003).

Results

Time-dependent values of the relative radiative forcing commitments (RRFCs) are presented in Fig. 2. It shows the greenhouse impacts estimated with RRFCs of the studied fuel chains as functions of time. The RRFCs for coal, natural gas, and peat fuel from forestry-drained peatlands grow over time. In the fossil fuel chains (coal and natural gas) and in the reed canary grass chain, all the emissions take place in year 1. The concentrations in the atmosphere and the RF go up rapidly and decrease slowly as the concentrations fall. However, Fig. 2 gives a cumulative picture in which almost all the curves increase with time. The cumulative time integral of GHG concentrations and RF (or RRFC, Formulae 1–3, the integral in Formula 3) is constantly increasing despite the decreasing rate.

The RRFC for reed canary grass is contributed to by emissions from fossil energy inputs for agricultural operations and due to emissions from fertilizer manufacture and use. The forest residue chain is also contributed to by small amounts of fossil fuel used in harvesting and transport, but also by differences between the rapid emissions from residue combustion in energy production and slow decomposition in the forest floor in the reference case.

The peat fuel chain (cultivated peatland–afforestation) based on the use of peat from agricultural peatland has a peculiar behavior. First, the RRFC rises quite steeply but then changes direction and reaches almost zero at 300 years. This is mainly due to the impact of emissions from the reference case (I_R, Eq. 1). In the reference case the peat layer in the cultivated peatland decays slowly and these emissions have a strong decreasing impact on the net result in the long term.

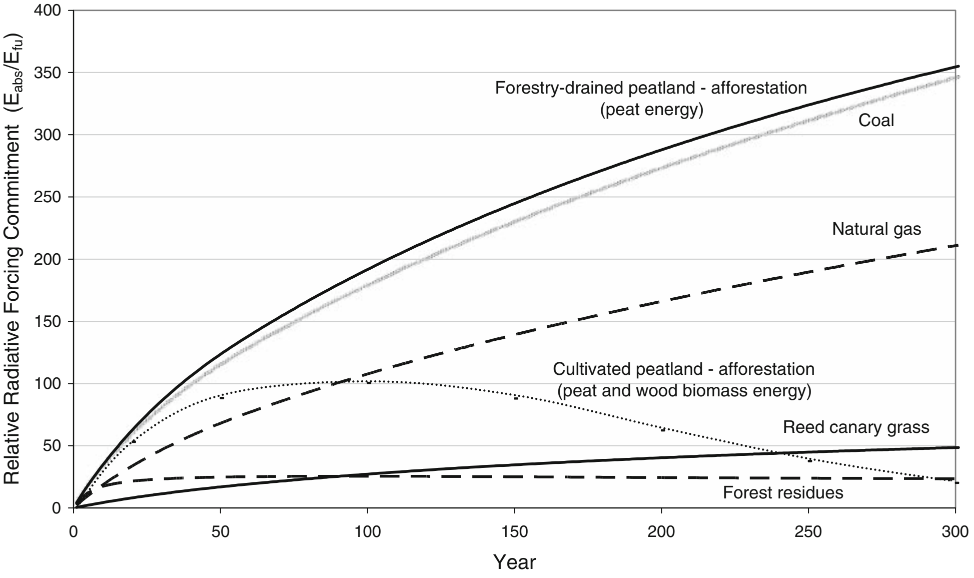
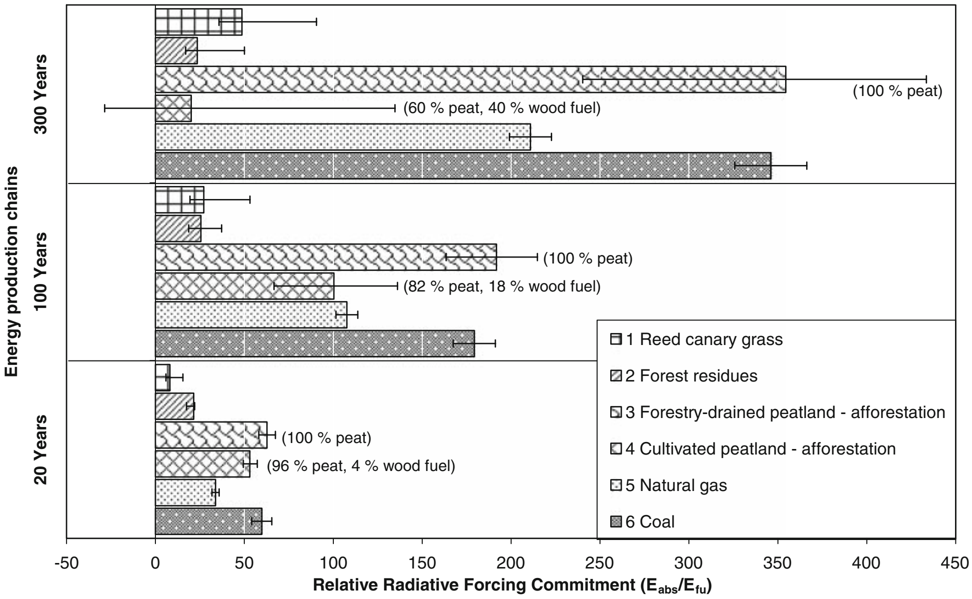


Fig. 2 Relative radiative forcing commitment (RRFC) due to various fuel chains as a function of time. RRFC: amount of energy (E_{abs}) absorbed by the Earth system (atmosphere, surface, oceans) due to increased greenhouse gas concentration from fuel-chain life-cycle emissions, divided by the energy produced (E_{fu}) by the fuel chain considered. For the coal fuel chain, roughly 170 times the produced energy is absorbed by the Earth system in 100 years. Reed canary grass and forest residues cause considerably lower RRFCs than coal. Peat fuel chains are comparable to coal for the first 50 years, then the peat chain based on the use of agricultural peatlands produces a RRCF lower than coal

In Fig. 3 the RRFCs and the uncertainties caused by emissions and sinks are shown for the accumulation time (time horizon *T*, Eq. 3) of 20, 100, and 300 years. For Chain 4, Fig. 3 gives the shares of peat fuel and wood fuel produced. The share of wood fuel is greater when the time horizon increases. The relative uncertainties are large in the cases of forest residues and agricultural peat fuel due to the uncertainly known emission development of their reference cases.

For forest residues (Chain 2) this can be seen in Fig. 4, which gives RRFCs and their uncertainties by components. In the case of reed canary grass (Chain 1) the uncertainty is contributed to especially by the poorly known N_2O emissions from the manufacture and use of fertilizers (Table 2). If the accumulation time considered is only 20 years (Fig. 3), the results are somewhat different from those in the case of 100 and 300 years. The RRFC for natural gas is

Fig. 3 RRFC within 20, 100, and 300 years due to the fuel chains considered. The uncertainty range for peat fuel harvested from agricultural peatland is large due to the wide range of emissions from this peat reserve. For natural gas and coal fuel chains the relative uncertainties are quite small compared to those for other fuel chains



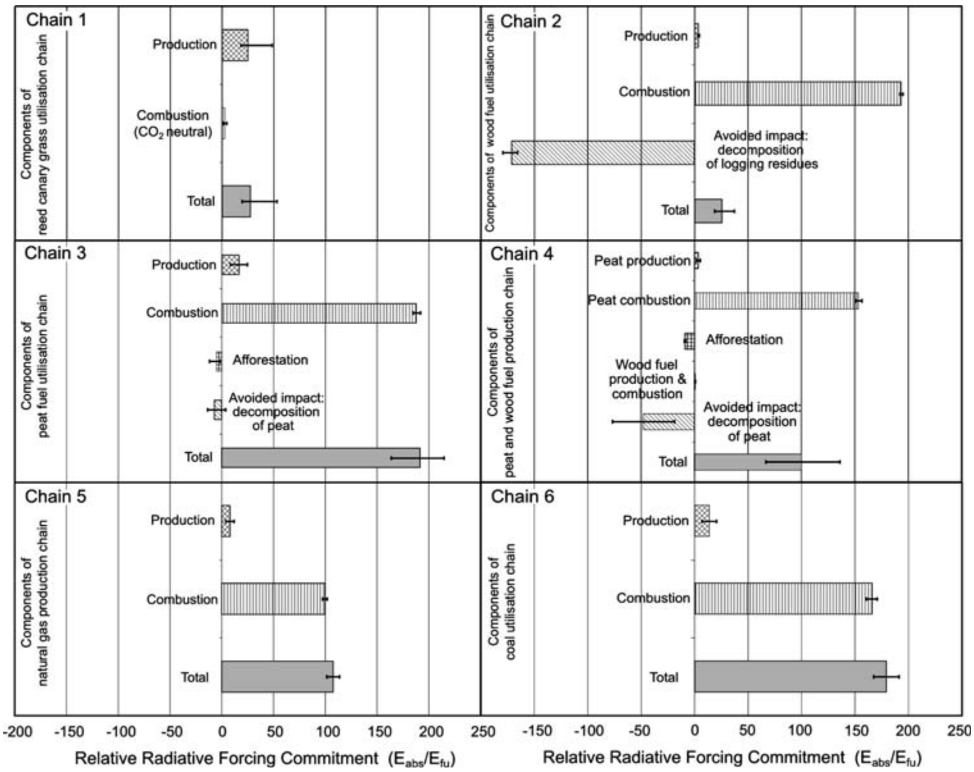


Fig. 4 Components of RRFC within 100 years for the studied fuel chains (see Table 1). The largest impact is from combustion (except for reed canary grass [Chain 1], which is assumed to be carbon-neutral due to its short rotation). Fuel production and transport have a minor impact only. In Chain 2 the avoided impact due to energy use of forest residues is also quite large, as practically all residues will decompose in the forest if they are not used, and therefore the overall net impact is quite small. In Chain 4 the avoided impact of peat decomposition in cultivated peatland, as in their natural state, lowers the total impact of peatland utilization

almost as low as that for forest residues. This is due to the relatively low combustion emissions factor for natural gas.

Concerning the numerical values of results we can conclude that if coal is used as a fuel, according to the calculations presented in this article, the RRFC is 160–180 in 100 years. Hence about 160 to 180 times more energy than what is produced in combustion is absorbed in 100 years by the thermodynamic system of the Earth due to increased GHG concentrations. A significant part of this impact is due to coal combustion, and a minor part to GHG emissions from other parts of the coal life cycle. The assessment is made for coal produced in Poland and combusted in Finland, but as the combustion part of the life cycle is dominant, the result is roughly valid for other countries also. In the case of natural gas RRFC is about 100 in 100 years. This impact is also mainly due to combustion of gas.

The peat fuel produced from forestry-drained peatlands has, according to the calculations, roughly the same greenhouse impact as coal (during the entire 300-year period). However, if the peat is produced from peatlands previously under agriculture, the greenhouse impact is clearly lower after 100 years than that of coal. This is because the peat layer decays under agriculture and causes emissions of CO_2 and N_2O. This emission source is assumed to cease when the peatland is used for peat fuel production and the ceased emissions are subtracted from the emissions of the energy production to obtain the net impact of the energy use of agricultural peatland. The uncertainty range of the greenhouse impact is large due to the great variability of the magnitude of emissions from peatlands in agriculture.

The energy use of forest residues has a relatively low greenhouse impact; the calculated RRFC varies between 20 and 40 in 100 years. The greenhouse impact is caused partly by fossil oil use in the logging and transport of forest residues, and partly by emissions taking place earlier if the residues are collected and combusted than when residues are left in the forest, where they form a carbon storage that decays slowly. This carbon storage impact has been recognized earlier by, e.g., Palosuo and others (2000).

The RRFC for canary reed grass is, according to the calculations of this article, from 20 to 50 for the 100-year time horizon. This is caused by the fossil energy input in fertilizer manufacture and agricultural operations, as well as nitrous oxide emissions from fertilizer manufacture and use in the agricultural field.

Discussion

The objective of the article is to present relative radiative forcing commitment (RRFC) and to illustrate the use of RRFC for assessing the relative greenhouse impact of the use of different fuels. RRFC provides a tool for climate policy analysts to assess the greenhouse impact of different alternatives, including dynamic considerations.

RRFC is a dimensionless ratio of the energy absorbed in the thermodynamic system of the Earth and the energy produced in the fuel chain considered. RRFC can be calculated for any energy production chain if the GHG emissions and sinks caused by the chain are known. The concept of RF can also be extended to cover changes of albedo. However, if the division by energy produced is omitted in Eq. 2, the entity can be calculated for any activity in principle. We selected to call the latter entity absolute radiative forcing commitment (ARFC), which shows the total energy absorbed within a given time frame in the Earth system due to the activity considered. ARFC can be used to describe the greenhouse impact of any activity and, also, the greenhouse impact of activities where the main product is not energy, such as steel or corn. The concept of cumulative RF (absolute global warming potential; AGWP) is given by the IPCC (1996) but without integration over the globe. Thus AGWP is calculated per square meter of the surface of the Earth.

The RF models used in this article do not include climatic feedbacks such as the forcing effect due to increased water evaporation as a consequence of warming. It is likely that the net impacts of these kinds of feedbacks are positive. They increase RF.

The accumulation time considered has a clear impact on the results. If the time span is only 20 years, natural gas has a relatively low RRFC. On the other hand, if the time span is 300 years, peat fuel produced from agricultural peatland turns out to have a very low RRFC. The choice of time span can be seen to depend on the time scale selected for mitigation of climate change. If the objective is to limit the global average temperature rise from the level of the preindustrial era to 2–3°C, considerable emission reduction measures are needed in the coming decades or half a century. This would emphasize a time span of about 100 years or even less, if RRFC is used as a measure to describe the relative greenhouse impact caused by various fuels. Very long time horizons like 300 years can be seen to be unrealistic, e.g., for the land use of the reference case (I_R in Eq. 1).

Particulate matter in the atmosphere has a negative effect on RF, resulting in a cooling impact. However, particles have not been considered in this study because their emissions and forcing impacts are very uncertain to assess and the emissions vary with the fuel combustion technology. Fine particles also have negative health impacts and their emissions should not be encouraged. Natural gas has a low impact on particulate emissions, whereas coal and biomass fuels have typically higher emissions depending on the technology used (Ohlström and others 2006). Large combustion facilities have typically lower emissions if scaled per capacity.

The results calculated in this article are expressed in relation to fuel energy. Another way could be to calculate the results for the energy produced by the power plant. Efficiencies of plants depend on technologies; typically the efficiency in electricity production is highest for natural gas-fired plants and somewhat lower for plants using other fuels. Often in northern countries a technology is used which allows the operation of the plant in coproduction mode: the plant can produce both heat for district heating and electricity for the electricity net (combined heat and power production; CHP). In Finland the typical efficiency of a CHP plant is 85–90% (IPCC 2007b). In Finland, gas, coal, peat, and renewable biomass are used as fuel in such plants (Kara and others 2001).

The uncertainty ranges given in the article show the uncertainty of input data describing GHG fluxes of fuel chains only. They do not represent the uncertainty due to models used to estimate GHG removal from the atmosphere or RF due to increased concentration. The models used are the same for all the energy chains considered, so one could assume that the relative positions of the chains are not affected by model uncertainty, especially since carbon dioxide is typically the dominant GHG in all the chains.

The uncertainty range of forest residue decomposition includes the parameter uncertainty but not the uncertainty of model structure. The uncertainties related to model structure can be significant (Chatfield 1995) but they are neglected here. A model comparison describing the decomposition of forest residues showed remarkable differences in the model-calculated decomposition processes of two decomposition models (Palosuo and others 2008). Also, different climatic conditions affect the decomposition, giving variation to the estimated decomposition.

There are a great number of ways to harvest wood for energy production and also several ways to extract peat fuel. In this article simple examples were selected, mainly to illustrate the dynamics of the greenhouse impact. The GHG emissions from other production methods of forest residue fuel can be assumed to be of the same magnitude as the fossil energy input in harvesting, and transport of residues is not very different (Wihersaari 2005).

Conclusion

RRFC can be used to give the relative greenhouse impacts and their dynamics for different sources of energy. This information can be used in the planning of policies for mitigation of climate change.

Different time horizons or accumulation times have also been used in this study. RRFC values increase, e.g., for coal and natural gas over time, but are roughly constant for forest residues. If the target is to halt the global average warming at levels of 2 to 3°C above the preindustrial level, considerable emission reduction should be undertaken during this century to stop the increase in GHG concentrations in the atmosphere. If RRFC is used to describe the relative greenhouse impact of energy sources, the time horizon of about 100 years can be seen to fit better than longer time horizons for this warming target, for which emission reduction measures should be implemented relatively quickly to slow the increase in GHG concentrations.

If the time horizon of 100 years is used, the fuel sources considered in this study can be ranked as follows: forest residues and reed canary grass have the lowest greenhouse impacts (RRFC, 20 to 50), coal and peat from forestry-drained peatlands have the highest impacts (160 to 210), and natural gas (100 to 110) and peat fuel from agricultural peatlands (70 to 140) are somewhere in between. However, the length of the time horizon to be considered depends on the climate change mitigation policy. Different time horizons can give somewhat different rankings for the fuels; e.g., if the aim of the policy is to limit the greenhouse impact slowly over 300 years, the cultivated peatland chain could be an advantageous alternative. However, we must recognize that the very long-term assumptions concerning land use in the reference case are likely to be unrealistic.

RRFC can be used to illustrate the greenhouse impacts of energy sources. First, the values can be used to give relative weights for different energy sources in the planning of climate change mitigation policies. Second, the numerical values and dynamics of RRFC can be of interest for information purposes, especially for a general understanding of the impact of fuel chains on the energy balance of the Earth.

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