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Climate impact from Peat Utilisation in Sweden

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Climate Impact from Peat Utilisation in Sweden

Sammanfattning/Summary

The climate impact from the use of peat for energy production in Sweden has been evaluated in terms of contribution to atmospheric radiative forcing. This was done by attempting to answer the question “What will be the climate impact if one would use 1 m^2 of mire for peat extraction during 20 years?”. Two different methods of after-treatment were studied: afforestation and restoration of wetland. The climate impact from a peatland – wetland energy scenario and a peatland – forestry energy scenario was compared to the climate impact from coal, natural gas and forest residues. Sensitivity analyses were performed to evaluate which parameters that are important to take into consideration in order to minimize the climate impact from peat utilisation.

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Abstract

The climate impact from the use of peat for energy production in Sweden has been evaluated in terms of contribution to atmospheric radiative forcing. This was done by attempting to answer the question “What will be the climate impact if one would use 1 m^2 of mire for peat extraction during 20 years?”. Two different methods of after-treatment were studied: afforestation and restoration of wetland. The climate impact from a peatland – wetland energy scenario and a peatland – forestry energy scenario was compared to the climate impact from coal, natural gas and forest residues. Sensitivity analyses were performed to evaluate which parameters that are important to take into consideration in order to minimize the climate impact from peat utilisation.

The main conclusions from the study are:

- The accumulated radiative forcing from the peatland – forestry energy scenario is comparable to natural gas in a 180-year perspective, and between forest residues and natural gas in a longer perspective (300 years) assuming a medium-high forest growth rate and original methane emissions from the virgin mire.

- The accumulated radiative forcing from the peatland – wetland energy scenario, will lie between coal and 2/3 of natural gas in a 300-year perspective, depending on the assumed carbon uptake rates for the wetland and assuming a medium-high methane emissions from a restored wetland.

- The climate impact from utilizing 1 m^2 mire for fuel production can be equivalent to using anything from forest residues to coal as energy source, depending on after-treatment and original conditions at the mire that has been utilized.

- It is important to consider methane emissions from the virgin mire when choosing mires for utilization. Low original methane emissions give significantly higher total climate impact than high original emissions do.

- Afforestation on areas previously used for peat extraction should be performed in a way that gives a high forest growth rate, both for the extraction area and the surrounding area. A high forest growth rate gives lower climate impact than a low forest growth rate.

- There are great uncertainties related to the data used for emissions and uptake of greenhouse gases in restored wetlands. The mechanisms affecting these emissions and uptake should be studied further.

Preface

This study was financed by the Swedish Peat Producers Association (SPPA) and the Swedish Environmental Protection Agency (EPA). A reference group consisting of Marianne Lilliesköld (EPA), Håkan Staaf (EPA), Klas Österberg (EPA), Magnus Brandel (SPPA), Lars Åstrand (SPPA) and the authors have had five meetings during the project period (May 2000 to July 2001). The study has been peer reviewed by Ilkka Savolainen, Research Professor, VTT Energy, Finland. Valuable comments have also been given by Ingvar Sundh, Assistant Professor, Department of Microbiology, Swedish University of Agricultural Sciences; Kim Holmén, Associate Professor, Department of Meteorology, Stockholm University; Torben R. Christensen, Assistant Professor, Centre for Geobiosphere Studies, Lund University and Mats Nilsson, Associate Professor, Department of Forest Ecology, Swedish University of Agricultural Sciences.

CONTENTS

1 Introduction

The climate impact from using peat as an energy source has been discussed intensely during the last years. Research has also been made on mechanisms (decomposition processes, biomass growth etc.) that govern the magnitude of the climate impact. In December 1998, the Swedish Environmental Protection Agency arranged a hearing where new research findings on greenhouse gas emissions connected to such mechanisms were discussed. This study was partly initiated as a follow-up to that hearing.

2 Objective of the study

The objective of this study is to evaluate the climate impact from the use of peat for energy production in Sweden. This is done by trying to answer the question “What will be the climate impact if one would use 1 m^2 of mire for peat extraction during 20 years?”. Two different options for after-treatment are studied: afforestation and restoration of wetland.

The climate impact from the use of peat for energy production has been studied before (e.g. Rodhe & Svensson, 1995; Savolainen et al., 1994; Zetterberg & Klemedtsson, 1996; Åstrand et al., 1997). The aims of this report are:

- to update results from previous reports by using the latest research findings available as input for the calculations
- to give the results as possible ranges for different scenarios, not as exact figures
- to assess which parameters are the most important to consider when attempting to minimize the climate impact from peat utilisation
- to compare the climate impact from peat utilisation with alternative energy sources

The time span studied here is up to 300 years, which is longer than what has been studied in previous reports. The purpose of this is to make it possible to assess long-term trends (e.g. over several forest generations) as well as impacts over a shorter time period.

3 Methods

In this report we approximate the contribution to climate impact by using the concept of *radiative forcing*. Radiative forcing, measured in W/m2 (instantaneous radiative forcing) or J/m^2 (accumulated radiative forcing), can be described as the change in radiative balance at the tropopause (the boundary between the troposphere and the stratosphere) due to for example emissions of greenhouse gases. In other words, it is the change in the difference between incoming and outgoing radiation through the tropopause. A positive radiative forcing tends to warm the earth’s surface, a negative radiative forcing tends to cool it.

The impact chain can be simplified as: *emissions* lead to *increased atmospheric concentrations* which lead to *radiative forcing,* which leads to *climate change.* Since we only calculate the radiative forcing in this study, one can say that the *potential* climate impact is calculated. For a full explanation of the concept of radiative forcing and the relationship between greenhouse gas concentrations and radiative forcing, see Zetterberg (1993), or Uppenberg & Åhman (1998).

The IPCC (Intergovernmental Panel on Climate Change) recommends that the GWP-concept (Global Warming Potential) should be used to calculate and compare greenhouse gas emissions on national and international level. With that method climate impact is calculated as the amount of greenhouse gas emitted, multiplied by the corresponding GWP-index. The GWP-indexes for different greenhouse gases are defined as the cumulative radiative forcing between the present and some chosen later time horizon, caused by a unit mass of gas emitted now, expressed relative to some reference gas (usually CO_2). The reason that radiative forcing (RF) is used in this study instead of GWP is that:

- RF can describe the impact of an emission scenario that stretches over a long time, which the GWP-concept can't.
- GWP is a relative measure. A GWP today is not the same as a GWP year 2100.
- According to model studies performed by the IPCC, there seems to exist a direct relation between RF and global average temperature.

Three greenhouse gases have been studied: CO_2, CH_4 and N_2O. The net emissions have been calculated by adding the emissions from different activities or processes connected to the extraction of peat. The unit used is g/(m2*year). All included activities and processes are described in the following sections.

The calculation of radiative forcing was made using a dynamic computer model. The model calculates the radiative forcing from an emission scenario in two steps. First the changes in atmospheric greenhouse gas concentrations are calculated, and then the radiative forcing is calculated from these concentrations. The computer model also includes an "overlap term" that is a result of that CH_4 and N_2O absorbs infrared radiation partly in the same wavelength range. The relations between emissions and changes in concentrations are expressed by exponential functions, and the relations between changes in concentration and radiative forcing are expressed by functions based on parametrisations of model results.

The calculated radiative forcing from the use of peat is compared to the radiative forcing resulting from the use of coal, natural gas and forest residues. The comparison is based on the assumption that equal amounts of energy are supplied in all the different fuel systems (see section 5.7).

In this study, we present the results both as instantaneous radiative forcing (W/m^2) and accumulated radiative forcing (J/m^2). The instantaneous forcing describes the actual radiative balance at a given moment in time, while the accumulated forcing describes the total net radiative balance over a period of time. One can say that the GWP-concept is a simplified way of calculating accumulated radiative forcing. Accumulated forcing divided by time gives the average forcing for the time period.

It is difficult to give the definite answer to whether instantaneous or accumulated radiative forcing is the most correct measure to use when evaluating the climate impact from peat utilisation. However, the inertia of the climate system gives a significant time lag in the cause-effect chain. This means that changes in radiative forcing does not immediately result in changes in global average temperature. The temperature changes more slowly, and as a result of the radiative forcing over a longer period of time. In that sense, the climate system can be described as having a memory.

All this considered, it is our view that one should focus on the accumulated radiative forcing in the evaluation of long term climate impact. But the instantaneous radiative forcing should also be considered since it describes how the climate system is affected in every given moment.

4 System boundaries and underlying assumptions

The scope of this study is peat utilisation under the conditions that are valid in Sweden. The different stages involved in the process of extracting peat for energy are described in table 1 below.

Table 1 *Description of the different stages of energy peat production.*

Stage	**Year**	**Description**
Virgin mire	before 0	The mire has not been affected by activities connected to peat extraction.
Drained mire, before extraction	0 – 5	During year 0, the covering vegetation is stripped off and ditches are made on the extraction area, with about 20 meters between each other. The area is then drained to lower the water content from 90 – 95 % to 80 – 85 %. This will normally take 1 – 5 years. We assume 5 years.
Extraction, transport and combustion of peat	6 – 25	When the water content has been lowered enough for the ground to carry the machines, extraction of peat can be started. This can be done either as milled peat or as sod peat. The extracted peat is dried lying in the field, and thereafter transported to large storage piles close to the extraction area. The peat extraction is carried out during the summer months. During the winter months, peat is transported directly from the storage piles to plants for heat/power production.
After-treatment	26 –	When the peat extraction has been finished after approximately 20 years, the area can be converted to agricultural land (not common in the modern peat industry) or forest, or it can be restored to new wetland.

The following assumptions for peat characteristics and impact area have been used in the study:

- The area affected by the drainage that is performed, is assumed to be twice the size of the *extraction area* (Larsson, pers. comm.; Åstrand, pers. comm.). This assumption is based on the fact that the influence distance of the drainage ditches is approximately 20 – 30 m outside the extraction area. The drained area that is not used for extraction, the *surrounding area*, is used for e.g. storage piles and access roads. Based on this assumption, every m^2 of mire that is used for peat extraction will cause 1 m^2 of drained surrounding area in the calculations.
- Average extracted peat depth on the extraction area: 1.4 m (Larsson, pers. comm.) The real extracted peat depth vary significantly for specific locations within the extraction area. Extracted peat depth does not include the surface layer of low-humified peat that is removed before extraction (often used as soil improver or for horticultural use), nor what is oxidized during extraction (see 5.3.1) or what is left after extraction (see 5.5.1). All these parameters included, average peat depth would be approximately 1.9 m.
- Peat density: 1000 kg/m^3 (Råsjö Torv, 2000; HMAB, 2000)
- Dry weight: 8 % (Råsjö Torv, 2000; HMAB, 2000)
- Carbon content: 50 % on dry solids (Råsjö Torv, 2000; HMAB, 2000)
- Energy content: 20 MJ/kg dry solids (Råsjö Torv, 2000; HMAB, 2000)

5 Greenhouse gas fluxes for peat

The net greenhouse gas emissions from peat utilisation are calculated as the difference between emissions from a utilised mire and a virgin mire, i.e. (net emissions) = (emissions from *drained mire, before extraction*) + (emissions from *extraction of peat*) + (emissions from *combustion of peat*) + (emissions from *after-treatment*) – (emissions from *virgin mire*), as described in the following sections.

5.1 Virgin mires

Different virgin peat bogs can have very different characteristics and it is therefore very difficult to generalise for an “average mire”. The figures used in this study are average values for Sweden, and not connected to a specific mire type.

5.1.1 Carbon dioxide

Most virgin mires accumulate carbon in the growing biomass and thereby act as sinks for atmospheric CO_2. The uptake can vary significantly depending on geographic location (climate) and age of the bog. A Finnish overview of greenhouse gas fluxes from peatlands (Crill et al., 2000) uses an average uptake rate of 75 g/m^2*year to calculate the national carbon accumulation in undisturbed peatlands. That figure is based on Turunen et al. (1999), in which the range is 62 – 96 g CO_2/m^2*year. A similar Swedish overview of greenhouse gas fluxes from peatlands (Kasimir-Klemedtsson et al., 2001) uses uptake rates of 51, 62 and 77 g/m^2*year for fens, mires and bogs respectively. Those figures are based on Turunen and Tolonen (1996). Previous Swedish climate studies for peat (Rodhe & Svensson, 1995; Zetterberg & Klemedtsson, 1996; Åstrand et al, 1997) have used an uptake rate of 37-48 g/m^2*year based on Tolonen et al. (1992). However, the range in uptake rates does not affect the results in any significant way why the different levels are not tried here. Since Kasimir-Klemedtsson et al. (2001) presents the latest findings assumed to be representative for Swedish conditions we use their values as input to the model. Based on that, an area-weighted mean value of 58 g/m^2*year is used as best estimate.

5.1.2 Methane

Methane emissions from virgin mires have been studied in several research programmes in different countries. An extensive study concerning methane emissions from Swedish mires was performed during 1994. Methane emissions were then measured at more than 600 sites all over Sweden. The results from that study are here assumed to be the most representative data available for Swedish conditions.

- The average methane emissions from Swedish mires can vary between 2 – 40 g CH_4/m^2*year depending on mire type and geographic location (Nilsson et al, 2000).
- The magnitude of the methane emissions also depends on if trees are growing on the mire or not (on the surrounding area). In this study we assume a reversed proportional relation between forest fraction and methane emission from surrounding area.
- The long-time average emission for Swedish mires has been modelled in Nilsson et al.(2000), considering climate data for a 17-year period. The calculated long-time average is 21 g CH_4/m^2*year (Nilsson, pers. comm.) which is used as best estimate here.

5.1.3 Nitrous oxide

The emission of N_2O from a virgin mire is assumed to be negligible (Kasimir-Klemedtsson et al, 2001).

5.2 Drained mire, before extraction (year 0 to 5)

Emissions from working machines connected to drainage of the ground take place during year 0, but they are relatively small and are ignored here.

5.2.1 Carbon dioxide

- The drainage causes an oxidation of the peat which results in a net emission of CO_2. Sundh et al. (2000) state that the emissions can be 230 – 1020 g CO_2/m^2*year, mean value 600 g CO_2/m^2*year, based on field measurements in Sweden. Finnish field measurements have given similar results; 880 g CO_2/m^2*year including the loss of average annual carbon accumulation occurring in natural mires (Nykänen et al., 1996). Here we assume a net emission of 1000 g CO_2/m^2*year, which can be seen as a worst case. The emission is assumed to increase linearly from 0 to 1000 g CO_2/m^2*year during year 0 – 3 and remain constant at 1000 g CO_2/m^2*year during year 4 – 5. We have chosen not to include the range in CO_2-emission from peat oxidation in the sensitivity analysis. This decision is based on the fact that the possibilities to actively limit the oxidation during drainage and extraction are very limited.
- The drainage will also cause an increased growth of trees and other vegetation which result in an uptake of CO_2. However, this uptake is negligible in comparison to the oxidation (Rodhe & Svensson, 1995) and is therefore ignored here.

5.2.2 Methane

When a mire is drained, the water table is lowered and the decomposition processes in the upper parts of the ground changes from anaerobic to aerobic. Thereby, the methane emissions from the ground are reduced substantially.

- ***Extraction area:*** The remaining CH_4-emission after drainage is in Sundh et al. (2000) estimated to be 0.4– 4.5 g CH_4/m^2 (approximately 10 % of the emissions from virgin mires). These figures include area weighted emissions from drainage ditches, which can be substantially higher than emissions from the extraction area because of vegetation in the ditches. The emissions from ditches can probably be kept low by keeping the ditches clear from vegetation (Sundh et al, 2000). Nykänen et al. (1996) estimate the methane emissions from peat mining areas to be approximately 0.32 g CH_4/m^2 both from the extraction area and from the ditches. Based on Sundh et al. (2000) we assume the methane emission to be 10 % of the original emission. This gives 0.2 – 4 g CH_4/m^2*year with 2.1 g CH_4/m^2*year as average.
- ***Surrounding area:*** The remaining CH_4-emission after drainage is assumed to be 25 % of the original emission because of more vegetation in the drainage ditches than in the production area (poorer maintenance of the ditches, see discussion above). This gives 0.5 – 10 g CH_4/m^2*year with 5.25 g CH_4/m^2*year as average.

5.2.3 Nitrous oxide

The N_2O-emission is assumed to be 0.02 – 0.1 g N_2O/m^2*year (Klemedtsson, pers. comm.).

5.3 Extraction of peat (year 6 – 25)

5.3.1 Carbon dioxide

- ***Extraction area:*** The oxidation of peat continues to stay high because of the working of the ground during extraction. This gives a CO_2-emission of 1000 g CO_2/m^2*year (see section 5.2.1) during the extraction period (year 6 – 25). Note that this oxidised peat is not subtracted from the average extracted peat depth (see section 4.), and thereby not included in the calculated total energy content. Approximately 6 % of the extractable peat is lost because of the oxidation (Sundh et al, 2000).

- ***Surrounding area:*** The oxidation of peat gives an emission of 1000 g CO_2/m^2*year (see section 5.2.1) during year 5-10. After that, the oxidation is assumed to decrease because of less working of the ground compared to the production area. The CO_2-emission is assumed to decrease linearly from 1000 to 300 g CO_2/m^2*year during year 11 – 25. 300 g CO_2/m^2*year corresponds approximately to oxidation of 3 mm peat per year. There will be a certain spontaneous growth of forest on the surrounding area, which will give an uptake of CO_2. Here we assume that a possible future forestry will be coordinated for the extraction area and the surrounding area, and therefore ignore forest growth at this stage.
- CO_2 is also emitted because of oxidation in stockpiles and other losses (e.g. dusting and self-burning). According to Nykänen et al. (1996) emissions from stockpiles are 175 g CO_2/m^2*year. These emissions are not explicitly included in this study, but can be seen as included since we have chosen a high value for emissions from the extraction area (1000 g CO_2/m^2*year). For a Finnish site Nykänen et al. (1996) estimated total emissions including emissions from stockpiles, ditches and the loss of average annual carbon accumulation in natural mires to 1064 g CO_2/m^2*year. Based on the mean value for emissions from the extraction area in Sundh et al. (2000), total emissions including emissions from stockpiles would be 775 g CO_2/m^2*year.
- Working machines and transports of peat are assumed to give an emission of 1 g CO_2/MJ extracted peat, based on an energy demand of 1.3 % of the extracted peat as diesel oil (Larsson, pers. comm.).

5.3.2 Methane

- ***Extraction area:*** The remaining CH_4-emission after draining is assumed to be 10 % of the original emission (see section 5.2.2). This gives 0.2 – 4 g CH_4/m^2*year with 2.1 g CH_4/m^2*year as average.
- ***Surrounding area:*** The remaining CH_4-emission after draining is assumed to be 25 % of the original emission because of more vegetation in the drainage ditches than in the production area (poorer maintenance of the ditches). This gives 0.5 – 10 g CH_4/m^2*year with 5.25 g CH_4/m^2*year as average. This emission is assumed to continue for a few years until tree growth has increased somewhat. The emission is assumed to be 0 g CH_4/m^2*year during year 8 – 25.
- Emissions from working machines and transports of peat are very small in comparison to emission from ground processes, and are ignored here.

5.3.3 Nitrous oxide

- ***Extraction area:*** During year 6 – 7, the emission is assumed to be 0.2 – 1 g N_2O/m^2*year. After that, the emission is assumed to decrease linearly down to 0.01 – 0.05 g N_2O/m^2*year during year 8 – 25 (Klemedtsson, pers. comm.).
- ***Surrounding area:*** The emission is assumed to be 0.2 – 1 g N_2O/m^2*year during year 5 – 25 (Klemedtsson, pers. comm.).
- Emissions from working machines and transports of peat are very small in comparison to emission from ground processes, and are ignored here.

5.4 Combustion of peat (year 6 – 25)

5.4.1 Carbon dioxide

The emission from combustion of peat has been calculated to 91 – 96 g CO_2/MJ peat depending on moisture content (6 – 50 %) based on heating values and elementary analysis from a number of Swedish mires (HMAB, 2000; Råsjö Torv, 2000). Varying the emission level within the range does not affect the calculated radiative forcing in any significant way, and thus the average value (93.5 g CO_2/MJ) was used in the calculations. This is a somewhat lower emission factor than usually recommended by e.g. IPCC (IPCC (1997): 106 g CO_2/MJ).

5.4.2 Methane

The average emission from combustion of peat in Swedish power/heat plants is assumed to be 0.005 g CH_4/MJ peat (Uppenberg et al, 1999).

5.4.3 Nitrous oxide

The average emission from combustion of peat in Swedish power/heat plants is assumed to be 0.006 g N_2O/MJ peat (Uppenberg et al, 1999).

5.5 After-treatment – Afforestation (year 26 –)

The following assumptions for timber characteristics have been used in the study:

Basic wood density (dry matter) = 430 kg/m3 (Norway spruce/birch; 9/1)
Carbon content = 50 %

5.5.1 Carbon dioxide

- ***Oxidation on extraction area:*** The oxidation of peat will continue until the remaining peat layer has disappeared. Assuming an average peat depth of 0,2 m after the extraction has finished, it will take approximately 22 years (until year 47) until the remaining peat has disappeared if the oxidation rate is 1000 g CO_2/m^2*year. That calculation is based on the assumption that approximately 50 % of the remaining peat is easily oxidable material (consisting mainly of hemicelluloses or cellulose). The other 50 % is assumed to be made up of resistant, highly humified material which decompose very slowly (this fraction will eventually decompose , but over a much longer time than this study covers). From year 48, the emission caused by oxidation is assumed to be 0. The fraction of easily oxidable peat in the deeper part of the bog can be lower than what is assumed here (30 % is stated by Åstrand (pers. comm.)).

- ***Oxidation on surrounding area:*** The oxidation of peat will continue as long as there is peat left and the water table is kept low through drainage. Here we assume that the oxidation will continue at the same rate as in the preceding stage, 300 g CO2/m2*year, throughout the study period.

- ***Accumulation of carbon in humus:*** Accumulation of carbon in humus: Following afforestation, a new forest floor (litter+ humus layer) will accumulate on the soil as a result of litter formation. The accumulation of carbon in the upper part of the soil is a balance between litter input and decomposition, and assuming a constant carbon input the forest floor will reach an approximate steady-state after 50 - 100 years (Lilliesköld & Nilsson, 1997). Thus, as a rough estimate we assume that the carbon accumulation will occur linearly during the first forest rotation and thereafter turns to zero. In a cold climate with low decomposition the steady-state will be reached later, perhaps after several hundred years, but, on the other hand, the absolute accumulation rate will be lower here.

Olsson et al. (1996) estimated the carbon pools of the humus layer of four clear-felled coniferous forests in Sweden to 1.7- 4.4 kg C/m2. At the two sites in southern Sweden the topsoil contained 2,9 and 4,4 kg C/m2. This could be compared with data from Gärdenäs (1998), who reported a mean value for the organic matter store in the forest floor of Norway spruce sites in northern Europe to 40 Mg/ha, i.e. about 2 kg C/m2. Based on the presented data we can assume that, as a maximum, afforested peatlands in southern Sweden could accumulate 3-4 kg C/m2 during a forest generation. Here we use a value of 3,5 kg C/m2, which over a 70-year period gives a mean uptake of 183 g CO2/m2*year. This is about half of the uptake rate used in the study by Zetterberg & Klemedtsson (1996). In a low-productive site (3,0 m3/ha year) the wood production and litter fall would be about one third of that found on the high-productive. However, also the decomposition rate would be somewhat lower and we assume a carbon uptake of 100 g/m2 year for the low-productive site.

- ***Forest growth:*** The range for carbon uptake in the forest planted on the extraction area as well as on the surrounding area has been calculated from Hånell (1997) According to Hånell the regional mean forest growth can reach between 3 m^3/ha*year (northern Sweden, Härjedalen and Västerbotten) and 8.5 m^3/ha*year (southern Sweden, Småland). For parts of Småland, the growth rate can be up to 10 m^3/ha*year (Anon, 1992). These figures imply a forest management without nitrogen fertilization but where the nutrient status of the soil is improved by wood-ash or other mineral fertilizer. The lower value would underestimate the expected growth rate in areas of northern Sweden where peat is extracted (Hånell (pers. comm.) and Åstrand (pers. comm.)) but still 3 m^3/ha*year was used as a worst-case scenario.

  The carbon net uptake in forest biomass for two sites, one with low and one with high growth rate, was calculated from data on volume production in Hånell (1997). The high-productive site (8,5 m^3/ha*year) was thus assumed to have a total stem volume production of 595 m^3/ha, harvested in thinnings and final cutting, over a forest rotation of 70 years, while the corresponding figure for the low-productive site (3,0 m^3/ha* year) was assumed to be 350 m^3/ha over a 100 year rotation. Furthermore, the total standing biomass at thinnings and final cutting, including stem, branches, needles, stump and roots, was assumed to amount to 1.5 times the stem biomass. The same assumption was also used by Zetterberg & Klemedtsson, (1996) and Åstrand et al. (1997). Lundmark (1988) stated that the total biomass/stem biomass ratio of mature conifer trees is 1.5 -1.7, but since younger trees harvested in thinnings has lower ratios the lower part of the range was used here. Using the above-mentioned figures and assumptions, an accumulation of 414 - 1006 g CO_2/m^2 year is estimated. If the growth rate 10 m^3/ha*year is used as the higher value, an accumulation of 1180 g CO_2/m^2 year is estimated following the calculations above. In the simulations we use the range 414 – 1180 g CO_2/m^2 year for carbon accumulation in forest growing on cut-away peatlands.

  Note that the average growth rates for northern and southern Sweden are used in this study as *examples* of low and high growth rates. It is possible to get a high growth rate also in northern Sweden depending on site specific geographic location and management conditions, and vice versa. The different growth rate scenarios are therefore named “low” and “high” in the model input and results sections, and should not be seen as specific for afforestation on utilised peat land in different parts of Sweden.

- ***Forest rotation period:*** The generation period for a forest with "low" growth rate is assumed to be 100 years and for a "high" growth rate, 70 years. The generation period for "best estimate" in the simulations is assumed to be 85 years.

- ***After felling:*** All harvested forest biomass (20 % of the standing biomass is assumed to be roots and stumps) is assumed to be combusted immediately after felling which results in an instantaneous emission of 33120 g CO_2/m^2 (low) to 66080 g CO_2/m^2 (high). This assumption is based on Eriksson (1994) who state that approximately 45 % of the harvested biomass goes directly to energy production, 35 % or more of the remaining harvested biomass goes to pulp and paper production and the rest (20 %) end up as sawmill products. The latter is partly used in buildings and other long-lived objects, and the rest is used as consumption material in e.g. construction work. Based on these assumptions, one can also argue that the CO_2-emissions should be distributed out over a time period of at least 10 – 15 years, with the major part of the emissions during the first 5 years. On the other hand, Eriksson (pers. comm.) states based on data from Statistics Sweden (SCB), that there is no significant change of the carbon pool (wooden buildings etc.) in the Swedish society. That assumption would also lead to an instantaneous emission of the forest biomass carbon in the calculations. However, the different scenarios do not change the results in any significant way, so these differences are not investigated further. The roots and stumps are assumed to decompose at a constant rate during 20 – 100 years, thereby emitting CO_2 during 20 – 100 years after felling.

  In this study, it is assumed that all the harvested forest biomass including branches and needles is used for energy production in some way. This assumption is valid if the forest is explicitly grown for energy production. However, it is not possible to restrict land owners to a specific after-treatment alternative for hundreds of years. In an average scenario, a large part of the forest biomass will probably go directly to energy production in both heat/power plants and industry, and some of it will first be transformed to paper and building material, and then gradually be used for energy production. But there will always be losses of biomass during processing of wood products, and some of the wood waste will end up in landfills and thereby decompose without being used for energy production. These losses are uncertain and highly influenced by legislation concerning waste handling. We have not tried to quantify these losses in this study, and thus the climate impact from the peat-afforestation scenario probably are underestimated for average forestry, compared to the other studied energy sources.

5.5.2 Methane

There will be a small uptake of CH_4 in forest soils during forest growth, but that uptake is ignored here.

5.5.3 Nitrous oxide

- ***Extraction area:*** The emission is assumed to decrease linearly from 0.1 – 0.5 g N_2O/m^2*year to 0.02 – 0.1 g N_2O/m^2*year during year 26 – 47 and thereafter stays constant (Klemedtsson, pers. comm.).
- ***Surrounding area:*** The emission is assumed to stay constant at 0.14 – 0.7 g N_2O/m^2*year from year 26 and throughout the study period (Klemedtsson, pers. comm.).

5.6 After-treatment – Restoration of wetland (year 26 –)

5.6.1 Carbon dioxide

There are very few studies on carbon uptake in a restored wetland and the data on uptake rates are uncertain. Tuittila et al. (1999) state that a restored wetland after only a few years will have a net accumulation of carbon and that the accumulation rate can be 108 - 160 g C/m^2*year. In Crill et al. (2000) these figures are used to calculate the total carbon sink capacity in restored Finnish cut-away peatlands. Savolainen et al. (1994) use an uptake rate of 64 g C/m^2*year for a restored peatland at the beginning of paludification, and 37 g C/m^2*year for lake formation, both values from Hillebrand & Wihersaari (1993). In Kasimir-Klemedtsson et al. (2001) it is shown that the carbon accumulation rate in a mire decreases significantly as the mire gets older. An example for a 2400 year old mire show that the accumulation rate during the first 400 years can reach between 60 and 120 g C/m^2*year. Tolonen & Turunen (1996) show mean accumulation rates from 77 to 126 g C/m^2*year for peat layers 9 – 102 years old (maximum 290 g C/m^2*year), and rates from 40 to 81 g C/m^2*year for peat layers 100 – 200 years old (Alm et al, 1992).

Since the uncertainties connected to the carbon uptake rate and how it will develop over time are very large, wide ranges has been studied – 37 g C/m^2*year as low value and 160 g C/m^2*year as high value, corresponding to 136 – 587 g CO_2/m^2*year. The carbon uptake rate is probably high in a young mire during the first decades or centuries whereafter it decreases gradually (probably exponentially) as the mire gets older (during several thousand years). The change in uptake rate is highly governed by climate and the data available are uncertain (Bohlin, pers. comm.; Tolonen & Turunen, 1996) since the process stretches over such long time periods. In this study we have not tried to quantify the temporal change in uptake rate. We assume that the uptake increase linearly from 0 to 136 – 587 g CO_2/m^2*year during year 26 – 31 and thereafter stays constant at that level throughout the study period.

5.6.2 Methane

The uncertainties on methane emissions from a restored wetland are also very large. Tuittila et al. (2000) state that the methane emissions can stay at a low level for a long period of time, even after sites have become fully vegetated and colonized by mire plants. We assume that the CH_4-emissions will increase linearly from 0 up to the level assumed for virgin mires, 2 – 40 g CH_4/m^2*year, during year 26 – 45, and thereafter stay constant at that level.

5.6.3 Nitrous oxide

No information on N_2O-emissions from restored wetlands were found.

5.7 Assumptions for the comparison to coal, natural gas and forest residues

The energy content of the peat layer under 1 m^2 of the extraction area is 2240 MJ based on the assumptions in section 4. This peat is extracted during 20 years, which gives 112 MJ/year. In the comparison of climate impact from the different fuels, the same amount of energy as coal, natural gas and forest residues is assumed to be combusted during the same 20 years.

All fuel systems are assumed to supply equal amounts of energy, also for the after-treatment stages. For the system with restoration of wetland as after-treatment this will have no effect on the calculations since no energy is produced in the peatland – wetland energy scenario after peat extraction has stopped. On the other hand, for the system based on afforestation as after-treatment this will have effect on the calculations since all the forest biomass that is produced on the utilised area is assumed to be used for energy production (see 5.5.1). In this peatland – forestry energy scenario forest biomass will in fact produce more than half of the total energy during 300 years. In the comparison equal amounts of energy are assumed to be produced by the other energy systems. The relevant amounts of energy produced from utilisation of 1 m^2 of mire are displayed in table 5 below.

The differences in efficiency between different fuels are small and vary with plant type. The plant efficiency is therefore not considered here.

Table 5. *Energy produced from utilisation of 1 m^2 mire for peat extraction during different stages in the process.*

Stage	**Year**	**Amount of energy (MJ/year)**
Extraction of peat	6 – 25	112
Afforestation, low	126, 226	662
Afforestation, b.e.	111, 196, 281	992
Afforestation, high	96, 166, 236	1322
Restoration of wetland	-	0

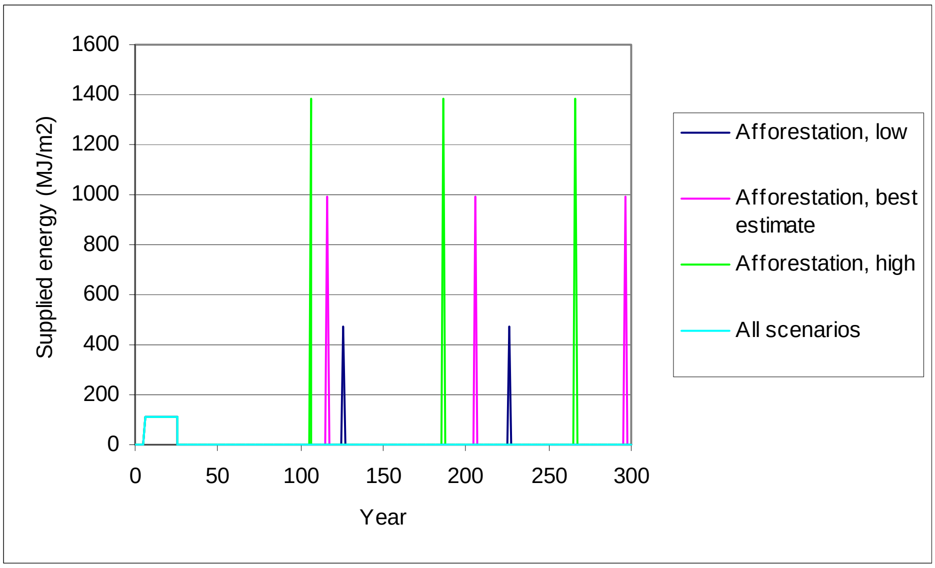

Figure 1. *Energy produced from utilisation of 1 m^2 mire for peat extraction during different stages in the process and for the different after-treatment scenarios studied here.*

5.8 Emissions summary – model input

5.8.1 Ground preparations and extraction of peat

Table 2. *Emission ranges for CO_2, CH_4 and N_2O from virgin mires and from ground processes and activities during preparations and extraction of peat. "b.e." means best estimate.*

Stage/ Activity	**Year**	**CO_2 (g/m^2*year)***		**CH_4 (g/m^2*year)***		**N_2O (g/m^2*year)***	
		Extraction area	**Surrounding area**	**Extraction area**	**Surrounding area**	**Extraction area**	**Surrounding area**
Virgin mire	before 0	-58	-58	2 – 40 b.e.=21	2 – 40 b.e.=21	0	0
Drained mire, before extraction	0 – 5	*year 0-3:* linearly increasing from 0 to 1000 *year 4-5:* 1000	*year 0-3:* linearly increasing from 0 to 1000 *year 4-5:* 1000	0.2 – 4 b.e.=2.1	0.5 – 10 b.e.=5.25	0.02 – 0.1 b.e.=0.06	0.02 – 0.1 b.e.=0.06
Extraction of peat	6 – 25	1000	*year 6-10:* 1000 *year 11-25:* linearly decreasing from 1000 to 300	0.2 – 4 b.e.=2.1	*year 6-7:* 0.5 – 10 b.e.=5.25 *year 8-25:* 0	*year 6-7:* 0.2 – 1 b.e.=0.6 *year 8-25:* linearly decreasing to 0.01 – 0.05 b.e.=0.03	0.2 – 1 b.e.=0.6
Working machines and transports	6 – 25	1 g/MJ peat		0		0	
Combustion of peat	6 – 25	93.5 g/MJ peat		0.005 g/MJ peat		0.006 g/MJ peat	

[*] The units for emissions from working machines, transports and combustion of peat are defined in the table

5.8.2 After-treatment – Afforestation

Table 3. *Emission ranges for CO_2, CH_4 and N_2O from ground processes and activities during after-treatment by afforestation. "b.e." means best estimate.*

Process/ Activity	**Year**	**CO_2 (g/m^2*year)**		**CH_4 (g/m^2*year)**		**N_2O (g/m^2*year)**	
		Extraction area	**Surrounding area**	**Extraction area**	**Surrounding area**	**Extraction area**	**Surrounding area**
Oxidation of remaining peat and other ground processes	26 – 300	*year 26-47:* 1000 *year 48-300:* 0	300	0	0	*year 26-47:* linearly decreasing from 0.1 – 0.5 b.e.=0.3 to 0.02 – 0.1 b.e.=0.06 *year 48-300:* 0.02 – 0.1 b.e.=0.06	0.14 – 0.7 b.e.=0.42
Accumulation of carbon in humus	26 – 300	*year 26-95:* -100 – -183 *year 96-300:* 0	*year 26-95:* -100 – -183 *year 96-300:* 0	x	x	x	x
Forest growth, emissions due to self-thinning are included	*low growth rate:* 26 – 125, 126 – 225, 226 – 300 *high growth rate:* 26 – 95, 96 – 165, 166 – 235 236 – 300	-414 – -1180 b.e.= -797	-414 – -1180 b.e.= -797	x	x	x	x
Combustion of forest biomass after felling	*low growth rate:* 126, 226 *high growth rate:* 96, 166, 236	33120 – 66080 b.e.=49600	33120 – 66080 b.e.=49600	x	x	x	x
Oxidation of roots and stumps	*low growth rate:* 126 – 145, 226 – 245 *high growth rate:* 96 – 115, 166 – 185 236 – 255	414 – 826 b.e.=620	414 – 826 b.e.=620	x	x	x	x

x = not relevant

5.8.3 After-treatment – Restoration of wetland

Table 4. *Emission ranges for CO_2, CH_4 and N_2O from ground processes during after-treatment by restoration of wetland. "b.e." means best estimate.*

Stage	**Year**	**CO_2 (g/m^2*year)**		**CH_4 (g/m^2*year)**		**N_2O (g/m^2*year)**	
		Extraction area	**Surrounding area**	**Extraction area**	**Surrounding area**	**Extraction area**	**Surrounding area**
Restored wetland	26 – 300	*year 26-31:* linearly increasing from 0 to -136 – -590 *year 32-300:* -136 – -590	*year 26-31:* linearly increasing from 0 to -136 – -590 *year 32-300:* -136 – -590	*year 26-45:* linearly increasing from 0 to 2 – 40 b.e.= 21 *year 46-300:* 2 – 40 b.e.= 21	*year 26-45:* linearly increasing from 0 to 2 – 40 b.e.= 21 *year 46-300:* 2 – 40 b.e.= 21	no data available	no data available

6 Greenhouse gas fluxes for coal, natural gas and forest residues

6.1 Coal

The direct (combustion) and indirect (production and transports) emissions from the coal fuel cycle are summarised in table 6.

Table 6. *Summary of greenhouse gas emission factors per MJ fuel for different stages in the coal fuel cycle (Uppenberg & Zetterberg, 1999).*

Greenhouse Gas	Indirect Emissions (g/MJ)	Direct Emissions (g/MJ)	Total Emissions (g/MJ)
CO_2	3.2	91	94.2
N_2O	-	0.012	0.012
CH_4	1.1	0.0005	1.1

6.2 Natural Gas

The direct (combustion) and indirect (production and transports) emissions from the natural gas fuel cycle are summarised in table 7.

Table 7. *Summary of greenhouse gas emission factors per MJ fuel for different stages in the natural gas life cycle (Uppenberg & Zetterberg, 1999). (b.e.= "best estimate")*

Greenhouse Gas	Indirect Emissions (g/MJ)	Direct Emissions (g/MJ)	Total Emissions (g/MJ)
CO_2	4.9	56	61
N_2O	0.0001	0.0005	0.0006
CH_4	0.003-0.41 (0.04 b.e.)	0.0001	0.003-0.41 (0.04 b.e.)

6.3 Forest residues

According to Zetterberg & Hansén (1998) the gross emissions from collecting and combusting forest residues are approximately 103 g CO_2/MJ; 0.0056 g CH_4/MJ and 0.005 g N_2O/MJ whereof 3 g CO_2/MJ come from the use of fossil fuels in forest machines. To calculate the net emissions of CO_2 one must also consider the decomposing of the forest residues that would have occured if they had been left on the ground. In Eriksson & Hallsby (1992) it is assumed as a rough approximation to estimate the climate impact of forest residues, that the forest residues are decomposed totally after 20 years and that the decomposition process is linear. Hyvönen et al. (2000) present a model for the decomposition based on empirical studies. The model describes an exponential decomposition process. This will result in a fast decomposition rate in the beginning but a slower rate after some years, and the process will continue for a long time, approaching zero. The net emissions of CO_2 over time for the use of forest residues for energy, based on both Eriksson and Hyvönen et al. are illustrated in figure 2 below. The model from Hyvönen et al. used here gives a halving of the initial carbon content in the forest residues after nine years. The model has been modified to give complete decomposition of the forest residues (no remaining carbon) after approximately 100 years. Other models suggest that the decomposition of organic matter in forest is not complete. Berg & Ekbohm (1993) e.g. developed a model based on asymptotic functions, indicating that 10 % of Scots pine needle litter is resistant to further decomposition. If this is true also for forest residues, the climatic impact of using forest biomass as fuel would be somewhat higher than calculated in this study.

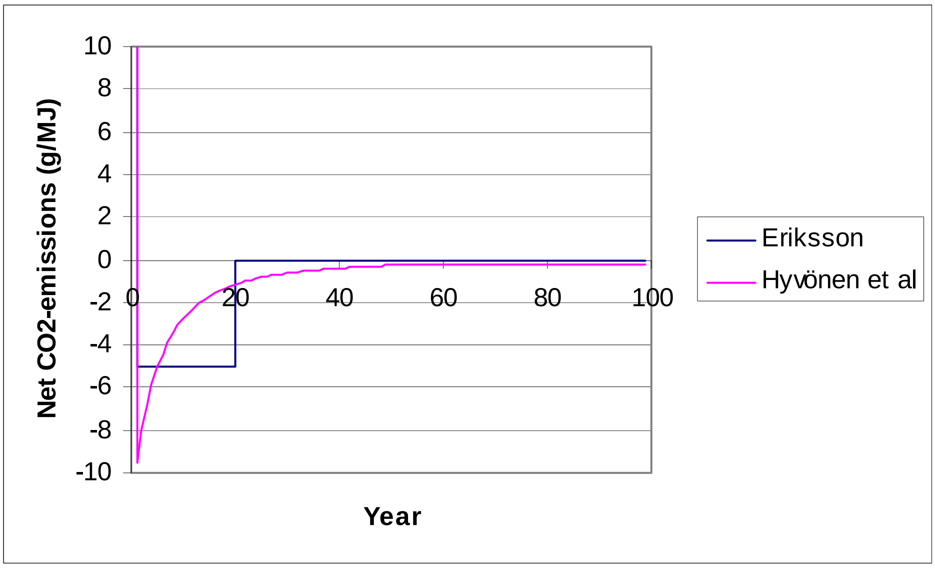

Figure 2. *Net emissions from the use of forest residues for fuel. Observe that the initial value (year0) for both scenarios should be 103 g/MJ. The range for the y-axis is decreased here to make it possible to see differences between the scenarios.*

The differences in climate impact from the use of forest residues for energy due to the different decomposition scenarios are displayed in figure 5 and 6 in section 7.1. As shown in these figures, the differences in climate impact due to different decomposition scenarios are marginal compared to the climate impact of the other fuels. Based on that result and with consideration to technical difficulties in the model implementation of Hyvönen et al. (2000), only the decomposition scenario according to Eriksson & Hallsby (1992) is used for comparison in the other result figures.

6.4 Discussion on oil

Oil is not included in the comparison of climate impact from the different fuels. The reason for this is that the fuels for the comparison were chosen to represent max and min values for net greenhouse gas emissions. Coal has the highest specific emissions of carbon dioxide while forest residues has the lowest. Above that, natural gas was included to represent greenhouse gas emissions in between the max and min values.

Fuel oil has a specific CO_2-emission of 76 g/MJ which puts it in between natural gas and coal (56 g CO_2/MJ and 91 g CO_2/MJ respectively) considering climate impact. This will result in a climate impact that will also lie in between natural gas and coal. So, to compare the results to oil, imagine a line in the diagrams between the lines for natural gas and coal, somewhat closer to coal than natural gas.

7 Results

In figure 3 and 4 below, instantaneous and accumulated radiative forcing from a strictly hypothetical scenario for peat utilisation without after-treatment is displayed and compared to the radiative forcing from the use of coal, natural gas and forest residues. For peat it is assumed that the emissions of all greenhouse gases will be zero after extraction has finished. That assumption will never be valid since the extracted peatland always will develop to form agricultural land, forest or wetland either by active cultivation or spontaneously, and the different options will result in different emission scenarios for greenhouse gases. The figures are displayed here only for comparison to the different after-treatment scenarios to show how the after-treatment affects the total climate impact from peat utilisation.

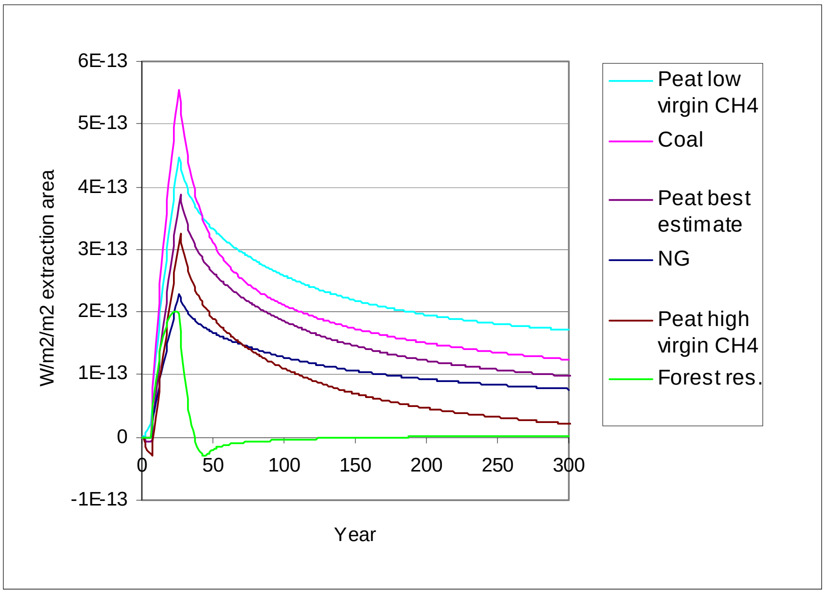

Figure 3. *Instantaneous radiative forcing from the use of coal, peat, natural gas and forest residues for energy. Emissions assumed to be zero after year 25. The amount of energy produced with coal, natural gas and forest residues is the same as the amount of energy produced from 1 m^2 peatland.*

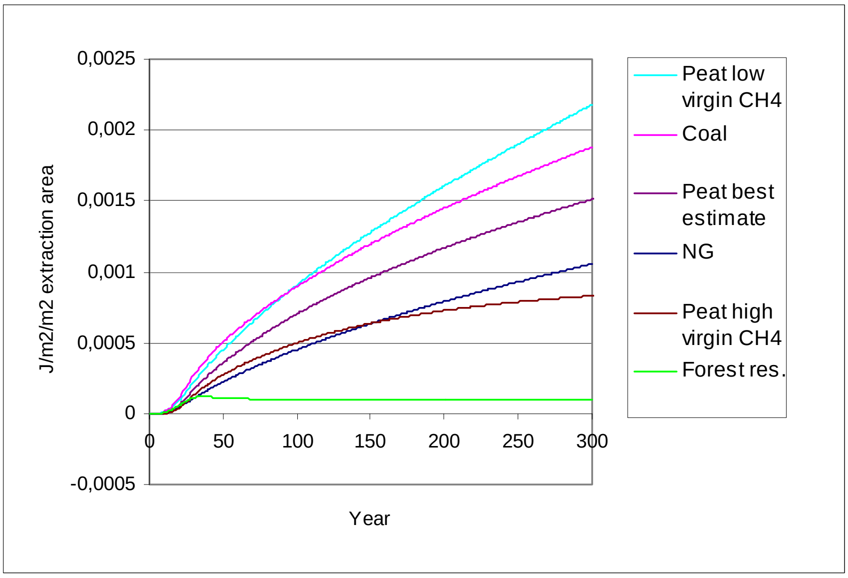

Figure 4. *Accumulated radiative forcing from the use of coal, peat, natural gas and forest residues for energy. Emissions assumed to be zero after year 25. The amount of energy produced with coal, natural gas and forest residues is the same as the amount of energy produced from 1 m^2 peatland.*

7.1 Peatland – forestry energy scenario

A comparison between best estimate for the peatland - forestry scenario and the other different fuel systems are presented in figure 5, 6 and 7 below as instantaneous and accumulated radiative forcing. Figure 7 shows radiative forcing per MJ energy produced. Equal amounts of energy are produced and the timing of energy use is the same in the different fuel systems.

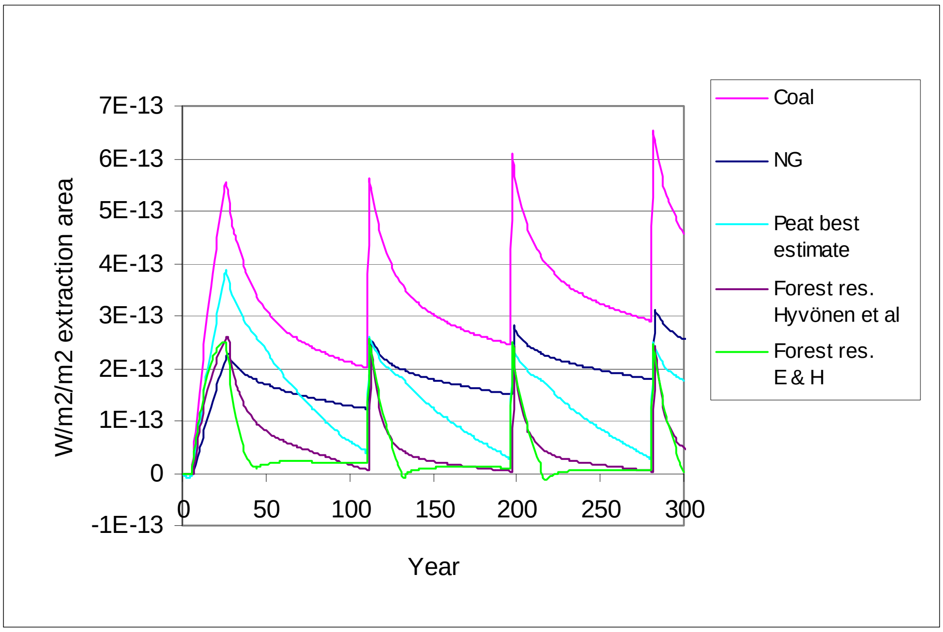

Figure 5. *Instantaneous radiative forcing from the use of coal, peat, natural gas and forest residues for energy. The amount of energy produced with coal, natural gas and forest residues is the same as the amount of energy produced by 1 m^2 peat area at different stages of the peatland – forestry scenario. Best estimate for forest growth is 6.5 m^3/ha*year.*

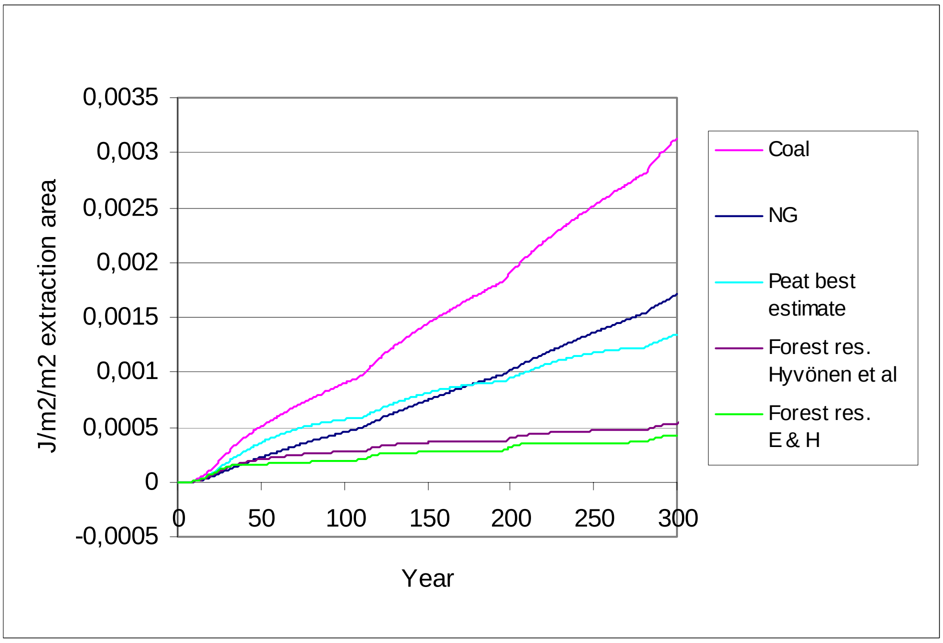

Figure 6. *Accumulated radiative forcing from the use of coal, peat, natural gas and forest residues for energy. The amount of energy produced with coal, natural gas and forest residues is the same as the amount of energy produced by 1 m^2 peat area at different stages of the peatland – forestry scenario. Best estimate for forest growth is 6.5 m^3/ha*year.*

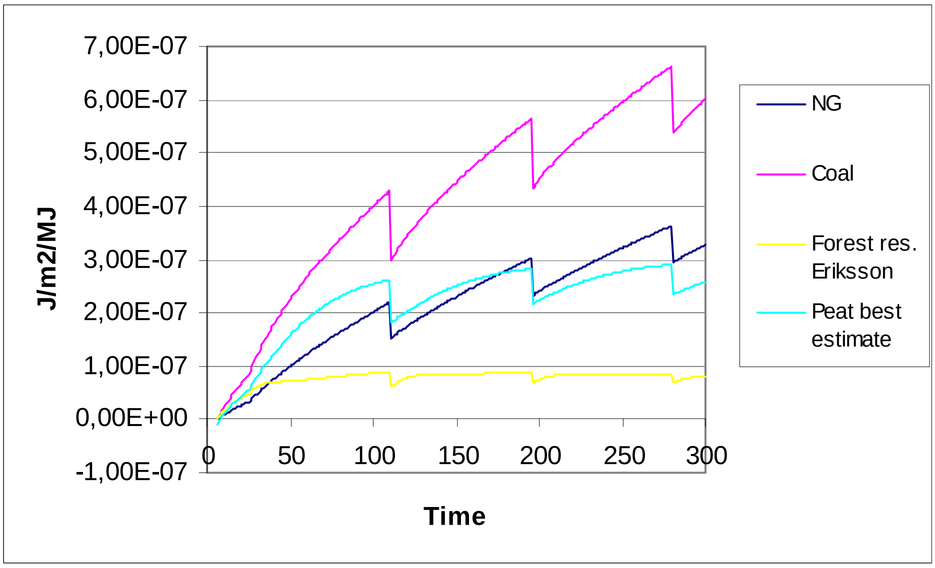

Figure 7. *Accumulated radiative forcing from the use of coal, peat, natural gas and forest residues for energy, per MJ energy produced. The amount of energy produced with coal, natural gas and forest residues is the same as the amount of energy produced by 1* m^2 *peat area at different stages of the peatland – forestry scenario. Best estimate for forest growth is 6.5* m^3*/ha*year.*

The instantaneous radiative forcing from peat lies between the radiative forcing from natural gas and coal during the extraction of peat, but the fact that forest is grown on the peat area after extraction makes the radiative forcing from peat decrease faster than from natural gas. The instantaneous radiative forcing from peat is equal to natural gas after approximately 70 years and approaching the radiative forcing from forest residues at the end of the first forest generation. In year 111, the forest is cut down and combusted making the radiative forcing increase instantaneously. The accumulated radiative forcing from peat is approximately equal to natural gas after 180 years and approximately 20 % lower than natural gas after 300 years. Figure 6 shows that the there is a marginal difference in climate impact between the two emission scenarios for forest residues.

The accumulated emissions of the three greenhouse gases CO_2, CH_4 and N_2O from the peat system are displayed in figure 8 below. The radiative forcing from CO_2, CH_4 and N_2O respectively is shown in figure 9.

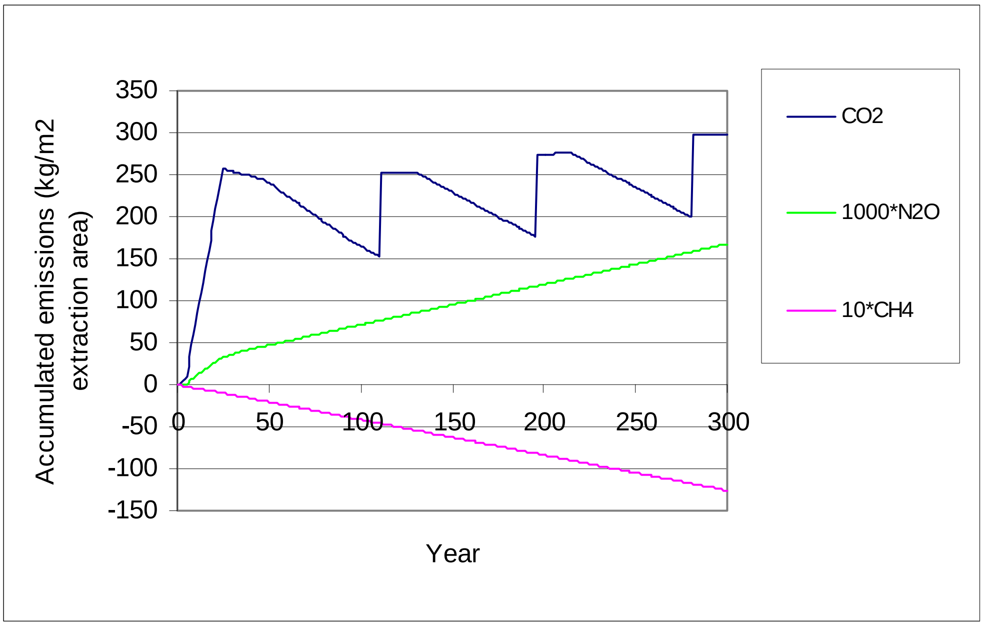

Figure 8. *Accumulated emissions of CO_2, CH_4 and N_2O from the use of 1 m^2 mire in the peatland – forestry energy scenario with forest growth rate 6.5 m^3/ha*year.*

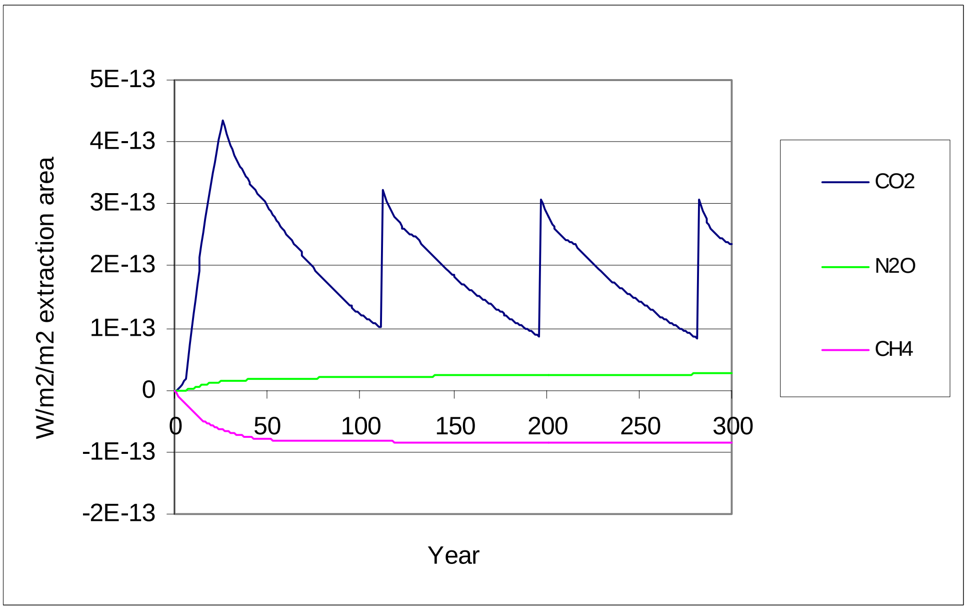

Figure 9. *Instantaneous emissions of CO_2, CH_4 and N_2O from the use of 1 m^2 mire in the peatland – forestry energy scenario with forest growth rate 6.5 m^3/ha*year.*

The negative emissions and radiative forcing from methane is due to the fact that the mire has been drained which has substantially reduced the methane emissions.

7.1.1 The importance of forest growth rate

The differences in accumulated radiative forcing from the peatland – forestry energy scenario depending on different CO_2-uptake rates in the forest that is planted after extraction, is shown in figure 10 and 11.

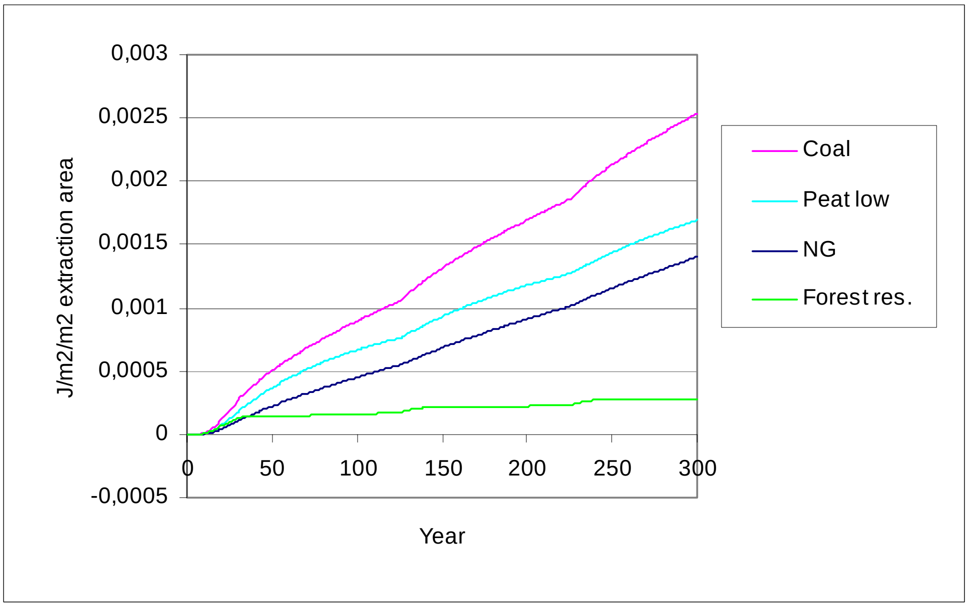

Figure 10. *Accumulated radiative forcing from the use of coal, peat, natural gas and forest residues for energy. The amount of energy produced with coal, natural gas and forest residues is the same as the amount of energy produced by 1 m^2 peat area at different stages. The forest growth rate is assumed to be low, corresponding to 3 m^3/ha*year.*

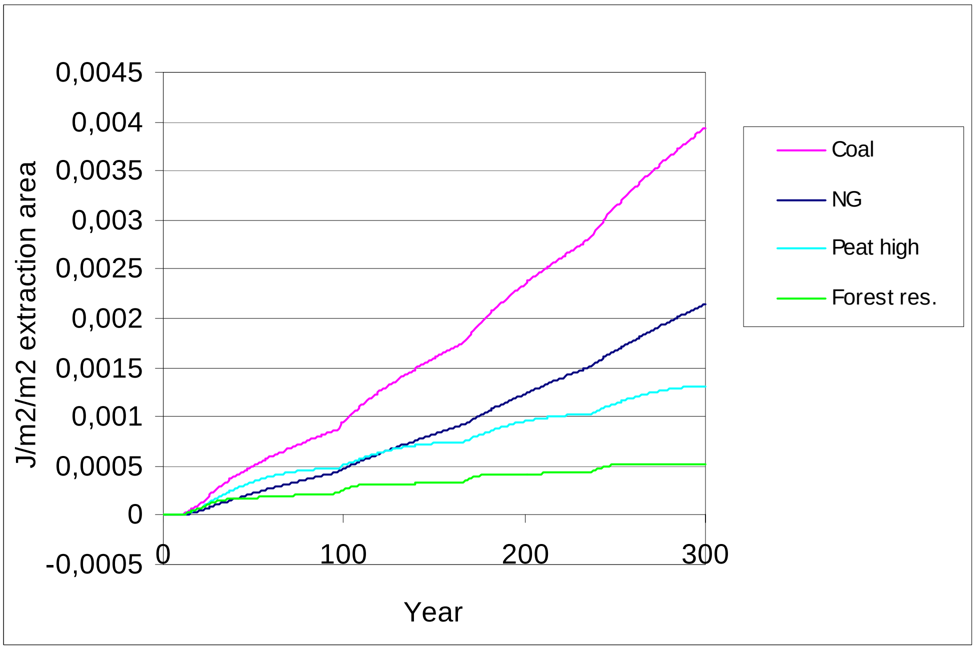

Figure 11. *Accumulated radiative forcing from the use of coal, peat, natural gas and forest residues for energy. The amount of energy produced with coal, natural gas and forest residues is the same as the amount of energy produced by 1 m^2 peat area at different stages. The forest growth rate is assumed be high, corresponding to 10 m^3/ha*year.*

If the forest that is planted after peat extraction accumulates carbon at a low rate ($3\ m^3$/ha*year), the long term accumulated radiative forcing from the use of peat lies in between coal and natural gas, closer to natural gas. If on the other hand the forest is assumed to accumulate carbon at a high rate ($10\ m^3$/ha*year), the accumulated radiative forcing from peat is equal to natural gas after 120 years and approximately 1/3 lower than natural gas after 300 years.

These examples are based on the assumption that forest is planted and grows at the same rate on both the extraction area and the surrounding area. Different growth rates for the extraction and surrounding area will result in a climate impact in between best and worst case. Assuming for example that the forest on the surrounding area will have a low growth rate while the extraction area will have a high growth rate (depending on differences in ground properties) makes the climate impact similar to best estimate.

7.1.2 The importance of methane emissions from virgin mires

The accumulated radiative forcing assuming different emission rates of CH_4 from virgin mires is displayed in figure 12.

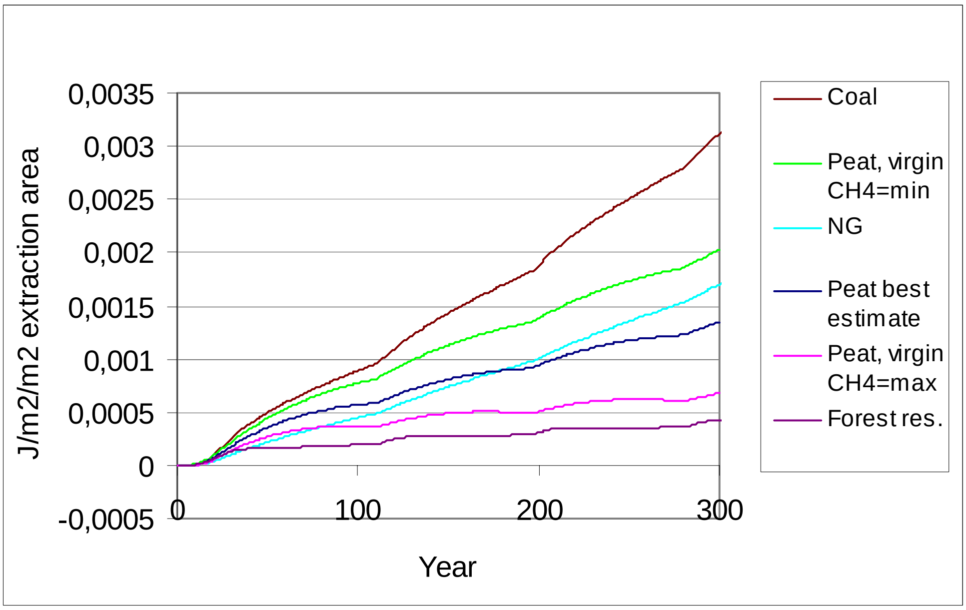

Figure 12. *Accumulated radiative forcing for different emission rates of CH_4 from virgin mires.*

When a mire is drained, the methane emissions from a virgin mire is dramatically reduced. Therefore, using a mire for peat extraction means avoiding a certain amount of methane emissions. The differences in long term accumulated radiative forcing between “best case” and “worst case” depending on methane emissions from virgin mires are approximately ± 50 % compared to best estimate. Very high methane emissions from virgin mires (best case) makes the accumulated radiative forcing from peat lie between forest residues and natural gas (closer to forest residues), while very low methane emissions (worst case) makes the long term accumulated radiative forcing from peat lie between natural gas and coal (closer to natural gas).

7.1.3 The importance of nitrous oxide emissions

The accumulated radiative forcing assuming different emission rates of N_2O from ground processes during the entire study period is displayed in figure 13.

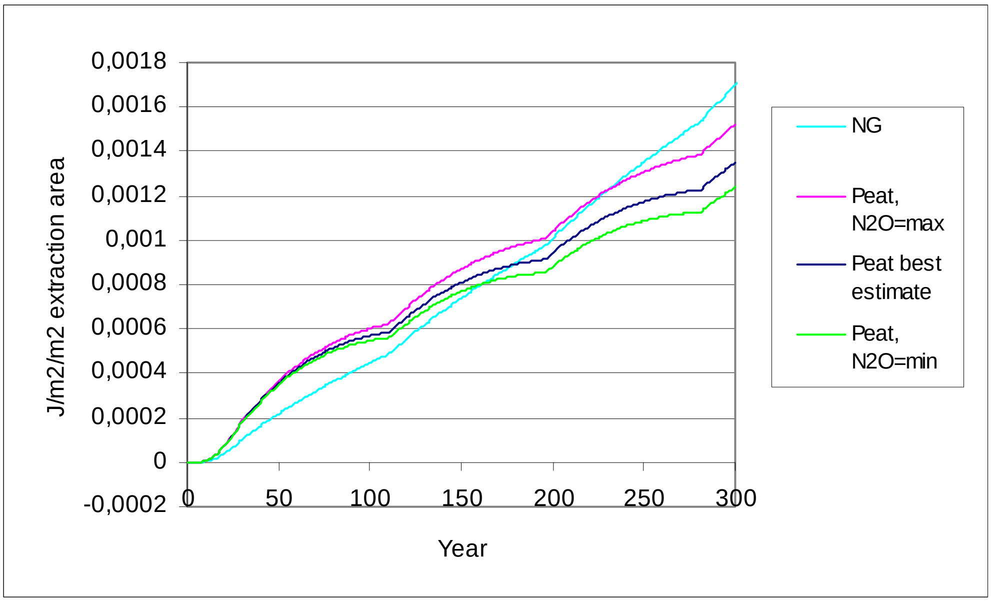

Figure 13. *Accumulated radiative forcing for different emission rates of N_2O from ground processes.*

The differences in long term accumulated radiative forcing between "best case" and "worst case" depending on nitrous oxide emissions from ground processes during extraction and afforestation are approximately ± 10 % compared to best estimate.

7.1.4 Summary of the results

The simulated climate impact of peat utilisation with afforestation as after-treatment, depends significantly on the assumed growth rate of the trees and the assumed original methane emissions from the virgin mire (emissions that are avoided when the mire is drained).

A "best-best-case" scenario (i.e. with high growth rate combined with high (avoided) methane emissions) will generate accumulated radiative forcing comparable to using forest residues for energy production. The "best-best-case" scenario is constructed by combining *Peat high* in Figure 11 with *Peat, virgin CH4=max* in Figure 12, and is not displayed explicitly in a figure.

A "worst-worst-case" scenario, with low growth rate and low (avoided) methane emissions, will generate radiative forcing somewhere in between natural gas and coal (closer to coal). The "worst-worst-case" scenario is constructed by combining *Peat low* in Figure 10 with *Peat, virgin CH4=min* in Figure 12, and is not displayed explicitly in a figure.

The best-case figures for methane emissions from virgin mires are very high and not representative as average values. For forest growth rate, however, the best-case figures are not at all unlikely to achieve according to Hånell (pers. comm.), on the condition that wood ashes are returned to the forest ground as fertilisation (no nitrogen fertilisation is assumed). The growth rate can, according to Hånell, under favourable growth conditions even be higher than the best-case scenario in this study.

The “best-best-case” and “worst-worst-case” scenarios described above are to be considered as extreme values for the climate impact of peat utilisation. It is unlikely that those conditions will occur very often. The “normal” climate impact of peat utilisation will lie somewhere in between the extreme values.

7.2 Peatland – wetland energy scenario

A comparison of radiative forcing from the peatland – wetland energy scenario and the other different fuel systems are presented in figure 14 and 15 below as instantaneous and accumulated radiative forcing respectively. For the peatland – wetland scenario, there is no "best-estimate" scenario displayed since there are great uncertainties connected to carbon uptake in restored wetlands. Equal amounts of energy are produced in all the different systems.

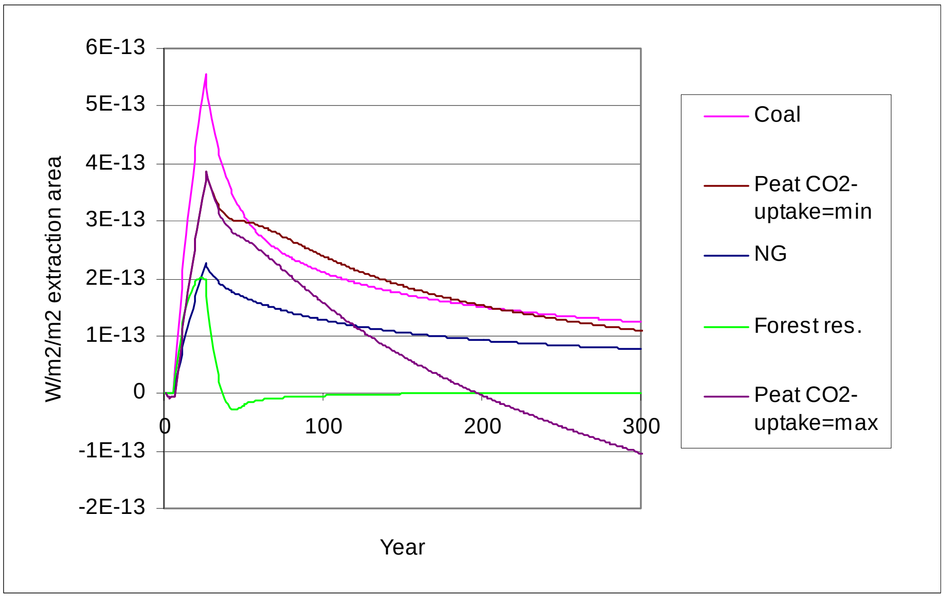

Figure 14 *Instantaneous radiative forcing from the use of coal, peat, natural gas and forest residues for energy. The amount of energy produced with coal, natural gas and forest residues is the same as the amount of energy produced by 1 m^2 peat area at different stages.*

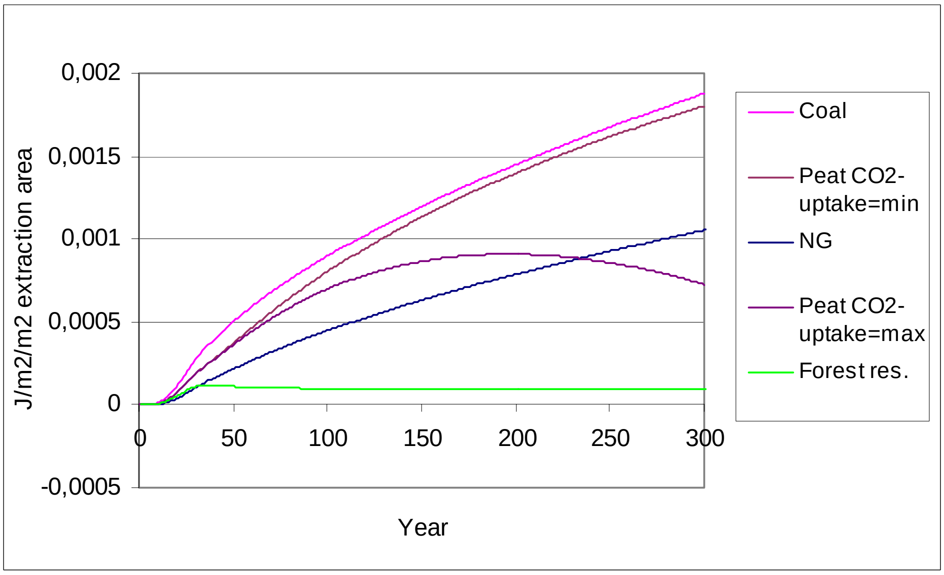

Figure 15 *Accumulated radiative forcing from the use of coal, peat, natural gas and forest residues for energy. The amount of energy produced with coal, natural gas and forest residues is the same as the amount of energy produced by 1 m^2 peat area at different stages.*

Looking at instantaneous radiative forcing (figure 14), the low value for carbon uptake rate in the wetland makes the potential climate impact from peat similar to coal over the entire study period. The high value for carbon uptake rate makes peat comparable to natural gas after approximately 120 years and the radiative forcing reaches zero after 200 years and continues to decrease below zero thereafter. With the high carbon accumulation rate, all the CO_2 emitted during peat extraction will have been accumulated again after approximately 300 years. The negative instantaneous radiative forcing after 300 years follows from the avoided methane emissions during extraction and the beginning of wetland restoration.

The results for accumulated radiative forcing (figure 15) also show that the potential climate impact from peat is comparable to coal if the low carbon uptake rate for the restored wetland is used. With the high carbon uptake rate however, accumulated radiative forcing from peat is comparable to natural gas after approximately 225 years and decreases below natural gas at the end of the study period.

The differences in long term accumulated radiative forcing between “best case” and “worst case”, depending on the magnitude of carbon uptake in the restored wetland, are approximately ± 50 % compared to the mean value.

The accumulated emissions of the three greenhouse gases CO_2, CH_4 and N_2O from the peat system are displayed in figure 16 below. The radiative forcing from CO_2, CH_4 and N_2O respectively is shown in figure 17.

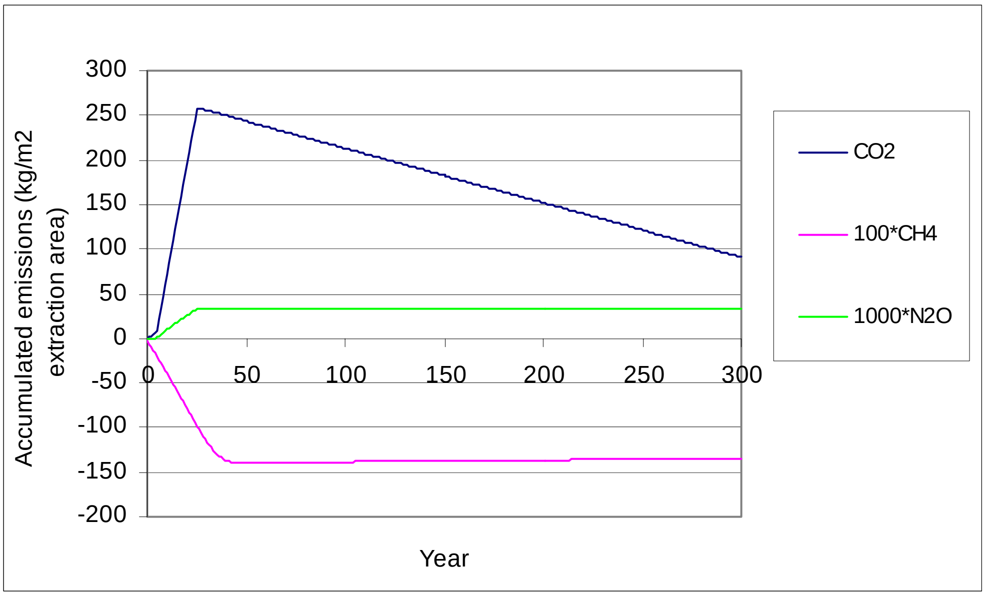

Figure 16. *Accumulated emissions of CO_2, CH_4 and N_2O from the use of 1 m^2 mire for peat production. Observe that the CH_4 and N_2O emissions are multiplied by 10 and 1000 respectively, in order to make them visible in the diagram. Carbon accumulation in the restored wetland assumed to be a mean value of high and low carbon uptake rate.*

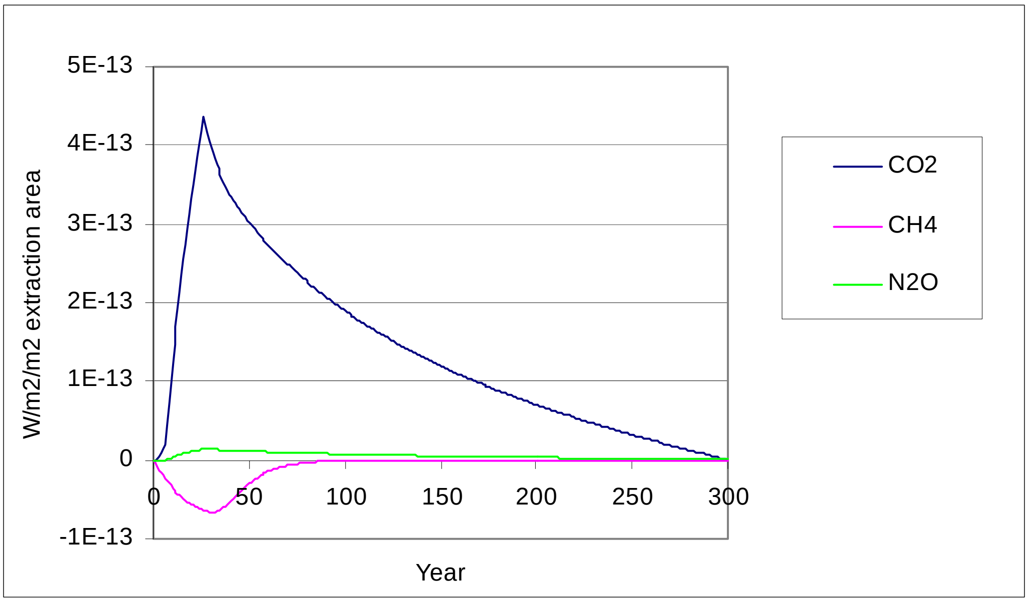

Figure 17. *Instantaneous radiative forcing from the emissions of CO_2, CH_4 and N_2O connected to the use of 1 m^2 mire for peat production. Carbon accumulation in the restored wetland assumed to be a mean value of high and low carbon uptake rate.*

The negative emissions and radiative forcing from methane during the first 25 years depend on the fact that methane emissions from the virgin mire have been substantially reduced because of the drainage of the mire. The restoration of wetland is assumed to cause increasing methane emissions again. After 50 years, the net methane emissions from the restored wetland compared to virgin mires are assumed to be zero.

7.2.1 The importance of methane emissions from restored wetland

The differences in instantaneous and accumulated radiative forcing from the peat system depending on different CH_4-emission rates from the restored wetland is shown in figure 18 and 19.

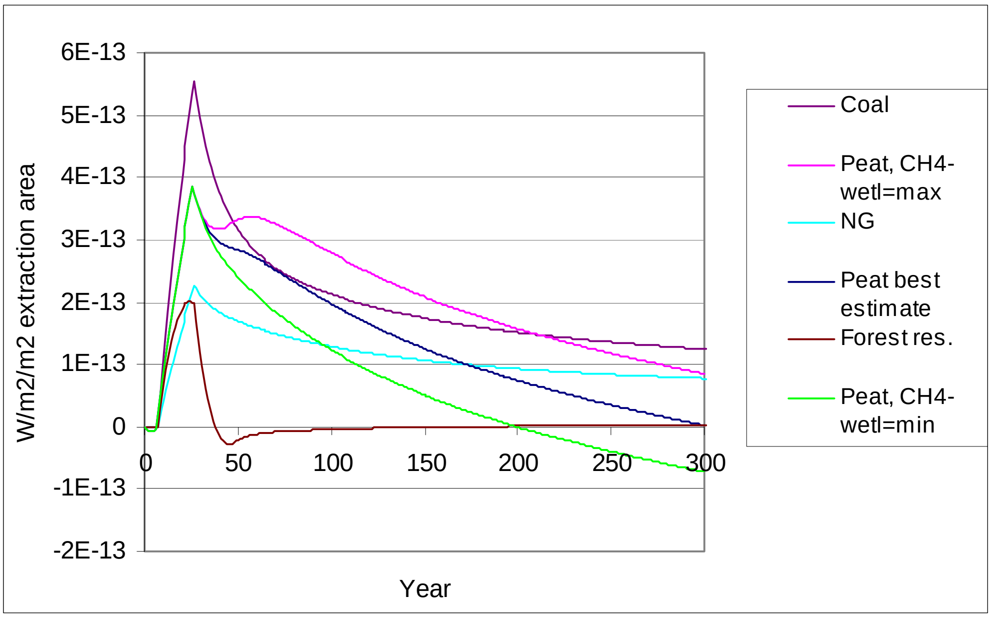

Figure 18. *Instantaneous radiative forcing for different emission rates of CH_4 from the restored wetland.*

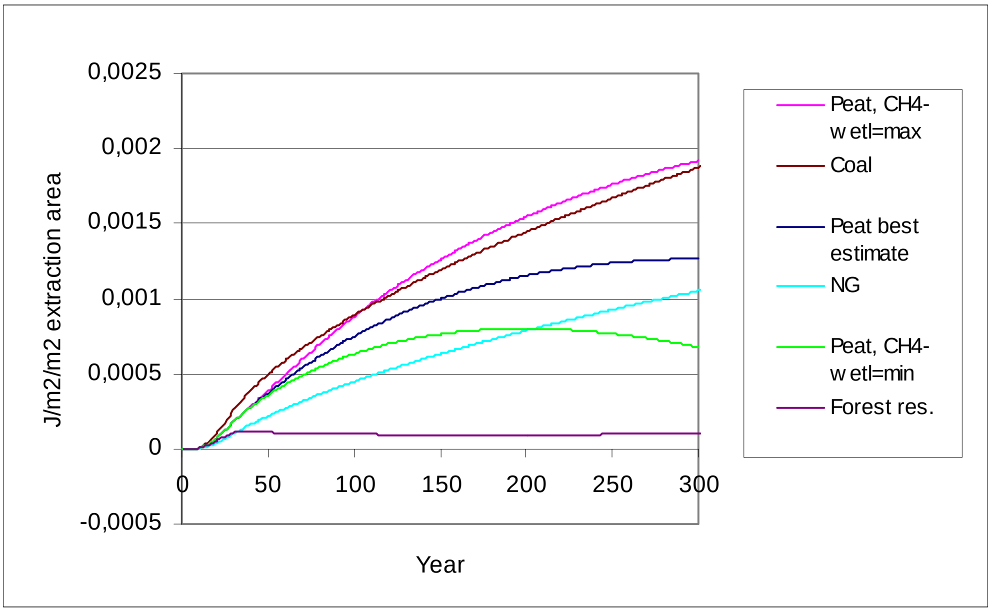

Figure 19 *Accumulated radiative forcing for different emission rates of CH_4 from the restored wetland.*

The differences in long term accumulated radiative forcing between “best case” and “worst case” depending on the magnitude of methane emissions from the restored wetland are approximately ± 50 % compared to best estimate (mean value for carbon uptake rate and “best estimate” for methane emissions). A very low CH_4-emission rate makes the accumulated radiative forcing from peat equal to natural gas at year 200 and about 2/3 of natural gas after 300 years. A very high CH_4-emission rate makes the accumulated radiative forcing from peat lie close to coal.

7.2.2 The importance of methane emissions from virgin mires

The instantaneous and accumulated radiative forcing assuming a mean value for carbon uptake rate and different emission rates of CH_4 from virgin mires are displayed in figure 20 and 21.

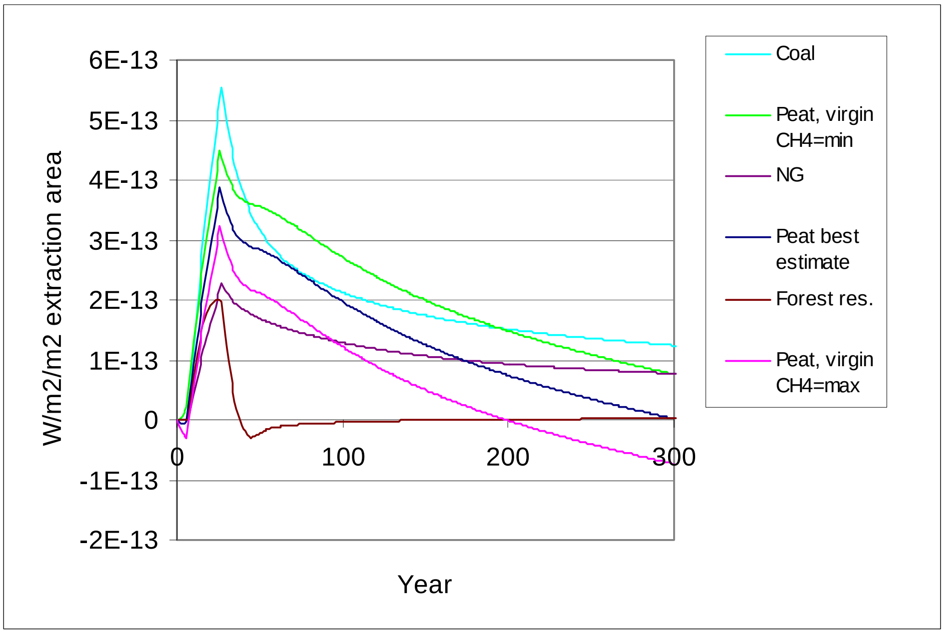

Figure 20. *Instantaneous radiative forcing for different emission rates of CH_4 from virgin mires. Mean value for carbon uptake rate assumed.*

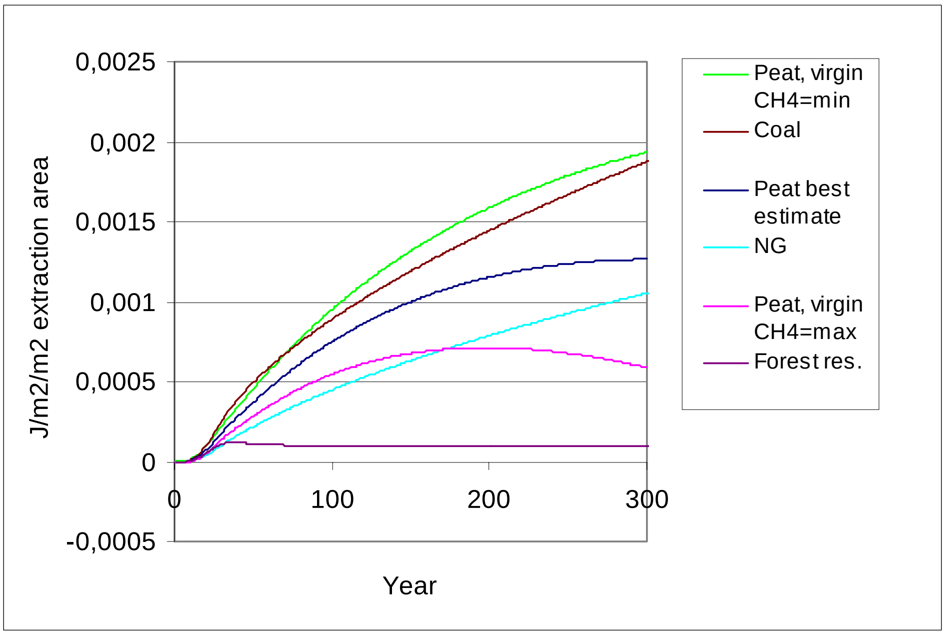

Figure 21. *Accumulated radiative forcing for different emission rates of CH_4 from virgin mires. Mean value for carbon uptake rate assumed.*

When a mire is drained, the methane emissions from a virgin mire is dramatically reduced. Therefore, using a mire for peat extraction means avoiding a certain amount of methane emissions. The differences in long term accumulated radiative forcing between “best case” and “worst case” depending on the magnitude of methane emissions from virgin mires are approximately ± 50 % compared to best estimate. A very high CH_4-emission rate makes the accumulated radiative forcing from peat equal to natural gas at year 170 and less than 2/3 of natural gas after 300 years. A very low CH_4-emission rate makes the accumulated radiative forcing from peat lie close to coal.

7.2.3 Summary of the results

The simulated climate impact of peat utilisation with restoration of wetland as after-treatment, is significantly dependent on the CO_2-uptake rate in the wetland as well as (avoided) methane emissions from the virgin mire and methane emissions from the restored wetland.

If we assume that a high CO_2-uptake rate is combined with high (avoided) methane emissions from the virgin mire and low methane emissions from the restored wetland (a really “best-best-case”), this will generate an accumulated radiative forcing comparable to natural gas in a 100-year perspective. After that the accumulated forcing will start to decrease, reaching zero after approximately 240 years. The “best-best-case” scenario is constructed by combining *Peat* CO_2*-uptake=max* in Figure 15 with *Peat, CH4-wetl=min* in Figure 19 and *Peat, virgin* CH_4*=max* in Figure 21, and is not displayed explicitly in a figure. The two last options can possibly be seen as contradictive to some degree if the peatland is not managed during the whole after-treatment period.

If on the other hand a “worst-worst-case” is assumed (i.e. with a low CO_2-uptake rate combined with low (avoided) methane emissions from the virgin mire and high methane emissions from the restored wetland), this will generate an accumulated radiative forcing higher than coal over the entire time period. The “worst-worst-case” scenario is constructed by combining *Peat* CO_2*-uptake=in* in Figure 15 with *Peat, CH4-wetl=max* in Figure 19 and *Peat, virgin* CH_4*=min* in Figure 21, and is not displayed explicitly in a figure.

The “best-best-case” and “worst-worst-case” scenarios described above are to be considered as extreme values for the climate impact from the peatland – wetland energy scenario. It is unlikely that those conditions will occur very often. The “normal” climate impact of peat utilisation with restoration of wetland as after-treatment will lie somewhere in between the extreme values. The data quality in this study for methane emissions and accumulation of carbon in a new, restored wetland is however unsatisfactory. The range in carbon uptake rate used here is very wide and the data are uncertain. The results for restoration of wetland as after-treatment are therefore to be considered more uncertain than for afforestation.

8 Discussion

The results from this study show that the range for radiative forcing from peat utilisation can be very large. This is also confirmed by the fact that previous studies on climate impact from peat utilisation have come to different conclusions, depending on the assumptions made for methane emissions from virgin mires, carbon uptake in forest biomass etc. Savolainen et al. (1994) state that the climate impact from peat utilisation is comparable to coal, Rodhe & Svensson (1995) compares peat to fossil oil, in Zetterberg & Klemedtsson (1996) peat is comparable to fossil oil or natural gas and in Åstrand et al. (1997) peat is comparable to forest residues. The sensitivity analysis performed in this study is an attempt to find the parameters that are most significant for the climate impact.

It is however very complex to calculate the climate impact from peat utilisation since there are many uncertainties in data and assumptions that can affect the results in different ways that have not been assessed here. Some examples are:

- A higher assumed extracted peat depth would for example increase the relative climate impact, while a decreased depth would decrease the climate impact. This is because the increased peat extraction depth decreases the peatland area needed to produce a given amount of energy, and the decreased area lowers the amount of avoided methane emissions.
- The original state of the mire that is utilised will have a significant impact on the results. If for example a forest-drained mire is utilised, the results will become quite different because of the original emissions of such a mire (no methane emissions, emission of carbon dioxide due to peat oxidation).
- No range in carbon dioxide emissions due to peat oxidation has been investigated here (a “worst case” was assumed). Lower emissions from peat oxidation would decrease the climate impact relative the other fuels.
- Different options for the use of the forest biomass produced on the utilised peatland has not been studied here (we assumed that all the harvested forest biomass will be used for energy production). The climate impact from peatland-forestry utilisation would increase relative the other fuels if a lower fraction of the forest biomass was assumed to be used for energy production.

9 Conclusions

Previous studies of the climate impact from peat utilisation state that the climate impact can be comparable both to coal (Savolainen et al, 1994) and fossil oil (Rodhe & Svensson, 1995) as well as comparable to forest residues (Åstrand et al, 1997). The range between the different previous results is large. The results from the present study show that all these scenarios are possible depending on the characteristics of the specific mire. For the peatland – forestry energy scenario, the climate impact is highly dependent on the methane emissions from the virgin mire, as well as the growth rate of the forest planted after peat extraction has finished. For the peatland – wetland energy scenario, the climate impact is highly dependent on the methane emissions from the virgin mire and the CO_2-uptake rate and methane emissions of the restored wetland. It is possible and recommended to take mire characteristics and after-treatment alternatives into consideration when planning peat utilisation, in order to minimize the climate impact. Such analyses in the planning-stage could be made quite easily with the help of a model similar to the one used in this study combined with an emission database for different mire types and after-treatment alternatives.

The calculated accumulated radiative forcing from the peatland – forestry energy scenario is comparable to natural gas in a 180-year perspective, and between forest residues and natural gas in a longer perspective (300 years) assuming what is here called “best estimate” for forest growth rate and original methane emissions from the virgin mire.

The calculated accumulated radiative forcing from the peatland – wetland energy scenario, will lie between coal and 2/3 of natural gas in a 300-year perspective, depending on the assumed carbon uptake rates for the wetland and assuming what is here called “best estimate” for methane emissions from a restored wetland.

There are great uncertainties related to the data used for emissions and uptake of greenhouse gases in restored wetlands. The most important factors to consider in that matter are emissions of methane, uptake of CO_2 and how these two parameters will change over time. The mechanisms affecting these parameters in a restored wetland should be studied further.

The importance of N_2O-emissions from soil processes on the climate impact from peat utilisation, have often been discussed (e.g. at the hearing mentioned in section 1). The results from this study show that the magnitude of these emissions can affect the result by approximately ± 10 %, but also that they are of minor importance compared to carbon uptake rate during after-treatment and methane emissions from virgin and restored mires.

All fuel systems studied here, except one, will generate an accumulated radiative forcing that is increasing over time. The only exception is the peatland – wetland energy scenario with a high carbon uptake rate in the restored wetland, where the results show that the accumulated radiative forcing will start to decrease after 200 – 250 years (as a result of that the instantaneous radiative forcing decreases below zero). It is however very difficult to predict how carbon uptake and methane emissions in a restored wetland will develop over time why these results are uncertain.

10 Recommendations for minimizing the climate impact from peat utilisation

- It is important to consider methane emissions from the virgin mire when choosing mires for utilisation. High original methane emissions will result in a significantly lower total climate impact than if we assume low original emissions (see 5.1 for definitions of high and low emissions). In order to minimize the climate impact one should preferably choose mires with high methane emissions for utilisation.

- If afforestation is chosen as after-treatment strategy, the goal should be to achieve a high forest growth rate, both for the extraction area and the surrounding area. A high forest growth rate gives lower climate impact than a low forest growth rate (see 5.5 for definitions of high and low growth rates). This is because in the peatland-forestry scenario a considerable fraction of the energy is produced with wood. A high forest growth rate increases this fraction.

- The results from this study shows that restoration of wetland can reduce the climate impact from peat utilisation substantially. That is, however, based on the assumption that the CO_2-uptake rate of the wetland is high and that the methane emissions from the restored wetland remains on a quite low level. Those factors should be considered in the planning of the restoration.

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