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The Contribution to the Greenhouse Effect from the Use of Peat and Coal for Energy

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Summary

Emissions and uptake of greenhouse gases have been estimated for the production and combustion of peat in four Swedish regions. Net emissions have been defined as the sum of emissions and uptake from mining, loading, transportation, combustion and forestation of the peat land minus emissions from the virgin peat land. Cropping of the forested peat land is not considered. Net CO_2-emissions from the production and combustion of peat is estimated to be 87 g/MJ in the regions *Bergslagen* and *Småland*, 99 g/MJ in *Härjedalen* and 95 g/MJ in *Västerbotten kustland.* Net N_2O-emissions are estimated to be 66 mg/MJ for all regions. Due to the natural methane emissions from a virgin peat bog, the production and combustion of peat reduces net CH_4-emissions by 0.9 g CH_4/MJ peat. A hypothetical case has been studied where all the drained peat areas are forested (instead of about half of the area as it is today). According to this scenario the net CO_2-emissions are reduced from 87 g to 57 g CO_2/MJ peat for Bergslagen. As a comparison, CO_2-emissions from the combustion of coal are ca 92 g CO_2/MJ.

Based on the emissions inventory the contribution to the greenhouse effect has been calculated in terms of the contribution to atmospheric radiative forcing. The net average contribution to radiative forcing over 100 years from the production and combustion of peat from Bergslagen is estimated to be ca 117 aW/m2/MJ *). Corresponding values for Småland, Härjedalen and Västerbotten kustland are 116, 125 and 123 aW/m2/MJ respectively. Using coal as an energy source is estimated to lead to a radiative forcing of ca 145 aW/m2/MJ as an average over 100 years. The dominating post for the peat cases is the combustion which contributes to ca 102 aW/m2/MJ. The reduction of natural CH_4-emissions from virgin peat land leads to a reduction in radiative forcing of ca 18 aW/m2/MJ as a 100 year average. Forestation of the mined peat bog leads to a further reduction in the radiative forcing corresponding to ca 19 aW/m2/MJ. If all the drained peat areas where forested (instead of half as it is today) this would reduce the radiative forcing from 117 to 100 aW/m2/MJ on average over 100 years.

In conclusion, the contribution to the greenhouse effect from the use of peat for energy from Southern Sweden (Småland and Bergslagen) is ca 20 % lower than the contribution from coal, counted as an average over 100 years after the mining starts. Corresponding figures for Northern Sweden (Härjedalen and Västerbotten kustland) is ca 15 % lower than coal.

Cropping of the forest is estimated to increase the contribution to radiative forcing from the peat cases. However, in the study, the effect of cropping has not been quantified.

*) 1 aW/m2/MJ = 10^{-18} W/m2/MJ

A scenario has been studied where the background atmospheric concentrations of greenhouse gases increase over the next 100 years (carbon dioxide from 355 to 560 ppmv, methane from 1714 to 2000 ppbv and nitrous oxide from 311 to 390 ppbv). Compared to the earlier cases where the backgound concentrations were assumed to be constant, the radiative forcing from both peat and coal is reduced, on average over 100 years, by ca 20 %. The ratio between peat and coal, however, is approximately the same.

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1. Introduction

This report presents a study to quantify the contribution to the greenhouse effect for the production and combustion of Swedish peat and compare the results with coal. The study has been financed by Vattenfall Utveckling AB and by the Swedish Environmental Protection Agency (Naturvårdsverket).

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2. Objectives and methodology

2.1 Objectives

The purpose of this report is to quantify the contribution to the greenhouse effect for the use of Swedish peat as an energy source and compare the results with coal. Based on these results the fuel with the least contribution to the greenhouse effect should be identified.

2.2 Methodology

The analysis is done in two steps:

- Emissions inventory. This inventory includes fluxes (emissions and uptake) of greenhouse gases during the different phases within the life cycle of the fuel. These phases are defined in the emissions inventory chapter.
- Assessment of the impact on the greenhouse effect. Based on the emissions inventory the impact on the greenhouse effect is calculated in terms of the contribution to radiative forcing.

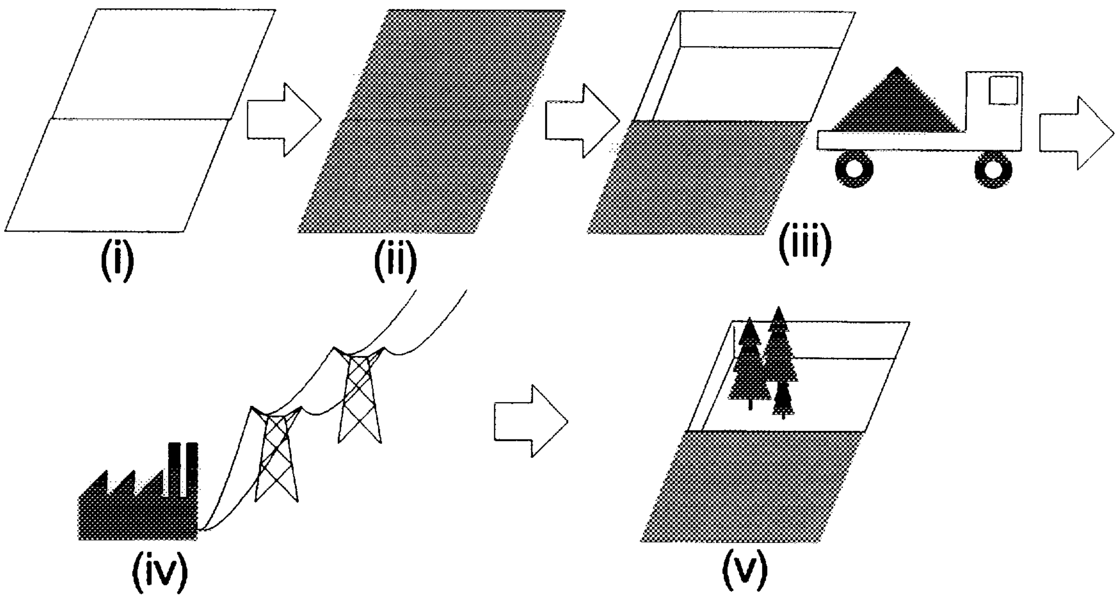


Figure 1. The stages involved in the production of peat today.

Two peat cases and one coal case have been considered:

Case 1. Peat today: This case describes peat mining as it is performed in Sweden today. The stages involved are illustrated in figure 1. Starting from a virgin peat bog (i), the area is drained (ii). It should be noted that the area that is drained is about twice the size of the area that later is mined (iii). The peat is combusted to produce electricity and heat (iv) and finally the mined area is forested (v). In this scenario we don't consider cropping of the forest, but assume that the forest is left standing.

Case 2. Peat modified.: This case is equivalent to *Peat today* but with the difference that the area that not mined is also forested.

Case 3. Coal today: This case describes the use of coal for the production of electricity and heat as it is done today. We have considered the stages mining, transportation and the combustion of coal.

The peat cases have been performed for four different regions in Sweden.

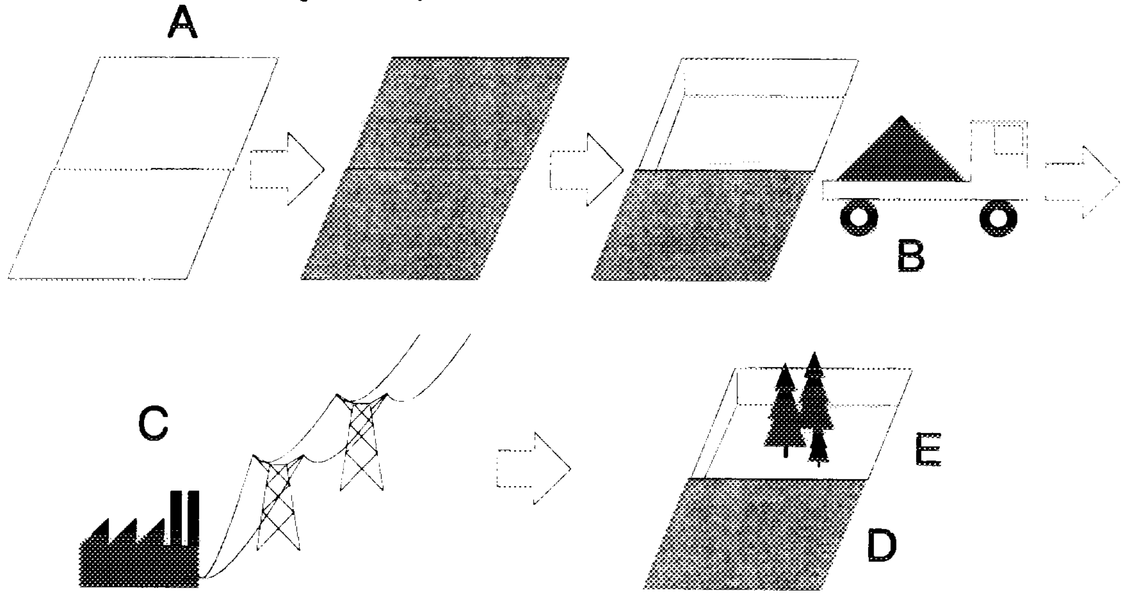
3. Fluxes of greenhouse gases for peat and coal

In this chapter flux inventories of emissions and uptakes of CO_2, N_2O and CH_4 are presented for the three cases.

3.1 Case 1. *Peat today*

3.1.1 Definition of system and conditions

Figure 2 illustrates the emissions and uptakes of greenhouse gases that have been considered in the case peat today.



A. Virgin peat land
Uptake of carbon, emissions of CH_4 and N_2O from virgin peat land.

B. Mining, loading and transportation of peat
Emissions of CO_2, CH_4 and N_2O from Mining, loading and transportation of peat.

C. Combustion of peat
Emissions of CO_2, CH_4 and N_2O from the combustion of peat.

D. Drained, but not mined peat areas.
Uptake of CO_2 in natural forest growth, emissions of CO_2 from oxidation of ground carbon, "uptake" of CH_4 due to oxidation of CH_4 and emissions of N_2O from soil processes.

E. Forestation of drained and mined areas
Forestation on drained, and mined peat areas: Uptake of CO_2 in growing biomass, emissions of CO_2 from oxidation of remaining peat, accumulation of ground based carbon in humus and litter, "uptake" of CH_4 due to oxidation of CH_4 and emissions of N_2O from soil processes.

Figure 2. Fluxes of greenhouse gases in the case peat today.

We define the net emissions of greenhouse gases from case *peat today* as:

Net emissions = -A+B+C+D+E

Furthermore, we assume the following conditions (Rodhe and Svensson, 1994):

- Peat depth 1,4 m
- Dry weight 8 %
- Peat density: 1000 kg/m3 => 112 kg peat/m2
- Energy content: 20 MJ/kg ts = 2240 MJ/m2 => 1000 MJ corresponds to 0.446 m2
- Drained at t=0 years, production at t=0 to 20 years, forestation at t=20 years.
- Combustion of peat is spread out over 20 years (t= 0 - 20)
- The total area drained is twice as large as the mined area.

3.1.2 Fluxes from A. Virgin peat land

This post includes fluxes of CO_2, CH_4 and N_2O from an area of the same type and equally large as the peat production area. Since the peat production area includes equal sizes of i) drained and harvested and ii) drained and not harvested peat land this reference area is twice the size of the drained and harvested area.

CO_2-uptake

According to Rodhe and Svensson (1994) the uptake of CO_2 in a peat bog is ca 13 g C/m2a. We wish to express the fluxes from the virgin peat land in units of flux per mined area. This conversion is done by multiplying the fluxes from the virgin peat land by a factor two. This gives us 13 g $C/m2_{virgin\ peat\ area}/a$ = 13*2 $C/m2_{mined\ area}/a$. In units of energy this is equivalent of 11.6 mg C/MJ peat.

CH_4-emissions

According to Savolainen et. al., 1994 CH_4-emissions from an untouched bog are approximately 7 g/m2a. Rodhe and Svensson (1994) estimates the CH_4-emissions to be 10 g/m2a. Using Rodhe and Svensson gives us 10 g $CH_4/m2_{virgin\ peat\ area}/a$ = 10*2 g $CH_4/m2_{mined\ area}/a$. In units of energy this is equivalent to 8.9 mg CH_4/MJ peat.

N_2O-emissions

Silvola (personal communication 1995) estimates N_2O-emissions from an untouched bog to be not higher than 0.004 g N_2O/m2a. We assume that we have 0.001 g $N_2O/m2_{virgin\ peat\ area}/a$ = 0.001*2 g $N_2O/m2_{mined\ area}/a$. In units of energy this is equivalent of 0.001 mg N_2O/MJ peat.

3.1.3 Fluxes from B. Transport, mining, loading

CO_2-emissions

Savolainen et. al. (1994) estimated CO_2-emissions from stockpiles, harvesting and machines to be ca 2.2 g CO_2/MJ. According to *Vattenfall Utveckling* transport, mining and loading of peat requires approximately the equivalent of 1.3 % of the mined peat as oil (Eriksson, S-O, personal communication 1996). In this report we use this figure to calculate the corresponding CO_2-emissions. 1.3 % of mined peat energy is equivalent to 0.013*2240 MJ/m2 = 29.1 MJ/m2. Oil emits ca 77 g CO_2/MJ, or counted as CO_2-C 21.0 g C/MJ. This gives us the total amount of CO_2 emitted from transport, mining and loading to be 21.0*29.1 = 611.5 g C/m2. In units of peat energy this is equivalent to 273 mg C/MJ. Spread out over 20 years this gives us 30.6 g C/m2a or 13.6 mg C/MJa.

N_2O-emissions

Burning of oil emits 2 mg N_2O/MJ (IVL, 1990). The total N_2O-emissions can then be calculated to be 29.1*0.002 = 0.057 g N_2O/m^2 or counted in units of energy 0.025 mg N_2O/MJ. If this emission is spread out over 20 years this gives us 0.003 g N_2O/m^2a or 0.0013 mg N_2O/MJa.

CH_4-emissions

Use of oil for energy purpose emits (including production and combustion) 0.055 g/MJ (Levander 1989). The total CH_4-emissions can then be calculated to be 29.1*0.055= 1,57 g CH_4/m^2 or 0.7 mg CH_4/MJ. If this emission is spread out over 20 years we have 0.078 g CH_4/m^2a or 0.035 mg CH_4/MJa

3.1.4 Fluxes from C. Combustion of peat

CO_2-emissions

According to the Swedish Environmental Protection Agency the combustion of peat releases the equivalent of 220 kg CO_2/m^2 = 107 g CO_2/MJ (Naturvårdsverket, 1992). Rodhe and Svensson estimated the CO_2-emission from the combustion of peat to be ca 200 kg CO_2/m^2 = 90 g CO_2/MJ (Rodhe and Svensson, 1994). This value is also stated by Vattenfall (Eriksson, S-O, personal communication 1996). In this report we use the value of 200 kg CO_2/m^2, which counted as CO_2-C is equivalent to 54.5 kg C/m^2 or in units of energy 24500 mg C/MJ. Spread out over 20 years this corresponds to 2725 g C/m^2a or 1225 mg C/MJa.

N_2O-emissions

We assume that the peat is fired in a fluidized bed boiler and use an emission factor of 60 mg/MJ (Lars-Erik Åmand, 1995), which counted per square meter peat is equivalent to 135 g N_2O/m^2. If we spread this emission over 20 years gives us 3.0 mg N_2O/MJa or 6.7 g N_2O/m^2a.

It should be noted that recent results from a 12 MW CFB indicate that significant reductions (ca 75 %) in N_2O-levels can be achieved for both coal and peat firing by "reverse air staging" without NO_x, SO_x or CO penalty.

CH_4-emissions

We assume the combustion takes place in a fluidized circulating bed and estimate the CH_4-emissions to be similar to those from the combustion of coal, ca 1 mg/MJ (EPA, 1993). In units of mined peat area this corresponds to 2.24 g CH_4/m^2. Spread out over 20 years this gives us 0.050 mg CH_4/MJa or 0.11 g CH_4/m^2a.

3.1.5 Fluxes from D. Drained, but not mined peat areas

We assume that the size of this area is equivalent to the area that is drained and mined.

CO_2-emissions due to oxidation of remaining peat

Based on measurements, Silvola (personal communication 1995) has estimated that a drained peat bog emits CO_2 corresponding to ca 270 g C/m^2a. This it assumed to be a result of oxidation of remaining peat. The emission has been observed to stay at this level for about 10 years, but it is very uncertain what then happens.

In this report we use the value of 270 g C/m2a for the first 10 years. We then assume that the emissions decrease exponentially toward zero so that the average flux over the first 100 years is 85 g C/m2a. This gives us:

0 - 10 years:	270 g C/m2a or 121 mg C/MJ	
10 - 100 years:	270*exp(-0,0458*(t-10)) g C/m2a	or
	121*exp(-0.0458(t-10)) mg C/MJ	
after 100 years:	0	

CO_2-uptake due to forestation

Peat areas that are drained, but not mined will have a certain forest development and thus an accumulation of carbon. In Rodhe and Svensson, 1994 this accumulation has been estimated to 2 kg C/m2 over a 100 year period. Spread out over a 100 year period this corresponds to 20 g C/m2a or 8.9 mg C/MJa.

N_2O-emissions

Based on measurements done on 30 year birch forest in Falköping, IVL has estimated N_2O-emission values to be of the order of 0.2 - 0.5 g N_2O/m2a. These values will probably decrease to values typical for forest land, i.e. 0.005 - 0.010 g N_2O/m2a (IVL, internal material 1995).

In this report we use the value of 0.2 g N_2O/m2a for the first 30 years (equivalent to 0.09 mg N_2O/MJ). After 30 years we use the value 0.0075 g N_2O/m2 (equivalent to 0.003 mg N_2O/MJ).

CH_4-oxidation

Based on measurements in an established forest at Lake Gårdsjön (Kasimir and Klemedtsson personal communication, 1996) and reforestation of agricultural land (Priemé personal communication, 1995) we estimate CH_4-uptake due to oxidation to be ca 0.025 g CH_4/m2a during the first 30 years and then increasing to stabilise around a value of ca 0.2 g CH_4/m2a after ca 80 years.

We use the value of 0.025 g CH_4/m2a for the first 30 years. We then assume that the uptake increases linearly to reach 0.2 CH_4/m2a after 80 years and stabilising at this level. This gives us:

0 -30 years:	-0.025 g CH_4/m2a or -0.011 mg/MJ
30 to 80 years:	-0.025 +0.0035*(t-30) g CH_4/m2a or
	-0.011-0.0016(t-30) mg/MJ
After 80 years:	-0.2 CH_4/m2a or -0.09 mg/MJ

3.1.6 Fluxes from E. Forestation of drained and mined areas

After mining, the area is forested. We have considered four regions in Sweden: *Småland*, *Bergslagen*, *Härjedalen* and *Västerbotten kustland*.

CO_2-fluxes due to forestation

We consider three CO_2-fluxes: i) uptake of carbon in growing biomass, ii) oxidation (emission) of remaining peat and iii) accumulation of ground carbon (in humus) due to litter fall.

Uptake of carbon in growing biomass

Hånell has estimated the forest production on a mined peat area, assuming that the production rate is comparable to the average production rate in the area (Hånell, 1995). The stem wood harvest in the four regions is estimated to be:

Småland	365 m^3sk/ha, 70 y. life cycle
Bergslagen	366 m^3sk/ha, 80 y. life cycle
Härjedalen	137 m^3sk/ha, 90 y. life cycle
Västerbotten kustland	209 m^3sk/ha, 100 y. life cycle

These values include stem wood and bark, but not branches, tops and roots. Biomass in thinnings is not included. According to Eriksson, 1991 in addition to stem wood biomass, branches and stumps biomass and roots biomass increase the total growing biomass by 25 % and 35 % respectively. For Bergslagen this gives us the total biomass in the tree at harvest to be 366*1.6 = 585.6 m^3 stem wood/ha. According to Eriksson 1 m^3 stem wood corresponds to 0.42 ton stem wood with a carbon content of 50 %. The total carbon content in the tree at harvest is thus 585.6*0.420*0.50 = 122.98 ton C/ha = 12 298 g C/m^2. In units of peat energy this is equivalent to a total carbon accumulation at harvest of 5490 mg C/MJ. Spread out on a 80 year life cycle this gives us 153.75 g C/m^2a or in units of energy 68.6 mg C/MJa.

Based on the values of sytem wood harvest from Hånell we can calculate corresponding fluxes in the three other regions:

Småland:

Accumulated carbon: 12 298*365/366 =	12 264 g C/m^2 = 5475 mg C/MJ
Spread out over 70 years life cycle:	175.2 g C/m^2a = 78.2 mg C/MJa

Härjedalen:

Accumulated carbon: 12 298*137/366 =	4 603 g C/m^2 = 2054 mg C/MJ
Spread out over 90 years life cycle:	51.1 g C/m^2a = 22.8 mg C/MJa

Västerbotten kustland:

Accumulated carbon: 12 300*209/366 =	7 022 g C/m^2 = 3134 mg C/MJ
Spread out over 100 years life cycle:	70.2 g C/m^2a = 31.3 mg C/MJa

N_2O-emissions

We use same values as for drained and not harvested peat land, i.e. 0.2 g N_2O/m^2a for the first 30 years (equivalent to 0.09 mg N_2O/MJ). After 30 years we use the value 0.0075 g N_2O/m^2 (equivalent to 0.003 mg N_2O/MJ).

CH_4-oxidation

We use same values as for drained and not harvested peat land, i.e.

0 -30 years:	-0.025 g CH_4/m^2a or -0.011 mg/MJ
30 to 80 years:	-0.025 -0.0035*(t-30) g CH_4/m^2a or -0.011 -0.0016*(t-30) mg/MJ
After 80 years:	-0.2 CH_4/m^2a or -0.09 mg/MJ

CO_2-emissions due to oxidation of remaining peat
We use same values as for drained and not harvested peat land, i.e.

0 - 10 years:	270 g C/m^2a or 121 mg C/MJ
10 - 100 years:	270*exp(-0,0458*(t-10)) g C/m^2a or 121*exp(-0.0458(t-10)) mg C/MJ
after 100 years:	0

CO_2-uptake due to accumulation of ground carbon in humus and litter
Alriksson and Olsson (1995) have studied the accumulation of ground based carbon on a very well drained agricultural land, planted with Norway spruce. 40 years after plantation the total amount of carbon in humus and litter corresponded to ca 19 ton C/ha. After 15 additional years no significant change could be observed, implicating that a quasi-equilibrium had been reached.

Ågren (personal communication 1995) suggests that based on model results from the so called Q-model the accumulation of ground based carbon in a forest of Norway spruce corresponds to ca 25 - 50 ton C/ha. Equilibrium conditions are reached after about three generations. This is in agreement with an estimate by Berg (1992), ca 50 ton C/ha, which has been calculated from decomposition rates for Norway spruce.

Based on the National Forest Survey, Alriksson and Eriksson (personal communication 1996) have estimated the average content of ground based carbon in the humus layer for different areas in Sweden. In the *Svealand* region, the average carbon content in moist forest soils is estimated to be ca 110 ton C/ha and in normal/moist forest soils ca 70 ton C/ha. For the rest of the country the average carbon content in normal/moist forest soils is estimated to be ca 45 - 103 ton C/ha, with higher values in the Southern parts. If we include litter, these values are increased by 5 - 10 %.

We suggest that the accumulation of ground carbon on forested peat land can best be compared with the accumulation in normal moist forest, and therefor estimate the total accumulation of ground based carbon in humus and litter on forested peat land will reach a value of ca 75 ton C/ha. It should noted, however, that this is a tentative estimate since the conditions on a forested peat area are not necessarily the same as in a normal moist forest.

In this report we assume that the level 75 ton C/ha is reached within 80 years (approximately one generation), and that we then have a quasi-balance between supply and consumption of carbon in humus and litter. In units of peat energy this is equivalent to 3.35 g C/MJ. If we assume that the yearly accumulation is constant during these 80 years, we can express the annual uptake of C to be ca 94 g C/m2a or 42 mg C/MJa.

We can note that the accumulation of carbon due to litter fall (75 ton C/ha) is of the same magnitude as the total amount of carbon emitted from oxidation of remaining peat (ca 85 ton C/ha) implicating that the net effect from these two posts is near to zero. However, it has been observed that in a more moist environment the accumulation of ground carbon will increase, but that the forest production will decrease. Since forests normally are managed towards drier conditions and increased production we estimate that it is more likely that the accumulation of ground carbon is lower than 75 ton C/ha rather than higher than this value. This implies that when adding the two posts ground carbon accumulation (from litter fall) and ground oxidation (from remaining peat) together, it is more likely that we have a net emission rather that a net accumulation of carbon.

3.1.7 Fluxes from Case 1. Peat today -Summary of emissions

Table 1 summarises fluxes of greenhouse gases from the case *Peat today.*

Table 1. Fluxes of greenhouse gases from the case *Peat today*. Fluxes are presented in units of mg/MJ peat. To convert into units of g/m^2 multiply by a factor 2.24.

	Emissions (mg/MJa)			Acc. em. 100 years (mg/MJ)		
	CO_2-C	CH_4	N_2O	CO_2-C	CH_4	N_2O
A. Virgin peat land	-11.6	8.9	0.001	-1160	890	0.1
B. Transport, mining, loading	0-20 y: 13.6	0-20 y: 0.035	0-20 y: 0.0013	273	0.7	0.025
C. Combustion	0-20 y: 1217	0-20 y: 0.050	0-20 y: 3.0	24330	1.0	60
D. Drained, but not mined peat areas						
Uptake in forest	0-100 y: -8.9 >100y: 0			-890		
Soil emissions	0-10 y: 121 10-100y: F1(t) >100y: 0	0-30 y: -0.011 30-80 y: F2(t) >80 y: -0.09	0-30 y: 0.09 >30 y: 0.003	3795	-4.7	2.9
E. Forestation						
Uptake in stem wood in:						
- Småland	20-90 y: -78.2			-5475		
- Bergslagen	20-100y: -68.6			-5490		
- Härjedalen	20-110y: -22.8			-2054		
- Västerbotten	20-120y: -31.3			-3134		
Soil emissions	0-10 y: 121 10-100y: F1(t) >100y: 0	0-30 y: -0.011 30-80 y: F2(t) >80 y: -0.09	0-30 y: 0.09 >30 y: 0.003	3795	-4.7	2.9
Accumulation of ground based carbon	0-100 y: -42 >100y: 0			-3348		
Sum: -A+B+C+D+E						
- Småland				23640	-898	66
- Bergslagen				23625	-898	66
- Härjedalen				27061	-898	66
- Västerbotten				25981	-898	66

F1(t)= 121*exp(-0.0458(t-10))
F2(t)= -0.011-0.0016(t-30)

Figures 3 to 5 show the emissions of CO_2, CH_4 and N_2O for the case *Peat today*, based on values in table 1 for Bergslagen. Figure 6 shows the accumulated CO_2-emissions over the period.

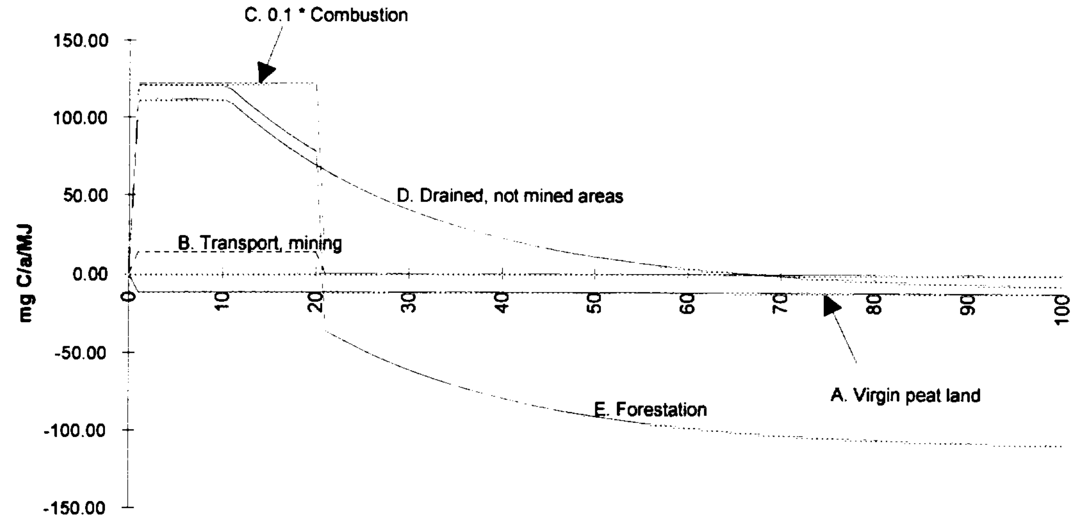


Figure 3. CO_2-emissions from the production and combustion of 1 MJ peat according to the case *Peat today*, in the region *Bergslagen* [g CO_2-C/MJ]. The post *C. Combustion* has been scaled down by a factor 10 in order to make the other posts visible.

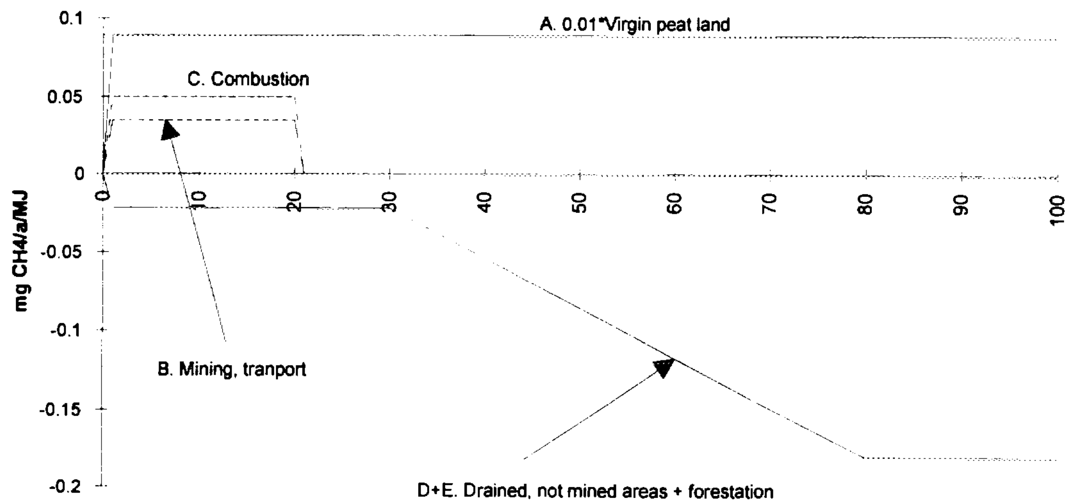


Figure 4. CH_4-emissions from the production and combustion of 1 MJ peat according to the case *Peat today*, in the region *Bergslagen* [g CH_4/MJ]. The post *A. Virgin peat land* has been scaled down by a factor 100 in order to make the other posts visible.

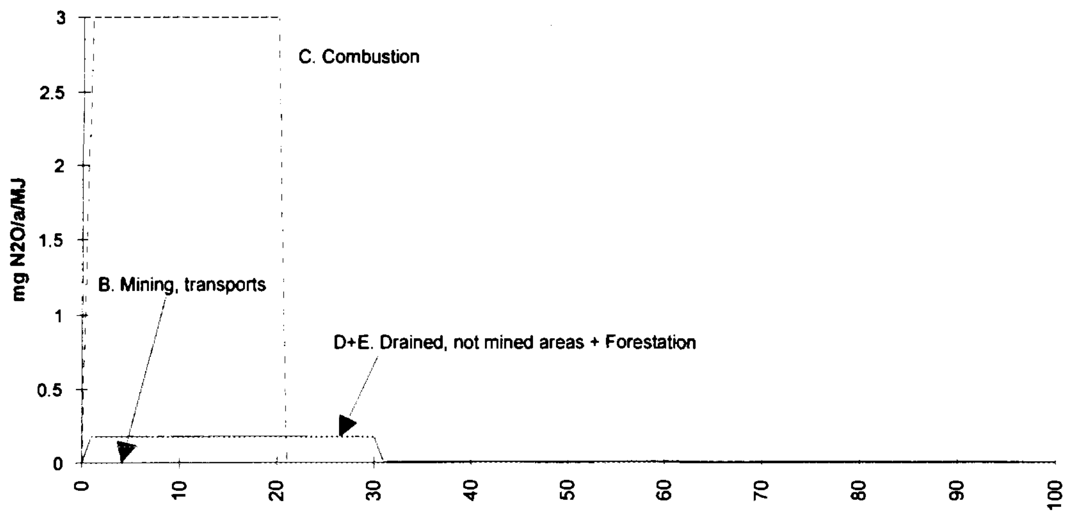


Figure 5. N2O-emissions from the production and combustion of 1 MJ peat according to the case *Peat today*, in the region *Bergslagen* [g N_2O/MJ].

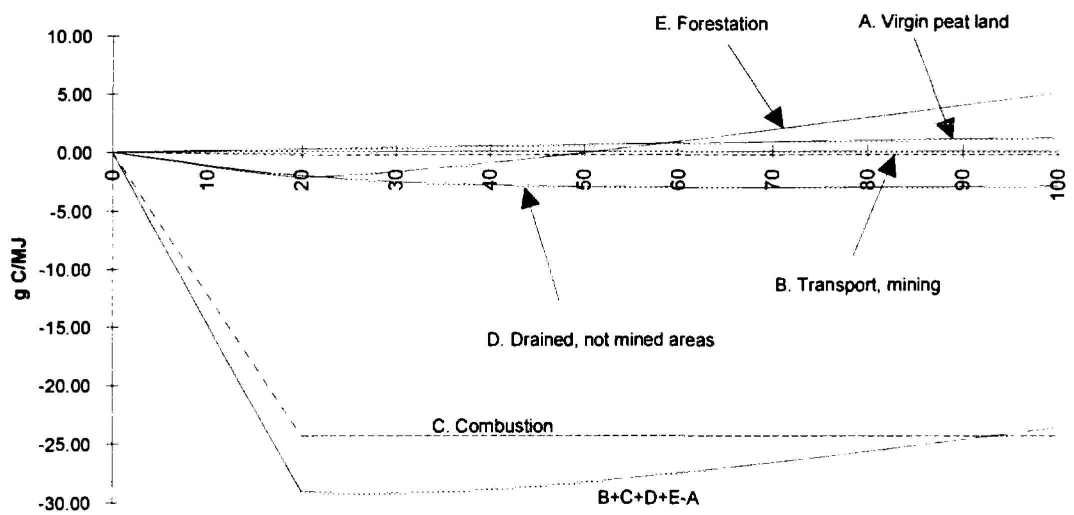


Figure 6. Accumulated CO2-emissions from the production and combustion of 1 MJ peat according to the case *Peat today*, in the region *Bergslagen* [g C/MJ].

3.1.8 Cropping of the forest

In our case peat today we have not considered cropping of the trees. There are here various possible scenarios. If the forest is not harvested the forest will reach a stage where the uptake of CO_2 is balanced by equally large emissions of CO_2 due to the decay of biomass, resulting in zero net CO_2 emissions. The carbon pool stored in the trees will remain as long as the trees are not harvested. Cropping of the trees will eventually lead to emissions of CO_2 corresponding to the carbon content in the harvested stem wood. If the wood is used for pulp production or for energy purposes the emissions will occur soon after harvest. Using the wood for construction purposes will hold the carbon fixed for a longer time, but as for pulp, the carbon will eventually be emitted as CO_2.

3.2 Case 2. *Peat modified*

This case is equivalent with the case peat today, but with the difference that the drained area that isn't mined is also forested. The net emissions from case *Peat modified* can therefor be expressed as:

Net peat emissions = -A+B+C+2*E

using the values from table 1. The resulting net emissions from case peat modified are presented in table 2. In this case we consider Bergslagen only.

Table 2. Case *Peat modified*: Net emissions of CO_2, N_2O and CH_4 from the use of peat during it's life cycle. In this case we assume that all drained area is harvested. To convert into units of g/m^2 multiply by a factor 2.24.

	Emissions (mg/MJa)			Acc. em. 100 years (mg/MJ)		
	CO_2-C	CH_4	N_2O	CO_2-C	CH_4	N_2O
A. Virgin peat land	-11.6	8.9	0.001	-1160	890	0.1
B. Transport, mining, loading	0-20 y: 13,6	0-20 y: 0.035	0-20 y: 0.0013	273	0.7	0.025
C. Combustion	0-20 y: 1217	0-20 y: 0.050	0-20 y: 3.0	24330	1.0	60
2*E. Forestation						
Uptake in stem wood	20-100y: -137 >100y: 0			-10980		
Soil emissions	0-10 y: 242 10-100y: F1(t) >100y: 0	0-30 y: -0.022 30-80 y: F2(t) >80 y: -0.18	0-30 y: 0.18 >30 y: 0.006	7590	-9.4	5.8
Accumulation of ground based carbon	20-100 y: -84 >100y: 0			-6696		
Sum: -A+B+C+2*E				15677	-898	66

F1(t)= 242*exp(-0.0458(t-10))
F2(t)= -0.022-0.0032(t-30)

3.3 Case *Coal today*

This case describes the use of coal for the production of electricity and heat as it is done today. We have considered the stages mining, transportation and the combustion of coal.

3.3.1 Mining

According to Levander, 1989, CH_4-emissions from mining of coal amounts to about 0.2 - 0.4 g/MJ. In this report we use the value 0.3 g/MJ.

3.3.2 Combustion

According to Levander CO_2-emissions from the combustion of coal is 92 g/MJ (Levander 1989). According to EPA emission factors from burning of coal in fluidized bed boiler CH_4-emissions are estimated to be are estimated to be 1 mg/MJ and N_2O-emissions 100 mg/MJ (EPA, 1993).

4. Assessment of the impact on the greenhouse effect

In this chapter, based on the emission inventories for the three cases *Peat today*, *Peat modified* and *Coal today* in chapter 3, the contribution to the greenhouse effect has been quantified using the concept *radiative forcing*. This concept is described in appendix A. The radiative forcing has been calculated using a model described in Zetterberg, 1993.

The emission inventories in the previous chapter are presented both as yearly emissions over the 100 year study period and as total emissions over the period. The radiative forcing has also been calculated as time dependent values, varying from year 0 to year 100. In order to enable comparison between the different cases in a single value the average radiative forcing over 100 years has also been calculated. As default we have assumed that the background atmospheric concentrations of greenhouse gases are unchanged over the study period. As a comparison, in the end of this chapter, we have presented a scenario where we assume changing background concentrations.

The radiative forcing is given in the unit aW/m2/MJ, which is equivalent of 10^{-18} W/m2/MJ.

4.1 Radiative forcing from case *Peat today*

Figures 7 and 8 show the calculated radiative forcing for the production and combustion of 1 MJ peat according to the case *Peat today* in *Bergslagen*. Figure 7 shows the contribution from different gases and figure 8 from the different activities. Based on these figures, table 3 shows the average radiative forcing integrated over 100 years.

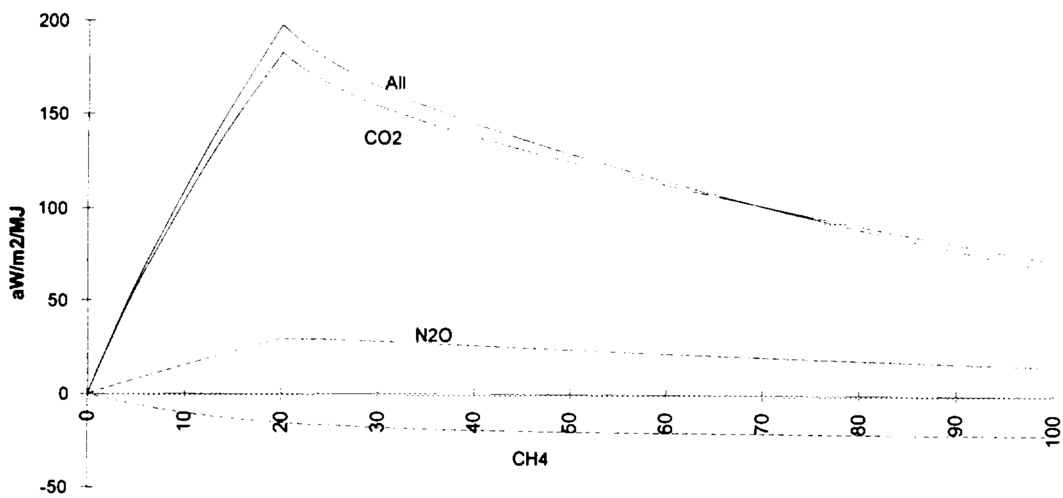


Figure 7. Calculated radiative forcing for the case *peat today (Bergslagen)*: the production and combustion of 1 MJ peat as it is done today. The contribution from each gas is shown. Values in aW/m2/MJ.

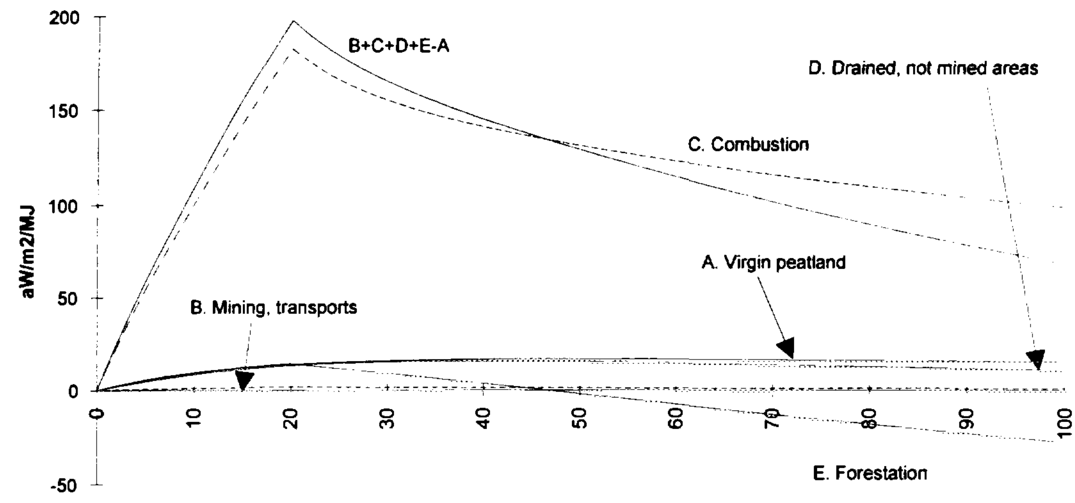


Figure 8. Calculated radiative forcing for the case *peat today (Bergslagen)*: the production and combustion of 1 MJ peat as it is done today. The contribution from each activity is shown. Values in $aW/m^2/MJ$.

Table 3. Average radiative forcing for the first 100 years for the case *peat today (Bergslagen)*. Values in $aW/m^2/MJ$.

	CO_2	CH_4	N_2O	**Sum**
A. Virgin peat land	-3	18	0.02	**15**
B. Mining, transport, loading	1	0.02	0.01	**1**
C. Peat combustion	102	0.02	19	**122**
D1. Drained, not mined areas, biomass uptake	-2			**-2**
D2. Drained, not mined areas, soil emissions	14	-0.08	0.9	**15**
E1. Forestation, biomass uptake	-12			**-12**
E2. Forestation, soil emissions	14	-0.08	0.9	**15**
E3. Forestation, ground C accum	-7			**-7**
B+C+D+E-A	**113**	**-18**	**21**	**117**

If we use the average radiative forcing over the 100 year period as a measure for comparison we can note that the dominating contribution to the total radiative forcing origins from CO_2-emissions from the combustion of peat (102 $aW/m^2/MJ$). The second largest post is the CO_2-emissions due to the oxidation of remaining peat (28 $aW/m^2/MJ$). The radiative forcing from N_2O-emissions from the combustion of peat is 19 $aW/m^2/MJ$.

Two factors reduce the total radiative forcing. The omission of CH_4-emissions from virgin peat land reduces the radiative forcing by 18 $aW/m^2/MJ$ on an average. Forestation leads to a reduction in the radiative forcing of 12 $aW/m^2/MJ$ due to uptake in stem wood and an additional 7 $aW/m^2/MJ$ due to the build up of carbon in the humus layer.

4.2 Radiative forcing from case *Peat modified*

When peat is mined today, a certain area is first drained. About half of this drained area is mined and later forested and the rest is left as it is. In this case we study a hypothetical scenario where we assume that all drained land is forested, i.e. both the mined and the unmined areas. Figure 9 shows the calculated radiative forcing for the case peat modified (Bergslagen), with the individual contribution from the different activities. Table 4 shows the average radiative forcing over 100 years for this case.

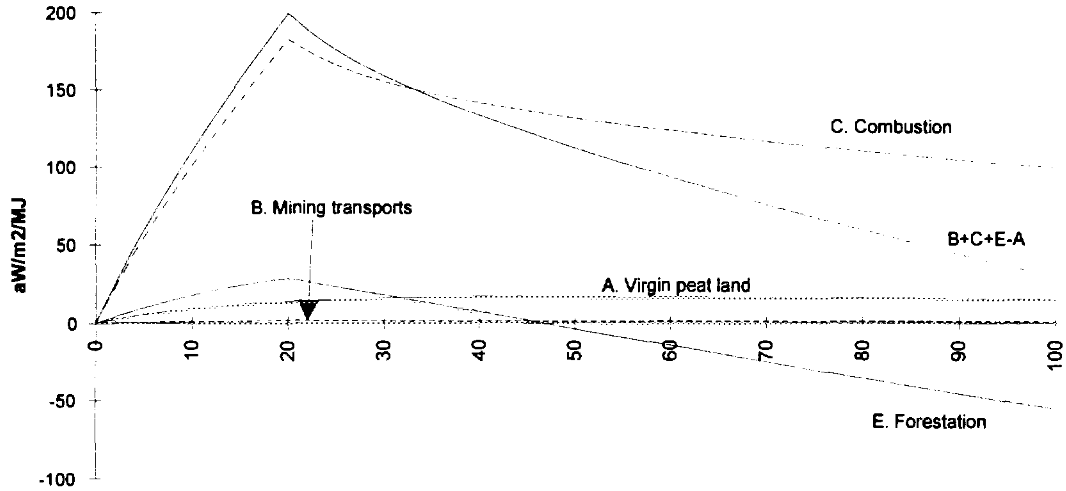


Figure 9. Calculated radiative forcing for the case *peat modified (Bergslagen)*: the production and combustion of 1 MJ peat assuming that all drained areas are forested. The contribution from each activity is shown. Values in $aW/m^2/MJ$.

Table 4. Average radiative forcing for the first 100 years for the case *peat modified.* Values in $aW/m^2/MJ$ peat.

	CO_2	CH_4	N_2O	**Sum**
A. Virgin peat land	-3	18	0.02	**15**
B. Mining, transport, loading	1	0.02	0.01	**1**
C. Peat combustion	102	0.02	19	**122**
E1. Forestation, biomass uptake	-24			**-24**
E2. Forestation, soil emissions	28	-0.16	1.8	**30**
E3. Forestation, ground C accum	-15			**-15**
B+C+E-A	**97**	**-18**	**21**	**100**

From the figure and table we can note that compared to the case *Peat today* we have a larger reduction of radiative fording due to forestation and a subsequent reduction of the total radiative fording from this case *Peat modified.* Integrated over a 100 years the case *Peat modified* leads to a 14 % lower contribution to radiative forcing than the case *Peat today.*

4.3 Radiative forcing from case coal today

Figure 10 shows the calculated radiative forcing for the case coal today, with the individual contribution from different greenhouse gases. Table 5 shows the average radiative forcing over the 100 year period.

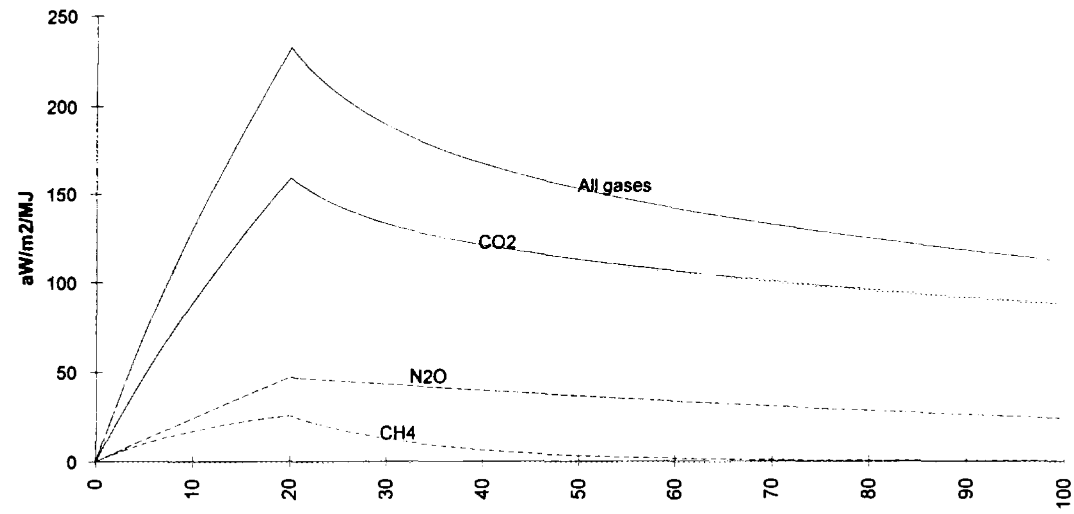


Figure 10. Calculated radiative forcing for the case *coal today*: the mining and combustion of 1 MJ coal as it is done today. The contribution from each greenhouse gas is shown. Values in aW/m2/MJ coal.

Table 5. Average radiative forcing for the first 100 years for the case *peat today*. Values in aW/m2/MJ coal.

	CO_2	CH_4	N_2O	**Sum**
A. Mining of coal		7		7
B. Combustion	106	0.02	32	**138**
A+B	**106**	7	**32**	**145**

4.4 Comparison of cases Peat today, Peat modified and Coal today

Figure 11 shows the calculated radiative forcing for the cases *Peat today*, *Peat modified* and *Coal today*. Case *Peat today* is shown for the four studied regions *Småland, Bergslagen, Härjedalen* and *Västerbotten kustland.* Table 6 shows the average radiative forcing over 100 years for the different cases.

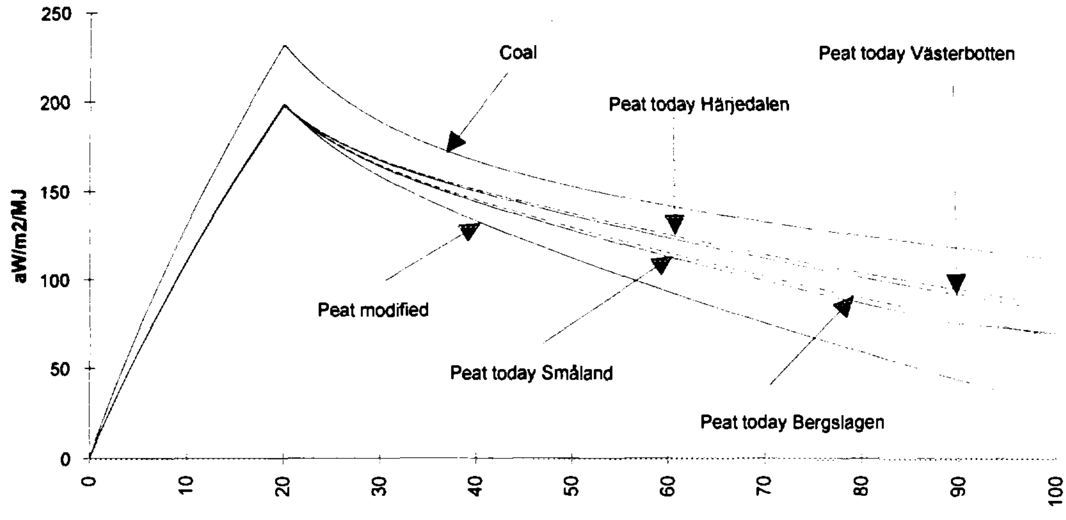


Figure 11. Radiative forcing for the different cases. Values in aW/m2/MJ.

Table 6. Radiative forcing at various times after mining starts for the different cases. Average radiative forcing over 100 years is also presented. In brackets percentage of case coal today.

	Radiative forcing [aW/m2/MJ]					
Case	20 years	40 years	60 years	80 years	100 yrs	Average 100 years
Peat today, Småland	198	144	113	87	70	116 (80 %)
Peat today, Bergslagen	198	145	115	90	68	117 (81 %)
Peat today, Härjedalen	198	151	125	104	86	125 (86 %)
Peat today, Västerbotten kustland	198	150	123	101	82	123 (85 %)
Peat modified	199	133	93	59	30	100 (69 %)
Coal today	232	167	142	125	112	145 (100 %)

We can note that the case coal today gives the highest contribution to radiative forcing. The contribution to the greenhouse effect from the use of peat for energy is ca 80 % to 85 % (depending on region) of the contribution from coal, counted as an average over 100 years after the mining starts. The case peat modified gives the lowest contribution to radiative forcing, 69 % of coal.

4.5 The effect of a changing atmosphere

Radiative forcing values have also been calculated on cases *Peat today (Bergslagen)* and *Coal today* under the assumption that the atmosphere's background concentrations of CO_2, CH_4 and N_2O changes during the study period 100 years. Due to saturation of the absorption band of the gases this is expected to lead to lower forcing values. The concentrations are assumed to change according to the following table:

Year	1995 (ppbv)	2015 (ppbv)	2045 (ppbv)	2095 (ppbv)
CO_2	355 000	396 000	452 500	560 000
CH_4	1714	1771	1857	2000
N_2O	311	326	350	390

Figure 12 shows the resulting radiative forcing values.

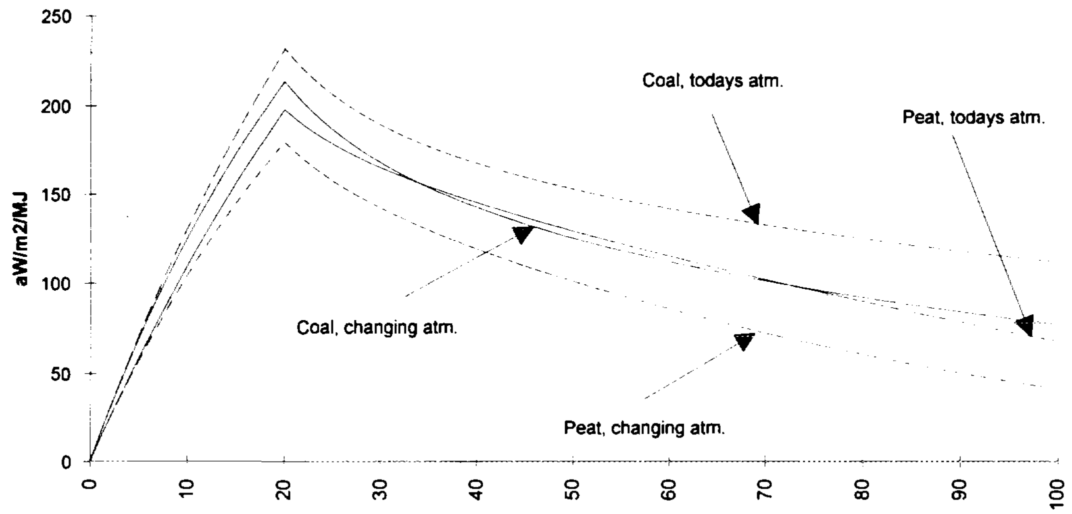


Figure 12. Comparison of the effects of changing the atmosphere's background concentrations. Radiative forcing for cases *Peat today* (Bergslagen) and *Coal today* assuming today's atmosphere compared to assuming a changing atmosphere.

Table 7 shows the average radiative forcing during 100 years for the cases.

Table 7. Average radiative forcing for cases peat today (Bergslagen) and Coal today assuming today's atmosphere compared to assuming a changing atmosphere. In brackets the ratio between peat today and coal today.

Case	Average radiative forcing 100 years (aW/m2/MJ)
Peat today, Bergslagen, today's atmosphere	117 (0.81)
Coal today, today's atmosphere	145 (1.0)
Peat today, Bergslagen, changing atmosphere	94 (0.78)
Coal today, changing atmosphere	121 (1.0)

Increasing the background concentrations according to table 6, results in a decrease in the radiative forcing for both cases peat today and coal by ca 20 %. The ratio peat and coal is changed from 0.81 to 0.78.

5. Conclusions

- Using peat from Bergslagen as an energy source is estimated to lead to emissions of 87 g CO_2, 66 mg N_2O and a reduction of CH_4-emissions of 900 mg CH_4/MJ peat. This includes fluxes during the different phases of using peat as an energy source(virgin peat land, drainage of the peat bog, harvesting, loading, transportation, combustion and forestation of the mined area). Corresponding CO_2-emissions for Småland, Härjedalen and Västerbotten kustland are 87, 99 and 95 g/MJ respectively. Emissions of CH_4 and N_2O in these regions are estimated to be close to those in Bergslagen.

- If all the drained peat areas where forested (instead of half as it is today) this would reduce the CO_2-emissions from 87 to 57 g CO_2/MJ peat for Bergslagen.

- Using coal as an energy source is estimated to lead to emissions of 92 g CO_2, 1 mg CH_4 and 0.3 g N_2O per MJ coal.

- Using peat from Bergslagen as an energy source contributes to radiative forcing with 117 aW/m2/MJ as an average over 100 years. 102 aW/m2/MJ originates from CO_2-emissions due to the combustion of peat, 28 aW/m2/MJ is due to the oxidation of remaining peat and 19 aW/m2/MJ of the total radiative forcing is due to N_2O-emissions from the combustion of peat. Two factors reduce the total radiative forcing. The mining of peat reduces the natural CH_4-emissions from a virgin peat bog. This reduction corresponds to 18 aW/m2/MJ as a 100 year average. Forestation leads to a further reduction in the radiative forcing corresponding to 12 aW/m2/MJ due to uptake in stem wood and 7 aW/m2/MJ due to the build up of carbon in the humus layer.

- If all the drained peat areas where forested (instead of half as it is today) this would reduce the radiative forcing from 117 aW/m2/MJ to 100 aW/m2/MJ on average over 100 years.

- Using coal as an energy source is estimated to lead to a radiative forcing of 145 aW/m2/MJ.

- The contribution to the greenhouse effect from the use of peat for energy in Bergslagen is ca 81 % of the contribution from coal, counted as an average over 100 years after the mining starts. Corresponding values for Småland, Härjedalen and Västerbotten are 80 %, 86 % and 85 % of coal respectively. The case peat modified gives the lowest contribution to radiative forcing, 69 % of coal.

- A scenario has been studied where the background concentration of CO_2 increases during the next 100 years from 355 ppmv to 560 ppmv, the concentration of CH_4 increas from 1714 ppbv to 2000 ppbv and the concentration of N_2O increases from 311 ppbv to 390 ppbv. If concentrations are increased in this manner the radiative forcing for the cases peat and coal is reduced, on average over 100 years, by ca 20 %. The ratio between peat and coal is changed from 0.81 to 0.78 for Bergslagen.

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Appendix A.

A.1 What is radiative forcing?

The sun is the energy source for all weather and climate on Earth. The incoming solar radiation amounts to about 340 W/m2. This radiation is absorbed by the Earth's surface and atmosphere and is balanced by outgoing radiation at infrared wavelengths. If there were no atmosphere the surface temperature would be about -19 degrees Celsius, thus balancing the incoming radiation. There are, however, gases in the atmosphere that absorbs the outgoing infrared radiation and re-emits it towards the Earth. This so called greenhouse effect is natural and keeps the surface temperature at about +15 degrees Celsius.

Emissions of greenhouse gases, as a result from human activities, are increasing the atmosphere's concentrations of greenhouse gases. This leads to changes in the radiative fluxes in the atmosphere - an enhancement of the greenhouse effect. Model calculations shows that the global average surface temperature can increase with several degrees during the next 100 years with serious consequences on natural ecosystems and human settlements.

The change in infrared thermal radiation through the tropopause due to changes in greenhouse gas concentrations is referred to as the *radiative forcing* (measured in W/m2) and is commonly used as a measure to quantify the expected climatic impact. A positive radiative forcing tends to heat the surface, a negative radiative forcing tends to cool. For a range of mechanisms there appears to be a relationship between global mean radiative forcing and global mean surface temperature change. The emissions of greenhouse gases caused by human activities since pre-industrial time has resulted in a change in radiative forcing with 2.5 W/m2.

For a doubling of the pre-industrial CO_2-concentration the global mean radiative forcing would be about 4 W/m2, in the absence of any other change. For a balance to be restored, the temperature of the troposphere and of the surface must increase, producing an increase in outgoing radiation. This would lead to an increase in surface temperature of about 1 degree Celsius, if other factors are held constant (e.g. clouds, water vapour etc.). Taking internal feed-backs into account, the 1990 IPCC report estimated that the increase in global average surface temperature at equilibrium resulting from a doubling of CO_2 would be likely to be between 1.5 and 4.5 degrees Celsius, with a best estimate of 2.5 degrees Celsius. If for example the atmospheric concentrations of other greenhouse lead to the same radiative forcing as a doubling of CO_2, 4 W/m2, it is believed that this change would lead to the same climatic effects.

In this study radiative forcing is used to assess the impact on the greenhouse effect from the peat and coal cases. It is calculated in two steps. First, based on emissions, the consequent increase in atmospheric concentrations are calculated. Secondly, based on these concentrations the radiative forcing is calculated.

A.2 The relationship between emissions and concentrations

A greenhouse gas that is emitted in the atmosphere will add to the atmospheric concentration of the gas but will also either immediately or after some time (e.g. after diffusion in the atmosphere) be involved in sink processes in the atmosphere. Such processes can be chemical reactions, photolysis, solution in the sea or biological uptake (IPCC, 1990).

Figure A.1 shows how carbon dioxide, methane and nitrous oxide decay after an instant release of 1 kg gas to the atmosphere.

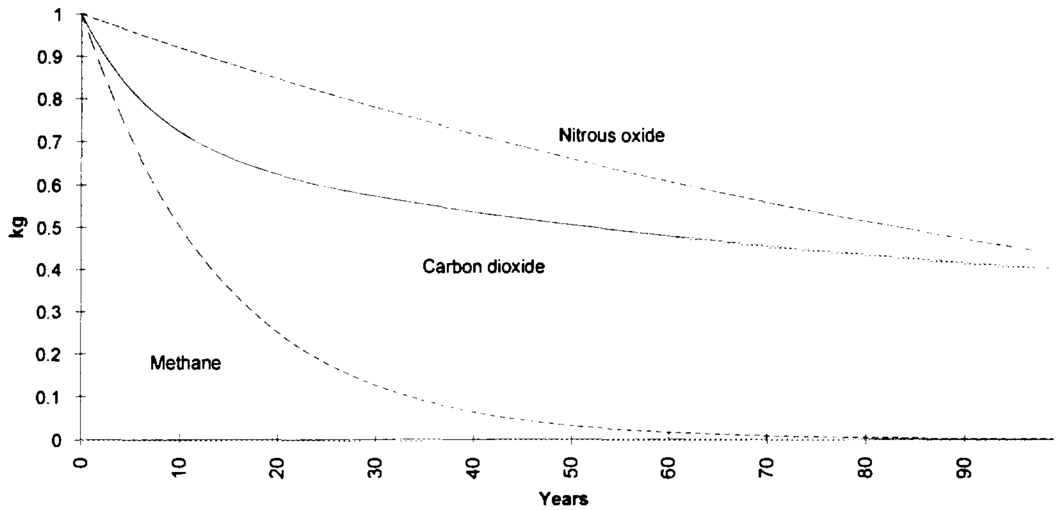

Figure A.1. The decay of carbon dioxide, methane and nitrous oxide. The figure shows how much of the gas that remains after an instant release of 1 kg of each gas at t=0.

The following expression can be used to calculate the remaining amount of gas in the atmosphere after an instant release of a greenhouse gas (Rodhe, 1990):

$$M = M_0 \cdot e^{-t/\tau} \quad (1)$$

where t is the time in years, M is the remaining mass in kg after t years and M_0 is the mass in kg at t=0. τ (tao) is called the atmospheric lifetime for the gas and is a specific parameter for each gas, and can be calculated in *chemistry transport models*. Table A.1 shows atmospheric lifetimes and atmospheric concentrations for carbon dioxide, methane and nitrous oxide.

Table A.1. Atmospheric lifetimes and present (1995) atmospheric concentrations for carbon dioxide, methane and nitrous oxide (IPCC, 1995).

Gas	Atmospheric lifetime [years]	Atmospheric concentration [ppbv]
Carbon dioxide, CO_2	*)	355 000
Methane, CH_4	14.5 +/- 2.5	1 714
Nitrous oxide, N_2O	120	311

*) Carbon dioxide is removed from the atmosphere through a chain of processes, which are not easily described by a single value of τ. The *Intergovernmental Panel on Climate Change*, IPCC, describes the decay characteristics of carbon dioxide by the following function (IPCC, 1995):
$F(CO_2(t))=0.30036\exp(-t/6.993)+0.34278\exp(-t/71.109)+0.35686\exp(-t/815.727)$.

The change in atmospheric concentrations due to an instant emission of 1 kg of carbon dioxide, methane and nitrous oxide can be calculated using the following expression:

$$\Delta C = M \cdot \frac{MW_{air}}{MW} \cdot \frac{1}{M_{air}} \cdot 10^6 \quad \text{in ppmv} \qquad (2)$$

where M is the remaining mass from our emission as calculated from eq. 1 or 2, MW_{air} is the mean mass of the air, 28.96 g mol^{-1}, MW is the molecular weight of the gas and M_{air} is the atmospheric mean mass, 5.136 $*10^{18}$ kg (Derwent, 1990). In table A.2, the change in atmospheric concentrations as a function of time after the emission of 1 kg of carbon dioxide, methane and nitrous oxide is shown.

Table A.2. The change in atmospheric concentrations as a function of time after the emission of 1 kg of carbon dioxide, methane and nitrous oxide at t = 0. Units in 10^{-10} ppbv.

Gas	0 years	20 years	40 years	60 years	80 years	100 years
CO_2	1.28	0.80	0.69	0.61	0.56	0.51
CH_4	3.52	0.89	0.22	0.06	0.01	0.003
N_2O	1.28	1.08	0.92	0.78	0.66	0.56

A.3 The relationship between concentrations and radiative forcing

Radiative transfer models are used to calculate radiative forcing due to changes in atmospheric concentrations. For well mixed greenhouse gases (like carbon dioxide, methane and nitrous oxide) the results from radiative transfer models can be used to parametrise the relationships between concentrations and radiative forcing and express them as simple functional relationships (IPCC, 1990).

Table A.3 shows the calculated radiative forcing due to the emission of 1 kg of carbon dioxide, methane and nitrous oxide at t = 0.

Table A.3 The calculated radiative forcing as a function of time after the emission of 1 kg of carbon dioxide, methane and nitrous oxide at t = 0. Units in 10^{-15} W/m^2.

Gas	0 years	20 years	40 years	60 years	80 years	100 years
CO_2	2.22	1.42	1.22	1.09	0.99	0.91
CH_4	153	39	9.7	2.4	0.6	0.2
N_2O	509	431	364	309	261	221

The method for calculating concentrations and radiative forcing from emissions of greenhouse gases is described in more detail in Zetterberg, 1993.

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