REPORT

The climate impact of future energy peat production

Linus Hagberg and Kristina Holmgren
B1796
September 2008

This report approved
2008-09-15
Peringe Grennfelt

Peringe Grennfelt
Scientific Director

IVL Swedish Environmental Research Institute

IVL Swedish Environmental Research Institute

Organization

IVL Swedish Environmental Research Institute Ltd.

Address

P.O. Box 21060
SE-100 31 Stockholm

Telephone

+46 (0)8-598 563 00

Report Summary

Project title

Assessment of the climate impact of future climate adjusted peat production and utilisation from a life cycle perspective

Project sponsor

The Swedish Peat Producers Association and The Swedish Environmental Protection Agency

Author

Linus Hagberg, Kristina Holmgren

Title and subtitle of the report

The climate impact of future energy peat production

Summary

The aim of this study was to estimate total greenhouse gas emissions and climate impact of different peat utilisation scenarios, using a life cycle perspective. This and previous studies show that the climate impact from energy peat utilisation is more complex than just considering the emissions at the combustion stage. There are important emissions and uptake of greenhouse gases that occur on the peatland before, during and after peat harvest. The results show that the climate impact of future peat utilisation can be significantly reduced compared to current utilisation and will be lower than the climate impact resulting from only the combustion phase. This can be achieved by choosing already drained peatlands with high greenhouse gas emissions, using a more efficient production method and by securing a low-emission aftertreatment of the cutaway (e.g. afforestation).

Keyword

Peat, greenhouse gases, emissions, life cycle, radiative forcing

Bibliographic data

IVL Report B1796

The report can be ordered via

Homepage: www.ivl.se, e-mail: publicationservice@ivl.se, fax+46 (0)8-598 563 90, or via IVL, P.O. Box 21060, SE-100 31 Stockholm Sweden

Acknowledgements

This study was financed by the Swedish Peat Producers Association (SPPA) and the Swedish Environmental Protection Agency (EPA). Valuable comments have been given by the reference group consisting of Anna Bäckman (EPA), Matti Parikka (the Swedish Energy Agency), Magnus Brandel (SPPA) and Lars Åstrand (SPPA).

Summary

According to IPCC (Intergovernmental Panel on Climate Change) peat is considered to be a fuel in its own class, residing between fossil fuels and biofuels. In the national reporting of emissions of greenhouse gases under the Climate Convention, emissions from peat combustion are treated in the same way as combustion of fossil fuels. Peat combustion is associated with a carbon dioxide emission factor of 106 g CO_2/MJ.

The Swedish government has decided that there is room for energy peat utilisation in a future sustainable energy system. Power producers using energy peat in the power production are rewarded with green electricity certificates. These producers must at the same time be able to present emission allowances according to the EU ETS (EU Emissions Trading Scheme) for the carbon dioxide emissions associated with the combustion of the peat, which in turn has a restraining effect on peat utilisation in all heat and power production utilities. The competitiveness of energy peat will be dependent on the price development of the EUAs (EU ETS emission allowances).

In recent years, the Swedish Peat Producers Association has investigated options of how to make the production and utilisation of Swedish energy peat more climate friendly, i.e. resulting in lower levels of greenhouse gas emissions from a life cycle perspective. The Swedish government has stated that ways to support peat utilisation and the development of a climate adjusted energy peat utilisation should be found (Regeringen, 2007).

Previous studies of energy peat utilisation considering the whole life cycle have shown that the climate impact is more complex than just considering the emissions at the combustion stage. There are important emissions and uptake of greenhouse gases that occur on the peatland before, during and after peat harvest. Various LCA-studies (Savolainen et al, 1996; Zetterberg et al, 2004; Nilsson & Nilsson, 2004; Holmgren et al, 2006; Holmgren, 2006; Kirkinen et al, 2007) have shown that with certain choice of peatland, production technology and aftertreatment, the climate impact of peat utilisation can be lower than if just considering the combustion emissions, and can be significantly reduced compared to the present peat utilisation.

As a basis for a future climate certification of peat, and for making future peat production more sustainable from a climate perspective, there is a need for a descriptive compilation of how choice of peatland, production methods, and aftertreatment will affect the climate impact compared to present peat utilisation. The aim of this study was to compile the results from earlier LCA-studies, and to include new published data on greenhouse gas fluxes, and to estimate the total emissions and climate impact for different peat utilisation scenarios. This was done by:

- Describing how the climate impact of energy peat utilisation can be reduced and how much compared to conventional utilisation.
- Compiling LCA estimates of greenhouse gas emissions of these future utilisation scenarios and comparing them with conventional peat utilisation and coal utilisation.
- Performing radiative forcing calculations for the compiled peat utilisation scenarios in order to show the difference between comparing emissions of greenhouse gases and actual climate impact (in terms of radiative forcing).

- Estimating the climate impact of a peat utilisation scenario where existing peat harvesting fields are shut down before harvesting is completed and aftertreatment is delayed due to low profitability of the peat production.

The results shown in Figure A indicate that the climate impact for all peat utilisation scenarios is comparable with coal during the first 30-40 years. During the first 100 years, the climate impact of the coal and the forestry drained scenarios are of comparable magnitude whereas the climate impact of the cultivated peatland scenarios are 33-55 % lower than the coal scenario. In a 300 year perspective, also the forestry drained peatland scenarios have a significantly lower climate impact than the coal scenario (15-46 %). The pristine mire scenarios have a higher climate impact than coal utilisation over the whole period studied.

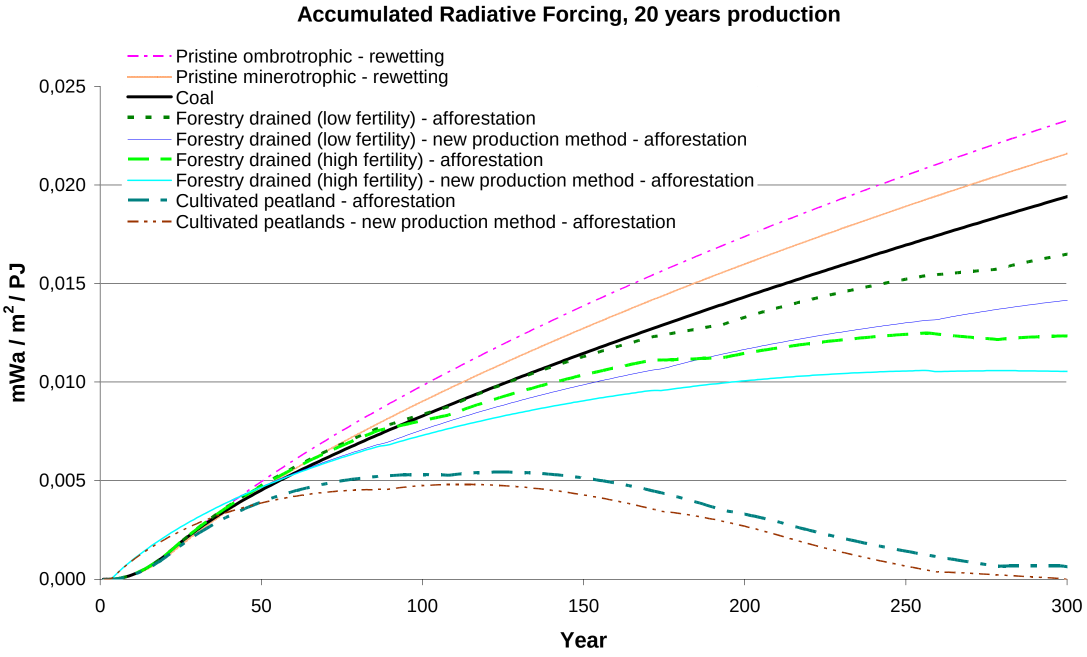


Figure A Accumulated radiative forcing due to energy peat utilisation from different peatland types. Pristine mires are assumed to be restored into new wetlands after harvesting, and drained peatlands used for forestry or cultivation are assumed to be afforested after harvesting. In three of the scenarios, the new production method is used instead of the conventional milling method.

The study shows that changes in greenhouse gas fluxes from the cultivated peatlands due to peat cutting and aftertreatment over time will compensate the emissions due to peat combustion. The same effect will be seen for other types of drained peatlands, but it will be smaller since greenhouse gas emissions from the initial peatlands are lower. The climate impact can also be reduced by using the new production method (biomass dryer). For pristine peatlands where the emissions are rather small in the reference scenario (before harvesting), the climate impact after 300 years is still dominated by the emissions from the combustion phase.

Figure B shows the difference between two best case scenarios where energy peat is produced from already drained peatlands, harvested with the new production technology, and where the cutaway is aftertreated by afforestation, and a scenario where only combustion emissions are considered. The results show that the there might be cases when the climate impact, considered over a long time period, from peat utilisation is significantly lower than the climate impact from the combustion stage only. During the first 20 years, the climate impact is similar in all three scenarios, whereas after 50 years the scenario based on cultivated peatlands has lower climate impact than the two others. After 100 years both drained peatland scenarios are lower than the combustion only scenario.

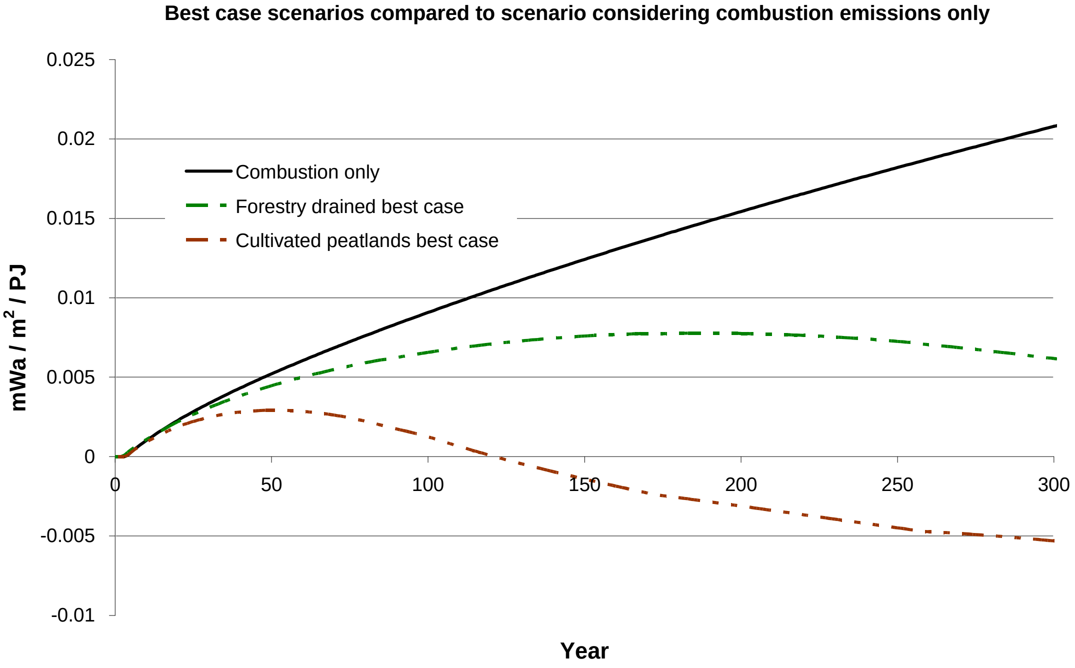


Figure B Best case scenarios for energy peat utilisation from forestry drained peatlands compared to scenario considering combustion emissions only. The diagram shows accumulated radiative forcing. Peat combustion occurs during year 1 (new production method).

Early shut downs and delayed aftertreatment of peat harvesting fields due to low profitability would lead to a minor increase of the climate impact of peat production per PJ. However, looking at a broader perspective, interrupted peat harvesting means postponing of emissions and could lead to either higher or lower long term emissions. From a climate viewpoint, it is not clear to say whether completion of harvesting area is better then closure. There are also other circumstances to consider in this matter (aftertreatment opportunities, energy efficiency, biological diversity etc). However, we conclude that there is only a small risk for early shut downs and delayed aftertreatment to occur.

The most important factors that influence the climate impact of the peat utilisation are:

- *Choice of peatland*
  In this study, average values of emissions from different types of peatlands are used. The study shows that there is great variation in emission levels within the different peatland types. If the choice of harvesting area should be used as a measure to reduce the climate impact from peat utilisation, there is a need for a simplified methodology (not including chamber or micrometeorological measurements) to determine/estimate emissions from individual sites. However, even if the methodology is developed, there will most probably be a significant degree of uncertainty also in the future, see Figure C. In addition, it is of

course impossible to base the decision of peat harvesting only on levels of greenhouse gas emissions of the harvesting area.

- *Production technology*
  The drier the peat the lower the combustion emission factor. The new production technology not only reduces the emissions from the peat production site during harvesting, it also results in drier peat, which leads to lower emissions from transport and combustion. In addition, the smaller amount of residual peat results in lower emissions from the aftertreated area (in the case of afforestation).

- *Aftertreatment*
  The choice of aftertreatment will depend on many factors. It is important to remember that the suitability of different aftertreatment choices will be dependent on the local conditions. If it is possible to create a system functioning as a carbon sink, this will result in a peat utilisation chain with reduced climate impact. Both afforestation and restoration into new wetland can result in net carbon sequestration. At an afforested site, the carbon uptake in the growing biomass can be rather large, but emissions will occur from the residual peat layer. Also in a wetland, carbon is fixed in growing vegetation, whereas emissions mainly are in the form of methane. Since methane is a stronger greenhouse gas than carbon dioxide this can result in a net negative climate impact. There are also additional options for aftertreatment that has not been included in this study, and that can lead to net carbon sequestration. An interesting example is cultivation of energy crops (e.g. reed canary grass).

Figure C shows the variation of emission estimates in the different stages of the peat utilisation chain found in the literature used for the compilation of this study. Note that the figure shows peat production of 1 PJ during 20 years, and that the emissions of greenhouse gases at each stage are summarised with GWP_{100}. GWP does not consider the timing of emissions, and does therefore not fully reflect the climate impact of the peat utilisation scenarios. The figure does not give the uncertainty in the calculations, but shows the variation of emission estimates in the used input data, and thus reflect the range within which the average scenarios may vary if other input data were used. The figure therefore gives an indication of the potential emission reductions that are possible in the different stages.

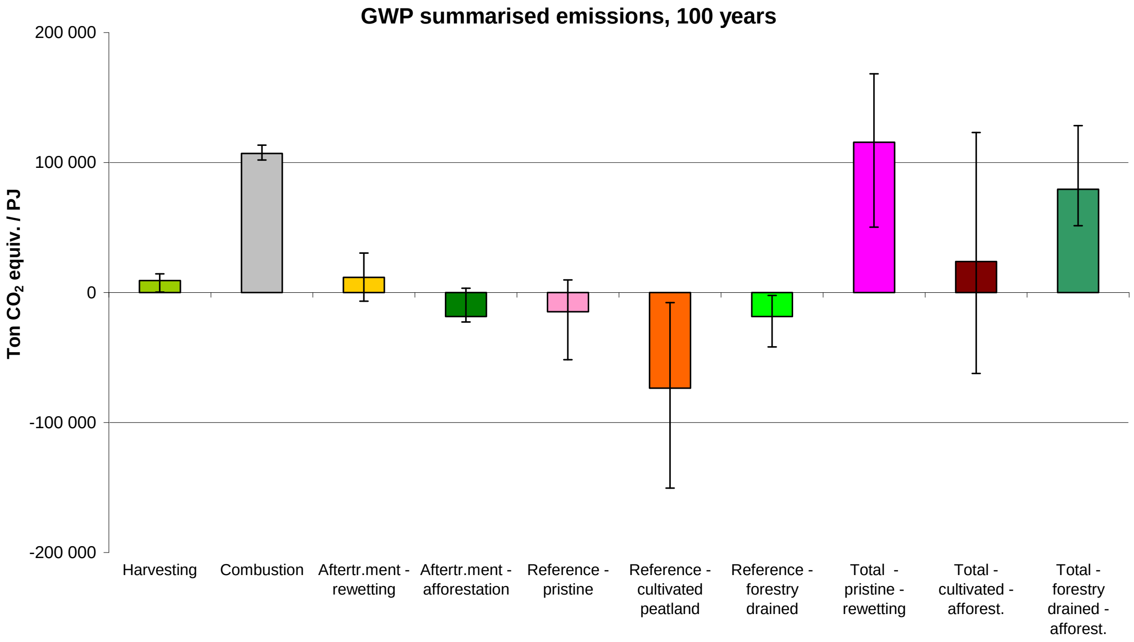


Figure C GWP summarised emissions of the peat scenarios in a 100 year perspective divided on the different stages of the peat utilisation chain. The staples represent average values of emission estimates whereas the bars show the variation found in the source literature. The emissions from the reference situation (before harvesting) are presented as negative in the figure, since these emissions are considered avoided. The total staples in the figure are the sum of the harvesting, combustion, aftertreatment and reference staples.

We conclude that in order to minimise climate impact of future peat utilisation one should:

- Focus peat production to drained peatlands with high greenhouse gas emissions, mainly:
    - Cultivated peatlands, which have high CO_2 and N_2O emissions
    - Forested peatlands with high peat decomposition rate and high N_2O emissions, typically peatlands with high fertility that are well drained. Since the forest productivity generally is high at these peatlands, the peat should be harvested in connection to planned tree cuttings and be performed as fast as possible (to shorten the harvesting period as much as possible).
- Use a peat production technology that minimises the harvesting time, and results in a dryer and denser peat which minimises the emissions from stockpiles, transports and combustion, and that leaves a thin residual peat layer
- Afforestate the cutaway peatland as soon as possible after harvesting, with soil preparation (including ash-application/fertilization) and forest management practices that maximise forest growth and minimise soil emissions.

In this study, an estimate of the effect on the climate impact of co-combustion of peat and wood-fuels was made. There are some positive effects on energy production in heat and power plants using wood fuels when co-combusted with peat. Lower maintenance costs and higher efficiency at the plants due to co-combustion with peat can potentially result in avoided emissions from the use of fossil fuels. These effects can be achieved by other means than co-combustion with peat and can therefore not be included in the LCA scenarios for peat utilisation. However, it could be considered when evaluating peat as a fuel in the Swedish energy system.

This study shows that to fully understand the climate impact of peat utilisation, a life cycle perspective is needed. Additionally, since the emissions from a peat utilisation chain are extended over a long time, an analytical tool that takes the dynamics and the atmospheric lifetime of the greenhouse gases into consideration should be used in the assessment. Therefore radiative forcing is used in this study, which expresses the actual climate impact over time, something that GWP (Global Warming Potential) does not. Despite large uncertainties in the emission estimates, the study clearly shows that by choosing already drained peatlands with high greenhouse gas emissions for peat production, using the new more efficient production method, and by securing a low-emission aftertreatment of the cutaway (e.g. afforestation), the climate impact of a future peat utilisation can be significantly reduced compared to present peat utilisation, and significantly lower than for scenarios which only consider the emissions from peat combustion. However, the time perspective used in the assessment is of great importance for the result. If the climate impact of the peat utilisation chain is considered over a short time perspective (< 100 years), the combustion emissions will clearly dominate and hence be comparable to scenarios where only combustion emissions are considered. If considering the climate impact over a longer time perspective (several hundreds of years), the reduced emissions at the peatland due to peat harvest and aftertreatment in the future peat utilisation scenarios will have time to more or less compensate the combustion emissions.

Sammanfattning

IPCC har klassificerat torven i en egen bränsleklass som ligger mellan biobränslen och fossila bränslen. I den nationella rapporteringen av utsläpp av klimatgaser enligt klimatkonventionen behandlas dock förbränning av torv på samma sätt som förbränning av fossila bränslen. Torvförbränning har i detta sammanhang en emissionsfaktor på 106 g CO_2/MJ.

Den svenska regeringen har bestämt att torv har en plats i ett framtida uthålligt energisystem. Elproduktion i kraftvärmeanläggningar baserat på torvbränsle premieras genom att berättiga till gröna el-certifikat. Samtidigt måste anläggningarna uppvisa utsläppsrätter i enlighet med EU:s utsläppshandelssystem för de CO_2 emissioner som förbränningen av torv resulterar i, något som hämmar torvanvändningen i samtliga värme- och kraftvärmeanläggningar. Energitorvens konkurrenskraft är och kommer att vara starkt beroende av prisutvecklingen på utsläppsrätterna.

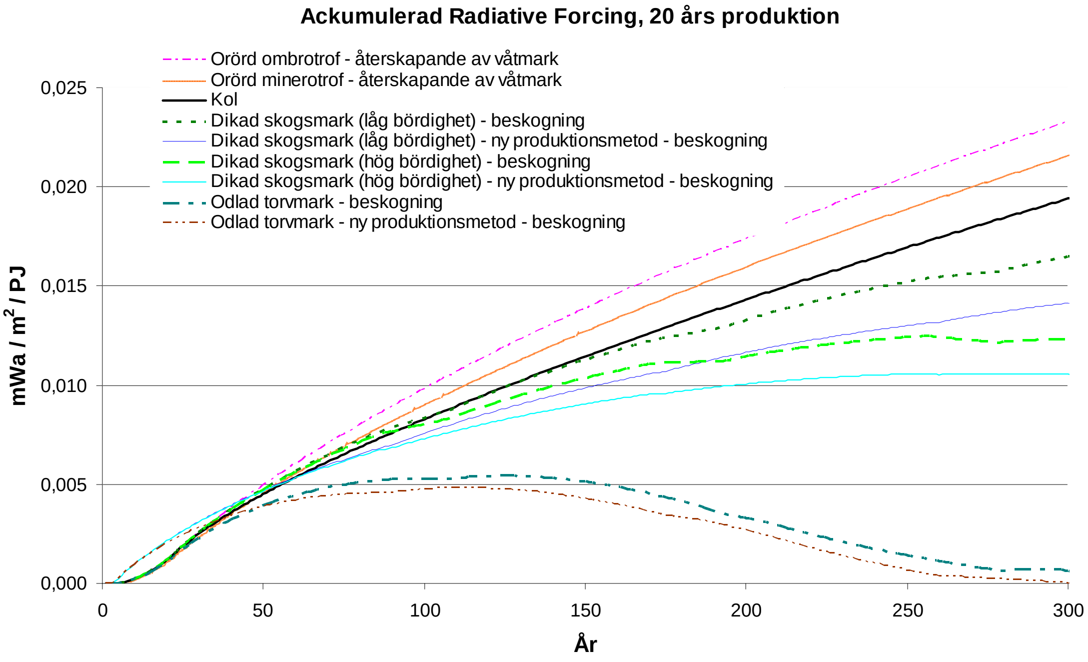
Svenska Torvproducentföreningen har de senaste åren undersökt möjligheterna att göra den svenska produktionen och användningen av energitorv mer klimatvänlig, d v s mindre utsläpp av växthusgaser sett ur ett livscykelperspektiv. Den svenska regeringen har uttryckt sitt stöd för utvecklingen av ett mer klimatanpassat torvbruk (Regeringen, 2007).

Tidigare studier som fokuserat på torvanvändning ur ett livscykelperspektiv har visat att klimatpåverkan är mer komplex än att bara betrakta emissionerna vid förbränningen. Det sker betydande emissioner och upptag av växthusgaser på torvmarken före skörd som helt klart påverkas av torvbrytningen och den efterföljande efterbehandlingen. Ett antal LCA-studier (Savolainen et al, 1996; Zetterberg et al, 2004; Nilsson & Nilsson, 2004; Holmgren et al, 2006; Holmgren, 2006; Kirkinen et al, 2007) har visat att genom rätt val av torvmark, produktionsmetod och efterbehandlingsalternativ kan torvanvändningens klimatpåverkan vara mindre än om endast emissionerna vid förbränningen betraktas och betydligt mindre än dagens torvanvändning.

Som en grund för ett framtida certifieringssystem för torv och för att uppnå ett mer hållbart torvbruk ur klimatsynpunkt, finns det ett behov av en övergripande sammanställning av hur val av torvmark, produktionsmetod och efterbehandling kan påverka klimatet jämfört med dagens torvanvändning. Syftet med denna studie var att sammanställa resultat från tidigare LCA-studier och inkludera ny publicerad data över växthusgasflöden samt att uppskatta totala emissioner och klimatpåverkan för olika torvanvändningsscenarier. Detta gjordes genom:

- Beskrivning av hur klimatpåverkan från energitorvanvändning kan minskas och hur mycket jämfört med konventionell användning.
- LCA-beräkningar av växthusgasemissioner för dessa framtida torvanvändningsscenarier och jämförelse med konventionell torvanvändning och kolanvändning.
- Radiative forcing beräkningar för att visa på skillnaden i att jämföra torvscenariernas växthusgasemissioner med att jämföra dess faktiska klimatpåverkan.
- Uppskattning av klimatpåverkan från ett scenario där torvbrytningen på existerande torvtäkter avbryts i förtid och efterbehandlingen skjuts på framtiden pga. låg lönsamhet i torvproduktionen.

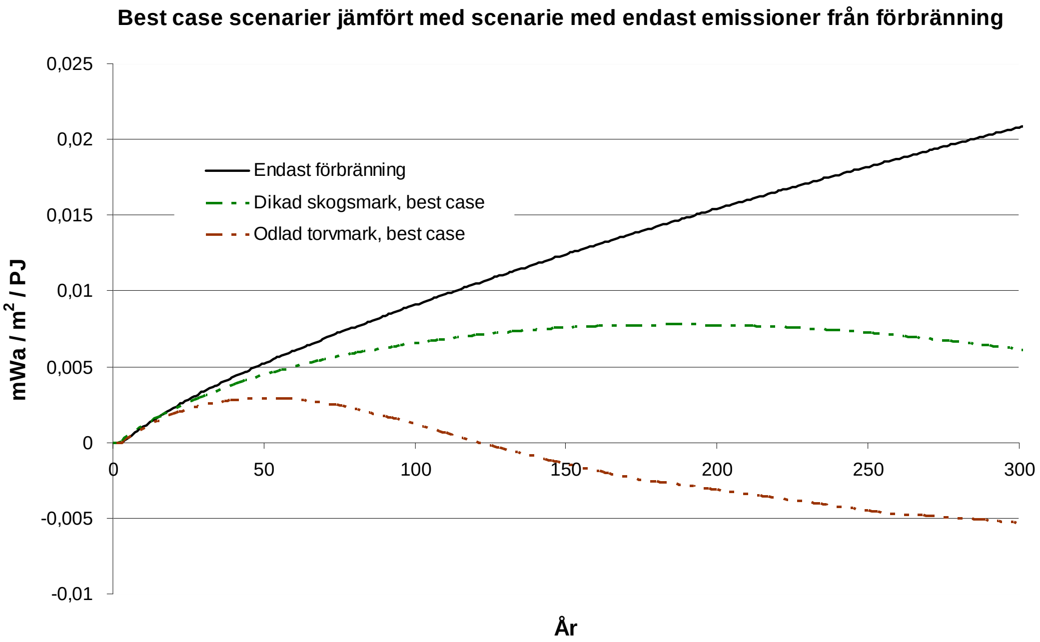
Resultaten i Figur A tyder på att klimatpåverkan för alla torvscenarier är jämförbara med kol under de första 30-40 åren. Under de första 100 åren är klimatpåverkan från kolscenariet och scenarierna med dikad skogsmark av samma storleksordning, medan klimatpåverkan från scenarierna med odlad torvmark (dikad torvmark som används för jordbruk) är 33-55 % lägre än kolscenariet. Efter 300 år är klimatpåverkan även från dikad skogsmark betydligt lägre än kolscenariet (15-46 %). Orörda myrar ger högre klimatpåverkan än kolscenariet över hela den studerade perioden.



Figur A. Ackumulerad radiative forcing (påverkan på strålningsbalansen) pga. energitorvsanvändning från olika torvmarkstyper. Orörda myrar antas restaureras till ny våtmark efter skörd och dränerade torvmarker som används för skogsbruk eller jordbruk antas beskogas efter skörd. I tre av scenarierna med dikade torvmarker har den nya produktionsmetoden använts istället för den konventionella fräsmetoden.

Studien visar att förändringen av växthusgasflöden från de odlade torvmarkerna pga. torvbrytning och efterbehandling med tiden kompenserar emissionerna från torvförbränningen. Motsvarande effekt fås för andra dikade torvmarker, men effekten blir mindre om emissionerna på den ursprungliga torvmarken är lägre. Som visas i Figur A kan också klimatpåverkan minskas genom att använda den nya produktionsmetoden (biomass dryer). För orörda myrar där emissionerna är relativt små i referensscenariot (före skörd) domineras klimatpåverkan efter 300 år fortfarande av emissionerna från torvförbränningen.

Figur B visar skillnaden mellan två best case scenarier där energitorv produceras på dränerade torvmarker med hjälp av den nya produktionsmetoden och där torvtäkten efterbehandlas genom beskogning samt ett scenario där endast förbränningsemissionerna inkluderas. Figuren visar att det i ett längre tidsperspektiv är möjlighet att få en klimatpåverkan från energitorvanvändningen som är betydligt lägre än om man endast tar hänsyn till förbränningsemissionerna. Under de första 20 åren är klimatpåverkan från de tre scenarierna lika, medan efter ca 50 år är klimatpåverkan från scenariot med utgångspunkt i odlad torvmark lägre än de andra två. Efter 100 år är även scenariot baserat på dränerad skogsmark lägre än scenariot där endast förbränningsemissioner inkluderas.



Figur B Best case scenarier för energitorvanvändning från dränerade torvmarker jämfört med ett scenario där endast förbränningsemissionerna är inkluderade. Figuren visar ackumulerad radiative forcing. Förbränningen av torv sker under fösta året i dessa scenarier eftersom nya produktionsmetoden används.

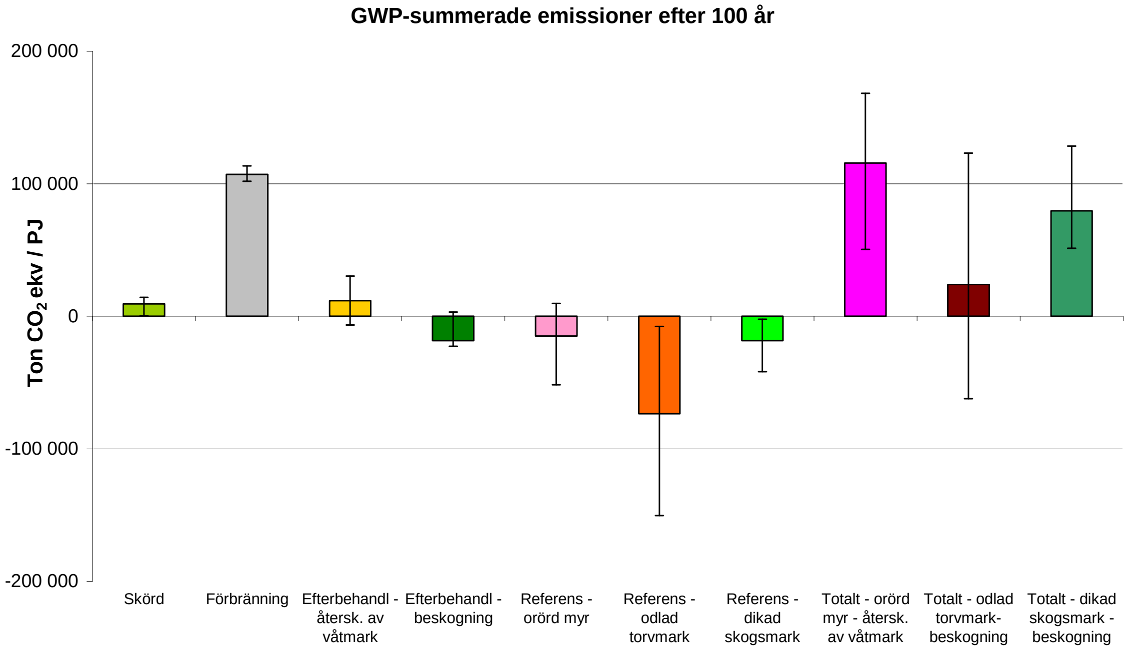
I studien studerades också hur klimatet påverkas vid ett scenario där torvbrytningen avbryts i förtid och där efterbehandlingen skjuts 10 år på framtiden pga. låg lönsamhet. Enligt beräkningarna blir klimatpåverkan per energienhet producerad torv något högre jämfört med om torvtäkten skördas färdigt. Sett ur ett bredare perspektiv så innebär avbruten torvbrytning senareläggning av emissioner och kan ge både lägre och högre långsiktiga emissioner. Ur klimatsynpunkt är det inte uppenbart om det är bättre att avsluta torvbrytningen eller att skörda färdigt. Det finns också andra omständigheter att beakta i detta sammanhang (möjliga efterbehandlingsalternativ, energieffektivitet, biologisk mångfald etc.). Vi drar emellertid slutsatsen att risken för att torvbrytningen skall avbrytas i förtid och efterbehandlingen skall försenas under en längre tid är liten.

De viktigaste faktorerna som påverkar torvanvändningens klimatpåverkan är:

- *Val av torvmark*
  I denna studie har genomsnittsvärden för emissioner från olika typer av torvmarker använts. Studien visar att det är stor variation på emissionsnivåerna inom de olika torvmarkstyperna. Om val av torvmark skall användas som en åtgärd för att minska klimatpåverkan från torvanvändning, behövs det en enkel metodik (som inte inkluderar kammarmätningar eller mikrometeorologiska mätningar) för att bestämma/uppskatta emissionerna från enskilda platser. Även om sådan metodik utvecklas kommer det med största sannolikhet kvarstå en betydande osäkerhet i uppskattningarna även i framtiden, se Figur C. Det är dessutom naturligtvis svårt att basera ett beslut om torvmark lämplig för torvskörd endast på hur stora växthusgasemissionerna är.

- *Produktionsmetod*
  Ju torrare torv desto lägre blir emissionsfaktorn vid förbränning. Den nya produktionsmetoden minskar inte bara emissionerna från produktionsytan under skörden. Den ger dessutom en torrare och kompaktare stycketorv som leder till lägre emissioner från transporter och förbränning. Eftersom ett tunnare torvlager lämnas kvar efter skörd blir också emissionerna från den efterbehandlade ytan lägre (vid beskogning).
- *Efterbehandling*
  Val av efterbehandling kommer att bero på många faktorer. Det är viktigt att påpeka att lämpligheten för ett visst efterbehandlingsalternativ beror på de lokala förutsättningarna. Om det är möjligt att skapa ett system som fungerar som kolsänka, leder det till ett torvscenario med minskad klimatpåverkan. Både beskogning och återskapande av våtmark kan resultera i ett nettoupptag av kol. På beskogade torvtäkter kan upptaget av kol i växande biomassa vara stort, men samtidigt sker emissioner från det kvarvarande torvlagret. Även på en våtmark fixeras atmosfäriskt kol i vegetationen, medan emissioner huvudsakligen sker i form av metan. Eftersom metan är en starkare växthusgas än koldioxid kan nettoeffekten vara en negativ klimatpåverkan. Det finns andra efterbehandlingsalternativ som inte har studerats i denna studie och som kan leda till ett nettoupptag av kol. Ett intressant exempel är odling av energigrödor (t ex rörflen).

Figur C visar variationen i emissionsuppskattningarna för torvanvändningskedjans olika delar från den litteratur som används i studien. Notera att figuren visar torvproduktion av 1 PJ under 20 år och att växthusgasemissionerna vid varje steg är summerade med GWP_{100}. GWP tar inte hänsyn till att emissionerna sker utdraget i tiden och ger därför inte en rättvisande bild av torvscenariernas klimatpåverkan. Figuren visar inte osäkerheten i beräkningarna utan anger det intervall inom vilket de genomsnittliga torvscenarierna kan variera beroende på torvmarkstyp, ny eller konventionell produktionsmetod eller antaganden om upptag/emissioner på den efterbehandlade ytan. Figuren ger därför också en indikation på potentiella emissionsreduktioner i torvanvändningskedjans olika delar.



Figur C GWP -summerade emissioner för torvscenarierna i ett 100-års-perspektiv uppdelat på torvanvändningskedjans olika delar. Staplarna representerar genomsnittliga värden på emissionsuppskattningarna, medan sträcken visar variationen utifrån den använda litteraturen. Emissionerna för referensfallet (före skörd) redovisas i figuren som negativa eftersom de betraktas som undvikta emissioner. De totala emissionerna i figuren fås genom att addera staplarna med emissioner under skörd, förbränning, efterbehandling och referensfallet.

Slutsatsen från studien är att för att minimera klimatpåverkan från ett framtida torvbruk bör man:

- Fokusera torvproduktionen till dränerade torvmarker med höga växthusgasemissioner, huvudsakligen:
    - Odlad torvmark (organogen jordbruksmark), som har höga emissioner av CO_2 och N_2O
    - Beskogade torvmarker med hög torvnedbrytningshastighet och höga N_2O emissioner, framförallt bördiga och väldränerade torvmarker. Eftersom skogsproduktiviteten i allmänhet är god på dessa torvmarker, bör torven skördas i anslutning till planerad skogsavverkning och med så kort skördetid som möjligt
- Använda en produktionsmetod som minimerar skördetiden, ger en torrare och kompaktare torv vilket minskar emissionerna från lagring, transporter och förbränning samt efterlämnar ett tunnare torvlager.
- Beskoga den färdigskördade torvtäkten så fort som möjligt med god markberedning (inklusive askåterföring/gödsling) och ett skogsbruk som maximerar skogstillväxt och minimerar växthusgasemissioner

Ett annat syfte med denna studie var att uppskatta vilken betydelse samförbränning av trädbränsle med torv har för torvanvändningens klimatpåverkan. Biobränsleeldade kraftvärmeverk där trädbränsle samförbränns med torv har visat sig ge bättre tillgänglighet och högre verkningsgrader, vilket potentiellt resulterar i undvikta emissioner från fossilbaserad energi. Sådana effekter kan dock erhållas med hjälp av andra metoder än samförbränning med torv och kan därför inte inkluderas i LCA beräkningarna för torv. Dock kan det utgöra en positiv omständighet att ta hänsyn till då man skall värdera torvens roll i det svenska energisystemet.

Sammanfattningsvis så visar denna studie att för att ge en komplett bild av torvanvändningens klimatpåverkan behöver ett livscykelperspektiv tillämpas. Eftersom emissionerna för en torvanvändningskedja sker utsträckt i tiden, bör man för att uppskatta klimatpåverkan dessutom använda en analysmetod som tar hänsyn till dynamiken och växthusgasernas atmosfäriska livslängd. Därför används i denna studie radiative forcing som ger uttryck för den faktiska klimatpåverkan över tiden, något som GWP (Global Warming Potential) inte gör på samma sätt. Trots stora osäkerheter i emissionsuppskattningarna visar studien tydligt att genom att bryta torv från redan dikade torvmarker med höga emissioner av växthusgaser, använda den nya effektivare produktionsmetoden och genom att beskoga den färdigskördade torvtäkten kan klimatpåverkan från ett framtida torvbruk bli betydligt mindre jämfört med att enbart betrakta emissionerna från torvförbränningen. Det har dock stor betydelse vilket tidsperspektiv som används när man jämför klimatpåverkan från olika scenarier. Om torvanvändningen betraktas under en kort tidsperiod (< 100 år) kommer emissionerna från torvförbränningen att dominera och därmed vara jämförbara med scenarier där man endast tar hänsyn till förbränningsemissionerna. Betraktar man torvanvändningskedjan under en längre tidsperiod (flera hundra år) kommer de minskade emissionerna på torvmarken till följd av torvbrytning och efterbehandling i de framtida torvanvändningsscenarierna mer eller mindre kompensera emissionerna från torvförbränningen.

Contents

1 Introduction

1.1 Background

Peat is an accumulation of partly decayed organic material (mainly plant matter) that is formed under anoxic (oxygen free) conditions in wetlands (mires). Approximately 14 % of the Swedish land area is covered by peat deposits that have been formed since the last ice age. In Sweden peat is used as fuel in heat and power production. According to IPCC (Intergovernmental Panel on Climate Change) peat is considered as a fuel in its own class, residing between fossil fuels and biofuels. However, this distinction was made only recently (in 2006), earlier peat was classified together with the fossil fuels. In the national reporting of emissions of greenhouse gases under the Climate Convention, emissions from peat combustion is treated as combustion of fossil fuels and peat combustion is associated with a carbon dioxide emission factor of 106 g CO_2/MJ.

The Swedish government has decided that there is room for energy peat utilisation in a future sustainable energy system. Power producers using energy peat in the production will receive green certificates for the electricity, hence promoting peat utilisation in power production. At the same time these producers must be able to present emission allowances according to the EU ETS (EU Emissions Trading Scheme) for the carbon dioxide emissions associated with the combustion of the peat, hence having a restraining effect on peat utilisation in all heat and power production utilities.

Since the price of the EUAs (emission allowances in the EU ETS) has been quite high from time to time the impact of the EU ETS has been the dominant one of the two economic instruments described above. This has made it profitable for power producers to find other options than peat to use in their fuel mix. For the Swedish peat producers this has of course been of great concern and still is, since the price of EUAs has recovered from the low levels during the end of the first trading period. When EUA prices were close to zero, the Swedish peat utilisation increased by 15 % compared to the previous year (Miljökraft 2008). Currently, the price of competing fuels such as coal is also high following the high oil prices and the demand for peat is maintained. The long term price signal of peat is however very dependent on the fact that peat combustion requires EUAs and the price of the EUAs. Since EUA prices are expected to increase in the long term this means that peat most likely will be expensive and peat users will find it interesting to find substitute fuels.

The Swedish Peat Producers Association has in recent years investigated options of how to make the production and utilisation of Swedish energy peat more climate friendly, i.e. resulting in lower emissions of greenhouse gases. The Swedish government has stated that they would like to find a way to support peat utilisation and the development of a climate adjusted energy peat utilisation (Energimyndigheten, 2008).

Previous studies of the life cycle of energy peat utilisation have shown that the climate impact is more complex than just considering the emissions at the combustion stage. There are important emissions and uptake of greenhouse gases that occur on the peatland before peat harvest and harvest of peat and the consequent aftertreatment of the harvested area clearly affects these greenhouse gas balances. Various LCA-studies (Savolainen et al, 1996; Zetterberg et al, 2004; Nilsson & Nilsson, 2004; Holmgren et al, 2006; Holmgren, 2006; Kirkinen et al, 2007) have shown that with a right choice of peatland, production method and aftertreatment, the climate impact of peat utilisation can be lower than if just considering the combustion emissions and can be significantly reduced compared to the present peat utilisation. For instance, if the peat production is focused on drained peatlands that are net sources of greenhouse gases, the cutaway peatland is successfully afforested and if a new more efficient peat harvesting technology is used, the climate impact can be reduced.

Another aspect of peat utilisation is the positive effects in the case of co-combustion with wood fuel in heat and power plants. Co-combustion of wood and peat in wood-fuel using plants has shown to increase the availability and efficiency of the plant which potentially also may lead to reduced emissions of fossil CO_2.

1.2 Objectives

As a basis for a future climate certification of peat and for making future peat production more sustainable from a climate perspective, there is a need for a descriptive compilation of how choice of peatland, different production methods and proper aftertreatment might affect the climate compared to present peat utilisation. The aim of this study is therefore to compile the results from earlier LCA-studies and to include new data of greenhouse gas fluxes and to estimate total emissions and climate impact for different peat utilisation scenarios. This is done by the following steps:

- To describe how and how much the climate impact of energy peat utilisation can be reduced and how much compared to conventional utilisation (using pristine mires).
- To compile LCA emission estimates of greenhouse gas emissions of these future utilisation scenarios and compare them to conventional utilisation and coal utilisation.
- To make radiative forcing calculations for some of the compiled peat utilisation scenarios in order to show the difference between comparing emissions of greenhouse gases and actual climate impact (in terms of radiative forcing).
- To estimate the climate impact of a peat utilisation scenario where existing peat cutting fields are shut down before harvesting is completed and aftertreatment is delayed due to low profitability of the peat production.

Factors that influence the climate impact of peat utilisation and which are emphasised in the study are: selection of peat reserve, production technology and choice of aftertreatment alternative of the cutaway peatland. Another objective of the study is to estimate the effect on the climate impact when peat is co-combusted with wood-fuels. Additionally, an important aim of the study is to present the results in a simple and communicative report.

1.3 Constraints/delimitations

This study only considers the climate impact of energy peat utilisation chains. Emissions of the greenhouse gases CO_2, N_2O and CH_4 from all parts of the production and utilisation chains are included. Other environmental aspects, such as other emissions than greenhouse gases, impact on biodiversity, dust or noise, associated with peat utilisation are not included.

An important aspect of this study was to present the results in a simple and communicative report. Therefore only a few representative scenarios have been studied. The scenarios do not cover the entire variability of emissions of different types of peatlands and local conditions. A set of representative peat utilisation scenarios valid for Swedish conditions have been chosen based on averages and best estimates of emissions from studies presented in the scientific literature. References to emission studies and ranges are given in more detail in Chapter 4. There is a brief explaination how the emissions have been chosen based on factors that influence the emissions from the different stages.

Within this study it was not possible to analyse the uncertainties in the emission estimates or to perform a thorough sensitivity analysis of the results and how different assumptions affect the result. For more information on uncertainties and sensitivity analysis we recommend earlier work by Holmgren et al (2006), Kirkinen et al (2007) and Nilsson & Nilsson (2004).

1.4 Outline of this report

The result of the climate impact estimate for a number of peat utilisation scenarios is presented in **Chapter 6**. The climate impact is presented as accumulated radiative forcing which describes how the climate impact changes over time (the scenarios are simulated over 300 years). For comparison, the GWP summarised total emissions are also calculated over 100 years and 300 years and presented. Chapter 6 illustrates the difference between using radiative forcing instead of GWP to estimate the climate impact of peat utilisation and also illustrates the importance of the time perspective in the climate impact estimates.

The peat utilisation scenarios that are analysed in this study are shortly presented in **Chapter 3**, and all input data in the calculations are summarised in the **Appendix**. A thorough inventory of emissions and uptake at each stage of the peat utilisation chain is found in **Chapter 4**. Here a background is given to the choices of emission estimates used in the calculations. A compilation of emission ranges and average emissions for different peatland types, production technologies and aftertreatment alternatives found in the scientific literature is given and at the end of each section we summarise the estimates used in the calculations and hence found to be most representative.

Chapter 2 presents the life cycle perspective that is used in this study to estimate climate impact of peat utilisation. The chapter also explains the difference of GWP and radiative forcing as analytical tools to calculate the climate impact of peat utilisation. The importance of taking the time perspective into consideration properly when estimating the climate impact of peat utilisation is also discussed.

A discussion of what implications early shut downs and delay of aftertreatment at existing peat cuttings might have on the climate impact is done in **Chapter 5,** where also scenario-calculations of such peat cutting areas are presented. The result of the calculations is found in **Chapter 6.** Early shut downs may be a consequence due to low profitability of energy peat.

Co-combustion of peat with wood-fuels has some positive effects that are discussed in **Chapter 7**. Calculations are also made for a scenario that includes potential efficiency gains due to co-combustion. This is put in a separate chapter since it requires an extension of the system boundaries compared to the boundaries used in the other scenario calculations.

The climate impact for two best case scenarios from drained peatlands are presented in **Chapter 8,** which are compared to a scenario where only peat combustion emissions are considered.

Finally, **Chapter 9** includes a discussion of the climate impact of peat utilisation and how it can be reduced based on the findings of this study. A brief discussion of the uncertainties and the representativeness of the results are also given. The main conclusions that can be drawn from the study are summarised in **Chapter 10**.

2 Methodology for estimating climate impact of energy peat utilisation

The use of peat for energy purposes is often associated with an emission factor of 105-108 g CO_2/MJ. The default emission factor used in the EU Emissions Trading System is 106 g CO_2/MJ. As a comparison combustion of coal is associated with an emission factor of 92-95 g CO_2/MJ. However, from a land-use and life cycle perspective the climate impact from the use of energy peat is more complex than just considering the emissions at the combustion stage. There are important emissions and uptake of greenhouse gases that occur on the peatland before, during and after peat harvest.

In this study a life cycle perspective is applied, including greenhouse gas fluxes from the different steps of peat production and utilisation. The climate impact is described by radiative forcing, which can be modelled based on emission scenarios. This study follows the same methodology that has been used in previous studies (Savolainen et al 1994, Uppenberg 2000, Nilsson & Nilsson, 2004; Holmgren, 2006; Holmgren et al, 2006 & Kirkinen et al, 2007).

A land-use and a life cycle perspective is used which includes all emissions and uptake of the greenhouse gases carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) in the peat production and utilisation chain. The emission scenarios are described by the figure and equation given below:

Reference scenario
E.g. drained peatland (forested) emissions of greenhouse gases, mainly CO_2 and N_2O.

Harvesting stage
Emissions from the harvesting area, storage transports and harvesting equipment.

Combustion stage
Great emissions of greenhouse gases.

Aftertreatment stage
E.g. afforestation (picture) or restoration into new wetland can result in carbon accumulating system.

Figure 1. Illustration of peat utilisation scenarios

Total emissions for peat utilisation scenario =
harvesting stage + combustion stage + aftertreatment stage – reference scenario

Where;

Harvesting stage = When peat is being harvesed. All emissions from the drained harvesting area and affected surrounding area, stockpiles, harvesting equipment and transports are included. The emissions depend on harvesting time and the production technology used. The lower the net emissions during peat harvesting, the lower the climate impact of the peat utilisation alternative.

Combustion stage = The emissions due to combustion of peat are the largest source of emissions during the peat utilisation chain. The emissions from the combustion depend mainly on the carbon content of the peat but other factors influencing are combustion technology and moisture content of the peat.

Aftertreatment stage = Emissions/uptake at the peatland after harvesting depends on the aftertreatment of the cutaway. In this study two options are included, restoration into new wetland and afforestation. The lower the net emissions at the cutaway peatland, the lower the climate impact of the peat utilisation chain.

Reference scenario = This is the non-utilisation scenario represented by the pre-harvesting conditions at the peatland. Emissions from this stage are considered to be avoided in the utilisation scenario (therefore the subtraction in the equation). The type of peatland will determine the magnitude of the emissions in the reference scenario.

The equation given above is also used in the modelling of radiative forcing.

In this study the climate impact of different peat utilisation scenarios is calculated and presented both as the total emissions expressed as GWP_{100} (CO_2-equivalents/PJ peat) and as accumulated radiative forcing (mWa/m^2/PJ peat) which show the climate impact as a function of time, see section 2.1 for description of Radiative forcing and GWP.

A detailed description of the radiative forcing model used in this study is given in Holmgren et al (2006). The model has been updated by the latest information on carbon cycling given in IPCC (2007). In addition the model now also includes the indirect effects of methane (through formation of stratospheric water vapour and due to increase of tropospheric ozone). The model does not consider an increasing background concentration of greenhouse gases in the atmosphere (see Holmgren et al, 2006 for a discussion on this topic).

2.1 Analytical tools to calculate the climate impact – GWP vs. Radiative Forcing

2.1.1 Definition of radiative forcing

Radiative forcing is a measure of how the energy balance of the Earth-atmosphere system is influenced when factors that affect climate are altered. The word radiative is used since these factors change the balance between incoming solar radiation and outgoing infrared radiation within the Earths atmosphere. The radiative balance controls the Earths surface temperature. The unit used for radiative forcing is W m^{-2} (watts per square metre). When radiative forcing from a factor or group of factors is evaluated positive, the energy of the Earth-atmosphere system is increasing leading to a warming of the system. On the contrary, negative radiative forcing leads to a decrease in energy resulting in a cooling of the system. One example of factors that affect the climate is the concentrations of greenhouse gases in the atmosphere. Increasing concentrations lead to positive radiative forcing, i.e. higher temperatures, whereas decreasing concentrations lead to negative radiative forcing and cooling.

2.1.2 Definition of GWP

The Global Warming Potential (GWP) concept was developed to compare the ability of each greenhouse gas to trap heat in the atmosphere relative to another gas. The GWP of a greenhouse gas is defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of a reference gas. The reference gas used is carbon dioxide (CO_2) and therefore GWP-weighted emissions are measured in tons of CO_2 equivalents.

2.1.3 Comparison: GWP and Radiative forcing

When describing and comparing the climate impact of energy production from different sources, greenhouse gas emissions from the combustion phase are most widely used. Emissions are calculated based on emission factors and summarised by GWP factors. For instantaneous emissions or for emissions that occur during a short time interval (such as combustion emissions) GWP-summarised emissions is an accurate and communicative measure. However, as for peat utilisation which include impacts on fluxes of greenhouse gases during long time periods, which is important to consider when comparing the climate impact from a LCA perspective, the GWP concept might be misleading. This since GWP describes what climate impact an *instantaneous* emission of 1 kg gas has *over a specific time perspective* compared to 1 kg CO_2. In section 6.4 we summarise emissions of different greenhouse gases occurring over long time periods and then multiply the result by appropriate GWP factors in order to get it in comparable CO_2 equivalents. The GWP summarised emissions are compared to modelled radiative forcing resulting from the same emission scenarios. The GWP factors used in this study are the ones valid for 100 years time frame and given in IPCC (2007), i.e. 25 for methane and 298 for nitrous oxide.

The concept of radiative forcing is better suited for comparing the climate impact of a system such as LCA climate impact of peat utilisation. The radiative forcing describes how a certain emission scenario affects the radiation balance in atmosphere in every instant moment and is closely related to expected temperature change in the atmosphere. Radiative forcing is an absolute measure and not a relative one such as the GWP, and it shows the climate impact as a function of time and makes it possible to estimate the climate impact for both short and long time perspectives in the same figure. Radiative forcing calculations takes into consideration both the effectiveness of trapping outgoing infrared radiation (warming of the atmosphere) of the different gases and the atmospheric lifetime of the gases. The higher the net emissions, the higher the radiative forcing and the greater the warming of the atmosphere.

2.2 The importance of the time perspective

The time perspective is crucial for the assessment of the climate impact of peat utilisation. The dominant source of emissions in all energy peat utilisation scenarios is the combustion phase where emissions occur within a short time period (20 years). However, as shown in this and previous studies, the combustion related emissions may under certain conditions be more or less compensated for by decreased emissions at the cutaway peatland compared to the situation before peat harvesting. Since these sources and sinks usually are extended in time it is of great importance what time perspective that is applied. With a time perspective of just 10-20 years, the total emissions from peat utilisation will practically be equal to peat combustion emissions. With a longer time perspective (several decades or centuries) also emissions and sinks due to land-use change will have an impact as the greenhouse gas fluxes from the land area before and after peat harvesting may have time to compensate the combustion related emissions significantly. A longer time perspective may thus provide a more complete assessment of the total climate impact of peatland utilisation. However, a long time perspective increases the uncertainty since the prevailing conditions at the land area most likely will change over time and hence the assumed emission levels might be impacted by changed conditions.

As shown in Holmgren et al (2007) the time perspective is important also when comparing climate impact of energy production from biofuels with other fuel alternatives. For instance energy from wood residues (e.g. logging residues) has, from a life cycle perspective, a climate impact comparable to the climate impact of natural gas the first 15-20 years but substantially lower in the long run. Despite this, wood fuels are associated with an emission factor of 0 in the EU Emission Trading Scheme. The main reason for this is probably that emissions from forest biomass is reported in the land-use sector and hence uptake in the form of forest growth and emissions in form of cuttings. To also report emissions from combustion would result in double counting. Hence, when CO_2 from the cut wood actually is released to the atmosphere it is not reported and the fact that different utilisation of the wood leads to different climate impact is not considered. This way of reporting means that growth is said to compensate for cuttings. Indirectly, this is a simplified life cycle approach where a time perspective is applied.

We find it appropriate to use a life cycle perspective (including land-use changes) and assess the climate impact also over a longer time when comparing climate impact from different energy sources. In this study, radiative forcing is used to express the climate impact of peat utilisation as a function of time, which makes it easy to assess the climate impact at different time perspectives.

However, early emission reductions may be crucial to combat climate change. Energy systems that lead to fast reductions of emissions may be as important to stop the accelerating global warming, as long term reductions. What time perspective that should be used when assessing the climate impact of different energy sources is thus a complex question and is political in nature. When building a sustainable energy system, climate impact both on short and long time range should be considered.

3 Peat utilisation scenarios

This chapter gives an overview of the different peat utilisation scenarios that are analysed in this study. A detailed description of the emissions of greenhouse gases associated with each stage of the peat utilisation chains is given in Chapter 4. All input data of greenhouse gas emissions for the climate impact calculations of the different scenarios are also given in Appendix. The results of the climate impact calculations (emissions and radiative forcing) are presented in Chapter 6.

3.1 Pristine mire – restoration into new wetland

It is estimated that 25-30 % of present energy peat production in Sweden takes place at originally pristine mires (Nilsson & Zetterberg, 2005). In this study peat harvesting from pristine mires is used for representing present conventional peat production with rather high climate impact. Since emissions/uptake at pristine mires varies greatly between different mire types, two scenarios have been used in this study:

- Minerotrophic mire (fen) – conventional peat production and utilisation – restoration
- Ombrotrophic mire (bog) – conventional peat production and utilisation – restoration

In order to limit the number of scenarios restoration is the only aftertreatment alternative considered for pristine mires in this study. It is assumed that pristine mires in most cases will be restored into new wetland due to preservation of that nature type and for biodiversity purposes. The climate impact of pristine mire – afforestation scenarios have been estimated in previous studies (Nilsson & Nilsson, 2004; Zetterberg et al, 2004).

The input data for the pristine mire scenarios is summarised in Table 7 in the Appendix.

3.2 Drained forested peatland – afforestation

In this study, two types of drained forested peatlands are distinguished; high fertility and low fertility, since the soil emissions and forest productivity have shown to differ significantly between peatlands with different fertility (see Chapter 4). These two categories will to some extent represent the upper and lower range of greenhouse gas fluxes from drained forested peatlands in Sweden. Calculations are made for peat production both with the conventional milling method and with a new method called the biomass-dryer method. Only afforestation is considered as aftertreatment for these scenarios.

The following scenarios are analysed in the study:

- Drained forested peatland (low fertility) – conventional peat production – afforestation
- Drained forested peatland (high fertility) – conventional peat production – afforestation
- Drained forested peatland (low fertility) – new production method – afforestation
- Drained forested peatland (high fertility) – new production method – afforestation

The input data for these scenarios is summarised in Table 8 in the Appendix.

3.3 Drained cultivated peatland – afforestation

The emissions from cultivated peatlands depend on the land-use, i.e. type of cropping system, need for fertilisation etc. Based on average emissions for different cropping systems and the current land-use of cultivated peatlands in Sweden a single scenario is used to represent cultivated peatlands in Sweden. Calculations are made for both the conventional milling method and the new production method. Only afforestation is considered as aftertreatment for these scenarios.

The following scenarios are analyzed in the study:

- Drained cultivated peatland – conventional peat production – afforestation
- Drained cultivated peatland – new production method – afforestation

The input data for these scenarios is summarised in Table 9 in the Appendix.

3.4 Best case scenarios

Two best case scenarios are made for drained forested peatlands and cultivated peatlands and are compared to a scenario where only emissions from peat combustion (using the emission factor used in EU ETS, 106 g CO_2/MJ). In the best case scenarios the higher range in the emission estimates for the drained peatlands are used instead of average emissions and the new production method is assumed. The following scenarios are made:

- Drained forested peatland (best case) – new production method – afforestation
- Cultivated peatland (best case) – new production method – afforestation
- Only peat combustion emissions

The results of the calculations for the best case scenarios are presented in Chapter 8 and the input data is summarised in Table 10 in the Appendix.

3.5 Early shut down of peat production areas

Two scenarios are made to estimate the climate impact of early shut down of peat cutting and delayed aftertreatment:

- Pristine mire – interrupted conventional peat production – restoration
- Pristine mire – interrupted conventional peat production – afforestation

Calculations are also made for the same scenarios but where the interrupted peat production is replaced with combustion of coal:

- Pristine mire – interrupted conventional peat production – restoration (coal)
- Pristine mire – interrupted conventional peat production – afforestation (coal)

The scenarios are explained separately in Chapter 5.1 and the input data is summarised in Table 7 in the Appendix.

3.6 Coal utilisation

A scenario where the same amount [in MJ] of coal is combusted has been included as a comparison to the peat utilisation scenarios. The scenario includes life cycle emissions of greenhouse gases from coal production, transportation and utilisation.

The input data for this scenario is summarised in Table 11 in the Appendix.

4 Emissions of greenhouse gases in the peat utilisation chain

In this chapter emissions and uptake of greenhouse gases at the different stages of the peat utilisation chains are compiled from the scientific literature. The emission inventory gives the background to the representative emission estimates that are selected for the scenario-calculations in this study. The applied emission estimates for each stage are summarised at the end of each section.

4.1 Reference scenario - before harvesting

4.1.1 Pristine mire

Emissions and uptake of greenhouse gases from pristine mires (not subject to human impact, such as drainage) can differ significantly between different mire types but also varies substantially with climatic conditions. Wet conditions favour carbon accumulation and CH_4 emissions. In this study two main types of pristine mires are considered: nutrient poor, ombrotrophic mire (bog) and nutrient rich, minerotrophic mire (fen). Bogs are generally older than fens and are less fertile as most of the nutrients are supplied by rainwater. Fens are generally in a younger stage and are fed with nutrients mainly from groundwater and surrounding areas.

CO_2 emissions and uptake
Studies of CO_2 fluxes from pristine mires indicate that they can be either net sources or net sinks of CO_2, and the measurements show great variability between sites and years. In a Finnish research program "Greenhouse impacts of the use of peat and peatlands in Finland" during 2001-2005 (hereafter Finnish peat research program), numerous emission measurements from different peatland types has been performed. Saarnio et al (2007), a review of available studies of annual CO_2 and CH_4 fluxes from boreal ombrotrophic and minerotrophic mires, shows that the average net flux of CO_2 from (emission) boreal ombrotrophic mires is 55 ± 230 g CO_2 m^{-2} yr^{-1} and the average net uptake on boreal minerotrophic mires is 55 ± 190 g CO_2 m^{-2} yr^{-1}. These results are in accordance with new measurement from ombrotrophic mires (raised bog) and minerotrophic mires (fen lagg) in southern Finland (Saarnio et al, 2007). The new measurements were made during 2.5 years and then a time series were calculated by simulations with 30 years of weather data. The results showed an average emission of approximately 150 g CO_2 m^{-2} yr^{-1} from the raised bog and an average uptake of about 230 g CO_2 m^{-2} yr^{-1} at the minerotrophic site (Saarnio et al, 2007). This is in contrast to previous LCA studies where a small uptake of 50-80 g CO_2 m^{-2} yr^{-1} was assumed for both bogs and fens (Nilsson & Nilsson, 2004 and Zetterberg et al, 2004). The estimates used in these previous studies were based on long time average fluxes.

In this study, the average values given in Saarnio et al (2007) for boreal ombrotrophic and minerotrophic mires, i.e. 55 g CO_2 m^{-2} yr^{-1} (ombrotrophic) and -55 g CO_2 m^{-2} yr^{-1} (minerotrophic) have been used.

CH_4 emissions

According to numerous studies reviewed in Saarnio et al (2007) emissions of CH_4 are generally higher from minerotrophic mires than from ombrotrophic mires. The average emission for minerotrophic mires is 17 ± 13 g CH_4 m^{-2} yr^{-1} and for ombrotrophic mires 7 ± 5 g CH_4 m^{-2} yr^{-1}. A comprehensive study (Nilsson et al, 2001) of CH_4 emissions from more than 600 Swedish mires is included in this review, which concludes that the emission varies between 2-40 g CH_4 m^{-2} yr^{-1} and differs not only between mire types but also widely between regions. For minerotrophic mires the emissions are generally greater in the north but for ombrotrophic mires no clear north-south trend is observed. Based on Nilsson et al (2001), Nilsson & Nilsson (2004) uses an emission of 6-23 g CH_4 m^{-2} yr^{-1} for minerotrophic mires (fens) in the calculations and 3.5-8 g CH_4 m^{-2} yr^{-1} for ombrotrophic mires (bogs). A best estimate of an average emission of 23 (15-31) g CH_4 m^{-2} yr^{-1} at pristine mires was used in Kirkinen et al (2007) based on the findings in the Finnish peat research program.

As representative averages for Swedish ombrotrophic and minerotrophic mires, the values 7 g CH_4 m^{-2} yr^{-1} and 17 g CH_4 m^{-2} yr^{-1} respectively are used in this study, based on Saarnio et al (2007) and Nilsson et al (2001).

N_2O emissions

Kasimir-Klemedtsson et al (2001) concludes that the emissions of N_2O from pristine mires are negligible. Measurements made by von Arnold (2004) and von Arnold et al (2005) at a minerotrophic mire in southern Sweden showed net emissions of N_2O of 20-30 mg m^{-2} yr^{-1}.

In this study, the N_2O emissions from pristine mires are assumed to be negligible.

4.1.2 Drained forested peatland

The net fluxes of greenhouse gases at drained forested peatlands vary widely between different sites. The CO_2 emissions from decomposition of peat vary with climate, drainage effectiveness, and fertility of the peatland. N_2O emissions may be significant at sites with high fertility (low C/N-ratio) and are lower in coniferous forests than in deciduous forests (von Arnold, 2004; von Arnold et al, 2005). The total balance also depends on carbon uptake in growing forest, which is much higher in the south than in the north and on peatlands with high fertility than in peatlands with low fertility. Due to great variability and differences due to different local conditions it is therefore difficult to find generalized emission factors that are representative for Swedish conditions for this type of peatland.

In this study, two types of drained forested peatlands are distinguished (based on Alm et al, 2007):

- Peatlands with high fertility
- Peatlands with low fertility

These two types will to some extent represent the upper and lower range of greenhouse gas fluxes from drained forested peatlands. It is, however, in this study not distinguished between northern sites and southern sites. Instead averages for Sweden as a whole is used. According to Minkkinen et al (2007) the annual CO_2 emissions may be higher in the north than in the south, but von Arnold (2004) and von Arnold et al (2005) could not find a significant difference between climatic zones.

How emissions and uptake of greenhouse gases at drained forested peatlands differ between regions is more thoroughly analysed in Nilsson & Nilsson (2004).

4.1.2.1 Soil emissions

CO_2 emissions
According to Finnish measurements that have been simulated with 30-years weather data from southern Finland, the CO_2 emissions from drained forested peatlands are 719-1911 g CO_2 m^{-2} yr^{-1}, being 880 g CO_2 m^{-2} yr^{-1} on average for low fertility sites and 1713 g CO_2 m^{-2} yr^{-1} for high fertility sites (Alm et al, 2007). These values are in accordance with measurements from drained forested peatlands in southern Sweden where average emissions of 900-1900 g CO_2 m^{-2} yr^{-1} were found (von Arnold, 2004; von Arnold et al, 2005). However, due to the chamber technique used in the measurements these figures also include emissions from root activity, which should be subtracted to get emissions from peat decomposition only. According to Olsson (2006) the CO_2 emissions from peat decomposition (heterotrophic respiration) at drained forested peatlands in southern Sweden were 257-1111 g CO_2 m^{-2} yr^{-1} based on von Arnold (2004) and von Arnold et al (2005). The average emission of CO_2 due to peat decomposition for high fertility peatlands was 818 g CO_2 m^{-2} yr^{-1} and for low fertility peatlands 458 g CO_2 m^{-2} yr^{-1}.

In this study, the CO_2 emissions at drained forested peatlands with low fertility are assumed to be 458 g CO_2 m^{-2} yr^{-1} and with high fertility 818 g CO_2 m^{-2} yr^{-1}, based on Olsson (2006), von Arnold (2004) and von Arnold et al (2005).

N_2O emissions
According to Finnish measurements that have been simulated with 30-years weather data from southern Finland, the N_2O emissions from drained forested peatlands are 0-0.81 g N_2O m^{-2} yr^{-1}, being 0.009 g N_2O m^{-2} yr^{-1} on average for low fertility sites and 0.56 g N_2O m^{-2} yr^{-1} for high fertility sites (Alm et al, 2007). A clear relationship between fertility and N_2O emissions have also been found by Klemedtsson et al (2005) where the C/N-ratio is used to predict N_2O emissions. For low fertility (C/N >25) and for high fertility (C/N ~18) sites the average N_2O emissions were 0.02 g N_2O m^{-2} yr^{-1} and 0.5 g N_2O m^{-2} yr^{-1}, respectively. The N_2O emissions at drained forested peatlands also seem to depend on the tree specie, being about ten times higher under deciduous forest (0.2-1.1 g N_2O m^{-2} yr^{-1}) than under coniferous forest (0.04-0.09 g N_2O m^{-2} yr^{-1}) according to Swedish measurements given by von Arnold (2004) and von Arnold et al (2005).

In this study, the N_2O emissions at drained forested peatlands with low fertility are assumed to be 0.01 g N_2O m^{-2} yr^{-1} and with high fertility 0.5 g N_2O m^{-2} yr^{-1}, based on Alm et al (2007) and Klemedtsson et al (2005).

CH_4 emissions
The CH_4 emissions from drained forested peatlands are generally small or even negative at well drained sites. According to Finnish measurements that have been simulated with 30-years weather data from southern Finland, the CH_4 emissions from drained forested peatlands are -0.82 - 3.5 g CH_4 m^{-2} yr^{-1} (Alm et al, 2007). Including estimated emissions from ditches (0.2-0.4 g CH_4 m^{-2} yr^{-1}) the average for low fertility sites an emission of 2.1 g CH_4 m^{-2} yr^{-1} and for high fertility sites an uptake of 0.2 g CH_4 m^{-2} yr^{-1}. Swedish measurements have reported similar figures, 0-1.6 g CH_4 m^{-2} yr^{-1} (von Arnold, 2004; von Arnold et al, 2005).

In this study, the CH_4 emissions at drained forested peatlands are assumed to be negligible for low fertility sites and 2 g CH_4 m^{-2} yr^{-1} for high fertility sites, mainly based on Alm et al (2007).

4.1.2.2 Carbon sequestration in growing forest

The carbon uptake in living biomass depends on the forest productivity at the drained forested peatland. At well-drained peatlands with high fertility the productivity can be very high, comparable to mineral soils. However, at poor and poorly drained peatlands the forest productivity may be very low. There is also a large difference in productivity between climatic regions, being twice as high in southern Sweden compared to northern Sweden (Hånell, 1991). Forest productivity of drained peatland in Sweden compared to average productivity for mineral soils is shown in Table 1.

Table 1 Forest productivity of drained peatland in Sweden compared to average productivity for mineral soils. Source: Johanssonrapporten (2006) based on Hånell (1991).

		Average productivity [m^3 ha^{-1} yr^{-1}]	
		Drained peatlands	**Mineral soils**
South of Sweden (Götaland)	High fertility	9.2 (6.9-11.4)	8.7
	Medium fertility	7.2 (4.4-9.9)	
	Low fertility	4.6 (2.4-6.7)	
Middle of Sweden (Svealand)	High fertility	7.7 (5.9-9.4)	6.3
	Medium fertility	6.3 (3.6-8.9)	
	Low fertility	3.8 (1.8-5.8)	
North of Sweden (Norrland)	High fertility	4.4 (2.5-6.3)	2.6-4.4
	Medium fertility	3.6 (1.2-5.9)	
	Low fertility	2.4 (1.0-3.7)	
Swedish average 1)	High fertility	7.1	6.2
	Low fertility	3.6	

1) Calculated from the averages given in the table for southern, middle and northern Sweden.

It is the difference in forest productivity before and after peat harvesting that is of importance for the climate impact scenarios. In this study the productivity at drained forested peatlands before harvesting is assumed to be 7.1 m^3 ha^{-1} and 3.6 m^3 ha^{-1} for peatlands with high and low fertility respectively, based on Hånell (1991). This corresponds to an uptake of 820 g CO_2 m^{-2} yr^{-1} and 416 g CO_2 m^{-2} yr^{-1}, respectively.[1] The absolute figures are not valid for all sites in Sweden (for instance in the north) but again, it is the relative increase (or decrease) in productivity after afforestation of the cutaway peatland that is of importance. In this study the forest productivity at the cutaways after afforestation is assumed to be 7.1 m^3 ha^{-1} (see section 4.4.2.3).

4.1.2.3 Carbon sequestration in soil

The carbon accumulation in soil organic matter is assumed to be zero at drained forested peatlands before harvesting. This since it is assumed that equilibrium between accumulation of new litter and decomposition of old litter has been reached at these sites.

4.1.3 Drained cultivated peatland

Drained cultivated peatlands can be large sources of both CO_2 and N_2O. The emissions vary with land-use, suggesting that soil management practices associated with different crops has a major

---

[1] Based on the following assumptions: dry density of stem wood = 420 kg m^{-3}, carbon content in stem wood = 50 %, total standing biomass in thinnings and final cutting (inclusive stem, branches, needles, stump and roots) is 1,5 times the stem biomass. Total uptake [kg C ha^{-1} $year^{-1}$] = 1,5 * 420 * 0,5 * productivity. This assumption is based on previous studies, i.e. Nilsson & Nilsson (2004).

influence on the emissions. This is shown in a number of Swedish and Finnish measurement studies (Maljanen et al 2007, Kasimir-Klemedtsson et al 1997, Maljanen et al 2004 and Regina et al 2004). The previous study on LCA emissions and climate impact of peat utilisation by Nilsson & Nilsson (2004) based their estimates of greenhouse gas emissions from cultivated peatlands on Kasimir-Klemedtsson et al (1997), Maljanen et al (2004) and Regina et al (2004). Average emissions of CO_2, N_2O and CH_4 cultivated peatlands with different crops according to Maljanen et al (2007) compared to the values used in Nilsson & Nilsson (2004) are shown in Table 2.

Table 2 Greenhouse gas emissions from cultivated peatlands with different land-use.

Land use	**[g m^{-2} yr^{-1}]**			**Reference**
	CO_2	**N_2O**	**CH_4**	
Cereals	2083 ± 1144	1.7 ± 0.9	-0.07	Maljanen et al (2007)
	2000	2.5	0	Nilsson & Nilsson (2004) based on: Kasimir-Klemedtsson et al (1997) Regina et al (2004)
Grass	1485 ± 1023	0.9 ± 0.5	0.09	Maljanen et al (2007)
	1100	1.0	0	Nilsson & Nilsson (2004) based on: Kasimir-Klemedtsson et al (1997)
Fallow (no plants)	2167 ± 1386	2.6 ± 2.2	0.3	Maljanen et al (2007)
Abandoned (mixed vegetation)	1188 ± 917	1.3 ± 1.4	-0.22	Maljanen et al (2007)
Row crops	7000	1.5	0	Nilsson & Nilsson (2004) based on: Kasimir-Klemedtsson et al (1997) Regina et al (2004) [1)]

1) No measurements were made in Maljanen et al (2007) for row crops.

Berglund & Berglund (2008) has surveyed the land use of organic agricultural soils in Sweden 2003. Of the total area of agricultural soil in Sweden (~ 3.5 million hectares) approximately 7 % was on peat and shallow peat. Of the peat and shallow peat soils about 24 % was used for annual crops (e.g. cereals), 36 % for pasture plants (grass), 38 % for extensive use (fallow and pasture) and 1 % for row crops.

In this study, the average values from Maljanen et al (2007) for the following cropping categories have been used: cereals, grass, fallow and abandoned. For row crops, the estimates given in Nilsson & Nilsson (2004) have been used. Weighted averages based on the land-use inventory made by Berglund & Berglund (2008) have been made. The land-use category 'extensive use' is assumed to correspond to the emissions from fallow and abandoned land in equal proportions. These assumptions results in average values for cultivated Swedish peatlands of 1780 g CO_2 m^{-2} yr^{-1} and 1.5 g N_2O m^{-2} yr^{-1}. CH_4 emissions are assumed to be negligible.

4.1.4 Summary of emissions before harvesting (reference scenario)

The emissions at the peatland before harvesting are dependent on type of peatland and the current land-use. In Table 3 the greenhouse gas emissions used in this study to represent different peatlands are summarised. They represent our best estimates of averages for Swedish peatlands based on available literature, but it is important to point out that the emissions are dependent on many factors and that the actual emissions from an individual site may be either higher or lower than these average figures.

Table 3 Summary of greenhouse gas emissions used in this study for different peatlands before harvesting. Positive value means emission and negative value means uptake.

Peatland	**Emissions used in this study**			**Main reference and range**		
	[g m^{-2} yr^{-1}]			**[g m^{-2} yr^{-1}]**		
	CO_2	**N_2O**	**CH_4**	**CO_2**	**N_2O**	**CH_4**
Pristine mire				Saarnio et al (2007)		
Ombrotrophic (bog)	55	very small	7	-175 - 285	-	2 - 12
Minerotrophic (fen)	-55	very small	17	-245 - 135	0-0.03	4 - 30
Drained forested peatland						
Soil emissions				Olsson (2006), Alm et al (2007)		
High fertility	818	0.5	0	257-1111	0.3-0.81	-0.4-0.0
Low fertility	458	0.01	2		0-0.018	-0.1-3.7
Carbon sequestration in living biomass				Hånell (1991)		
High fertility	-820	-	-	-290--1310		
Low fertility	-416	-	-	-120--770		
Soil carbon sequestration	0	-	-			
Drained cultivated peatland				Maljanen et al (2007) & Berglund & Berglund (2008)		
Soil emissions	1780	1.5	0	270 – 3550 (7000)	-0.1-4.8	-0.22-0.3

4.2 During harvesting – production stage

In this study, the energy peat production is assumed to be done with the traditional milling method, which is described in chapter 4.2.1. Calculations are also made for a few peat scenarios based on a new harvesting method under development called the biomass dryer (described in chapter 4.2.2).

4.2.1 Conventional peat production – milling method

Before peat harvesting can start, all vegetation is removed, and the site is effectively drained. In the conventional milling method a thin granular layer of fine peat "dust" is milled at a time, which is then dried on the surface of the field to a moisture content of approximately 45 %. Dry peat is then ridged on the middle of the strip before actual collection and storage in stockpiles at the side of the extraction area.

Emissions during the peat production stage include emissions from the drained extraction area and any surrounding area affected by the drainage, from stockpiles and from harvesting equipment and transports.

The following assumptions are made in this study:

- **Drainage time before peat harvesting**
  Prior to harvesting the peatland must be drained to decrease the water content. The drainage time is assumed to be 2 years before harvesting for pristine mires and drained forested peatlands. At drained cultivated peatlands it is assumed that no further drainage is required before harvesting. Forested peatlands are also drained, but after the trees are removed the water table will rise, and additional drainage is assumed to be necessary before harvesting.

- **Harvesting time**
  After the drainage stage peat harvesting is assumed to take 20 years to complete. Harvested peat is continuously combusted during the harvesting period (see section 4.3).
- **Moisture content**

  The moisture content of the peat is assumed to be 45 % after drying (when delivered).
- **Surrounding area**
  Drainage of the extraction area also affects a surrounding area outside the circumference ditches. For already drained peatlands the impact of the surrounding area is assumed to be minor, but for pristine mires the surrounding area affected by the drainage is assumed to be 50 % the size of the extraction area. The peat depth at the surrounding area is on average assumed to be half the depth at the extraction area (1 m). These assumptions are based on the best estimates made by Holmgren et al (2006).

4.2.1.1 Emissions from peat harvesting area

CO_2 emissions
According to Alm et al (2007) the annual average emission of CO_2 due to peat oxidation from milled peat harvesting areas in southern Finland is 980 g CO_2 m^{-2} yr^{-1}. The value is based on measurements and simulations with 30 years weather data. Swedish estimates by Sundh et al (2000) included only summer time emissions and were 400-1020 g CO_2 m^{-2} yr^{-1} for southern regions and 230-720 g CO_2 m^{-2} yr^{-1} for northern regions. According to Alm et al (2007) the winter time emissions were estimated to 280 g CO_2 m^{-2} yr^{-1}. According to this, the value used in Nilsson & Nilsson (2004) of 1000 g CO_2 m^{-2} yr^{-1} is in accordance with both Sundh et al (2000) and Alm et al (2007).

The emissions from the peat harvesting area may depend on what the emissions were before peat harvesting, but it is not described by Alm et al (2007) what the emissions were on the sites before harvesting. Nilsson & Nilsson (2004) assumes that for drained peatlands with initially high emissions the emissions stay constant on the higher level throughout the harvesting period. Measurements in an unpublished study by Silvan & Laine however, indicates that the emissions of greenhouse gases may decrease significantly during harvesting, possibly explained by the removal of active micro organisms when the peat is removed.

In this study, the emissions during harvesting are assumed to be 980 g CO_2 m^{-2} yr^{-1}, based on Alm et al (2007). For pristine mires and drained forested peatlands the CO_2 emissions are assumed to increase linearly during the drainage stage (2 years) to reach 980 g CO_2 m^{-2} yr^{-1} at the beginning of peat harvesting and stay on that level throughout the harvesting period. For cultivated peatlands the emissions of CO_2 are assumed to decrease linearly to 980 g CO_2 m^{-2} yr^{-1} after 10 years of harvesting and then stay constant on that level throughout the whole harvesting period.

CH_4 emissions
CH_4 emissions at the harvesting area mainly origin from ditches. According to Finnish measurements presented in Alm et al (2007) the average emission of CH_4 from the harvesting areas (including ditches) is 7.2 g CH_4 m^{-2} yr^{-1} (summer 0.3-9.1 g CH_4 m^{-2} yr^{-1} and winter 1.2 g CH_4 m^{-2} yr^{-1}). Swedish measurements have reported summer emissions of 0.4-4.5 g CH_4 m^{-2} yr^{-1} from peat harvesting areas (Sundh et al, 2000). Nykänen et al (1996) have reported similar emissions from harvesting areas (1.3-5.3 g CH_4 m^{-2} yr^{-1}).

In this study, the emissions during harvesting are assumed to be 3.7 g CH_4 m^{-2} yr^{-1}, which is the average given by Sundh et al (2000) plus winter emissions according to Alm et al (2007). For pristine mires and drained forested peatlands the CH_4 emissions decrease/increase linearly during drainage stage to reach 3.7 g CH_4 m^{-2} yr^{-1} at the beginning of peat harvesting and stay on that level throughout the whole harvesting period. For cultivated peatlands 3.7 g CH_4 m^{-2} yr^{-1} is assumed throughout the whole harvesting period.

N_2O emissions

According to measurements by Alm et al (2007) the average N_2O emission from peat harvesting areas (including ditches) is 0.31 g N_2O m^{-2} yr^{-1} (summer 0.06-0.5 g N_2O m^{-2} yr^{-1} and winter 0.05 g N_2O m^{-2} yr^{-1}). Nilsson & Nilsson (2004) assumed emissions of 0.1-0.5 g N_2O m^{-2} yr^{-1} during harvesting, depending on initial emissions at the peatland.

In this study, the emissions during harvesting are assumed to be 0.3 g N_2O m^{-2} yr^{-1}, based on Alm et al (2007). For pristine mires and drained forested peatlands with low fertility the N_2O emissions are assumed to increase linearly during the drainage stage (2 years) to reach 0.3 g N_2O m^{-2} yr^{-1} at the beginning of peat harvesting and stay on that level throughout the harvesting period. For drained forested peatlands with high fertility the initial N_2O emissions are assumed to stay constant during drainage stage and then decrease linearly to 0.3 g N_2O m^{-2} yr^{-1} during the first 5 years of harvesting to stay constant on that level throughout the whole harvesting period. For cultivated peatlands the N_2O emissions are assumed decrease linearly to reach 0.3 g N_2O m^{-2} yr^{-1} after 10 years of harvesting and then stay constant on that level throughout the whole harvesting period.

4.2.1.2 Emissions from surrounding area (pristine mires)

The emissions at the surrounding area (considered for pristine mires only) are assumed to be the same as for the harvesting area initially, but the N_2O emissions declines to 0.08 g N_2O m^{-2} yr^{-1} during the five first years of harvesting. This is the same assumption as in Nilsson & Nilsson (2004).

4.2.1.3 Emissions from stockpiles

The CO_2 emissions from stockpiles have been estimated to 250 ± 125 g CO_2 m^{-2} yr^{-1} (per peat harvesting area) according to Kirkinen et al (2007) based on Finnish measurements in Nykänen et al (1996). This is also in accordance with measurements in Alm et al (2007). In this study 250 g CO_2 m^{-2} yr^{-1} will be used for all peatland types with the milling method.

The CH_4 emissions from stockpiles are 19.5 g CH_4 m^{-2} yr^{-1} (per stockpile area) according to Alm et al (2007). Since the area of the stockpiles is very small compared to the harvesting area the CH_4 emissions are assumed to be negligible in the study.

N_2O emissions from stockpiles are assumed to be negligible, based on Alm et al (2007).

4.2.1.4 Emissions from harvesting equipment and transports

In this study we have used the same estimates of emissions from harvesting equipment and transports as Nilsson & Nilsson (2004) and Zetterberg et al (2004). The emission estimates are 1 g CO_2, 0.7 mg CH_4 and 0.025 mg N_2O per MJ peat.

4.2.2 New production method – biomass dryer

In the new peat production method peat is harvested with an excavator, pumped directly to a separate (asphalted) peat drying field (biomass drier), spread onto the biomass dryer with a special tractor-pulled spreader cart and finally collected with a traditional collector cart. The drying is much faster and more effective than in the traditional milling method and the final product is small-sized sod peat with a moisture content of about 30 %. Since a small area is completely harvested at a time no effective drainage is needed and the vegetation cover can be kept at the peat harvesting area until the harvesting starts. With the new method almost no residual peat is left at the harvesting area. According to Silvan (2005) and Silvan (pers. comm.) the harvesting capacity is 10 to 20 times larger with the new method and emissions during harvesting is reduced significantly compared to the milling method due to more efficient harvesting and lower stockpile emissions.

The following assumptions are made for scenarios with the new production method:

- The same peatland area will be harvested in 1 year instead of 20 years[2]
- No drainage is needed and vegetation is not removed until the harvesting starts
- The moisture content of the peat will be 30 % after drying instead of 45 %
- A residual peat layer of 5 cm is left after harvesting instead of 20 cm

4.2.2.1 Emissions from peat harvesting area

The whole area is assumed to be completely harvested during the same year. The emissions from the harvesting area during the harvesting year are assumed be 770 g CO_2 m^{-2} yr^{-1}, 0.1 g N_2O m^{-2} yr^{-1} and 0 g CH_4 m^{-2} yr^{-1} (see also chapter 4.4.2.2).

4.2.2.2 Emissions from stockpiles

According to measurements in an unpublished study by Silvan & Laine the CO_2 emissions from stockpiles and drying areas in the biomass dryer are only 6-10 % of the emissions from milling method stockpiles. CH_4 and N_2O emissions are also significantly lower. Based on that, the CO_2 emissions from stockpiles with the new method are in this study assumed to be 8 % of 250 g CO_2 m^{-2} yr^{-1}, which corresponds to 20 g CO_2 m^{-2} yr^{-1}. Emissions of CH_4 and N_2O are assumed to negligible. Since it is assumed that the same peatland area is harvested and combusted in 1 year instead of 20 years, also the emissions from stockpiles are assumed to take place in 1 year instead of 20 years.

Thus, the CO_2 emissions from stockpiles are in the calculations assumed to be 400 g CO_2 m^{-2} yr^{-1} during one year.

4.2.2.3 Emissions from harvesting equipment and transports

Due to more efficient harvesting and dryer and more compact peat, emissions from harvesting equipment and transports are assumed to be half the emissions with the new production method compared to traditional peat harvesting (same assumption as used in Kirkinen et al, 2007), which corresponds to 0.5 g CO_2, 0.35 mg CH_4 and 0.012 mg N_2O per MJ peat.

---

[2] Production efficiency is according to tests 10-20 times higher than for the milling method, corresponding to a harvesting period of 1-2 years (Silvan & Laine, unpubl.) and (Silvan, personal communication). Calculating with 1 or 2 years will have a minor impact on the result.

4.2.3 Summary of emissions at the production stage

The emissions during the production stage derive from the drained harvesting area, any affected surrounding area, stockpiles and from harvesting equipment and transports. The emissions from the production stage used in the calculations are summarised in Table 4.

For all scenarios it is assumed that the average peat depth at the harvesting area is 2.1 m (mineable 1.9 m) and each square meter is assumed to contain 150 MJ peat[3], based on Nilsson & Nilsson (2004).

Table 4 Summary of greenhouse gas emissions during the production stage used in this study.

	Pristine mires	**Forested drained peatland**		**Drained cultivated peatland**	**Main reference and range**
		Low fertility	**High fertility**		
Conventional peat harvesting (milling method)					
Harvesting area during drainage stage (2 years)	Lin. increase/ decrease from initial value to 980 g CO_2 m^{-2} yr^{-1} 3.7 g CH_4 m^{-2} yr^{-1} 0.3 g N_2O m^{-2} yr^{-1}	Lin. increase from initial value to 980 g CO_2 m^{-2} yr^{-1} 3.7 g CH_4 m^{-2} yr^{-1} 0.3 g N_2O m^{-2} yr^{-1}	Lin. increase from initial value to 980 g CO_2 m^{-2} yr^{-1} 3.7 g CH_4 m^{-2} yr^{-1} Initial emissions of N_2O	Not applicable since no drainage stage for these scenarios.	Alm et al (2007)
Harvesting area (20 years)	980 g CO_2 m^{-2} yr^{-1} 3.7 g CH_4 m^{-2} yr^{-1} 0.3 g N_2O m^{-2} yr^{-1}	980 g CO_2 m^{-2} yr^{-1} 3.7 g CH_4 m^{-2} yr^{-1} 0.3 g N_2O m^{-2} yr^{-1}	980 g CO_2 m^{-2} yr^{-1} 3.7 g CH_4 m^{-2} yr^{-1} linear decrease to 0.3 g N_2O m^{-2} yr^{-1}	Linear increase or decrease to 980 g CO_2 m^{-2} yr^{-1} 3.7 g CH_4 m^{-2} yr^{-1} 0.3 g N_2O m^{-2} yr^{-1}	Alm et al (2007), Sundh et al (2000) 504-1490 g CO_2 m^{-2} yr^{-1} 1.6-5.7 g CH_4 m^{-2} yr^{-1} 0.1-0.55 g N_2O m^{-2} yr^{-1}
Surrounding area (2+20 years)	Emissions same as for harvesting area. N_2O decrease after 5 years to 0.08 g N_2O m^{-2} yr^{-1}	No surrounding area is assumed	No surrounding area is assumed	No surrounding area is assumed	Assumption
Stockpiles (20 years)	250 g CO_2 m^{-2} yr^{-1} N2O and CH4 negligible				Kirkinen et al (2007) 125-375 g CO_2 m^{-2} yr^{-1}
Harvesting equipment & transports	1 g CO_2 MJ^{-1} 0.7 mg CH_4 MJ^{-1} 0.025 mg N_2O MJ^{-1}				Zetterberg et al (2004), Nilsson & Nilsson (2004)
New harvesting method (the biomass dryer)					
Harvesting area (1 year)	770 g CO_2 m^{-2} yr^{-1} 0.1 g N_2O m^{-2} yr^{-1} CH_4 negligible				Assumption based on Silvan & Laine (unpubl.), Alm et al (2007)
Stockpiles (1 year)	400 g CO_2 m^{-2} yr^{-1} N2O and CH4 negligible				Silvan & Laine (unpubl.), Kirkinen et al (2007)
Harvesting equipment & transports	0.5 g CO_2 MJ^{-1} 0.35 mg CH_4 MJ^{-1} 0.012 mg N_2O MJ^{-1}				Assumption based on Zetterberg et al (2004), Kirkinen et al (2007)

---

[3] Based on the following assumptions: Average moisture content of energy peat = 45 %, density = 330 kg m^{-3}, net calorific value = 10.28 MJ/kg (as delivered). Approx. 2 m^3 peat in undrained state is required for the production of 1 m^3 energy peat at 45 % moisture content. Average mineable peat depth = 1.9 m. With a harvesting period of 20 years the energy content at the extraction area is then 150 MJ m^{-2}.

4.3 Peat combustion – utilisation stage

4.3.1 Combustion emission factors

CO_2 emissions

As for any fuel, the CO_2 emission factor for combustion of energy peat is dependent on the moisture content of the peat. Nilsson (2004) has estimated the Swedish national average emission factor for peat to be 105.2 g CO_2 MJ^{-1}, based on a average moisture content of 45 %. This value is used in Nilsson & Nilsson (2004). With a moisture content of 30 % the corresponding emission factor would be 3-5 % lower based on Nilsson (2004) and Vesterinen (2003), or 100.0-101.8 g CO_2 MJ^{-1}. For peat bricks with a moisture content of approx. 10 %, the emission factor would be even lower (~97 g CO_2 MJ^{-1}). In the case of peat bricks you have to also consider any emissions associated with the drying method. Combustion of peat bricks is, however, not considered in this study.

In this study, an emission factor for peat combustion of 105.2 g CO_2 MJ^{-1} is used, but for the new production method where peat moisture content is 30 % an emission factor of 100.0 g CO_2 MJ^{-1} is used. An oxidation factor of 0.99 is assumed during all peat combustion, thus the emissions from peat combustion is 104.1 g CO_2 MJ^{-1} and 99.0 g CO_2 MJ^{-1} respectively.

N_2O emissions

The N_2O emissions from peat combustion depend a lot on the combustion technology, where emissions from fluidized bed combustion (FBC) is ten times higher than for other technologies (0.04 g N_2O MJ^{-1} compared to 0.004 g N_2O MJ^{-1}). An average value for Swedish power and/or heat plants is estimated to 0.006 g N_2O MJ^{-1} (Uppenberg et al, 2001), which was used in Nilsson & Nilsson (2004).

CH_4 emissions

The average CH_4 emission from peat combustion in Swedish power and/or heat plants is estimated to 0.005 g CH_4 MJ^{-1} (Uppenberg et al, 2001).

4.3.2 Summary of emissions from peat combustion

In the climate impact calculations it is assumed that peat harvesting and peat combustion is carried out during 20 years. For the scenarios where peat is harvested with the new production method (the biomass dryer), the same peatland area is assumed to be harvested and combusted in one year.

Table 5 Emission factors for combustion of peat at different moisture content. Estimates used in this study.

	Moisture content	**Emission factor [1)]**	**Main reference**
Conventional peat production (milling method)	45 %	105.2 g CO_2 MJ^{-1} 0.006 g N_2O MJ^{-1} 0.005 g CH4 MJ^{-1}	Nilsson (2004) Uppenberg et al (2001) Uppenberg et al (2001)
New production method (biomass dryer)	30 %	100 g CO_2 MJ^{-1} 0.006 g N_2O MJ^{-1} 0.005 g CH4 MJ^{-1}	Calc. from Nilsson (2004) Uppenberg et al (2001) Uppenberg et al (2001)

1) An oxidation factor of 0.99 is also used in the model.

4.4 After harvesting – aftertreatment

Two aftertreatment options are analysed in this study; afforestation or restoration into new wetland.

4.4.1 Restoration into new wetland

It is very difficult to estimate how the emissions and uptake of greenhouse gases will develop at the cutaway peatland after it has been re-wetted and restored into a new wetland. There are studies covering a few years at occasional sites, but long time series of measurements are lacking.

CO_2 uptake
When the cutaway peatland is re-wetted the CO_2 emissions from peat decomposition is likely to cease. As new vegetation is established the new wetland can function as a CO_2 sink as in many pristine mires (mainly fens). A restored wetland will probably function as a young fen, suggesting that there will be a larger net uptake of CO_2 at restored wetland than at older mires.

Based on 2-years measurements made at regenerated peat trenches 50 years after harvesting by Yli-Petäys et al (2007) an average uptake of 80 ± 190 g CO_2 m^{-2} yr^{-1} (including winter emissions) was reported. At a restored mire in southern Finland the C-gas balance was measured to an uptake of 244 ± 225 g CO_2 m^{-2} yr^{-1} 10 years after restoration, but also summer CH_4 emissions are included in these figures (Alm et al, 2007). A best estimate of an average uptake of 122 (28-270) g CO_2 m^{-2} yr^{-1} at restored mires was used by Kirkinen et al (2007) based on the findings in the Finnish peat research program. Nilsson & Nilsson (2004) assumed an uptake of 362 g CO_2 m^{-2} yr^{-1}, based on Tuittila et al (1999), but this value was based on one measurement only.

In this study, the average uptake at the restored mire is assumed to be 120 g CO_2 m^{-2} yr^{-1}, mainly based on Kirkinen et al (2007). This value is associated with large uncertainties.

CH_4 emissions
When the peatland is re-wetted the CH_4 emissions will increase. It is likely that CH_4 emissions will increase the first years after restoration, but may continue to be lower than at pristine mires even after full vegetation (Tuittila et al, 2000).

Yli-Petäys et al (2007) reported emissions of 15-47 g CH_4 m^{-2} yr^{-1} (including winter emissions of 8.5 g CH_4 m^{-2} yr^{-1}) 50 years after rewetting. According to summer time measurements from a cutaway peatland 10 years after restoration emissions of 1-11 g CH_4 m^{-2} yr^{-1} was reported (Alm et al, 2007).

Both Nilsson & Nilsson (2004) and Kirkinen et al (2007) assumed that the CH_4 emissions after restoration will reach the same level as for the pristine mire.

In this study, the CH_4 emissions at restored wetlands are assumed to be the same as for pristine minerotrophic mires (fens), 17 g CH_4 m^{-2} yr^{-1}, based on Alm et al (2007). This value is associated with significant uncertainty.

N_2O emissions
No studies of N_2O emissions from restored peatlands were found but just as for pristine mires the N_2O emissions are assumed to be negligible. This assumption was used also in previous studies (Nilsson & Nilsson, 2004; Zetterberg et al, 2004; Kirkinen et al, 2007).

4.4.2 Afforestation

At the afforested cutaway peatland there are both emissions and uptakes of greenhouse gases. The emissions consist mainly of CO_2 emissions from decomposition of residual peat and various amounts of soil emissions of N_2O. At the same time CO_2 uptake in growing biomass occur both above and below ground. How large this uptake is depends mainly on the forest productivity of the cutaway peatland. It is also crucial how the uptake in the forest is considered; average uptake over many tree rotation periods, uptake only during first rotation, uptake and emissions every rotation, or even including energy production from the biomass. In this study continuous forestry is considered and the CO_2 uptake in living biomass during forest growth is considered for each rotation period (85 years). The same amount of CO_2 is then released each time the forest is cut down (see section 4.4.2.4).

4.4.2.1 Soil emissions – conventional harvesting method

CO_2 emissions
Finnish measurements from 6 afforested cutaway peatlands (9-35 years after afforestation) indicate that the peat decomposition rate continues to be high, or may be even higher after harvesting than during harvesting (Alm et al, 2007; Mäkiranta et al, 2007). This is explained by the soil preparation that is done before the plantation. The CO_2 emissions were on average 1397 (1008-1756) g CO_2 m^{-2} yr^{-1} (Alm et al, 2007), which is similar to measurements from afforested croplands (Mäkiranta et al, 2007). However, due to the chamber technique used in the measurements these figures also include emissions from root activity, which should be subtracted to get emissions from peat decomposition only. It is not quantified how large part of the emissions that is due to peat decomposition. Nilsson & Nilsson (2004) assumes that the decomposition rate during harvesting is maintained also at the afforested cutaways until most of the residual peat is decomposed. Kirkinen et al (2007) assumes that peat decomposition decreases exponentially from about 1150 g CO_2 m^{-2} yr^{-1} until approx. 1.6 cm peat is left after 300 years.

In this study, it is assumed that the CO_2 emissions at the afforested cutaway peatland decrease exponentially from 1100 g CO_2 m^{-2} yr^{-1} during the first rotation period when 50% of the residual peat has been decomposed. Thereafter slow release during the rest of the simulation period. This assumption is used for all scenarios with the conventional harvesting method, with the motivation that the conditions should be rather similar after almost all peat is removed and with the same soil preparation, regardless of land-use on the peatland before harvesting.

N_2O emissions

According to Finnish measurements from afforested cutaways the average N_2O emissions are 0.15 (0.02-0.75) g N_2O m^{-2} yr^{-1} 9-35 years after afforestation (Alm et al, 2007; Mäkiranta et al, 2007). This is in the same range as reported for drained forested peatlands (0-0.81 g N_2O m^{-2} yr^{-1}), where the higher N_2O emissions were found in peatlands with high fertility whereas the emissions were very low from peatlands with low fertility. The N_2O emissions at drained forested peatlands also seem to depend on the tree species, being about ten times higher for deciduous forest (0.2-1.1 g N_2O m^{-2} yr^{-1}) than for coniferous forest (0.04-0.09 g N_2O m^{-2} yr^{-1}) according to Swedish measurements in von Arnold (2004) and von Arnold et al (2005). In Sweden most of the forests consist of coniferous species.

It is likely, that the N_2O emissions at the cutaway peatland are not higher than at drained forested peatlands and that the emissions will decrease some time after afforestation as the residual peat layer decomposes (Nilsson & Nilsson, 2004). If fertilisation or ash application is made at the cutaway in order to increase the forest productivity this might influence the N_2O emissions. However, little research has been made in this field so no general conclusion can be drawn on this matter.

In this study, it is assumed that N_2O emissions will be 0.15 g N_2O m^{-2} yr^{-1} after afforestation and decrease linearly to 0.06 g N_2O m^{-2} yr^{-1} after 45 years and then stay on that level throughout the study period (based on Alm et al, 2007; von Arnold, 2004; von Arnold et al, 2005; Nilsson & Nilsson, 2004). The emissions may be larger at sites with initially higher N_2O emissions (e.g. high fertility drained forested peatlands and cultivated peatlands) but in this study it is assumed that the conditions after peat harvesting and afforestation is rather similar for all scenarios. It is assumed that coniferous forest is planted, which today is the most common way in the Swedish forestry.

CH_4 emissions

Just as for drained forested peatlands and cultivated peatlands the CH_4 emissions are probably very low or even negative at afforested cutaways (Alm et al, 2007; Mäkiranta et al, 2007). CH_4 emissions may occur from ditches, but no studies that quantify such emissions have been found. However, Alm et al (2007) has estimated CH_4 emissions from ditches at drained forested peatlands to be very low, 0.2-0.4 g CH_4 m^{-2} yr^{-1}.

In this study, the CH_4 emissions at afforested cutaway peatlands are assumed to be negligible.

4.4.2.2 Soil emissions – new harvesting method

Silvan & Laine (unpubl.) has measured and compared the emissions from harvesting areas and stockpiles for the conventional milling method and the new biomass-drier method. The emissions were lower at the peatland after peat harvesting than at the peatland before harvesting for both harvesting methods. However, with the new production method the CO_2 emissions from the cutaway area were 30-60 % lower than with the milling method. Similarly, the CH_4 emissions were 70-80 % lower and the N_2O emissions 0-60 % lower with the new method compared to the milling method.

One probable reason for lower emissions after peat harvesting, may be that a considerable share of the microbial population responsible for soil respiration, methanogesis and N_2O formation was removed during harvesting. However, since the whole peat layer was removed in one operation with the new method, compared to only a few centimeters surface peat per year with the milling method, the negative impact on microbial activity is higher with the new method. The lower emissions with the new method, according to Silvan & Laine (unpubl), may also be explained by the much thinner residual peat layer.

The CO_2 emissions from the afforested cutaway peatland after harvesting with the new method are assumed to be 50 % lower than the emissions with the milling method at the same stage and the N_2O emissions 30 % lower. That corresponds to 550 g CO_2 m^{-2} yr^{-1} and 0.1 g N_2O m^{-2} yr^{-1}. In this study it is assumed that the CO_2 emissions decrease exponentially from 550 g CO_2 m^{-2} yr^{-1} during 45 years when 50% of residual peat has been decomposed. Thereafter, a slow release during the rest of the simulation period is assumed. The N_2O emissions will decrease linearly from 0.1 g N_2O m^{-2} yr^{-1} to 0.06 g N_2O m^{-2} yr^{-1} after 15 years. The CH_4 emissions are assumed to be negligible.

4.4.2.3 Carbon sequestration in growing forest

The CO_2 uptake in growing forest at the cutaway peatland after afforestation depends on the forest productivity. How high the forest productivity is after peat harvesting, when most of the peat layer is removed, depends on many factors and few long term studies have been carried out. Climatic conditions, how much residual peat that is left, drainage effectiveness, nutrient status of the residual peat and the sub-soil as well as forest management practices all influence the forest productivity. However, there are several reasons why higher productivity can be achieved after peat harvesting:

- When most of the peat layer is removed (20 cm is assumed to be left with conventional peat milling) nutrients from the mineral soil can be reached
- The drainage is probably easier to keep effective when the peat is removed. And effective drainage generally leads to higher productivity.
- Various studies have shown that if PK-fertilization[4] (e.g. wood ash recycling) is applied at the plantations the forest productivity on cutaway peatlands can be very high, higher than the average productivity in the region (Pitman, 2006; Leupold, 2005; Lehto, 2005; Latinen et al, 2005). Due to raised pH and increased nutrient availability, organic matter breakdown rates are accelerated and N is released from the (remaining) peat layer for take up by the trees.
- Trees growing on deep peatlands are probably also more sensitive to wind felling than on cutaway peatlands.

However, the forest productivity at nutrient rich drained forested peatlands in Sweden can be higher than at forests on mineral soil (see Table 1). For these peatlands it might be difficult to achieve higher forest productivity after peat harvesting than before.

A Swedish study (Lehto, 2005) of afforestation on a cutaway peatland in Värmland (mid-west Sweden) showed that with PK-fertilization the average forest productivity was 7-8 m^3 ha^{-1}, which is about 40 % higher than the average productivity in the region (5.4 m^3 ha^{-1}). Another Swedish study (Leupold, 2005) concludes that 13 years after afforestation the biomass production at the PK-fertilized plantations was 55-96 tonnes ha^{-1} compared to 5-7 tonnes ha^{-1} for control plots. According to Pitman (2006) long-term trials on drained peatlands has shown that forest productivity with wood-ash application was 4-17 times higher than control plots.

In this study, it is assumed that an annual forest productivity of 7.1 m^3 ha^{-1} can be reached at the cutaway peatland after afforestation (subject to fertilization or ash-application), which is the same as the average productivity at drained forested peatlands with high fertility in Sweden (see chapter

---

[4] Phosphorous and potassium

4.1.2.2). With a rotation period of 85 years this corresponds to 820 g CO_2 m^{-2} yr^{-1}.[5]. That means that for drained forested peatlands with low fertility the forest productivity is assumed to increase by 3.5 m^3 ha^{-1} after afforestation but is assumed to be sustained on the same level for high fertility sites. It should be noted that this value is a best estimate for Sweden and is for instance to high for north of Sweden, whereas it could be higher in the south.

4.4.2.4 Accounting of carbon sequestration in growing forest in peat utilisation scenarios

In this study a land-use perspective is applied. Hence emissions and uptake of greenhouse gases from the land area before, during and after peat harvesting are included. In the case of afforestation continuous forestry is considered. The CO_2 uptake in living biomass during forest growth is considered for each tree rotation period, and that the same amount of CO_2 is released each time the forest is cut down. A rotation period of 85 years is assumed. 80 % of the sequestered carbon is assumed to be released instantaneously at cutting (illustrating the removal of biomass from the land-area) whereas 20 % is assumed to be left at the site and decompose during the coming rotation period.

In this study no consideration to the use of the biomass (bioenergy, paper or construction etc.) was taken. The assumption that the removed biomass releases 80 % of the carbon content to the atmosphere the same year as cutting and the rest during the coming rotation period is not a correct description of reality. The wood is used for many different purposes, e.g. paper, construction materials and bioenergy, and the carbon will be stored in the products for some time depending on the lifetime of the product. The delayed emissions of CO_2 will reduce the climate impact. The use of wood for energy purposes may also replace fossil fuels and thus indirectly lead to lower emissions and lower total climate impact. These positive effects of afforestation should also be evaluated when considering different aftertreatment alternatives. However, we have not attributed the further storage of carbon after cutting or avoided emissions due to use of wood to peat utilisation. It should also be noted that it is only the *increased* biomass production after peat harvesting compared to before that gives these additional climate advantages. Especially for cultivated peatlands, with no forest production before peat harvesting, the increased wood biomass production may indirectly lead to lower climate impact than what is accounted for in this study. It should also be noted, that in this study we have not considered what the cultivated crops in the reference case are used for (i.e. they might have similar positive effects as the harvested wood).

4.4.2.5 Carbon sequestration in soil

After the peat is removed and the cutaway peatland is afforested, carbon accumulation in soil organic matter will start and continue until equilibrium between accumulation and decomposition is reached. In this study, carbon accumulation in humus is assumed to occur at a constant rate until 3.5 kg C m^{-2} is reached after one rotation period, based on Zetterberg et al (2004). With a rotation period of 85 years the annual uptake will be 150 g CO_2 m^{-2}.

---

[5] Based on the following assumptions: dry density of stem wood = 420 kg m^{-3}, carbon content in stem wood = 50 %, total standing biomass in thinnings and final cutting (inclusive stem, branches, needles, stump and roots) is 1,5 times the stem biomass. Total uptake [kg C ha^{-1} $year^{-1}$]= 1,5 * 420 * 0,5 * productivity

4.4.3 Summary of emissions after harvesting

Table 6 Summary of greenhouse gas emissions after harvesting used in this study. Positive value means emission and negative value means uptake.

	[g m^{-2} yr^{-1}]			Main reference
	CO2	N2O	CH4	
Afforestation				
Soil emissions (conventional production method)	1100 exponential decrease during first rotation period when 50% of the residual peat has been decomposed. Thereafter slow release during rest of simulation period.	Linear decrease from 0.15 to 0.06 after 45 years.	0	Kirkinen (2007), Alm et al (2007), von Arnold (2004), von Arnold et al (2005)
Soil emissions (new production method)	550 exponential decrease during 45 years when 50% of residual peat has been decomposed. Thereafter slow release during rest of simulation period.	Linear decrease from 0.15 to 0.06 after 15 years.	0	Silvan & Laine (unpubl.)
Carbon sequestration in living biomass	-820 during every rotation (7.1 m^3 ha^{-1} yr^{-1}) emission every cutting down	-	-	
Soil carbon sequestration	-150 during one rotation	-	-	
Restoration into new wetland				
Cutaway peatland	-120	0	17	Kirkinen et al (2007), Alm et al (2007),
Surrounding area	-120	0	17	

5 Early shut down due to low profitability

Combustion of energy peat is today associated with an emission factor of 106 g CO_2 MJ^{-1} in the EU ETS (Emission Trading Scheme). As a comparison combustion of coal is associated with an emission factor of 92-95 g CO_2/MJ and biomass 0 g CO_2/MJ. Due to the price of the emission allowances that is needed for energy peat utilisation, the Swedish peat industry is presently in a difficult situation, and the peat utilisation is declining in Sweden. The Swedish government has said that a sustainable Swedish energy system also involves energy peat, if only to a limited extent. Discussions are going on in Sweden, Finland and EU about how peat should be treated in future policy instruments such as certification systems for climate adjusted peat and economical subsidies.

If the demand for energy peat declines, producers might stop peat harvesting at existing harvesting fields and wait a few years to see if the market turns (production break) and then finalise the harvesting or the aftertreatment. In either case this might result in the harvesting area being open for a longer time period resulting in higher emissions of greenhouse gases. Due to the rules of the producer being responsible for aftertreatment there should be no risk (or a very small risk) for areas being left without aftertreatment (Holmgren et al, 2006).

As discussed previously there are a few factors determining the emissions/uptake of greenhouse gases from the aftertreated area. For restored sites (rewetted sites), CO_2 uptake will be dependent on the growth of the new vegetation and methane emissions will be very dependent on what species that are present and the water level. For afforested sites the decomposition rate of the residual peat layer and the productivity of the new forest are important factors. Generally, if there is a substantial residual peat layer and the aftertreatment chosen would be afforestation there is a risk for substantial and long-term emissions of CO_2 due to decomposition of residual peat and the risk of low productivity of the forest. Of course all this is also dependent on what type of land the harvesting area was before the start of peat harvesting. The risk for low productivity of the forest is due to the fact that a thick residual peat layer will not let the trees to get minerals from the mineral soil and hence they might lack nutrients. A less risky alternative of aftertreatment at areas with substantial layers of residual peat is probably to restore the site. Of course there is always a risk for high methane emissions depending on what type of vegetation you get on the restored area, but the risk for decomposition of the residual peat and thereby emissions of CO_2 will be low. If the aftertreatment is done in a good way there is also a possibility for a net uptake of CO_2 due to the new plants. This means that if peat harvesting areas are closed down in advance, with peat left, the choice of aftertreatment will be important. According to Östlund (2006, personal communication) it is more probable that the land-owner would prefer afforestation if peat harvesting was finished in advance. However, the final decision on what option that should be used for the after-treatment is in Sweden made by the County Administrative Board (Länsstyrelsen).

According to Östlund (2006, personal communication) it is also more probable that early close down would occur in remote areas. In peat harvesting areas situated close to densely populated areas there would probably still be a demand for horticultural peat so that peat harvesting at least would continue to a lesser extent even if energy peat harvesting would not be profitable.

In Sweden it is necessary to have a concession in order to harvest peat. Normally these concessions are valid for 25 years and if the peat harvesting is not finished by then a new application will have to be made. Production breaks during this period are allowed. There is no deadline set for when aftertreatment should be finished but the contract guarantee securing the aftertreatment will not be returned until the restoration has been approved. The peat harvesting is considered finalised when the aftertreatment has been approved. Holmgren et al (2006).

5.1 Scenario description - interrupted peat production and delayed aftertreatment

As described in section 3.4 two scenarios are made to estimate the climate impact of early shut down of peat harvesting and delayed aftertreatment:

- Pristine mire – interrupted conventional peat production – restoration
- Pristine mire – interrupted conventional peat production – afforestation

The same emissions that are valid for minerotrophic mires are used for these scenarios (see section 3.1 and chapter 4). The differences are:

- Peat production and combustion only occur during 10 years
- The emissions at the harvesting field and the surrounding area are assumed to stay constant when the production is interrupted.
- Aftertreatment of the cutaway peatland is carried out first 10 years after peat production was interrupted, the residual peat layer is 1.15 m instead of 0.2 m
- The emissions/uptake of greenhouse gases after restoration are assumed to be the same as before harvesting since the mayor part of the peat layer is left, meaning that a lower CO_2 uptake (55 g CO_2 m^{-2} $year^{-1}$) is assumed than for completely harvested cutaways (120 g CO_2 m^{-2} $year^{-1}$)

- The soil emissions of greenhouse gases after afforestation are assumed to be about the same as for the other scenarios with afforestation, but the forest productivity is assumed to be between drained forested peatlands with low and high fertility (5.35 m³/ha)

The input data for the interrupted peat harvesting scenarios are found in Table 7 in Appendix.

Additionally, calculations are also made for the two interrupted peat harvesting scenarios but where the energy peat production is replaced by coal during the last ten years.

6 Results -climate impact of peat utilisation

6.1 Climate impact of peat utilisation from pristine mires and for early shut-downs

As shown in Figure 2 the climate impact of peat utilisation from pristine mires aftertreated by restoration, is comparable to coal utilisation during almost the entire simulation period (300 years).

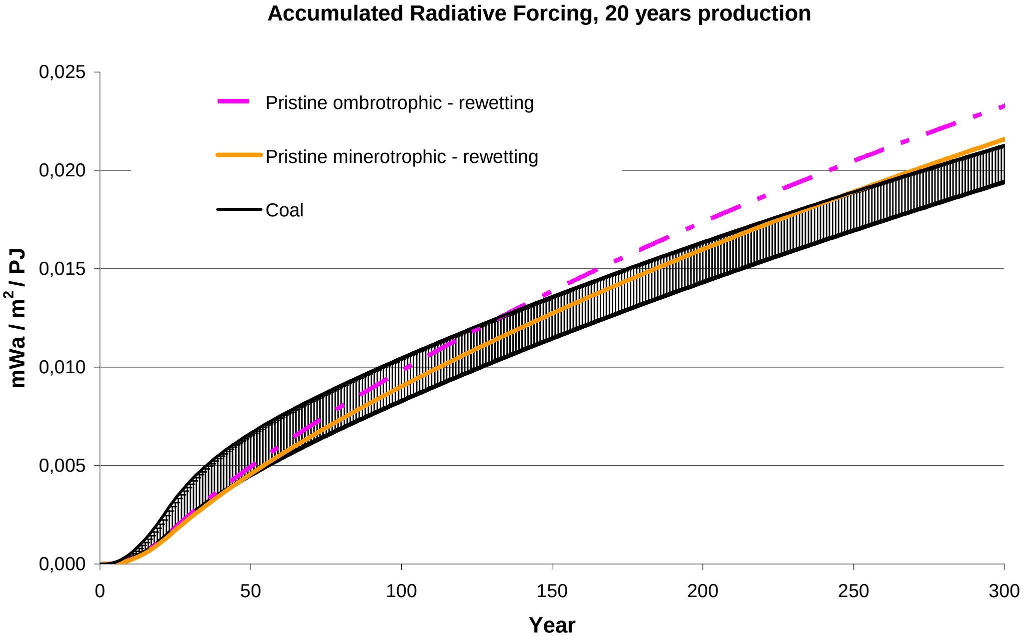


Figure 2 Accumulated radiative forcing due to peat utilisation from pristine mires that after harvesting are restored into new wetlands. The two coal scenarios given as an interval in Figure 2 indicate the uncertainty range of the of emission estimates for coal utilisation due to differences in input data from different LCA studies.

The two coal scenarios given as an interval in Figure 2 indicate the uncertainty range of the emission estimates for coal utilisation due to differences in input data from different LCA studies. The higher values are based on Swedish LCA data from Uppenberg et al (2001) that was used in earlier IVL-studies. The lower values are based on more recent Finnish data from Sokka et al (2005) (given in Kirkinen et al, 2008). The main difference is the estimate of CH_4 emissions during production and transportation of coal, which are lower in the Finnish estimate. In the coming figures we use only one of the coal scenarios, i.e. the one based on data given in Kirkinen et al (2008) (represented by the lower values in Figure 2).

Figure 3 shows the climate impact from two peat harvesting scenarios where harvesting is interrupted when half the peat layer has been harvested and the production area is abandoned for 10 years before aftertreatment is carried out. In these scenarios the land area is aftertreated either by afforestation or restoration into new wetland. The afforestation scenario results in the climate impact per PJ of peat produced being somewhat lower the first couple of hundreds of years but then rises to higher levels than the other scenarios. The lower climate impact during the first centuries is due to rapid carbon sequestration in the growing forest but CO_2 emissions from decomposition of the deep residual peat layer (since production was interrupted and not completed) will eventually be of greater importance. The comparison afforestation - restoration also highlights the importance of the timing of the emissions.

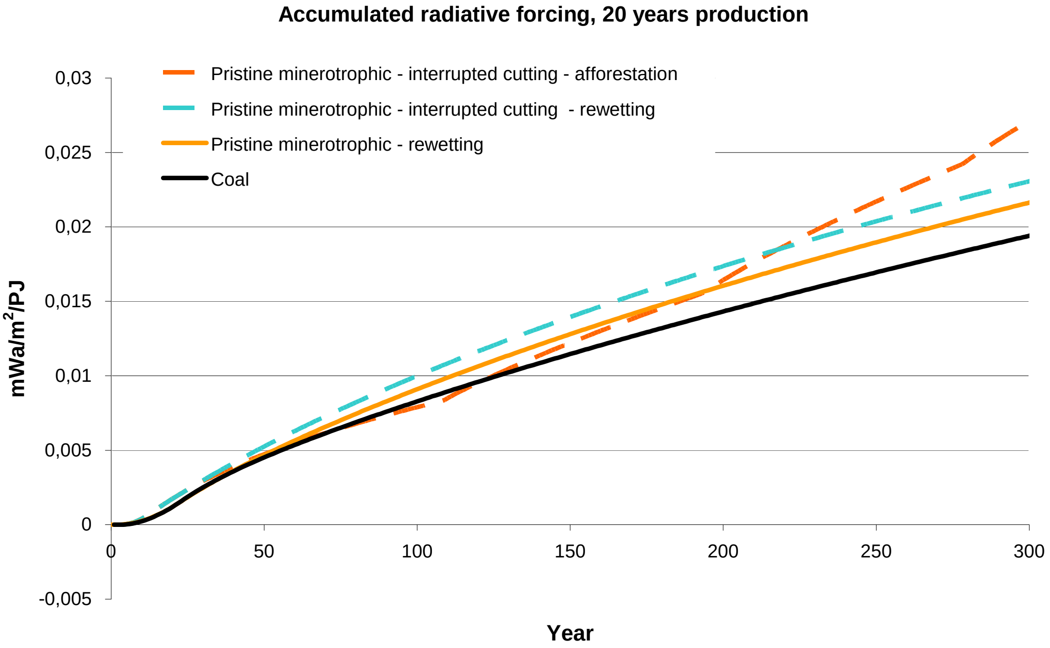


Figure 3 Accumulated radiative forcing per PJ of produced peat for interrupted peat harvesting scenarios. Two scenarios where peat cutting is interrupted after 10 years of production and aftertreatment (afforestation or restoration) is delayed 10 years are shown as well as the corresponding scenario where peat cutting is completed.

Figure 4 shows two scenarios with interrupted peat harvesting just as in Figure 3 but where the energy peat production is replaced by coal during the last ten years. The results show that both interrupted scenarios are very similar to the conventional harvesting during the entire study period. In the case of restoration the climate impact will even be somewhat lower than the conventional harvesting since the residual peat layer will not decompose (due to the assumed waterlogged conditions) and the fact that the LCA emissions for coal is lower than the combustion emissions of peat. In the case of afforestation the interrupted harvesting scenario will in theory result in higher emissions in the long run, given that all of the residual peat will oxidise. The scenario will then include both peat emissions and coal emissions. If some other fuel or energy source would replace the peat which is not utilised in the interrupted scenarios the climate impact of the interrupted scenarios will be lower since coal has higher LCA emissions than other possible fuels/energy sources.

If similar calculations would have been made for other peatland types (forestry drained peatlands or cultivated peatlands) the effect would be the same but time scales different; if an area with interrupted peat harvesting is rewetted the scenario will result in lower climate impact compared to completed harvesting since residual peat is not oxidised, afforestation of the interrupted harvesting area eventually results in higher total emissions since the residual peat layer is assumed to oxidise. However, in the case of interrupted harvesting the emissions are delayed which means a lower climate impact compared to completed harvesting.

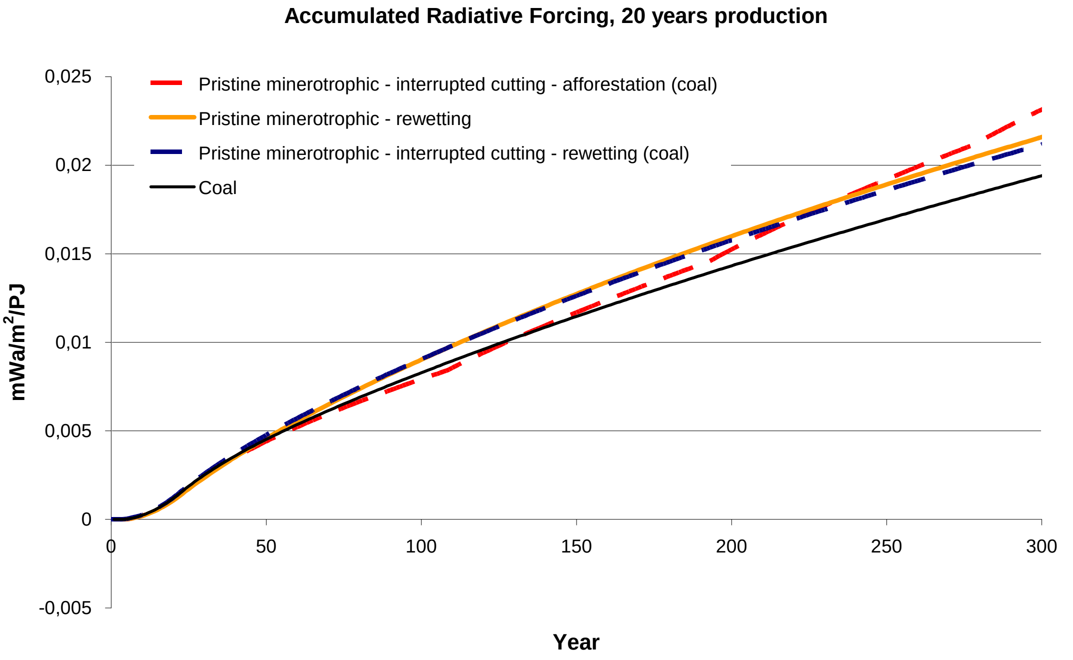


Figure 4 Accumulated radiative forcing of interrupted per PJ of produced fuel. Two scenarios where peat cutting is interrupted after 10 years of production and aftertreatment (afforestation or restoration) is delayed 10 years are shown. During the 10 years when peat is not produced, coal has been used as substitute fuel.

It should be emphasised that we had to make many assumptions concerning the greenhouse gas fluxes of the interrupted harvesting areas and aftertreated areas which means that the differences between these scenarios and the conventional production scenarios are within the uncertainty range.

6.2 Climate impact of peat utilisation from drained peatlands aftertreated by afforestation

The climate impact of peat utilisation from drained forested peatlands and drained cultivated peatlands are shown in Figure 5. In all scenarios the cutaway peatland is afforested.

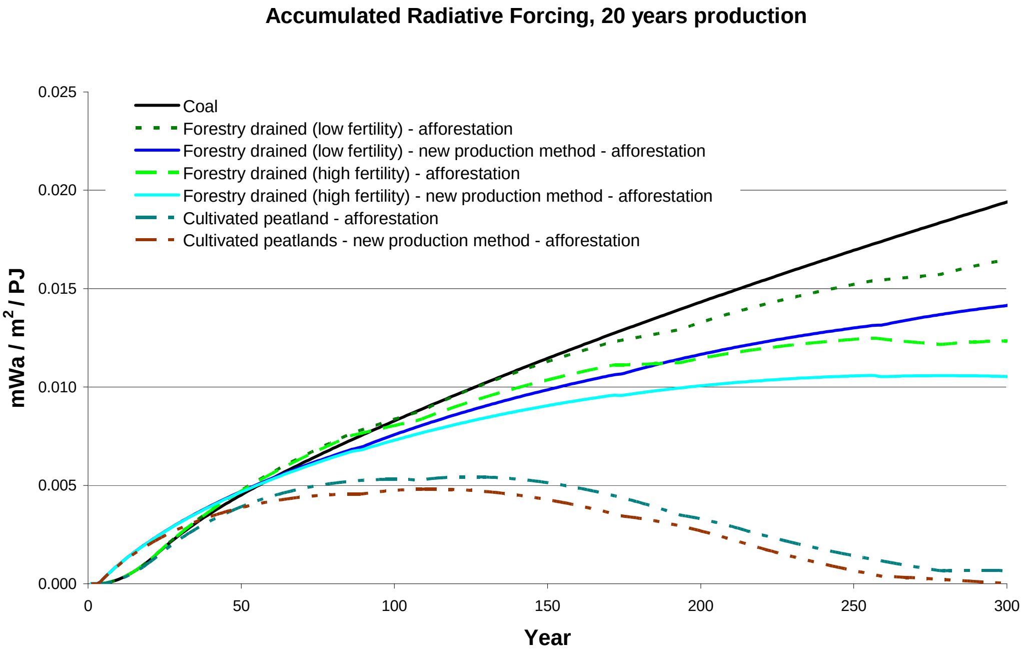


Figure 5 Accumulated radiative forcing due to peat utilisation from drained peatlands used for forestry or cultivation that after harvesting are afforested. For three scenarios new production method is used instead of the conventional milling method.

The result indicates that all peat utilisation scenarios are comparable with coal during the first 30-40 years. The cultivated peatland scenarios result in lower climate impact than the forestry drained peatland scenarios and coal and a significant difference can be seen within the first 100 years when the cultivated peatland scenarios are 33-55 % lower than the coal scenario. During the first 100 years of the simulation period the climate impact of the coal and the forestry drained scenarios are of comparable magnitude. After 300 years the climate impact of the forestry drained peatland scenarios are lower than the coal scenario. The lowest climate impact after 300 years has peat utilisation from drained cultivated peatlands and drained forested peatlands with high fertility. For these scenarios the accumulated radiative forcing after 300 years is 35-100 % lower than the coal scenario. The reason for this is that the initially high soil emissions of CO_2 and N_2O at these peatlands (highest for cultivated peatlands) are significantly reduced after harvesting and in addition there is CO_2 uptake in growing forest. The net emissions from the peatland area will in other words be lower after peat harvesting than before, and this change in greenhouse gas fluxes will with time compensate for the emissions due to peat combustion. Also peat utilisation from drained forested peatlands with low fertility has lower climate impact than coal after 300 years. However, since these peatlands have lower initial emissions than the forestry drained peatlands with high fertility the compensating effect of the changes in greenhouse gas fluxes due to peat harvesting is not as large as for the high fertility sites.

In Figure 5 peat utilisation scenarios where a new, more efficient production method is applied are presented. The results show that the climate impact of peat utilisation can be reduced with the new peat production technology. Since the same amount of peat is harvested and combusted within one year instead of 20 years, the climate impact will be higher the first years. The climate impact will, however, with time be lower with the new production technology. The reasons for this are that the dryer sod peat leads to somewhat lower CO2 emissions during combustion, the short harvesting period leads to faster afforestation of the cutaway area and lower emissions during harvesting and the thinner residual layer leads to lower soil emissions after harvesting.

6.3 Summarised emissions of the different stages in the peat utilisation chain

Figure 6 and Figure 7 illustrate how large the summarised emissions are in each stage of the peat utilisation chains and how it differs between pristine mire (high climate impact) and cultivated peatlands (lower climate impact) compared to coal utilisation. Note that the figures show peat production of 1 PJ during 20 years, and that the emissions of greenhouse gases at each stage are summarised with GWP_{100}. GWP does not consider the timing of emissions and does therefore not fully reflect the climate impact of the peat utilisation scenarios, where the emissions are extended in time.

These figures also clearly illustrate the importance of what time perspective that is used. After 100 years (Figure 6) emissions from the combustion stage clearly dominate in all scenarios. For cultivated peatlands there is a small net uptake in the aftertreatment stage due to uptake in growing forest. The emissions in the reference case (peatlands left in their current state) are much higher for cultivated peatlands than for pristine mires, but the combustion emissions are still higher than the summarised emissions from the reference case after 100 years. After 300 years (Figure 7) the summarised emissions in the reference case is higher than the combustion emissions in the cultivated peatland scenario. For pristine mire, where the emissions are rather small before harvesting (reference case), combustion emissions will still dominate after 300 years.

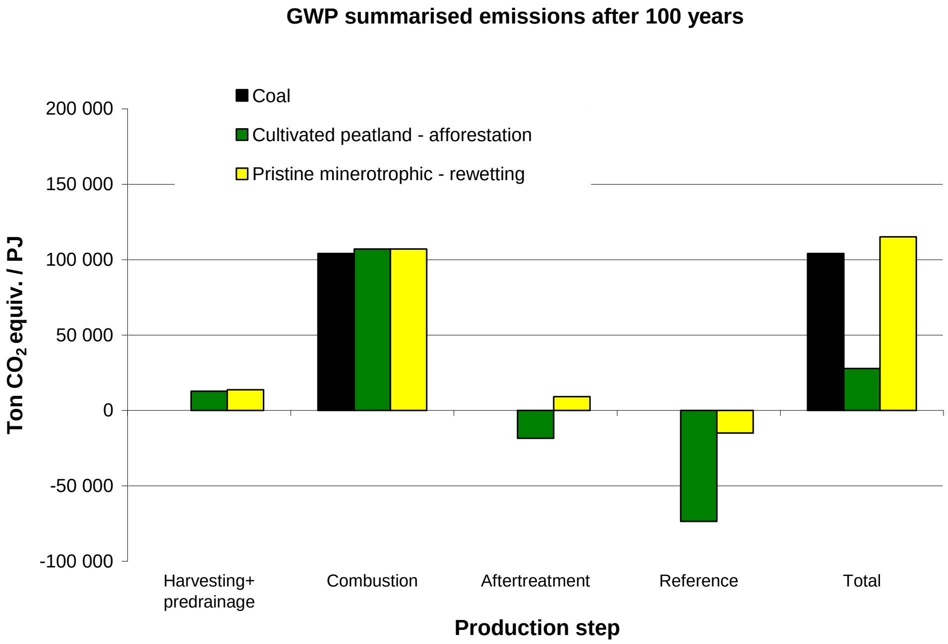


Figure 6 Summarised emissions for the different stages after 100 years for the coal, cultivated peatland and pristine mire scenarios, expressed as ton CO_2-equivalents/PJ peat using GWP_{100}. The emissions from the reference situation (before harvesting) are presented as negative in the figure, since these emissions are considered avoided (see Chapter 2). The total staples in the figure are the sum of the harvesting, combustion, aftertreatment and reference staples. The coal scenario includes life cycle emissions although only presented in one staple (combustion)..

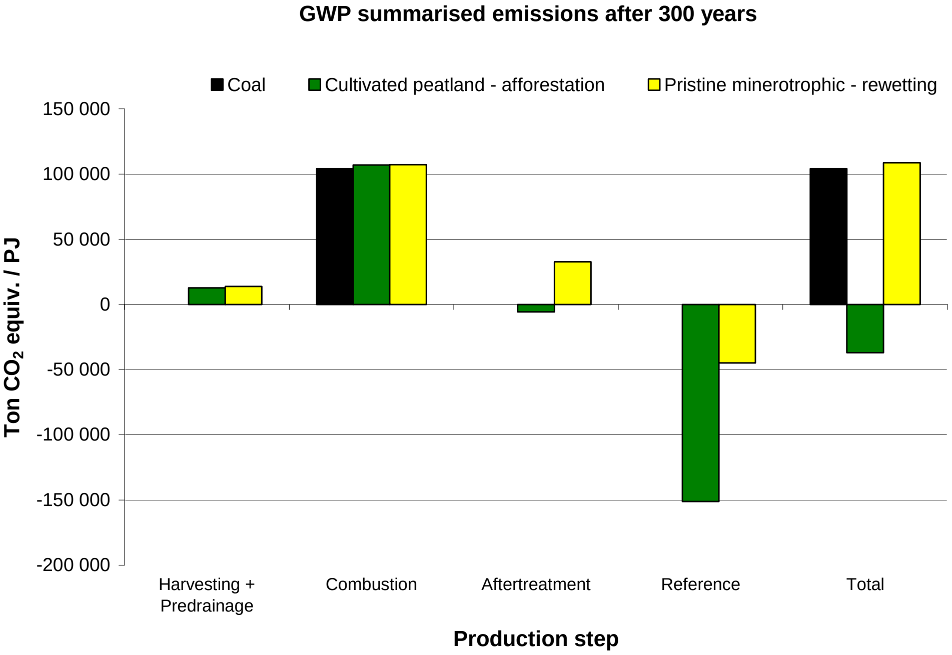


Figure 7 Summarised emissions for the different stages after 300 years for the coal, cultivated peatland and pristine mire scenarios, expressed as ton CO2-equivalents/PJ using GWP100. The emissions from the reference situation (before harvesting) are presented as negative in the figure, since these emissions are considered avoided (see Chapter 2). The total staples in the figure are the sum of the harvesting, combustion, aftertreatment and reference staples. The coal scenario includes life cycle emissions although only presented in one staple (combustion).

6.4 Summary – climate adjusted peat utilisation

As shown in Figure 8 below and as presented in previous sections the climate impact of future peat utilisation can, from a life cycle perspective, be significantly reduced compared to peat utilisation from pristine mires. If drained forested peatlands are selected for peat harvesting and successful afforestation with fertilization (e.g. by wood/peat ash-application) is carried out at the cutaway peatland after harvesting, the climate impact will be somewhat lower compared to pristine mires already after 100 years and the difference will increase with time. The type of the selected forested peatland also clearly influences the climate impact of peat utilisation. The climate impact is lower if high fertility peatlands are selected than for low fertility, even though the forest productivity after harvesting is assumed to be the same. The best peatlands to use for peat harvesting from a climate impact viewpoint are peatlands used for cultivation due to the high net emissions from these land areas. After harvesting and afforestation, the emissions will decrease substantially compared to the business-as-usual-scenario (continued agriculture with high soil emissions), and over time compensate for the emissions from peat combustion.

The production technology will also have some effect on the climate impact from a life cycle perspective. Peat production with the new biomass-dryer technology shortens the harvesting time and lower the emissions during harvesting, produces sod peat with lower moisture content and leaves a much thinner residual peat layer, which lead to lower climate impact compared to present peat production technologies.

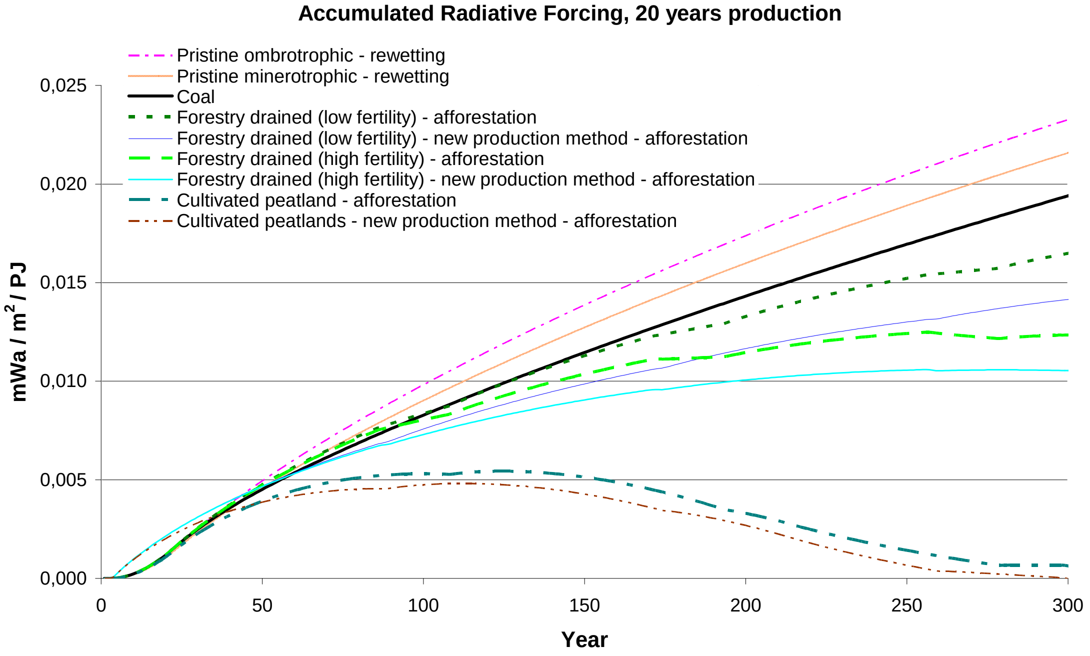


Figure 8 Accumulated radiative forcing due to energy peat utilisation from different peatland types. Pristine mires are restored into new wetlands after harvesting and drained peatlands used for forestry or cultivation are afforested after harvesting. For three scenarios new production technology is used instead of the conventional milling method.

If GWP (Global Warming Potential) is used to summarise total emissions for the different peat utilisation scenarios it gives a somewhat different picture (Figure 9) compared to the radiative forcing scenarios. The timing and dynamics of emissions that occur at different times extended over a long time can not be understood with GWP, hence it is not always a good measure to use for the climate impact.

If we compare the scenarios in Figure 8 and Figure 9 we can see that whereas the GWP summarised emissions for the cultivated peatland scenarios (to the right in Figure 9) for the 300 year period (dashed staples) are negative, the corresponding scenarios in Figure 8 are close to zero but positive. The difference is that the radiative forcing takes the dynamics and atmospheric lifetime of the greenhouse gases into consideration. This is just one example of how comparison of emissions emitted over a long time period not directly is related to the climate impact.

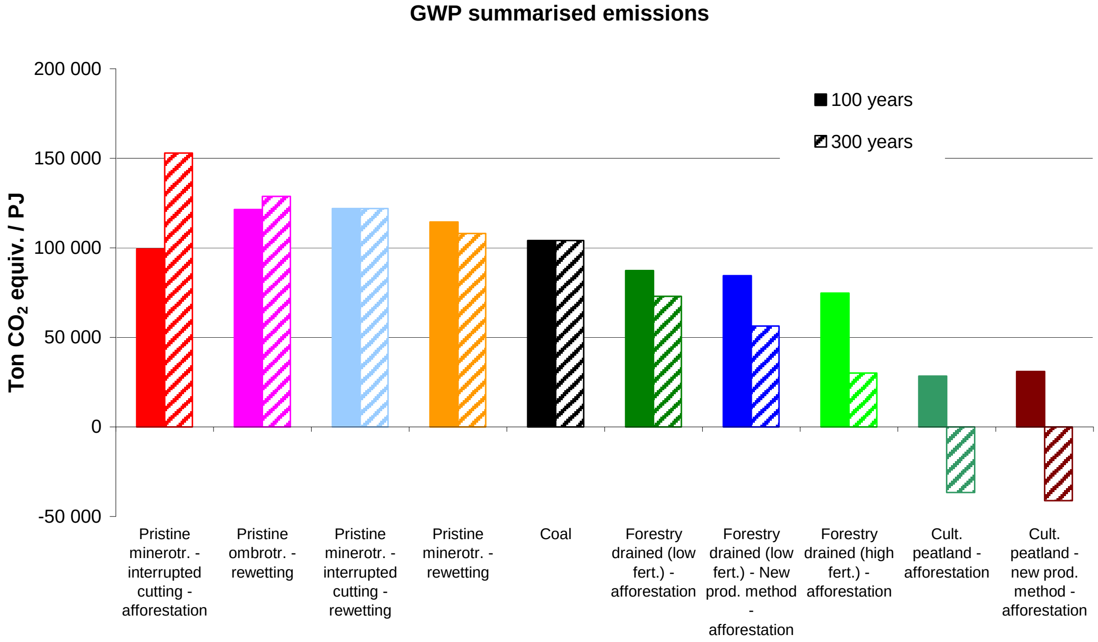


Figure 9 Total summarised emissions after 100 years and 300 years for all analysed peat utilisation scenarios, expressed as ton CO_2-equivalents/PJ peat using GWP_{100}.

6.5 The impact of variation in emission estimates

In Figure 10, GWP summarised emissions for the peat utilisation scenarios in a 100 year perspective are given, divided into the different stages of production. Note that the figure shows peat production of 1 PJ during 20 years, and that the emissions of greenhouse gases at each stage are summarised with GWP_{100}. GWP does not consider the timing of emissions and does therefore not fully reflect the climate impact of the peat utilisation scenarios. In order to get the total staples in the figure the emissions from harvesting, combustion, aftertreatment and the reference situation (before harvesting) should be summarised. The emissions from the reference situation (before harvesting) are therefore presented as negative emissions in the figure, since these are avoided.

Included in the figure are also the variation of emissions in each stage (indicated by the bars) based on the literature sources used in the calculations. The figure gives an idea of how the emissions may vary for individual sites, if conventional or new production method is used and depending on assumptions of emissions/uptake at the aftertreated cutaway. However, not all sources for variation are included. For instance, in the aftertreatment case of afforestation the variation given is only the difference between the forest productivity used in this study.

Please also note that this figure does not give the uncertainty in the calculations. They give the variation of emission estimates in the used input data and thus reflect the range within which the average scenarios may vary if other input data where used. The figure thus somehow illustrates the potential emission reductions that are possible in the different stages. The input data for Figure 10 is summarised in Table 13 in Appendix.

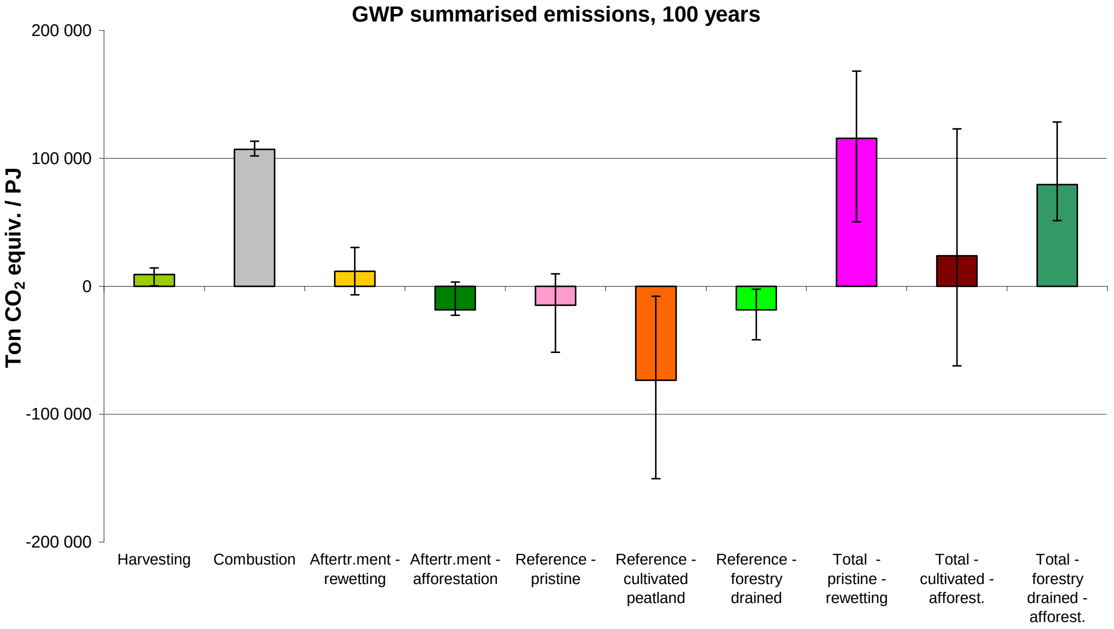


Figure 10 GWP summarised emissions of the peat scenarios in a 100 year perspective divided on the different stages of the peat utilisation chain. The staples represent average values of emission estimates whereas the bars show the variation found in the source literature. The emissions from the reference situation (before harvesting) are presented as negative in the figure, since these emissions are considered avoided. The total staples in the figure are the sum of the harvesting, combustion, aftertreatment and reference staples.

7 Co-combustion of peat and biomass

About 70 % of all energy peat in Sweden was 2007 utilised in combined heat and power plants, the rest in heat plants (Miljökraft, 2008). Research and experience from Swedish biomass-fuelled plants has shown that co-combustion with peat has some positive effects. According to Miljökraft (2008) co-combustion of peat with biofuel in Swedish heat and power plants decreases operation and maintenance costs, improves the energy efficiency and thus reduces the utilisation of oil in the plants. The study also concludes that if the peat utilisation is completely replaced with biofuels it would lead to more corrosion and lining and an increased risk for sintering, which lead to lower availability of the plants that in many cases require oil combustion during operation stops. It has been shown that if biofuels are co-combusted with 10-30 % peat the power efficiency can increase by approx. 2 %, or the total power production by 6-8 % compared to utilisation of only biofuels (Burvall & Öhman, 2006). To reach the same effect as with peat, co-combustion with coal or additions of additives like sulphur may be possible (Burvall & Öhman, 2006).

According to plant operators 10-20 % lower maintenance costs can be achieved due to co-combustion with peat, and the loss in energy production would in many cases otherwise be replaced with energy from reserve oil-fuelled plants (Miljökraft, 2008).

7.1 Scenario that accounts for potential positive effects of co-combustion

In this study a scenario calculation is made to estimate what impact co-combustion effects may have on the total climate impact from peat utilisation scenarios. It is assumed that peat is co-combusted with biofuel in heat and power plants and that peat utilisation leads to a 10 % increase in energy production at the plant (due to higher availability of the plant and higher power efficiency). The value is given by The Swedish Peat Producers Association (Brandel, 2008 pers. comm.) as an example of a possible efficiency gain based on the experience and studies presented in the previous section. It is assumed that the increased energy production (10 %) replaces energy from oil-fuelled plants. The avoided emissions from the replaced oil combustion are thus included in the scenario.

It is important to point out that this scenario is not valid for all plants in Sweden where co-combustion of peat is applied, and it should also be noted that the same efficiency gain may be achieved with other measures than by co-combustion with peat (e.g. co-combustion with coal). The scenario, however, indicates how the climate impact is affected if potentially avoided emissions due to co-combustion are considered.

The potential effect of co-combustion is estimated by comparing the following two scenarios:

- Drained forested peatland (low fertility) – afforestation
- Drained forested peatland (low fertility) – co-combustion – afforestation

Peat production is carried out with the conventional milling method. The input data for these scenarios is summarised in Table 12 in Appendix.

The effect of co-combustion on the climate impact of peat utilisation is shown in Figure 11. The relative effect would be about the same for all peat utilisation scenarios, possibly somewhat different for scenarios where the new production method is used (due to shorter harvesting and combustion period). It should be noted that including efficiency gains due to co-combustion and associated avoided emissions means an extension of the system boundaries compared to the other scenarios and they are therefore not comparable with one another. The used value of 10 % higher energy production is only indicative. It is also very questionable if such avoided emissions can be attributed to peat utilisation only. For instance, since it is probably possible to achieve the same positive effect in wood-fired heat and power plants by co-combustion with coal instead of peat, a similar calculation could be made for a coal scenario.

However, this scenario was included in order to be used as a basis for discussion of climate effects of different energy systems and the achievement of an efficient energy production in the society.

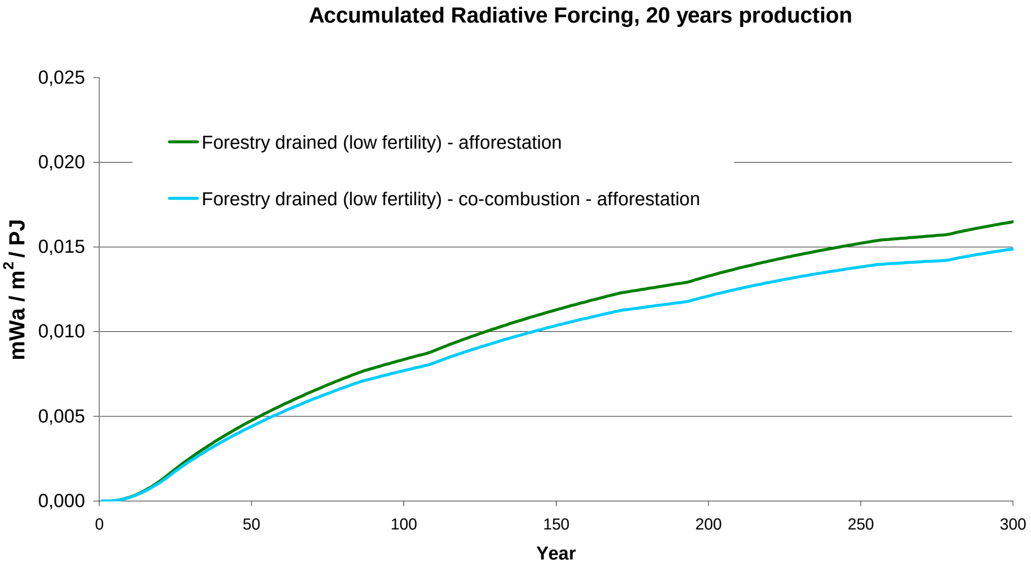


Figure 11 Accumulated radiative forcing due to energy peat utilisation from drained forested peatlands with low fertility that are afforested after peat harvesting, including the potential positive effect of co-combustion with wood. Co-combustion is assumed to increase the efficiency/energy production of wood-fuelled heat and power plants with 10 % which replaces energy production from oil.

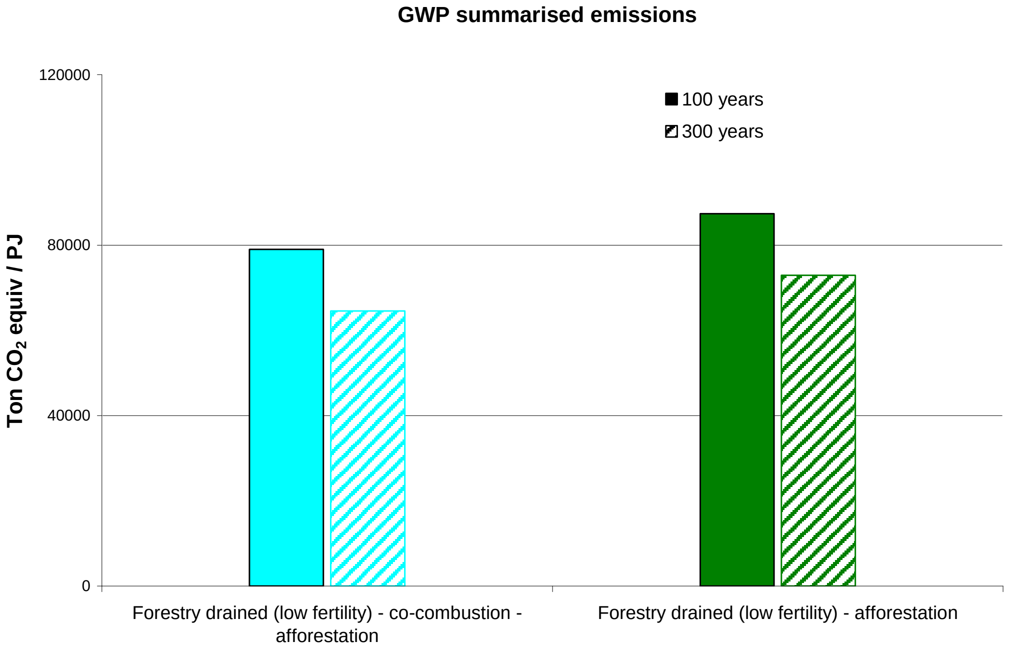


Figure 12 Accumulated emissions summarised by GWP after 100 years and 300 years for energy peat utilisation from drained forested peatlands with low fertility, with and without the effect of co-combustion included.

8 Best case scenarios

In order to show the potential for reduction of the climate impact of energy peat utilisation and to show the difference between considering combustion emissions only and to consider life cycle emissions we have calculated two best case scenarios for utilisation of energy peat from forestry drained peatlands and from cultivated peatlands respectively. These two scenarios are presented in Figure 13 and compared to a scenario where combustion emissions only are considered. The input data for the best case scenarios are given in Table 10 in the Appendix but are generally based on the highest estimates of emissions found in the literature used for the emission estimates of this study. The estimate for the forestry drained scenario is based on von Arnold (2004) and von Arnold et al (2005) whereas the estimate for the cultivated peatland is based on Maljanen et al (2007). In both scenarios the new production technology is assumed to be used and afforestation is used as aftertreatment. The forest growth is assumed to stay at the pre-harvesting level in the case of forestry drained peatland and it is assumed to be at a medium level at the cutaway cultivated peatland.

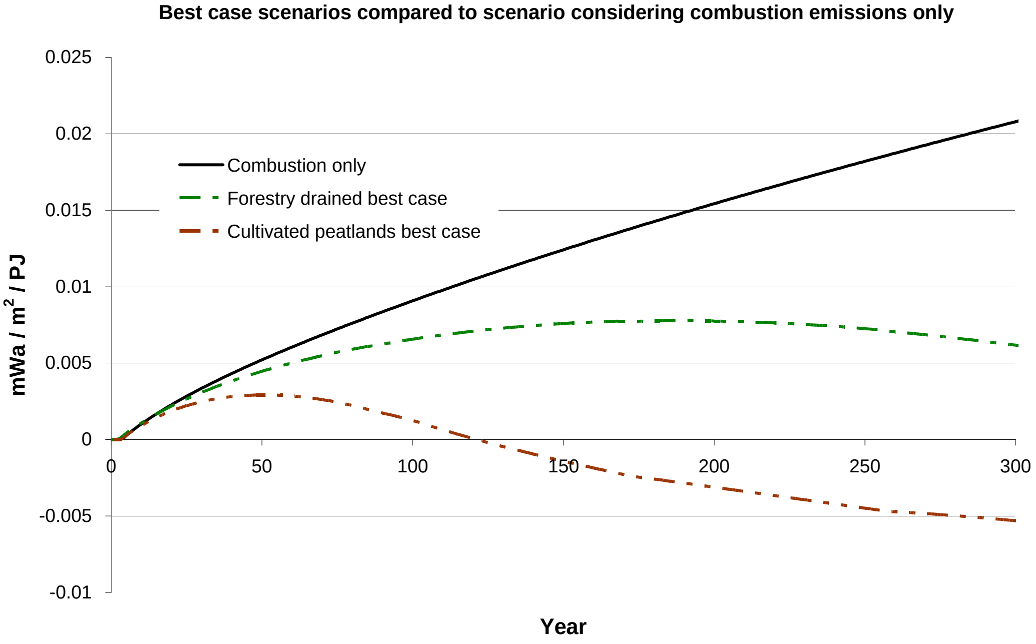


Figure 13 Best case scenarios for energy peat utilisation from forestry drained peatlands compared to scenario considering combustion emissions only. In the combustion only scenario, the default emission factor for peat in the EU ETS 106 g CO_2/MJ was used. The diagram show accumulated radiative forcing. Peat combustion occurs during year 1, since the new production method is assumed.

Compared to the combustion only scenario in Figure 13 the best case scenario for cultivated peatlands is 87 % lower after 100 years and the forestry drained scenario is 28 % lower after 100 years. After 300 years the best case scenario for cultivated peatlands is negative (hence positive impact on the climate) whereas the forestry drained scenario is 70 % lower than the combustion only scenario.

Similar comparisons have also been made between a combustion only scenario, and the average drained peatland scenarios presented in Chapter 6.2 (not best case and the scenarios where the conventional production method is used). For the average cultivated peatland scenario, the calculations result in 37 % lower climate impact after 100 years when the life cycle emissions are considered, compared to considering only the combustion emissions. For the average forestry drained peatland scenarios, the climate impact is 0-4 % lower when the life cycle emissions are considered compared to considering only the combustion emissions. After 300 years the same figures are 97 % lower climate impact for cultivated peatlands and 20-40 % lower climate impact for forestry drained peatlands.

It should be noted that no worst case scenarios have been made in this study. The climate impact of peat utilisation would correspondingly be higher than the average scenarios of this study if worst case scenarios were done.

9 Discussion

9.1 How can the climate impact from peat utilisation be reduced?

As shown in this study the climate impact of peat utilisation is more complex than just considering the combustion emissions. There are important sources and sinks at the peatland before harvesting, during harvesting and after harvesting that are taken into account when applying a land-use and life cycle perspective.

The results show that selection of peatland is of great importance for the long-term climate impact, as well as the aftertreatment. Peatlands that are large sources of greenhouse gases, for instance already drained peatlands, are better to choose for peat harvesting than peatlands with lower emissions such as pristine mires.

Cultivated peatlands are generally large sources of CO_2 and N_2O due to peat decomposition and nitrogen mineralization. Cultivated peatlands are, from a climate viewpoint, the best choice for peat production. When peat is removed the emissions will be lower and by successful afforestation there will be an uptake in growing forest biomass. With a long time perspective (300 years) the emissions from peat combustion will be almost completely compensated by the reduced emissions at the cutaway peatland after harvesting.

Soil emissions of greenhouse gases from drained forested peatlands are generally high, and if these peatlands are harvested and afforested the emissions will decrease substantially compared to a business as usual scenario. From a climate impact viewpoint, forested peatlands with high fertility are better to choose than low fertility peatlands, due to the higher initial emissions of CO_2 and N_2O at high fertility sites. However, the possible change in forest productivity at the site after peat harvesting is also important. If an increase is possible a lower climate impact will be achieved. There is not so much information available about the forest productivity at cutaway peatlands but the probability for a production increase is probably larger at low fertility sites than on high fertility sites.

The study also shows that the climate impact of peat utilisation can be reduced to some extent with the new peat production technology (biomass dryer). The main reasons for this are that a drier sod peat is produced leading to lower emissions during combustion and that a thinner residual peat layer is left after harvesting, reducing soil emissions. Due to more efficient harvesting the emissions during peat harvesting are also reduced.

The scenarios with the highest climate impact are peat utilisation from pristine mires with conventional production technology. The climate impact of the "pristine mire – restoration into new wetland" scenarios are after 300 years comparable with, or higher, than coal utilisation. The reasons for this is that the emissions of greenhouse gases from pristine mires are generally small and these emissions are not assumed to be reduced so much at the restored cutaway.

Early shut downs and delayed aftertreatment of peat harvesting fields lead to a minor increase of the climate impact of peat utilisation (per PJ produced peat). Afforestation of a partly completed cutaway leads to somewhat lower climate impact than restoration into new wetland the first hundreds of years but in the longer run the restoration leads to lower climate impact. The reason for this is that the soil emissions due to decomposition of residual peat is assumed to continue for a long time at the afforested site, whereas the wet conditions at the restored sites prevents peat decomposition. However, looking in a broader perspective interrupted peat harvesting means postponing of emissions and could lead to either higher or lower long term emissions. The climate impact of interrupted peat harvesting depends on what energy production that replaces the not harvested peat. From a climate viewpoint it is therefore not straight forward to say whether completion of harvesting is better then closure. There are also other circumstances to consider in this matter (aftertreatment opportunities, energy efficiency, biological diversity etc). However, we conclude that that there is only a small risk for early shut downs and delayed aftertreatment to occur.

A comparison of what aftertreatment alternative that is best has not been analysed in this study. It is assumed that pristine mires in most cases will be restored into new wetland due to preservation of that nature type and for biodiversity purposes. For already drained peatlands only afforestation is considered. The choice of aftertreatment is, however, also dependent on local conditions such as hydrological conditions etc. Hence, there might be a choice between restoration and afforestation (or perhaps cultivation). Based on the few scientific studies of emissions at restored and afforested cutaways that have been done, we conclude that successful afforestation probably leads to lower climate impact than restoration into new wetland. This is illustrated in Figure 6 and Figure 7 where the summarised emissions at the aftertreatment stage for the "pristine minerotrophic mire-rewetting" and the "cultivated peatland-afforestation" scenarios are compared. The figures show that the summarised emissions are higher for the rewetted cutaway than for the afforested cutaway after 100 and 300 years. However, more research is needed for better estimations of emissions and uptake at restored mires as well as afforested cutaways.

If the peat utilisation scenarios with afforestation lead to increased wood biomass production there are also additional positive effects from a climate viewpoint, which is not considered in this study. First, the carbon sequestered in the wood biomass may be stored for some time in wood products with long lifetime. Secondly, large part of the wood is also directly, or when the wood products have served out, used for energy production and may thus replace fossil fuels. This will also have a positive effect on the climate change that also should be evaluated.

9.2 How representative are the results?

A very important objective was to present the results of the study in a simple and communicative report. Therefore only a few representative scenarios have been studied. The emission estimates for different peatland types before, during and after harvesting used in the calculations are based on studies presented in the scientific literature and we have consequently tried to use average emissions for the respective peatland type from Swedish or Finnish measurements. However, as shown in the emission inventory in Chapter 4 the emissions vary greatly between different measurements, different peatland types and also depend on climatic conditions. The scenarios therefore do not cover the variability of emissions of specific peatland types or local conditions.

Great variation in emissions is found for pristine mires, for which it is very difficult to set generalized emission factors based on available scientific literature. The emission estimates for restored peatlands are associated with considerable uncertainties, since long-term studies are lacking. This is of great importance of the results since the aftertreatment stage is lasting for a long time in the calculations. More research is needed to fully understand emissions and uptake at restored wetlands.

For drained forested peatlands there are a number of Swedish and Finnish emission measurements covering different peatland types and locations. The CO_2 estimates in Finnish data includes not only peat decomposition but also root activity and since it was not quantified how large part of the emissions that are due to peat decomposition these figures was not used in this study. It seems, however, as the Swedish measurements by von Arnold (2004) and von Arnold et al (2005) that are used in this study are in accordance with the Finnish results. More research is needed to find general criteria for what types of forested peatlands that are best suited for peat harvesting from a climate viewpoint.

Also estimations of emissions and uptake at afforested cutaways are associated with a great deal of uncertainty, since few long-term studies of soil emissions and forest productivity has been done. It should be noted that the assumed forest productivity (7.1 m^3/ha) at afforested cutaways is an estimated average for Sweden if fertilisation (such as ash-application) and proper forest management is applied. It is of course not valid for all sites in Sweden (lower in the north for instance). It is, however, the difference in forest productivity before and after harvesting that is of importance. Higher forest growth at the cutaways leads to lower climate impact of the peat utilisation scenario. Another uncertainty for afforested cutaways is that no emissions associated with fertilisation are considered in this study. Fertilisation may affect the peat decomposition rate and N_2O formation, but since no applicable studies were found in the literature it was not considered.

For more information on uncertainties and sensitivity analysis we recommend earlier work by Holmgren et al (2006), Kirkinen et al (2007) and Nilsson & Nilsson (2004).

However, despite large uncertainties in the emission estimates the study clearly shows that the climate impact of peat utilisation can be substantially reduced if peat production is focused on drained peatlands used for forestry or cultivation, if the new production method is used and if the cutaways are afforested.

Further research should be focused on greenhouse gas fluxes at drained peatlands to develop criteria of what peatlands to be chosen for future peat production. Research should also be focused on measures that can be done to secure low emissions (or possibly a net uptake) of greenhouse gases at the aftertreated cutaway. This includes soil and forest management practices at afforested sites as well as successful management of restored wetlands.

10 Conclusions

From this and previous studies we conclude that energy peat utilisation can have a lower climate impact if viewed upon from a life cycle perspective than if just considering the emissions at the combustion stage. A lower climate impact is more probable if peat is produced from peatlands already drained and impacted by human activity. The total emissions and climate impact can also be affected by the production and combustion technology.

Our results show that the climate impact over a 100 year period is approximately 7-18 % lower if using drained forested peatlands compared to pristine mires and approximately 42-46% lower if using cultivated peatlands compared to pristine mires. How much the emissions from current peat production and utilisation can be reduced is difficult to say since the peatlands in production today are a mixture of peatlands with different land use history, including pristine mires, forestry drained mires, cultivated peatlands and peatlands that have been under human impact for a long time.

We conclude that the most important factors for reducing the climate impact of energy peat production and utilisation are:

- *Choice of peatland*
  Choice of peatland is the most important factor for reducing the climate impact. The calculations in this study are based on average values of emissions from different types of peatlands. Our study shows that there is a wide variability in emission levels within the different peatland types and there is a need for a methodology to determine/estimate emissions from individual sites.
- *Production technology*
  The new production technology not only reduces the emissions from the field during harvesting, it also results in drier peat, which leads to lower emissions from transport and combustion. The drier the peat the lower the emission factor. In addition the smaller amount of residual peat results in lower emissions from the aftertreated area (in the case afforestation).
- *Aftertreatment*
  The choice of aftertreatment will depend on many factors. It is important to remember that the suitability of different aftertreatment choices will be dependent on the local conditions. If it is possible to create a system functioning as a carbon sink, this will result in a peat utilisation chain with reduced climate impact. Both afforestation and restoration into new wetland could result in a carbon sink. At an afforested site the carbon uptake in the growing biomass can be quite high, emissions will occur from the residual peat layer. Also in a wetland carbon is fixed in growing vegetation whereas emissions mainly are in the form of methane. Since methane is a stronger greenhouse gas than CO_2 the net effect of the wetland can be negative climate impact. There are also additional options for aftertreatment that has not been included in this study and that also can lead to carbon sequestration. An interesting example is cultivation of energy crops (e.g. reed canary grass).

The production technology is the most easily adjusted issue. To choose harvesting area in a way that minimises the climate impact is more difficult. A first step could be taken by only using already drained and human impacted areas. Generally more fertile sites and well drained sites are larger sources of greenhouse gases, but to exactly determine the size of the greenhouse gas emissions from a peatland is difficult without making measurements. There is a need for developing methodology for determining levels of greenhouse gas emissions from different types of peatlands. However, also with such methods available a substantial amount of uncertainty will remain. In addition it is of course difficult to base the decision of peat harvesting only on levels of greenhouse gas emissions. Concerning the aftertreatment further studies are needed in order to better understand the development of greenhouse gas fluxes from aftertreated cutaways.

We conclude that in order to minimise climate impact of future peat utilisation one should:

- Focus peat production to drained peatlands with high greenhouse gas emissions, mainly:
    - Cultivated peatlands
    - Forested peatlands with high peat decomposition rate and high N_2O emissions, typically peatlands with high fertility that are well drained. Since the forest productivity generally is good at these peatlands the peat should be harvested in connection to planned tree cuttings and be performed as fast as possible (to shorten the harvesting period as much as possible).
- Use a peat production technology that minimises the harvesting time, that creates a dryer and denser peat which minimises the emissions from stockpiles, transports and combustion and that leaves only a thin residual peat layer.
- Afforestate the cutaway peatland as soon as possible after harvesting, with soil preparation (including ash-application/fertilization) and forest management practices that maximise forest growth and minimise soil emissions.

Concerning early shut downs of opened peat harvesting areas we conclude based on previous studies (Holmgren et al 2006) that there is only a small risk for this to occur and even if it would occur the climate impact is limited. Early shut downs and delayed aftertreatment of peat harvesting fields due to low profitability would lead to a minor increase of the climate impact of peat production per PJ of produced peat (since a smaller amount of produced peat will have to bear the LCA emissions). However, looking in a broader perspective interrupted peat harvesting means postponing of emissions (due to slower emissions from oxidation in field than combustion) and could lead to either higher or lower long term emissions. From a climate viewpoint it is not straight forward to say whether completion of harvesting area is better than closure. There are also other circumstances to consider in this matter (aftertreatment opportunities, energy efficiency, biological diversity etc).

We also conclude that there are some positive effects on energy production in wood-fuelled heat and power plants that are co-combusted with peat. Lower maintenance costs and higher efficiency at the plants due to co-combustion with peat can potentially result in avoided emissions from the use of fossil fuels. These effects can be achieved by other means than co-combustion with peat and can therefore not be included in the LCA scenarios for peat utilisation. However, it could be considered when evaluating peat as a fuel in the Swedish energy system.

11 Further research

This study shows that to reduce the climate impact of peat utilisation, peat production should be focused on already drained peatlands with high CO_2 emissions and N_2O emissions. Research should therefore be focused on better understanding of greenhouse gas emissions from drained peatlands used for forestry and agriculture and to find determining parameters so that emissions from a certain type of peatland can be easily estimated with simple measures. For instance the relationship between C/N-ratio (fertility), vegetation type, drainage depth and climatic conditions and the fluxes of greenhouse gases should be better investigated to provide simple analytical tools that can be used for selection of the best peatlands for future peat production.

Proper aftertreatment of the cutaway has also been shown to be important for the overall climate impact of peat utilisation. More studies should be carried out to develop and evaluate aftertreatment methods that lead to lowest possible greenhouse gas emissions at the cutaway and high carbon sequestration into new biomass. This includes different methods for restoration into new wetland and a better understanding on long-term greenhouse gas fluxes of restored wetlands as well as management practices that maximises biomass growth and minimises emissions in the case of afforestation or cultivation of energy crops. Ash-fertilisation and how it affects biomass growth and emissions of CO_2 and N_2O in different conditions need more research.

11.1 Development of criteria for climate adjusted peat production

There is a broad interest for developing a certification system for sustainable or climate friendly peat production (Swedish authorities, the Swedish Peat Producers Association and the International Peat Society). In fact several actions have already been taken by the International Peat Society by putting forward a plan for developing and implementing a global certification scheme for Sustainable Peatland Management (IPS, 2008).

The development of a Swedish certification system should be compatible with any suggested international scheme. We suggest that a national initiative is taken in order to develop a plan for a national certification system of sustainable peat production.

One critical part is to identify what criteria that could be set for sustainable peat production. The first steps are to identify what areas that should be covered by the certification system and then to identify what information is needed, what information is lacking, how we can get hold of lacking information (further research, studies etc.) The national initiative should also closely follow the work done by IPS concerning the certification on a global scale.

Criteria for the climate impact of sustainable peat production requires development of a simple and scientifically acceptable methodology for determining levels of greenhouse gas emissions from different types of peatlands and from the aftertreated cutaway. This probably includes criteria for production method and the different aftertreatment alternatives. A well defined certification system that secures (among other things) limited climate impact of the peat utilisation could then be coupled to policy instruments such as the EU ETS and the Swedish electricity certificate system.

12 References

Alm, J., Shurpali, N. J., Minkkinen, K., Aro, L., Hytönen, J., Laurila, T., Lohila, A., Maljanen, M., Martikainen, P. J., Mäkiranta, P., Penttilä, T., Saarnio, S., Silvan, N., Tuittila, E.-S. & Laine, J., **2007**. *Emission factors and their uncertainty for the exchange of* CO_2*,* CH_4 *and* N_2O *in Finnish managed peatlands*. Boreal Env. Res. 12: 191-209.

Berglund, Ö. & Berglund, K., **2008**. *Odlad organogen jord i Sverige 2003. Areal och grödfördelning uppskattad med hjälp av digitaliserade databaser.* Rapport 7, Swedish University of Agricultural Sciences, Department of Soil Sciences, Division of Hydrotechnics, Uppsala. ISSN 1653-6797.

Brandel, Magnus, Swedish Peat Producers Association (STPF). Personal communication, 2008.

Burvall J. & Öhman M., 2006. *Samförbränning av torv och biobränslen – askrelaterade systemfördelar.* Swedish Energy Agency, ER 2006 33.

Energimyndigheten, 2008. *Uppdrag avseende ett klimatanpassat torvbruk. Slutredovisning - Certifikatsystem för torv.* ISSN 1403-1892.

Holmgren, K., **2006**. *Climate impact of energy utilisation scenarios for forestry-drained peatlands.* IVL B-rapport 1683, Stockholm.

Holmgren, K., Kirkinen, J. & Savolainen, I. **2006**. *The Climate Impact of energy peat utilisation – comparison and sensitivity analysis of Finnish and Swedish results.* IVL Brapport 1681, Stockholm.

Holmgren, K., Eriksson, E., Olsson, O., Olsson, M., Hillring, B. & Parikka, M., **2007**. *Biofuels and climate neutrality – system analysis of production and utilisation.* Elforsk rapport 07:35.

Hånell, B., **1991**. *Forest classificatiion of peatlands in Sweden - a field guide.* Swedish University of Agricultural Sciences, Depatment of Silviculture, Umeå.

Hånell, B., **1997**. *Beräkningar av skogsproduktionens storlek efter beskogning på färdigbrutna torvtäkter.* Bilaga 2 i *Torvbränsle och växthuseffekten.* Rapport från Vattenfall Utveckling AB, 1997/8. ISSN 1100-5130.

IPCC 2007. Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, , J. Nganga, R.. Prinn, G. Raga, M. Schulz and R. Van Dorland, 2007: Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M- Marquie, K-B-Averyt, M. Tignoer and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York , NY, USA.

IPS, 2008. *Project Plan for the Development of International Certification Scheme for Sustainable Peatland Management.* International Peat Society, Helsinki, May 2009.

Johanssongruppen, **2006**. *Ett långsiktigt hållbart torvbruk.* Rapport från torvbrachens arbetsgrupp för vissa torvfrågor – Johanssongruppen, december 2006, Stockholm.

Kasimir-Klemedtsson Å., Klemedtsson, L., Berglund, K., Martikainen, P.J., Silvola, J., Oenema, O., **1997**. *Greenhouse Gas Emissions from farmed organic soils: a review.* Soil Use and Management, no 13 1997, pp 245–250.

Kasimir-Klemedtsson, Å., Nilsson, M., Sundh, I. & Svensson, B., **2001**. *Växthusgasflöden från myrar och organogena jordar.* Naturvårdsverket Rapport 5132.

Kirkinen, J., Minkkinen, K., Penttilä, T., Kojola, S., Sievänen, R, Alm, J., Saarnio, S., Silvan, N., Laine, J., & Savolainen, I., **2007**. *Greenhouse gas impact due to peat fuel use – A life cycle approach.* Boreal Env. Res. 12: 211-223.

Kirkinen, J., Palosuo, T., Holmgren, K. & Savolainen, I. **2008**. *Greenhouse Impact Due to the Use of Combustible Fuels: Life Cycle Viewpoint and Relative Radiative Forcing Commitment.* Journal of Environmental Management online 3 June 2008.

Klemendtsson, L., von Arnold, K., Weslien, P., **2005**. *Soil CN ratio as a scalar to predict nitrous oxide emissions.* Global Change Biology no 11 2005, pp 1142-1147.

Laitinen T., Lindh T., **2005**. *Ash recycling in Finland.* Prague Recash International Seminar. Prague, 8 - 9 Nov. 2005. Forests of the Czech Republic, S.E.; Regional Forestry Board of Värmland - Örebro. Regular recycling of wood ash to prevent waste production, proceedings (2005), pp. 66 – 71.

Lehto B., **2005**. *Stand growth 20 years after planting on Flakmossen - the significance of drainage and fertilization in an afforestation trial on a peat harvesting field in the province of Värmland, West Central Sweden.* Master Thesis, Swedish University of Agricultural Sciences, Umeå.

Leupold S, **2005**. *Vegetation succession and biomass production after peat ash and PKfertilization on the cutaway peatland of Näsmyran in Hälsingland, Sweden.* Graduate Thesis in Biology, ISSN 1104-1870, Swedish University of Agricultural Sciences, Department of Forest Ecology, Umeå.

Lundin, L. & Finnveden, G. **2006**. Underlagsrapport för Naturvårdsverkets och Energimyndighetens ställningstagande till ett svenskt torvbruk, som är gynnsammare vad avser växthusgaser ur ett livscykelperspektiv – en kritisk analys. 2006-05-30. Underlagsrapport till regeringsuppdrag ”Uppdrag avseende de ekonomiska förutsättningarna i vissa regioner mot bakgrund av situation för torvbruket” (M2005//6132/E).

Maljanen, M., Hytönen, J., Mäkiranta, P., Alm, J., Minkkinen, K., Laine, J. & Martikainen PJ, **2007**. *Greenhouse gas emissions from cultivated and abandoned organic croplands in Finland.* Boreal Env. Res. 12: 133-140.

Maljanen, M., Hytönen, J., Mäkiranta, P., Laine, J., Minkkinen, K. & Martikainen, P. J., **2004**. *Does Afforestation lower N_2O Emissions from Peat Soils drained for Agriculture?* Proceedings of the 12th International Peat Congress held in Tampere, Finland 6-11 June 2004. Vol. 2, pp 1000-1002.

Minkkinen, K., Laine, J., Shurpali, N. J., Mäkiranta, P., Alm, J. & Penttilä, T., **2007**. *Heterotrophic soil respiration in forestry-drained peatlands.* Boreal Env. Res. 12: 115-126.

Mäkiranta, P., Hytönen, J., Aro, L., Maljanen, M., Pihlatie, M., Potila, H., Shurpali, N. J., Laine, J., Lohila, A., Martikainen, P. J. & Minkkinen, K., **2007**. *Soil greenhouse gas emissions from afforested organic soil croplands and cutaway peatlands.* Boreal Env. Res. 12:159-175.

Miljökraft, 2008. *Användning av energitorv och torvens effekter vid sameldning i svenska anläggningar.* PM for the Swedish Peat Producers Association, Stockholm.

Nilsson, K., **2004**. *The carbon dioxide emission factor for combustion of Swedish peat.* Päivänen, J. (ed.) Wise use of Peatlands in Global Climatic Change, Proceeding of the 12th International Peat Congress held in Tampere, Finland 6-11 June 2004. Vol. 1, pp 157-161.

Nilsson, K. & Nilsson M., **2004**. *The climate impact of energy peat utilisation in Sweden – the effect of former land-use and aftertreatment.* IVL B-rapport 1606, Stockholm.

Nilsson M., Mikkelä, C., Sundh, I., Granberg, G., Svensson, B.H., & Ranneby B., **2001**. *Methane emissions from Swedish mires: National and regional budgets and dependence on mire vegetation.* Journal of Geophysical Research Vol. 106, No D18 pp 20 847 – 20 860.

Nykänen H., Alm J., Lång K., Silvola J., Martikainen P.J., **1996**. *Emissions of CH_4, N_2O and CO_2 from a virgin fen and a fen drained for grassland in Finland.* Journal of Biogeography 22, pp. 351–357.

Regeringen, **2007**. *Promemoria om uppdrag till Statens energimyndighet och Naturvårdsverket avseende ett klimatanpassat torvbruk.* Regeringskansliet, Näringsdepartementet, 2007-04-18.

Regina, K., Syväsalo, E., Hannukkala, A. & Esala, M. **2004**. *Fluxes of N_2O from farmed peat soils in Finland.* European Journal of Soil Science, Vol. 55, pp 591-599.

Pitman R.. M., **2006**. *Wood ash use in forestry – a review of the environmental impacts.* Published by Oxford University Press on behalf of Institute of Chartered Foresters, 2006. Forestry, Vol. 79, No. 5, 2006. Environmental and Human Sciences Division, Forest Research, Surrey, England.

Rinne, S., Lindh, T., Isännäinen, S., Järvelä, E., Korpijärvi, K., Paappanen, T., Mursunen, H. & Laitinen, T., **2005**. *The possibilities to use ashes of biopower plants for forest fertiliser.* Bioenergy in Wood Industry 2005 - Book of Proceedings. Jyväskylä 12. - 15.9.2005 (2005), pp. 451 – 456.

Saarnio, S., Morero, M., Shurpali, N. J., Tuittila, E.-S., Mäkilä, M. & Alm, J., **2007**. Annual CO_2 and CH_4 fluxes of pristine boreal mires as a background for the lifecycle analyses of peat energy. Boreal Env. Res. 12: 101-113.

Savolainen, I., Hillebrand, K., Nousainen, I., Sinisalo, J., **1994**. *Comparison of Radiative Forcing Impacts of the Use of Wood, Peat and Fossil Fuels.* World Resource Review, Vol. 6, No. 2, pp 248 – 262.

Silvan, Niko, The Finnish Forest Research Institute. Personal communication, February 2007.

Silvan, N. & Laine, J., **2008** (unpublished). *Reduced climatic impact using the new method for energy peat production.* Finnsih Research Institute, Parkano Research Unit, Finland.

Sokka L., Koskela, S. & Seppälä, J. 2005. Life cycle inventory analysis of hard coal based electricity generation. The Finnish Environment 797. Finnish Environment Institute, Helsinki.

Sundh, I., Nilsson, M., Mikkelä, C., Granberg, G., Svensson, B.H., **2000**. *Fluxes of Methane and carbon Dioxide on Peat-mining Areas in Sweden.* Ambio vol. 29, no 8, pp 499-503.

Tuittila, E.-S., Komulainen, V.-M., Vasander, H. & Laine, J., **1999**. *Restored cut-away peatland as a sink for atmospheric CO_2.* Oecologica Vol. 120, pp 563-574. Springer-Verlag.

Tuittila, E.-S., Komulainen, V.-M., Vasander, H., Nykänen, H., Martikainen P. J, Laine, J. **2000**. *Methane Dynamics of a restored cut-away peatland.* Global Change Biology Vol. 6, pp 569-581. Blackwell Science Ltd.

Uppdrag av seende de ekonomiska förutsättningarna i vissa regioner mot bakgrund av situationen för torvbruket. Nutek, Statens Energimyndighet, Naturvårdsverket och ITPS, juni **2006**.

Uppenberg, S., Almemark, M., Brandel, M., Lindfors, L-G., Marcus, H-O., Stripple, H., Wachtmeister, A., Zetterberg, L., **2001**. *Miljöfaktabok för bränslen*, IVL-rapport B1334B-2, Swedish Environmental Research Institute Ltd, Stockholm.

Uppenberg, S., Zetterberg, L. & Åhman M. 2000. *Climate Impact from Peat Utilisation in Sweden.* IVL B-report 1423, Stockholm, Sweden.

Vesterinen, R., **2003**. *Estimation of CO_2 emission factors for peat combustion on the basis of analyses of peat delivered to power plants.* Research report PRO2/P6020/03. VTT Processes, Energy Production. Jyväskylä. 25 pp. + app. 5 pp.

von Arnold, K., **2004**. *Forests and greenhouse gases. Fluxes of CO_2, CH_4 and N_2O from drained forests on organic soils.* Linköping Studies in arts and Science No 302, Linköping University. ISSN: 0282-9800.

von Arnold, K., Hånell, B., Stendahl, J., Klemedtsson, L., **2005**. *Greenhouse gas fluxes from drained organic forestland in Sweden*, Scandinavian Journal of Forest Research, 20, 400 – 411.

Yli-Petäys, M., Laine, J., Vasander, H. & Tuittila, E.-S., **2007**. Carbon gas exchange of a re-vegetated cut-away peatland five decades after abandonment. Boreal Env. Res. 12: 177-190.

Zetterberg, L., Uppenberg, S. & Åhman M. **2004**. Climate impact from Peat Utilisation in Sweden. Mitigation and Adaptation Strategies for Global Change. Vol 9, pp 37-76, 2004.

Östlund, Stefan, Råsjö Torv. Personal communication, May 2006.

Appendix

Input data in the calculations

Table 7 Emissions estimates for the different stages of the pristine peatland scenarios. Positive sign is emission from ecosystem to atmosphere and negative sign is uptake.

	Pristine mires		
	CO_2 [g m^{-2} yr^{-1}]	N_2O [g m^{-2} yr^{-1}]	CH_4 [g m^{-2} yr^{-1}]
Initial stage			
Ombrotrophic site	55	0	7
Minerotrophic site	-55	0	17
During harvesting			
Production area	980	0.3	3.7
Stockpiles	250	0	0
Harvesting equipment and transports	1 g CO_2 MJ^{-1}	0.025 mg N_2O MJ^{-1}	0.7 mg CH_4 MJ^{-1}
Surrounding area	980	0.3 during first five years, then decrease to 0.08	3.7
Combustion stage			
Combustion	105.2 g CO_2 MJ^{-1}	6 mg N_2O MJ^{-1}	5 mg CH_4 MJ^{-1}
Aftertreatment			
Wetland restoration – after conventional harvesting			
Harvesting area	-120	0	17
Surrounding area	Same as for harvesting area	0	Same as for surrounding area
Wetland restoration – after interrupted peat harvesting			
Harvesting area	-120	0	17
Surrounding area	-55	0	17
Afforestation – after interrupted peat harvesting			
Harvesting area			
Soil emissions	980[1] exponential decrease during 45 years until a level of 500 g CO2/m2 is reached. This level is then assumed for the rest or the simulation period.	Linear decrease from 0.15 to 0.06 after 45 years	0
C uptake in growing forest	-618 (between low and high productive)	-	-
Soil C acc. (humus)	-150 until 3.5 kg C/m^2	-	-
Surrounding area			
Soil emissions	980 linear decrease to 0 when 2 cm left	Linear decrease from 0.08 to 0.06 when 2 cm left	-
C uptake in growing forest	-618 (same as harvesting area)	-	-
Soil C accumulation	-150 during first rotation period. Equilibrium is then reached.	-	-

[1] We assume emissions from harvesting area only and no emissions from stockpiles.

Table 8 Emissions estimates for the different stages of the drained forested peatland scenarios. Positive sign is emission from ecosystem to atmosphere and negative sign is uptake.

	Drained forested peatlands		
	CO_2 [g m^{-2} yr^{-1}]	N_2O [g m^{-2} yr^{-1}]	CH_4 [g m^{-2} yr^{-1}]
Initial stage			
Soil emissions			
High fertility	818	0.5	0
Low fertility	458	0.01	2
C uptake in growing biomass			
High fertility	-820	-	-
Low fertility	-416	-	-
During harvesting (conventional production method)			
Production area	Linear increase to 980	Linear increase/decrease to 0.3	Linear increase to 3.7
Stockpiles	250	0	0
Harvesting equipment and transports	1 g CO_2 MJ^{-1}	0.025 mg N_2O MJ^{-1}	0.7 mg CH_4 MJ^{-1}
During harvesting (new production method)			
Production area	770	0.1	0
Stockpiles	400	0	0
Harvesting equipment and transports	0.5 g CO^2 MJ^{-1}	0.012 mg N_2O MJ^{-1}	0.35 mg CH_4 MJ^{-1}
Combustion stage			
Conventional production method	105.2 g CO_2 MJ^{-1}	6 mg N_2O MJ^{-1}	5 mg CH_4 MJ^{-1}
New production method	100 g CO_2 MJ^{-1}	6 mg N_2O MJ^{-1}	5 mg CH_4 MJ^{-1}
Aftertreatment - afforestation			
Soil emissions after conventional production method	1100 exponential decrease during first rotation period when 50% of the residual peat has been decomposed. Thereafter slow release during rest of simulation period.	Linear decrease from 0.15 to 0.06 g after 45 years.	0
Soil emissions after new production method	550 exponential decrease during 45 years when 50% of residual peat has been decomposed. Thereafter slow release during rest of simulation period.	Linear decrease from 0.15 to 0.06 g after 15 years.	0
C uptake in growing forest			
High fertility	-820	-	-
C accumulation in soil (humus)	-150 during first rotation period. Equilibrium is then reached.	-	-

Table 9 Emissions estimates for the different stages of the cultivated peatland scenarios. Positive sign is emission from ecosystem to atmosphere and negative sign is uptake.

Cultivated peatlands			
	CO_2 [g m^{-2} yr^{-1}]	N_2O [g m^{-2} yr^{-1}]	CH_4 [g m^{-2} yr^{-1}]
Initial stage			
Soil emissions	1780	1.5	0
During harvesting (conventional production method)			
Production area	Linear decrease to 980	Linear decrease to 0.3	Linear increase to 3.7
Stockpiles	250	0	0
Harvesting equipment and transports	1 g CO_2 MJ^{-1}	0.025 mg N_2O MJ^{-1}	0.7 mg CH_4 MJ^{-1}
During harvesting (new production method)			
Production area	770	0.1	0
Stockpiles	400	0	0
Harvesting equipment and transports	0.5 g CO^2 MJ^{-1}	0.012 mg N_2O MJ^{-1}	0.35 mg CH_4 MJ^{-1}
Combustion stage			
Conventional production method	105.2 g CO_2 MJ^{-1}	6 mg N_2O MJ^{-1}	5 mg CH_4 MJ^{-1}
New production method	100 g CO_2 MJ^{-1}	6 mg N_2O MJ^{-1}	5 mg CH_4 MJ^{-1}
Aftertreatment- afforestation			
Soil emissions after conventional production method	1100 exponential decrease during first rotation period when 50% of the residual peat has been decomposed. Thereafter slow release during rest of simulation period.	Linear decrease from 0.15 to 0.06 g after 45 years.	0
Soil emissions after new production method	550 exponential decrease during 45 years when 50% of residual peat has been decomposed. Thereafter slow release during rest of simulation period.	Linear decrease from 0.15 to 0.06 g after 15 years.	0
C uptake in growing forest	-820	-	-
C accumulation in soil (humus)	-150 During first rotation period. Equilibrium is then reached.	-	-

Table 10 Estimates for best case scenarios. Positive sign is emission from ecosystem to atmosphere and negative sign is uptake

	CO_2 [g m^{-2} yr^{-1}]	N_2O [g m^{-2} yr^{-1}]	CH_4 [g m^{-2} yr^{-1}]
Cultivated peatlands			
Initial stage			
Soil emissions	3550	4.8	0.3
During harvesting (new production method)			
Production area	770	0.1	0
Stockpiles	400	0	0
Harvesting equipment and transports	0.5 g CO^2 MJ^{-1}	0.012 mg N_2O MJ^{-1}	0.35 mg CH_4 MJ^{-1}
Combustion stage (new production method)			
	100 g CO_2 MJ^{-1}	6 mg N_2O MJ^{-1}	5 mg CH_4 MJ^{-1}
Aftertreatment- afforestation			
Soil emissions after new production method	550 exponential decrease during 45 years when 50% of residual peat has been decomposed. Thereafter slow release during rest of simulation period.	Linear decrease from 0.15 to 0.06 g after 15 years.	0
C uptake in growing forest	-618	-	-
C accumulation in soil (humus)	-150 During first rotation period. Equilibrium is then reached.	-	-
Forestry drained peatlands			
Initial stage			
Soil emissions	1111	0.81	3.7
C uptake in growing biomass	-618		
During harvesting (new production method)			
Production area	770	0.1	0
Stockpiles	400	0	0
Harvesting equipment and transports	0.5 g CO^2 MJ^{-1}	0.012 mg N_2O MJ^{-1}	0.35 mg CH_4 MJ^{-1}
Combustion stage (new production method)	100 g CO_2 MJ^{-1}	6 mg N_2O MJ^{-1}	5 mg CH_4 MJ^{-1}
Aftertreatment- afforestation			
Soil emissions after new production method	550 exponential decrease during 45 years when 50% of residual peat has been decomposed. Thereafter slow release during rest of simulation period.	Linear decrease from 0.15 to 0.06 g after 15 years.	0
C uptake in growing forest	-618	-	-
C accumulation in soil (humus)	-150 During first rotation period. Equilibrium is then reached.	-	-

Table 11 Emission estimates for the coal chain

	CO_2 [g MJ^{-1}]	N_2O [mg MJ^{-1}]	CH_4 [g MJ^{-1}]
Coal, Finnish estimates[*]			
Fuel production, transport & processing	4.09	0.02	0.21
Combustion	94.6	0.5	0.0007
Total	98.69	0.52	0.2107
Coal, Swedish estimates[**]			
Fuel production, transport & processing	3.2	-	1.1
Combustion	91.0	12	0.0005
Total	94.2	12	1.1005

[*] Based on Kirkinen et al 2008. [**] Based on Uppenberg et al 2001.

Table 12 Emission estimates for the co-combustion scenario

	CO_2 [g m^{-2} yr^{-1}]	N_2O [g m^{-2} yr^{-1}]	CH_4 [g m^{-2} yr^{-1}]
Initial stage	Same as forestry drained low fertility		
During harvesting (conventional method)	Same as all other scenarios with conventional harvesting method		
Combustion stage	97.76	0.006	0.0056
Aftertreatment - afforestation	Same as forestry drained low fertility		

Table 13 Values used in the variation diagram given in section 6.5. Note that the variation given here is based on the studies used for the emission estimates in this study and is not a complete variation based on all studies found in the literature. Positive values indicate emission to the atmosphere and negative values indicate uptake.

	Average			**Min**			**Max**		
	CO_2	**N_2O**	**CH_4**	**CO_2**	**N_2O**	**CH_4**	**CO_2**	**N_2O**	**CH_4**
Reference (before harvesting)									
Pristine mire	0	0	12	-245	0	2	285	0.03	30
Cultivated peatland	1780	1.5	0	270	-0.1	-0.22	7000	4.8	0.3
Forestry drained									
soil emissions	638	0.25	1	257	0	-0.4	1111	0.81	3.7
carbon seq. in biomass	-618			-618			-618		
Production stage									
Conventional prod									
Soil emissions	980	0.3	3.7	new production is used			1490	0.55	5.7
Stockpiles	250						375		
Harvesting equipment [g $m^{-2}yr^{-1}$]	150	0.00375	0 105						
New production									
Soil emissions (1 year)	770	0.1	0						
Stockpiles (1 year)	400	0	0						
Harvesting equipment [g $m^{-2}yr^{-1}$]	75	0.001875	0.0525						
Combustion stage [g MJ^{-1}]									
Conventional production	105.2	0.006	0.005	new production is used			106.5	0.0224	0.0106
New production	100	0.006	0.005						
Aftertreatment stage									
Restoration	-120	0	17	-271	0	4	28	0.03	30
Afforestation									
Soil emissions conv. prod.	1125	0.15	0	new production is used			1125	0.75	3.7
Soil emissions new prod.	550	0.1	0						
Carbon seq. in biomass	-820			-1310			-120		
Carbon seq. in soil	-150								