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Climate impacts of peat fuel utilization chains – a critical review of the Finnish and Swedish life cycle assessments

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PREFACE

The climate impacts of peat fuel utilization have been a controversial issue. The aim of this report was to clarify the debate and give a better basis for the Finnish energy policy decision-making by summarizing the recent scientific knowledge about the climate impacts of peat fuel utilization based on the life cycle assessment (LCA) methodology. The starting point for this process originated from a seminar arranged by the Finnish National Climate Change Panel in October 2008. On the basis of recommendations in the seminar the Ministry of the Environment decided to order a critical review on the climate impacts of peat fuel utilization chains at the end of 2008.

The critical review team consisted of

- Jyri Seppälä (coordinator), Juha Grönroos, Sirkka Koskela, Anne Holma, Pekka Leskinen, Jari Liski (Finnish Environment Institute)
- Juha-Pekka Tuovinen, Tuomas Laurila (Finnish Meteorological Institute)
- Jukka Turunen (Geological Survey of Finland – Kuopio Office)
- Saara Lind, Marja Maljanen, Pertti Martikainen, Antti Kilpeläinen (University of Eastern Finland – Faculty of Science and Forestry)

The draft review study was sent for comments in October 2009. The experts from the following organizations made comments:

- Vapo Oy (Kari Mutka, Päivi Picken, Pirkko Selin)
- VTT Technical Research Centre of Finland (Ilkka Savolainen, Kim Pingoud)
- METLA Finnish Forest Research Institute, (Jukka Laine, Jukka Alm, Pasi Puttonen)
- University of Helsinki (Kari Minkkinen)
- TEM Ministry of Employment and the Economy (Hanne Siikavirta)
- IVL Swedish Environmental Research Institute (Kristina Holmgren)

The comments were carefully considered by the review team, and the new draft was completed at the beginning of January 2010. The controversial issues were discussed in a national seminar arranged on 12 February 2010 in Helsinki. After the seminar the manuscript was improved. During the process, Aleksi Lehtonen (METLA), Timo Kareinen (Statistics Finland), Kristiina Regina (MTT Agrifood Research Finland) and Annalea Lohila (Finnish Meteorological Institute) gave valuable information about the calculation system of national greenhouse gas inventories. The preliminary version was presented in an international workshop held on 27 May 2010 in Helsinki. In the workshop Linus Hagberg from IVL gave his comments on the study. After the workshop the final version was finished.

The review team thanks all the commentators for their comments, which significantly increased the value of the work and its usefulness for policy decision making. Jaakko Ojala and Risto Kuusisto in the Ministry of the Environment deserve special thanks for providing the opportunity to carry out the review process. In addition, their opinions about the content of the report were very valuable.

CONTENTS

Executive summary

In recent years there has been a lively debate in Finland and Sweden on the climate impact of peat fuel utilization. Life cycle assessments of peat fuel carried out in both countries contributed significantly to this debate. In these assessments climate impacts have been determined on the basis of radiative forcing caused by the complete peat fuel utilization chain. However, some interpretations of the potential of peat as an energy source compared to fossil fuels, such as coal, were controversial.

The aim of this study was to clarify the contradictions between the Finnish and Swedish studies and provide a better basis for energy policy decision-making by summarizing the recent scientific knowledge about the climate impacts of peat fuel utilization chains based on the life cycle assessment (LCA) methodology. A starting point for this study was to carry out a critical review of three life cycle studies of the climate impacts of peat fuel utilization chains (Kirkinen et al. 2007 (FI 2007), Nilsson and Nilsson 2004 (SE 2004), Hagberg and Holmgren 2008 (SE 2008)). The critical review was conducted according to the recommendations of international standards (ISO 1040 and 1044) and its aim was to ensure that the methods, data and interpretation of results were carried out in a scientifically and technically valid way. During the review the available data (mostly published) on the greenhouse gas (GHG) balances and the radiative forcing impacts of GHGs were gathered and updated. Recalculations for different peat utilization chains and sensitivity analyses for the most critical assumptions were conducted on the basis of findings in the critical review. Finally, the most up to date knowledge about the climate impacts of peat fuel utilization and opinions about the meaning of the results for peat fuel utilization were addressed.

In order to reach a consensus on the climate impact of peat utilization chains the draft manuscript of the study was sent for comments in Finland and Sweden. The comments were carefully discussed in the review team, and the new draft was also discussed in an international seminar arranged in Helsinki. After the seminar the final version was completed.

Peat fuel utilization chains taken into account in the critical review were consisted of mire drainage, peat extraction, peat combustion and after-treatment (afforestation or restoration). The critical review focused on three alternative sources of peat: pristine mire, forestry drained peatlands and cultivated peatlands.

The critical review of materials and methods of the studies showed that:

1. The radiative forcing (RF) calculation is a proper methodology to quantify the climate impacts of peat fuel utilization chains. There were no significant differences in the radiative forcing (RF) calculation models between the reviewed studies, although some differences were identified in the individual models.
2. Slightly greater GHG emissions for coal combustion in the Swedish (SE 2004) study compared to the emissions used in the other studies gave more positive results for peat fuel utilization following the interpretation of the RF calculations.
3. The exclusion of the surrounding area (area around the actual peat extraction area) for forestry drained and cultivated peatlands in the latest studies is considered to be a correct assumption, resulting in reductions in the climate impacts of peat fuel utilization chains.

4. The determination of reference situations is one of the critical points in the calculations. The greater GHG emissions from an initial reference situation (peatland before peat production activities) are, the greater the benefits for peat fuel utilization. The reference situations used in the production reserves of pristine fen and forestry drained peatlands of the Finnish and Swedish studies were accepted, whereas in the case of cultivated peatland a consensus was not achieved for the initial reference situation. The review recommends using alternative initial references: abandoned organic croplands and actively cultivated peatlands. Abandoned organic croplands have not been considered an initial reference situation in the earlier LCAs. The CO_2 equivalent emissions of abandoned organic croplands are smaller than the emissions of cultivated peatlands.
5. An important difference between the Swedish and Finnish reports was found in the magnitude of net soil CO_2 emissions for forestry-drained peatlands. The value used in the Finnish study (FI2007) is based on the same information than the official Finnish greenhouse gas inventory and the assessment methodology used in the inventory can be considered the best way to determine net soil CO_2 emissions. Annual carbon sequestration by the trees and litter production in the context of afforestation were documented in the reviewed studies, but the use of them in the calculations was insufficiently described to be repeated exactly. The review showed that carbon accumulation in the soil caused by afforestation was not assessed in the right way in any of the reviewed studies although this has quit a small impact on the final results.. The re-calculations demonstrated that carbon accumulation in the soil has a slightly greater influence on the results than the earlier studies showed. Increased carbon accumulation in the soil in the afforestation phase slightly improves the climate impact of peat utilization compared to the impacts of coal utilization.
6. In the LCAs, several assumptions have to be applied about the GHG emissions caused by land use before, during and after peat extraction. It is well known that GHG emissions, carbon sequestration, litter and peat decomposition depend on the different conditions in peatlands and the current experimental data does not cover all the relevant conditions. Especially, emissions of nitrous oxides (N_2O) are poorly known, causing uncertainty in the results. In addition, the calculation system of land use in the LCAs are not based on dynamic modeling in which forest growth and soil emissions are handled together. It is important to understand that the LCA results are indicative, and the final results will change strongly case by case due to the large variation and uncertainty in the input data of different peatland types. In the future, an improvement in the calculation system and a continuation of experimental research is needed in order to get more reliable data for the calculations of climate impacts. The aim should be that data used in the official Finnish GHG emission inventory and in the LCAs of peat fuel utilization chains is consistent with each other.
7. The inventory data quality requirements in inventory analyses were not considered in the reviewed studies. In general, the input data of different life cycle stages in the Finnish and Swedish studies were well documented. However, there were many points in which the authors did not clearly explain the basis of their choices.
8. In general calculation methods used in the reviewed studies were according to the LCA principles. A key question in the method is how to determine initial and final reference situations in the calculations.

The sensitivity analysis showed that the climate impacts of peat fuel utilization chains are mostly caused by the carbon dioxide released by peat combustion. Another factor, although less important, is the type of peatland because the land use due to peat utilization will change the peatland's initial greenhouse gas balances. The effects of the emissions from the peat fuel production area in the harvesting phase are of minor importance and the emissions from transport and working machines are in practice insignificant.

The re-calculations showed that the peat utilization chain "Pristine mire – restoration" causes similar life cycle climate impact as it does in the reviewed studies. The result is worse than for the coal utilization chain, whereas the climate impact of "Pristine mire – afforestation" utilization chain is similar to the climate impact of coal utilization over a time perspective of 100 years. The result of the peat utilization chain with afforestation corresponds to the results obtained from Finnish study (FI 2007) and the most recent Swedish study (SE 2008).

The peat utilization chain "Forestry-drained peatlands – afforestration" causes a slightly higher climate impact on average than the coal utilization chain does. From the viewpoint of peat utilization the result was similar to the result of Finnish study (FI 2007), whereas it was worse compared to the result produced by the most recent Swedish study (SE 2008). It is well known that the results of forestry-drained peat utilization chains vary considerably according to the peat land type. The energy peat from high fertility forestry-drained peatlands caused smaller a climate impact compared to the impacts caused by the energy peat from low fertility forestry-drained peatlands. However, the results obtained from the different studies – whether taking fertility aspects into account or not - are very similar in terms of a 100 years perspective: the climate impact of a forestry-drained peat fuel utilization chain correspond to the climate impact of a coal energy utilization chain.

According to the reviewed studies the use of cultivated peatlands causes the lowest climate impact compared to the climate impacts of the other peatlands. However, the critical review showed that the earlier calculations included controversial assumptions about the options of land use in cultivated peatlands. It is not clear that the climate impact should be calculated on the basis of croplands as an initial state. There are also reasons for using abandoned organic croplands as an initial reference situation. The use of abandoned organic croplands causes a smaller climate impact of the peat fuel utilization chain than the coal energy utilization chain does. Due to unpredictable land use options in the future clear results for the climate impacts could not be produced in the review. However, in general it can be said that the climate impact of the peat fuel utilization chain "Cultivated peatlands-afforestation" is greater than the reviewed Finnish and Swedish studies have earlier showed.

The time perspective of the climate impact calculations in the peat fuel LCAs was 300 years. The fact is that such a long time perspective requires, for example, the assessment of changes in the soil greenhouse gas (GHG) balances in the modelling. However, the development of the GHG balances is very difficult to assess reliably in the changing climate. For this reason, the calculations are based on data representing the current state. As the various dynamical effects cannot be considered in the modelling, results become increasingly uncertain over longer periods of time. In practice, a time perspective of over 100 years includes so much uncertainty that such results are not recommended for use in decision making. The use of a shorter time perspective is justified because climate change mitigation requires fast actions over the next decades. Even a reduction of 80-95% in greenhouse gas emissions by 2050 should be done according to the Environmental Council of the EU environmental ministers.

It is important to notice that peat utilization chains based on the most common peatlands used for peat extraction (pristine mires and forestry-drained peatlands) cause similar climate impacts to coal energy utilization. In practice the use of afforestation as an after-treatment option does not change the climate impacts over a 100 years perspective. In addition, biodiversity conservation aspects must be considered in the use of pristine mires.

In the future, the climate impacts of peat energy utilization chains can be slightly reduced by selecting peatland production areas which have lower life cycle GHG emissions, such as cultivated or high fertility forestry-drained peatlands, and by using new extraction technologies. From the viewpoint of GHG emissions, it is important that the use of croplands for peat extraction does not move the cultivation of crops to abandoned organic croplands or new organic fields causing the same GHG emissions as the original croplands.

In any case, the separate use of peat in energy production is always problematic from the viewpoint of the climate impact. The combustion of peat releases carbon storage accumulated over thousands of years in a short time and the limited carbon sequestration due to after-treatment activities can only compensate the releases by some per cents over a 100 years' perspective.

Presented with the current challenges of climate change mitigation peat should be regarded as a promoter and an auxiliary fuel for the use of carbon neutral biomass. Peat can act as a reserve or back-up fuel for biomass because it is easy to store and the availability of biomass often varies in practice. Small fraction of peat in fuel can also reduce corrosion in some boilers. The mixture fuel of biomass and peat can substitute fossil fuels and thus significant emission reductions can be reached, although the CO_2 emissions from the peat combustion diminish the climate benefits of bioenergy.

Yhteenveto

Viime vuosina turpeen energiakäytön ilmastovaikutuksista on käyty vilkasta keskustelua Suomessa ja Ruotsissa. Keskusteluun ovat tuoneet oman lisänsä kummassakin maassa tehdyt energiaturpeen elinkaariarvioinnit, joissa energiaturpeen käytön ilmastovaikutukset on määritelty kasvihuonekaasupäästöjen säteilypakotteen (ilmastoa lämmittävän vaikutuksen) avulla. Elinkaariarvioinnin tulokset eivät ole olleet kaikilta osiltaan yksiselitteisiä. Tuloksilla on sekä perusteltu että vastustettu turpeen energiakäyttöä.

Työn tarkoituksena on ollut muodostaa tieteellisesti perusteltu kokonaiskuva energiaturpeen ilmastovaikutuksista. Tavoitteena on ollut selventää energiaturpeen ympärillä käytyä keskustelua ja parantaa päätöksentekoon liittyvää tietopohjaa turpeen energiakäytöstä. Työn lähtökohtana on ollut Suomessa ja Ruotsissa tehtyjen energiaturpeen elinkaariarviointitutkimusten (Kirkinen ym. 2007 (FI 2007), Nilsson ja Nilsson 2004 (SE 2004), Hagberg ja Holmgren 2008 (SE 2008)) kriittinen arviointi. Kriittinen arviointi tehtiin kansainvälisten standardien (ISO 1040 ja 1044) suositusten mukaisesti ja sen tarkoituksena oli saada varmistus siitä, että elinkaariarvioinneissa käytetyt menetelmät, aineistot sekä tulosten tulkinta on tehty tieteellisesti ja teknisesti oikein. Arvioinnin yhteydessä koottiin ja päivitettiin saatavilla oleva (pääsääntöisesti julkaistu) tietoaineisto soiden kasvihuonekaasutaseista ja kasvihuonekaasujen säteilypakotevaikutuksista. Kriittisessä arvioinnissa tehtyjen havaintojen perusteella erilaisille energiaturpeen hyödyntämisketjuille tehtiin uusintalaskelmat ja arvioitiin tulosten herkkyys tärkeiksi tunnistetuille elinkaarimallin tekijöille. Työn perusteella muodostettiin uusimman tiedon mukainen käsitys energiaturpeen ilmastovaikutuksista ja tulosten merkityksestä turpeen energiahyödyntämisen kannalta.

Työssä pyrittiin muodostamaan tutkijayhteisön yhteinen näkemys turpeen energiakäytön ilmastovaikutuksista. Sen vuoksi käsikirjoitus lähetettiin kommentoitavaksi alan keskeisille tutkijoille ja sidosryhmille Suomessa. Kommentit käsiteltiin huolellisesti tutkimusryhmässä ja epäselvistä asioista järjestettiin erikseen tutkijatapaamisia. Uusittua raporttiluonnosta käsiteltiin edelleen Helsingissä järjestetyssä kansainvälisessä seminaarissa.

Kriittisessä arvioinnissa energiaturpeen hyödyntämisen vaiheet olivat tuotantoon tulevan suon lähtötilanne (luonnontilainen suo, metsäojitettu suo tai suopelto), mahdollinen kuivaus, turpeenotto, kuljetukset, turpeen poltto ja turpeenottoalueen jälkikäyttö (metsitys tai ennallistaminen).

Arvioinnin yhteydessä koottiin ja päivitettiin saatavilla oleva (pääsääntöisesti julkaistu) tietoaineisto soiden kasvihuonekaasutaseista ja kasvihuonekaasujen säteilypakotevaikutuksista. Kriittisen arvioinnin aineiston ja menetelmien läpikäynti osoitti, että

1. Elinkaariarviointitöissä käytetty säteilypakotelaskelma on hyvä menetelmä energiaturpeen ilmastovaikutusten arviointiin. Kasvihuonekaasupäästöjen säteilypakotemallien tulokset eivät eronneet merkittävästi toisistaan, vaikka eri töissä käytetyt mallit erosivatkin joidenkin ominaisuuksien suhteen.

2. Aikaisemmassa ruotsalaisessa tutkimuksessa (SE 2004) on käytetty jonkin verran liian suuria hiilen energiatuotannon kasvihuonekaasupäästöjä, minkä seurauksena turpeen energiakäytön ilmastovaikutukset näyttäytyvät ko. tutkimuksessa liian edullisessa valossa suhteessa hiilen polton elinkaarisiin ilmastovaikutuksiin.
3. Varsinaisen turvetuotantoalueen ulkopuolisen alueen sisällyttäminen kasvihuonekaasulaskelmiin samoilla päästöoletuksilla ei ole perusteltavissa metsäojitettujen soiden ja suopeltojen yhteydessä. Suomalainen (FI 2007) ja uusin ruotsalainen tutkimus (SE 2008) ovat noudattaneet tätä periaatetta, mikä johtaa pienempiin ilmastovaikutuksiin ko. suotyypeillä aikaisempaan ruotsalaiseen tutkimukseen (SE 2004) verrattuna.
4. Turpeenottoalueen referenssitilanteet ovat kriittisiä valintoja ilmastovaikutusten laskennassa. Referenssitilanteilla tarkoitetaan suoalueen alkutilannetta ennen turpeenottotoimintaa ja lopputilanteella turpeenoton jälkeistä tilannetta. Mitä suurempi alkutilanteen kasvihuonekaasupäästöt ovat, sitä edullisempi tilanne on energiaturpeen ilmastovaikutuksille. Suomalaisessa ja ruotsalaisessa tutkimuksessa käytetyt referenssitilanteet ovat luonnontilaisen ja metsäojitettujen soiden tapauksessa hyvin perusteltavissa, mutta suopeltojen yhteydessä kriittinen arviointi tuotti toisenlaisen suosituksen referenssitilanteeksi kuin mitä arvioitavat tutkimukset olivat käyttäneet. Suopeltojen energiaturpeen hyödyntämisen tulokset ovat tarkoituksenmukaista esittää kahden vaihtoehtoisen referenssitilanteen avulla. Alkutilanne on joko hylätty suopelto tai keskimääräistä aktiiviviljelyä vastaava suopelto. Hylätyn suopellon, jota ei ole ollut alkutilanteena aikaisemmissa elinkaariarviointitöissä, kasvihuonekaasupäästöt ovat pienemmät kuin aktiiviviljelyksessä olevan suopellon.
5. Suomalaisen tutkimuksen ja ruotsalaisten tutkimusten lähtötiedot eroavat merkittävällä tavalla metsäojitettujen soiden maaperän hiilidioksidipäästöjen osalta. Suomalaisen työn (FI 2007) lähestymistapa perustui kansallisessa päästöinventaariossa käytettyyn menetelmään, mitä voidaan pitää parhaana lähestymistapana keskimääräisen metsäojitetun suon lähtötietojen arvioimiseksi. Metsän kasvun aiheuttama vuosittainen hiilensidonta puihin ja karikkeen muodostuminen oli dokumentoitu arvioitavissa elinkaariarviointitöissä, mutta turvealueiden jälkikäytön metsityksen arviointiperusteita ei ollut esitetty selkeästi. Kriittisen arvioinnin yhteydessä havaittiin, etteivät mitkään aikaisemmat elinkaariarviointityöt ole käsitelleet metsitysvaiheen aiheuttamaa hiilen varastoitumista maaperään oikealla tavalla. Kriittisen arvioinnin yhteydessä tehdyt maaperän hiilivaraston muutoslaskelmat osoittivat, että maaperään sitoutuu hiiltä hiukan aikaisemmin oletettua enemmän. Tämä parantaa hieman turpeen energiakäytön ilmastovaikutuksia hiilen polton ilmastovaikutuksiin verrattuna.
6. Elinkaariarviointitöissä on jouduttu tekemään monia oletuksia maankäyttöön liittyvistä kasvihuonekaasupäästöistä. Nykyinen kokeellinen aineisto ei ole tarpeeksi kattavaa ja sitä on vaikea saada edustavaksi, sillä hiilensidonnan, turpeen ja karikkeen hajoamisen sekä hiilidioksidi-, metaani- ja typpioksiduulipäästöjen tiedetään vaihtelevan suuresti erilaisissa olosuhteissa. Erityisesti typpioksiduulipäästöihin sisältyy suurta epävarmuutta. Maankäytön arviointi elinkaariarvioinneissa ei myöskään perustu dynaamiseen mallinnukseen, jossa sekä puunkasvu että maaperän päästöt käsiteltäisiin yhdessä. On tärkeää huomata, että elinkaaritulokset ovat suuntaa-antavia. Tulokset ja siten myös niiden epävarmuus vaihtelevat tapauskohtaisesti suuresti. Tulevaisuudessa tarvitaan lisää sekä laskentamallien kehitystyötä että kokeellisesta mittaustietoa erilaisten soiden hiilitaseista ja kasvihuonekaasupäästöistä luotettavampien tulosten aikaansaamiseksi. Tavoitteena tulee olla, että energianturpeen elinkaari-

arvioinneissa käytettävät tiedot ovat samat kuin virallisessa Suomen kasvihuonekaasupäästöinventaariossa.

7. Elinkaariarviointitöissä ei ole käsitelty lähtötietojen laatuvaatimuksiin liittyviä näkökohtia. Yleisesti voidaan kuitenkin todeta, että lähtötiedot on dokumentoitu hyvin. Toisaalta töissä on useita kohtia, joissa valintojen perusteluja ei ole riittävästi avattu lukijalle.
8. Arvioitavissa elinkaariarviointitöissä käytetyt laskentamenetelmät ovat yleisesti ottaen elinkaariarviointimenetelmän perusperiaatteiden mukaisia. Keskeinen tekijä menetelmässä on se, kuinka alku- ja lopputilanteiden referenssit on otettu huomioon laskelmissa.

Energiaturpeen ilmastovaikutukset aiheutuvat pääasiassa turpeen poltossa syntyvästä hiilidioksidipäästöstä, joka tunnetaan suhteellisen tarkasti. Tärkeä tekijä, joskin paljon polton päästöä vähämerkityksellisempi, on turpeenottoalueen suotyyppi, jonka luontaisia kasvihuonekaasutaseita turpeenoton maankäyttötoimenpiteet muuttavat. Turpeen tuotantoalueen päästöt ovat kolmanneksi tärkein seikka, mutta kuljetusten merkitys ilmastollisessa kokonaisvaikutuksessa on vähäinen.

Kriittinen arviointi osoitti, että luonnontilaisten soiden turpeen käyttö energiatuotannossa, jos jälkikäyttönä on ennallistaminen, johtaa hiukan suurempiin elinkaaren aikaisiin ilmastovaikutuksiin kuin mitä energiatuotanto kivihiilellä aiheuttaa. Tulos on sama kuin mihin suomalaiset ja ruotsalaiset energiaturpeen elinkaariarviointityöt olivat päätyneet aikaisemmin. Metsitys jälkikäyttönä parantaa luonnontilaisen suon turpeen energiakäytön ilmastovaikutuksia kivihiilen energiakäyttöön verrattuna. Kriittisen arvion mukaan turpeen ja kivihiilen energiakäytön ilmastovaikutukset ovat samaa luokkaa 100 vuoden aikajänteellä, mikä on linjassa suomalaisen (FI 2007) ja viimeisimmän ruotsalaisen (SE 2008) tutkimusten kanssa.

Metsäojitettujen soiden turpeen energiakäyttö aiheuttaa kivihiileen verrattuna keskimäärin hieman suuremman ilmastovaikutuksen sadan vuoden aikana. Tulos on turpeen hyödyntämisen kannalta samanlainen kuin aiemmassa suomalaisessa elinkaaritutkimuksessa (FI 2007), mutta selvästi huonompi kuin viimeisin ruotsalainen tutkimus (SE 2008) osoitti. Tulos kuitenkin vaihtelee suuresti suotyypeittäin. Ravinnerikkailla metsäojitetuilla soilla voidaan saavuttaa parempi ilmastohyöty kuin ravinneköyhillä soilla. Tulosten tulkinnassa on erittäin tärkeää huomata se, että eri tutkimusten tulokset – otettiin metsäojitettujen soiden ravinteikkuus huomioon tai ei – antavat sadan vuoden aikajaksolla samanlaisen tuloksen: metsäojitettujen soiden turpeen energiakäyttö aiheuttaa likimain samansuuruisen ilmastovaikutuksen kuin kivihiili.

Suopeltojen turpeen käytön on uskottu aikaisempien elinkaaritutkimusten perusteella aiheuttavan muita turvemaita selvästi alhaisemmat kasvihuonekaasupäästöt. Kriittinen arviointi kuitenkin osoitti, että ilmastovaikutushyödyn laskentaan liittyy kiistanalaisia oletuksia suopeltojen tulevaisuuden maankäytöstä. Aktiiviviljelyksessä olevan suopellon käyttö referenssitilanteena ei ole itsestään selvää. On olemassa myös perusteita käyttää hylättyä suopeltoa alkureferenssinä. Jälkimmäinen vaihtoehto tuottaa hieman pienemmän ilmastovaikutuksen kuin hiilienergian käyttö. Koska tulevaisuuden maankäyttömuotoja on vaikea ennustaa, suopeltoon liittyvää tulosta ei pystytty esittämään tässä yhteydessä yksiselitteisesti. Yleistäen voidaan kuitenkin sanoa, että lopputulos oli suopeltojen turpeen ilmastovaikutusten kannalta huonompi kuin mitä suomalaiset ja ruotsalaiset elinkaaritutkimukset ovat aikaisemmin osoittaneet.

Energiaturpeen elinkaariarvioinneissa ilmastovaikutuslaskelmat on ulotettu 300 vuoden päähän. Maankäyttövaikutusten huomioon ottaminen näin pitkällä aikajänteellä edellyttäisi oletuksia muun muassa turvemaiden kasvihuonekaasutaseiden muutoksista. Taseiden kehityksen luotettava arviointi muuttuvassa ilmastossa on hyvin vaikeaa, minkä vuoksi laskelmat on tehty käyttämällä nykytilannetta kuvaavia lähtötietoja. Menettelytapa johtaa siihen, että tulokset tulevat sitä epävarmemmiksi, mitä kauemmaksi nykyhetkestä edetään. Sadan vuoden jälkeistä tilannetta kuvaavien tulosten käyttö päätöksenteossa on tieteellisesti epävarmaa. Lyhyen aikaperspektiivin valintaa tulosten tulkinnassa puoltaa myös se, että ilmastonmuutoksen hillintä vaatii nopeita toimia seuraavien vuosikymmenien aikana. Esimerkiksi EU:n ympäristöministerien neuvoston mukaan päästöjä tulisi vähentää vuoteen 2050 mennessä 80 - 95 prosenttia.

Kriittisen arvioinnin keskeinen johtopäätös on, että energiaturpeen otto tavallisimmilta turvetuotantoalueilta (luonnontilaiset suot ja metsäojitetut suot) aiheuttaa samaa luokkaa olevan ilmastovaikutuksen kuin kivihiilen käyttö. Metsitys jälkikäsittelynä ei muuta tulosta 100 vuoden tarkastelujakson aikana. Lisäksi biodiversiteettikysymykset nousevat esiin luonnontilaisten soiden käyttöä arvioitaessa.

Tulevaisuudessa turpeen polton ilmastovaikutuksia voidaan vähentää hiukan kohdentamalla turpeenotto suopelloille ja reheville metsäojitetuille soille sekä ottamalla käyttöön uusia turpeenottomenetelmiä. Päästöjen kannalta on merkittävää, ettei suopelloilta vapautuva viljelytoiminta hakeudu hylätyille suopelloille tai ettei uusia suopeltoja raivata käyttöön. Tällöin aikaisemmilta suopelloilta vältetyt päästöt siirtyvät uuteen kohteeseen.

Turpeen erilliskäyttö energiatuotannossa on aina ongelmallista ilmastonmuutoksen hillinnän näkökulmasta. Turpeen poltossa vapautuu vuosituhansien aikana sitoutuneet suuret hiilivarannot nopeasti ilmakehään, ja jälkikäytön mahdollisuudet hiilen sidontaan 100 vuoden aikajaksolla ovat rajalliset.

Ilmastonmuutoksen hillinnän haasteiden edessä turve tulisi nähdä entistä enemmän hiilineutraalien biomassojen käytön edistäjänä ja lisäpolttoaineena. Turve voi olla varapolttoaine, koska sitä voidaan helposti varastoida. Turpeen käyttö vähentää myös syöpymistä eräissä voimalaitoskattiloissa. Turpeen ja uusiutuvan biomassan seoksella voidaan korvata fossiilisia polttoaineita, ja näin saavutettaisiin merkittäviä päästövähennyksiä, vaikka turpeen poltosta vapautuva hiilidioksidi vähentääkin tuotetun bioenergian ilmastohyötyjä.

1 Introduction

Peat is formed as a result of the accumulation of carbon over centuries and millenniums. Studies conducted in Finland and Sweden demonstrate that greenhouse gas emissions from the energy utilization of these reserves are relatively high (Hillebrand 1993, Savolainen et al. 1994a, 1994b, Uppenberg et al. 2001). In recent years there has been a debate in both countries about the climate impact of peat utilization and the classification of peat as an energy source. In Finland, peat is classified as a slowly renewable biomass fuel (Ministry of Trade and Industry 2001). Also IPCC 2006 guidelines classify peat in a category of its own which is reported in emission tables between renewable and fossil fuels. However, even though peat is not considered to be a fossil fuel, the emissions from peat combustion are considered to be comparable to those of fossil fuels in greenhouse gas inventories according to the IPCC 2006 Guidelines. In Sweden it is argued that peat should not be classified, since that might "conceal the complexity of its actual impact" (Nilsson and Nilsson 2004). Internationally peat is considered a fossil fuel (European Union Emission Trading Scheme, Statistics of OECD/IEA and Eurostat).

It is crucial to cut GHG emissions in order to stabilise carbon levels in the atmosphere and therefore to limit global temperature rise to below 2 -3 °C. Global emissions should be reduced by 50-85% compared to the year 2000 level by the year 2050 (IPCC 2007). This also means that greenhouse gas emissions need to be considered using a time span of a maximum of only100 years. Especially the greenhouse gas emissions of energy production need to be reduced to reach the climate target. Quick decisions have to be made concerning the use of various energy sources. Valid and up-to-date information on the climate impacts of peat is also needed to support decision making.

Life cycle assessments of peat energy utilization have been performed both in Finland by the VTT Technical Research Centre and in Sweden by the IVL Swedish Environmental Research Institute Ltd from the viewpoint of climate impacts. Three main greenhouse gases - carbon dioxide, CO_2, methane, CH_4, and nitrous oxide, N_2O - were included in both studies. The main Finnish study was "Greenhouse impact due to different peat utilization chains in Finland – a life-cycle approach" (Kirkinen et al. 2007) and the Swedish study was "The climate impact of energy peat utilization in Sweden – the effect of former land-use and after-treatment" (Nilsson and Nilsson 2004). Some of the results of these studies were controversial in their interpretation of the potential of peat as energy source compared to fossil fuels such as coal. For this reason, VTT and IVL conducted a comparison and sensitivity study of Finnish and Swedish LCAs (Holmgren et al. 2006). The aim was to clarify the reasons for differences and similarities in the results of the studies. To get a consensus about the climate impact of use of peat for energy purposes has proven to be difficult since even after these studies a debate on peat as energy is still going on in Finnish society.

In October 2008, the Finnish National Climate Change panel arranged a seminar to clarify the debate surrounding peat energy. However, the short discussion could not give a final answer for the climate impact of peat energy utilization. For this reason, one main conclusion of the seminar was that there is a need to conduct a critical review process on the existing peat life cycle assessments (LCAs) following ISO standards.

This study addresses a critical review of the Finnish and Swedish LCA studies on peat energy utilization. The Finnish and partly the Swedish results were recalculated. It should be noted that during the review process a new Swedish study of peat utilization was published. This latest Swedish report entitled "The Climate Impact of Future Energy Peat Production" by IVL (Hagberg and Holmgren 2008) was also examined in this review.

In addition to the ISO review process, the authors highlighted sensitivities and changes in the interpretation of the previous results based on the findings of the critical ISO review. Finally, based on these revised results future trends for the sustainable use of peat fuel are outlined.

2 Critical review process

According to the international standards (ISO 14040 and ISO 14044) a critical review is a process to verify whether a LCA met the requirements for methodology, data, interpretation and reporting and whether it is consistent with the principles of ISO 14040-43. More exactly, critical reviews should ensure that

1) the methods used to carry out the LCA are consistent with the international standard;
2) the methods used to carry out the LCA are scientifically and technically valid;
3) the data used are appropriate and reasonable in relation to the goal of the study;
4) the interpretations reflect the limitations identified and the goal of the study and
5) the study report is transparent and consistent.

A starting point for the Finnish review process on LCAs of peat energy utilization was to fulfil these five points. It is important to note that although the VTT and IVL studies have been performed according to the rules of life cycle assessment, their documentation did not exactly follow the formats required in the LCA standards. For this reason, the first point regarding critical reviews was omitted in this work.

A life cycle assessment should include the phases of goal and scope definition, inventory analysis, impact assessment and interpretation of results. In the review there is a need to follow these phases in the studied cases. For this reason, the titles of chapters (sections) in this review report were arranged according to the phases of LCA.

In the review process two main Swedish studies were reviewed. The work done by Nilsson and Nilsson (2004) was the basic Swedish study, referred to as the Swedish study (SE 2004). The work of Hagberg and Holmgren (2008) was referred to as the Swedish study (SE 2008), otherwise known as the most recent Swedish study. The Finnish study (Kirkinen et al. 2007) is referred to as Finnish study (FI 2007).

Section 3 (“Evaluation of materials and methods”) in this report includes an evaluation of the second and third requirements of critical reviews, i.e. the aim was to ensure that the LCAs were conducted in a scientifically and technically valid way in relation to the goal of the study.

Section 4 (“Recalculations and sensitivity of results”) shows the final results with factors causing changes in the results. In addition, the fourth requirement of critical reviews (interpretation aspects) is described under this section.

The requirements for reporting (transparency and consistency) were ensured by repeating the calculations used in the studies.

It is important to notice that during the review the available data (mostly published) on the greenhouse gas (GHG) balances and a method to calculate the radiative forcing impacts of GHGs were gathered and updated (Appendixes 1 and 2). Furthermore, new calculations for carbon accumulation in the soil were carried out (Appendix 3). The checking process was carried out in a more detailed way than a critical review requires according to the ISO standards. In addition, sensitivity analysis and recalculations (Section 4) based on the findings gathered in the evaluation of materials and methods are additional to the needs of the critical review based on the ISO standards. Thus, the critical review carried out in this work does not directly correspond to the critical review process of the ISO.

A special feature of the critical review carried out was also related to the publication process. In order to reach a consensus on the climate impacts of peat fuel utilization chains a draft manuscript of the study was sent for comments in Finland. The comments were carefully considered by the review team, and the new draft was discussed in an international workshop arranged in Helsinki. After the workshop the final version was finished.

3 Evaluation of materials and methods

3.1

Goal and scope definition

3.1.1

Aim of the study

The objectives of the studies were well defined. The audience - i.e. to whom the results of the studies are intended to be communicated - is not, however, explicitly explained.

The objectives of the studies were somewhat different. The aim of the Finnish study (FI 2007) was to find a peat production chain with low climate impacts and to evaluate the types of peatlands and after-treatment methods most preferable for use from a climate perspective. The aim was also to assess the sensitivity and uncertainty of the results. In addition, the Finnish study aimed to produce new information on the climate impact of peat energy utilization for the reporting of GHG-emissions according to the IPCC guidelines for the UN Framework Convention on Climate Change.

The aim of the Swedish study (SE 2004) was to estimate the climate impact of the current use of peat fuel in Sweden and investigate the greenhouse gas reduction potential by choosing the right extraction sites and after-treatment methods.

Both the studies aimed to compare the greenhouse gas impact of peat energy utilization with the climate impacts of coal energy utilization. In addition, in the Swedish study (SE 2004), the results of peat energy utilization were compared to the results of natural gas energy utilization. The comparison was also within the scope of this review process, i.e. *how much peat energy utilization causes climate impacts compared to climate impacts released from coal*?

The aim of the latest Swedish study (SE 2008) was to compile the results from the earlier LCA-studies, to include new data of greenhouse gas fluxes and to estimate total emissions and climate impacts for different peat utilization scenarios. Thus, the aim had similarities with this review process.

3.1.2

Functional unit and energy content of peatlands

Within the studies, alternative peat fuel utilization chains were compared using the same functional unit and equivalent methodological considerations as mentioned in the LCA standards (such as performance, system boundaries, data quality, allocation procedures, decision rules and impact assessment). However, between the original studies functional units differ.

In the Finnish study the functional unit is clearly described, whereas the Swedish studies' functional unit is not explicitly expressed.

In the Finnish study (FI 2007) the functional unit is 1 PJ of peat fuel energy (combusted in a power plant). In the Swedish studies (SE 2004, SE 2008) emissions and radiative forcing were calculated per square meter of extraction area. Both of the approaches are suitable when relative differences in the climate impacts of different peat fuel production cases are compared within a study.

If the results of different studies are compared, however, the functional unit must be equal. This was the case in the comparative study of Holmgren et al. (2006). There the results of the Swedish studies were converted to meet the equal functional unit of the Finnish study (1 PJ of peat fuel energy). The same functional unit has also been used in this critical review.

The energy content of peatlands in the calculations of the Finnish study (FI 2007) was 3384 MJ/m^2, whereas in the Swedish studies (SE 2004, 2008) it was 3030 MJ/m^2. This means that it is assumed that one PJ of peat fuel energy requires a peat extraction area of 30 ha in the Finnish study (FI 2007) and of 33 ha in the Swedish studies (SE 2004, 2008). It is important to notice that according to the Finnish greenhouse gas inventory (Statistics Finland 2010) the relationship between the energy content and peat extraction area is only 2200 MJ/m^2 when the amounts of produced peat fuel energy are divided by the peat extraction areas in 2000-2008. In this case one PJ of peat fuel energy requires a peat extraction area of 45 ha. However, it is not clear how reliable and suitable this value is for the LCA applications. On the other hand, the basis for the value used in the Finnish study (FI 2007) can be found from the earlier research studies. For this reason, it is recommended to use the value of the Finnish study (FI 2007) in the Finnish LCA applications.

In the calculations of the reviewed studies it was assumed that the thickness of peat layer is 2 m. The same thickness has also been used in the critical review.

3.1.3

Alternative peat fuel utilization chains

In the reviewed studies several different alternatives for peat fuel utilization chains were considered. In all chains peat combustion is applied to produce electricity/heat (Fig. 1). The critical review focused on three alternative chains with different source of peat and after-use (=land-use after the peat extraction at the site has ceased):

1) pristine mire with afforestation or restoration as the after-use option
2) forestry drained peatland a with afforestation as the after-use option
3) cultivated peatland with afforestation as the after-use option.

The basic structure of a peat fuel utilization chain is quite simple. The main life cycle stages are the same in all the alternative chains (Fig. 1).

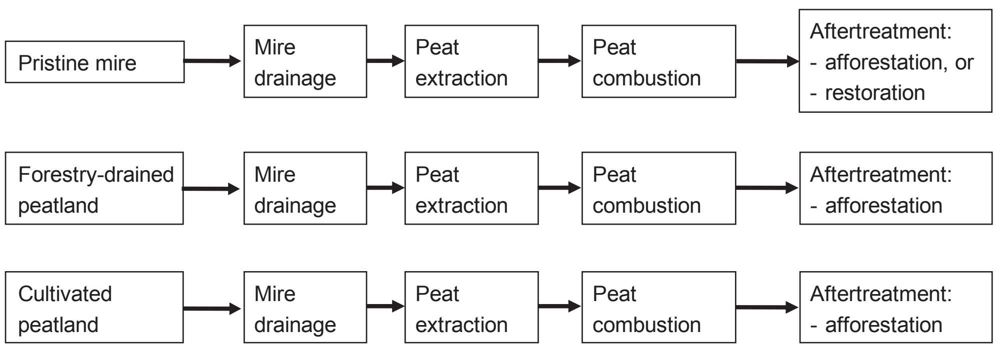

Figure 1. General view of the alternative peat fuel utilization chains considered in this report. The main life cycle stages are similar in the three alternative chains.

3.1.4
System boundaries and unit processes included

Although the main life cycle stages were the same, there were differences in the system boundaries and unit processes between the reviewed studies (Table 1). The main differences between the studies were:

- *the drainage phase of mire was not considered in the Finnish study,* whereas in the Swedish study (2004) a five year period between mire vegetation stripping and ditching (= year 0) and starting the peat extraction (= year 6) was included. In the Swedish study (SE 2008), the drainage time for pristine mires and drained forested peatlands was assumed to be 2 years before extraction. However, for drained cultivated peatlands further drainage was not considered.

- *the surrounding area (area around the actual peat extraction area) was not considered in the Finnish study*, whereas in the Swedish study (SE 2004) the impact of drainage on the GHG-balances in the surrounding area was estimated. It was assumed that the surrounding area was equal to the area of the actual extraction site. However, in the Swedish study (SE 2008) the surrounding area affected by the drainage was changed to 50 % of the extraction area for the pristine mires but for the forestry drained peatlands and drained cultivated peatlands the surrounding area was not considered.

In the Swedish study (SE 2004) the scientific basis to use the same area for the surrounding area and production field was not shown. On the other hand, in the report of Holmgren et al. (2006) it was estimated that the surrounding area may vary from 12 to30 % of the area of the production site. It is obvious, however, that the size of the surrounding area varies case by case. In the Swedish study (SE 2008), the results of Olsson (2006) were used to justify the size assumptions of the surrounding area.

In the Finnish study, the decision to omit the mire drainage phase and the surrounding area was not stated or justified, and the potential impacts on the outcome of the study due to these limitations was not discussed. The importance of the above mentioned differences on the final results are discussed later in this report.

Unit processes are the smallest units for which information is gathered in LC inventories. The unit processes in the context of peatland differ from unit processes typically used in LCAs. The task of peat energy LCAs includes the assessment of net GHG emission change in peat production area before (=initial reference situation) and after peat extraction (=after-treatment situation). For this purpose, it is necessary to assess sequestration of carbon (C) caused by forest growth in the peatland before and after peat extraction. Furthermore, forest growth causes an input of C to the soil through above and underground forest litter. Part of this litter production will be decomposed. In addition, peat in the reference, extraction and after-treatment situations will be decomposed. In order to assess net GHG emission change in the peatland, C fluxes due to litter production and soil respiration should be known (Fig 2).

In general, the calculation bases for net soil GHG emissions were not clearly documented in the reviewed studies (see Sections 3.2.1 and 3.2.6).

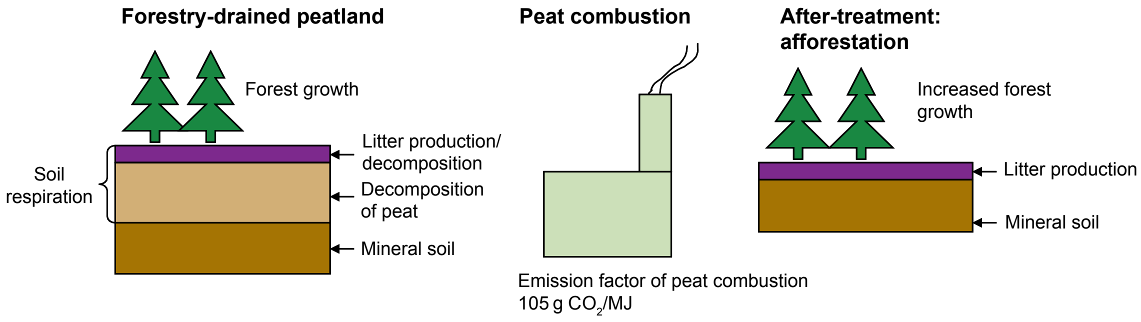

Figure 2. Basic land use processes before and after peat extraction causing GHG emissions in the case of peat utilization scenario "Forestry-drained peatland – afforestation" (modified from the presentation of Kari Mutka presented in Finnish IPCC workshop 29.10.2008).

Table 1. Process units of life cycle stages included in the Finnish (FI) and Swedish (SE) studies.

Stage	**SE (2004)**	**SE (2008)**	**FI (2007)**
Initial state, (production reserve) [1]	Included (surrounding area included)	Included (surrounding area *only* for pristine mire included)	Included (surrounding area *not* included)
Drainage stage:			
- production field	Included (5 years)	Included (2 years) except cultivated peatlands	*Not* included
- surrounding area	Included (5 years)	Included (5 years)	*Not* included
Peat extraction:	(20 years)	(20 years)	(20 years)
- production field	Included	Included	Included
- surrounding area	Included	*Only* for pristine mire included	*Not* included
- working machines	Included	Included	Included
- stockpiles	Included	Included	Included
- peat transportation	Included	Included	Included
Peat combustion	Included	Included	Included
After-treatment options:			
Restoration	Included (surrounding area included)	Included (surrounding area *only* for pristine mire included)	Included (surrounding area *not* included)
Afforestation:			
- C-sequestration to forest	Included (surrounding area included)	Included (surrounding area *only* for pristine mire included)	Included (surrounding area *not* included)
- decomposition of residual peat	Included (surrounding area included)	Included (surrounding area *only* for pristine mire included)	Included (surrounding area *not* included)
- Accumulation of aboveground forest litter	Included (surrounding area included)	Included (surrounding area *only* for pristine mire included)	Included (surrounding area *not* included)
- Accumulation of below ground forest litter	*Not* included (surrounding area **not** included)	*Not* included (surrounding area *not* included)	Included (surrounding area *not* included)
Note: [1] = the state before peat utilization: pristine mire, forestry-drained peatland or cultivated peatland			

3.1.5

Methodology for impact assessment

In the impact assessment only climate change was considered due to the objectives of the studies, i.e. to study the impacts of different peat fuel energy production systems on climate change and to compare them with the impacts of fossil fuels. In both studies a climate change impact assessment was carried out by using the concept of radiative forcing. The details concerning the radiative forcing calculations were not explicitly discussed in the research reports.

3.1.6

Data quality requirements in inventory analysis

Inventory data quality requirements in inventory analysis were not considered in the reviewed studies.

3.1.7

Reference systems and scenarios

In the LCA studies, coal was used as a reference fuel to which the climate impact of the peat fuel utilization chain was compared. In the coal utilization chain all the phases of the life cycle - coal mining, transport and processing, coal combustion - were taken into account according to the life cycle approach. Greenhouse gas emission credits from by-products such as fly ash, bottom ash and gypsum were not taken into account. This is justified on the basis that all activities outside peat extraction areas after peat combustion were also omitted in the peat fuel utilization chain. Thus, the results of LCAs on peat and coal were comparable. The selected approach seems to be appropriate because the emission credits do not play an important role in the GHG emissions of the coal energy system (e.g. Seppälä et al. 2005).

In the Swedish study (SE 2004) natural gas energy utilization was also taken into account in order to obtain a more complete view of the climate impact of peat energy utilization.

A starting point for the comparisons of different alternative peat fuel utilization chains was to calculate the changes in greenhouse gas balances in the peat fuel production area over time. For this reason, the reviewed studies needed to determine a *reference scenario*. The reference scenario describes the non-utilization situation that corresponds to the pre-extraction conditions in the peatland. Emissions from this stage are considered to be avoided in the *utilization scenario* which covers all activities of the peat fuel utilization chain starting from the area of the peat production reserve. The utilization scenarios also include the effects of after-treatment options. Thus, the calculation equation is

$$I = I_u - I_r \qquad (1)$$

where I is the net climate impact (expressed by radiative forcing calculations) caused by the peat utilization chain, I_u is the climate impacts caused by the peat utilisation scenario and I_r is the climate impact caused by the reference scenario. All the reviewed studies have used the same equation for the calculation of the net climate impact.

In the review process, it is pointed out that there is a need to determine two different reference situations for each peat production reserve - pristine mire, forestry drained and cultivated peatlands - in order to calculate the avoided emissions of scenarios in the right way. The state of the area before peat utilization comprises an *initial reference situation* and the final state of the peat production area used in the LCA calculations comprises a *final reference situation* (known as the final phase in the Finnish study). It is important to understand that the initial and final reference situations can also differ from each other in the case of the reference scenario even without peat extraction.

Determination of the reference situations was based on the approach chosen for the calculation rules of inventory analysis (see Section 3.3). In the review process, the reference situations used in the studies for production reserves of pristine fen and forestry drained peatlands were accepted, whereas in the case of cultivated peatland different reference situations were chosen compared to the choices used in the Finnish and in the Swedish studies (Table 2). Emission credits (sequestration of C) due to the forest growth resulting from afforestation cannot be automatically allocated to the peat fuel utilization chain there because afforestation could also be conducted without peat fuel production in cultivated peatlands. In principle, the additional growth caused by afforestation due to changes in the growth conditions in cultivated peatlands could be included in calculations as an advantage of the peat fuel utilization chain from a climate perspective. However, there are no specific data for this calculation, and changes in growth may vary case by case resulting from the variable site conditions.

The determination of the initial reference situation in cultivated peatland presented above is a controversial issue. One can argue that current cultivated croplands will be cultivated in the future due to the expected increased demand of global food production and due to expected warmer climatic conditions. Therefore even if peat extraction avoids GHG emissions by replacing cultivated cropland it is highly likely that the cultivated cropland will move to new land or abandoned cropland. Thus the avoided emissions should not automatically be attributed to peat energy utilization.

Due to unclear future land use options in cultivated organic peatlands, two alternative initial reference situations were recommended for use in the calculations: abandoned organic croplands with afforestation option and cultivated organic croplands representing the current average situation in Finland. The final reference situation after peat extraction in both situations was afforestation (see Table 2).

In the case of cultivated peatlands abandoned organic croplands should be used as a proper reference scenario. A former agricultural activity causing a high climate impact cannot be used as an initial reference situation because peat production in the cultivated peatland is not the only measure to avoid the emissions of actively cultivated peatlands. Termination of the active farming is the simplest method to decrease the emissions of cultivated peatlands, starting peat production is not required for that.

In Maljanen et al. (2007), the net emission level of CO_2 in abandoned organic agricultural cropland is lower than that in actively cultivated land (barley or grass). The average N_2O emission level of abandoned land is between barley and grass and it is a small sink of CH_4. In the Swedish studies (SE 2004, 2008), very high emission values for row-crops were also used. However, the emissions were based on unpublished data. Thus, the results of the peat fuel utilization are likely to alter using the new alternative reference situations outlined above.

Table 2. Initial and final reference situations used in the studies (FI= Finnish, SE=Swedish, RW=review)

Production reserve	After-treatment	Initial reference situation	Final reference situation	Study
Pristine fen	Restoration Afforestation	Pristine fen Pristine fen	Pristine fen Forestry drained peatland	FI, SE, RW FI, SE,RW
Forestry drained peatland	Afforestation	Forestry drained peatland	Forestry drained area	FI, SE, RW
Cultivated peatland	Afforestation	Cultivated organic cropland -grass, barley or row-crops covered (SE 2004, 2008) - mean value for grass and barley (FI 2007) - Abandoned organic cropland with forest growth - Average cultivated cropland in Finland	Afforested cropland Afforested cropland Afforested cropland	FI, SE RW

3.2

Inventory analysis: data collection and calculation

3.2.1

Initial stage

Pristine fen

The annual spatial and temporal variability of carbon dioxide (CO_2) emissions/sinks between different studies, sites and measuring periods is very large (see review by Saarnio et al. 2007). The same concerns methane (CH_4) emissions (i.e. review by Saarnio et al. 2007). In practice, the contribution of nitrous oxide (N_2O) to climate impact caused by pristine fen is negligible (Martikainen et al. 1993).

In general, the greenhouse gas emissions from pristine peatlands were well documented in the Finnish and Swedish studies. However, there were some minor inconsistencies between the reported values in the Swedish study (SE 2004) and the original references (see Appendix 1), but they have no effect on the final results.

The differences between annual CO_2 sequestration rates of pristine mires used in the Finnish and Swedish studies were marginal. Also, the CH_4 and N_2O emissions rates used were similar and within the range obtained from corresponding mire types (Saarnio et al. 2007).

A clear limitation of the Finnish study was that only fens were included in the LCA analysis. At present, new annual long-term net ecosystem CO_2 exchange (NEE) measurements using the micrometeorological eddy covariance method are available for both pristine fens and bogs. The mean values of these new studies (Appendix 1) are slightly higher compared to the CO_2 sequestration rates used in the Finnish and Swedish studies. The corresponding CH_4 and N_2O measurements are of the same magnitude compared to the values used in the Finnish and Swedish studies.

The current best available GHG flux values of pristine boreal fen/mire (Table 3) are based on Aurela et al. (2004, 2007, 2009; Saarnio et al. 2007; von Arnold et al. 2005a; see Appendix 1). The small differences between the reviewed studies and current best available values were found in the context of CO_2 and CH_4 (Table 3).

In the case of pristine fen, all the reviewed studies assumed that there was no forest growth in the initial reference situation. The assumption is acceptable.

Forestry-drained peatland

An important difference between the Swedish and Finnish studies can be found in the magnitude of soil CO_2 emissions for forestry-drained peatlands (Table 3). Swedish estimates of CO_2 emissions are significantly higher compared to the corresponding Finnish estimates (Table 3). The reason for the significant difference originates from the different calculation methods for the CO_2 change in below ground soil organic matter (SOM). In the Swedish studies (SE 2004, 2008), the assessment basis of below ground litter input were not clear. The earlier Swedish estimates (2004) only included the peat decomposition and root associated respiration (heterotrophic respiration), whereas in the most recent Swedish study (SE 2008) the estimation was based on the measurements of heterotrophic respiration in forestry-drained peatlands in southern Sweden and expert judgements (Minkkinen 2010, personal communication). The theoretical basis of the Finnish estimate (FI 2007) can be found from the Finnish greenhouse gas inventory, and the estimate (224 g CO_2 m^{-2} a^{-1}) represents the modeled average change in the net soil emission for forestry-drained peatlands. In the Finnish study, the outputs from aboveground litter were modeled using the Yasso decomposition model (Liski et al. 2005). Decomposition of peat and belowground litter was based on chamber measurements. It is notable that the measurements of heterotrophic respiration are an important input for the calculations of change in the net soil emission. The original Finnish CO_2 soil heterotrophic respiration values (about 1000 g CO_2 m^{-2} a^{-1}) are of the same magnitude as the Swedish estimates.

In the review, it is recommended to assess net soil emission for the initial reference situation of forestry-drained peatlands. The net soil emission represents an aggregated estimate of the litter, dead wood and soil organic matter (DOM+SOM). Furthermore, it is recommended to make the assessment with the help of a methodology used in the Finnish greenhouse gas inventory (Statistics Finland 2010). The above ground litter production from tree and ground vegetation was modelled using allometric biomass equations and estimates of biomass turnover (Liski et al. 2006), whereas decomposition of organic material in soil was estimated using the Yasso decomposition model (Liski et al. 2005). Carbon stock changes in below ground SOM in peatlands are estimated as the difference between annual below ground litter inputs and annual decomposition emissions of SOM (Statistics Finland 2010):

Change in below ground SOM = below ground litter input – emission from soil (2)

Litter inputs to the below ground SOM consisted of annual litter production from roots of trees, shrubs and graminoids and roots of trees subjected to cuttings or natural losses. Emissions from the soil (annual decomposition of SOM) in Equation (2) correspond to so-called heterotrophic soil respiration caused by the decomposition of below ground litter input and peat. In the results, a positive sign indicates GHG emissions and a negative sign represents a sink.

The estimation of carbon stock change in above ground SOM is based on data of biomass stocks in living trees, biomass increment due to tree growth and drain of the growing stock. These biomass stocks are needed for the calculation of change in below ground SOM because litter production is produced as a product of biomass estimate above ground SOM.

In this review, the best value for carbon stock change in the soil (= net soil emission) was chosen directly from estimates made in the latest Finnish GHG inventory (Statistics Finland 2010). In this calculation, carbon emissions due to heterotrophic soil respiration from five different groups of forestry drained peatlands were obtained from Minkkinen et al. (2007) and the weighted average figure based on the corresponding areas of the peatland groups was calculated. The net soil emission value was modelled taking into account the estimation of biomass above ground SOM. The final result, net soil emission, was 141 g CO_2 m^{-2} a^{-1}, which is smaller than the estimate in the Finnish study (FI 2007). The result represents the average situation in forestry drained peatlands in Finland.

The above mentioned average estimation (141 g CO_2 m^{-2} a^{-1}) was obtained by dividing the average net soil emission of CO_2 of Finnish forestry-drained peatlands in 2008 (6150 Gg CO_2 in Table 7.1-2 of Statistics Finland (2010)) by the size of Finnish forestry-drained peatlands (4367 kha, from Table 7.2-12 of Statistics Finland (2010)). It is important to notice that this estimation has been decreased during the years. According to Statistics Finland (2010) it was 297 g CO_2 m^{-2} a^{-1} in 1990 and 184 g CO_2 m^{-2} a^{-1} in 1999. Thus, it is unclear how the selected estimation (141 g CO_2 m^{-2} a^{-1}) will represent the net soil emission in the long term. Thus, the estimation includes large uncertainty.

The annual emission values of CH_4 in forestry-drained peatlands used in the Finnish and Swedish studies were similar. In the Finnish study, the N_2O emissions were ignored. However, the N_2O emission level depends on the nutrient level of the drained forested peatland (see Martikainen et al. 1993, review by Alm et al. 2007).

Generally, emissions of N_2O and CH_4 do not appear to play an important role in the total greenhouse gas emissions of forestry drained peatlands, although their global warming potentials (GWPs) are higher than CO_2 emissions' GWP. However, new results from Maljanen et al. (2009b) show high N_2O emissions on cultivated (up to 5.5 g N_2O m^{-2} a^{-1}) and forestry-drained peatlands (up to 4 g N_2O m^{-2} a^{-1}) as a result of high winter emissions (Table 3). However, further research is needed before the results regarding higher emissions can be generalized.

In order to calculate the GHG fluxes of the initial reference situation of forestry-drained peatlands there is a need to assess carbon sequestration to trees due to the forest growth. This requires the assessment of average forest growth during the rotation period. On the other hand, the assessment of net soil emission also requires information on forest growth. The average forest growth used in the calculation of Statistics Finland (2010), however, was not available in the review. For this reason, the link between forest growth and net soil emission can include errors. The effect of this uncertainty has been discussed in Section 4.5.

In the Finnish study (FI 2007), it was assumed that forest growth in forestry-drained peatlands corresponds to an average growth of 2-3 m^3 ha^{-1} a^{-1} (as round wood), whereas in the most recent Swedish study (SE 2008) two alternative growth situations were presented. The growth was 7.1 m^3 ha^{-1} a^{-1} (= 820 g CO_2 m^{-2} a^{-1}) for high fertility forestry-drained peatlands and 3.6 m^3 ha^{-1} a^{-1} (= 416 g CO_2 m^{-2} a^{-1}) for low fertility forestry-drained peatlands. The assumptions of both studies are acceptable. However, the average growth (2.5 m^3 ha^{-1} a^{-1} (= 289 g CO_2 m^{-2} a^{-1}) presented in the Finnish study (FI 2007) can be considered more appropriate for Finnish conditions.

Cultivated peatlands

The GHG emissions from peatlands used for agriculture can differ in magnitude depending on differences in soil properties, cultivation practices (crops, tilling, fertilization etc.) and weather conditions. Peatlands used for crop production are significant sources of CO_2 and N_2O. Depending on the water table level, croplands on peat soils are small sinks or sources of CH_4. In general, GHG emissions from heterotrophic respiration of cultivated peatlands are well documented in the Finnish and Swedish studies.

Emissions of CO_2 are the main contribution to the total GHG emissions of cultivated peatlands. The variation in GHG emissions within different crops seems to be large (Table 3).

In the Swedish study (SE 2008), the GHG emissions of heterotrophic respiration from grasslands are similar to the values used in the Finnish study (SE 2007) but the

Swedish study (SE 2004) used lower emission for cultivated peatlands. Due to the large variation in CO_2 emissions, the choice of crop on the cultivated peatlands is a key factor for the final results (see Sections 3.1.7 and 4.5).

According to the discussion in Section 3.1.7, it is appropriate to determine the CO_2 emissions originating from the oxidation of the peat material in both abandoned organic croplands and average cultivated peatlands in Finland. In principle, the CO_2 emission for average cultivated peatlands (1840 g CO_2 m^2 a^{-1}) can be found from the Finnish greenhouse gas inventory (Statistics Finland 2010). The estimation is based on the measurements made by Maljanen et al. (2007) and Lohila et al. 2004. The best estimation for abandoned organic croplands (appr. 1180 g CO_2 m^2 a^{-1}) is based on the measurements made by Maljanen et al. (2007).

Fluxes for CH_4 and N_2O were assumed to correspond to the figures from Maljanen et al. (2007) (Table 2).

Due to the high decomposition rate of peat in cultivated peatlands, it is appropriate to assume that the initial reference state of cultivated peatlands will only take 200 years. After this, there will be no peat in the cultivation fields. This was also the assumption used in the Finnish study (FI 2007).

In this report, the concepts of cropland and abandoned organic croplands are determined according to Statistics Finland (2010)**.** The area of *cropland* comprises the area under arable crops, grass (< 5 years), set-aside, permanent horticultural crops, greenhouses and kitchen gardens. *Abandoned organic cropland* (known as **g**rassland in the report of Statistics Finland (2010)) includes an area of grass (≥ 5 years), ditches associated with agricultural land and abandoned arable land. Abandoned arable land in this context means fields that are no longer used for agricultural production and where natural reforestation is possible or is already going on.

Table 3. GHG fluxes from different initial stages according to Swedish (SE) and Finnish (FI) studies and current best available data. A positive value indicates emissions from soil to the atmosphere and a negative value is the net uptake of gas from the atmosphere by the ecosystem.

Initial stage	SE 2004	SE 2008	FI 2007	Current best available value
CO_2 flux (g CO_2 m^{-2} a^{-1})				
Pristine fen/mire	-51, -62	-55-55	-73 (0 to -147)	-112 (-12 to -219)
Forestry drained peatland	Coniferous: 450, 900, 1900 Deciduous: 700, 1400, 2300	458 (low fertility) -818 (high fertility)	224 (0-448)	141
Cultivated peatland	Grass 700-1500 Cereals 2000 Row crops 7000	1780	1760 (705-2815)	Abandoned organic croplands: 1180 Croplands: 1840
CH_4 flux (g CH_4 m^{-2} a^{-1})				
Pristine fen/mire	6, 10, 20,23	7-17	22.66 (14.66 -30.66)	17 ± 13
Forestry drained peatland	0	0-2	0	0-2
Cultivated peatland	ignored	0	-0.147 (-0.26 to -0.031)	Abandoned organic croplands: - 0.22 Croplands: 0.1 (range -0.5 - 0.6)
N_2O flux (g N_2O m^{-2} a^{-1})				
Pristine fen/mire	0.02	0	0	~ 0
Forestry drained peatland	Coniferous: 0.08 Deciduous: 0.2, 0.9	0.01-0.5	0	0.009-4.1
Cultivated peatland	Grass 1.0 Cereals 2.5 Row crops 1.5	1.5	1.297	Abandoned organic croplands : 1.3 Croplands: 1.5 (range 0.1 – 5.5)

On the basis of the Finnish GHG emission inventory (Statistics Finland (2010)) the net CO_2 emission in the soil of abandoned organic cropland in 2008 can be calculated to the magnitude of 130 g CO_2 m^{-2} a^{-1}. The value differs remarkably from the value of 1180 g CO_2 m^{-2} a^{-1} used as a best estimation in this review.

3.2.2
Drainage stage and surrounding area

In the Swedish study (SE 2004), a drainage stage of 5 years was assumed before the actual extraction started. Also, during the drainage and extraction stages, the peatland area affected by the drainage was assumed to be twice the size of the extraction area. The surrounding area before extraction was assumed to be forestry-drained peatland. However, with the agricultural peatlands, the surrounding area was assumed to be agricultural organic soil (see also Appendix 1).

In the Swedish study (SE 2008), the drainage time for pristine mires and drained forested peatlands was assumed to be 2 years before the actual extraction. However, for drained cultivated peatlands no further drainage was considered. Also, for pristine mires, during the drainage and extraction stages, the surrounding area affected by the drainage was assumed to be half the size of the extraction area but for the forested drained peatlands and drained cultivated peatlands the surrounding area was not considered.

In the Finnish study (FI 2007), a separate drainage stage or surrounding area were not considered.

In the review, the drainage stage was not taken into account in the recalculations (Section 4) but the surrounding area is recommended to be taken into account according to the most recent Swedish study (SE 2008). Thus, the surrounding area for pristine mires is considered and its size is half of the extraction area. The emissions of the surrounding area were assumed to correspond to the emissions of production area without stockpiles (Section 3.2.3 and Table 4).

3.2.3
Peat extraction

In all three studies (SE 2004, FI 2007, SE 2008), the peat extraction was assumed to occur over a period of 20 years. Emissions during extraction were estimated for the production area (strips, ditches and stockpiles). In both Swedish studies, the emissions during extraction were also estimated separately for each of the initial states, i.e., pristine mire (Table 4), foresty-drained peatlands (Table 5) and agricultural peatlands (Table 6). It is possible that the initial land-use affects the emissions, however, due to a lack of data the effect is difficult to estimate.

The current best available CO_2 flux emissions of extraction area (Table 4) based on Sundh et al. (2000; winter emissions 15% of the reported total emissions), Alm et al. (2007), Nykänen et al. (1996) and Shurpali et al. (2008) by combining the reported emissions. Average emission from strips was 653 g CO_2 m^{-2} a^{-1}. The corresponding values from ditches were assumed as 9 g CO_2 m^{-2} a^{-1} (by Sundh et al. 2000 and Nykänen et al. 1996). The annual CO_2 emission from stockpiles was estimated to be 17082 g CO_2 m^{-2} a^{-1} (Nykänen et al. 1996; winter emissions estimated to be 30% of the growing season emissions), which contributes to the emissions from peat extraction area differently depending on the area of the stockpiles (assumed to be 1% now). The best available CH_4 emission rates for peat extraction area are based on Nykänen et al. (1996), Sundh et al. (2000); winter emissions 15% of the reported total emissions) and Hyvönen et al. (2009) by combining the reported emissions. The average emission from the peat extraction site was 1.37 g CH_4 m^{-2} a^{-1}. Emissions from ditches were based on Nykänen et al. (1996) and Sundh et al. (2000; winter emissions 15% of the reported total emissions). Possible emissions from stockpiles were not included. The best available N_2O emission rates for peat extraction area are based on Nykänen et al. (1996), Regina et al. (1996), Alm et al. (2007) and Hyvönen et al. (2009) by combining the reported emissions. Emissions from ditches were considered low. Possible emissions from stockpiles were not included (see Appendix 1).

The CO_2 emissions during extraction from the peat production area, with pristine mire as the initial state, were relatively similar in the three studies (Table 4). The current best available value estimated for CO_2 is lower than those in the Swedish and Finnish studies; however, it is within the range given in the Finnish study. The CH_4 emissions were estimated to be low in all of the studies. The highest emissions were estimated in the Swedish study (SE 2008), 3.7 g m^{-2} a^{-1}, and the lowest in the Finnish study, 0.66 g m^{-2} a^{-1}. The current best available value is within the range of these values. Also, the N_2O emissions were estimated to be low or low enough to be ignored. The main reason for the differences in GHG emissions during the extraction between the three studies was the differences in the considerations of the surrounding area. In the Swedish study (SE 2004), the surrounding area affects the overall emissions the most, since the surrounding area was assumed to be as large as the actual extraction site. In the other Swedish study (SE 2008) the effect of the surrounding area was smaller, since the area was half the size of the extraction area in the case of pristine mire.

The estimations of GHG emissions assessed in the review differ from the results of the national GHG emission inventory (Statistics Finland 2010). On the basis of the inventory the average emissions caused by peat extractions in 1999-2008 were: 1513 g CO_2 m^{-2} a^{-1}, 2.26 g CH_4 m^{-2} a^{-1}, 3.17 g N_2O m^{-2} a^{-1}.

Generally, annual and long-term data is needed for a more reliable estimation of the GHG emissions during extraction. Furthermore, the GHG emission data during the extraction is needed from extraction sites with different peat depths and types and also from stockpiles. In addition, the different initial states should also be studied.

Table 4. GHG fluxes from peat extraction (initial state pristine mire) according to Swedish (SE) and Finnish (FI) studies and current best available data. A positive value indicates emission to the atmosphere and a negative value uptake by the ecosystem.

Peat extraction	**SE 2004**	**SE 2008**	**FI 2007 (min-max)**	**Current best available value (min-max)**
CO_2 flux	**(g CO_2 m^{-2} a^{-1})**			
	-production area: 1000 -surrounding area: *5-10 years: 1000 *11-25 years: linear decrease from 1000 to 300	- production area: 980 - stockpiles: 250 - surrounding area: 980	-production area: 1157 (579-1734) -peat stockpile: 250 (29-377)	-extraction area (strip+ditch+stockpiles): 960 - surrounding area: 629
CH_4 flux (g CH_4 m^{-2} a^{-1})				
	- production area: 10 % of the pristine mire emission, but not lower than 1.5 -surrounding area: *emissions higher than on extraction area *decrease to 0 by year 8 and stays 0 until the end	- production area: 3.7 - stockpiles: 0 - surrounding area: 3.7	-production area: 0.66 (0.32-0.98)	-extraction area (strip+ditch, no stockpiles): 2.25 (0.83-5.85) - surrounding area: 2.25 (0.83-5.85)
N_2O flux (g N_2O m^{-2} a^{-1})				
	- production area: *decrease from 0.15 to 0.1 by the 10^{th} year of extraction *increase to 0.15 by end of the extraction -surrounding area: decrease from 0.15 to 0.08 during first 5 extraction years	- production area: 0.3 - stockpiles: 0 - surrounding area: decrease from 0.3 to 0.08 during first 5 extraction years	-ignored	-extraction area (strip+ditch, no stockpiles): 0.06 (0.005-0.079) - surrounding area: 0. 06 (0.005-0.079)

Table 5. Soil GHG fluxes from peat extraction (initial state forestry-drained peatland) according to Swedish (SE) studies A positive value means emission to the atmosphere and a negative value uptake by the ecosystem.

Peat extraction	SE 2004	SE 2008
CO_2 flux (g CO_2 m^{-2} a^{-1})		
	-coniferous: assumption same as for pristine mire during extraction *extraction area: stays constant *surrounding area: decreases somewhat -deciduous: generally higher emissions than from coniferous sites	- low and high fertility *production area: 980 *surrounding area: not included *stockpiles: 250
CH_4 flux (g CH_4 m^{-2} a^{-1})		
	-negligible	- low and high fertility *production area: 3.7 *surrounding area: not included *stockpiles: negligible
N_2O flux (g N_2O m^{-2} a^{-1})		
	-extraction area: *initial emission 0.08 and 0.2 : same assumptions as for originally pristine mire *initial emission 0.9 : emission will decrease to 0.5 in 10 years and stay at that level -surrounding area: *initial emission 0.08 and 0.2 : same assumptions as for originally pristine mire *initial emission 0.9: emission will decrease to 0.5 in 5 years and stay at that level	- low fertility *production area: 0.3 *surrounding area: not included *stockpiles: negligible -high fertility *production area: linear decrease to 0.3 during first 5 years of extraction -> stays constant *surrounding area: not included *stockpiles: negligible

Table 6. Soil GHG fluxess from peat extraction (initial state agricultural peatland) according to Swedish (SE) studies. A positive value means emission to the atmosphere and a negative value uptake by the ecosystem.

Peat extraction	SE 2004	SE 2008
CO_2 flux (g CO_2 m^{-2} a^{-1})		
	- extraction area: *emissions will stay high -surrounding area: *first 5 years: high emissions between extraction *years 5 to 20: emissions will decrease linearly to half of the initial emissions by the end of the extraction	-production area: linear decrease after 10 years of extraction to 980 -> constant after that -surrounding area: not included -stockpiles: 250
CH_4 flux (g CH_4 m^{-2} a^{-1})		
	-negligible	-production area: 3.7 -surrounding area: not included -stockpiles: negligible
N_2O flux (g N_2O m^{-2} a^{-1})		
	-extraction and surrounding area: *grassland: 1.0 g *cereals: 2.5 *row crops: 1.5	-production area: linear decrease to 0.3 after 10 years of extraction -> stays constant -surrounding area: not included -stockpiles: negligible

3.2.4

Working machines and peat transport

In the reviewed studies, emissions from working machines included emissions from peat extraction machinery and peat transport to a power plant. In the Finnish and Swedish studies the same data source (Uppenberg et al. 2001) and, thus, the same value for CO_2 (1 g CO_2 MJ^{-1}) was used. In the Swedish studies emissions of CH_4 (0.7 mg CH_4 MJ^{-1}) and N_2O (0.025 mg N_2O MJ^{-1}) were also included whereas in the Finnish study these emissions were considered negligible. The estimate of Uppenberg et al. (2001) is based on one personal communication whereby the energy demand of machinery and peat transport is 1.3% of the extracted peat as diesel oil. It is obvious that the effect of the emissions from the machinery on the final results is very small. However, energy (diesel oil) consumption during peat extraction and transport is an issue that should be studied more closely.

It is worth noting that in the study of Leijting (1999) the CO_2-emissions of machinery and transport was 1.1 g CO_2 MJ^{-1} on average, whereas the energy demand of machinery and transport was only 0.5% of the energy content of extracted peat.

According to the Swedish study (2008) the new production method will half the greenhouse gas emissions of extraction equipment and transport.

3.2.5

Peat combustion

Emissions of CO_2 from peat combustion were very similar in the reviewed studies, whereas in the Finnish study somewhat bigger values were used for CH_4 and N_2O emissions (Table 7). However, when different peat production scenarios are compared within a study and the different scenarios have the same emission data for combustion, the combustion phase emissions have no impact on the rank-order of the production scenarios (see Section 4.1).

The Swedish study (SE 2008) also addressed the emissions of the new production method for peat combustion. The new production technology results in drier peat, which leads to lower emissions from combustion. Emissions of CO_2 will decrease by 5,2 g / MJ, i.e. the total emissions of CO_2 from the combustion stage will be 100 g CO_2 MJ^{-1}. The new production method will not make changes in emissions of CH_4 and N_2O.

Table 7. Greenhouse gas emissions of peat combustion due to the conventional production method in the Swedish (SE 2004 & 2008) and Finnish (FI) studies.

Gas	Swedish studies	Finnish study
CO_2	105.2 g CO_2/MJ	105.9 g CO_2/MJ
CH_4	0.005 g CH_4/MJ	0.0085 g CH_4/MJ
N_2O	0.006 g N_2O/MJ	0.0128 g N_2O/MJ

3.2.6

After-treatment phase

Restoration

So far only a limited number of results about the GHG fluxes after the restoration of a peat extraction area have been reported. These studies have been carried out in Aitoneva, Finland, and they mainly report CO_2 and CH_4 fluxes during summer time. Only one of them, Yli-Petäys et al. (2007), reports annual CH_4 emission and CO_2 balance. Emissions of N_2O have not been reported.

Greenhouse gas fluxes from the extraction area were similar in all three studies (SE 2004, FI 2007 and SE 2008, Table 8). Considerations of the surrounding area caused the differences between the studies, since both the size of the surrounding area and flux values used varied. In addition, the GHG fluxes during restoration in the Swedish study (SE 2004) were estimated separately for each of the initial states, i.e., for pristine mires, forestry-drained peatlands and agricultural peatlands. However, the values used for initially forestry-drained peatlands and agricultural peatlands were mainly the same as the values for pristine mires (Table 8).

No attempt was made to estimate the currently best available value during the restoration of peat extraction area, since only one new article (Soini et al. 2009) has been published since the Finnish and Swedish studies and that data is within the range of the previous values from Aitoneva. There is a lack of data considering GHG fluxes from restored peat extraction areas. Annual and long-term GHG flux data is needed. Data should also be collected from restored peat extraction areas in different parts of Finland.

Table 8. *GHG fluxes from restoration according to Swedish (SE) and Finnish (FI) studies and current best available data.* A positive value means emission to the atmosphere and a negative value uptake by the ecosystem.

Restoration	SE 2004	SE 2008	FI 2007	Current best available value
CO_2 flux (g CO_2 m^{-2} a^{-1})				
	-extraction area: *linear increase to -363 during the first 5 years of the restoration, after that stays constant -surrounding area: * coniferous peatlands: 450, 900, 1900 *deciduous peatlands: 700, 1400, 2300 *biomass growth -346.5	extraction area and surrounding area: -120	-121.6 (27.6 to -271.0)	-not estimated
CH_4 flux (g CH_4 m^{-2} a^{-1})				
	-extraction area *emissions increase linearly during the first 20 years from 0 to the original value of the pristine mire -surrounding area: 0	extraction area and surrounding area: 17	22.66 (14.66 to 30.66)	-new data not available
N_2O flux (g N_2O m^{-2} a^{-1})				
	-extraction area: *emission 0.02 -surrounding area: *coniferous peatlands: 0.008 *deciduous peatlands: 0.2 or 0.9	0	0	-new data not available

Afforestation

The effect of afforestation on the climate impact of peat fuel can be divided into two parts. Firstly, the CO_2, CH_4 and N_2O emissions from soil must be addressed. The CO_2 emissions are caused by the decomposition of the residual peat and the CO_2 emission level has a clear impact on the final results, whereas the emissions of the other gases are negligible (Table 9). Secondly, carbon sequestration by the growth of trees and litter accumulation in the soil should also be addressed. Between the reviewed studies there were differences in the way carbon sequestration was defined.

In the reviewed studies, the net sequestration of C into trees is based on the additional growth of trees caused by peat production. The annual values of C sequestration into trees and litter were documented in the reviewed studies and were of the same magnitude, but the use of information in the calculations was not transparently described in order to repeat the calculations. In the Finnish study, the sequestration values were based on the growth simulations for low and high productivity stands and were similar to empirical values measured for forestry drained peatlands (VSR) (e.g. Seppälä 1969, Heikurainen and Seppälä 1973) shown as the current best available values for forest growth in Table 9 (see Appendix 1). In the Swedish studies the results were based on the average productivity given for an area. Sequestration values for litter fall were of the same magnitude in both studies and they were relatively similar to those values found in the literature (e,g, Finér 1996, Starr et al. 2005) (see Appendix 1). However, the values are smaller compared to the results by Matala et al. 2008, who related litter fall to annual stem wood growth.

The main difference in the calculations of the reviewed studies was that in the Finnish study (FI 2007) an average carbon stock approach was applied, i.e. carbon sequestration was considered until the average carbon stock of trees (and also of above-ground litter) over forthcoming rotation periods was reached (by taking into account thinning and final cut). In the Swedish study, the carbon sequestration calcu-

Table 9. GHG fluxes from afforestation according to Swedish (SE) and Finnish (FI) studies and current best available data when the conventional peat production method is used. A positive value means emission to the atmosphere and a negative value uptake by the ecosystem.

Afforestation	**SE 2004**	**SE 2008**	**FI 2007**	**Current best available value**
CO_2 flux (g CO_2 m^{-2} a^{-1})				
Soil emission caused by the decomposition of residual peat C-uptake by the growing forest: C-accumulation in the soil by litter input	Pristine mire and forestry drained peatland: 1000 during 22 years after the afforestation, thereafter 0. Cultivated peatland: Slow decomposition (1100 g CO2 m^{-2} a^{-1}): constant during 20 years thereafter 0 Higher decomposition: Constant during 5 years, linear decrease after that and ceases after 20 years Highest decomposition: ceases after 8 years (emissions from surrounding areas: see appendix A1.8) min. - 289, max -1155 min. -81, max -183	Emission starts from 1100, then exponential decrease during first rotation period until 50% of the residual peat has decomposed. Thereafter slow release during rest of simulation period. Increase by an annual forest productivity of 3.5 m^3 $ha^{-1}$for low fertility forestry-drained sites: -404 and no increase for high fertility sites(-820 with annual productivity of 7.1 m^3 ha^{-1}) during the first rotation period of 85 years. - 820 for pristine fens and cultivated peatlands during the first rotation period of 85 years. For low fertility sites:-150 during the first rotation period of 85 years. Equilibrium is then reached.	Emission decreases exponentially from 1150 during 300 years. Increase by an annual forest productivity: - 448 (min. -359, max -505) (during 45 years) -163 (min. -122, max -175) (over 45 years)	Emission starts from 1000, then exponential decrease during first 85 years until 50% of the residual peat has decomposed. Thereafter slow release so that 1200 g C m-2 at the end of simulation period (280 years). Increase by an annual forest productivity: - 413 for the forestry-drained peatlands and abandoned organic croplands (during 45 years) - 716 for cultivated peatlands and pristine fens (during 45 years) 0-45 years: - 297* 46-90 years: -149* 91-180 years: -59* 181-280 years: -20*
CH_4 flux (g CH_4 m^{-2} a^{-1})				
	0	0	0	mean -0.05 min -0.09 max -0.03
N_2O flux (g N_2O m^{-2} a^{-1})				
	-	Linear decrease from 0.15 to 0.06 after 45 years.	-	mean 0.35 min 0.04 max 1.76
Note*: Carbon accumulation in the soil corresponds to the annual forest growth of 6.2 m3 ha^{-1} a^{-1}. In the cases of abandoned organic croplands, forestry-drained peatlands and the surrounding areas of pristine mires the accumulation values were decreased by the proportions of changed forest growth.				

lation assumed that the forest at the end of a rotation is a natural forest in which the decomposition and sequestration of carbon are in balance. In practice, the different approaches mean that in the Finnish study (FI 2007) carbon sequestration by trees due to the additional forest growth is taken into account for half of the rotation period (45 years), whereas in the Swedish study (SE 2008) carbon sequestration by trees is taken into account for the whole rotation period (85 years).

In the Finnish study (FI 2007) it was assumed that forest tree biomass sequesters carbon until the average value (5.5 kg C m^{-2}) over the rotation is reached. This value approximates the average carbon stock of trees in a landscape where forest stands are managed and harvested in the same way as the simulated stand. The Finnish approach (FI 2007) is recommended because it is more consistent with the carbon stock calculation method used in the review (Appendix 3).

In the Swedish (SE 2004) and Finnish (FI 2007) studies, CH_4 and N_2O emissions from afforested peat extraction sites were assumed to be negligible. A recent study (Mäkiranta et al. 2007) showed that afforested peat extraction sites can be sources of N_2O and small sinks for CH_4 (Table 9). In the Swedish study (SE 2008) N_2O emissions were assumed to decrease with time after afforestation in contrast to the results of Mäkiranta et al. (2007) who did not find any correlation between the age of afforestation and N_2O emissions.

It should be noted that in the most recent Swedish study (SE 2008) it is only increased biomass production after peat extraction compared to before extraction that gives the additional climate advantage. With a rotation period of 85 years this corresponds to 820 g CO_2 m^{-2} yr^{-1}. That means that for drained forested peatlands with low fertility the forest productivity is assumed to increase by 3.5 m3 ha^{-1} after afforestation but is assumed to be sustained on the same level for high fertility sites. The same forest productivity (820 g CO_2 m^{-2} yr^{-1}) in afforestation was assumed for cultivated peatlands.

The Swedish and Finnish studies (FI 2007, SE 2008) assumed that the amount of residual peat is 15 000 (0-22 500) g m^{-2} which equals approx. a 20 cm thick peat layer. This assumption is acceptable and small differences in the shape of decomposition function between the studies have no effects on the final results.

The review process highlighted that (see Eq. 2 in Section 3.2.1) below ground litter input plays an important role in the carbon stock calculations. It should be taken into account correctly in the initial reference situations and afforestation phases. In the earlier Swedish study (SE 2004) it was not reported and taken into account in the initial reference situation where the measured results of heterotrophic respiration should have been changed to the net soil emissions (see Equation 2). In the most recent Swedish study (SE 2008) below ground litter input was roughly included in the initial state of forestry-drained peatlands. In the Finnish study (FI 2007), below ground litter input was taken into account in the initial reference situation. However, the basis for the estimation was not clearly described.

In the afforestation phase, carbon stock change in the soil consists of decomposition of residual peat and carbon accumulation in the soil due to litter production.

In the review, it was assumed that forest in the afforestation phase sequesters carbon until the average value (5.5 kg C m^{-2}) over the rotation is reached. The assumption corresponds to the assumption made in the Finnish study (FI 2007). They assumed that afforestation causes additional growth of 3.7 m^3 ha^{-1} a^{-1} compared to the initial reference situation of forestry-drained peatlands in which the forest growth was assumed to be 2,5 m^3 ha^{-1} a^{-1}. Thus, the total growth of afforestation is about 6.2 m^3 ha^{-1} a^{-1} that corresponds to average carbon sequestration (5.5 kg C m^{-2}).

The development of carbon stock in the soil of the finished peat production area due to afforestation was estimated using the Yasso07 model (Tuomi et al. 2009, manuscript, www.environment.fi/syke/yasso). The results showed greater carbon accumulation in the soil than the reviewed studies showed (Table 9 and Appendix 3). In addition, carbon accumulation does not only exist during the first rotation period, on the contrary it continues during the whole period of 280 years.

The net carbon accumulation values in the soil for the different time intervals were derived from Figure 1 of Appendix 3. The simulation corresponds to the forest growth of 6.8 m^3 ha^{-1} a^{-1}. For this reason, the results of the used basic forest growth (6.2 m^3 ha^{-1} a^{-1}) were simply obtained by multiplying the values of 6.8 m^3 ha^{-1} a^{-1} by the quotient of 6.2/6.8. The same conversion method for other forest growth was used.

In the review it was assumed according to the reviewed studies that forest growth in the afforestation phase is similar in the cases of forestry-drained and cultivated peatlands. In the most recent Swedish study (SE 2008) this means that the forest growth causes carbon sequestration -820 g CO_2 m^{-2} a^{-1}, whereas in the review and the Finnish study (FI 2007) it was assumed to be -716 g CO_2 m^{-2} a^{-1} (=6,2 m^3 ha^{-1} a^{-1}). However, this amount was not clearly reported in the Finnish study (FI 2007).

A starting point in the reviewed studies was that it is the difference in forest productivity before and after interrupted peat extraction that is of importance for the climate impact scenarios. For this reason, the effects of forest productivity are taken into account as additional growth in the calculation rule of Equation 1. In the Swedish study (2008) this means that C uptake in the growing forest of low fertility forestry-drained peatlands in the afforestation phase corresponds to C caused by the additional growth of 3.5 m^3 ha^{-1} a^{-1} (see Section 3.2.1). For high fertility forestry-drained peatlands the forest growth was assumed to be same before and after peat extraction. Thus, there is no increase in biomass. In the case of cultivated peatlands (without forest growth in the initial sate) the C uptake in growing forest corresponds to a forest growth of 7.1 m^3 ha^{-1} a^{-1}, whereas in the case of pristine fen increase in forest biomass was assumed to correspond to a forest growth of 5.3 m^3 ha^{-1} a^{-1}. It is important to note that although the forest growth in the afforestation phase varies, carbon accumulation in the soil (-150 g CO_2 m^{-2} a^{-1}) was the same in all the cases. However, the reality is that the C accumulation varies on the basis of forest growth.

In the Finnish study (FI 2007), C uptake in growing forest corresponds to an additional growth of 3.9 m^3 ha^{-1} a^{-1} in all the peat utilization cases although there is no forest growth in the initial stages of pristine mires and cultivated peatlands. In addition, carbon accumulation in the soil was kept constant in all the cases.

In the review, the carbon accumulation of soil in the afforestation phase of pristine mires, forestry-drained and cultivated pealtlands was calculated on the basis of forest growth of 6,2 m^3 ha^{-1} a^{-1}. Carbon uptake in growing forest of forestry-drained peatlands corresponds to an additional growth of 3.7 m^3 ha^{-1} a^{-1} (thus a growth of 2.5 m^3 ha^{-1} a^{-1} was assumed in the initial state), whereas in the case of cultivated peatlands and pristine mires it corresponds to a growth of 6.2 m^3 ha^{-1} a^{-1} (there is no forest growth in the initial state).

Carbon uptake in the growing forest of abandoned organic croplands was assumed to be same as in the case of forestry-drained peatlands because it is assumed that the forest will start to grow at a rate of 2.5 m^3 ha^{-1} a^{-1} in abandoned organic croplands during the peat extraction. For this reason, carbon accumulation in the soil in the afforestation phase of abandoned organic croplands was also decreased by 40 per cent compared to carbon accumulation in the soil in the other energy peat utilization cases.

It is important to notice that the assumed forest growth (6.2 m^3 ha^{-1} a^{-1}) in afforestation is greater than the average forest growth in Finland (4 m^3 ha^{-1} a^{-1}, Statistics Finland 2004). It can be assumed that the increase is partly due to the more effective fertilization. On the other hand, the fertilization causes the emissions of N_2O. For this reason, it is assumed that N_2O emissions in forestry-drained peatlands are not greater in the initial reference situation than after-treatment phase.

3.2.7
Coal and natural gas energy utilization chains

In the reviewed studies coal is used as a reference fuel to which the climate impact of peat is compared. Besides the combustion phase other phases of the life cycle of coal - coal mining, transport and processing - are also taken into account.

According to the RF-calculations in Section 4 the differences in emission levels between the Finnish and Swedish (SE 2004) studies (Table 10) cause a somewhat bigger climate impact for coal when the Swedish values are used. This means that in the Swedish case the reference level (coal) for fuel peat is a little bit higher than in the Finnish case, and the result seems to be slightly more positive for peat in the Swedish case when the climate impact of fuel peat is compared with the climate impact of coal.

Table 10. Greenhouse gas emissions (g MJ^{-1}) of the coal utilization chain (including coal mining, transport, processing and combustion) applied in the Swedish (SE) and Finnish (FI) studies.

Gas	SE 2004	FI 2007	SE 2008
CO_2	94.4	95.18	98.69
CH_4	1.1	0.34	0.2107
N_2O	0.012	0.002	0.00052

The latest Swedish study (SE 2008) used the emissions obtained from the OSELCA project (Sokka et al. 2005) for the comparison calculations. As they represent the current best available values for the coal utilization chain they were also used as the reference values for coal energy system in the recalculations of this review work.

In the Swedish study (SE 2004) natural gas was also used as a reference fuel. Emission factors including both direct emissions from combustion and indirect emissions from gas production and transport were: 59 g CO_2 MJ^{-1}, $2.8*10^{-3}$ g CH_4 MJ^{-1}, $5,6*10^{-4}$ g N_2O MJ^{-1}.

3.3
Inventory analysis: calculation rules

3.3.1
General calculation rules

In the reviewed studies, a calculation procedure was used with the aim of measuring the net GHG emissions of peat energy utilization caused by the use of fuels and changes in land use. To take the land use into account there is a need to determine the reference state of the peat fuel production area, i.e. reference situations (see Equation 1 in Section 3.1.7). Thus, the aim is to quantify the difference in GHG emissions in a certain peat production area before and after the peat fuel utilization. The state before the peat fuel production corresponds to the initial reference situation. The state after the peat fuel production includes all the states of the chosen peat area due to changes in human activities from mire drainage to a final reference situation.

The net GHG emission approach means that, for example, in the case of forestry drained peatland as a reference situation the CO_2 emissions from peat oxidation can be avoided when peat fuel production starts. The higher the avoided emissions, the smaller the climate impact of peat.

The calculation method used is according to the LCA principles in which the aim is to assess how the human activity actually causes the GHG emissions. However, the key question is how to determine the initial and final reference situations in the calculations.

The approach includes the net GHG emissions of all after-treatment chains in a peat fuel production field in the future. This approach is based on an assumption that peat fuel production will offer possibilities to arrange the land use of an abandoned peat fuel production field in a better way in terms of the climate impact compared with the initial reference situation. Furthermore, the avoided emissions caused by the after-treatment option should be taken into account in the calculations of the GHG emissions released from the peat fuel utilization chain.

To strictly follow the guidelines of LCA standards, avoided emissions due to activities, can be calculated in the comparative LCA studies if such activities are really used. This is not the situation in the case of future after-treatment options. However, the traditional calculation rules of LCAs have not been developed from the viewpoints of land use effects. There is on-going development regarding the use of future aspects in LCAs.

The right staring point is that any land use causing changes in the net GHG emissions of a studied area should be taken into account for comparison. If peat extraction could avoid the GHG emissions or increase the C-sequestration of a current peatland, the decrease in the GHG emissions should be taken into account in the calculations. This aspect was also included in the Finnish and Swedish studies.

3.3.2
Allocation and carbon sequestration

Great care must be taken when sequestered carbon by trees and litter after afforestation is allocated to the benefits of peat utilization. Only the change in C-sequestration due to peat extraction compared to the reference state can be allocated to peat. If there is an increase in the wood biomass accumulation e.g. due to fertilizing, the benefit (sequestered C increase) cannot be directly allocated to peat. There are differences between the reviewed studies in the way carbon sequestration is defined. It is also unclear what the calculation assumptions are and how the results are applied in the LCA-modelling.

The review showed that the differences in C-sequestration in biomass between the studies did not have a significant impact on the final results. The contribution of emission levels from the initial reference situation is typically more important than the level of CO_2 sequestration by tree growth and litter accumulation in the afforestation phase when considering the climate impact of peat fuel. On the other hand, the review showed that carbon accumulation to soil was imperfectly calculated in the reviewed studies and it has greater impact on the results than the earlier studies showed (Section 3.2.6).

It can be argued that additional wood biomass accumulation due to peat production can be used to replace oil, gas or coal as an energy source, and this should be considered as a benefit of peat energy utilization. This was not done in the reviewed studies. It is true that this is a common approach in comparative LCA studies. However, the starting point in these cases is that the replacement is actually realised. This is not the case in the future peat scenarios where the final use of the additional wood growth is unknown. Thus, the chosen rule in the reviewed studies is acceptable.

For the sensitivity purposes, in the recalculations of this review the positive effects of afforestation have been studied using the avoided emission approach of LCA. The increased biomass storage of carbon after cutting (45 years) is used for replacing heavy oil in energy production. The sensitivity calculation was carried out for the case of forestry-drained peatlands.

The general calculation rule for the assessment of climate impact for the energy peat utilization chain of "Forestry-drained peatlands – afforestation" is

$$I=I_u-I_R=IPE_{EA}+IPE_{WT}+IPC+IAF_{DRP}+IAF_{CT}+IAF_{CAS}-(IR_{NS}+IR_{CT}) \quad (3)$$

where I is the net climate impact caused by the peat utilization chain, I_u is the climate impacts caused by the peat utilisation scenario, I_r is the climate impact caused by the reference scenario,

IPE_{EA} is the climate impact caused by *GHG* emissions from peat extraction area, IPE_{WT} is the climate impact caused by GHG emissions from working machines and transportation, *IPC* is the climate impacts caused by GHG emissions from peat combustion, IAF_{DRP} is the climate impact caused by the decomposition of residual peat in the afforestation phase, IAF_{CT} is the climate impact caused by carbon sequestration to trees in the afforestation phase, IAF_{CAS} is the climate impact caused by carbon accumulation in the soil in the afforestation phase, IR_{NS} is the climate impact caused by the net soil emissions of GHG in the initial reference situation, IR_{CT} is the climate impact caused by carbon sequestration to trees in the initial reference situation.

In the Finnish and the most recent Swedish reviewed studies (FI 2007, SE 2008), the calculation rule corresponds to be Eq. 3. The values of IAF_{CAS} are constant in the reviewed studies. However, the values of IAF_{CAS} in the recalculations (Section 4) vary depending on the difference of AF_{CT} and $IR_{CT.}$ The change in carbon accumulation is assumed to be linear. It is important to notice that this calculation rule assumes that IR_{CAS} (carbon accumulation in the soil in the reference situation) is $IR_{CT} * IAF_{CAS}/IAF_{CT}$. This simplification can be assumed to underestimate the carbon accumulation in the soil of afforestation phase because the carbon accumulation in the soil of the initial reference situation can be nearly zero. On the other hand, in this case peat extraction will destroy the earlier accumulated carbon stock due to tree growth and ground vegetation. For this reason, it can be said that the calculation rule underestimates the climate effects of peat energy utilization as a whole. In addition, the peat extraction totally prevents the growth of forest in the extraction area for 20 years, and this should be included in calculations as a disadvantage of peat fuel production. However, the reviewed studies and the recalculations do not take this aspect into account.

3.3.3 Defining the surrounding area

Information on the size of the surrounding area, i.e. the area around the actual peat extraction area that is affected by drainage is very uncertain. It is obvious that the size varies dramatically case by case. Additionally, the emissions from that area are unknown.

As is highlighted in the comparison report (Holmgren et al. 2006) inclusion of the surrounding area may have a significant impact on the results. If peat extraction leads to a state with lower emissions of greenhouse gases in the surrounding area it results in a smaller climate impact for peat fuel compared to a case where the surrounding area is not considered.

In the Swedish study (SE 2004), the area affected by drainage was assumed to be twice the size of the extraction area while in the Finnish study the surrounding area was not considered. This is one of the main reasons for the different results between the two studies. Especially the use of cultivated peatland including the surrounding area - i.e. surrounding cultivated peatlands - in the climate impact calculations is very questionable because there is no evidence that the peat extraction would affect that area and because the surrounding area is apparently used for agriculture. In the Swedish study (SE 2008), the assumptions regarding the surrounding area were changed;

for pristine mires the surrounding area affected by the drainage was assumed to be half the size of the extraction area but for the forested drained peatlands and drained cultivated peatlands the surrounding area was omitted.

In the review, the assumptions used in the Swedish study (SE 2008) were accepted as the best current available assumptions for the effects of the surrounding area.

3.4

Impact assessment: radiative forcing calculations

3.4.1

Climate impact calculations

Both the Finnish and Swedish studies evaluated the climate impacts of greenhouse gas (GHG) emissions in terms of the radiative forcing (RF) concept. They also consider the same three long-lived GHGs (CO_2, CH_4 and N_2O) and calculate the RF of these GHGs using structurally identical models. In both models, the estimation of the RF increase due to the activity under consideration consists of the following components: (1) atmospheric mixing, (2) atmospheric residence time, (3) RF function, (4) reference (background) concentration and (5) time integration. Atmospheric mixing is modelled in a very simple way by instantaneously diluting an emission pulse throughout the atmosphere. Thus this model component does not involve any significant uncertainties and is not considered here. In addition, it is assumed that the last component, which has not been documented in the reports under examination (FI 2007, SE 2004), has no effect on the differences in the model results, and in the following only the calculation steps (2)–(4) above are considered. Details of the model analysis are presented in the Appendix 2.

3.4.2

Atmospheric residence time

The atmospheric lifetime functions used in the Finnish and Swedish models are not explicitly presented in the reports under examination (FI 2007, SE 2004), but are clearly documented elsewhere (e.g. Holmgren et al. 2006). For CO_2, the differences in the form and parameterisation of this function only result in small (< 10%) differences in the airborne fraction of the emitted CO_2 within a 300-year calculation period. However, for the first 100 years both models produce higher concentrations, and thus RF estimates, than the function used by the IPCC (2007). This function is also used in the updated version of the Swedish model (SE 2008). There are large differences in the lifetime functions of CH_4 that result in significantly different airborne fractions, with the Swedish and IPCC models representing a much slower removal of an emission pulse from the atmosphere than the Finnish model. For N_2O, the differences between the models are insignificant, at least for the first 100 years.

3.4.3

RF function

The RF functions are not explicitly presented in the reports under examination (FI 2007, SE 2004), but are detailed elsewhere (Holmgren et al. 2006, Monni et al. 2003). Both the Finnish and Swedish models employ the same basic functions, which were also used by the IPCC (2007). However, there are some significant distinctions between the models. Within the Finnish model, two different RF concepts are defined ("marginal" and "average" RF) (Monni et al. 2003), resulting in different estimates of climate impacts. Kirkinen et al. (2007) and Holmgren et al. (2006) do not explicitly state on which of these two RF definitions the Finnish results are based. However, this review's accurate replication of the "Coal scenario" calculations by Kirkinen et al. (2007) and Holmgren et al. (2006) indicates that these results correspond to the average RF, which exhibits a stronger response to a concentration change than the marginal RF (Appendix 2). According to Nilsson and Nilsson (2004), the Swedish calculations correspond to the marginal RF concept, which is confirmed by the model formulations and replication results in Appendix 2. The Finnish model also includes an estimate of indirect RF effects of CH_4, which will enhance the RF of this GHG. These indirect effects have been added to the updated version of the Swedish model (SE 2008).

3.4.4
Reference concentration

A constant reference concentration, needed for the RF calculation, is assumed in the Swedish model, while a variable reference level is defined in the Finnish model. The variable concentration, which has been derived from an IPCC SRES scenario, better reflects the expected RF development in the long term, reducing the rate of RF increase with increasing background concentration.

3.4.5
Time perspective

It should be noted that, even though the RF calculations in the reviewed studies are carried out over a period as long as 300 years, the key input data, i.e. the gas exchange rates, represent the present-day conditions. The understanding of atmosphere-biosphere exchange of GHGs has advanced considerably during the last decade, including the responses to climate change, but is still clearly insufficient for incorporating any temporal variations into a LCA. Furthermore, this would require regional-scale information on the development of meteorological and hydrological conditions over an extended period and scenarios for additional external factors such as forest management practices. Therefore it is important to understand that the LCA results become increasingly uncertain with time, as the various dynamical effects cannot be considered in the present context.

4 Recalculations and sensitivity of results

In this Section the significance of findings made in the materials and methods of the reviewed studies on the climate impact of peat fuel are discussed. The aim was to show how the changes in assumptions on emission data, definition of system boundaries and calculation rules affect the LCA results and their interpretation. The radiative forcing model used for assessing climate change impacts corresponds to the Finnish model updated with the IPCC's lifetime functions and time constants.

4.1

Radiative forcing calculations

Some significant differences were identified in the individual model components of the radiative forcing calculations between the Finnish, Swedish and IPCC models. When considering the complete models and the combined climate impact of different GHGs, the integrated effect of these differences does not appear significantly large and is unlikely to affect the interpretation of the results of life-cycle assessments (Appendix 2).

4.2

Emissions of peat combustion

In the case of the conventional peat production method, the emissions of CO_2 for peat combustion used in the reviewed studies were very similar, whereas in the Finnish study somewhat greater values were used for the CH_4 and N_2O emissions (Table 4). However, according to the RF-calculations (Fig. 3) small differences in emission values in the peat combustion phase makes no difference in the RF-results between the Finnish and Swedish studies. This means, that even though the combustion phase is a significant emission source in the entire peat fuel utilization chain, the differences between the Swedish and Finnish studies must originate from other production phases.

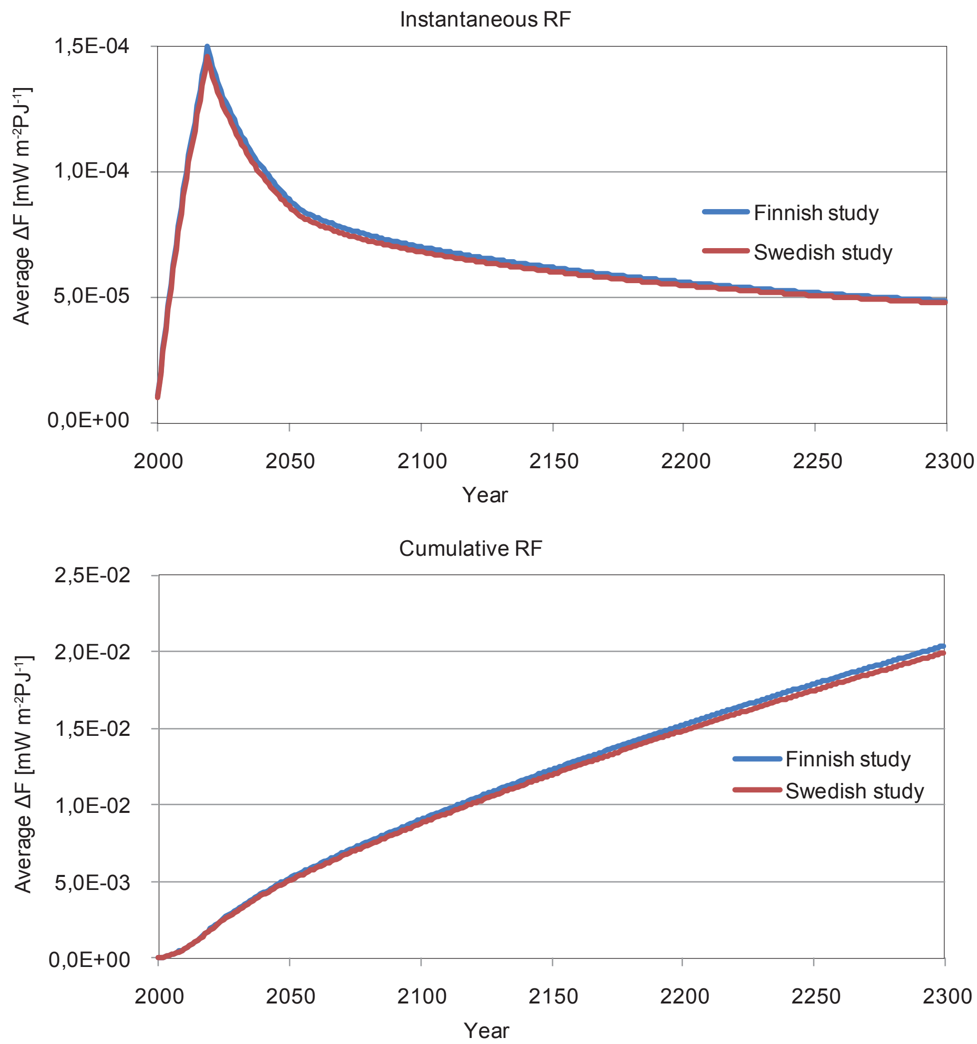

Figure 3. Instantaneous (upper figure) and cumulative (lower figure) radiative forcing effect (mW m^{-2} PJ^{-1}) caused by peat combustion when the emission factors of conventional peat production technology in the Finnish (FI 2007) and Swedish (SE 2004) studies are used.

4.3
Reference fuels: coal and natural gas

In the reviewed studies coal is used as a reference fuel to which the climate impact of peat is compared. Besides the combustion phase other phases of the life cycle of coal - coal mining, transport and processing - are also taken into account.

The somewhat greater GHG emissions of coal combustion used in the Swedish (SE 2004) study has a clear influence on the interpretation of the RF calculations (Fig. 4). This means that the reference RF level in the Swedish study (SE 2004) is slightly higher than in the Finnish case, and the results seem to be marginally more positive for peat in the Swedish case when the climate impact of peat fuel is compared with the climate impact of coal. It is important to note that in the latest Swedish study (SE 2008) the emissions of the coal reference correspond to the emissions used in the Finnish study.

In the Swedish study (SE 2004) natural gas was also used as a reference fuel. The radiative forcing effect of natural gas differs remarkably from the effects of coal (Fig. 5). If natural gas is used as a reference for peat energy utilization, this results in a more negative interpretation of peat as an energy source compared to the situation where coal is used as a reference fuel.

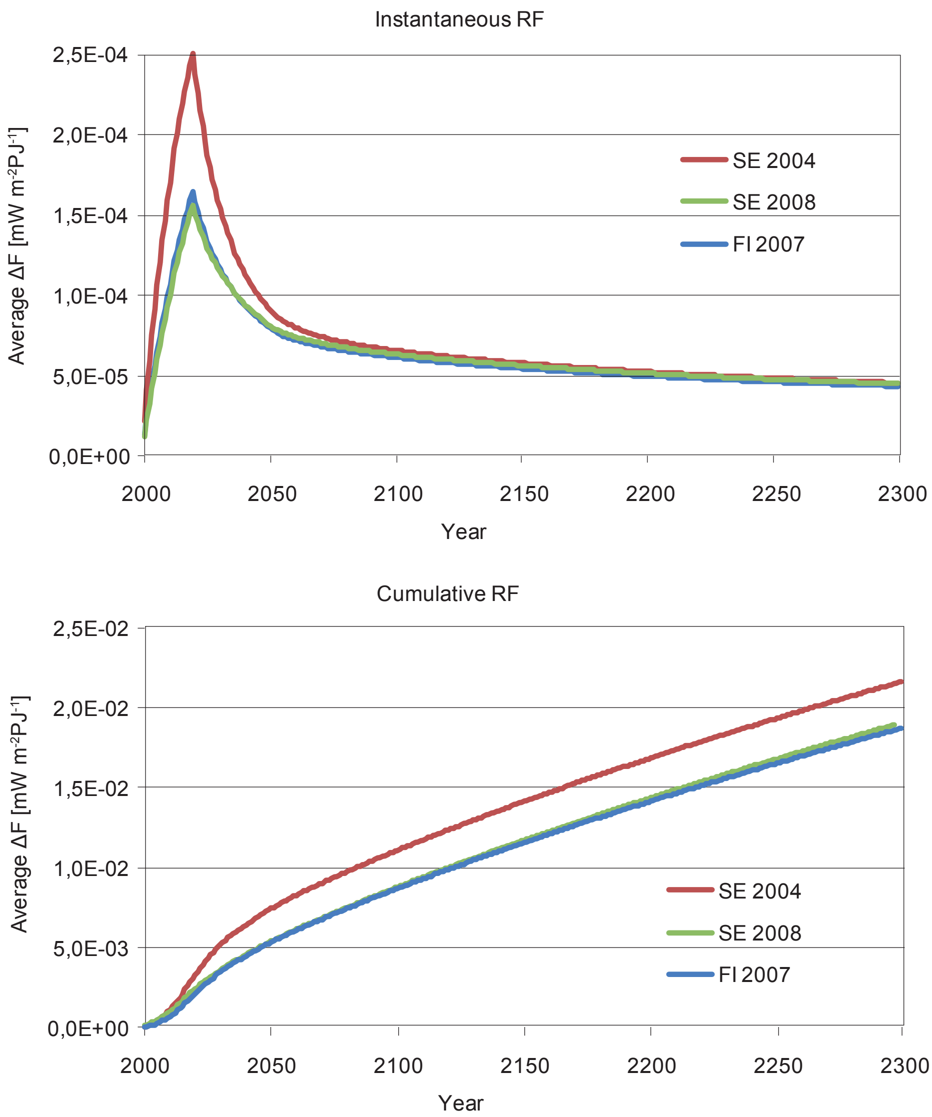

Figure 4. Instantaneous (upper figure) and cumulative (lower figure) radiative forcing effect (mW m^{-2} PJ^{-1}) caused by the coal energy utilization chain when emission factors used in the Swedish (SE 2004 and SE 2008) and Finnish (FI 2007) studies are used.

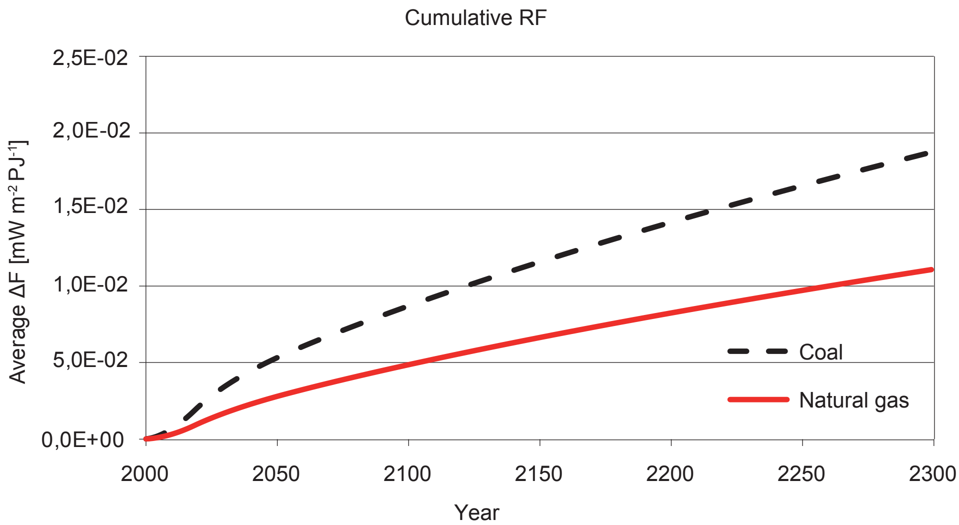

Figure 5. Natural gas utilization chain's cumulative radiative forcing effect (mW m^{-2} PJ^{-1}) when the emission factors of Swedish study (SE 2004) were used. The figure for coal was calculated using emission factors from the Swedish study (SE 2008).

4.4
Peat energy utilization – pristine mire

Cumulative radiative forcing calculations were performed for the "Pristine mire – afforestation" and "Pristine mire – restoration" scenarios using the best estimated average values for the reference state (see Tables 3 and 11). The same assumption for the emissions and acreage of the surrounding area (50% of the acreage of actual peat extraction area) was used as the most recent Swedish study (SE 2008) in order to show the effects of the surrounding area included in the Swedish study.

Peat energy utilization using pristine mire as a production reserve causes greater radiative forcing effects than coal energy utilization when restoration is the after-treatment option in the peat energy utilization chain (Figure 6). The results are according to the reviewed studies.

The climate impact of the utilization chain "Pristine mire – afforestation" is similar to the climate impact of coal utilization. In practice, the result of the peat utilization chain with afforestation does not differ from the results of the reviewed studies (Figure 7).

In both the restoration and afforestation cases the surrounding area does not play an important role (Figure 6).

The results will be slightly worse from the viewpoint of energy peat if it is assumed that the estimation of Statistics Finland (2010) (see Section 4.2.3) for the GHG emissions of peat extraction is better than the estimation of this review (Figure 7).

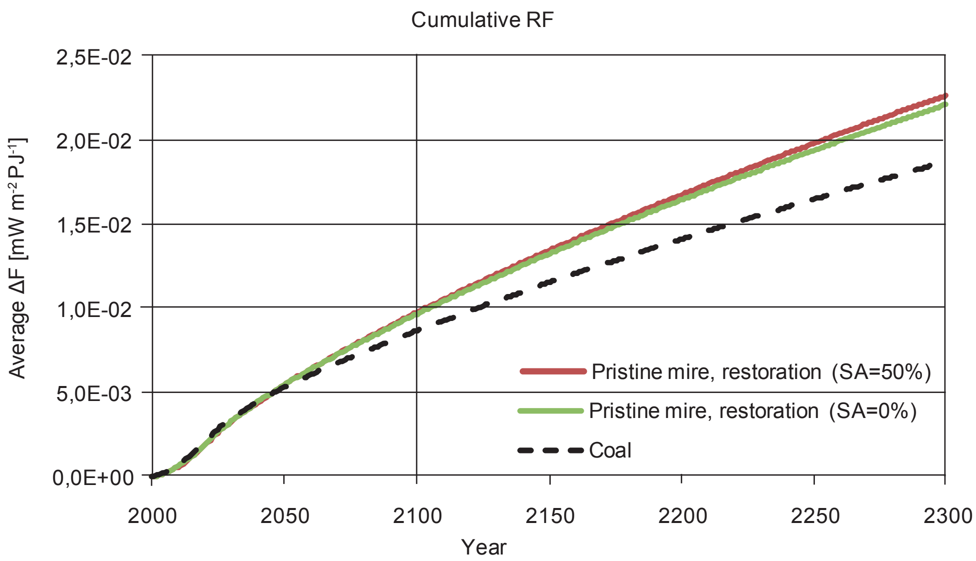

Figure 6. Cumulative radiative forcing effect (mW m-2 PJ-1) caused by peat fuel utilization chain "Pristine mire - restoration". Two different assumptions for the surrounding area were used: surrounding area ignored (SA=0%), acreage of the surrounding area 50% of the acreage of the peat production field (SA=50%). It is recommended to use the latter assumption. The reference fuel is coal. The vertical dotted line has drawn in the figure to describe a critical point in the interpretation of the results. Over a time perspective of 100 years the results includes so much uncertainty that they are not recommended for use in decision making. In addition, the climate change mitigation requires the rapid actions to reduce climate impacts even before a time perspective of 100 years.

Table 11. Emission estimates used in the recalculations of the review study for the different stages of the *pristine peatland scenarios* (positive values= loss to the atmosphere, negative values= uptake by the ecosystem).

Pristine mire				
	CO_2	CH_4	N_2O	**Unit**
Initial stage (reference) Net soil emissions	-112.0	17.0	0	g $m^{-2}a^{-1}$
During peat extraction Extraction area (incl. stockpiles)	5.68	0.0133	0.0004	g MJ^{-1}
Working machines + transports	1.00	0	0	g MJ^{-1}
Surrounding area	1.86	0.0053	0.0002	g MJ^{-1}
Peat combustion	105.9	0.0085	0.0128	g MJ^{-1}
After peat extraction *Restoration* - Extraction area - Surrounding area*	-112.0 - 55.0	17.0 17.0	0 0	g $m^{-2}a^{-1}$ g $m^{-2}a^{-1}$
Afforestation				
- Decomposition of residual peat Extraction area Surrounding area	Emission starts from 1000, then exponential decrease during first 85 years until 50% of the residual peat has decomposed (7500 g C m^{-2}). Thereafter slow release so that 1200 g C m^{-2} at the end of simulation period (280 years) 980 linear decrease to 0	0 0	0.35 0.35	g $m^{-2}a^{-1}$ g $m^{-2}a^{-1}$
- Increased C uptake by trees Extraction area Surrounding area	-716** -289**	- -	- -	g $m^{-2}a^{-1}$ g $m^{-2}a^{-1}$
- C accumulation in the soil Extraction area Surrounding area	0-45 years: - 297 46-90 years: -149 91-180 years: -59 181-280 years: -20 0-45 years: - 120 46-90 years: -60 91-180 years: -24 181-280 years: -8	- -	- -	g m-2a-1 g m-2a-1
* Surrounding area is assumed to be 50% of extraction area **Forest sequesters carbon during the period of 45 years				

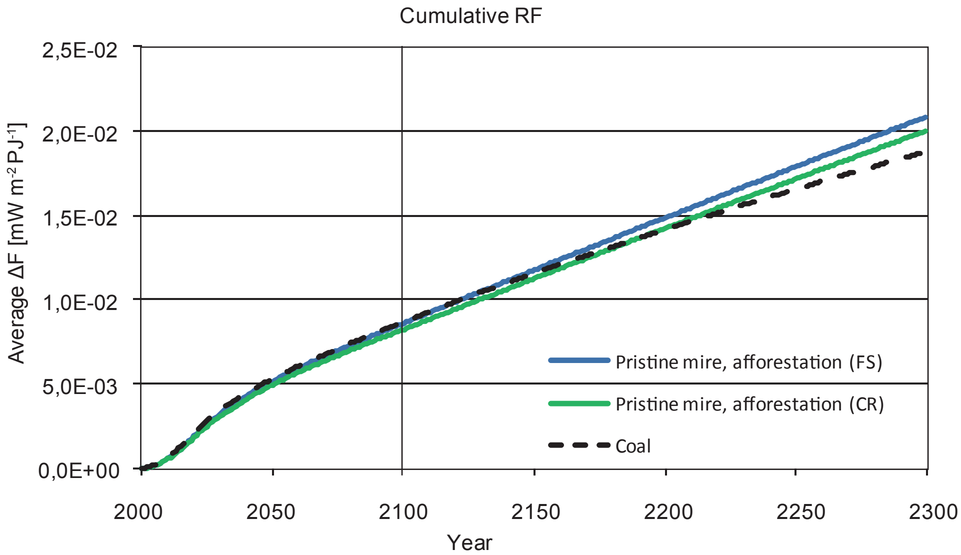

Figure 7. Cumulative radiative forcing effect (mW m^{-2} PJ^{-1}) caused by peat fuel utilization chain "Pristine mire - afforestation". The alternative assumption for the emissions of peat extraction according to Statistics Finland (SF) was used; peat extraction area: 9 g CO_2 MJ^{-1}, 0.0134 g CH_4 MJ^{-1}, 0.0019 g N_2O MJ^{-1} and surrounding area: 2.6 g CO_2 MJ^{-1}, 0.005 g CH_4 MJ^{-1}, 0.0008 g N_2O MJ^{-1}. CR= the result of this critical review study.

4.5

Peat energy utilization – forestry-drained peatland

The peat energy utilization chain "Forestry-drained peatlands – afforestration" causes slightly higher climate impacts on average than the coal utilization chain does (Figure 8 and Table 12). From the viewpoint of peat utilization the result was similar to the result of the Finnish study (FI 2007), whereas it was worse compared to the result produced by the most recent Swedish study (SE 2008). However, the results obtained from the different studies are very similar in terms of a 100 years perspective: the climate impact of forestry-drained peat energy utilization chain corresponds to the impact of coal energy utilization chain.

The results of forestry-drained peat utilization chains vary considerably according to the peat type and climatic conditions. Data on CO_2 net fluxes from drained forests are still uncertain and further research is needed (old peat, litter, other biomass). A recent study (Maa- ja metsätalousministeriö 2007) indicates that the peat of high and medium productive drained peatland sites acts as a C source and only the poor productive drained peatland sites may act as C sinks. The area of nutrient poor forestry-drained peatlands in Finland is significant, approximately 2 500 000 ha, and further research is needed to evaluate the C balance of these sites. However, in general it can be said that the energy peat of high fertility forestry-drained peatlands caused smaller climate impact compared to the impact caused by the energy peat of low fertility forestry-drained peatlands. It can be assumed that the variation between the results of "average" forestry drained peatland corresponds to the variation between low and high fertility forestry drained peatlands presented in the Swedish study (SE 2008) (Figure 8a).

The choice of forest growth in the after-treatment phase has also effects on the final results (Figure 8b). The growth of 9 m^3 ha^{-1} a^{-1} during the rotation period can be considered as an overestimation because the average growth of Finnish forest is only 4 m^3 ha^{-1} a^{-1} (Finnish Forest Research Institute 2004).

In practice, the situation does not change if in the calculations it is assumed that increased forest growth (3.7 m^3 ha^{-1} yr^{-1}, after 45 years) due to afforestation in peat extraction area is used to replace heavy oils in the energy production (Figure 9).

In Section 3.2.6 it was discussed that the estimation of the net CO_2 emission in the soil (141 g CO_2 m^{-2} a^{-1}) includes large uncertainty in the initial stage of forestry-drained peatlands. If the estimation will be smaller, the result will be worse from the viewpoint of energy peat. On the other hand, the real value for the net CO_2 emission can be higher causing the better result for the peat energy utilisation chain. To illustrate the sensitivity of the result to the change in the net CO_2 emission in the soil it was assumed that the value is 500 g CO_2 m^{-2} a^{-1}. This value fits to the value range used in the recent Swedish study (SE 2008). However, from a viewpoint of a 100 years perspective the climate impact of forestry-drained peat energy utilization chain still corresponds to the impact of coal energy utilization chain (Figure 10).

In practice, the results do not change if it is assumed that one PJ of peat fuel energy requires a peat extraction area of 45 ha (see Section 3.1.2) instead of 30 ha (=the recommended value of the review) (Figure 11).

Table 12. Emission estimates used in the recalculations of the review study for the different stages of the *forestry-drained peatland scenario* (positive values= loss to the atmosphere, negative values= uptake by the ecosystem).

Forestry-drained peatland				
	CO_2	**CH_4**	**N_2O**	**Unit**
Initial stage (reference)				
Net soil emissions	141	1.0	0.35	g m^{-2} a^{-1}
Forest growth (2,5 m^3 $ha^{-1}a^{-1}$)	-289	–	–	
During peat extraction				
Extraction area (incl. stockpiles)	5.68	0.0133	0.0004	g MJ^{-1}
Working machines + transports	1.00	0	0	g MJ^{-1}
Peat combustion	105.9	0.0085	0.0128	g MJ^{-1}
Aftertreatment, afforestation:				
Decomposition of residual peat	Emission starts from 1000, then exponential decrease during first 85 years until 50% of the residual peat has decomposed (7500 g C m^{-2}). Thereafter slow release so that 1200 g C m^{-2} at the end of simulation period (280 years)	0	0.35	g m^{-2} a^{-1}
Forest growth (6,2 m^3 $ha^{-1}a^{-1}$)	- 716*	–	–	g m^{-2} a^{-1}
C accumulation in the soil	0-45 years: - 177 46-90 years: - 89 91-180 years: -35 181-280 years: -12	–	–	g $m^{-2}a^{-1}$
*C uptake by trees was taken into account by taking the amount of forest growth in the initial state off the amount of forest growth in the afforestation phase (=448 g CO_2 m^{-2} a^{-1}). Forest sequesters the difference amount of carbon during the period of 45 years				

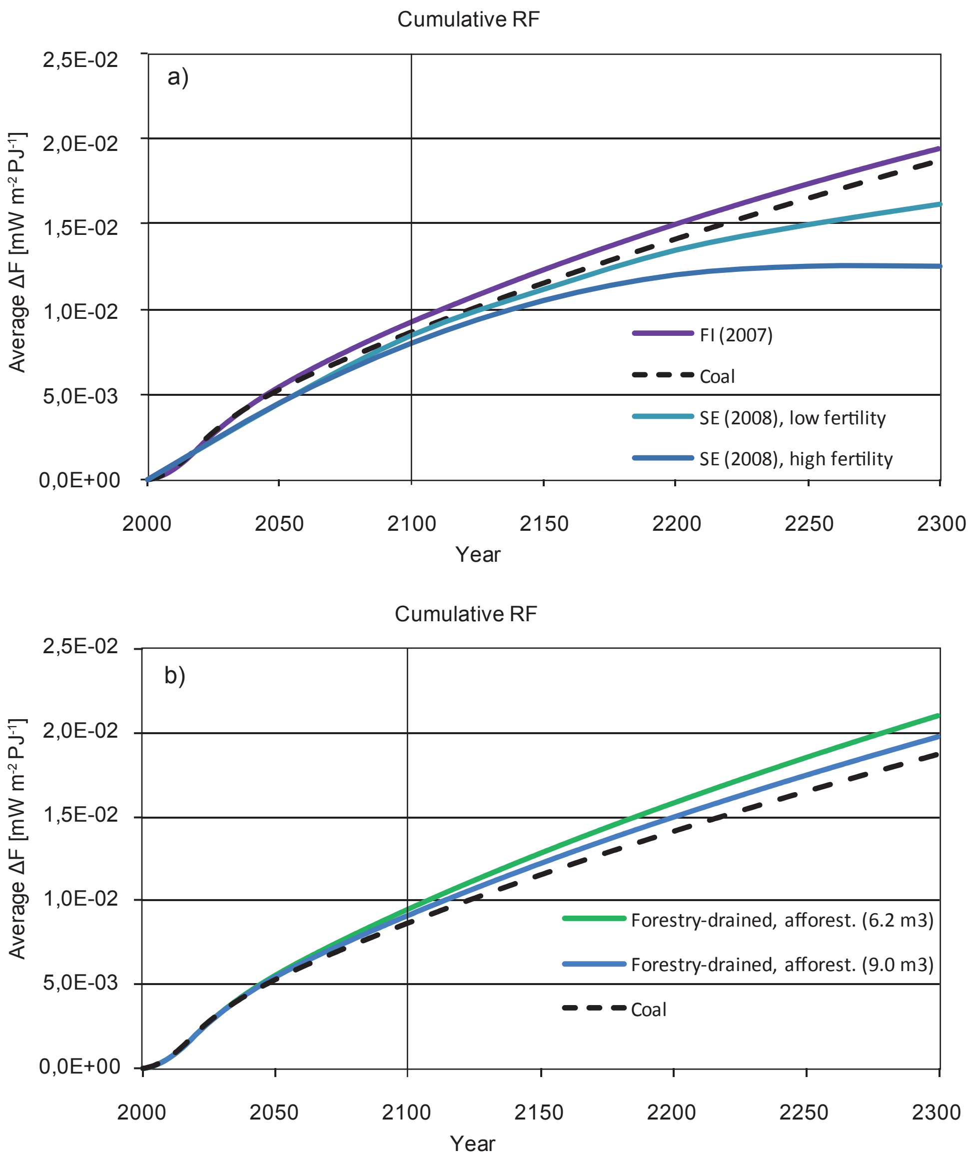

Figure 8. Cumulative radiative forcing effect (mW m^{-2} PJ^{-1}) of the "Forestry-drained peatland - afforestation" –scenario obtained form the Finnish study (FI 2007), the Swedish study (SE 2008) (a) and the best values of the review study on the bases of two forest growth assumptions in the afforestation phase (b). The assumption with the forest growth of 6.2 m^2 corresponds to the estimation of the average forest growth in the afforestation phase.

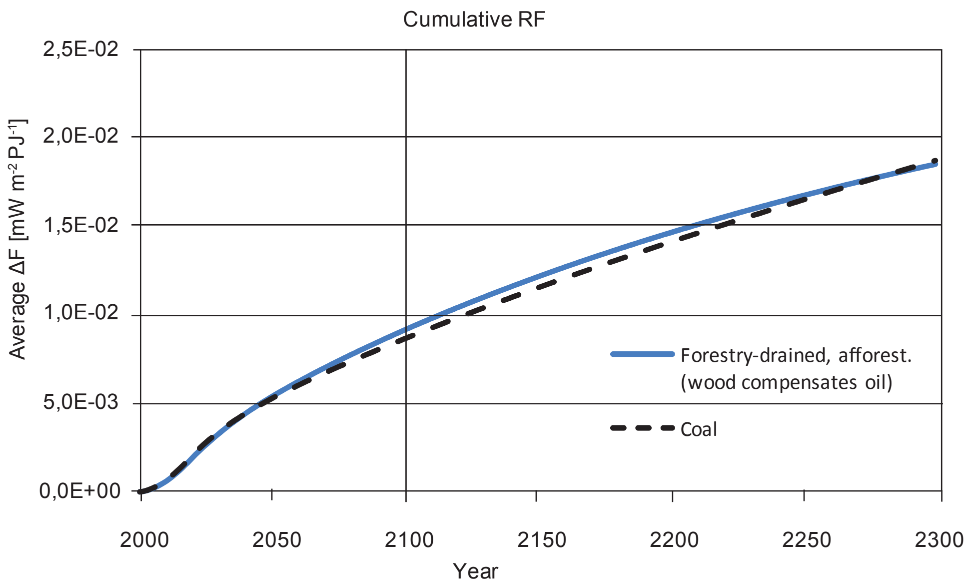

Figure 9. Cumulative radiative forcing effect (mW m^{-2} PJ^{-1}) of the "Forestry-drained peatland - afforestation" scenario calculated by the assumptions in which the increased biomass growth (3.7 m3 ha^{-1} yr^{-1}, after 45 years) due to peat production compensates the use of heavy oil in energy production and in which the increased biomass growth does not compensate the use of fossil fuels.

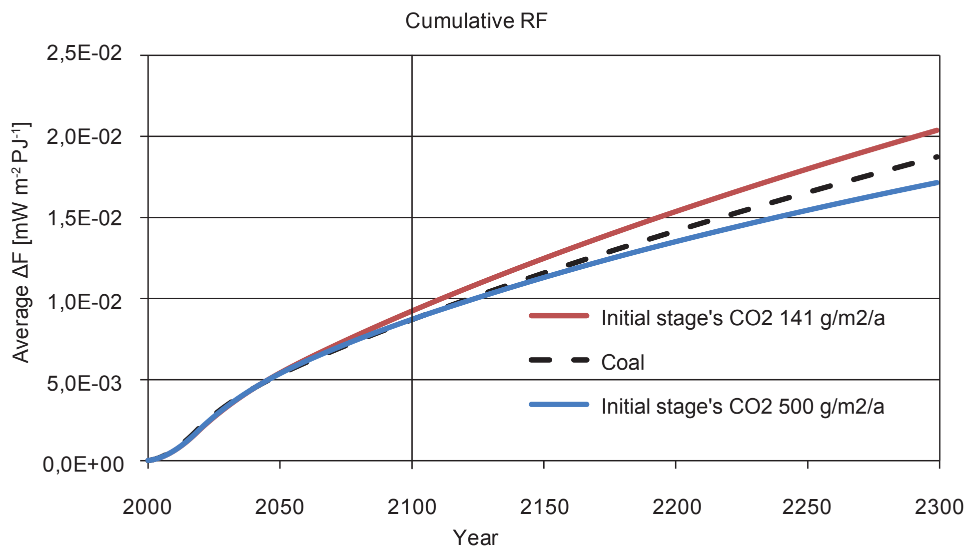

Figure 10. Sensitivity analysis: cumulative radiative forcing effect (mW m^{-2} PJ^{-1}) of the "Forestry-drained peatland - afforestation" scenario calculated assuming that the net CO_2 emission in the soil is 141 g CO_2 m^{-2} a^{-1} (=the recommended value of the review) or 500 g CO_2 m^{-2} a^{-1}.

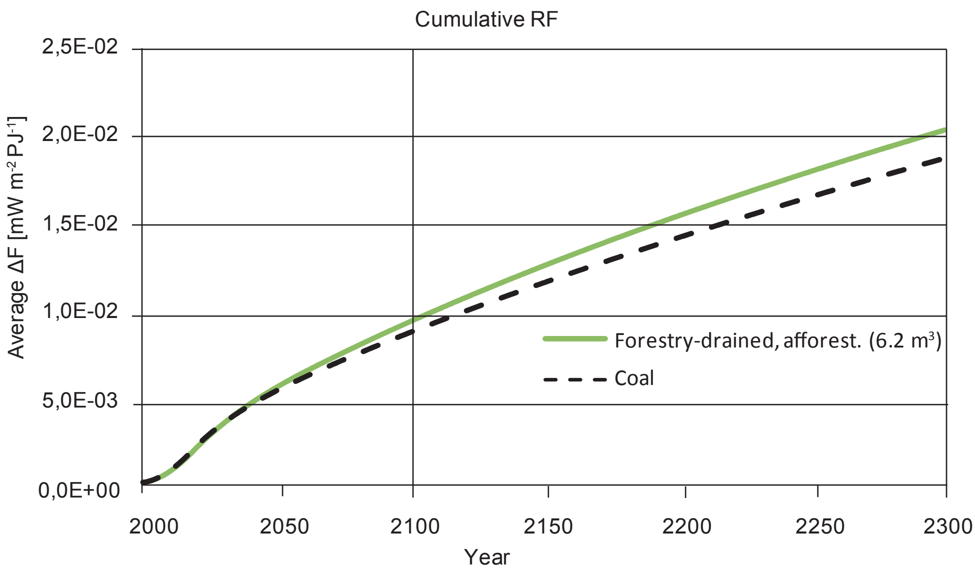

Figure 11. Sensitivity analysis: cumulative radiative forcing effect (mW m^{-2} PJ^{-1}) of the "Forestry-drained peatland - afforestation" scenario calculated assuming that one PJ of peat fuel energy requires a peat extraction area of 45 ha instead of 30 ha (=the recommended value of the review).

4.6

Peat energy utilization – cultivated peatland

According to the reviewed studies the use of cultivated peatlands causes the lowest climate impacts compared to the climate impacts of the other peatlands. However, the critical review showed that the earlier calculations included controversial assumptions about the options of land use in cultivated peatlands (Section 3.17). It is not clear that the climate impacts should be calculated on the basis of croplands as an initial state. There are also bases for using abandoned organic croplands as an initial state. The use of abandoned organic croplands causes smaller climate impacts of energy peat utilization chain than the peat from cultivated peatlands does (Figure 12 and Tables 13). Due to uncertainty in the soil emissions of initial states and to unpredictable land use options in the future a clear result for the climate impact could not be produced in the review. However, in general it can be assumed that the climate impact of the peat utilization chain "Cultivated peatlands-afforestation" corresponds more to the results of the energy peat utilization chain " Abandoned organic croplands - afforestation" than the results of the chain "Organic croplands – afforestation". The review produced the greater climate impacts for peat energy utilization chain than the reviewed Finnish and Swedish studies had earlier showed.

On the basis of the Finnish GHG emission inventory (Statistics Finland 2010) the net CO_2 emission in the soil of abandoned organic soils in 2008 was 130 g CO_2 m^{-2} a^{-1} instead of 1180 g CO_2 m^{-2} a^{-1}. If the estimation of the Finnish GHG inventory is used in the calculations, the curve of abandoned cultivated peatlands corresponds to the curve of coal in the Figure 12.

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Table 13. Emission estimates used in the recalculations (case B) for the different stages of the *cultivated peatland scenarios* (positive values= loss to the atmosphere, negative values= uptake by the ecosystem).

Cultivated peatland				
	CO_2	**CH_4**	**N_2O**	**Unit**
Initial stage (reference):				
Net soil emissions -Abandoned peatlands -Croplands Forest growth - Abandoned peatlands (2.5 m^3 ha^{-1} a^{-1})	 1180 1840 -289	 -0.2 0.1 –	 1.3 1.5 –	 g m^{-2} a^{-1} g m^{-2} a^{-1} g m^{-2} a^{-1}
During peat extraction				
Extraction area (incl. stockpiles) Working machines	5.68 1.00	0.0133 0	0.0004 0	g MJ^{-1} g MJ^{-1}
Peat combustion	105.9	0.0085	0.0128	g MJ^{-1}
After-treatment, afforestation:				
Decomposition of residual peat (for abandoned peatlands and croplands)	Emission starts from 1000, then exponential decrease during first 85 years until 50% of the residual peat has decomposed (7500 g C m^{-2}). Thereafter slow release so that 1200 g C m^{-2} at the end of simulation period (280 years)	0	0.35	g m^{-2} a^{-1}
Increased C uptake by trees - Abandoned peatlands - Croplands	 - 716* - 716*	 – –	 – –	 g m^{-2} a^{-1} g m^{-2} a^{-1}
C accumulation in the soil - Abandoned peatlands**	 0-45 years: -177 46-90 years: -89 91-180 years: -35 181-280 years: -12	 –	 –	 g m^{-2} a^{-1}
- Croplands	0-45 years: -297 46-90 years: -149 91-180 years: -59 181-280 years: -20	–	–	g m^{-2} a^{-1}

* C uptake by trees was taken into account by taking the amount of forest growth in the initial state off the amount of forest growth in the afforestation phase. Forest sequesters the difference amount of carbon during the period of 45 years
** Only the effects of difference in forest growth before and after peat extraction (3.7 m^3 ha^{-1} a^{-1}= (6,2 - 2.5) m^3 ha^{-1} a^{-1}) are taken into account for carbon accumulation in the soil

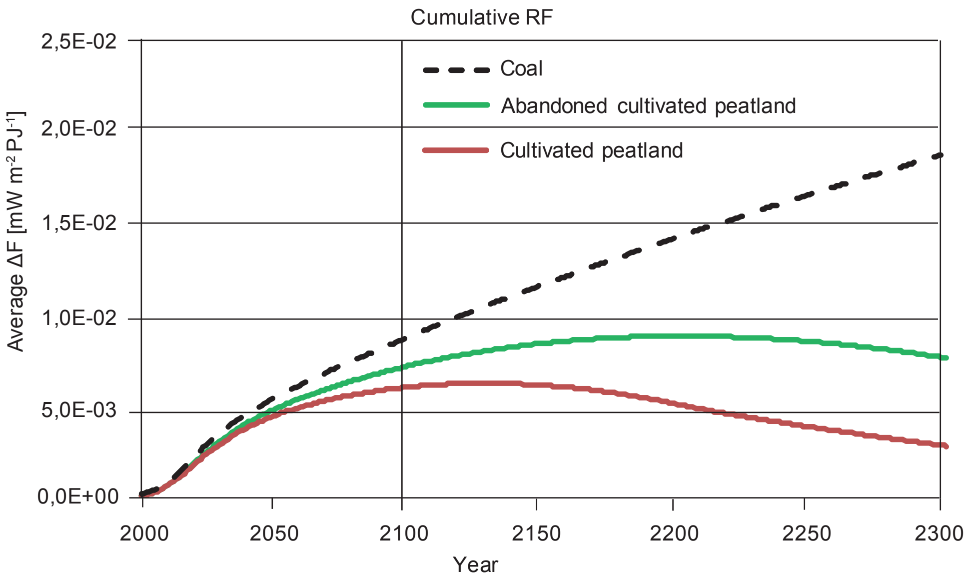

Figure 12. Cumulative radiative forcing effect (mW m^{-2} PJ^{-1}) caused by the "Cultivated peatland - afforestation" scenario when the values of abandoned organic croplands and cultivated peatlands were used as emission values for the initial reference situations.

5 Summary and conclusions of the critical review and recalculations

The critical review conducted according to international standards (ISO 14040 and ISO 14044) was a process to verify whether the Finnish and Swedish LCA studies on peat fuel utilization chains met the requirements for methodology, data, interpretation and reporting. The comparison between peat and fossil fuels was also in the scope of the review process, i.e. to compare the climate impacts of peat fuel utilization with those of coal.

The peat energy utilization chains studied in the reviewed process differed from each other in terms of their peat production reserves and after-treatments. The peat energy utilization chains studied were

- pristine mire and afforestation or restoration
- forestry drained peatland and afforestation,
- cultivated peatland and afforestation.

Climate impact assessment

In the Finnish and Swedish studies a climate change impact assessment was carried out by using the concept of radiative forcing (RF). This is a very appropriate methodology to quantify the net GHG emissions in land use related studies such as peat fuel utilization. However, the details concerning the radiative forcing calculations were not discussed in the research reports.

The review process revealed that *there are no significant differences in the radiative forcing calculation models between the studies,* although some significant differences were identified in the individual model components between the Finnish, Swedish and IPCC models. However, when considering the complete models and the combined climate impact of different GHGs, the integrated effect of these differences does not appear significantly large and is unlikely to affect the interpretation of the results of life-cycle assessments.

Reference fuels

In the Finnish and Swedish studies coal was used as a reference fuel to which the climate impact of peat fuel utilization is compared. The somewhat greater GHG emissions of coal combustion used in the Swedish (SE 2004) study has a clear influence on the interpretation of the RF calculations. This means that the reference RF level in the Swedish study (SE 2004) is slightly higher than in the Finnish case, and *the results seem to be slightly more positive for peat in the Swedish case when the climate impact of peat fuel is compared with the climate impact of coal*. It is important to note that in the latest Swedish study (SE 2008) the emissions of the coal reference correspond to the emissions used in the Finnish study (FI 2007). In addition, the selection of a reference fuel can have an effect on how the climate impacts of peat fuel are interpreted. Coal's climate impact is worse than other fossil fuels. In the Swedish study natural gas was also used as a reference fuel causing a significant difference in the interpretation of peat as a fuel.

System boundaries
In LCA studies the definition of system boundaries typically plays an important role in the final results. This is also the situation for the LCAs on peat fuel utilization. In the Finnish study (FI 2007), the surrounding area (area around the actual peat extraction area) was not considered, while in the Swedish study (SE 2004) the impact of drainage on the GHG-balances in the surrounding area for all the three different peat production reserves (pristine mire, forestry drained and cultivated peatlands) was taken into account. In the Swedish study (SE 2004) it was supposed that the surrounding area was as large as the actual extraction site.

The study has shown that a consideration of the surrounding area affects the final results, especially in the case of forestry drained peatland- afforestation. However, in the latest Swedish study (SE 2008) the effects of the surrounding area were omitted in the cases of forestry drained and cultivated peatlands. The decision to omit the surrounding area is considered to be correct. In the case of pristine mire, the inclusion of the surrounding area only has a minor effect on the final climate impacts of the peat fuel utilization chain.

In the mire drainage phase, there is also a clear difference between the studies. In the Finnish study (FI 2007), the mire drainage phase was not considered, whereas in the Swedish study (SE 2004) a five year period between mire vegetation stripping, ditching and starting the peat extraction was included. In practice, this difference does not play a significant role in the final results.

Reference situations
In order to calculate changes in greenhouse gases in the peat fuel production area, there is a need to determine the state of the area before peat extraction (known as an initial reference situation) and the final state of the peat production area used in the LCA calculation (known as a final reference situation). T*he study has shown that the determination of reference situations will be one of the critical points in the calculations*.

In the review process the reference situations used in the production reserves of pristine fen and forestry drained peatlands of the Finnish and Swedish studies were accepted, whereas in the case of cultivated peatland the initial reference situation should be abandoned organic croplands with forest growth and organic croplands. Due to unpredictable land use options in the future both initial reference situations can be used for quantifying the climate impacts of cultivated energy peat utilization chain. The results of abandoned organic croplands describe probably better the final impacts of the energy peat use of cultivated croplands.

Inventory data
The inventory data quality requirements in inventory analysis were not considered in the reviewed studies. In general, the input data of different life cycle stages in the Finnish and Swedish studies were well documented. However, there were many points in which the authors did not clearly explain the basis for their choices. In addition, there were some minor inconsistencies between the reported values in the Swedish study (SE 2004) and the original references but they had no effect on the final results.

An important difference between the Swedish and Finnish reports was found in the magnitude of soil CO_2 emissions data for forestry-drained peatlands. The value used in the Finnish study (FI 2007) is based on the same methodology and data which are used for the official Finnish greenhouse gas inventory and can be considered the best way to determine net soil CO_2 emissions. Annual carbon sequestration by the trees and litter accumulation in the context of afforestation were documented in the reviewed studies, but the use of them in the calculations was insufficiently described to be repeated exactly. The review showed that carbon accumulation in the soil caused by afforestation was not assessed in the right way in any of the reviewed studies.

The re-calculations demonstrated that carbon accumulation in the soil has a greater influence on the results than the earlier studies showed. This slightly improves the climate impact of energy peat utilization compared to the impact of coal utilization.

The review pointed out that there is a very large variation in the GHG emissions of different peatland types. For example, there is a considerable difference in net greenhouse gas balances of drained forest sites depending on trophic and climatic conditions. Data on the CO_2 net fluxes from drained forests are still uncertain and further research is needed (old peat, litter, other biomass) especially on intermediate and mineral rich drained sites because of their potential for peat production. There is also uncertainty in the CO_2 net fluxes from cultivated peatlands. Most of the net ecosystem CO_2 exchange (NEE) estimates are based on respiration measurements using closed chamber techniques and the input of plant components (litter, roots and stems) and ground vegetation have been separately measured or modelled. The net gas balance of an ecosystem is a result of these separately measured inputs and outputs. However, one major difficulty has been to separate soil C efflux into heterotrophic (old peat and litter decomposition) and autotrophic (root respiration) components. Also, the estimation of the amount and turnover rate of belowground litter on peatlands is difficult to determine. More data is needed to reliably separate the heterotrophic and autotrophic components.

One way to determine the annual net CO_2 balance of the ecosystem is the micrometeorological eddy covariance method. In Finland, there is only one published eddy-covariance data on net ecosystem CO_2 exchange (NEE) presently available for the forestry drained treed peatlands (Laurila et al. 2007, Minkkinen et al. 2007). However, more eddy-covariance data are needed from different types of drained peatlands.

Also, eddy covariance measurements are needed to validate the NEE derived from separately measured input and output results from the chamber technique.

Data on the N_2O net fluxes from peatlands before, during and after peat extraction are still uncertain and further research is needed.

LCA calculation methods

In the reviewed studies, a calculation procedure was used with the aim of measuring the net GHG emissions of peat energy utilization caused by the use of fuels and changes in land use. The calculation method used was according to the LCA principles in which the aim is to assess how human activity actually affects GHG emissions. However, the key question is how to determine initial and final reference situations in the calculations.

In general, the calculation system of land use in the LCAs are not based on dynamic modeling in which forest growth and soil emissions are handled together. For this reason, there is a risk that different input data gathered from different sources are not consistent with each other and the time aspects are not taken into account in the right way between different "unit processes". In the future, there is a need to improve the calculation system.

Incorrect determinations for the reference situations of cultivated peatlands could lead to misunderstandings in the possibilities to reduce the GHG emissions of the peat fuel utilization chain. The smaller GHG emissions of abandoned organic agricultural land compared with the emissions of actively cultivated peatland causes smaller avoided emissions for the peat fuel utilization chains. In addition, the increase of forest productivity due to fertilization cannot be directly allocated to peat energy utilization because fertilization could be conducted without peat fuel production in forestry-drained peatlands.

In the Finnish and Swedish studies, there were no calculations in which the increased biomass due to afforestation would replace fossil fuels in energy production. The review team also agreed to omit this credit calculation in the future options. On the other hand, the sensitivity analysis showed that this assumption has only small effects on the results.

Time perspective

The time perspective, e.g. 50, 100 and 300 years, of the climate impact results has a strong effect on the final interpretation because there are different opinions about what constitutes an "acceptable" time perspective in the context of climate change mitigation. In general, it can be said that the threat of rapid climate change requires energy production solutions with very low radiative forcing in the short-term (clearly under a 100 years perspective). The impact calculations with cumulative and instantaneous radiative forcing of the Finnish and Swedish studies offer a good starting point for analysis.

It is important to understand that the LCA results become increasingly uncertain with time, as the various dynamical effects cannot be considered in the modelling. In practice, the time perspective over 100 years includes so much uncertainty that such results are not recommended to use for decision making.

Interpretation of results

In this study, the recalculations for the use of peat for energy production were carried out on the basis of findings made in the review process. In the calculations, the best current average values for input data and the choices of system boundaries and reference situations recommended in the review were used.

It is important to understand that the results are indicative due to the large variation and uncertainty in the input data of different peatland types. However, in the case of pristine mires with restoration the message from the Finnish and Swedish studies and the review are similar: peat causes greater radiative forcing effects than coal energy utilization does. Afforestation as an after-treatment option for pristine mires slightly reduce the GHG emissions of the peat energy utilization chain, but the climate impact still remains at the same level as that caused by the coal utilization chain.

The re-calculation for the peat energy utilization chain "Forestry-drained peatland –afforestation" caused a climate impact that was similar to the impact of the Finnish study (FI 2007), whereas from the viewpoint of peat utilization it was worse compared to the result produced by the most recent Swedish study (SE 2008). It is well known that the results of forestry-drained peat utilization chains vary considerably according to the peat type. The energy peat of high fertility forestry-drained peatlands caused a smaller climate impact compared to the impact caused by the energy peat of low fertility forestry-drained peatlands. However, the results obtained from the different studies – whether taking fertility aspects into account or not - are very similar in terms of a 100 years perspective: the climate impact of a forestry-drained peat energy utilization chain corresponds to the climate impact of a coal energy utilization chain.

In the case of cultivated peatland, the results produced by this study differ from the results of the earlier Finnish and Swedish studies. The critical review showed that the earlier calculations included controversial assumptions about the options of land use in cultivated peatlands. In terms of climate impacts, the benefits of using cultivated peatlands as a peat production source are less than expected earlier.

The results outlined above are based on the use of conventional peat production technology in the calculations. The Finnish (FI 2007) and Swedish (SE 2008) studies pointed out that a new peat production technology could reduce GHG emissions by some per cents over a 100 years' perspective compared to the conventional technology. However, an evaluation of the new production technology was not included in this review process.

6 Future outlooks

The LCA results on the climate impacts of peat fuel utilization chains are indicative, and the final results will change strongly case by case due to the large variation and uncertainty in the input data of different peatland types. In the future, an improvement in the modelling system and a continuation of experimental research is needed in order to get more reliable data for the calculations of climate impacts. The aim should be that data used in the official Finnish GHG emission inventory and in the LCAs of peat fuel utilization chains is consistent with each other.

The time perspective of the climate impact calculations in the LCAs on peat energy utilization was 300 years. The fact is that such a long time perspective requires, for example, the assessment of changes in the green house gas (GHG) balances in peatlands in the modelling. However, the development of the GHG balances is very difficult to assess reliably in the changing climate. For this reason, the calculations have been based on input data representing the current sate. As the various dynamical effects cannot be considered in the modelling, results become increasingly uncertain over longer periods of time. In practice, a time perspective of over 100 years includes so much uncertainty that such results are not recommended for use in decision making. The use of a shorter time perspective is justified because climate change mitigation requires fast actions over the next decades. Even a reduction of 80-95% in greenhouse gas emissions by 2050 should be done according to the Environmental Council of the EU environmental ministers.

It is important to notice that peat fuel utilization chains based on the most common peatlands used for energy peat extraction (pristine mires and forestry-drained peatlands) cause similar climate impacts to coal energy utilization. In practice the use of afforestation as an after-treatment option does not change the climate impacts over a 100 years perspective. In addition, biodiversity conservation aspects must be considered in the use of pristine mires.

In the future, the climate impacts of peat energy utilization can be slightly reduced by selecting peatland production areas which have lower life cycle GHG emissions, such as cultivated or high fertility forestry-drained peatlands, and by using new extraction technologies. From the viewpoint of GHG emissions, it is important that the use of croplands for peat extraction does not move the cultivation of crops to abandoned organic croplands or new organic fields causing the same GHG emissions as the original croplands.

In any case, the separate use of peat in energy production is always problematic from the viewpoint of climate impacts. The combustion of peat releases carbon storage accumulated over thousands of years in a short time and the limited carbon sequestration due to after-treatment activities can only compensate the releases by some per cents over a 100 years' perspective.

Presented with the current challenges of climate change mitigation peat should be regarded as a promoter and an auxiliary fuel for the use of carbon neutral biomass. Peat can act as a reserve or back-up fuel for biomass because it is easy to store and the availability of biomass often varies in practice. Small fraction of peat in fuel can also reduce corrosion in some boilers. The mixture fuel of biomass and peat can substitute fossil fuels and thus significant emission reductions can be reached, although the CO_2 emissions from the peat combustion diminish the climate benefits of bioenergy.

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Title of publication	**Climate impacts of peat fuel utilization chains – a critical review of the Finnish and Swedish life cycle assessments**	
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Abstract	In recent years there has been a lively debate in Finland and Sweden on the climate impact of peat fuel utilization. The aim of this study was to clarify the contradictions between the Finnish and Swedish studies and provide a better basis for energy policy decision-making by summarizing the recent scientific knowledge about the climate impacts of peat fuel utilization chains based on the life cycle assessment (LCA) methodology. A starting point for this study was to carry out a critical review of Finnish and Swedish life cycle studies of the climate impacts of peat fuel utilization chains. The critical review was conducted according to the recommendations of international standards and its aim was to ensure that the methods, data and interpretation of results were carried out in a scientifically and technically valid way. During the review the available data (mostly published) on the greenhouse gas (GHG) balances and the radiative forcing impacts of GHGs were gathered and updated. The re-calculations showed that the climate impact of "Pristine mire – afforestation" utilization chain is similar to the climate impact of coal utilization, whereas the result of the peat utilization chain "Pristine mire – restoration" is slightly worse than for the coal utilization chain. The results were similar in the reviewed studies. The peat utilization chain "Forestry-drained peatlands – afforestration" causes a slightly higher climate impact on average than the coal utilization chain does. From the viewpoint of peat utilization the result was similar to the result of Finnish study. According to the reviewed studies the use of cultivated peatlands causes the lowest climate impact compared to the climate impacts of the other peatlands. However, cultivated peatlands do not play important role as an extraction area for peat utilization. From the viewpoint of peat utilization the result of cultivated peatland was worse compared to the result produced by the Finnish and Swedish studies. The climate impacts of peat fuel utilization chains are mostly caused by the carbon dioxide released by peat combustion. These emissions are known quite well. However, the emission assessments of different peat types include large uncertainty before, during and after peat extraction. In spite of that it can be said that land change options related to peat extraction and after-treatments have very limited effects on the climate impacts of peat utilization chain.	
Keywords	peat, greenhouse gases, emissions, life cycle, radiative forcing	
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<tr><td>Tiivistelmä</td><td colspan="4">Viime vuosina turpeen energiakäytön ilmastovaikutuksista on käyty vilkasta keskustelua Suomessa ja Ruotsissa. Työn tarkoituksena on ollut muodostaa tieteellisesti perusteltu kokonaiskuva energiaturpeen ilmastovaikutuksista. Tavoitteena on ollut selventää energiaturpeen ympärillä käytyä keskustelua ja parantaa päätöksentekoon liittyvää tietopohjaa turpeen energiakäytöstä. Työn lähtökohtana on ollut Suomessa ja Ruotsissa tehtyjen energiaturpeen elinkaariarviointitutkimusten kriittinen arviointi. Kriittinen arviointi tehtiin kansainvälisten standardien suositusten mukaisesti ja sen tarkoituksena oli saada varmistus siitä, että elinkaariarvioinneissa käytetyt menetelmät, aineistot sekä tulosten tulkinta on tehty tieteellisesti ja teknisesti oikein. Arvioinnin yhteydessä koottiin ja päivitettiin saatavilla oleva (pääsääntöisesti julkaistu) tietoaineisto soiden kasvihuonekaasutaseista ja kasvihuonekaasujen säteilypakotevaikutuksista. Kriittisessä arvioinnissa tehtyjen havaintojen perusteella erilaisille energiaturpeen hyödyntämisketjuille tehtiin uusintalaskelmat ja arvioitiin tulosten herkkyys tärkeiksi tunnistetuille elinkaarimallin tekijöille. Työ osoitti, että luonnontilaisesta suosta otetun turpeen ja kivihiilen energiakäytön ilmastovaikutukset ovat samaa luokkaa kun turvetuotantoalueen jälkikäyttönä on metsitys turpeenoton päätyttyä. Turvetuotannosta poistuneen suon ennallistaminen johtaa energiaturpeen kannalta huonompaan ilmastovaikutukseen kuin alueen metsitys. Tulokset ovat linjassa suomalaisen ja viimeisimmän ruotsalaisen tutkimusten kanssa. Metsäojitettujen soiden turpeen energiakäyttö aiheuttaa keskimäärin hieman kivihiiltä suuremman ilmastovaikutuksen. Tulos on turpeen hyödyntämisen kannalta samanlainen kuin aikaisemman suomalaisen tutkimuksen tulos. Suopeltojen turpeen käyttö aiheuttaa elinkaaritutkimusten perusteella pienemmät päästöt kuin kivihiilen poltto. Suopeltojen merkitys turvetuotannon lähteenä on kuitenkin vähäinen. Kriittisen arvioinnin lopputulos oli suopeltojen turpeen ilmastovaikutusten kannalta aikaisempia suomalaisia ja ruotsalaisia elinkaaritutkimuksia huonompi. Energiaturpeen ilmastovaikutukset aiheutuvat pääasiassa turpeen poltossa syntyvästä hiilidioksidipäästöstä, joka tunnetaan suhteellisen tarkasti. Soiden kasvihuonekaasupäästöihin liittyy puolestaan suuria epävarmuuksia ennen ja jälkeen turpeenoton. Tästä huolimatta voidaan sanoa, että turpeenottoon liittyvillä maankäyttötoimenpiteillä voidaan vaikuttaa energianturpeen elinkaarisiin ilmastovaikutuksiin hyvin rajallisesti.</td></tr>
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Sammandrag	Under de senaste åren har det förts en livlig debatt i Finland och Sverige om klimateffekterna av utnyttjande av torv som bränsle. Syftet med denna studie har varit att klargöra motsättningarna mellan de finländska och svenska studierna som gjorts på området. Avsikten har varit att skapa en bättre grund för det energipolitiska beslutsfattandet genom att summera de senaste kunskaperna om torvförbränningens klimateffekter utgående från en livscykelanalysmetod. En utgångspunkt för studien var att kritiskt granska de finländska och svenska livscykelstudier som gjorts om klimateffekterna av torvförbränningens kedja. Den kritiska bedömningen gjordes i enlighet med internationella standardrekommendationer för att säkerställa den vetenskapliga och tekniska validiteten av de metoder och data som användes och de tolkningar som gjordes. I samband med utvärderingen samlade och uppdaterade man data som fanns tillgängligt (mestadels publicerat) om växthusgasbalans och påverkan av växthusgasers s.k. "radiative forcing". På basen av de upptäckter man gjorde i den kritiska granskningen så kalkylerade man på nytt olika torvutvinningsscenarier och gjorde sensitivitetsanalyser för de mest kritiska antagandena. Omräkningarna visade att klimateffekterna av torvenergiutvinning med beskogning från myrar i naturtillstånd är likartade med klimateffekterna av kolanvändning, medan resultaten av energitorvanvändningsscenariot "orörd torv - restaurerad torvtäktsmyr" är något sämre än för kolanvändningsscenariot. Torvanvändningsscenariot "dikad skogsmarksmyr med beskogning" ger i medeltal en något högre klimatpåverkan jämfört med kolanvändningsscenariot. Resultaten är i linje med de tidigare finländska och de senaste svenska resultaten. Utvinning av energitorv från myråkrar förorsakar i enlighet med livscykelundersökningar lägre utsläpp än förbränning av stenkol. Myråkrarnas betydelse som källa för torvanvändningen är ändå liten. Slutresultaten av den kritiska analysen var att klimatpåverkan från odlad torvmark var värre än resultaten från de tidigare både finska och svenska livscykelanalyser. Energitorvens klimatpåverkan förorsakas huvudsakligen av koldioxid som frigörs då torven bränns. Dessa utsläpp känner man till rätt ganska exakt. Vad gäller uppskattningen av växthusgasutsläppen från myrarna så är emellertid osäkerhetens stor, och gäller såväl innan, under som efter torvbrytningen. Trots detta så kan man säga, att med markförändringsåtgärder relaterade till utvinning av torv och den därpå följande efterbehandlingen så kan man påverka torvutvinningens klimateffekter ur ett livscykelperspektiv ytterst begränsat.			
Nyckelord	Torv, växthusgas, utsläpp, livscykel, klimateffekter			
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The climate impacts of peat fuel utilization have been a controversial issue. This report clarifies the debate and provides a better basis for the Finnish energy policy decision-making by summarizing the recent scientific knowledge about the climate impacts of peat fuel utilization based on the life cycle assessment (LCA) methodology.

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