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Energy related emissions of non-CO_2 greenhouse gases and the climate impact of forest residues – a synthesis

Lars Zetterberg, Ida Adolfsson, Jonas Höglund, Jenny Gode, Julia Hansson

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John Munthe
Vice President, Research

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Telephone +46 (0)8-598 563 00	
Author Lars Zetterberg, Ida Adolfsson, Jonas Höglund, Jenny Gode, Julia Hansson	
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Summary

This report describes measures to reduce non-CO_2 greenhouse gas emissions and estimates CO_2 emissions from using forest residues for energy due to impacts on biogenic carbon stocks.

Measures to reduce emissions of methane, nitrous oxide and fluorinated gases have been described and quantified where possible. The measures presented for methane is reduced methane leakage from landfills, leakage from transmission and distribution of natural gas and methane from incomplete combustion. Landfills are currently the second largest source of methane emissions in Sweden and the potential to reduce methane leakage is estimated to be 800 kilotonnes of carbon dioxide equivalents, or more than 60% reduction from present emissions. The potential to reduce methane leakage from natural gas pipelines have not been quantified. It is estimated that methane from incomplete combustion could be almost entirely avoided. For nitrous oxide, two different measures were studied. Nitrous oxide from fluidized beds has a reduction potential estimated to around 20 %. However, a study of the reduction potential in the EU-27 shows significantly higher reduction potential. Projections of nitrous oxide emissions from road vehicles show increased emissions to 2020 despite measures. The fluorinated gases analysed is HFC leakage from air conditioners and SF_6 from switchgears and switchers. The reduction potential is considered high for HFC leakage from AC in vehicles, mainly due to the replacement of HFCs with a high GWP to HFCs with lower climate impact. For sulphur hexafluoride, emission projections show only modest reductions to 2020.

It is often argued that the use of biomass for energy purposes does not yield any net carbon dioxide to the atmosphere, because the carbon released was once bound in the growing forest, thus closing the biogenic carbon cycle. However, bioenergy production may influence biogenic carbon stocks and atmospheric CO_2 significantly. There are also emissions arising from the need for auxiliary energy for production and transport of biofuels and potential emissions of other greenhouse gases than carbon dioxide. The climate impact due to the release of carbon to the atmosphere is of transient character. Net

emissions start as an instant emission at the time for extraction and combustion. The emissions are then reduced over time approaching zero. The report describes climate impact of forest residues and stumps and a comparison is made to coal. The results show that forest residues have lower climate impact than stumps which in turn are better than coal. The significance of the chosen time horizon is also assessed by comparing a 20 years perspective with a 100 year perspective. The shorter time frame gives higher climate impact and the decomposition rate of biomass has great significance for the results.

Sammanfattning

Syftet med studien har varit att dels beskriva och kvantifiera några åtgärder för att minska utsläppen av andra växthusgaser än koldioxid till 2020 och dels att ta fram en syntes över biobränslens klimatpåverkan med fokus på tidsaspekter.

Åtgärder för minskade utsläpp av metan, lustgas och fluorerade gaser har beskrivits och kvantifierats där så varit möjligt. De åtgärder som presenterats för metan är minskat metanläckage från deponier, läckage från transmission och distribution av naturgas samt metan från ofullständig förbränning. Deponier är idag näst största källan till metanutsläpp i Sverige och potentialen för att minska metanläckaget uppskattas vara 800 kton koldioxidekvivalenter, eller motsvarande drygt 60% minskning. Potentialen för att minska metanläckage från naturgasledningar har inte kunnat kvantifieras, medan metan från ofullständig förbränning bör kunna i princip helt undvikas. För lustgas har två olika åtgärder studerats, dels lustgas från fluidiserade bäddar och dels lustgas från vägfordon. Trots åtgärder för att minska utsläppen av lustgas från vägfordon så ökar emissionerna enligt de prognoser som studerats. Däremot finns det potential att minska lustgasutsläppen från fluidiserade bäddar. De svenska uppskattningarna ligger på ca 20% reduktions-potential, medan en studie av reduktionspotentialen i EU-27 visar på betydligt större potential. De fluorerade gaser som analyserats HFC i luftkonditioneringsanläggningar samt SF6 i transformatorer. Reduktionspotentialen bedöms vara stor för HFC-läckage från luftkonditionering i fordon, vilket främst beror på utfasning av HFC med högt GWP. För svavelhexafluorid visar utsläppsprognoser på ganska måttliga reduktioner fram till 2020.

Användning av biomassa för energiändamål har ofta ansetts inte innebära några nettoutsläpp av koldioxid till atmosfären. Exempelvis inkluderas inte biobränsleförbränning i EU:s utsläppshandel. I själva verket innebär biobränsleförbränning påverkan på klimatet exempelvis genom förändrat markkol vid uttag av biomassa, genom behov av hjälpenergi för produktion och transport av biobränslen samt genom utsläpp av andra växthusgaser än koldioxid. Det finns också en tidsaspekt i koldioxidbalansen genom att förbränning av biobränslen innebär en tidigareläggning av emissionerna jämfört med om biomassan hade fått brytas ned i naturen istället. I rapporten beskrivs biobränslens klimatprestanda och en

jämförelse görs mellan olika biobränslen och mellan biobränslen och kol. Resultaten visar att GROT är bättre än stubbar som i sin tur är bättre än kol. En jämförelse görs också av vilken betydelse det valda tidsperspektivet har för resultaten. 20- respektive 100-årsperspektiv studerades. Det kortare tidsperspektivet ger högre klimatpåverkan, vilket beror på att endast en del av biomassan då hunnit brytas ned naturligt. Nedbrytningshastigheten för biomassan har stor betydelse för resultaten.

Contents

1 Introduction

This report describes energy related emission data to be used for modelling Swedish energy scenarios within the research programme *North European Power Perspectives – NEPP*. The NEPP programme conducts research on the future Nordic electricity market and power system in the perspective of integration towards a coherent European electricity market. The focus of the program lies in syntheses in a system perspective. An important part of the programme is future energy scenarios and the role of this particular study has been to support the scenarios with greenhouse gas emission data focused on non-CO_2 emissions and climate impact of biomass.

Chapter 2 describes measures to reduce energy related emissions from greenhouse gases other than carbon dioxide. Chapter 3 estimates CO_2-emissions from using forest residues for energy due to impacts on biogenic carbon stocks.

2 Measures to reduce emissions of non-CO_2 greenhouse gases

This chapter focuses on measures to reduce emissions from greenhouse gases other than carbon dioxide in the energy sector. The greenhouse gases that have been analyzed are methane, nitrous oxide, fluorinated greenhouse gases (f-gases) and short lived climate pollutants (SLCP).

Figure 1 shows current emissions (year 2011) of various greenhouse gases and their sources. The emissions of non-CO_2 greenhouse gases are low compared to that of carbon dioxide and the emission sources also show different patterns. The largest sources of carbon dioxide emissions are transport and industry whereas the dominating source of methane and nitrous oxide emissions is agriculture. Industry is the sole emission source of f-gases (HFC, PFC and SF_6). However, f-gases are also used in other sectors (e.g. SF_6 for insulation of switch gears in the energy sector), but the f-gas emissions are sorted under industry in the greenhouse gas statistics.

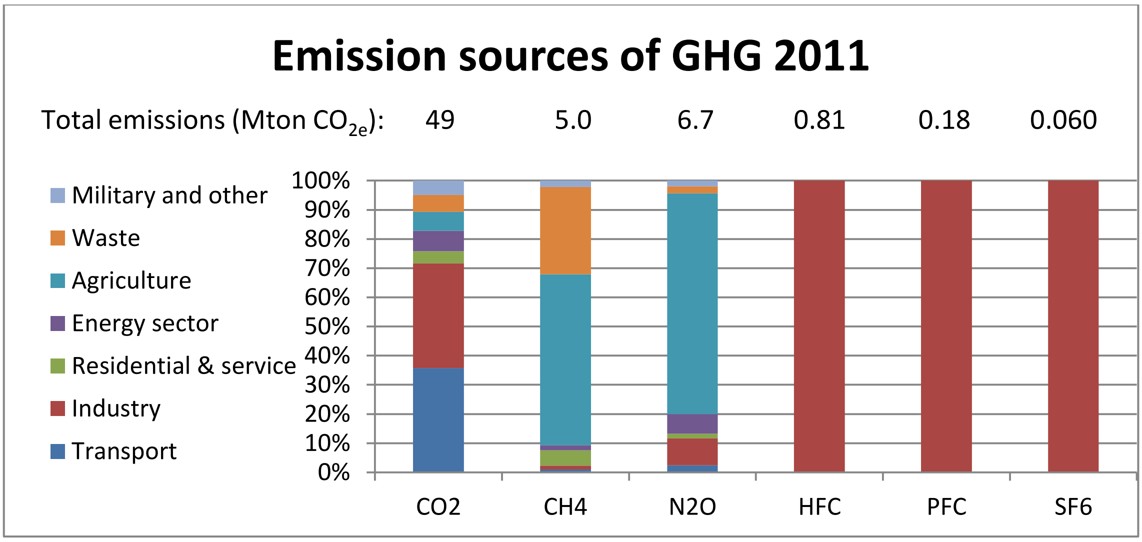

Figure 1. Emissions of greenhouse gases from different sectors in 2011 (source: Swedish Environmental Protection Agency, 2012a)

2.1 Methane

2.1.1 Methane from landfills

Landfills are the second largest emissions source of methane in Sweden after livestock farming. Landfills in Sweden emit almost 1.3 Mtons of carbon dioxide equivalents which is approximately 2 % of Sweden's total greenhouse gas emissions of 61 Mton in 2011 (Swedish Environmental Protection Agency, 2012). Over the last 20 years the methane emissions from landfills have steadily declined, mainly thanks to policies against landfilling organic material and improvements in the methods of collecting methane gas (Swedish Environmental Protection Agency, 2012a). In 2010, there were 76 active landfills in Sweden of which 53% collected gas. Complementary to these, there is also gas collection at 17 inactive landfills (Lindelöf, 2012). With these measures emissions are expected to decrease to 500 ktons CO_2 e in 2020 (Ministry of the Environment, 2009). This corresponds to a reduction potential of 62 %. For comparison, in the EU-27 the reduction potential between the years 2005 and 2030 is estimated to be 61 % (Höglund-Isaksson et. al., 2010).

2.1.2 Methane leakage from transmission and distribution of natural gas

The national reporting of climate change to UNFCCC allows different options for calculating leakage of methane from transmission and distribution of natural gas. Where national estimations are missing, IPCC default emission factors may be used (2.9 ton CH_4/km transmission pipeline and 0.615 ton CH_4/km distribution pipeline, Swedish Environmental Protection Agency, 2012a). In the Swedish national inventory reports from 2010 and 2012, the IPCC default values were used. With activity data of 620 km of transmission pipelines and 2600 km of distribution pipelines, the estimated annual emissions add up to 38 ktons CO_2 e from the transmission system and 34 ktons CO_2e from the distribution system (Swedish Environmental Protection Agency, 2012a). This corresponds to a total leakage of 0.25 %.

However, Jerksjö et al (2013) criticizes this method's ability to correctly estimate the emissions. They made a comprehensive review of existing emission factors and estimations of methane from transmission and distribution pipelines. They conclude that estimations of methane leakage from transmission and distribution in 2012 of natural gas vary widely from 0.025-38 kton CO_2e for transmission and 0.12-78 kton CO_2e for distribution. Their recommendation is to use emission factors from Swedegas for methane leakage from transmission pipelines and from Wikkerink (2006) for the distribution of natural gas. These emission factors are considered best reflect the Swedish conditions. The emissions from methane leakage from transmission and distribution would then be 0.040 kton CO_2e (transmission) and 5.5 kton CO_2e (distribution), i.e. substantially lower than the estimations by using IPCC default emission factors (Jerksjö et al, 2013). Jerksjö et al (2013) also estimated the emissions of methane subjected to distribution of biogas and gas works gas, and concluded that these are 0.27 kton CO_2e (biogas) and 36 kton CO_2e (gasworks gas).

No estimates showing the possible emission reduction for Sweden have been found. However, according to Höglund-Isaksson et. al, (2010) in EU-27 emissions from long-distance gas transmission system can be reduced by 6 % between the years 2005 and 2030.

2.1.3 Methane from incomplete biomass combustion

Incomplete combustion may lead to methane emissions. Combustion of biofuels and waste generally generates higher emissions of methane compared to that of oil and energy gases. There is also a scale dependency where combustion of biomass in larger industry plants and in district heating plants results in lower emissions of methane than combustion in small-scale heating systems.

The emissions from small-scale biomass boilers vary depending on the combustion conditions. Boilers without a thermal heat storage tank usually generate relatively high emissions. In 2003, boilers which were not environmentally certified[1] dominated in the residential sector. Measures to reduce the emissions include installation of environmentally

[1] According to the Swedish National board of housing, building and planning

certified boilers, installation of thermal heat storage tanks, and to change the fuel quality, e.g. to switch from wet wood to wood pellets.

Linda Johansson et. al. (2003) developed a scenario where 90 % of the boilers which were not environmentally certified were replaced with environmentally certified boilers and the remaining 10 % were replaced with pellets boilers. As a result of these measures, the emissions were reduced from 74 ktons to 1.4 ktons of methane. No more recent estimations have been found.

2.2 Nitrous oxide

2.2.1 Nitrous oxide from fluidized beds

Combustion in fluidized bed combustors (FBC) is a significant source of nitrous oxide emissions. The Swedish emissions of nitrous oxide from FBC:s in 2010 was around 500 ktons CO_2e (Swedish Environmental Protection Agency, 2012a). Emissions from conventional combustors (other than FBC, e.g. grate combustors) are generally very low. The reason nitrous oxide emissions appear in FBC is because of catalytic processes taking place in an FBC (IEAGHG, 2000). The emissions of nitrous oxide vary depending on the fuel, bed temperature and access to oxygen (Tsupari et al 2007). A change in one of those parameters will also affect other emissions such as SO_2, NO and CO. Nitrous oxide is only formed in temperatures between 527-927ºC (IEAGHG, 2000). N_2O emissions are generally higher for bituminous coal than e.g. peat and biomass. Circulating fluidized beds tend to produce more nitrous oxide than bubbling fluidized beds (IEA GHG, 2000) because of longer residence time.

The measures to reduce emissions of nitrous oxide can be divided into primary and secondary measures. Examples of primary measures include advanced staging and afterburning which affect the combustor conditions. An example of a secondary measure includes the installation of flue-gas cleaning systems. The effectiveness of the secondary measure depends on the formation and reduction of nitrous oxide which in turn are related to the combustion chamber process. Knowledge about the combustion chamber process still needs to be developed and therefore primary measures are preferred (Leckner, 2006).

The reduction potential of nitrous oxide from fluidized beds depends on both the development of the fuel mix and of technologies and measures that will be applied to the existing and new FBC:s. The literature is very scarce in estimations of future N_2O emissions from FBC:s However, in the fifth national report on climate change (Ministry of the Environment, 2009) the emission of nitrous oxide from fluidized bed combustors are projected to be reduced to 400 ktons CO_2 in 2020 compared to 2010. This corresponds to a reduction potential of 20 % only. This is significantly lower estimate than the EU-27 reduction potential of 91 % between the years 2010 and 2030 estimated by Höglund-Isaksson et. al. (2010). The reason for this difference has not been analyzed further.

2.2.2 Nitrous oxide from vehicles in the road transport sector

In the road transport sector emissions of nitrous oxide are very small compared to the emissions of CO_2. 0.5 % of the total greenhouse gas emissions from the transport sector originate from nitrous oxide gas which corresponds to 108 ktons CO_2e (Swedish Environmental Protection Agency, 2012a). When catalytic converters were introduced to reduce emissions of primarily NO_x, CO and VOC, the emissions of nitrous oxide increased due to incomplete reduction of NO in the catalyst (Swedish Environmental Protection Agency, 2012a).

Few estimations exist on reduction potential of N_2O from vehicles. The projections used in the roadmap towards an emissions neutral Sweden (Swedish Environmental Protection Agency, 2012b) shows increased emissions of nitrous oxide from road transport from present 108 kton CO_2e to 152 kton in 2020. These projections may be compared to older estimations in the Swedish fifths national report on climate change (Swedish Ministry of Environment, 2009), where the reduction potential from 1990-2020 was estimated to 5%. With an emission level of 157 kton CO_2e in 1990, this would result in 149 kton in 2020. A comparison to the EU level reduction potential made by Höglund-Isaksson et. al., (2010) shows a much higher estimation of 28 % between the years 2005 and 2030.

2.3 F-gases

2.3.1 HFC from refrigerant leakage

The largest source of emissions of refrigerants is mobile AC systems. The most common fluorinated greenhouse gas in refrigerants is HFC-134a which has a GWP factor of 1430[2] (IPCC 2007). Emissions from mobile AC systems in Sweden are estimated to be 463 ktons CO_2 equivalents.

A new European directive (2006/40/EG) restricts the use of refrigerants with a GWP factor higher than 150. Kindbom et al (2006) presented three scenarios of HFC emissions from mobile AC systems based on different assumptions on the replacement of HFC-134a to HFC-152a. HFC-152a has a significantly lower GWP_{100} of 124 compared to HFC-134a (GWP_{100} = 1430). The study included estimations and projections of fleet development. The results shows estimated emissions of HFC in 2020 of 29-193 kton CO_2e, or 58-94% reduction potential compared to present emissions (Kindbom et al 2006).

Based on the EU directive and the projection made by Kindbom et al (2006), Gustafsson et al (2011) estimates a successive replacement of HFC-134a by HFC-152a resulting in a decrease of f-gas emissions from mobile AC systems to 27 ktons CO_2e in 2030 (Gustafsson et al, 2011). This corresponds to a reduction potential of 94 %, which is in line with the estimated EU-27 reduction potential of 91 % from 2005 to 2030 (Höglund-Isaksson et al.,2010).

2.3.2 Leakage of SF_6 from electrical equipment

Sulphur hexafluoride, SF_6, is used as insulation gas in switchgears and switchers. The total present emissions of SF_6 from electrical equipment are estimated to be 31 ktons CO_2e (Swedish Environmental Protection Agency, 2012a). Today both consumers and producers strive at reducing the emissions of SF_6 by developing routines to avoid leakage.

[2] Global Warming Potential (GWP) describes the expected climate impact from the emission of 1 kg of the greenhouse gas in question compared to the emission of 1 kg carbon dioxide

Kindbom et al (2006) made projections of f-gas emissions including SF_6. The estimated emissions decreased from present 31 kton CO_2e to 20 kton CO_2e in 2020, or an emission reduction potential of 35 %. For comparison, in the EU-27 the reduction potential is estimated to be 73 % between the years 2005 and 2030 (Höglund-Isaksson et. al., 2010). The high discrepancy between the Swedish and European estimations have not been analyzed further, but may be due to lower leakage in present Swedish switchgears and switchers.

2.4 Short lived climate pollutants, SLCP

Short lived climate pollutants, SLCP (sometimes referred to as SLCF = short lived climate forcers), is a generic term for methane (CH_4), black carbon, ozone (O_3) and hydrofluorocarbons (HFC). All pollutants except fluorinated greenhouse gases have a short atmospheric lifetime of weeks to months. SLCP impact climate change and some of the pollutants also have negative effects on health and crop production.

Emission sources of the SLCP:s black carbon and tropospheric ozone are describe below as well as the main measures to reduce the SLCP emissions. However, no quantification of the abatement measures has been made. Abatement measures for methane and HFC are described separately above.

2.4.1 Black carbon

Black carbon is an aerosol particle with the potential to contribute to global warming. A high proportion of soot is black carbon. Soot is a product from incomplete combustion of both fossil and renewable fuels. In Europe emissions from diesel engines are the dominant emission sources of black carbon while in developing countries emissions from combustion in residential heating, cooking and industry is a major source of black carbon emissions. Black carbon effects the global warming in several ways. In the atmosphere black carbon absorbs solar radiation and emits heat which makes the atmosphere warmer. If the black carbon falls down on snow or ice the melting process will increase. Black carbon may also disturb cloud formation. By installing particle filters on diesel vehicles, utilizing biomass boilers and prevent open burning of biomass the emissions of black carbon may decrease.

2.4.2 Tropospheric ozone

Tropospheric ozone is formed by a chemical reaction between sunlight and nitric oxide (NO_x), volatile organic compounds (VOCs) or carbon monoxide (CO). Tropospheric ozone is a reactive greenhouse gas and harmful to human health and crop cultivation. Over the last hundred years the amount of tropospheric ozone has tripled and on a global scale. Methane (a VOC gas) is responsible for approximately two-thirds of this rise (Institute for Governance and sustainable Development, 2012). There are both anthropogenic and natural sources of emissions of nitric oxide, NO_x. The largest emissions source of nitric oxide is combustion of fossil fuels where the transport sector represents the primary source. Forest fires are a natural source of nitric oxide. The largest emissions sources for VOC are the transport sector and the petrochemical industry. The transportation sector and the incomplete combustion in small-scale boilers are the largest emissions sources of carbon monoxide.

Measures to reduce formation of tropospheric ozone include the reduction of substances which can give rise to ozone. Such measures include installation of flue gas cleaning systems, to introduce catalytic converters in vehicles and to reduce the leakage of VOC in the petrochemical industry (Zetterberg, Särnholm, 2007).

2.5 Summary of reduction potential

Table 1 below shows current emissions of non-CO_2 greenhouse gases from different sources and the reduction potential for each source for the year 2020. Some of the emissions data is from older reports (italic). A short description of how the emissions occur and measures to reduce those is provided in the sections to follow.

Table 1. Current emissions of non-CO_2 greenhouse gases in the Swedish energy sector and reduction potentials for the year 2020. Estimated reduction potentials in the EU are presented for comparison. Older data are given in italics.

Measures	Current emissions in Sweden [ktons CO_2e]	Reduction potential to 2020 in Sweden [ktons CO_2e] (percentage)	Reduction potential 2005-2030 in EU-27 [Percentage]
Methane (CH_4) from landfills	1 300[1]	-800[2] (-62%)	-61 %[3]
Methane (CH_4) leakage from transmission and distribution of natural gas	5.5[4]	-	-6% [3] *
Methane (CH_4) from incomplete combustion	*74*[5]	*-73*[5] (-98 %)	-
Nitrous Oxide (N_2O) from fluidized beds	500[1]	-100[2] (-20%)	-15% [3] **
Nitrous Oxide (N_2O) from vehicle catalysts	108[1]	+44 (+41%)	-28% [3]
HFC leakage from refrigerants (HFC-134a)	463[6]	-270 to -434[6] (-58 to -94%)	-91% [3]
SF_6 leakage from switchgear	31[1]	-11[7] (-35%)	-73% [3]

* Refers to long-distance gas transmission system.

** The reduction potential is between the years 2010 to 2030

[1] Swedish Environmental Protection Agency, 2012a

[2] Ministry of the Environment, 2009

[3] Höglund-Isaksson et. al., 2010

[4] Jerksjö et al (2013)

[5] Johansson L et. al. 2003

[6] SMED, 2012

[7] The Swedish Environmental Protection Agency, 2003

3 Carbon dioxide emissions from using forest residues for energy due to impacts on biogenic carbon stocks

The objective of this chapter is to estimate the climate impacts from the use of forest residues for energy due to their impacts on forest carbon. The results will be expressed as emission factors on the form g CO_2/MJ fuel.

3.1 Is solid biomass climate neutral?

When biomass is combusted the carbon that once was bound in the growing forest is released, thus closing the biogenic carbon cycle. For this reason combustion of bioenergy is often associated with a CO_2 emission factor of zero. For instance, CO_2 emissions from biofuels are not included in the EU emission trading system (European Commission, 2003). However, bioenergy production may influence biogenic carbon stocks and atmospheric CO_2 significantly in either a positive or negative way (IEA 2011). Forest residues are important biofuels in Sweden accounting for approximately 14 TWh (Swedish Energy Agency, 2013). Eriksson and Hallsby (1992) showed that using logging residues for energy, instead of leaving them on the ground, could lead to lower carbon storage in litter and soils. But this effect is of transient character. If forest residues or stumps are left on/in the ground, the major part would decompose and release CO_2 to the atmosphere. This is described in figure 1. The diagram is based on modelling of tops and branches from spruce forest in southern Sweden (Ågren 2011). The top curve (reference case) shows the case when the forest residues are left in the soil to decay naturally. The second curve from the top (utilisation case), shows the case when the residues are harvested. Net emissions, illustrated by the bottom curve have been calculated as the difference between the reference case and the utilisation case.

Net emissions (bottom curve) start as an instant emission at the time for extraction and combustion, which is reduced over time approaching zero. After a few decades there is almost no residual effect. The reason for this is that if the residues were left on the ground, they would decay and release carbon to the atmosphere. Using forest residues and stumps for energy can be seen as shifting the emissions earlier in time compared to leaving them on the ground to decompose (Lindholm et al, 2010). Over time the emission related emissions are compensated due to the avoided emissions from decay and therefore over long time the extraction of forest residues is practically carbon neutral.

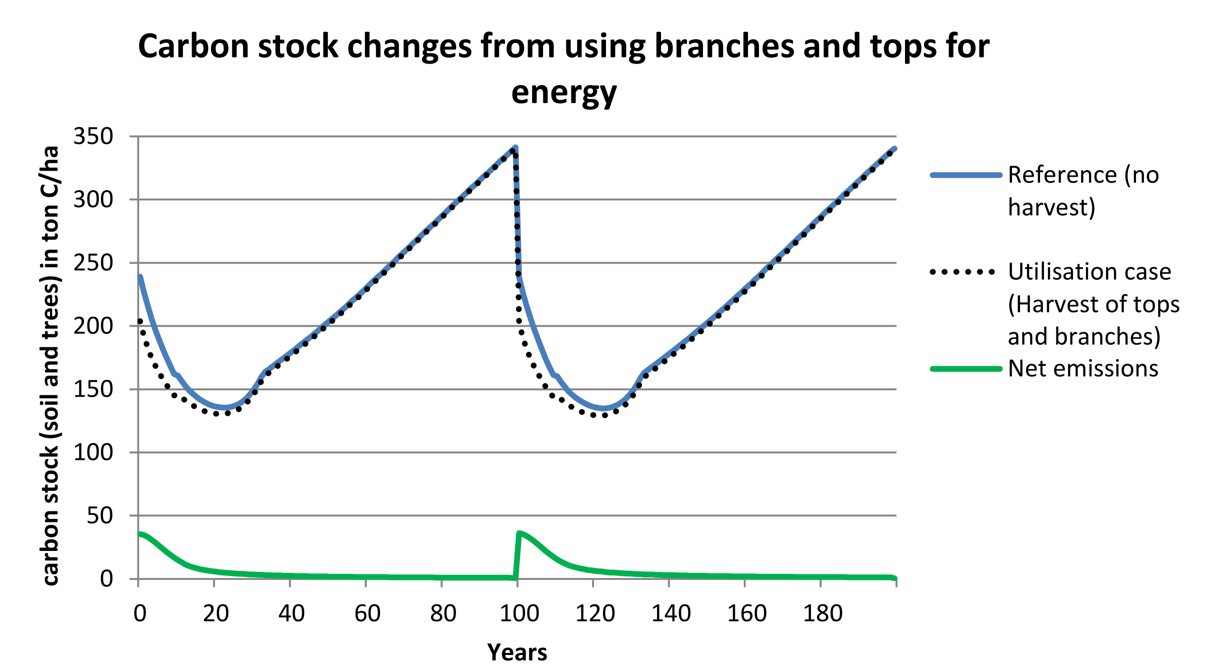

Figure 1. Illustration of how net emissions are calculated as carbon stock changes from the reference case (no harvest) minus carbon stock changes from the utilisation case (harvest of branches and tops). Data from Ågren (2011).

In addition to the impacts on biogenic carbon, the use of biofuels affects climate in other ways, for instance use of fossil fuels for harvest, transportation and drying the biofuels and emissions of other greenhouse gases. Different studies estimate these emissions to be approximately 1-3 g CO_2/MJ, which is relatively low compared to the carbon content of biofuels of approximately 95 g CO_2/MJ. In addition, there are indirect effects to consider, for instance the substitution effect of biofuels replacing fossil fuels or the displacement of food stock production.

3.2 Comparison forest residues and coal

Figure 2 shows the net emissions for different types of forest residues, assuming that 1 MJ fuel is combusted at t = 0. The diagram shows emissions for branches and stumps, according to a Swedish model, called the *Q-model* and a Finnish model called *Yasso*. Net emissions are calculated using the same methodology as in figure 1 as the difference between extracting the residues compared to leaving them in the forest to decay. The corresponding emissions from using coal for energy are shown for comparison.

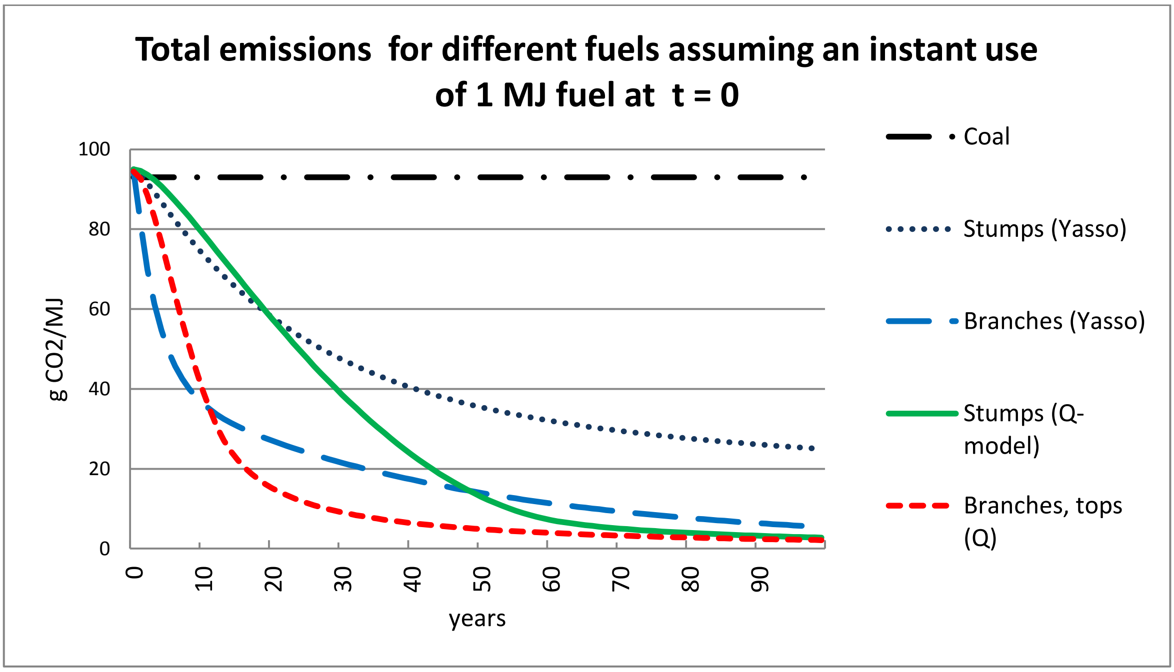

Figure 2. Net emissions for different types of forest residues, assuming that 1 MJ fuel is combusted at t = 0.

For all biofuels, the net emissions follow the same dynamic characteristic, starting with a pulse emission that decreases over time due to the avoided emissions from the reference case. In contrast, the emissions from using coal are constant over time. The figure shows that initially, the emissions from forest residues are as high as for coal, but decrease due to the avoided emissions from the reference case where the residues are left on the ground to decay. The time perspective over which the analysis is done is crucial for the climate impact of biofuels. The figure shows that over a 100 year perspective the use of branches and tops are close to being carb neutral, while stumps may have a climate impact, depending on model. Over a 20 year time perspective branches and tops are significantly better than stumps, which in turn are better than coal. However over a 20 year time perspective the relative differences between the fuels are smaller.

In conclusion, there is a climate impact from using forest residues for energy, which depends on how the extraction of the fuels from the forest impacts on the biogenic carbon stocks in the forest. There is a difference between biofuels. The analysis shows that branches and tops are better than stumps which in turn are better than coal. The time perspective over which the analysis is done has great importance for the results. Over 100 years biofuels are significantly better than coal. Over 10 or 20 years, the relative difference between the fuels is smaller.

3.3 Establishment of a new forest

As shown in section 3.4, using forest residues for energy leads to a temporary increase of CO_2 in the atmosphere. However, there are bioenergy scenarios which may lead to decreased CO_2 in the atmosphere and have a cooling effect on climate. If, for instance a new forest is established on land that is previously used for agriculture this will lead to the creation of a new carbon stock and hence a decrease of atmospheric CO_2. In addition, when this new forest is mature for harvest, biofuels may be produced. However, since the newly established forest replaces crops, a relevant question to ask is how the crops are replaced. If the replaced crops are produced elsewhere through intensified agriculture or on new agricultural land, the analysis of the climate effects of the new forest should also include the net effects of relocating the crops.

3.4 How are land use related emissions accounted for in the Kyoto protocol?

Following the insights of how biofuels have an impact on forest carbon stocks, there has been a debate about the carbon neutrality of biofuels. For instance, Searchinger et al (2009) argue that there is 'a serious accounting error' when biofuels are considered carbon neutral. Is this the case?

The most important accounting system for greenhouse gas emissions from energy use in Europe is the Kyoto protocol and the EU emissions trading system. According to the Kyoto protocol, bioenergy is treated as CO_2-neutral in the energy sector (Cowie, 2012). However, the impacts on forest carbon stock are in fact accounted for, although separately and in the sector Land use, Land Use Change and Forestry (LULUCF). Fossil fuels used for the production of biofuels are reported in the energy sector. Non CO_2 greenhouse gases, such as Nitrous oxide, N_2O and methane, CH_4 are included in the agricultural sector. If this reporting format is followed, the greenhouse gas emissions from using biofuels will be correct. A problem is that only Annex I countries (countries that have an commitment according to the Kyoto protocol) are covered by this reporting. This means that land-use related emissions from imported biofuels from non-Annex I-countries are not included. Most countries do not estimate forest carbon stock changes, but will in the future when new accounting rules apply.

The EU ETS follows the accounting rules for the Kyoto protocol. This means that emissions from combustion of bioenergy are treated as CO_2-neutral. Land use related emissions due to the production of biofuels are not included in the trading system, but are accounted for in the non-trading sector. With the start of the second compliance period of the Kyoto protocol in 2013, emissions occurring in the LULUCF-sector are included in the EU and national commitments. This means that the loss of one ton carbon in the forest due to the extraction of biofuels will be equally important to the national commitment as an emission of 1 ton carbon from fossil fuels in the energy sector.

3.5 How can impacts on biogenic carbon stocks from the use of bioenergy be included in future energy road maps?

There is an increasing interest in developing national or regional energy road maps with the objectives of minimizing climate impacts towards 2050 (European Commission 2011, Naturvårdsverket 2012, North European Power Perspectives 2013, IEA 2013). Some of these road maps assume a substantial use of bioenergy. In order to give a correct description of the climate impacts of biofuels, one may argue that a life cycle approach needs to be applied including for instance the impacts on biogenic carbon stocks from the production and extraction of biofuels. Consequently, for fossil fuels, upstream effects such as leakage of methane in the production and distribution of the fuels should be included. In the following, we show how emissions factors can be derived for forest residues that include the impacts on biogenic carbon stocks. A warning is in place here. Since changes in biogenic carbon pools are normally reported under LULUCF, including land use effects of biofuels in an energy scenario may lead to double counting. This may happen if a road map for the energy sector includes biogenic carbon impacts and this sector road map is used in a more comprehensive national road map, where land use effects also are reported in the LULUCF-sector. It is therefore very important that energy scenarios that include the land-use related emissions communicate this in a transparent way.

With this in mind, emission factors for forest residues that include impacts on biogenic carbon stocks can be estimated based on results presented in figure 2. These emissions have a temporal dependency making them more complex to describe than fossil fuels. One way to describe this is to designate a time integrated emission factor to the biofuel based on the average net CO_2-emission over a given time period. Based on the results in figure 2 we have calculated corresponding CO_2-emission factors for branches and tops and stumps for two different time perspectives: 20 years and 100 years. The resulting emission factors are presented in table 2.

Table 2. Estimated emission factors for forest residues due to impacts on biogenic carbon stocks. In the UN framework these emissions are normally reported under LULUCF (Land Use, Land Use Change and Forestry).

Emission due to expected impacts on forest carbon stocks	**20 years [g biogenic CO_2/MJ_{fuel}]**	**100 years [g biogenic CO_2/MJ_{fuel}]**
Branches and tops	15-27	2-5
Stumps	57-58	3-25

Table 2 shows that there is an initial climate impact from using forest residues for energy, which decreases over time. The decomposition rate is critical for the results. Branches and tops, with a fast decomposition rate, have lower climate impacts than stumps with a slower decomposition rate. On a more general note - if we assess the carbon impacts from solid biofuels over a shorter time perspective than the rotation time (or in the case of residues the time to reach carbon neutrality) – there will be a climate impact.

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