# Biofuels and climate neutrality

– system analysis of production and utilisation

Biobränslen och klimatneutralitet – systemanalys av produktion och användning

Elforsk rapport 07:35

Kristina Holmgren, Erik Eriksson, Olle Olsson, Mats Olsson, Bengt Hillring & Matti Parikka

Juni 2007

ELFORSK

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# Förord

Föreliggande projekt har initierats inom Elforsks programråd för El- och värmeproduktion. Syftet med projektet har varit att sammanställa den litteratur som finns på området biobränslen och klimatneutralitet samt att bedöma om det finns kunskapsluckor som motiverar att gå vidare i en fördjupad studie. Studien har genomförts av IVL Svenska Miljöinstitutet AB och SLU, institutionerna för bioenergi och skoglig marklära på uppdrag av Elforsk och Naturvårdsverket.

Till projektet har knutits en referensgrupp, bestående av Lars Wrangensten, Elforsk, Bengt Hanell Elforsk, Hans Nordström, Vattenfall Värme Norden, Björn Möller Fredriksson, E.ON, Ivan Sundström, Umeå Energi, Anna Lundborg, Energimyndigheten, Klas Österberg, Naturvårdsverket samt Jenny Gode och Lars Zetterberg, IVL Svenska Miljöinstitutet. Elforsk och författarna vill tacka gruppen för värdefulla kommentarer.

Diskussioner i referensgruppen har visat att området är komplext och att många olika betraktelsesätt och synsätt finns, bl.a. med tanke på allokeringar av emissioner till olika verksamheter och näringar samt vilka referensalternativ som gäller till att nyttja olika biobränslefraktioner för förbränning och energiutvinning.

Elforsks programråd kommer att diskutera resultatet av rapporten under höstens strategimöte och då ta ställning till vilka fortsatta FoU-insatser som krävs inom området.

Elforsk i juni 2007

Lars Wrangensten

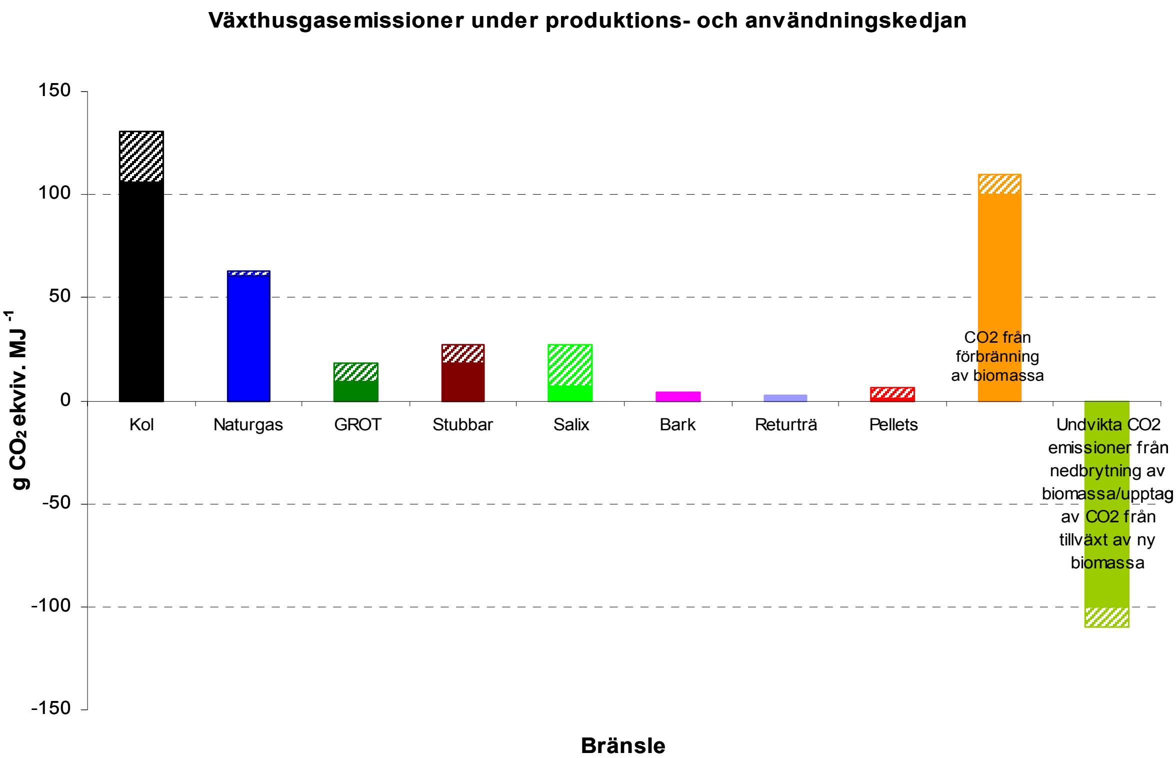
Programområdesansvarig för
El - och Värmeproduktion.

# Sammanfattning


Syftet med denna studie var att undersöka i vilken utsträckning biobränslen kan sägas vara klimatneutrala. Baserat på befintlig litteratur har en sammanställning av emissionsdata för produktions- och användningskedjorna för ett antal fasta biobränslen genomförts. Dessa data har använts för beräkningar av påverkan på strålningsbalansen[1] (*radiative forcing*). I studien har också en jämförelse mellan importerade och inhemska biobränslen gjorts.

## Resultat och slutsatser

Vi drar slutsatsen att inga av de undersökta biobränslekedjorna kan kallas "klimatneutrala" eftersom samtliga resulterar i nettoemissioner av växthusgaser. Även om samtliga av de undersökta biobränslekedjorna resulterar i nettoemissioner av växthusgaser så är emissionerna i samtliga fall betydligt lägre än motsvarande för fossila bränslen. Emissionerna varierar för olika bränslekedjor beroende på bränsle och hur systemgränserna är satta i olika studier.


Figur A. Jämförelse av emissioner från bränslekedjor baserat på data från litteraturen (se Table 5.10). De två staplarna till höger visar $CO_2$ emissioner från förbränning respektive nedbrytning/upptag i biomassa. Sett över en längre tidsperiod kan dessa två staplar antas vara lika stora. De skuggade delarna av staplarna visar variationen mellan olika produktions- och användningskedjor av samma bränsle. Notera att i staplarna för biobränslekedjorna är inte emissionerna från förbränning och nedbrytning/upptag inkluderade (dessa emissioner antas ta ut varandra över tiden och storleken på dem illustreras av staplarna längst till höger i figuren).

[1] Påverkan på strålningsbalansen d.v.s. balansen mellan inkommande och utgående energi, eller radiative forcing mäts i $Wm^{-2}$.

Figur A visar en sammanställning av nettoemissioner av växthusgaser för de undersökta biobränslekedjorna samt motsvarande emissioner för kol och naturgas.

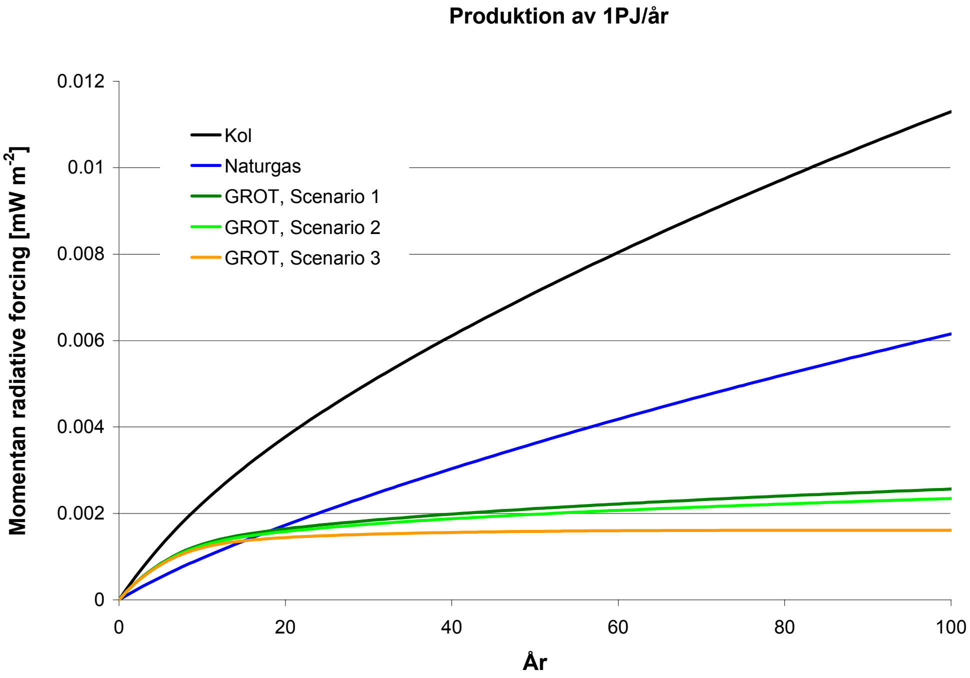
Resultatet visar att det är skillnad i nettoemissioner mellan olika typer av biobränslen och att det finns osäkerheter i uppskattningarna som kan minskas. Följande faktorer kan bidra signifikant till de totala emissionerna av växthusgaser i produktions- och användningskedjorna för olika biobränslen; produktionssystemets påverkan på markkolet, marksötselmetoder (särskilt på dränerad torvmark), användning av gödselmedel (både direkt och indirekt påverkan på växthusgasemissioner), förbränningtekniken, förädling av bränslet (t.ex. pelletstillverkning) och lagring (särskilt för finfördelade bränslen). Andra källor som också bidrar till emissionerna under en produktions- och användningskedja är: skördemaskiner, transporter och avfallshantering.

Lägg märke till att i figuren vägs $CO_2$ emissionerna från förbränningen av biobränslena upp av de emissioner som skulle ägt rum om materialet istället brutits ned i naturen eller av koldioxidupptag i växande biomassa. Eftersom det är stor skillnad i utsläppsförloppet mellan förbränningsscenariet och nedbrytningsscenariet/upptagsscenariet; vid förbränning sker emissionerna direkt medan nedbrytningen/upptaget tar många år, årtionden eller t.o.m. längre beroende på vilket biobränsle man talar om, innebär detta att man betraktar utsläppen över en viss tidsperiod. Längden på denna tidsperiod varierar från bränsle till bränsle.

Genom beräkningar av påverkan på strålningsbalansen till följd av växthusgasemissionerna under produktions- och användningskedjorna från de olika biobränslena får man en bättre bild av bränslenas potentiella påverkan på klimatet.

Klimatpåverkan från emissionerna från ett av biobränslena, GROT, jämfördes med klimatpåverkan från fossila bränslen med hjälp av beräkningar av påverkan på strålningsbalansen[1]. I dessa beräkningar inkluderades såväl emissioner av $CO_2$ vid förbränning som de emissioner av $CO_2$ som skulle ha uppstått till följd av nedbrytning om biomassan lämnats kvar i skogen. Dessutom tas hänsyn till tidsaspekten. Resultaten av beräkningarna redovisas i Figur B. Nollinjen representeras av påverkan från de emissioner som skett även om bränslena inte utnyttjats. För kol och naturgas innebär det att kolet och gasen lämnats i marken och inte utvunnits. För GROT innebär det att hyggesresterna lämnats i skogen och brutits ner. Nedbrytningen ger upphov till emissioner av koldioxid under en lång tid i en mängd som motsvarar de emissioner som släpps ut vid förbränningen. Figuren visar att påverkan från GROT-scenariet på sikt planar ut; nivån beror till stor del på den tidigareläggning av koldioxidemissionerna som förbränningen innebär. Endast en liten andel beror av hjälpenergi vid uttaget (arbetsmaskiner, flisning och transporter) och den minskning i markkolförrådet man kan förvänta sig till följd av uttaget. Detta betyder att biobränslen med kort omloppstid ger upphov till en lägre påverkan på strålningsbalansen än bränslen med längre omloppstid, förutsatt att insatt energi och övrigt är lika.

Figur B visar att det är en väsentlig skillnad mellan biobränslen och fossila bränslen, eftersom påverkan på strålningsbalansen från de fossila bränslena stiger kontinuerligt medan den från biobränslescenarierna når en stabil nivå. Vilket tidsperspektiv man skall ha vid bedömning av påverkan på strålningsbalansen till följd av växthusgasutsläpp är inte självklart.




Figur B. Momentan påverkan på strålningsbalansen (radiative forcing) från bränslekedjor där 1 PJ bränsle produceras och används varje år. Se avsnitt 7.1 för en förklaring av de olika scenarierna.

## Helhetsperspektiv och systemgränser

För att kunna uppskatta mängden växthusgaser som ett visst biobränsle ger upphov till krävs det att man gör en livscykelanalys, det vill säga analyserar och beskriver alla växthusgasflöden som kan knytas till hanteringen av bränslet under produktion, transport, förädling, användning och avfallshantering. Det är också av stor betydelse hur man gör systemavgränsningar i livscykelanalysen. Exempel på viktiga systemavgränsningar är huruvida bränslet definieras som en biprodukt eller hur markemissioner från produktionsytan skall beaktas.

En annan viktig systemgräns är tidsperspektivet. FN:s klimatpanel (IPCC) ger i sin fjärde rapport om klimatförändringarna ingen entydig rekommendation om vilken tidshorisont man skall använda vid jämförelser av växthusgasemissioner genom GWP-faktorer (Global Warming Potential). Inom ramen för Kyotoprotokollet har man dock valt ett hundraårsperspektiv. Ett tidsperspektiv på hundra år inkluderar också trögheten i oceanerna och deras inverkan på den globala medeltemperaturen. Kolcykelmodeller visar också att ett hundraårsperspektiv representerar en tidsskala under vilken en betydande del av ett utsläpp av koldioxid har lämnat atmosfären. Detta talar för att man behöver ett långt tidsperspektiv vid jämförelsen av olika bränslesystem. Det betyder också att även om den momentana påverkan från GROT-scenariot i figur B är jämförbar med naturgasscenariot under de första 15-20 åren så har det liten betydelse i det långa loppet.

### Importerade biobränslen

I denna studie har också nettoemissioner av växthusgaser från importerade biobränslen undersökts. Fokus var på emissioner från transporter och lagstiftning rörande återplantering. Sverige importerar biobränslen från de baltiska länderna, Kanada, Finland och en del andra europeiska länder. De importerade bränslena skeppas vanligen till Sverige. Emissionerna av växthusgaser per tonkilometer är vanligen lägre för sjötransporter än för transporter med lastbil. Beroende på avstånd till exportlandet kan transportemissionerna för importerade biobränslen vara antingen lägre eller högre än för inhemskt producerade bränslen.

Att bränsleproduktionssystemen är uthålliga är av stor vikt eftersom det försäkrar en kontinuerlig produktionspotential och kontinuerlig cirkulation av kol mellan växande biomassa och atmosfären som gör att den atmosfäriska koncentrationen av koldioxid inte stiger. Detta gör också att återplantering och uthålligt skogsbruk är mycket viktiga frågor. Enligt granskad litteratur, verkar lagstiftningen för återplantering i Finland och Litauen vara omfattande, medan lagstiftningen i Estland lämnar mer utrymme för tolkning. Information om regelverken i Kanada och Lettland, från vilka Sverige importerar betydande mängder biobränslen idag var begränsad i den granskade litteraturen. Utöver lagstiftning kan dock certifiering av skogsproduktion ses som en garanti för uthållighet och inkluderar dessutom både återplantering och andra aspekter.

### Fortsatt arbete

För det fortsatta arbetet tycker vi att det vore värdefullt att ha livscykelanalyser gjorda för flera bränslen med samma systemavgränsningar. Detta skulle minska osäkerheten vid jämförelsen mellan olika bränslen. Vi tror också att befintliga jämförelser av nationella skogslagstiftningar behöver kompletteras med återstående europeiska länder samt de viktigaste skogsnationerna i världen.

Om man för något syfte behöver ta fram kriterier för biobränslen med låga nettoemissioner av växthusgaser, föreslår vi att så många av berörda parter (myndigheter, industrier, markägare etc.) som möjligt inkluderas i processen med att ta fram kriterierna. Emissioner från bränslekedjorna bör beaktas ur ett livscykelperspektiv och man kan sätta begränsningar för de enskilda delprocesserna i respektive kedja. Dessutom bör man göra jämförelser av nettoemissionernas påverkan på strålningsbalansen genom radiative forcing beräkningar. Sådana beräkningar visar betydelsen av när emissioner äger rum i tiden.

# Summary

The objectives of this study were to investigate to what extent biofuels can be said to be climate neutral. An assessment of greenhouse gas emissions from the production and utilisation chains of a number of solid biofuels were made based on data available in the literature. The data has been used for making radiative forcing calculations. The study also includes a comparison between imported and domestic solid biofuels.

**Results and discussion**

We conclude that none of the investigated biofuel chains are "climate neutral" since all of them result in net emissions of greenhouse gases. However, even though all of the investigated biofuel chains result in net emissions of greenhouse gases, all of the chains result in lower emissions than corresponding emissions from the use of fossil fuels. The emission estimates for the fuel chains varies depending on fuels and on how system boundaries have been set in the different studies.

Figure A summaries the net greenhouse gas emissions from the different production and utilisation chains of the biofuels investigated, and include the corresponding emissions for coal and natural gas.

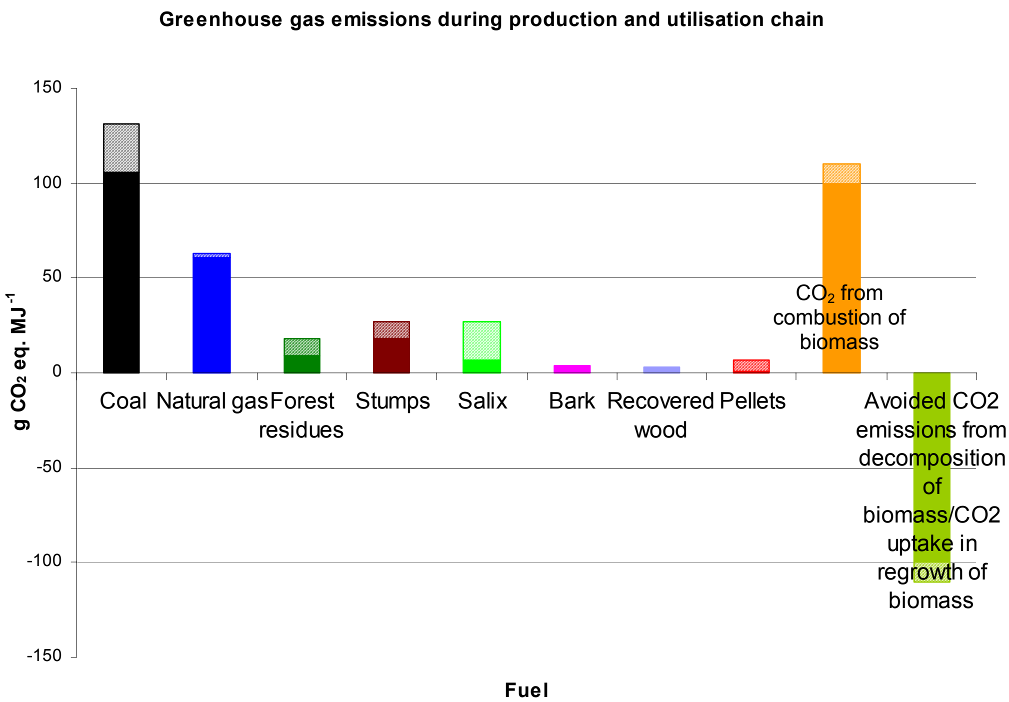



Figure A. Comparison of emissions from fuel production chains based on data from literature (see Table 5.10). The two staples to the right show the $CO_2$ emissions from combustion and decomposition of biomass, which in a longer time perspective can be assumed to be equally large. Dashed parts of staples show the variation range between different production systems of the same fuel. Note that in the biofuel chains the combustion emissions and avoided emissions are not included (these emissions are assumed to equal out over time, but the size of them are shown by the two staples to the right).

The figure shows that there is a difference in net greenhouse gas emissions between different types of biofuels and that there are uncertainties that could be reduced. The following factors can contribute significantly to the total emissions of greenhouse gases of the production and utilisation chain of a biofuel: impact of production system on soil carbon storage, land use-methods (especially use of drained peatlands), the use of fertilisers (both direct and indirect), combustion technology, refining of the fuel (i.e. pelletisation) and storage (especially of comminuted fuels). Other sources that also contribute to the emissions during a production and utilisation chain are; harvesting machines, transportation and waste handling.

Note that in figure A, $CO_2$ emissions from the combustion of biofuels are equalled out by the emissions that would have occurred if the biofuel would have decomposed naturally or by the $CO_2$ uptake in growing biomass. However, the dynamics of the combustion and decomposition/regrowth processes are very different; combustion will occur at once whereas decomposition/re-growth will take years, decades or even longer, depending on the type of biofuel. Hence, saying that combustion and decomposition/regrowth equals each other out means that a certain time perspective is assumed. This time perspective is different for different biofuels.

By radiative forcing calculations based on the greenhouse gas emissions caused by the fuel production and utilisation chain a better estimate of the potential climate impact of the fuels can be obtained.

The climate impacts of the greenhouse gas emissions from one of the biofuels, i.e. forest residues, were compared to the impacts of fossil fuels by the concept of radiative forcing. In the radiative forcing calculations the $CO_2$ emissions from combustion of biofuels and the $CO_2$ emissions that would have occurred if the residues had been left in the forest to decompose were included, and their different dynamics taken into consideration. The results are presented in Figure B. The baseline is represented by a case where the fuels are not used. In the case of coal and natural gas, this means that the coal and the gas is not extracted but left in the earth crust. For the forest residues this means that they are left in the forest to decompose. The decomposition results in $CO_2$ emissions during a long time period and in an amount equalling those that are emitted during combustion. The figure shows that in the long run the forest residue scenario reaches a steady state, at what level depends mainly on the fact that $CO_2$ emissions occur at an earlier stage in the fuel scenario compared to the baseline scenario. Only a minor part is due to the energy input at production (working machines, chipping and transport) and the expected reduction in soil carbon from utilising the residues. This means that biofuels with a short rotation period will result in lower radiative forcing than fuels with a longer rotation period, assuming all other factors equal.

Figure B shows that there is a significant difference between solid biofuels and fossil fuels. The radiative impact from the fossil fuels continues to rise whereas the radiative impact from the biofuels reaches a steady state. What time perspective to apply when assessing the radiative impact due to emissions is not obvious.

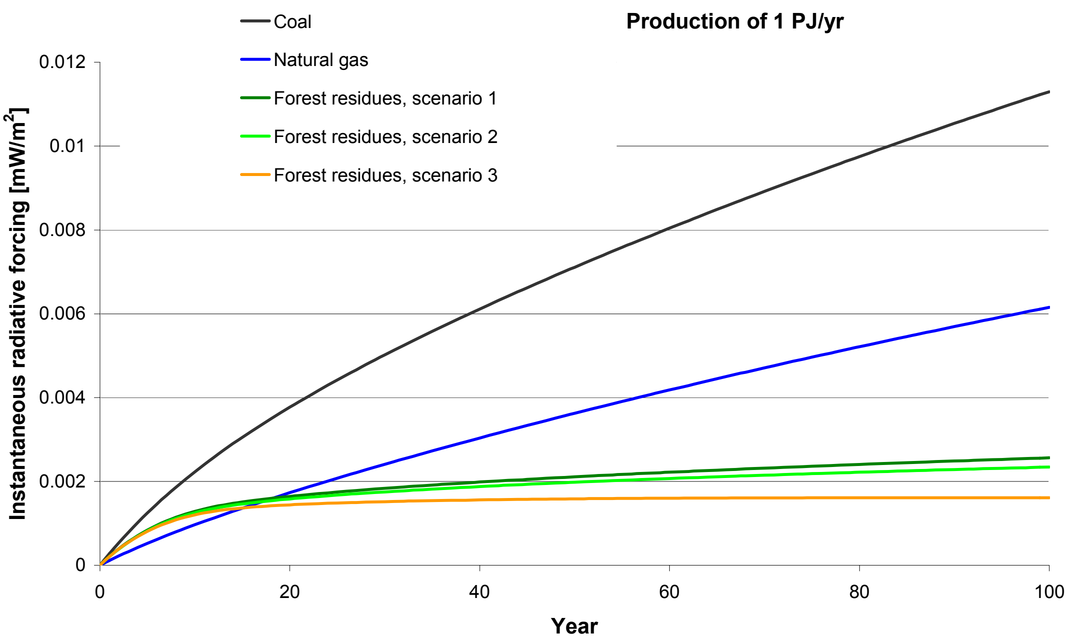



Figure B. Instantaneous radiative forcing from energy production scenarios where 1 PJ of fuel is produced each year. See section 7.1 for further explanation of the different scenarios.

## Lifecycle perspective and system boundaries

In order to estimate the amount of greenhouse gases emitted from a biofuel chain a life cycle analysis is needed, i.e. all greenhouse gas fluxes that are associated with the production, transportation, refining, utilisation and waste handling in the fuel chain should be described and analysed. How system boundaries are set in such a lifecycle assessment are of significant importance. Examples of important boundary definitions are whether the fuel is regarded as a bi-product or not and how soil emissions from the production area should be treated.

Another important system boundary is the time perspective applied. In its fourth report on climate change the IPCC (International Panel on Climate Change) gives no explicit recommendation on what time perspective that should be applied when comparing greenhouse gas emissions by the use of GWP-factors (Global Warming Potentials). Within the Kyoto-framework a 100-year perspective has been chosen. A 100-year perspective will include the thermal inertia of the oceans and their impact on global average temperatures. Carbon cycle models also show that within this time frame a considerable part of an emission of $CO_2$ has left the atmosphere. These facts speak in favour of a long time perspective when comparing different fuel chains. This means that even if the instantaneous impact from the forest residue scenario in figure B is comparable to the natural gas scenario during the first 15-20 years this is of little importance in the longer run.

### Imported biofuels

In this study, net greenhouse gas emissions from imported biofuels have also been analysed. Focus was on emissions related to transports and forest legislation of the exporting countries. Sweden imports biofuels from the Baltic States, Canada, Finland and some other European countries. The imported fuels are usually shipped from the export country to Sweden. The emissions of greenhouse gases from ship transportation are lower per tonne-kilometre than for truck transports. Depending on the distance from the export country, the emissions from transportation of imported fuels can be either lower or higher than for domestic fuels.

Sustainability in fuel production systems is of great importance since that ensures a continuous production potential and a continuous circulation of carbon between growing biomass and the atmosphere, which does not increase the atmospheric concentration of the gas. This makes the question of reforestation and sustainable management important. According to reviewed literature, the reforestation policies in Finland and Lithuania seem to be comprehensive whereas policies in Estonia seem to be more open for interpretation. We have found little information on policies in Canada and Latvia, from which Sweden import significant amounts of biofuels today. Certification is a way to ascertain sustainability of forestry systems, which often includes both reforestation and other aspects.

### Further studies

For further research we think it would be useful to make life cycle analyses of several fuels at the time, setting the same system boundaries, which enable a fully valid comparison and would reduce uncertainties. In addition we think that existing comparisons of national legislation concerning reforestation legislation needs to be amended in future studies with all European countries as well as other important forest nations of the world.

If criteria for biofuels with low net greenhouse gas emissions are found to be needed for a specific purpose we suggest that all parties concerned (authorities, industry, land-owners etc.) are involved in the process of establishing the criteria. Emissions from the fuel chains should be considered from a life-cycle point of view and limits for the different steps of the production and utilisation chain could be set. In addition comparison of the climate impact of the emissions should be done by using radiative forcing calculations. The radiative impact will show the important impact of timing of emissions.

# Abbreviations

C - Carbon

CHP – combined heat and power plant

CN ratio – carbon to nitrogen ratio

CPO – crude palm oil

DH – district heating

GHG – greenhouse gas

GWP – global warming potential

LCA – Life cycle assessment/analysis

LULUCF – Land Use, Land Use Change and Forestry

N – nitrogen

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# 1 Introduction

Biofuels used in heat and power production are not considered to contribute to the increasing $CO_2$ concentrations in the atmosphere. This can be motivated in two ways:

1. the new plants and trees replacing the harvested and burnt biomass will assimilate corresponding amounts of $CO_2$ from the atmosphere as will be emitted during combustion
2. if the biomass was not harvested and burnt, it would anyway die and decompose, and in the decomposition process carbon will be emitted to the atmosphere in corresponding amounts as during combustion.

Carbon dioxide emissions from combustion of biomass are not included in commitments made by industrial countries under the Kyoto Protocol. In the international reporting systems of greenhouse gas emissions submitted by nations to the UNFCCC[2] emissions and uptake of greenhouse gases are reported under a number of different categories and sources. For the sectors Land Use, Land Use Change and Forestry (LULUCF) changes in carbon stocks are reported. Harvested wood belongs to this category and is assumed to oxidize (i.e. to decompose and result in $CO_2$ emissions) in the year of removal (cutting). Of course, this is not what strictly happens but it is a simplification in order not to have to keep track of all the different wood products that the harvested wood will result in (IPCC 2003). This is also the explanation to why emissions of $CO_2$ from the combustion of biomass in heat and electricity production are not accounted for separately (but only reported as memo items); since that would result in double counting. However, we should still remember that production and combustion of biofuels result in emissions of both carbon dioxide and other greenhouse gases.

As the awareness and concern of climate change has become more substantial there is an increased demand for technologies and raw materials with less impact on the greenhouse gas balance. This includes an increased demand for biomass, both for utilisation in heat and electricity production, for production of liquid or gaseous biofuels for transports and for building material etc. As the demand for biomass increases, the interest in intensifying and developing the production systems follows. The amplification of the output from biomass production system might, in the forestry sector, include removal of forest residues from clear fellings (including branches, tops and needles) as well as stump removal; fertilisation of forest stands in order to increase the growth; more intensive forest management; use of new tree species etc. In the agricultural sector it might involve introduction of new crops and cropping systems. All these changes in land-use management can have impacts on the greenhouse gas balances. Especially the soil carbon can be influenced (either positively or negatively) by the management methods. In addition biofuels are less energy intensive than fossil fuels and if the same transport systems are used for the distribution of the biomass (and the refined products) the relative impact of transports will be larger.

[2] UNFCCC = United Nations Framework Convention on Climate Change.

Demand and prices will be important factors to influence what future biofuel systems that will be developed. However, it is important to be aware of the impact on the greenhouse gas balance of the different alternatives for instance when designing policy instruments for greenhouse gas emission reductions, so that production systems with least greenhouse gas emissions are promoted before others.

# 2 Objectives

The objective of the study was to investigate the concept of climate neutrality and its applicability to biofuels. To answer the questions whether there are reasons for not considering all biofuels as climate neutral and if so, what criteria should be fulfilled in order to classify fuels as climate neutral? In addition a comparison of greenhouse gas emissions from the production and utilisation of domestic (i.e. Swedish) and imported biofuels should be made. To define the level of climate neutrality we compare the emissions of greenhouse gases from the production and utilisation chains of different fuels over certain time periods and we also give an example of how the climate impacts of the emissions can be compared by using the concept of radiative forcing.

The objectives of the study were fulfilled by performing the following steps:

1. A literature overview of biofuels and climate neutrality was made. Criteria used when describing climate neutrality and climate neutral fuels in the scientific literature were investigated. In addition, a discussion on the concept of climate neutrality compared to other concepts such as carbon dioxide neutrality and net emissions of greenhouse gases was performed. The study considers carbon dioxide ($CO_2$), nitrous oxide ($N_2O$) and methane ($CH_4$) emissions emitted during the production and utilisation of solid biofuels.

2. The production and utilisation chain of a number of different types of solid biofuels were described. In order to determine the total greenhouse gas emissions from a specific fuel the uptake and emissions during the entire production and utilisation chain was assessed from LCA studies. The production and utilisation chain includes emissions during combustion, storage, processing, transportation and production. During production there are sometimes indirect effects, such as impacts on soil carbon content, that also were considered. The result for each fuel is presented by summarising the emissions by using $GWP_{100}$. In the GWP summarised emission estimates, all emissions except the $CO_2$ emissions from combustion were included since these emissions were assumed to be equally large to $CO_2$ emissions that would have occurred if the biomass had been left to decompose. For one of the fuel chains (forest residues) the radiative forcing caused by the emissions was calculated. In the radiative forcing calculations the $CO_2$ emissions from the combustion were also taken into consideration and compared to a defined reference situation (i.e. decomposition of residues in the forest). This way of comparing the climate impact of emissions from fuel chains also takes into consideration the important time perspective.

   The following fuels were included in this study:

   a. Wood fuel from forest: Forest residues (tops, branches and needles) and stumps

   b. Energy crops produced on arable land: Salix

c. Solid by-product fuels from forest industry: Bark, sawdust and dry chips

d. Residual fuels: Recovered wood fuel

e. Refined fuels: Pellets

f. Fossil fuels: Coal and natural gas

Two fossil fuels (i.e. coal and natural gas) were included as comparison. The reason for choosing these fuels were that coal, which is commonly used within Europe today and resources are expected to last for long, is at the higher end of specific emissions of $CO_2$ of the fossil fuels, whereas natural gas, which is also commonly used in Europe, is at the lower end. Hence choosing these two fossil fuels will more or less show the minimum and maximum limits of the alternative use of fossil fuels.

3. A schematic description of the greenhouse gas emissions of biofuels was made. Emissions and uptake of greenhouse gases during the production and utilisation chain are shown in a schematic picture. The impact of timing of emissions was described by using the concept of radiative forcing.

4. Included is also an overview of international studies on greenhouse gas emissions from traded biofuels and of certification schemes as a tool to determine the sustainability of biofuel production and trade. A comparison between the production chains of domestic and imported biofuels was also made.

5. A description of a possible way to establish criteria for defining how far from or close to being greenhouse gas neutral different biofuels are, was made. Based on the results in the previously described parts a proposal for criteria for biofuels with low impact on the greenhouse gas balance was assessed. In addition areas where further research is needed were pointed out.

# 3 How greenhouse gases impact the radiative balance

The balance between the incoming short-wave solar radiation and the outgoing long-wave planetary radiation determines the temperature of the Earth's surface and lower atmosphere. The solar radiation absorbed by Earth, i.e. by the surface and atmosphere, is balanced at the top of the atmosphere by the outgoing planetary radiation. A change in the net radiation at the tropopause[3] caused by either a change in solar radiation or planetary radiation is defined as radiative forcing and is measured in watts per square meter [$W/m^2$]. There are many different types of radiative forcing agents that can cause changes in the net radiative balance, for instance the atmospheric concentrations of greenhouse gases, aerosols or changes in the planetary albedo[4].

The transparency of the atmosphere to radiation of different wavelengths is determined by the composition of gases and other constituents.

Greenhouse gases have the ability to absorb the outgoing infrared radiation from earth. The chemical characteristics of a gas determine what wavelengths it absorbs, and is specific to each gas. The absorbed radiation is reradiated and this process increases the temperature of the lower layers of the atmosphere.

Another characteristic of the greenhouse gases is their long atmospheric lifetime (>1 year). The longer the atmospheric lifetime, the longer the gas will stay in the atmosphere and impact the radiative balance. The decomposition or uptake in natural systems of greenhouse gases is dependent on many factors. For carbon dioxide it is not possible to determine a single lifetime since it is involved in many different processes with very different turnover times. However, altogether carbon dioxide remains in the atmosphere for at least a hundred years. Methane has an atmospheric lifetime of approximately 8 years, whereas the atmospheric lifetime of nitrous oxide is almost 114 years (Monni et al. 2003).

## 3.1 Global warming potentials

In order to compare the radiative impact of emissions of different greenhouse gases in simple way (without using complicated computer models) a concept called Global Warming Potential (GWP) has been developed. The GWP is the time-integrated contribution to radiative forcing from the instantaneous release of one kg of gas compared to that from one kilogram of carbon dioxide[5]. The mathematical expression is given below (Ramaswamy, 2001).

[3] The tropopause is the boundary layer between the lower part of the atmosphere, know as the troposphere and the overlaying layer called the stratosphere.
[4] The albedo is a measure indicative of a surface's or body's diffuse reflectivity. It is the ratio of reflected to incident electromagnetic radiation power.
[5] or other reference gas

The GWP concept is often used for summarising emissions of different greenhouse gases into $CO_2$ equivalents.

$$GWP_{TH}(x) = \frac{\int_0^{TH} a_x \cdot [x(t)] \cdot dt}{\int_0^{TH} a_{CO_2} \cdot [CO_2(t)] \cdot dt}$$

TH = time horizon over which the calculation is made

$a_x$ = the radiative efficiency [W/m$^2$ kg]

x(t) = the decay of abundance after the instantaneous release of one unit of gas.

## 3.2 Comparison between GWP and radiative forcing

The radiative impact due to emissions from the production and utilisation (combustion) of 1 GJ of coal (during one year) is expressed by $GWP_{20}$ and $GWP_{100}$ in Figure 3.1 and by instantaneous and accumulated radiative forcing over a time period of 140 years in Figure 3.2 and Figure 3.3 respectively. The emission estimates for the production and utilisation of coal are based on the lower estimates according to Holmgren et al. (2006).

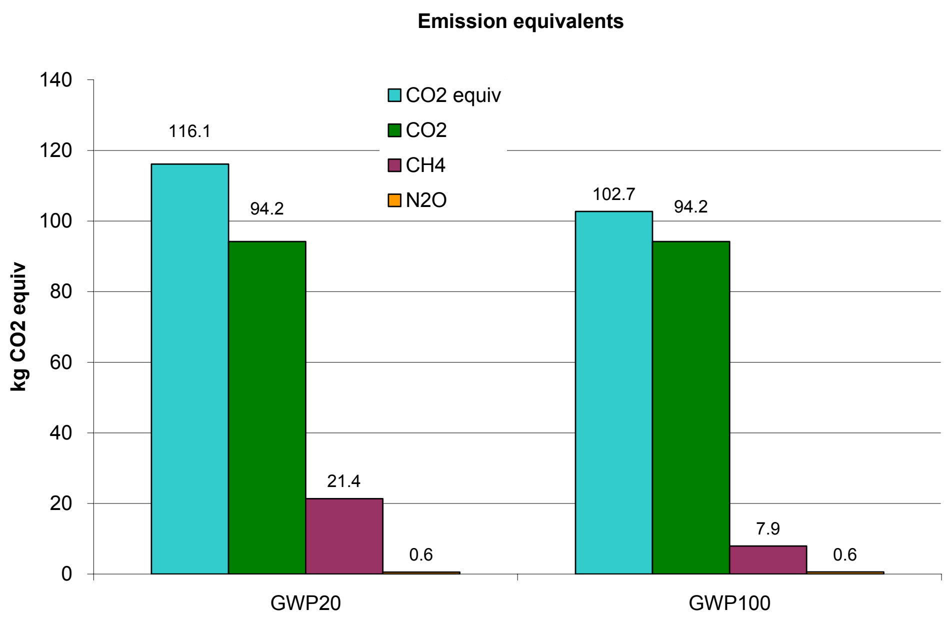


Figure 3.1. Emission equivalents of emissions due to the production and combustion of 1 GJ of coal.

The GWP values used are the ones presented in IPCC 2001 and are given in Table 3.1.

Table 3.1. GWP values according to IPCC 2001.

| | $CH_4$ | $N_2O$ | $CO_2$ |
|---|---|---|---|
| $GWP_{20}$ | 62 | 275 | 1 |
| $GWP_{100}$ | 23 | 296 | 1 |

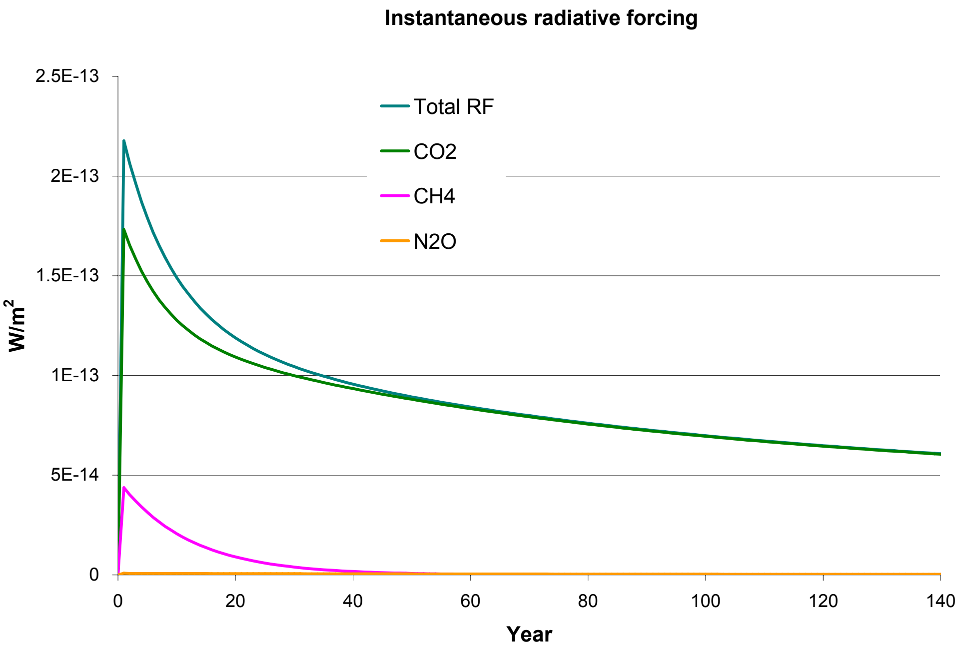


Figure 3.2. Instantaneous radiative forcing due to emissions from the production and utilisation of 1 GJ of coal.

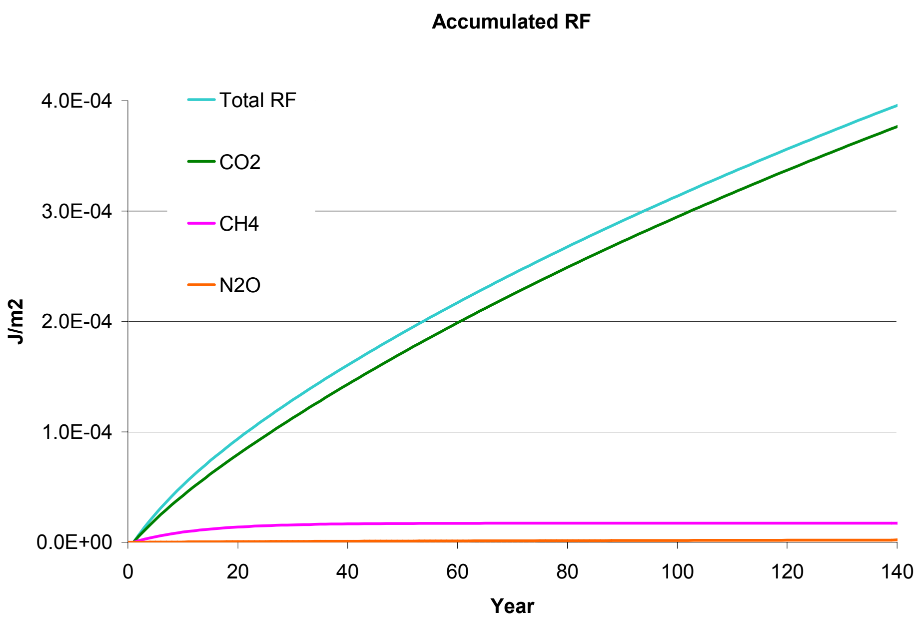


Figure 3.3. Accumulated radiative forcing due to emissions from the production and utilisation of 1 GJ of coal.

# 4 Greenhouse gas emissions from biofuel production and utilisation

In this study the total greenhouse gas emissions of the production and utilisation of a selection of solid biofuels is investigated. An LCA (life cycle analysis) perspective has been applied where all greenhouse gas emissions during the different stages of the production and utilisation chain are included. Similar studies for different fuels have been done before. But the aspects considered vary between the different studies. Schlamadinger et al. (1997) have made a thorough analysis of the advantages in terms of greenhouse gas emissions reductions of replacing fossil fuels by bioenergy systems. They have developed a methodology which considers:

- i) time period and changes of carbon stocks
- ii) reference energy systems
- iii) energy inputs required to produce, process and transport fuels
- iv) mass and energy losses
- v) emissions from construction/dismantling of infrastructure
- vi) distribution systems
- vii) cogeneration systems
- viii) by-products
- ix) waste wood and other biomass waste for energy and reference land-use
- x) reference land use
- xi) other environmental impacts

The system boundaries used by Schlamadinger et al. (1997) include the entire life cycle, also the use of by-products and the avoided reference use of the biomass or the area. The emissions from the production of products substituted by by-products are subtracted from the energy systems. The reference situation describes what happens to the biomass, if it is not used for energy production or what happen on an arable area if no biogenic resources are produced. The energy is produced in some alternative way in the reference system. An alternative to the described choice of reference is to have no heat or electricity production as reference case.

## 4.1 Schematic description of greenhouse gas emissions of fuel chains

By characterising the greenhouse gas emissions from the different stages of the fuel production and utilisation chains it is possible to make a schematic picture. Since there might exist different options for each stage of the production and utilisation chain it is not possible to produce a single general picture for each fuel.

Figure 4.1 is a schematic description of the production and utilisation of forest residues. The figure shows both the reference situation, hence the emissions and uptake that would occur in the case when residues were not used for energy production but let to decompose in the forest, the production and utilisation phase, and the disposal phase. In the reference situation, $CO_2$ emissions would occur due to the decomposition of the material but at the same time uptake will occur due to the new plantation. In the production and utilisation phase emissions of (mainly) $CO_2$ will occur due to the production (working machines), transportation, chipping and storage. During storage, $CH_4$ emissions might be significant compared to $CO_2$ emissions depending on conditions. The combustion results in emissions of all three greenhouse gases, whereas $CO_2$ is assimilated by growing biomass in the reforestation phase. After the combustion the ashes are disposed, which might result in $N_2O$ emissions.

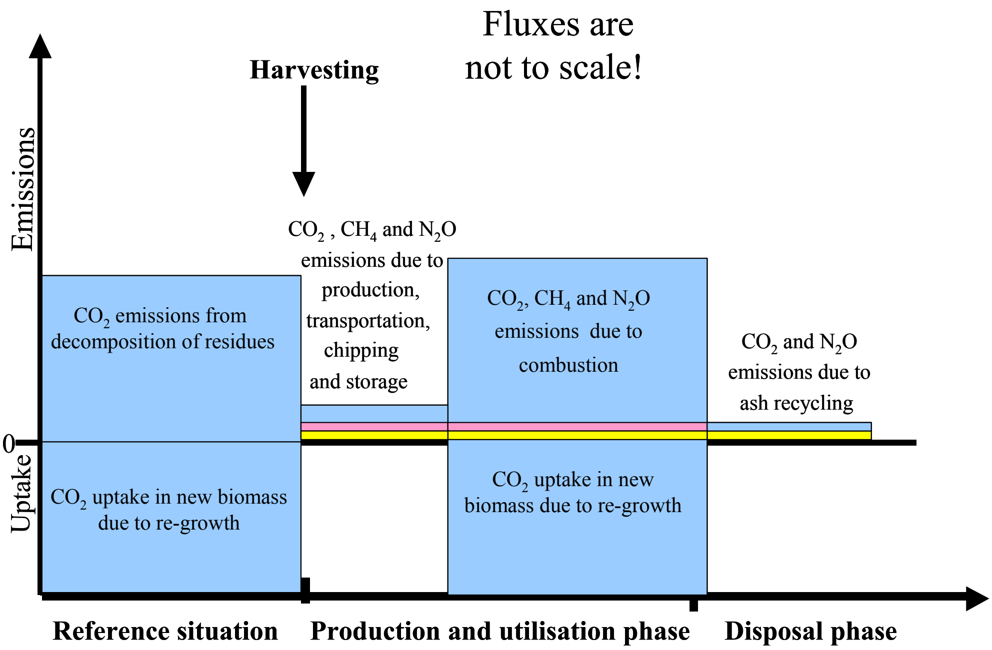


Figure 4.1. Schematic figure of greenhouse gas emissions from the production and utilisation chain of forest residues. Note that fluxes are not to scale and that different production systems might eliminate or enhance some of the gas emissions in the specific stages.

This is a simple figure of the greenhouse impact and the basic data can be reduced into more dense descriptions of the greenhouse impact by using he concept of radiative forcing. In chapter 7.1 such descriptions have been made for forest residues and fossil fuels. The calculations made in chapter 7 are based on a comparison between the reference situation and the production and utilisation + disposal phase described by the equation below. In the calculations the dynamics of the emissions are taken into account. Hence the $CO_2$ emissions due to decomposition of forest residues left in the forest are represented by time dependent functions.

$E_{prod+utilisation}+E_{disp}-E_{ref}$ where

$E_{prod+utilisation}$ = emissions during production and utilisation phase

$E_{disp}$ = emissions during disposal phase

$E_{ref}$ = emissions during reference phase

## 4.2 Impact of the reference situation

The reference situation (i.e. what would happen to the biomass if it was not used for heat and electricity production) is very important. $CO_2$ is assimilated from the atmosphere by growing biomass and released as the biomass is burnt or as it decomposes. Harvest of biomass means an immediate loss of biomass carbon in the forest which in the reference situation (where the biomass would have decomposed) would have taken much longer time. Therefore zero net $CO_2$ emissions from the combustion of biofuels are true only if it is viewed upon over a certain time period. The required length of the time period will differ for different fuels. For straw for instance, the time period is short. If the straw was not removed from the field and burnt in a heating- or CHP-plant, it would be left to decay in the field, hence also resulting in $CO_2$ emissions. The decomposition process will take a few years. On the other hand if considering forest residues or stumps, the time period will be significantly longer. The decomposition of branches and tops will take several years (Eriksson & Hallsby 1992; Ågren & Hyvönen, 2003, Ågren & Hyvönen-Olsson, 2006). For stumps the time of decay is significantly longer (see also section 5.2.3 for estimates of decomposition times). The decomposition of residues if left in the forest and the impacts on emissions is described in more detail in sections 5.2.3 and 5.2.6.

If forests are cleared and replaced by short rotation biofuel plantations[6], the establishment of the production system can have a significant impact on the carbon balance. In temperate or boreal climates such establishments might be associated with significant losses of carbon, whereas losses are not likely in the tropic regions where short rotation forests such as Eucalyptus may hold large amount of carbon and will sequester carbon at a high rate. On the contrary, if biofuel plantations are established at previously sparsely vegetated areas, it may be associated with a significant initial build up of carbon stock, both in the soil and in the standing biomass (Grubb et al. 2001; Azar et al., 2006, Berndes et al., 2006).

## 4.3 Carbon stock in living biomass

If biofuels are produced in systems with continuous reforestation, a closed carbon cycle with no net increase in atmospheric $CO_2$ levels is maintained.

The carbon loss in both the utilisation and the reference case (combustion and decomposition) is only slowly compensated for by uptake in a new forest. This may take up to 100 years in the boreal zone but only 10 years in the tropical zone. In comparison to other fuels this initial loss of carbon stock is in general of minor importance since the loss is limited (the carbon stock in the soil and biomass is limited), whereas the substitution effects (benefits in terms of emission reductions from replacing fossil fuels by biofuels) are unlimited; which means that over time the substitution effects will be the most important. Eriksson et al. (2007) showed that the use of biomass as a substitute for coal and natural gas reduced $CO_2$ emissions far more than would the sink resulting from leaving the residues in the forest.

[6] This is not likely in Sweden today. Usually agricultural land (which is not forested) are used for short rotation energy crops.

## 4.4 Soil carbon stock

When assessing the carbon or $CO_2$ emissions of biofuel systems and their radiative impact, other parts of the production and utilisation chain than the combustion need to be included as well. For biofuels the impact on the carbon stock (both in the soil and in the standing biomass) is important. Some biofuel systems could reduce the soil carbon and some could enhance it.

Production and management of crops affect soil carbon stocks through its impact on litter input and $CO_2$ losses through soil respiration (decomposition of organic matter). The amount of litter supplied is determined by the net ecosystem productivity, type of crop and losses through harvest or disturbances. The respiration rates are dependent on the quality of the biomass and site conditions such as moisture conditions, temperature and nitrogen availability. Interesting for Swedish forestry is that in general, spruce seems to produce more biomass and litter than many other tree species. At the same time the litter has a rather low quality whereby the soil carbon stocks are higher under spruce than under e.g. pine and most of the deciduous species.

Disturbed systems such as drained peatlands or ploughed arable land tend to have enhanced emission rates with decreasing soil carbon stocks as a result. Peatlands needs special attention since management and disturbances not only affect $CO_2$ but also $N_2O$ and $CH_4$ emissions. In forest ecosystems the supply of litter in terms of harvest residues are low in relation to the annual input of litter such as needles or fine roots, hence, removal of residues have a limited impact on soil carbon stocks. On arable land the harvest residues are relatively considered more important for sustaining the soil carbon stock. However, for both forest land and farm land there is a conflict between biomass harvest and soil carbon stocks. The higher the harvest of residues is, the lower the soil carbon stock will be.

Nitrogen has a double impact on soil carbon stocks since it not only increases net ecosystem productivity and hence the litter supplies to the soil, but also reduces long term respiration rates. Nitrogen fertilisation is therefore an effective method to increase biomass harvest and to increase soil carbon stocks.

## 4.5 Importance of timing of emissions

Figure 4.2 illustrate the importance of early reductions of greenhouse gas emissions. The figure shows the difference in actual emissions between different pathways of reaching a specified emission target. Making substantial emissions reductions early, result in less total emissions to the atmosphere. This is quite straight forward to understand whereas it might be less obvious to understand that when in time the emissions are reduced also affects the climate system and the radiative forcing. By looking at the three different emission scenarios in Figure 4.3 where the total amount of emissions is equal, but differently distributed over time, and Figure 4.4 and Figure 4.5 where the instantaneous and accumulated radiative forcing caused by the emission scenarios in Figure 4.3 are shown we can illustrate the importance of when emissions occur.

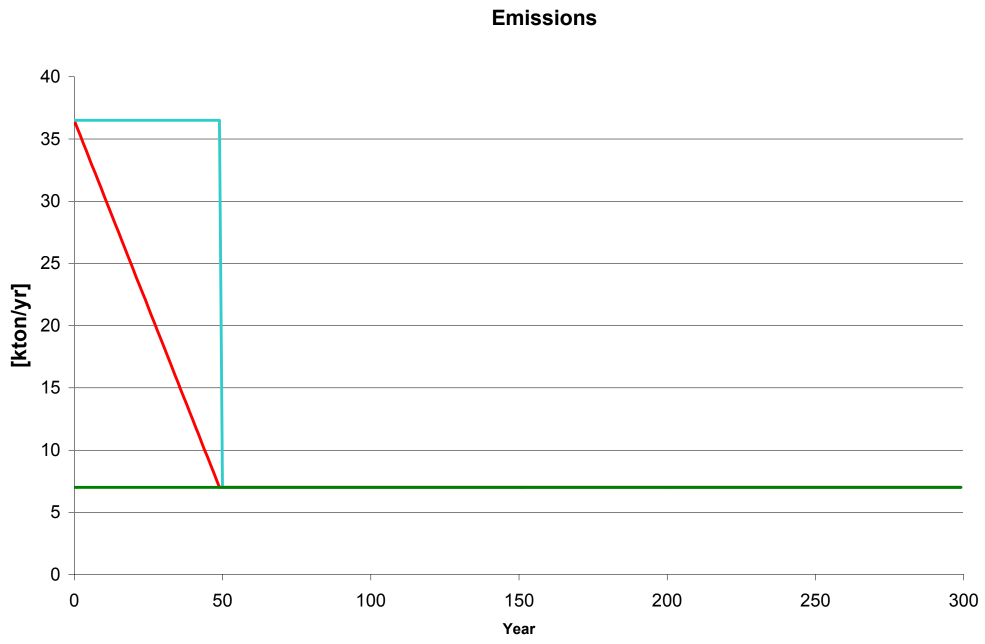


Figure 4.2. Emissions scenarios with same emission reduction target in year 50, but different pathways. The accumulated emissions during the first 50 years differ significantly between the three scenarios (i.e. compare area under curves).

Figure 4.4 shows the expected effect that there is a difference in the instantaneous radiative forcing that eventually will decrease. However, there is a small but persisting difference in the accumulated radiative forcing (Figure 4.5). This is of importance since this is a measure of the impact on the climate system over time.

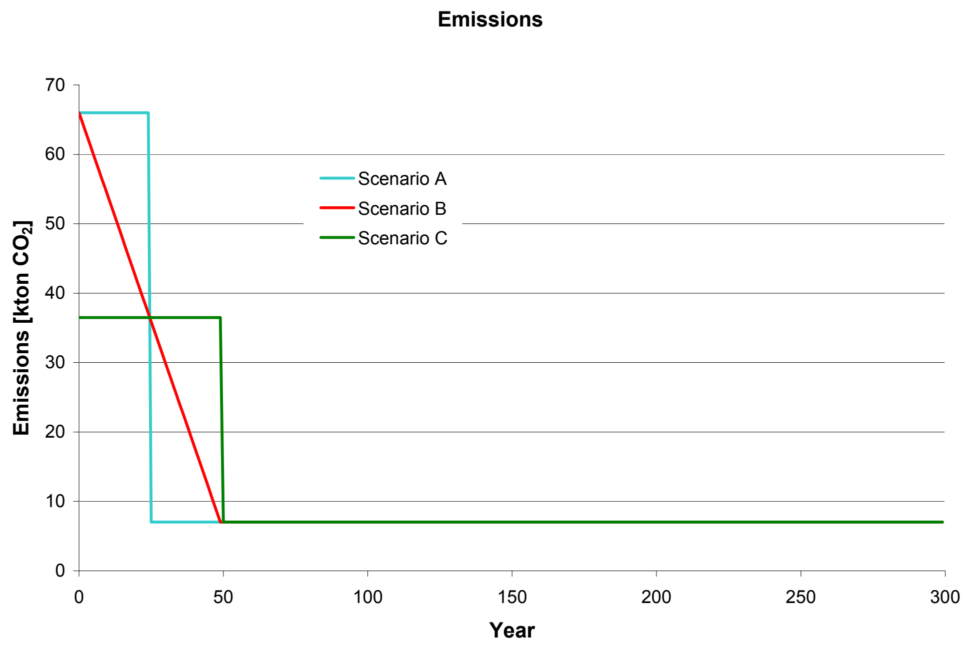


Figure 4.3. Emission scenarios with common emission target in year 50 and equal amounts of total emissions of greenhouse gases during the 50 years but with different distribution in time.

In scenario A the initial emission level is high and the reduction target is met earlier than in the other scenarios. However, reductions are not started until halfway through the period. In scenario B the reductions are carried out evenly distributed during the entire 50-year period whereas in scenario C, which has a lower initial emission level, emission reduction measures are not introduced until very late in the period.

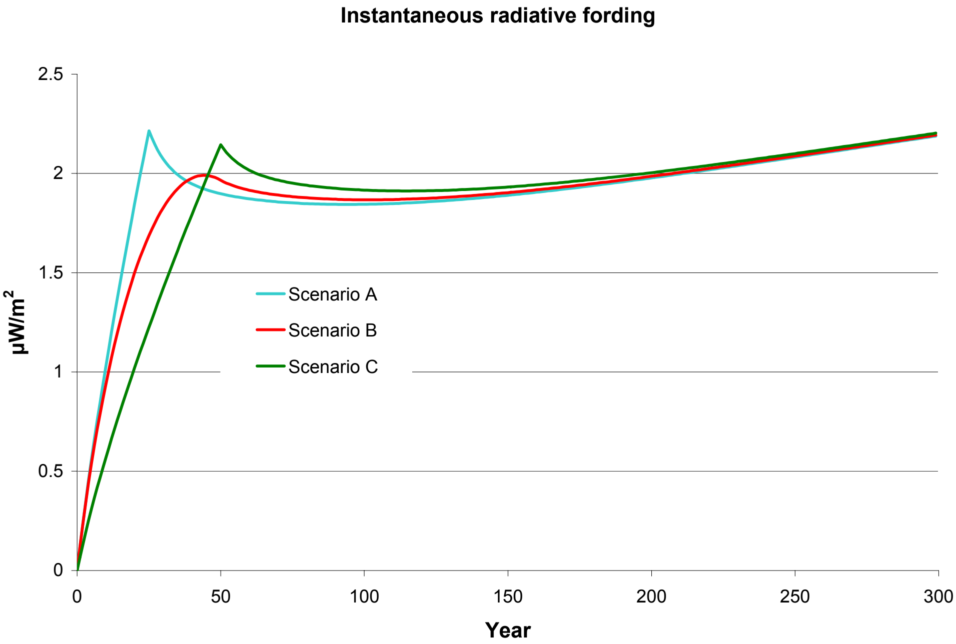


Figure 4.4. Instantaneous radiative forcing caused by the emission scenarios in Figure 4.3.

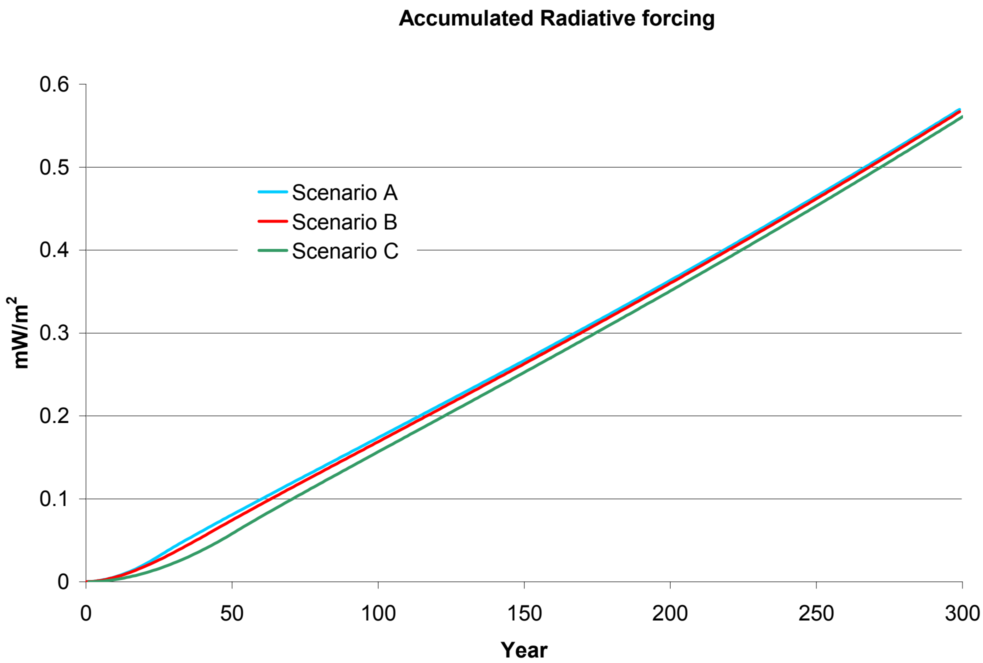


Figure 4.5. Accumulated radiative forcing resulting form the emission scenarios in Figure 4.3.

## 4.6 The concept of climate neutrality

Climate neutrality is a concept used by many despite the lack of an actual general definition. By analysing how the term is used it can be concluded that it refers to activities resulting in no emissions of greenhouse gases or activities where greenhouse gas emissions are compensated for by investments in emission reducing measures elsewhere. For instance a company calls itself climate neutral, either if its activities do not result in any greenhouse gas emissions, or if the greenhouse gas emissions are compensated for by investments in emission reducing projects. Activities do generally not include utilisation of biofuels since they are considered as carbon dioxide neutral, with a combustion emission factor of 0 g $CO_2$/MJ. It should also be noted that the expression "climate neutrality" is mainly used outside the strict scientific sphere. The reason is probably that the subject is rather net emissions of greenhouse gases (as described for climate neutral companies) and that is not the same as no net impact on the climate (as described in the previous section by the importance of timing of emissions).

Human activities result in emissions of greenhouse gases and the atmospheric concentrations of the greenhouse gases increase. This will impact the radiative balance of the lower layers of the atmosphere (see chapter 3 for further explanation), which in turn will impact the temperature. How the response to the changes in the radiative balance and temperature will influence the climate is very uncertain and the climate sensitivity might not be linear, which means that a certain change of the radiative balance today at the current levels of greenhouse gases in the atmosphere might result in a smaller or larger impact on the temperature and climate than a similar change occurring in 50 years when the concentrations have risen further. Similarly, reductions in greenhouse gas concentrations might not result in the corresponding reductions in temperatures. Hence these nonlinearities make it difficult to say anything about climate neutrality over certain time periods.

Another concept used is $CO_2$ neutrality or carbon neutrality, which only takes $CO_2$ emissions or losses of carbon into account. Correspondingly it then means an activity which results in no $CO_2$ emissions or where emissions are compensated for by investments in $CO_2$ reducing measures. Unlike climate neutrality the concept of $CO_2$ neutrality is used in scientific texts (Azar et al. 2006, Grubb et al. 2001).

We believe that for fuels and comparisons of the contribution to the anthropogenic greenhouse effect of the production and utilisation of them, either emission of greenhouse gases expressed in a single term by using GWP-factors or the climate impact of these emissions expressed by radiative forcing, could be used.

## 4.7 Other concepts

There are a lot of concepts evaluating the greenness of fuels. Renewable and sustainable are examples of such concepts. In this report the concept to be evaluated was climate neutrality. We have therefore looked at the greenhouse gas emissions during the production and utilisation of the different fuels and showed how the climate impact of the emissions could be compared by radiative forcing. It is important to note that there are differences between net greenhouse gas emissions and the other concepts.

Renewable means that it is possible to renew but does not include pollution or use of fossil fuels and chemicals. Examples of renewable energy sources are: solar, wind hydropower and biomass etc. Generally some kind of timeframe is set for renewability.

Sustainable means that resources are not exhausted and that the activity does not lead to other significantly negative environmental, social or economic impact. Hence biofuel produced in a way where re-growth is not applied is not sustainable. On the contrary one could claim that the use of energy peat (which is classified in its own category by IPCC; not being a fossil fuel and not a biomass fuel) is sustainable on a national level if the harvest of peat does not exceed the estimated re-growth.

If defining greenhouse gas neutral as the net emissions of greenhouse gases of the fuel production and utilisation chain being zero, a timeframe needs to be defined. Again energy peat is an interesting example where the use of peat from a pristine mire, that if not harvested would continue to sequester carbon, will not be greenhouse gas neutral[7], whereas a drained peatland, slowly decomposing and resulting in $CO_2$ emissions also in the case of no harvest (and potentially also $N_2O$ emissions), theoretically could be greenhouse gas neutral in a very long time perspective.

### 4.7.1 Sustainability of biomass utilisation in the Netherlands

In the Netherlands the government has taken the initiative to develop a tool of transition management in order to increase the use of biomass for energy, transport and chemistry (Bergsma et al. 2005)

The following three issues are considered the most important for the sustainability of biomass utilisation:

1. The greenhouse gas emissions over the entire biomass chain; including cultivation, carbon effects in the soil and the effects on the other markets which also use biomass
2. The acid and toxic emissions from conversion of biomass to bio-products like electricity
3. The socio-economic effects and biodiversity effects of import of biomass from developing countries

Calculation methods which can be used to calculate net greenhouse gas profits for all bio-products have been developed. The methods are used in the judgment of government support for projects. The calculation methods follow standard LCA (Life Cycle Assessment) rules and agreements as basic methodology. The effects considered in the guidelines are;

- impacts on the soil (carbon stock etc.)
- impacts on the biomass supply market (i.e. using raw material for livestock farming to achieve energy targets can result in additional use of fertilizer within the livestock farming sector)
- allocation of $CO_2$ emissions from processes where several products are produced

[7] Unless the pristine area is a significant source of methane and a very long time period (> 500 years) is considered.

- references for electricity generation and diesel/petrol statistics for today 2020 and 2040
- standard data for $N_2O$ emissions from agriculture and forestry
- standard data from IPCC concerning soil impacts

It is specifically pointed out that even if the primary focus is to increase the utilisation of renewable energy also other emissions are important from a sustainability point of view (Bergsma et al. 2005).

The Dutch government has also appointed a commission to develop sustainability criteria for biofuels. The criteria covered six themes, among these the greenhouse balance of the production and processing chains. The commission came up with a long list of recommendations for criteria which have to be met for a biomass system to be considered sustainable. For greenhouse gases, the suggested criteria for the year 2007 are that if biomass is used to replace fossil fuels, it has to reduce the net emissions of the total production chain by 30%. In 2011, this criterion is to be sharpened to 50%. (Cramer et al., 2006).

## 4.8 The accounting of greenhouse gas emissions from biofuel systems

The carbon dioxide emissions from the combustion of biofuels and the possible impact on carbon stocks in soil and living biomass as well as other emissions of greenhouse gases associated with the production and transport of biofuels are not accounted for within the same category in the current international reporting system for greenhouse gas emissions. Only the emissions of methane and nitrous oxide resulting from the combustion of biofuels are accounted for under combustion. However, there are important reasons for these differences in accounting. Net carbon emissions from the biosphere differ from fossil fuel based emissions in three ways:

1. a large proportion of biospheric carbon exchange is not under direct human control
2. land-use decisions often have only small short-term effect on net emissions, but a large long-term effect
3. biospheric carbon exchange is potentially reversible.

Because of these differences carbon accounting also needs to be different for fossil fuel and biosphere based emissions. (Kirschbaum & Cowie, 2004).

## 4.9 Discussion and suggestion of criteria for grading biofuels according to greenhouse gas emissions

Different accounting systems for emissions from biofuel systems described in the previous section make it difficult to make comparisons between different types of biofuels and other fuels. However, it is still interesting to have a comparative measure to rank fuels depending on the amount of greenhouse gas emissions from its production and utilisation chain.

The duration from combustion of biomass until the $CO_2$ emissions have been compensated for by uptake will vary for different types of biofuels and climatic zones. It will be shorter for agricultural crops than for forest crops and for southern sites and fertile soils than for northern sites with low production rate. In forestry it may vary between tree species[8].

There are clear indications that the majority of production and utilisation chains of solid biofuels are not $CO_2$ neutral. Even if the $CO_2$ emitted during combustion is compensated for by re-growth of biomass, there are many parts of the production chain that are associated with emissions of greenhouse gases. Thus, the concept of $CO_2$ neutrality is not well suited for categorizing biofuels according to climate impact. We suggest that the concept net greenhouse gas emissions, expressed as $CO_2$-eq. $MJ^{-1}$ is used instead. In addition we think that it is important to remember that the timeframes in a comparison is very important and it should always be mentioned what time period that has been considered in a comparative study. A good way of comparing the greenhouse impact of the emissions from different fuel chains is to use the radiative forcing concept (see chapters 3 and 7) of the full life cycle of the fuel. This will give a dynamic picture and the impact of different time perspectives can be seen.

Finally we also think that it is very important to consider the renewability and sustainability of the biofuel systems. Reforestation and sustainable land use is very important.

[8] for instance spruce has a shorter rotation and faster growth than pine.

# 5 Biofuels – description of supply chain systems for selected fuels

## 5.1 System boundaries

LCA (Life Cycle Assessment) is a tool for evaluating the environmental impact of a product or process (including its production, usage, and disposal) over the whole course of its life or duration. The results from an LCA can be used in several ways, for example to identify environmental impacts of a product or a process (Lindholm, 2006). In an LCA, emissions of several substances are included (e.g. CO, HC, $NO_x$, $N_2O$, $CO_2$, $CH_4$) but in this report we have only included the most important greenhouse gases (i.e. $CO_2$, $N_2O$ and $CH_4$). LCA, or LCI (Life Cycle Inventory), have previously been used to evaluate environmental impacts of solid biofuels (e.g. Brännström-Norberg & Dethlefsen, 1997; Forsberg, 1999, Karlopoulos et al. 2005; Börjesson, 2006; Petersen Raymer, 2006).

The selection of system boundaries is essential in an LCA, since only processes within the boundaries are considered. Hence by defining the system boundaries the performer of the LCA decides what processes and activities that are included in the study. Therefore, in a comparison between solid biofuels and their emissions of greenhouse gases, it is important to highlight how the system boundary for each biofuel system was chosen and which processes that are included, and how changes of boundary systems may affect the result of the study. Due to the complexity of the LCA and the level of aggregation in the presentation of results it is often difficult to compare the results of different LCA studies of the same product or process, even if the system boundaries are well defined. For example in the report by Brännström-Norberg & Dethlefsen (1997), ammonia is used both in fertilizer production and to reduce $NO_x$ emissions during combustion. However, the resource ammonia is not separated between these two processes, which makes it difficult to compare with other studies where reduction of $NO_x$ or fertilizer production is not included.

Another dilemma is the processes included. Often it is clear what to include, but sometimes it is not obvious. For example, should harvesting of trees be included in an LCA of bark (by-product from sawmills and pulp mills) (e.g. Petersen Raymer, 2006)? How should the use of electricity in pellets production be treated? Electricity causes no emissions within the system boundary and therefore several LCAs treat the use of electricity as no impact (i.e. zero emissions) (e.g. Forsberg, 1999). However, it is important to know how the electricity was generated (hydro power, nuclear power, wind power, biofuels, coal, natural gas, etc), since it could affect the results considerably.

Another aspect which makes it difficult to compare solid biofuels and their emissions of greenhouse gases is that several solid biofuels in Sweden are by-products from the forest industry (i.e. logging residues, bark, sawdust, black liquors, raw material for pellets production, recovered wood, etc.). Energy crops, on the other hand, are examples of solid biofuels that are grown only for the purpose of energy generation. This means that solid biofuels that origin from the forest industry has an advantage in a comparison with energy crops since usually no emissions associated with the forestry (plantation, management, cutting etc.) are allocated to the biofuels. In a way this could be considered to be justified, since there is a simultaneous production of other products. However, if energy forests are established on former arable land as Anon. (2006a) recommended, the whole effect would probably be allocated to the solid biofuel since it would be the main product.

An interesting question arises if pulp wood would be used as fuel in heat plants instead of raw material in pulp mills, or if stumps and harvest residues in the future would be regarded as main products and thereby as an incentive for more intensive forestry or changes in land use. This would logically mean that emissions associated with all forest measures should be accounted for in the biofuel chain. Thus, emissions associated with forest regeneration, thinning, N-fertilisation and harvest should be included, as well as emissions of $CO_2$ and $N_2O$ from the soil (which could be significant in for instance drained peatlands). If the emissions occurring prior to the harvest of residues should be included there is a need for a logical way of allocating emissions between the main product such as roundwood and the by-products such as harvest residues. Such a way could be to allocate in relation to the economic value of the products.

An additional problem of the choice of system boundaries is that removal of residues from forest ecosystems under certain conditions may reduce future biomass production, mainly due to loss of nitrogen from the system (Egnell et al. 1998). This is particularly the case if needles are removed. This could be accounted for in different ways in the LCA. One solution is to assume that N levels should be kept at an unchanged level and, thus, that compensating nitrogen has to be added. The emissions associated with N application should then be included in the LCA. However, under certain conditions, in particular fertile soils in south-western Sweden the soil N availability is so high that it may cause $N_2O$ emissions. Loss of N through harvest would under such conditions reduce emissions of greenhouse gases. Likewise, the removal of biomass may necessitate wood ash recycling to the forest soils. Emissions associated with wood ash recycling should be included in a complete LCA.

The standpoint we chose in this study was to include only emissions related to the period after the point of decision to remove residues from the forests. Thus, emissions associated with forest establishment, N fertilization and logging operations etc. are excluded. This means in most cases an underestimation of emissions of greenhouse gases. However, in most cases the underestimation is very low since the economic value of harvest residues is low compared to timber and the total emissions from these sources are comparably low. But in the case of forest production on peatland the underestimation might be more significant since those systems may have generated a substantial amount of greenhouse gases from decomposing peat and temporarily formation of $N_2O$.

## 5.2 Wood fuels from the forest

During the past 20 years, most of the energy wood from the forest has been produced by using residues (i.e. branches and tops) from final felling operations. Another wood fuel production system is the tree-section system in pre-commercial or early thinning operations. However, tree-section systems are not very common in Sweden today, due to the roundwood supply system in the forest industry (Lönner et al. 1998; Parikka, 2003), and will not be described in this report. Energy wood from the forest can also be produced by removing stumps from the clear felled area. This is a more energy-intense operation compared to the above-mentioned systems, but could give considerable amounts of wood fuel. Pulp wood from thinnings or final fellings could be used as fuel, but will not be discussed in this report.

### 5.2.1 Production and utilization chains of logging residues

In commercial operations of forest residues, there are mainly three energy wood supply chains: 1) Wood chips from logging residues; 2) Loose logging residues; and 3) Bundles from logging residues (Madlener & Parikka, 2005). The systems are mainly separated by the way the energy wood is transported to the end use facility. The basic operations for each system are presented in Figure 5.1.

If logging residues are to be used for energy purposes, the harvester should pile the residues along the strip roads instead of directly in front of the machine for protection of the ground layer (Ranta, 2002). The residues are then forwarded to roadside, either simultaneously with roundwood or through a separate operation. The same forwarder can be used for logging residues and roundwood but forwarding residues and roundwood in mixed loads are not profitable (Alakangas et al. 1999). Instead of forwarding the residues or chipping at site, the logging residues could be bundled into cylindrical bundles using a bundling machine (Lönner et al. 1998). The bundling method could be divided into three phases (Ranta, 2002). First, logging residues are pressed by feeder rolls and then the compacting continues in a rectangular presser. Finally, the compacted bundles of residues are roped and cut into the desired length with a chainsaw. The normal length of the bundles is 3.2 m and the diameter is about 700 mm. The weight of the bundles is 450–550 kg per unit (Ranta 2002). An advantage of bundling systems is that the same handling and administrative routines can be used as in conventional roundwood logging (Lönner et al. 1998; Ranta 2002).

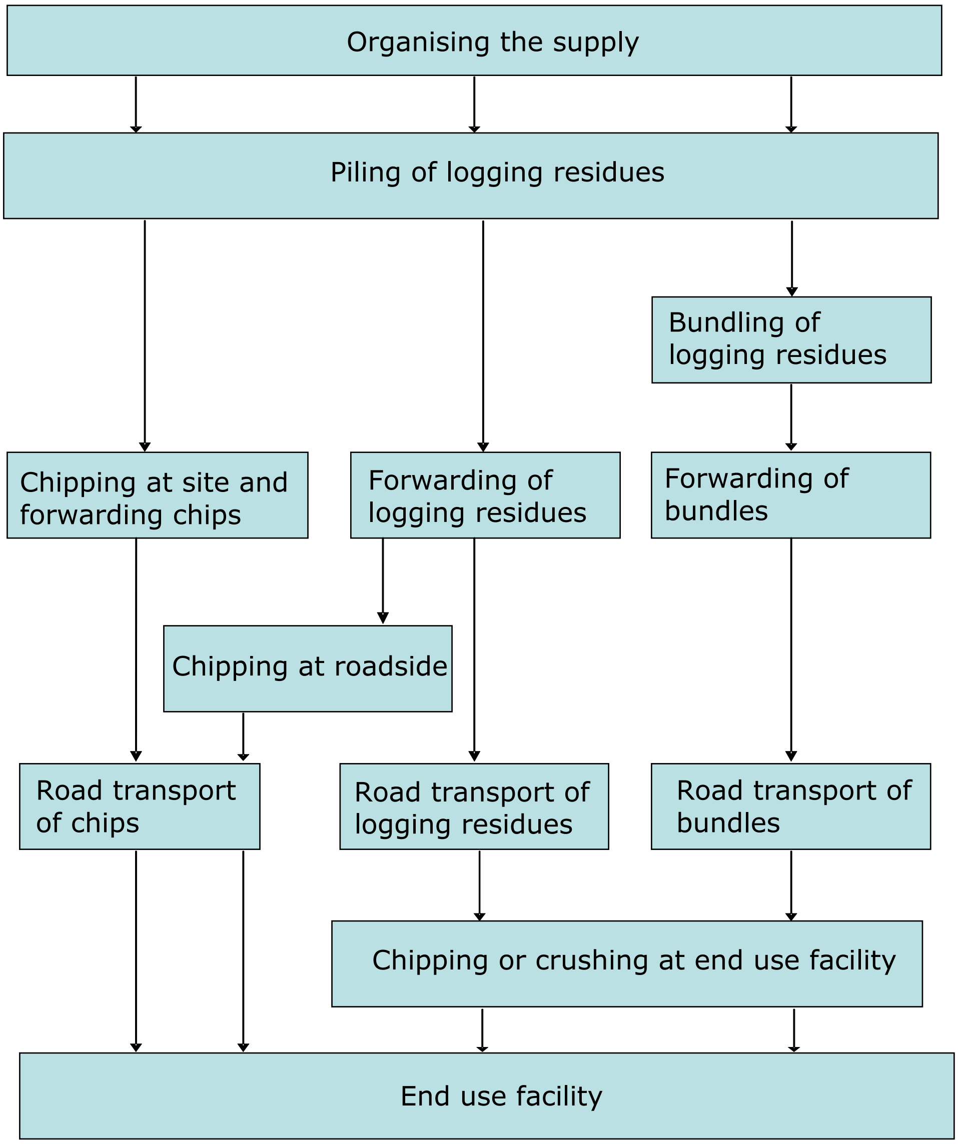


Figure 5.1**.** Basic operations for energy wood production chains. Data adapted from Ranta (2002) and Madlener & Parikka (2005).

Chipping and crushing of residues can be conducted at site, on roadside, or at terminals or utility sites. Roadside chipping method is widely used in Sweden and Finland (Lönner et al. 1998; Ranta 2002) but chipping at site could be an alternative method (Parikka, 2003). Crushers are often heavy and powerful units and are therefore usually found in terminals or at utility sites as semi-mobile or fixed installations (Lönner et al. 1998).

Storing is an important part of the wood fuel supply chain, because it secures the availability of fuel during the whole year and even possibly improves the fuel quality. When planning for storage the following aspects are included: storing time, storage location, scheduling of storing, and the form in which the material is stored (Madlener & Parikka, 2005). Storage could improve the fuel quality since the material could be dried and the calorific heat value could increase. However, some loss of substance may occur during the storage period because of the green particles (i.e. needles) in the residue material (Jirjis 1995, Lehtikangas & Jirjis 1998) will fall off. Therefore, the logging residues should be placed on heaps after the trees have been felled. Then, the material dries and much of the needles fall to the ground, which will result in nutrient recovery to the forest soil (Egnell et al. 1998). However, it is not possible to remove residues and leave all needles on the site. In biomass resource estimations, it is often assumed that 25% of the needles and 75% of the branches and tops are removed in logging residue operations.

Finally, bundles, logging residues, or wood chips are transported by trucks from roadside to intermediate storage site or to a utility facility, such as a heat plant or a combined heat and power plant. The transport efficiency depends on factors such as the shape of material (comminuted or uncomminuted), solid volume, moisture content of the material, transport distances, and the vehicle used (Madlener & Parikka, 2005).

### 5.2.2 Emissions from collecting, chipping and transporting residues

There are several studies dealing with emissions of greenhouse gases due to collecting, chipping and transportation of logging residues (Table 5.1). However, the system boundaries and the units differ between the references. Therefore, both the reference value and our estimates (g $CO_2$-eq. $MJ^{-1}$) are presented in Table 5.1. The assessment shows that most of the references have estimates of the emissions for collecting, chipping and transporting residues that range between 1.2 to 3.2 g $CO_2$-eq. $MJ^{-1}$. The differences are due to different supply chain systems.

Table 5.1 Greenhouse gas emissions due to collecting, chipping and transporting of logging residues.

| Reference | Reference´s value | Authors' conversons g $CO_2$-eq. $MJ^{-1}$ |
|---|---|---|
| Lundborg (1994) | 19 kg $CO_2$ $MWh^{-1}$ | 5.3[a] |
| Börjesson & Gustavsson (1996) | 0.85 kg C $GJ^{-1}$ | 3.1 |
| Brännström-Norberg & Dethlefsen (1997) | 11.7 g $CO_2$-eq. $kWh^{-1}$ | 3.2[b] |
| Forsberg (1999) | 17 kg $CO_2$-eq. $MWh_{electricity}^{-1}$ | 2.0[c,d] |
| Börjesson (2000) | 1.0 kg C $GJ^{-1}$ | 3.7[e] |
| Wihersaari (2005a) | 4.3-7.5 kg $CO_2$-eq. $MJ_{chip}^{-1}$ | 1.2-2.1[f] |
| Näslund & Gustavsson (2007) | 1.5-2.7 kg C $MWh^{-1}$ | 1.5-2.7[f] |

[a] Includes decreased forest yield due to removal of residues.
[b] 1/3 electricity and 2/3 heat is produced.
[c] 1 $MWh_{electricity}$ = 0.865 $tonne_{wood\ fuel}$ and heating value was assumed to be 9800 MJ $tonne_{wood\ fuel}^{-1}$ (moisture content = 45%) (Forsberg, 1999)
[d] Baling system.
[e] Includes emissions from harvest and transport of residues, and spreading of wood ash.
[f] The range is due to different production chains.

### 5.2.3 Impact of residue removal on soil emissions

The removal of logging residues from the forest site results in a reduction of the input of carbon to the soil, which induces a lower soil carbon stock. When residues are removed, the stock of carbon will generally be lower than in a reference situation where residues are not removed. As a consequence, the decrease in the carbon stock can be considered as indirect emissions. However, residues are only successively decomposed during hundreds of years and after a certain period of time the major part of the residues are lost as $CO_2$ to the atmosphere. Hence, the time perspective is an important factor for determining the indirect soil emissions.

It should be stressed that according to the Kyoto protocol and IPCC Good Practice Guidance (GPG) the residues would not initially be categorized as soil carbon but as litter or dead wood. However, this fact has no relevance for carbon stock reporting since all carbon stocks should be reported.

The difference in $CO_2$ emissions between an utilisation (combustion) case and the reference case (decomposition) is largest directly after combustion, since that is a simultaneous effect whereas the decomposition will occur over a long time period. The decomposition rate of the residues declines exponentially over time. Initially the decomposition is very fast, but after ca. 100 years it is almost zero. A certain fraction, around 5%, can be considered as stable and forms the humus pool in the soil. The decomposition rate varies between different residue types with a high rate for needle litter, lower for branches and still lower for stumps and coarse roots. As an example, after a period of 10 years; 16%, 47% and 85% of added needles, branches and stumps, respectively, remain at a mean annual temperature of 5°C (calculated after Ågren et al., 2007). After a period of 75 years, the remaining parts are only 2, 4 and 6%, respectively. Removal of stumps therefore results in more long lasting indirect emissions than removal of needles. Also site conditions may have an impact. Thus, at mean annual temperature of 7°C 14% of stumps carbon remains after 50 years. Corresponding value at 2°C is 20%. Also atmospheric N deposition and N fertilisation may have an impact on decomposition rates by reducing them, which increases the soil carbon stock at such sites. This also means that indirect emissions of carbon after removal of forest residues in fertilised forests might be larger.

Wihersaari (2005a) showed that if the achieved energy from logging residues was 486-540 GJ $ha^{-1}$ the indirect emissions of $CO_2$ from decreasing the soil carbon stock would be 11-13 g $CO_2$-equivalents $MJ^{-1}$. Ågren & Hyvönen (2003) reported that removal of all residues in Sweden would decrease the soil carbon stock by 59 Tg C after 150 years (i.e. 0.4 Tg C $year^{-1}$) (Table 5.2) compared with a reference scenario where residues are left on site, but losses of soil carbon would be compensated by extraction of harvesting residues of 11 Tg C $year^{-1}$ and using them to replace fossil fuels. This amount of logging residues corresponds to an energy content of 100-110 TWh $year^{-1}$ (depending on moisture content) and results in emissions of $CO_2$ from a decreasing soil carbon stock of 3.5-4 g $CO_2$ $MJ^{-1}$ (Table 5.2).

Table 5.2 Expected decrease in the build-up of soil carbon stock due to removal of logging residues.

| Reference | Simulation length (years) | Decrease in build-up of soil carbon stock | |
|---|---|---|---|
| | | Reference´s value | Authors' estimates |
| Ågren & Hyvönen (2003)[a] | 150 | 17 kg C $ha^{-1}$ $yr^{-1}$ [b] | 3.5-4 g $CO_2$ $MJ^{-1}$ |
| Wihersaari (2005b) | 100 | 17 kg C $ha^{-1}$ $yr^{-1}$ | 11-13 $CO_2$ $MJ^{-1}$ |
| Eriksson et al. (2007)[c] | 300 | 23 kg C $ha^{-1}$ $yr^{-1}$ | 7-8 g $CO_2$ $MJ^{-1}$ |
| Ågren et al. (2007) [d] | 75 | 26-32 kg C $ha^{-1}$ $yr^{-1}$ [e] | ?? |

[a] All residues from spruce and pine stands were removed in a simulation on national level.
[b] The forest land was expected to be 23 x $10^6$ ha.
[c] 75% of the branches and tops, and 25% of the needles were removed from thinnings and final felling from a simulation in a spruce stand.
[d] The decrease in soil carbon stock is calculated by using the results from Ågren et al. (2007) and Eriksson et al. (2007).
[e] For pine and spruce, respectively.

According to a study by Eriksson et al. (2007), removal of residues results in a lower build-up of soil organic carbon stock by 23 kg C $ha^{-1}$ $year^{-1}$ compared to a reference scenario where residues are left on site while the reduction of $CO_2$ increased by 300 kg C $ha^{-1}$ $year^{-1}$ if residues were used to replace coal. Assuming that the energy achieved during a period of 300 years would be 900-1000 MWh (depending on moisture content), a decrease in soil carbon stock would be 7-8 g $CO_2$ $MJ^{-1}$ (Table 5.2). The reference values of the decrease on the build-up soil carbon stock in Table 5.2 are similar, while our conversions (g $CO_2$ $MJ^{-1}$) differ between the references. This is because different amount of achieved energy from logging residues was assumed.

According to Ågren et al. (2007), annual removal of all needles, branches and tops in Swedish forests would after 75 years correspond to a loss in built up carbon of in average 7560 kg C $ha^{-1}$ in spruce forests and 4980 kg C $ha^{-1}$ in pine forests compared with a scenario where residues are left on site. However, in reality only about 50% of the total branch production during one rotation will be harvested whereas the rest will be recycled within the forest as litter (calculated from Eriksson et al. 2007). Of needles, only 2–3% is removed from the stand through the harvest of residues (calculated from Eriksson et al. 2007). Based on these figures it can be estimated that the loss of soil carbon over a 75 year period is, on average, 2430 and 1980 kg C $ha^{-1}$, respectively, for spruce and pine. This is equivalent to 32 and 26 kg C $ha^{-1}$ $year^{-1}$ for spruce and pine, respectively (Table 5.2). It should be noticed that these values are cumulative values assuming that residues are removed annually in Swedish forests.

Over a period of several hundreds of years the removal of litter should lead to a new steady state situation of soil carbon stocks in the soil. Ågren et al. (2007) estimated that the origin of soil carbon in a Swedish average spruce forest was 27% needles, 23% branches, 13% stumps and 3% tops. In an average pine forest was 21% needles, 27% branches, 19% stumps and 5% tops. Assuming (as above) that only 50% of branch production and 2-3% of needle production is harvested as residues, and that the average soil carbon stock is around 80 000 kg C $ha^{-1}$, the removal of needles, branches and tops would after several 100 years decrease the soil carbon stock by roughly 12 000 kg C $ha^{-1}$ and 15 000 kg C $ha^{-1}$ for spruce and pine, respectively. Corresponding values for stumps are 10 000 and 15 000 kg C $ha^{-1}$.

Leaving the needles has an almost negligible impact on the carbon balance since the needle biomass removed at logging operations is only a small fraction of the total amount of needles produced during a rotation period (Ågren & Hyvönen, 2003). According to Egnell et al. (1998), removal of residues will not affect the carbon stock in soil and the increment of the trees permanently as long as the needles are left on site, while Lilliesköld & Nilsson (1997) argued that removal of foliage and fine branches, which result in reduced yield, could deplete the carbon stock in soil.

### 5.2.4 Emissions of greenhouse gases from the supply chain system

The emissions from the decrease in soil carbon stock and due to collecting, chipping and transportation of residues should be compared to the other direct and indirect emissions from utilisation of residues as biofuel. In Table 5.3, the emissions of greenhouse gases from harvesting residues are presented. It should be noted that Wihersaari (2005a) used $GWP_{100}$, while

Brännström-Norberg & Dethlefsen (1997) used $GWP_{20}$ (Table 5.3). Wihersaari (2005a) concluded that the energy input is 2-3% of the energy in the produced biofuel.

Table 5.3. Greenhouse gas emissions (g CO2-equivalents MJ-1) from logging residues due to production and utilisation. Note that $CO_2$ emissions from combustion are not included.

| Emission source | Wihersaari (2005a) | Brännström-Norberg & Dethlefsen (1997) |
|---|---|---|
| Collecting, chipping and transporting | 1.2-2.1 | 3.2 |
| Combustion of biofuel in heat plant | 0.6[a] | 1.5[b] |
| Production of ammonia for $NO_x$-cleaning in CHP[c] | - | 0.4 |
| N fertilisation | 1.9[a, d] | - |
| Ash recycling | 0.05 | 0.01 |
| Decrease of soil carbon | 11.1-12.5 | - |
| SUM | 15-17 | 5.1 |

[a] $GWP_{100}$ for $N_2O$ = 296 and for $CH_4$ = 23.
[b] $GWP_{20}$ for $N_2O$ = 280 and for $CH_4$ = 56.
[c] CHP = Combined heat and power plant.
[d] Greenhouse gas emissions from N fertilisation due to compensation of N losses.

The emissions of greenhouse gases were three times larger in the report by Wihersaari (2005b) compared to the report by Brännström-Norberg & Dethlefsen (1997). The main differences between the studies were that Wihersaari (2005a) included two emission sources (i.e. decrease in soil carbon stock and emissions from N fertilisation) which were not included in the report by Brännström-Norberg & Dethlefsen (1997). On the other hand, the latter included emissions due to $NO_x$-cleaning in the CHP. However, this emission source is low compared to the decrease in soil carbon stock. According to recommendations by Egnell et al. (1998) applying fertilizer in order to compensate for N losses is not necessary if residues are removed only once per rotation. However, if the competition of woody biomass increases and residues are removed several times during one rotation (i.e. cleanings, thinnings and final fellings) it may be necessary to compensate for the N losses, especially in the central and north of Sweden where the deposition of N from the atmosphere is low. In south Sweden, removal of residues may be in favour for the N balance due to the high deposition of N (Eriksson et al. 1998).

Zetterberg & Hansén (1998) reported that if logging residues are harvested, the net emission of $CO_2$ to the atmosphere is 16.1 g $CO_2$-equivalents $MJ^{-1}$, during a rotation period of 80 years, compared to a reference scenario where the residues are left on site. The utilization of fossil fuel contributes by 3.2 g $CO_2$-equivalents $MJ^{-1}$. In their study, net emissions include: fossil fuel usage connected to collection, chipping and transportation of the residues; uptake of carbon in the terrestrial system; total emissions from combustion of biomass; and indirect emissions caused by usage of residues.

Storage of comminuted wood fuel could be a significant emitter of greenhouse gases. Wihersaari (2005b) estimated that the emissions of $N_2O$ and $CH_4$ from storage of comminuted forest residues amount to 16-40 g $CO_2$-equivalents $MJ_{chip}^{-1}$ after 6 months. There are few studies supporting these results, but if the emissions of storing residues are of this size the total emissions of greenhouse gases from the supply chain system would be much larger.

### 5.2.5 Removal of stumps from the harvested area

Stump and root biomass has historically been used to produce tar and charcoal. However, during the 1970s and 1980s, there were some experiments in Finland and Sweden to use stump wood as raw material in the pulp and energy industries. These experiments were stopped more than 20 years ago since the cost was found to be excessive (Kallio & Leinonen, 2005). Nevertheless, since the Millennium stump removal for energy purposes has been practised in Finland, and the description in this chapter deals with the technology used in Finland. However, the supply chain system for stump removal is not expected to differ between the countries

If stumps are being removed after harvesting of trees, the area has to be selected carefully. The preferable area includes spruce dominating stands. The soil should contain low amount of stones and the logging residues should have been harvested (Kallio & Leinonen, 2005). Only spruce stumps that are larger than 15 cm and smaller than 50 cm in diameter should be removed, i.e. pine and birch stumps should be left on site. This means that 20-30% of the stump biomass and the majority of the roots are left in the soil (Kallio & Leinonen, 2005). However, there are large uncertainties regarding the proportion of roots left in the soil. After final felling of the stems, the stumps are pulled up by using excavators. When pulled, the stumps are torn to 2-5 pieces and then piled up at the harvesting site (Leinonen et al. 2005). By splitting the stumps and shaking them during the lift, part of the soil including stones fall out and fill the pit. Splitting the stumps also results in lower moisture content. Stumps are stored at the site for several months to allow rain and wind to clean the material. After storage the stumps are then forwarded to roadside landing for further storage. Normally, the stumps are stored at roadside for at least a year (Anon. 2004). During this long-term storage the quality of the stumps will be improved due to further drying and due to rain and wind, which will clean the stumps (Kallio & Leinonen, 2005). Finally, special designed trucks transport the stumps to the power/heating plants, where they are crushed. Stumps are often combusted as mixed fuel in large fluidised bed boilers (Leinonen et al. 2005).

### 5.2.6 Emissions due to stump removal

There are few studies dealing with the indirect emissions from stump removal. However, Näslund & Gustavsson (2007) reported that the emissions for lifting, collecting, transporting, and chipping the stumps are 3.7 g $CO_2$-equivalents $MJ_{fuel}^{-1}$, which were, according to the authors, more than twice as much as the emissions for removal of logging residues (Table 5.2). Eriksson et al. (2007) assumed that removal of stumps to roadside require twice as much energy as removal of logging residues to roadside, but the energy needed to transport stumps and residues were assumed to be the same. The authors showed that logging residue and stump removal results in a lower build-up of soil carbon stock (54 kg C $ha^{-1}$ $year^{-1}$) compared to the scenario where stumps are left in soil, while the fossil fuel substitution effect increased by 500 kg C $ha^{-1}$ $year^{-1}$ if residues were used to replace coal and 260 kg C $ha^{-1}$ $year^{-1}$ if residues were used to replace natural gas. According to Hyvönen-Olsson & Grelle (2007), the difference in carbon fluxes between removal of stumps and non-removal of stumps is large after final felling, but after 20-30 years the carbon balance is positive and the difference between the scenarios are small. It should be noted that Hyvönen-Olsson & Grelle (2007) only considered the fluxes of $CO_2$. The substitution effect of fossil fuel was not included.

If the same assumption is made for stumps as for logging residues (i.e. calculations from Eriksson et al. (2007) and Ågren et al. (2007)), for the decrease in build-up of soil carbon, annual removal of stumps in Swedish forests would after 75 years result in a lower build-up of carbon stock in the soil amounting to 3350 kg C $ha^{-1}$ (45 kg C $ha^{-1}$ $year^{-1}$) in spruce stands and 3240 kg C $ha^{-1}$ (43 kg C $ha^{-1}$ $year^{-1}$) in pine stands compared with a reference scenario where stumps are left in soil. This is lower compared with the report by Eriksson et al. (2007) (see above). Assuming that energy achieved would be 150-250 MWh $ha^{-1}$, the calculated emission of $CO_2$ from the decrease in soil carbon would be in the range of 14-23 g $CO_2$ $MJ^{-1}$. This is more than the decrease in soil carbon due to removal of residues (Table 5.2).

Removal of stumps not only affects the build-up of new soil carbon, but also the decomposition of old organic matter in the soil. During removal of stumps the soil is being more or less mixed and this will have consequences for decomposition processes. The main part of the soil carbon stock is found in the B horizon at a depth from about 10 cm to 50 cm below the soil surface. The age of this organic matter is very high (e.g. mean residence time of 2000 years, and may be considered as very stabile. There are no published studies of how stump and coarse root removal will affect the decomposition of this organic matter (although there might be ongoing studies), but from studies on soil preparation, with mixing of soil, it can be concluded that decomposition rates increase. It could also be argued that if stumps are removed there is less need for ground preparation before the next plantation. However, there will still be a need for it, even if it might be easier to perform and thereby associated with lower cost. This means that stump removal will not replace the need for ground preparation.

## 5.3 Energy crops from agricultural land

Several crops grown on agricultural land can be used for energy purposes. Today, the energy supply from agricultural land is ca. 1 TWh, of which 0.5 TWh origins from straw, 0.3 TWh from ethanol of grain, 0.2 TWh from *Salix*, and 0.1 TWh from grain as solid fuel (Anon. 2006a). In this report, the focus will be on *Salix* but other crops will be discussed.

To receive an acceptable return on investment, the *Salix* plantation should be established on fertile soils, where nutrients, water and air are available in sufficient amounts. The pH should be 5.5 to 7.5 and the plantation should be close to the end-use facilities (i.e. <30 km). Furthermore, the size of the plantation has to be at least 5 ha. A well managed S*alix* plantation is productive during ca. 25 years, which means that 5 to 6 harvestings can be performed. The average increment for a well managed *Salix* plantation could be 8-10 ton dry weight (d.w.) $ha^{-1}$ (Gustafsson et al. 2007).

The production chain in a *Salix* plantation consists of four main phases: 1) Establishment (weed-control, soil preparation, planting), 2) Management (weed-control, fertilization), 3) Harvesting (cutting & chipping, transportation to end-user), and 4) Termination of plantation. The basic operations for production of *Salix* chips are presented in Figure 5.2.

Before plantation, selection of land and weed-control are important factors to receive good results (Sennerby-Forsse & Johansson, 1989). A year before plantation, chemicals are applied to control weed and then ploughing and harrowing is conducted. Plantation is performed in double rows by using 1-year old long shoots (1-3 m) that are cut into ca. 18 cm long cuttings in the plantation machine (Gustafsson et al. 2007). It is recommended that ca. 13 000 cuttings $ha^{-1}$ is planted. The cuttings are planted with a specified distance, which makes it possible to perform mechanical weed-control, fertilization and harvesting. Weed-control is essential during the first year and within a week after plantation; chemicals should be applied followed by mechanical treatment (Gustafsson et al. 2007).

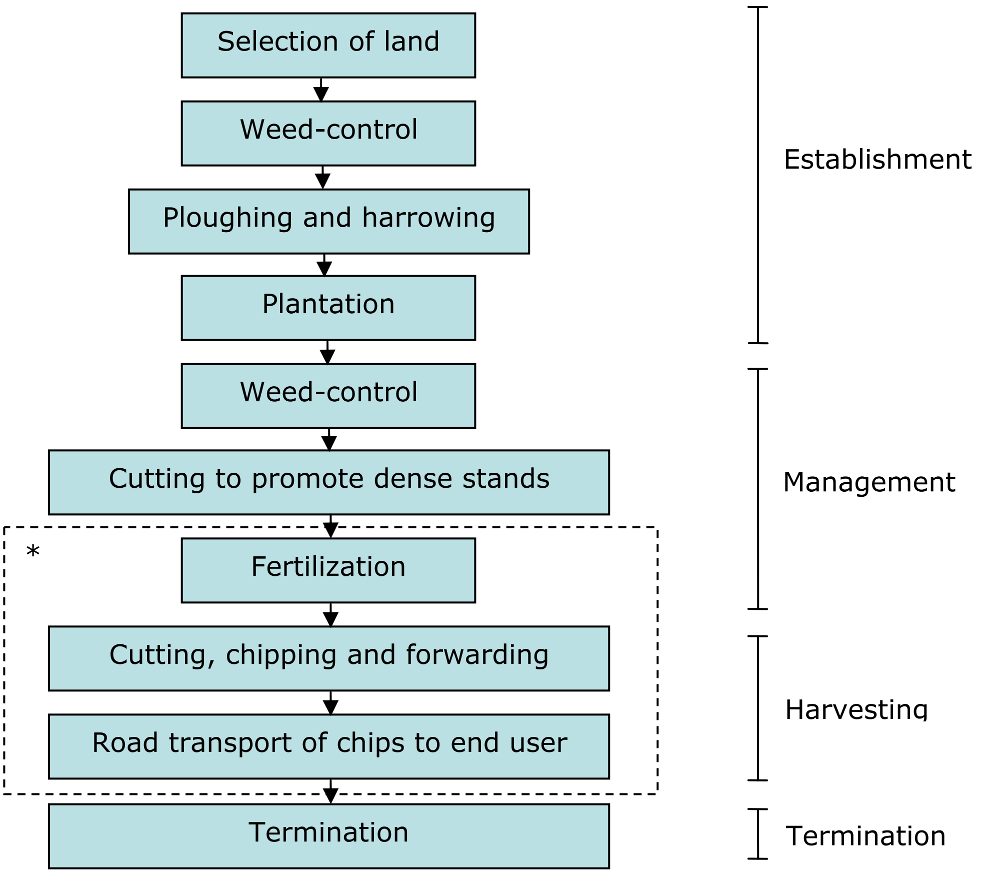


Figure 5.2 Basic operations for *Salix* chips production chain. * The processes within the dashed box are repeated 4-5 times in a *Salix* production system.

Sometimes it is necessary to perform weed-control (chemically and mechanically) even after the first year. During the winter after the plantation year, the shoots are cut to promote a dense stand. Fertilizer is then applied. The fertilizer could either be commercial fertilizer or nutrient-rich organic waste products, such as municipal waste water or sewage sludge. In Table 5.4, a recommendation for the annual application of fertilizer is presented (Gustafsson et al. 2007).

Table 5.4. Amount of fertilizer applied during two harvesting periods (Gustafsson et al. 2007).

| Year | Amount of fertilizer (kg $ha^{-1}$) |
|---|---|
| Plantation | 0 |
| Year 1 | 45 |
| Year 2 | 100-150 |
| Year 3 | 0 [a] |
| Harvest 1 | - |
| Year 4 | 100-150 |
| Year 5 | 100 |
| Year 6 | 0 [a] |
| Harvest 2 | - |

[a] Fertilizer is not applied during year 3 and 6 due to difficulties in applying fertilizer in mature stands.

After 3-4 years, the stand is harvested, which is performed during winter. The shoots are cut and chipped with the same machine. The chips are then loaded on a truck and transported to the plant. Combustion of *Salix* is often performed without drying and in a fuel mix (5-25% *Salix* chips) (Gustafsson et al. 2007).

After 5-6 harvestings (ca. 25 years), there is a risk for lower production in the *Salix* plantation and the farmer has to decide if other crops should be used or if a new *Salix* plantation should be established. In both cases, the old *Salix* plantation has to be terminated. After the last harvest, the stand will produce new shoots, which will be sprayed with chemicals during next summer. The shoots and stumps are then immediately cut, and finally the soil is cultivated to split the stump and root system (Gustafsson et al. 2007).

### 5.3.1 Emissions from production of *Salix* chips

According to an LCA by Börjesson (2006), the production of *Salix* chips is an energy efficient biomass production system. The system gives 20 times more energy than the required energy input, which means that the energy input is 5% of energy from the harvested biomass. In a review, Blümer (1997) showed similar figures and Parikka & Hektor (2000) reported that the energy input is ca. 6% of energy in the harvested *Salix* chips. Production of fertilizer requires the largest energy input and results in the highest emissions of greenhouse gases (Table 5.5) (Brännström-Norberg & Dethlefsen, 1997; Börjesson, 2006). In a life cycle inventory (LCI) for *Salix*, Brännström-Norberg & Dethlefsen (1997) included emissions from combustion of *Salix* chips and $NO_x$-cleaning in the CHP. If these emission sources were excluded, the total greenhouse gas emissions from the report by Brännström-Norberg & Dethlefsen (1997) would be 50% lower compared with the report by Börjesson (2006) (Table 5.5). A difference between the reports is the different time perspective for the greenhouse gases. Brännström-Norberg & Dethlefsen (1997) used $GWP_{20}$, while Börjesson (2006) used $GWP_{100}$. However, that does not explain the large difference in emissions from fertilization.

The emissions reported for *Salix* in Table 5.5 are larger than reported for logging residues (Table 5.2). If the emissions of $N_2O$ from the production of fertilizer would be decreased, as discussed by Börjesson (2006), the emissions of greenhouse gases could be decreased by 40%. Another alternative to reduce the emissions of greenhouse gases in the *Salix* production system is to replace commercial fertilizer with municipal waste water (Börjesson & Berndes, 2006) or sewage sludge.

In comparison with annual crops, such as rape and wheat, *Salix* has approximately three times higher energy balance (energy output / energy input) (Blümer, 1997; Börjesson, 2006; Berndes et al. 2006) and 3.5 to 4.5 times lower emissions of greenhouse gases (Börjesson, 2006). In these comparisons, carbon sequestration in biomass and soil were not included. If these parameters were included, the benefit of using *Salix* would be even larger (see section 5.3.2).

Table 5.5. Energy input (GJ $ha^{-1}year^{-1}$) and greenhouse gas emissions (GHG) (g $CO_2$-equivalents $MJ^{-1}$) in *Salix* chips production and utilisation. Note that $CO_2$ emissions from combustion of chips are not included.

| Processes | Energy input[a] | Emissions of GHG Börjesson (2006) | Emissions of GHG Brännström-Norberg & Dethlefsen (1997) |
|---|---|---|---|
| Establishment and restoration | 0.7 | 0.4 | 0.3[b] |
| Fertilization | 3.7 | 5.9[c] | 1.8[d] |
| Harvesting | 2.2 | 1.2 | 0.9 |
| Transport | 0.7 | 0.4 | 1.1 |
| Combustion | - | - | 1.5[d, e] |
| $NO_x$-cleaning | - | - | 0.4[d, f] |
| Ash recycling | - | - | 0.02 |
| SUM | 7.3 | 7.9 | 6.0 |

[a] Börjesson (2006).
[b] Only establishment.
[c] $GWP_{100}$ for $N_2O$ = 320.
[d] $GWP_{20}$ for $N_2O$ = 280 and for $CH_4$ = 56.
[e] Emissions of $CH_4$ and $N_2O$ due to combustion of biofuel.
[f] Emissions due to production of ammonia for $NO_x$-cleaning in CHP.

### 5.3.2 Impact of *Salix* production on soil carbon and soil emissions

Biofuel production systems affect the soil carbon stock differently. Growing *Salix* on agricultural land results in a build-up of the soil carbon stock, while removal of wood fuel from the forest decreases the soil carbon stock (e.g. Ågren & Hyvönen-Olsson, 2006). Weih & Bussel (2006) estimated that the mean carbon sequestration in soil (0-23 cm) for *Salix* on agricultural land was 80 (40-120) kg C $ha^{-1}$ $year^{-1}$ after one cutting cycle (i.e. 3 years). Assuming that energy achieved would be 150 GJ $ha^{-1}$ $year^{-1}$, the calculated uptake of carbon in soil would be 2 g $CO_2$ $MJ^{-1}$.This figure should be compared with the decrease in build-up of soil carbon that Eriksson et al. (2007) and Ågren & Hyvönen (2003) reported for removal of wood fuel from the forest (Table 5.2). According to Grogan & Matthews (2002), soil carbon sequestration may constitute about 5% of the carbon reduction benefit arising from *Salix* plantations. Grogan & Matthews (2002) reported a larger mean carbon sequestration in soil compared to Weih & Bussel (2006), which is partly due to larger biomass growth. Establishing *Salix* will also result in a larger above-ground carbon stock compared to annual crops. Eriksson & Hallsby (1992) reported that planting *Salix* would increase the carbon stock by 40 tonne C $ha^{-1}$ after 100 years and Ågren & Hyvönen-Olsson (2006) discussed that establishment of *Salix* increases the carbon stock in biomass compared to annual crops, which results in reduction of $CO_2$ in the atmosphere.

Salix production may under certain conditions emit $N_2O$. Particularly at sites where the groundwater level is high and the soil is rich in nitrogen with CN ratio below 20 (Klemedtsson 2005) and/or have been fertilised with N. According to Granhall (2000) about 24 – 30 % of added nitrogen fertiliser may be lost through denitrification, most likely mainly as $N_2O$. Assuming an application of 200 kg N over 3 years, 25 % denitrification losses whereof $N_2O$

constitutes 50 % and an annual dry matter production of 7 ton per ha, would correspond to emissions of 19 g $CO_2$ equivalents $MJ^{-1}$ in the form of $N_2O$. This value is of similar size as may be calculated from Klemedtsson (2005). All emissions that are due to active management in the production of biofuels should be included in an LCA. Important management methods are N-fertilisation and ditching/keeping areas drained.

## 5.4 By-products from the forest industry

Wood fuel has been an important energy source for the forest industry for a long time and some of the technology used in the supply chain system and combustion of wood fuel originates from the forest industry (Nilsson, 1999). In Sweden, the forest industry is one of the largest consumers of energy, but the forest industry also generates large amount of energy. In 2005, the industry generated 55 TWh from by-products, of which black liquors from the pulp industry contributed by 38 TWh (Anon. 2006b). Other by-products (i.e. bark and sawdust) from the pulp and sawmill industry, and electricity generation in the forest industry contributed by 7.4, 5, and 4.4 TWh, respectively (Anon. 2006b). The use of solid biofuels in the forest industry has been fairly constant the past 10 years. There have been some variations, mainly due to changes in production volumes. However, there are potentials to further increase the use of wood fuel in the industry by replacing fossil fuel and by generating electricity with back-pressure. Traditionally, by-products that have had an economical value, such as chips for pulp production and sawdust for fibreboard production, have been sold to other industries, while bark and black liquors have remained within the industry for internal use. This is mainly the situation even today, with the exception that sawdust and shavings are sold to the pellets industry.

### 5.4.1 Emissions from production and utilization of by-products

The greenhouse gas emissions from production and utilization of bark and sawdust are 19 and 25 kg $CO_2$-equivalents $m^3_{fuel}{}^{-1}$ (4.9-7.8 and 3.6-6.3 g $CO_2$-equivalents $MJ^{-1}$), respectively (Table 5.6). It should be observed that in these estimates harvesting of trees and transport are included (Petersen Raymer, 2006). However, it could be argued that these processes should not be allocated to bark and sawdust since these fuels are by-products and the emissions would occur also in the case when the products were not used for energy production. Excluding harvesting and transport would result in greenhouse gas emissions of 10 and 16 kg $CO_2$-equivalents $m^3_{fuel}{}^{-1}$ (2.6-4.1 and 2.3-4.1 g $CO_2$-equivalents $MJ^{-1}$), respectively (Table 5.6). The process with the largest impact is combustion, due to emissions of $CH_4$ and $N_2O$. Emissions from combustion are large for bark and sawdust in comparison with the other solid biofuels in this report (Table 5.3 and Table 5.5).

Table 5.6. Greenhouse gas emissions over a life cycle of bark and sawdust (Petersen Raymer, 2006). Note that $CO_2$ emissions from combustion of bark sawdust are not included.

| Processes | Bark | | Sawdust | |
|---|---|---|---|---|
| | kg $CO_2$-eq. $m^3_{fuel}{}^{-1}$ | g $CO_2$-eq. $MJ_{fuel}{}^{-1}$ [a] | kg $CO_2$-eq. $m^3_{fuel}{}^{-1}$ | g $CO_2$-eq. $MJ^{-1}$ [a] |
| Harvesting | 5 | 2.0/1.3 | 5 | 1.3/0.7 |
| Transport | 4 | 1.6/1.0 | 4 | 1.0/0.6 |
| Production[b] | 3 | 1.2/0.8 | 3 | 0.8/0.4 |
| Transport to consumer | 0 | 0/0 | 2 | 0.5/0.3 |
| Combustion[c] | 7 | 2.8/1.8 | 11 | 2.8/1.6 |
| SUM | 19 | 7.6/4.9 | 25 | 6.3/3.6 |

[a] Authors' conversions. Heating value was assumed to be 2.5 and 4 GJ $m^{-3}$ for bark and 4 and 7 GJ $m^{-3}$ for sawdust.
[b] Diesel consumption from handling and transport at the sawmill.
[c] GWP for $CO_2$ = 1, $N_2O$ = 270.1 and $CH_4$ = 11.6.

## 5.5 Recovered wood

Recovered wood includes all kinds of wooden material that is available at the end of its use as a wooden product and mainly covers packaging materials, demolition wood, timber from building sites, and fractions of used wood from residential, industrial and commercial activities (Gallis, 2005). The options for recovered wood are: 1) Disposal, 2) Recycling of the material, and 3) Energy generation (Figure 5.3). The two most commonly used disposal strategies are to place recovered wood on landfills and combustion without energy generation. However, landfills of biomass are considered to be responsible for a substantial amount of the human induced emissions of $CH_4$ and avoiding disposal could therefore reduce emissions of greenhouse gases.

Recovered wood for industrial processes is mostly used in the production of fibreboard and particleboard, and is limited to the non-hazardous fractions. Utilization of recovered wood for energy generation could contribute in two ways. Firstly, recovered wood could replace fossil fuels and secondly, the emissions of $CH_4$ would be reduced if the material were not placed on landfills. Gallis (2005) estimated that recovered wood potential in Europe has an energy content of 750-1350 PJ.

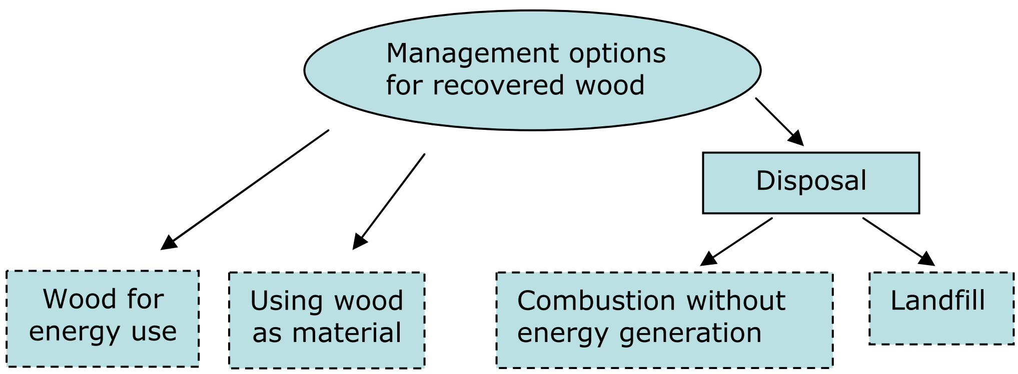


Figure 5.3 Management options for recovered wood (Gallis, 2005)

In Sweden the major part of recovered wood is combusted, either in conventional heating/CHP plants or in special (hazardous) waste combustion units which deliver district heating.

### 5.5.1 Emissions from production and utilization of recovered wood

Karlopoulos et al. (2005) reported that collecting, transporting and chipping of medium density fibreboard (MDF) for energy wood contributed with 40% of the total greenhouse gas emissions associated with production and utilization of recovered wood. Combustion of MDF contributed with the remaining 60%, mainly due to emissions of $N_2O$. Petersen Raymer (2006) only included combustion when estimating the greenhouse gas emissions for demolition wood (Table 5.7). Reduced emissions of $CH_4$ due to that the wooden material is not disposed on landfill are not included in these studies, but would of course reduce the total emissions.

Table 5.7 Greenhouse gas emissions from combustion of demolition wood for different species and heating values (Petersen Raymer, 2006).

| Species | kg $CO_2$-eq. $m^3{}_{fuel}{}^{-1}$ [a] | g $CO_2$-eq. $MJ_{fuel}{}^{-1}$ [a, b] | | | |
|---|---|---|---|---|---|
| | | 3000 MJ $m^{-3}$ | 5000 MJ $m^{-3}$ | 7000 MJ $m^{-3}$ | 9000 MJ $m^{-3}$ |
| Spruce | 11 | 3.6 | 2.2 | 1.6 | 1.2 |
| Pine | 12 | 4.0 | 2.4 | 1.7 | 1.3 |
| Birch | 14 | 4.7 | 2.8 | 2.0 | 1.6 |
| Aspen | 11 | 3.6 | 2.2 | 1.6 | 1.2 |

[a] GWP for $CO_2$ = 1, $N_2O$ = 270.1 and $CH_4$ = 11.6.
[b] Authors' conversions. Heating values differ due to moisture content.

## 5.6 Refined wood fuels

There are several refined wood fuels (e.g. pellets, briquettes), but pellets are mostly utilized contributing with 8 TWh to the Swedish energy supply system in 2005 (Anon. 2006b). Pelletisation of woody biomass is a method in which the raw material is compacted to achieve uniform properties. The raw materials are by-products from sawmill and pulp mill industries and consists of sawdust, chips, or shavings. The end-product is cylindrical with a diameter of 6-12 mm and the length must not be more than four times the diameter. Untreated raw material has normally a moisture content of 50%, while the moisture content of the compacted product is about 8-10%. Pelletisation increases the density, which results in a fuel with high energy content. Pellets are therefore, and due to the uniform shape, more efficient to transport and to store compared to unrefined wood fuels.

The production process can be divided into five main activities: 1) Preparation of the raw material, 2) Drying, 3) Grinding, 4) Pressing, and 5) Cooling (Figure 5.4). Preparation of the material means removal of contaminating material such as stones, gravels, and scrap metal, as well as grinding of the raw material to small and uniform pieces. It is necessary that the particle size is even to facilitate the drying process. Heterogeneous particles could result in that small particles are completely dried before larger ones, and that larger particles may become dry on the surface, while moisture still remains in its core. After drying, the material is grinded to a fine powder. For dry raw material, such as planing shavings, the drying phase is not necessary and the material could be grinded to fine powder immediately after the preparation. The fine powder is fed into a rotating press. The rotation forces the material through a dye which compresses it into pellets. Lignin and moisture within the material are sufficient to get the powder to stick, thus no additives are required. The pellets have a high temperature (i.e. 60-90°C) when leaving the press and have to be cooled. The cooling process removes some moisture and the strength of the final product increases.

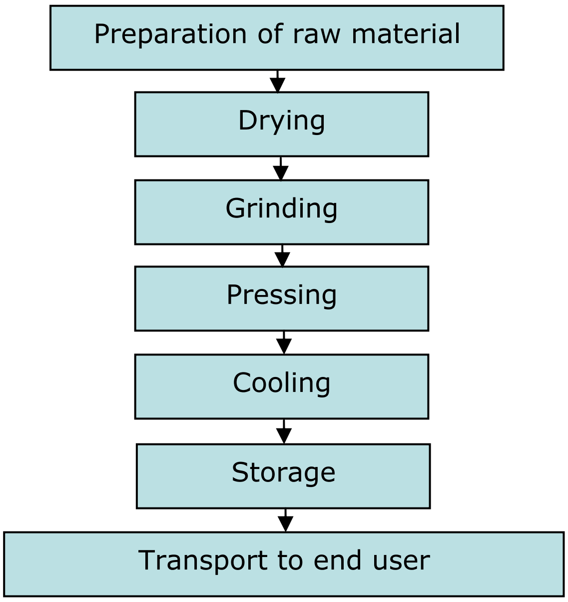


Figure 5.4. Basic operations for pellets production.

### 5.6.1 Emissions from pellets production

According to Petersen Raymer (2006), greenhouse gas emissions over a life cycle of pellets are 59 kg $CO_2$-equivalents $tonne_{fuel}^{-1}$ (3.5 g $CO_2$-equivalents $MJ^{-1}$). In these estimates emissions from the production of sawdust are included. It could be argued that production of sawdust is not within the system boundary and should therefore not be included. Excluding sawdust production would result in greenhouse gas emissions of 30 kg $CO_2$-equivalents $tonne_{fuel}^{-1}$ (1.8 g $CO_2$-equivalents $MJ^{-1}$), which is a low figure compared to other solid biofuels in this study (Table 5.1, 5.3, 5.5-5.6). In Table 5.8, the greenhouse gas emissions for pellets are presented. According to Petersen Raymer (2006), the pressing of pellets caused no emissions of greenhouse gases (Table 5.8). However, electricity is used in the pressing process and the overall carbon balance could therefore be affected if the electricity was generated by fossil fuels.

Table 5.8. Energy consumption and greenhouse gas emissions (GHG) over a life cycle of 1 tonne pellets (Petersen Raymer, 2006).

| Processes | Energy consumption ($kWh\ tonne^{-1}$) | | | Emissions of GHG | |
|---|---|---|---|---|---|
| | Electricity | Fossil fuels | Bioenergy | kg $CO_2$-eq. $tonne^{-1}$ | g $CO_2$-eq. $MJ^{-1}$ [a] |
| Production of sawdust | 86 | 112 | - | 29 | 1.7 |
| Transport | - | - | - | 6 | 0.3 |
| Drying | - | - | 68 | 1 | 0.1 |
| Pressing | 253 | - | - | 0 | 0 |
| Transport to consumer | - | 10 | - | 1 | 0.1 |
| Combustion[b] | - | - | - | 22 | 1.3 |
| SUM | 339 | 122 | 68 | 59 | 3.5 |

[a] Authors' conversions. Heating value for 1 tonne pellets was assumed to be 17000 MJ.
[b] GWP for $CO_2$ = 1, $N_2O$ = 270.1 and $CH_4$ = 11.6.

Forsberg (1999) studied the emissions over a life cycle for pellets. He estimated the emissions of greenhouse gases from a pellets production system where logging residues were used as raw material (Table 5.9). Producing pellets from residues are not in practice today, but could be profitable if the competition of raw material increases. Transport to consumer had the largest impact on the emissions according to Forsberg (1999). There were no emissions of greenhouse gases from the pelletisation process since electricity was used for crushing, grinding and pressing, and wood powder was used for drying.

Table 5.9. Energy consumption and greenhouse gas emissions (GHG) over a life cycle of pellets (Forsberg, 1999). Note that emissions of $CO_2$ due to combustion of pellets are not included.

| Processes | Energy consumption (kWh $MWh_{el}^{-1}$) | | | Emissions of GHG | |
|---|---|---|---|---|---|
| | Electricity | Fossil fuels | Bioenergy | kg CO2-eq. $MWh_{el}^{-1}$ | g $CO_2$-eq. $MJ^{-1}$ [a] |
| Forwarding residues | - | 23 | - | 6 | 0.6. |
| Baling of residues | - | 29 | - | 8 | 0.8 |
| Forwarding of bales | - | 7 | - | 2 | 0.2 |
| Road transport | - | 8 | - | 2 | 0.2 |
| Crushing | 7 | - | - | 0 | 0 |
| Grinding | 30 | - | - | 0 | 0 |
| Drying | - | - | 406 | 0 | 0 |
| Pressing | 25 | - | - | 0 | 0 |
| Transport to consumer[b] | - | 36 | - | 9 | 0.9 |
| Combustion | - | - | - | 5[c] | 0.5[c] |
| SUM | 62 | 103 | 406 | 32 | 3.2 |

[a] Authors' estimations. 1 $MWh_{electricity}$= 0.563 tonne pellets and the heating value was assumed to be 17000 MJ tonne pellets (Forsberg, 1999)
[b] Shipping pellets.
[c] Authors' calculations. GWP for $CO_2$ = 1 and $N_2O$ = 296.

The emissions of greenhouse gases from production of pellets are similar in the reports mentioned above (Table 5.9 - Table 5.10). Transport to consumer and combustion differ between the studies, while production and transport of sawdust is similar (i.e. 1.8–2.0 g $CO_2$-equivalents $MJ^{-1}$). Another difference is that electricity seems to contribute more to the overall energy consumption in the study by Petersen Raymer (2006) than in the study by Forsberg (1999), while the use of bioenergy seems to be larger in Forsberg's (1999) report. Both studies assumed that there were no emissions from the pelletisation process since electricity was used.

## 5.7 Comparison between different solid biofuels

In order to perform a valuable comparison between solid biofuels and their emissions of greenhouse gases from the supply chain systems, the same system boundaries should be used. However, that is not possible since authors of LCA and LCI use different system boundaries and thereby includes different processes in their studies. Another aspect that makes it difficult to compare solid biofuels is that a majority of the solid biofuels are by-products from the forest industry, while others are produced only for energy generation (e.g. energy crops). Furthermore, some by-products arise from the logging operations in the forest, while others origin from the industry processes, which has an impact on the estimations of the greenhouse gas emissions. These differences should be observed when comparing solid biofuels. In Table 5.10, we have made a comparison between emissions from different solid biofuels, and included the processes we believe are the most important. Emissions are given in $CO_2$ equivalents per MJ based on the lower heating value of the fuel.

Table 5.10. Emissions of greenhouse gases (g $CO_2$-eq. $MJ^{-1}$) from production and utilisation of solid biofuels. Note that emissions of $CO_2$ from the combustion of the biofuels are not included.

| Processes | Residues | Stumps | *Salix* | Bark [f] | Recovered wood [g] | Pellets |
|---|---|---|---|---|---|---|
| Establishment and restoration | - | - | 0.4 | - | - | - |
| Fertilization | -[a] | - | 5.9 | - | - | - |
| Collecting, chipping, transportation, etc. | 1.2-3.2 | 3.7 | 1.6-2.0 | 1.2 | 1.1[h] | 0.3[i] |
| Pelletisation | - | - | - | - | - | 0.1-5.0[j] |
| Combustion | 0.6-1.5[b] | ? | 1.5-2.0[b] | 2.8 | 1.6 | 0.5 -1.3 |
| Ash recycling/landfill | 0.05 | ? | 0.02 | ? | ? | ? |
| Decrease of soil C | 7-13[c] | 14-23[d] | - | - | - | - |
| Increase of C in soil | - | - | -2.0 | - | - | - |
| Soil $N_2O$ emissions | | | 0-19[e] | | | |
| SUM | 9-18 | 18-27 | 7-27 | 4.0 | 2.7 | 0.9-6.6 |

[a] Fertilization is not included here since only 20 000 ha in Sweden is fertilized and that is mainly to increase the production at poor sites where forest residues not have been removed.
[b] Includes only emissions of $CH_4$ and $N_2O$.
[c] Estimates based on site studies. The estimates from Ågren & Hyvönen (2003) presented in Table 5.2 were not included since these are theoretical values.
[d] Only the decrease in build-up of soil carbon is included. The impact on the existing organic carbon in soil is excluded due to uncertainties.
[e] Under certain conditions the emissions of $N_2O$ from Salix plantation could be very high.
[f] Heating value for bark was assumed to be 2.5 GJ $m^{-3}$
[g] Heating value for demolition wood (spruce) was assumed to be 7 GJ $m^{-3}$.
[h] This process is estimated by assuming that transportation and crushing corresponds to 40% of the emissions of greenhouse gases in the supply chain system (Karlopoulos et al. 2005).
[i] Includes transport to pellets industry.
[j] The lower value assumes zero emissions from the use of electricity, whereas the higher value includes emissions from the generation of electricity in a coal condensing plant. Electricity consumption is based on figures from Table 5.9 and the emission factor for electricity is set to 750 g $CO_2$ kWh.

Stumps gave the largest emissions of greenhouse gases of the solid biofuels due to the decrease in build-up of soil carbon (Table 5.10). There are few studies dealing with the effect of stump removal on soil carbon stock, but the impact of whole tree harvesting has been studied frequently the past 20 years (e.g. Bengtsson & Wikström, 1993; Ågren & Hyvönen, 2003; Wihersaari, 2005a, Eriksson et al. 2007) and the same model can be used to estimate the effect of stump removal on the decrease in soil carbon stock. It should be observed that only the decrease in build-up of soil carbon is estimated for stumps. The impact on the existing organic carbon in soil is excluded since the knowledge of the effect is poor. Including this effect could increase the emissions from stumps considerably. It should also be noted that methane and nitrous oxide emissions due to the combustion are not included for stumps, due to lack of data. However, these emissions are probably in the same range as for the other woody material (i.e. residues, salix etc.).

Under certain conditions, the soil $N_2O$ emissions from *Salix* plantations (and other crops) may be significant. Such conditions could occur on e.g. drained peatlands with high fertility (low CN-ratio) or that have been N-fertilised. The emissions could be as high as 19 g $CO_2$ $MJ^{-1}$, which by far exceeds the carbon sequestration in soil and is much larger than all other emissions in the supply chain system of *Salix*. Including these emissions would result in that *Salix* plantations (or other biofuels produced on drained peatlands) have among the largest emissions of greenhouse gases compared to the other solid biofuels in Table 5.10. Again we stress that all emissions that are due to active management of the production of a biofuel should be included.

Recovered wood and pellets gave the lowest emissions of greenhouse gases during production and utilization (Table 5.10). However, the effect of transporting and crushing recovered wood is not clear. Karlopoulos et al. (2005) reported that collecting, transporting and chipping of medium density fibreboard (MDF) for energy purposes contributed with 40% of the total greenhouse gas emissions in the supply chain system. This would mean that these processes contributed by 1.1 g $CO_2$ $MJ^{-1}$ (calculated from Petersen Raymer (2006)).

The low emissions for pellets are due to zero allocation of emissions from electricity utilisation[9] in the pelletisation process and because the raw material used to produce pellets (i.e. sawdust) is a by-product from the forest industry. The latter means that the emissions caused by the production of sawdust often are allocated to another production system (i.e. sawmill industry). In Table 5.10, the production of sawdust is not allocated to the pellets supply chain system. If this process was allocated to pellets, the emissions from the supply chain system of pellets would be increased by approximately 1.5 g $CO_2$ $MJ^{-1}$.

The emissions of greenhouse gases for bark are relatively large due to low heating value. A drier material, whit a higher heating value (i.e. 4 GJ $m^{-3}$), would have resulted in lower emissions (2.6 g $CO_2$ $MJ^{-1}$). Harvesting of trees and transport to industry is not included in Table 5.10 but if these processes were allocated to bark the emissions for bark would be increased by 90%. Petersen Raymer (2006) included harvesting of trees and transport, but today bark would have been produced anyway, since it is a by-product from the forest industry. However, if there is a demand for bark in the future (e.g. for pellets production) these processes should be included.

Logging residues is the most commonly used solid biofuel in the Swedish heat and power plants. Often, the decrease of soil carbon is not included in studies of logging residues and their emissions of greenhouse gases (e.g. Börjesson & Gustavsson, 1996; Brännström-Norberg & Dethlefsen, 1997; Forsberg, 1999; Ekström et al. 2001; Näslund & Gustavsson, 2007), which results in emissions close to the estimated values for bark, recovered wood, and pellets (Table 5.10). However, if the impact of residue removal on the soil carbon stock is included, the emissions of greenhouse gases in the supply chain system would increase considerably (e.g. Börjesson, 2000; Wihersaari, 2005a). Furthermore, a majority of the studies argues that the emissions due to decrease in soil carbon stock are larger than the emissions from collecting, chipping and transporting the residues.

Emission estimates for $CH_4$ and $N_2O$ from combustion are quite small for all fuels. However, it should be noted that according to Cooper et al. (2003) methane emissions from small scale use of wood fuel can be significantly higher than the estimates indicated in all studies.

## 5.8 Fossil fuels

The production and utilisation of fossil fuels will not be described in detail but figures on greenhouse gas emissions during the different stages have been

[9] This assumption is made for the lower value for pellets, for the higher estimate emissions from electricity generation are included.

assessed from available literature. Emissions data for production and utilisation of natural gas and coal was included for comparative reasons.

### 5.8.1 Natural gas

Natural gas used in Sweden comes mainly from the Danish gas field *Tyra* in the North Sea. The transmissions system only covers the south western part of Sweden. Emission factors for the production, distribution and combustion of natural gas utilised in Sweden are summarised in Table 5.11. It should be noted that the emissions of especially carbon dioxide and methane from the production and distribution phase can differ significantly compared to natural gas produced in other countries than Denmark. For instance the emissions from the Russian production and distribution net are estimated to be significantly higher (10 g $CO_2$/MJ and 62 mg $CH_4$/MJ respectively) (SGC 2005).

Table 5.11.Net emissions from production and utilisation of natural gas in Sweden.

| Natural gas | Emission factor | Uncertainty range | Reference |
|---|---|---|---|
| $CO_2$, combustion in heating and power stations | 56.5 g $MJ^{-1}$ | ~2% (55.4 - 57.6) | Swedish NIR 2007, Energinet.dk, Danish NIR 2004 |
| $CO_2$, production and distribution | 4.3 g $MJ^{-1}$ | n.a. | SGC, 2005 Uppenberg et al. 2001. |
| $CH_4$, combustion in heating and power stations | 1 mg $MJ^{-1}$ | ~10-30% (0.7 – 1.3) | Swedish NIR 2007, Boström et al. 2004. |
| $CH_4$, production and distribution | 12 mg $MJ^{-1}$ | n.a. | SGC 2005, Uppenberg et al. 2001. |
| $N_2O$, combustion in heating and power stations | 2 mg $MJ^{-1}$ | ~10-30% (1.4 – 2.6) | Swedish NIR 2007, Boström et al. 2004 |
| $N_2O$, production and distribution | 0.098 mg $MJ^{-1}$ | n.a. | SGC 2005, Uppenberg et al. 2001. |
| SUM | 61.7 g $CO_2$-eq. $MJ^{-1}$ [a] | 60.6 – 62.8 g $CO_2$-eq. $MJ^{-1}$ [a] | |

[a.] This value is calculated by using $GWP_{100}$ values (i.e. 23 for methane, and 296 for nitrous oxide).

### 5.8.2 Coal

Only few power and heating plants in Sweden still use coal as a fuel. In the table below emission factors for the production, distribution and combustion of coal in power and heating plants in Sweden are presented.

Table 5.12.Net emissions from production and utilisation of coal in Swedish power and heating plants.

| Coal | Emission factor | Uncertainty range | Reference |
|---|---|---|---|
| $CO_2$, combustion in heating and power stations | 93 g $MJ^{-1}$ | 2 % (1-10%) (91 -95) | Swedish NIR 2007, Boström et al. 2004. |
| $CO_2$, production and distribution | 3.2 g $MJ^{-1}$ | n.a. | SGC, 2005 Uppenberg et al. 2001. |
| $CH_4$, combustion in heating and power stations | 2 mg $MJ^{-1}$ | 10-30% (1.4 – 2.6) | Swedish NIR 2007, Boström et al. 2004 |
| $CH_4$, production and distribution | 0.73 g $MJ^{-1}$ | 0.35 – 1.1 | SGC 2005, Uppenberg et al. 2001. Kirkinen et al. (in prep) |
| $N_2O$, combustion in heating and power stations | 20 mg $MJ^{-1}$ | 10–30% (14 – 26) | Swedish NIR 2007, Boström et al. 2004 |
| $N_2O$, production and distribution | - mg $MJ^{-1}$ | - | SGC 2005, Uppenberg et al. 2001. |
| SUM | 119 g $CO_2$-eq. $MJ^{-1}$ [a] | 106 – 131 g $CO_2$- eq. $MJ^{-1}$ [a] | |

[a] This value is calculated by using $GWP_{100}$ values (i.e. 23 for methane, and 296 for nitrous oxide).

# 6 Imported biofuels

## 6.1 The Swedish biofuel import

Even though Sweden has vast forest resources which can be used for energy purposes, the country also imports large amounts of biomass for use in district heating (DH) and combined heat and power (CHP) plants. Wood chips from the Baltic States, pellets from Canada and recovered wood from Mainland Europe are imported for use as fuel in the production of heat and electricity in Sweden. The amount of the annual import of biofuels is difficult to quantify due to lack of reliable statistics; but studies (e.g. Hillring & Vinterbäck, 2000; Ericsson & Nilsson, 2003; Olsson, 2006) estimate the import to be 5-9 TWh, or 10-20% of the total fuel supply of Swedish DH and CHP plants. Figure 6.1 shows Swedish biofuel import patterns in 2003 according to Olsson (2006).

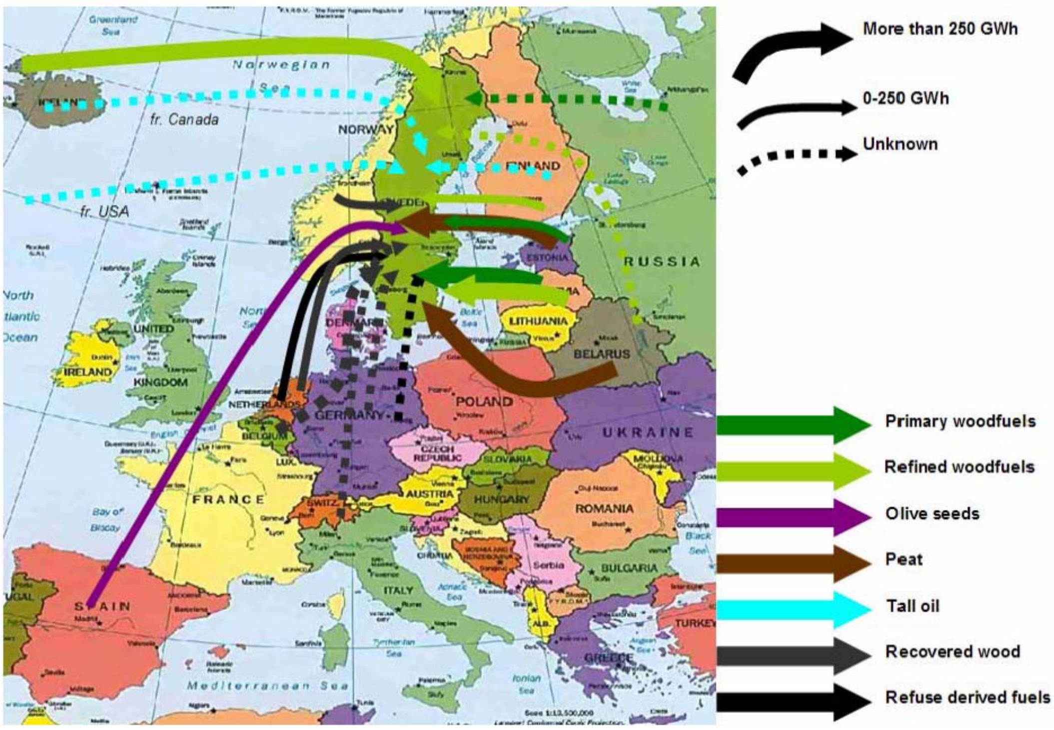


Figure 6.1. The Swedish biofuel import in 2003 (Olsson, 2006). "Primary wood fuels" is the term used for wood chips made from logging residues.

The Swedish biofuel import is not a question of lack of domestic supply, but rather a question of prices and more precisely, transport costs. Sweden has large biomass resources, but Sweden is a rather large country and the regions with large biomass resources are seldom the same regions where biomass demand is the highest. This means that highway transports are required to supply the large district heating and CHP plants located in urban parts of the country. Since the range of highway transport is limited due to high costs, it is not surprising that plants located in coastal areas have sought other alternatives for their fuel supply. The low cost of transporting biofuels on sea compared to road or railway transports is very beneficiary for Swedish district heating and CHP plants located close to the coastline. Having access to ship transport gives these plants a significantly larger freedom of choice of options compared to inland plants regarding diversification of fuel supply. For instance, one of the large CHP plants providing Stockholm with power and heat is largely supplied by pellets transported by ship from a production plant in Northern Sweden (see e.g. Hirsmark, 2002). The low cost of ship transportation is also one of the main reasons for the large Swedish biofuel import. For example, large amounts of wood chips are transported from the Baltic States to the area around Lake Mälaren. The reason for this is both the difference in production costs, which are considerably lower in the Baltic States, as well as the difference in transport costs (Olsson, 2006).

## 6.2 Greenhouse gas emissions of imported biofuels

There are no comprehensive studies available on the greenhouse gas emissions of the production chains of biofuels imported to Sweden. Therefore, the topic will be dealt with from a number of perspectives which together provide an overview of the key aspects that are at hand. The first part of this chapter discusses how greenhouse gas emissions from international biofuel trade in general have been studied and in the second part of the chapter, some LCAs of Swedish and foreign pellet production chains will be compared and discussed.

## 6.3 Greenhouse gas emissions and sustainability of traded biofuels

### 6.3.1 Reforestation in countries from which Sweden imports biofuels for energy conversion

As has previously been mentioned, reforestation is an important part of the carbon balance of biofuel production chains. Table 6.1 shows the forest area change in some selected countries for the time periods 1990-2000 and 2000-2005 respectively. Although forest area has generally increased in Europe and North America since the beginning of the 1990´s, this increment is small compared to the massive deforestation that is taking place in South America and South East Asia.

UNECE and FAO have conducted a study (UNECE & FAO, 2004) in which forest legislation in 23 European countries is examined. Three major areas were in focus: public access to forests, use of non-wood forest products and reforestation. The authors review the applicable laws for the respective topics and grade the countries from 1 to 3 depending on how thorough the legislation is. 1= general description and 3 = specific description.

Table 6.1 Change in forest area during different time periods. Positive value means increase whereas negative value means decrease in forested area. Source: FAO, 2007.

| Country | 1990 – 2000 [1000]ha | 2000 – 2005 [1000 ha] |
|---|---|---|
| Sweden | 11 | 11 |
| Finland | 28 | 5 |
| Estonia | 8 | 8 |
| Latvia | 11 | 11 |
| Lithuania | 8 | 16 |
| Russia | 32 | -96 |
| USA | 165 | 159 |
| Canada | 0 | 0 |
| Brazil | -2681 | -3103 |
| Indonesia | -1872 | -1871 |
| Malaysia | -78 | -140 |

The UNECE & FAO review presents a rather concise overview of the reforestation in Europe. However, for the purpose of examining the reforestation policies of the countries which export biofuels to Sweden, the report is not complete. This since the two largest exporters (according to Olsson, 2006; see Figure 6.1) of virgin (i.e. not recovered wood) biomass to Sweden; Canada and Latvia; are not included. As for some of the other countries it can be noted that Lithuania and Finland get the grade 3 for reforestation legislation whereas Estonia and Russia get the grade 2. Sweden itself gets 3.

### 6.3.2 Comparing pellet production LCAs: domestic production vs. imports

To highlight some of the differences between the production chains for domestic and imported biofuels, this section will discuss LCAs for pellet production chains. The reason for choosing pellets is that it is the most standardised solid biofuel, a fact that increases the validity of comparing the different chains, and pellets are also a biofuel for which there is a large and growing intercontinental market. The high energy density and low moisture content of pellets make it economically viable to transport pellets much longer distances than e.g. wood chips. Furthermore, it is possible to co-fire pellets in e.g. existing coal-fuelled power plants without major technical adjustments. In 2005, 7.1 TWh of pellets were used in Sweden of which 20-25% were imported from other countries (Swedish Association of pellets producers, 2007).

Three studies will be compared herein. Two of the studies, Forsberg (1999) and Petersen Raymer (2006) have already been mentioned in this report, in section 5.6.1. These two studies will be used as examples of domestically produced pellets. Although no LCAs of pellets imported to Sweden are available, Dutch researchers have conducted studies on imports of pellets from Canada to Holland. Since Sweden also imports large amounts of pellets from Canada, the Dutch studies can be seen as good approximations of the import of Canadian pellets to Sweden. The only major differences would be the ocean transport distance to Sweden which is slightly longer than to Holland, and that the last part of the transport chain is on barges in Holland due to the extensive canal system. The Dutch study, used as an example of the import of pellets, has been conducted by Damen & Faaij (2003). A pellet production chain in which pellets produced in Canada and transported across the Atlantic for co-combustion with coal in Dutch coal-fired power plants has been studied. The table below shows the emissions, excluding combustion emissions, from different parts of the production chains of the respective processes.

Table 6.2. Three LCAs of pellet production chains. Colours of shaded cells can be used to compare this data with Figure 6.2 below.

| **Canada-Holland (Damen & Faaij)** | | **Sweden (Forsberg)** | | **Norway (Petersen Raymer)** | |
|---|---|---|---|---|---|
| | | | | | |
| ***Process*** | **GHG emissions [g $CO_2$-eq./ $MJ_{fuel}$]** | ***Process*** | **GHG emissions [g $CO_2$-eq./ $MJ_{fuel}$]** | ***Process*** | **GHG emissions [g $CO_2$-eq./ $MJ_{fuel}$]** |
| Harvesting and transporting trees | 1.8 | Forwarding residues | 0.6 | Production of sawdust | 1.7 |
| Debarking | 0.2 | Baling of residues | 0.8 | Transport | 0.3 |
| Truck transport of residues | 0.3 | Forwarding of bales | 0.2 | Drying | 0.1 |
| Pelletisation | 5.9 | Road transport | 0.2 | Production | 0 |
| Truck transport of pellets | 0.6 | Crushing | 0 | Transport to consumer | 0.1 |
| Ocean transport of pellets | 2.6 | Grinding | 0 | | |
| Barge transport of pellets | 0.2 | Drying | 0 | | |
| | | Pressing | 0 | | |
| | | Transport to consumer | 0.9 | | |
| ***Total*** | **11.6** | ***Total*** | **2.7** | ***Total*** | **2.2** |

As can be seen, the results of the studies differ significantly. The greenhouse gas emissions from the Canada-Holland production chain are more than 4 times those of the locally produced pellets in Sweden and Norway. In order to simplify comparison between the studies, the different categories used by the respective authors has been generalized into just four categories as presented in Figure 6.2.

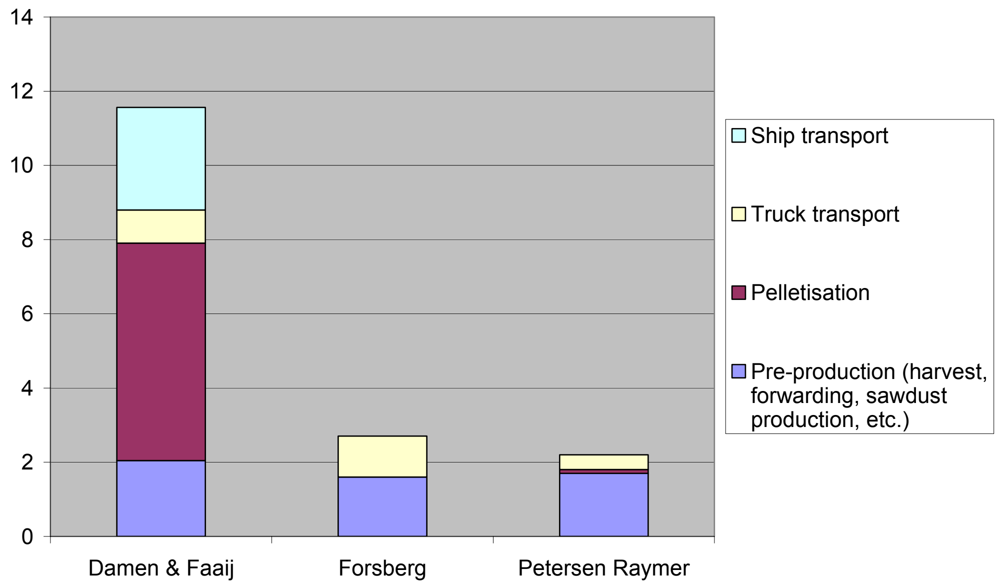


Figure 6.2. GHG emissions from pellet production chains (g $CO_2$ equivalents/$MJ_{fuel}$)

While the emissions from pre-production and truck transport are rather similar in all three studies, the factors that make up the major part of the difference between the "domestic" studies and the "import" study is made up by emissions from the pelletisation process and the additional ocean transport that is required in the Canada-Holland production chain. It is important to note that carbon stock changes are not accounted for in any of these studies. This means that the emission estimates in all the abovementioned studies could be underestimates.

### 6.3.3 Certification - a way to monitor sustainability in biofuel systems?

The sustainability and environmental impacts of biofuels are increasingly being put under scrutiny (see example of palm oil in section 6.3.4). Currently there is an international discussion on how to properly deal with sustainability of biofuel production. One option being discussed is to introduce certification schemes for biofuels, similar to e.g. the forestry certification schemes like the Forest Stewardship Council (FSC) and Programme for the Endorsement of Forest Certification schemes (PEFC). This section will shortly discuss some of the existing certification schemes that either directly or indirectly are connected to biofuel production. The focus here is on to what extent the schemes deal with the greenhouse gas balance of biofuel production chains.

Both FSC[10] and PEFC[11] regulations have paragraphs that focus on the importance of sustainable yield (see sections 4.7 and 4.9 for the distinction between greenhouse gas emissions and sustainability). However, from studies that have been made, it seems as if neither PEFC nor FSC or any other certification organisation has put much work into examining the greenhouse gas balance of the production chains. This is highlighted by Verdonk (2006) as well. He has conducted a study where a model of a possible biofuel certification scheme is developed with inspiration from existing certification schemes for coffee, sugar and wood. One of the systems examined is the FSC and the author concludes that "...the end scoring of the FSC governance system with regard to the areas of concern, are high scores, except for the 'GHG mitigation area of concern', which has a mediocre scoring." (Verdonk, 2006, p.108)

The World Wide Fund for Nature (WWF) has published a report (WWF, 2006) in which sustainability standards of bioenergy production are discussed. The authors put up a set of concerns (both social and environmental) which they consider important to address and focus on when determining whether a bioenergy production system is sustainable or not. Several different certification schemes are examined in order to determine to what extent the different areas of concern are sufficiently covered in each scheme. When it comes to the question of greenhouse gas emissions from bioenergy production, this seems to be a field which almost none of the schemes seem to have put much focus on. In fact, of all the eleven schemes examined, only

[10] E.g. paragraph 5.6 of the FSC criteria states that "...the rate of harvest of forest products shall not exceed levels which can be permanently sustained." (http://www.metafore.org/downloads/fscprinciplescriteria.pdf, 070404)
[11] PEFC criteria are based on the Montreal Process Working Group Criteria for Sustainable Forestry, which demands that "...timber and other forest resources are not being harvested unsustainably from a given forest area." (http://silvae.cfr.washington.edu/ecosystem-management/Montreal.html, 070404)

the Roundtable on Sustainable Palm Oil (RSPO) has any policy at all regarding greenhouse gas emissions from production and transport of biofuels. The RSPO criteria state that "plans to reduce pollution and emissions, including greenhouse gases, are developed, implemented and monitored". (WWF, 2006, p.56)

### 6.3.4 Palm oil

A biofuel that has been increasingly used in recent years is palm oil. One of the main reasons for its popularity is that it can easily be used in existing facilities as a substitute for fossil oil. However, there are many environmentally questionable aspects of the production of palm oil. Large areas of rainforest are cleared to make room for the oil palm plantations. This has not only increased the threat to several endangered species such as the orang-utan and the Sumatran tiger, but the production of palm oil has also caused large emissions of carbon into the atmosphere. The latter is especially true when oil palm plantations are located on drained peat lands, which 27% of oil palm plantations are, according to a study by Hooijer et al. (2006). The authors have studied $CO_2$ emissions from tropical peatlands and conclude that 2000 Mt of $CO_2$ is released annually from drained peatlands in Indonesia, 1400 Mt from peatland fires and 600 Mt from decomposition of drained peatlands. The authors note that this "…equals almost 8% of global emissions from fossil fuel combustion" (Hooijer et al., 2006, summary) and that this will help put Indonesia "…in 3$^{rd}$ place (after the USA and China) in the global $CO_2$ ranking" (ib.). Note that not all palm oil is produced in this exploitive way and that there is a Round Table on Sustainable Palm Oil, which has defined criteria for ecologically and socially sustainable production of palm oil.

The Dutch government has cut all subsidies for palm oil as a biofuel, and similar development can be seen in Sweden. For instance Fortum Värme, which previously used 1.9 TWh[12] of palm oil (of which 20% crude palm oil) annually for heat and electricity generation, announced in April 2007 that they would stop the use of crude palm oil. (HN 2007-04-07).

## 6.4 Transport emissions

The large difference in emissions from transport between the domestic and import production chains discussed in 6.3.2 is mainly a consequence of the longer transport distance for imported fuels. In addition to the truck transports, which are rather similar in all three studies, the Canadian pellets have to be transported 5000 kilometres across the Atlantic in order to reach Holland. Figure 6.3 show the specific $CO_2$ emissions for different types of transport modes.

[12] 190 000 tonnes. Palm oil has a heating value of 36.7 MJ/kg or 10.2 MWh/tonne according to http://www.codeart.org/en/technique/energie/huile_de_palme_combustible_moteur/060627s-Engine%20running%20on%20palm%20oil-%20anglais.pdf

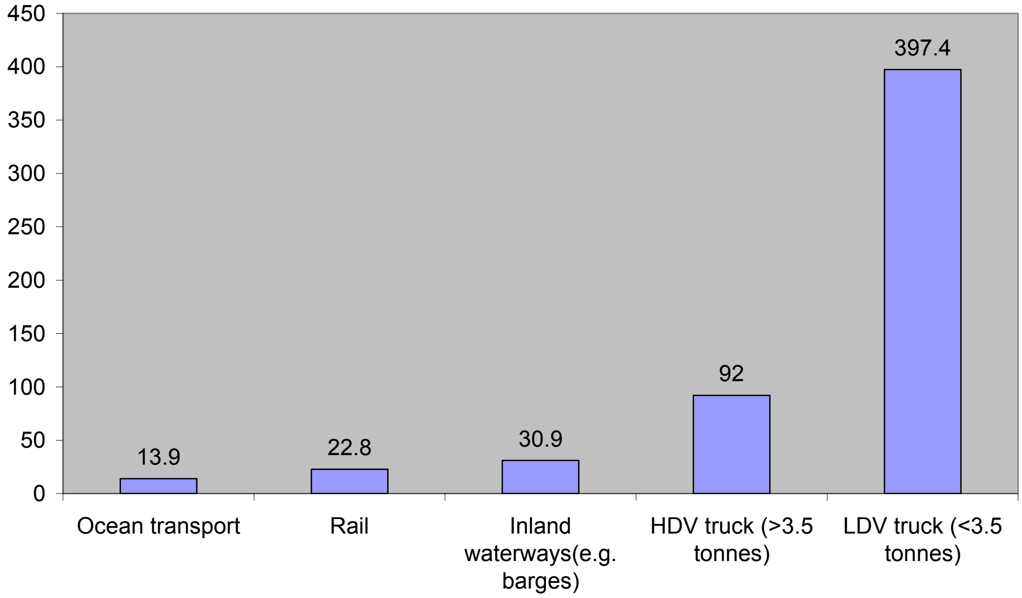


Figure 6.3. $CO_2$ emissions in grams per tonne-kilometre for freight transport in Europe. (European Environmental Agency, 2003)[13]. HDV = Heavy Duty Vehicle, LDV = Light Duty Vehicle.

### 6.4.1 Pelletisation emissions

Apart from ocean transport emissions, the major difference between the Scandinavian studies and the Dutch study is the emissions from the energy-demanding pelletisation process. The emissions from pelletisation in Damen and Faaijs study are more than twice the *total* emissions in Forsbergs and Petersen Raymers studies. This can largely be attributed to two issues: firstly, how the respective authors have decided to treat indirect emissions from electricity used in the pelletisation process and secondly, $N_2O$ emissions from combustion of sawdust for the drying process. Whereas Forsberg and Petersen Raymer assume that $CO_2$ emissions from electricity are zero, Damen & Faaij have made calculations on the emissions using mean emissions from Canadian electricity production. Furthermore, whereas the $N_2O$ emissions from the pelletisation process make 30% of the total greenhouse gas emissions in the Canadian case, they are negligible or none in the studies conducted by Forsberg and Petersen Raymer. It is not evident in the report by Damen & Faaij how much of the $N_2O$ emissions from the pelletisation process that come from electricity production and how much that come from sawdust combustion for production of heat for drying.

### 6.4.2 Discussion section

The comparison of the three LCAs presented above make clear that there are important questions to be discussed when trying to compare the greenhouse gas impact of imported and domestic biofuels, respectively.

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[13] Out of the railway emissions, roughly ¾ are from electric trains and ¼ from diesel trains. Emissions from electrical trains are based on electricity-mixes in the respective European countries. (Trends, 2003)

To begin with, comparing LCAs is always complicated. Issues like the choice of raw material for pellets (which affects the energy consumption in the pelletisation process), the way emissions from harvesting and sawdust production are allocated etc. are important choices that should be made in the same way for the resulting figures to be appropriate. Therefore the difference in emissions between the "domestic production" and the "import" studies presented above should not be understood as actual differences in emissions but could be due to differences in the system boundaries. It is however important to look more closely into the two parts of the production chains which were the cause of the large difference, namely the ship transport and the pelletisation process.

There is no doubt that the high emissions from transport are an inevitable drawback of intercontinental biofuel trade. A problem is that the environmental gains in transporting bulk goods such as pellets on ships instead of trucks are not as significant as the economical gains.

While it must be remembered that the data in Figure 6.3 is rather generic and consists of Pan-European mean values for the emissions from the different means of transport, the comparison still provides some input for the discussion. Data presented by Hektor & Lundberg (2006) suggests that the difference in transport *costs* between ocean and highway transport per tonne-kilometre could be as much as a factor 50. This can be compared to the difference in transport *emissions* of greenhouse gases which is only about a factor 7, as presented in Figure 6.3. A conclusion from this comparison is that ocean transport is less expensive than other modes of transport, but the difference in greenhouse gas emissions caused per tonne-kilometre is not as significant.

The largest difference between the domestic pellets production chains presented by Forsberg and Petersen Raymer, and the import chain presented by Damen & Faaij was the emissions from production of heat and electricity required in the pelletisation process. As was previously stated, it is unclear how much of the greenhouse gas emissions stem from $N_2O$ emissions from internal heat production and how much is indirect emissions from electricity production. It should be noted that the $N_2O$ emissions from the combustion of sawdust in the pelletisation process in the study by Damen & Faaij are unusually large. That could contribute significantly to the overall high emissions from the pelletisation process. However, the most important difference in LCA methodology between the studies is the way indirect emissions from electricity are handled. Damen & Faaij note that "… a large share of the generated hydropower in Canada is exported to California, so the capacity for internal use is […] more carbon intensive" (Damen & Faaij, 2003, p.39) which highlights just one of the problematic aspects of how to deal with emissions from electricity in LCAs. Again we stress that in all LCAs it is important to note how much electricity that has been used so that the reader and user of the LCA can choose what emission factor to use for the electricity.

The fact that different countries and regions have different electricity production mixes could still have implications on the choice of import countries. Pellets produced with electricity from low-$CO_2$ sources such as hydro power or other renewables would score better in LCAs and could be e.g.

used in advertising[14] to promote the environmental benefits of the pellets. An integrated production chain, where waste heat or internally produced steam is used for the drying process is a better choice from a resource perspective.

It is of significant importance to note that none of the LCA studies compared herein included soil carbon factors in their studies. As was discussed earlier in this report, soil carbon changes could be the most important greenhouse gas emission source of any biofuel production chain. Hence since the studies do not include this issue, the emission estimates might be underestimates. It should also be noted that the greenhouse gas emissions from biomass production at soils with different properties might vary significantly.

As for the possibilities to use certification schemes for guidance on the net greenhouse gas emissions of different biofuels, it seems at present no existing certification system has properly addressed the issue. This means that there is no available label to look for if one is searching for e.g. pellets with low net emissions of greenhouse gases. However, it must be said that forestry certification systems such as the FSC and PEFC at least indirectly have a policy on the topic by claiming to defend forests against deforestation; neither of the two have criteria mentioning the greenhouse gas balance of production and transport of wood products. Since major parts of global greenhouse gas emissions are a consequence of changes in land use and forestry, the greenhouse gas balance is an issue that the forestry certification organisations may have to focus more on in the near future. With the ever-increasing public concerns about global warming, not having criteria for e.g. maximum amount of greenhouse gases emitted during production and transport could become a serious threat to credibility of the major certification organisations such as the FSC and PEFC.

[14] This is already being done by the Swedish railroad operator SJ, which claims to only use renewable electricity to power locomotives. This is used extensively in the company's advertising campaigns to promote railway as an environmentally friendly alternative to air travel.

# 7 Case study: Radiative impact of forest residues

## 7.1 Specific description of the climate impact of forest residues

As described in chapter 5 we have compiled emission estimates from the production and utilisation (combustion) phase of forest residues. We have used these estimates to make calculations of the impact on the radiative balance. In Table 7.1 we summarise the emission estimates used in our calculations.

Table 7.1. Emission factors of forest residues production and combustion with uncertainty boundaries used in the calculations

| Emission factors | Average/ best estimate | Lower case | Upper case | Reference |
|---|---|---|---|---|
| **Production, direct** | | | | |
| CO2 (g $MJ^{-1}$) | 2.2 | 1.2 | 3.2 | Kirkinen et al. 2007; see also Table 5.1 and Table 5.10. |
| CH4 (g $MJ^{-1}$) | [a] | | | |
| N2O (g $MJ^{-1}$) | [a] | | | |
| **Production, indirect** | | | | |
| Decrease of soil carbon (g CO2 $MJ^{-1}$) | 10 | 7 | 13 | Wihersaari, 2005b; Eriksson et al. 2007. |
| **Combustion** | | | | |
| CO2 (g $MJ^{-1}$) | 110 | 100 | 110 | Kirkinen et al. 2007, Zetterberg & Hansén, 1998, |
| CH4[c] (g $MJ^{-1}$) | 0.0056[b] | 0.003 | 0.03 | Zetterberg et al. 2004; Kirkinen et al. 2007; Swedish NIR, 2007. |
| N2O[c] (g $MJ^{-1}$) | 0.0055 | 0.005[b] | 0.006 | Boström et al. 2004; Zetterberg et al. 2004; Swedish NIR 2007. |
| **Waste handling** | | | | |
| Ash recycling (g CO2 $MJ^{-1}$) | 0.05 | | | Wihersaari, 2005a |
| **Reference situation** | | | | |
| $CO_2$ emissions from decomposition of forest residues | 100 | | | Dynamics based on decomposition functions given in Ågren et al. 2007 |
| SUM | 124 g $CO_2$ eq./MJ | | | |

[a] The average length for transportation of forest residues is estimated to 50 km.

[b.] This value includes both emissions from combustion and collecting and transporting the forest residues.

[c] The average/best estimate of the $CH_4$ and $N_2O$ emissions from combustion is 1.8 g $CO_2$ eq./MJ which is higher than the estimates given in Table 5.10. However, we have chosen to use these values since these are the ones used in the Swedish NIR. These values should be considered to be in the higher range and rather to be overestimates than underestimates.

For the calculations of the radiative forcing we have used the IVL-model which has been described in detail in Holmgren et al. (2006). See also section 4.1 for a further explanation of the emission scenarios.

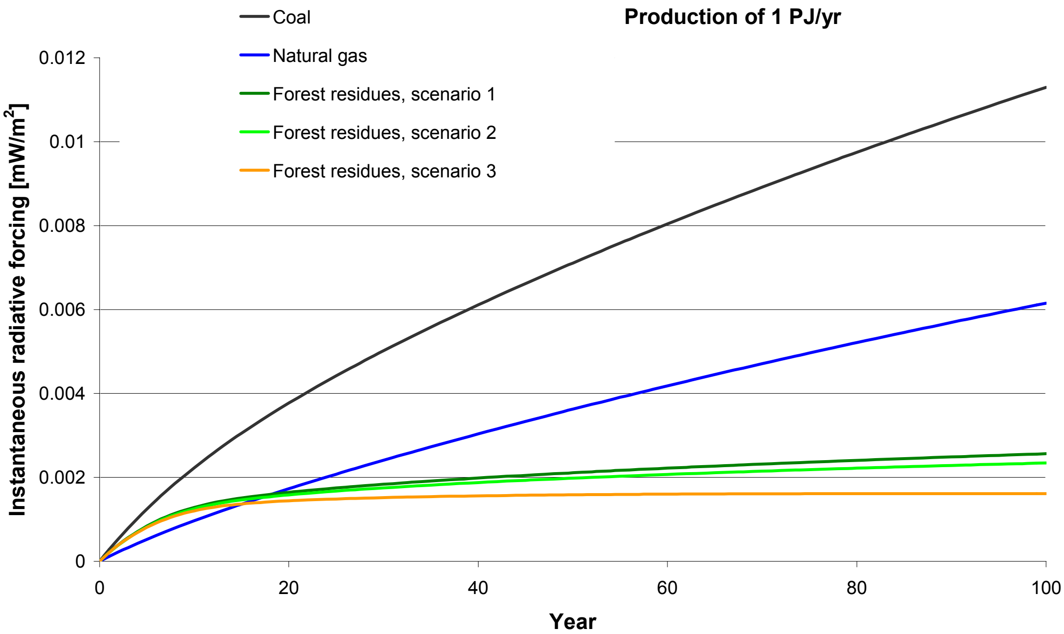


Figure 7.1 Instantaneous radiative forcing from energy production scenarios where 1 PJ of fuel is produced each year from year 0. The decomposition rate of the forest residue is based on estimates by Ågren et al. Note that the accumulated radiative forcing of each scenario is represented by the area between the x-axis and the respective curves.

Figure 7.1 shows the greenhouse impact from fossil fuels, e.g. coal and natural gas, and forest residues based on the data assessed (from the literature) in this study. 1 PJ of fuel is produced each year during 100 years. Emissions from the combustion are included. Table 5.12 and Table 5.11 show the emission estimates used for coal and natural gas whereas Table 7.1 shows the emission estimates used for forest residues. It should be noted that (combustion) plant efficiency is not taken into account when reporting emissions from the different fuels but are based on thermal values (lower heating values) of the input fuels and combustion emission factors.

It is also important to know what the references are in the calculations presented in Figure 7.1. For all fuels the reference scenario is that no energy production takes place and for coal and natural gas it is assumed that the natural gas and the coal are left in the belowground reserves. For forest residues the reference case means that the residues are left to decompose at the site of the cutting. This means that for forest residues we consider the emissions of $CO_2$ from the decomposition in the reference case as avoided in the fuel chain since they are "replaced" by the combustion phase.

The explanation to the level of the radiative forcing from production and utilisation of forest residues is the timing of $CO_2$ compared to the reference case; i.e. when combusting the forest residues, the $CO_2$ is released sooner to the atmosphere than what would be the case if the decomposition occurred naturally at the cutting site. The emissions caused by working machines and transports of the forest residues to the power plant and the emissions of other greenhouse gases than $CO_2$ only make a minor contribution to the radiative impact of forest residues as can be seen by comparing the different scenarios for the forest residues in Figure 7.1. In scenario 1 all emissions are included, in scenario 2 the emissions caused by transport and working machines (i.e. the help energy) are omitted and in the third scenario the impact on the soil carbon is excluded. In all scenarios the energy utilisation is continuous.

## 7.2 Comparison to previous studies

Our results could be compared to earlier studies of the radiative forcing of fuel chains. In Figure 7.2 the results from Savolainen et al. (1994) are presented. In the study by Savolainen et al. (1994) a number of different biofuels, as well as fossil fuels and peat were included. The explanation to the favourable situation for the use of wood waste is that the authors assumed that in the reference case the wood waste would be placed in a landfill and the decomposition would result in emissions of methane, which is a stronger greenhouse gas than $CO_2$. Hence by combusting wood waste, methane emissions were avoided.

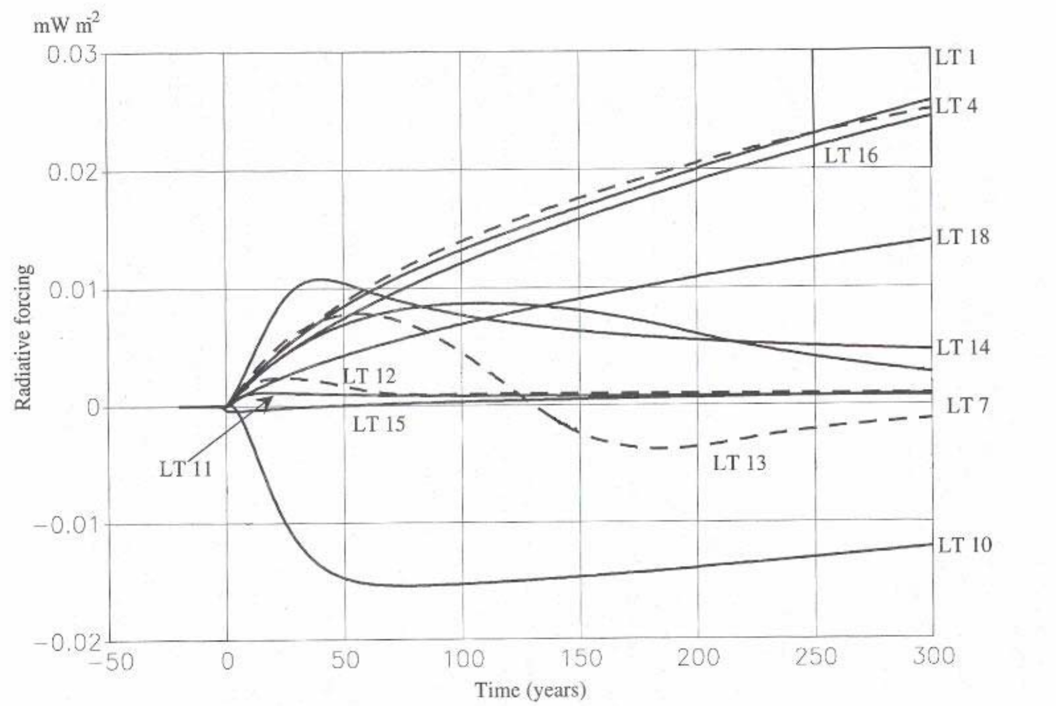


Figure 7.2 Radiative forcing caused by the energy production chains for different fuels. 1 PJ of energy is produced annually. Source: Savolainen et al. 1994. The table below explains what fuels the different chains represent.

Table 7.2. The different fuels included in the Savolainen et al. 1994 study.

| Name in figure | Fuel |
|---|---|
| LT 1 | Peat from pristine peatland |
| LT 4 | Peat from forest drained peatland |
| LT 16 | Coal |
| LT 18 | Natural gas |
| LT 14 | Wood from coppice forest |
| LT 7 | Peat from cultivated peatland |
| LT 12 | Wood from first thinnings |
| LT 11 | Forest residues (from harvesting) |
| LT 13 | Unused merchantable wood |
| LT 10 | Wood waste |

In Figure 7.3 the results from another lifecycle study of fuel chains, Zetterberg et al. (2004) are presented. In their study forest residues, fossil fuels and peat were included. However, in the figure below we have omitted the results for peat since peat is not in focus of this study.

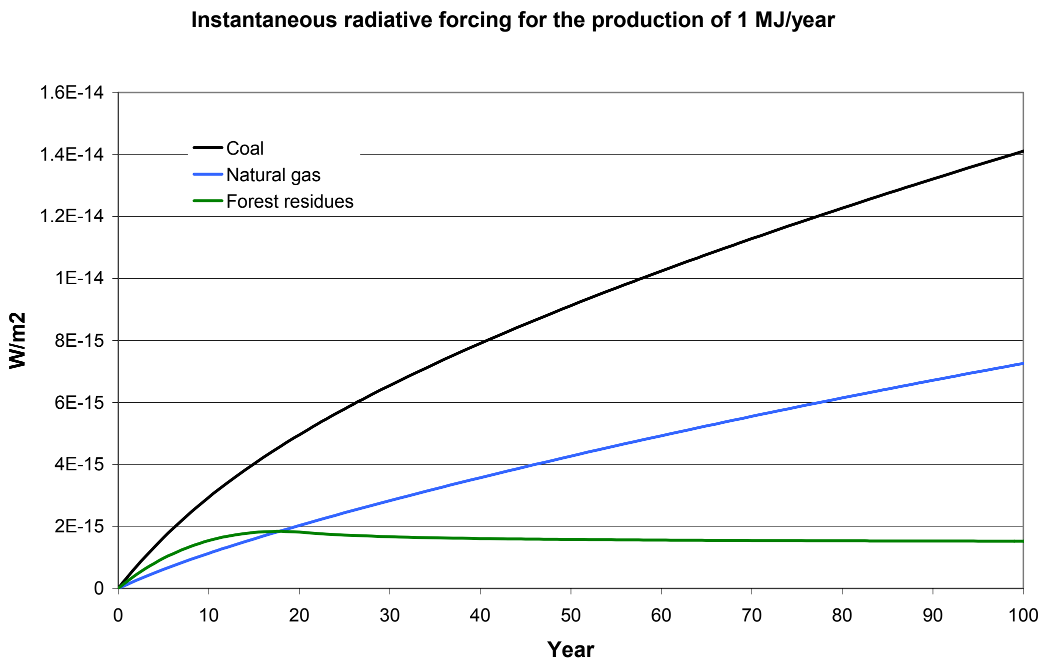


Figure 7.3 Instantaneous radiative forcing for the production of 1 MJ/year of coal, natural gas and forest residues. Results from Zetterberg et al. 2004.

The difference in the level of the radiative impact from forest residues between Figure 7.1 and the levels in Figure 7.2 and Figure 7.3 can be explained by the fact that a much shorter faster decomposition rate was assumed for the forest residues in Figure 7.2 (the study by Savolainen et al.). The comparison between studies gives an indication of the difference between biofuels with different decay rates. Hence the radiative impact from stumps, which have a significantly slower decay rate than the forest residues will be greater whereas the radiative impact from a biofuel with shorter rotation period (like energy grass) will be smaller.

Both in Figure 7.1 and Figure 7.3 we can see that in the very short perspective 0-20 years the radiative forcing caused by natural gas utilisation and forest residues are within the same range. However, in a longer perspective there is a significant difference between the fossil fuels and the forest residues. The impact on the radiative balance from forest residues reaches a steady level whereas the impact form the fossil fuels continue to rise. Since greenhouse gases and $CO_2$ (which is the main part of the greenhouse gas emissions in these fuel chains) remains for a long time in the atmosphere the longer time perspective is the most important. Hence a short time perspective does not motivate the use of natural gas instead of forest residues.

# 8 Discussion

## 8.1 Discussion on the greenhouse gas emissions of biofuels

The net emissions of greenhouse gases (i.e. carbon dioxide, methane and nitrous oxide) from the production and utilisation chains of solid biofuels are not zero. According to the compilation of emission estimates in chapter 5 the amount of emissions of greenhouse gases from the different fuel chains investigated in this study are in all cases positive, i.e. net emissions of greenhouse gases occurs. However, the evaluation does not include the substitution effect, i.e. that biofuels can be used to replace fossil fuels and in that sense, save emissions of carbon dioxide and other greenhouse gases. The reason is to keep the comparison simple and to enable comparison with fossil fuels and other studies.

One of the most important sources of greenhouse gases from the biofuel production and utilisation chains, the soil emissions, are difficult to quantify and at least for some fuels the magnitude is not well known. For forest residues and stumps it seems as if the impact of harvest probably results in reductions of the soil carbon stock, whereas for other fuels, mainly agricultural biofuels, the impact could be increasing soil carbon. However, for agricultural biofuels, emissions of $N_2O$ associated with temporarily high groundwater level, fertile sites, N-fertilization and soil preparation can be significant. In this study the only energy crop considered was *Salix* and no annual crop (e.g. reed canary grass, hemp, etc.) was included. For such crops the total balance might look different. Also for other types of biofuels, not considered in this study, (e.g. biogas, liquid biofuels used in the transport sector etc.) the total balance might be very different. According to a study by Börjesson & Berglund (2003) the total balance for biogas is negative due to lower emissions of methane in the reference case. According to Mäkinen et al. (2006) the greenhouse gas emissions associated with production and use of some biofuels can be significant. Systems with intensive use of fertilisers are especially pointed out as high emission systems.

Since the emissions of greenhouse gases from different biofuel production and utilisation chains can vary substantially it is of importance to study the fuel chains and to take them into consideration when making strategic decisions for the future fuel and energy production systems.

### 8.1.1 The importance of the time perspective

According to Figure 7.1 the time perspective is of great importance when comparing different fuels. In the short perspective, 20 years, the impact on the radiative forcing from the biofuel system is comparable to the impact from natural gas. What does this mean? Should we rather use natural gas? Part of the answer can be seen in the same figure since there is a fundamental difference between the biofuel (i.e. forest residues) and the fossil fuels in the long run. As the radiative impact from biofuel reaches a steady state, the impact from the fossil fuels continues to rise. The main part of the greenhouse gas emissions in all fuel chains included in this study is $CO_2$, which remains in the atmosphere for approximately 100 years. Since the greenhouse gases remains for a long time in the atmosphere a long time perspective is also most relevant.

Important to note from Figure 7.1 is that the net radiative impact from the use of biofuels is not zero, even if there might be other biofuels where the impact is even smaller than from the forest residues. We should be aware that more or less all energy consumption results in greenhouse gas emissions in one way or the other so the best way of reducing emissions is to reduce our need for energy and use energy more efficiently.

Figure 7.1 also shows that the timing of emissions is important. The main reason for the radiative impact of the forest residues to level out on a positive level is that $CO_2$ emissions occur faster in a combustion scenario than in a decomposition scenario. For biofuels with shorter decomposition time than forest residues, this effect will be smaller whereas for biofuels with longer decomposition rate (e.g. stumps) the impact will be larger.

Further, the importance of sustainable production systems should be acknowledged. Most of the studies upon which the input data to this study was based on have not included any estimates on a possible change in productivity of the systems. In the case of forest residues this means that we have not considered that the removal of residues from the forest might result in a reduced productivity of the site. The reason for not including this is that there are few studies made and according to studies where N (nitrogen) fertilisation is made in order to compensate for losses, fertilisation does only influence the overall emission estimates marginally. However, this effect should be considered also for other biofuel systems. This is connected to the sustainability and renewability of the resource. Also re-growth/plantation of new forest/crops is of importance for the systems. In our calculations we have assumed that the areas of biofuel production are continuously used for biofuel production, and according to Figure 4.1 the result would look very different if reforestation is applied in the reference situation but not in the fuel production scenario. In Sweden there are very few exceptions where reforestation is not applied, due to the forestry law. Exceptions could be when the land is cleared due to some new use such as construction of infrastructure etc.

### 8.1.2 Time perspective comparison between peat and biofuels

The time perspective today establishes the boarder between biofuels and peat. Peat is a material which is constituted by partly decayed plant material and was until recently considered a fossil fuel. Today it is classified in its own fuel category but emissions are accounted for in the same way as fossil fuels. Peat in a natural peatland is accumulating due to the poor conditions for decomposition. This means that combustion of peat results in $CO_2$ emissions occurring thousands of years in advance (assuming that the climatic and hydrologic conditions of the peatland will prevail). On the other hand, on a drained peatland, the conditions for decomposition have changed and the peat is decomposing and $CO_2$ emitted to the atmosphere. This means that combusting peat from an already drained peatland might add the $CO_2$ emissions a hundred or a few hundred years earlier. Today no distinction is made between peat from natural or already drained peatlands.

## 8.2 Discussion on system boundaries for LCA analysis of biofuel production and utilisation chains

### 8.2.1 By-product or main product?

Many of the biofuels investigated in this report are considered to be by-products (or to use by-products as raw material) from other production systems; i.e. forest residues are by-products from forest operations; bark, sawdust and dry chips are all by-products from the forest industry; recovered fuel in it self is a by-product and pellets are usually produced from sawdust which is a by-product. In this study by-products have not been charged for emissions occurring due to the production of the main product in their system (for the forestry systems the main products are timber and pulpwood). However, one could consider allocating the emissions in a production system between main product and by-product. For instance such allocation could be based on the economic value of the products. For forest residues this means that emissions due to normal management of the forest is divided between the main product/s (timber and pulpwood) and the forest residues based on the relative economic value of the different products.

Allocating the emissions for forestry between the different products, including forest residues, based on the economic value could be reasonable since the increasing demand for biomass can change the economic incentives in forestry and also the management methods. For sawdust and bark it might also be appropriate. For most forested land and with current prices the difference between the two approaches is very small, due to the higher value of the main products. Hence we think that it is appropriate to use the current simplification of considering these products as by-products. However, drained peatland under forests may emit large amounts of $CO_2$ and $N_2O$ and if these are to be accounted for in the future (due to changed prices) it may drastically increase the net emissions related to forested residues from drained peatlands.

### 8.2.2 The impact on the soil carbon

The impact of the fuel production system on the soil carbon stock can be of great importance to the total greenhouse gas balance of the production and utilisation chain. When considering soil emissions it is important to know what the reference situation is. There are soils which emit large amounts of greenhouse gases (mainly $CO_2$ and $N_2O$) irrespectively what kind of crop that is grown on them. An important category here is drained peatlands which are used for either agriculture or forestry. Reasons for high emissions of greenhouse gases are: the drained state, and low CN (carbon –nitrogen) ratios In order to keep the productivity of the system, the drainage system needs to be maintained, an active management which keeps emissions high. In addition fertilisation also contributes to high greenhouse gas emissions. One could discuss what reference level to choose for such systems but of course emissions occurring due to active management should be accounted for.

What is then the reference? For cultivated peatlands this is a delicate question. The emissions might change to some extent depending on what crop is grown, since management methods differ (site preparation and fertilisation). If choosing the most recent cropping system as reference, energy crops grown on land where row-crops (e.g. carrots, potatoes) previously were cultivated would probably have a better balance than if the previous crop was some kind of perennial grass. Should the reference instead be the situation before drainage? That might at least in Sweden mean a situation several hundred years before present. We think that it is most appropriate to use the most likely recent scenario as a reference. Hence if information on what kind of crops that actually has been cultivated at the area during recent years is available, that should be used

For forested peatlands similar questions arise since also from these soils the emissions of greenhouse gases ($CO_2$ and $N_2O$) can be significant. What is our reference? Is it that the production forestry would go on and include clearing of old ditches which will maintain the productivity of the forest but might increase soil emissions? Or should we consider the situation before drainage? We think that the most appropriate reference option for forestry drained peatlands is to assume that the forestry would continue with necessary and normal management, which will keep the productivity (hence clearing of ditches will be included).

### 8.2.3 The importance of substitution

The net emissions of greenhouse gases from the production and utilisation of biofuels are not zero, and for the particular biofuels investigated in this study, the net emissions are positive, hence contributing to the increasing greenhouse effect. Hence we also conclude that the net greenhouse gas emissions are significantly smaller for biofuels than for fossil fuels. Some of the carbon emissions associated with the use of biofuels are caused by losses in carbon storage and according to several previous studies (Eriksson & Hallsby, 1992; Eriksson et al. 2007; Berndes et al., 2006; Alriksson 1988; Schlamadinger et al. 1995 and Cowie et al. 2006) such emissions looses significance in the long-term perspective (i.e.> 100 years) since the effect of replacing fossil fuels by biofuels is a continuous effect (and therefore unlimited) whereas the losses in soil carbon are limited. Figure 7.1 shows continuous utilisation of each fuel, and if biofuels would replace fossil fuels the substitution effect (the difference between the curves) will increase over time.

### 8.2.4 Importance of the reference situation

In section 5.4 and 5.5 the emission estimates presented for by-products from the forest industry and recovered wood do not have a reference scenario where the wood would be placed in a landfill as suggested by other studies. We think that the reference case should reflect the current situation and since the energy content of the wood is significant it is not likely that it would be placed in a landfill. In addition depositing material on landfills is prohibited in Sweden which further decreases the likelihood of this option.

For pellets, emission estimates including emissions associated with the production of sawdust, (the assumed raw material for the production of the pellets) have been presented. This could be questioned since sawdust is a by-product that would be produced anyway. However, the supply of sawdust currently seems to be smaller than the request for pellet raw material, which implies that other raw-materials could be used.

### 8.2.5 The impact of climate change

Studies of the impact of climate change show that many regions in Sweden will experience higher biomass production due to higher temperatures and prolonged growing season. The changes may also result in faster decomposition of organic matter. The net result of soil organic matter due to higher litter supplies (due to higher production rates) and faster decomposition is not fully known. Further, it strongly interacts with other environmental changes such as precipitation patterns and N deposition. However, faster decomposition rates mean a faster recirculation of $CO_2$ from forest residues to the atmosphere and hence using it as biofuel will be more attractive from a greenhouse gas point of view. Increased production rates and increased decomposition may also shorten the time period needed for compensation of the emissions from biofuels. Climate change may also, due to its impact on soil moisture, affect greenhouse gases from drained organic soils, both $CO_2$ and $N_2O$, which may change the net emissions following drainage and fertilising. However, most of the studies on the future impacts on biomass production are based on climate scenarios and do not include non-meteorological factors such as increased exposure and vulnerability of ecosystems to pathogens and pests. Few of the models include all of the climatic factors and a transient development of the climatic changes. Feedbacks and the overall impact are therefore estimated by separate calculations. This makes the uncertainty of the estimated changes large.

The future changes in climate and other environmental factors and their impact on the biomass production systems are not fully known and in this study we have not been able to include any such effects.

### 8.2.6 Impact of other sources

As stated in chapter 4 and chapter 5.1, LCAs normally consider all emissions associated with an activity. This includes emissions from the production of machines and infrastructure used in the production of the product. However, it has been concluded that for most fuels this is a very small part of the total emissions. For that reason we have excluded such emission sources.

There is a lack of estimates of greenhouse gas emissions from storage of biofuels. However, for instance Wihersaari 2005b indicate that the emissions of greenhouse gases, mainly methane but also nitrous oxide, from comminuted biofuels (such as chip or sawdust) can be significant and actually larger than the greenhouse gas emission from the production and transportation of the fuel. We think that it is important to also take these emissions into consideration in future comparisons and there is need for further research within this topic.

In some of the references we used for the emission data compilation, it had been assumed that the use of electricity is associated with zero emissions. However, this is a simplification since all electricity generation causes greenhouse gas emissions. Even if some nations have electricity generation associated with low emissions of greenhouse gases (due to high shares of nuclear power, hydro or other renewable sources) the transfer capacity between countries (at least in the Nordic countries and in many European countries) is significant and the marginal production is usually based on some fossil fuel. An alternative to using an emission factor for electricity based on a countries average production mix, is the use of an emission factor for the marginal production. The difference between these approaches is further discussed in STEM (2006), and Sköldberg et al. (2006). However, whatever approach is used for assessing LCA emissions from biofuels we think it is necessary to point that out and to acknowledge the amount of electricity used so that the reader easily can make own calculations and compare with an electricity production associated with certain amount of greenhouse gas emissions. In this study that was done for pellets.

## 8.3 Discussion on origin of biofuels (domestic vs. imported)

In chapter 6, a comparison was made between LCA studies of pellet production chains for domestic production and trans-continental production of Canadian pellets for consumption in Holland. The comparison resulted in large differences in greenhouse gas emissions between domestic and imported pellets. However, due to differences in system boundaries between the studies (in the domestic studies electricity were assumed to result in zero emissions of greenhouse gases, whereas in the Canadian production it was given a high emission factor) and differences between the specific conditions (in the Canadian case a sawdust boiler with low efficiency was used) it is difficult to draw any general conclusions from this comparison. Hence, it is not possible to say whether the production of pellets per se produces more greenhouse gas emissions in e.g. Canada or Sweden.

It is also difficult to draw any conclusion on whether transport emissions from imported biofuels are larger than transport emissions from domestically produced biofuels. For instance, the transport distance across the Baltic Sea from e.g. Latvia to Stockholm could be shorter than the distance from the Northern parts of Sweden to Stockholm. On the other hand, the emissions from long distance ship transport of pellets, e.g. across the Atlantic from Canada or the US to Sweden, does certainly cause significant additional emissions compared to locally produced and transported biofuels. The discrepancy between the cost of shipping fuel and the corresponding emission factor is a key issue.

It is generally difficult to overview the greenhouse gas emissions and overall sustainability of production systems in other countries. Some guarantees of sustainability are given by the certification of forestry, whereas the issue of greenhouse gas emissions seem not to have been approached in a comprehensive way by existing certification schemes.

# 9 Results and conclusions

## 9.1 Biofuels and climate neutrality

We conclude that there are reasons not to consider biofuels as "climate neutral" since all production and utilisation chains of biofuels result in emissions (or uptake of) greenhouse gases. In this study we have chosen to look at net greenhouse gas emissions (carbon dioxide, methane and nitrous oxide) of production and utilisation chains of biofuels and to compare the climate impact of the emissions by radiative forcing calculations. We conclude that all of the investigated fuel chains (only solid biofuels) result in net emissions of greenhouse gases. However, the net emissions of the investigated biofuels were in all cases lower than corresponding emissions for fossil fuels. The emission estimates for fuel chains varies depending on fuels and on how system boundaries have been set in the different LCA studies upon which we have based the assessment.

The following factors can contribute significantly to the total emissions of greenhouse gas emissions of a biofuel production and utilisation chain:

- Impact of production system on soil carbon storage. The impact can be either increased emissions from the soil or an increase in the soil carbon storage (hence uptake from the atmosphere). For forest fuels, the soil carbon impact is likely to be negative whereas it for some energy crops from agricultural land might be positive. This may particularly be the case if the crop is N-fertilised, since that reduces decomposition.
- Land use-methods (especially use of drained peatlands). Drained peatlands used in intensive cropping systems (agriculture) can be significant sources of $CO_2$ and $N_2O$. $N_2O$ emissions can also be high due to site preparation and use of fertilisers.
- Use of fertilisers (both direct and indirect)
- Combustion technology (e.g. certain systems for domestic heating can result in high greenhouse gas emissions (Cooper et al. 2003)
- Refining of the fuel (i.e. drying and pelletisation). Such processes can require significant energy use and depending on what form of energy (electricity, heat from own production based on by products etc.) that is used it will be associated with different amounts of greenhouse gas emissions
- Storage (especially of comminuted fuels). Due to lack of data, this has not been investigate thoroughly in this study but needs to be investigated further.

Other sources that contribute to the emissions during a production and utilisation chain are; harvesting machines, transportation and waste handling.

The comparison of emissions shows that all biofuel chains investigated have significantly lower emissions than fossil fuels (i.e. coal and natural gas) and hence can be used to replace fossil fuels and thereby reduce greenhouse gas emissions. The setting of system boundaries in the LCAs is crucial for the results (e.g. how the allocation between main products and by-products is made, how emissions from use of electricity is accounted for etc). Note that in the comparison of emissions from the different biofuel chains, $CO_2$ emissions from combustion and decomposition are not included since they are assumed be equally large, if allowing time frames to be sufficiently long.

When comparing the climate impact of the greenhouse gas emissions by using radiative forcing the $CO_2$ emissions from combustion and decomposition of biofuels were included. The radiative impact of forest residues is significantly lower than the impact from fossil fuels. Since $CO_2$ remains for a long time in the atmosphere and there is great inertia in the climate system the time perspective applied for fuel systems needs to be long.

Most of the biofuels imported to Sweden are transported by ship. Ship transports result in lower emissions of $CO_2$ per tonne-kilometre than freight transport. Depending on the distance between the export country and Sweden, the emissions from transportation of imported fuels can be either lower or higher than for domestic fuels.

We conclude that since sustainability in fuel production systems is important, the question of reforestation is important. The reforestation legislations in Finland and Lithuania seem to be comprehensive, whereas policies in Estonia and Russia seem to be more open for interpretation. We have found little information on policies in Canada and Latvia, from which Sweden import significant amounts of biofuels today. There is a need for a comprehensive study of forest legislation of the most important export countries of biofuels. Certification could also be a tool to ascertain sustainability of forestry systems.

The net emissions of greenhouse gases from biofuel production systems shall be considered when making strategic decisions on future fuel production systems, in order to minimize greenhouse gas emissions.

## 9.2 Criteria for “climate neutral” biofuels

We prefer the terminology; criteria for biofuels with low net greenhouse gas emissions. In order to establish criteria for biofuels with lowest possible emissions of greenhouse gases during the production and utilisation chain, we believe it is important to first define the purpose of such criteria. What would be the use and application of the criteria? The parties concerned (authorities, industry, land-owners etc.) should be involved in the process.

How criteria are set up depends on the purpose, and the below description could be a possible procedure. As an example we have chosen forest residues, but a similar approach could be applied to other fuels as well.

1. Define the different steps in the production and utilisation chain.
2. For each step divide different options in low and high ghg (greenhouse gas) emission alternatives. The limits set for each of these two categories should be based on an overall analysis of the total emissions from the entire fuel-chain.

Example; Forest residues:

**General:** Forest residues should only be used from land that is managed in a sustainable way, i.e. with respect to sustaining economical, social and ecological values of the land. One way to certify this is to use residues only from certified forestry.

**Site conditions and land management:** From what sites are residues harvested?
Low ghg emissions: Mineral soils with moderate or low fertility and with fresh or dry moisture conditions.
High ghg emissions: Soils rich in nitrogen (N) (low CN ratio) and/or N fertilized soils. These sites show a slower decomposition rate and residues left on the forest land would have a greater impact on soil carbon stocks. A high N availability in the soil might also lead to emissions of $N_2O$. Forestry on peatland with sustained drainage might also lead to significant emissions of greenhouse gases.

**Harvesting:** How is forest residues harvested?
Low ghg emissions: The residues are left to dry in the field for some time, allowing the nutrient rich needles to fall off. Harvesting less needles will lead to lower impact on growth of next generation.
High ghg emissions: Residues are removed directly and almost all needles are removed. This might lead to lower productivity for the next generation, if not compensated for by fertilisers.

From what sites are residues harvested?
Low ghg emissions: From rich sites with high nitrogen deposition. (Likely to have small or no impact on productivity).
High ghg emissions: From poor sites with low nitrogen deposition. (This might again have influence on productivity if not compensated for by fertilisers)

What quality of the residues is removed?
Low ghg emissions: Branches and tops – these qualities decompose relatively fast and the difference compared to leave them at the site will be small
High ghg emissions: Stumps and coarse roots – these qualities decompose slowly and the extraction might speed up decomposition of old organic matter in the soil.

**Transportation:** How and how far is the fuel transported?
Low ghg emissions: short distances by low emission transport modes
High ghg emissions: Long distance by trucks

**Upgrading:** Is the fuel dried artificially?
Low ghg emissions: No or with waste heat from some industry
High ghg emissions: Yes, by using electricity or fossil fuels.
Is the fuel comminuted?
Low ghg emissions: Yes, before transportation to save

transportation costs
High ghg emissions: Yes after transport

**Storage:** Is the fuel stored?
Low ghg emissions: Yes, for some time in the field, but for a short time at the plant.
High ghg emissions: Yes for a long time comminuted in stacks at the plant. This might lead to significant emissions of methane and nitrous oxide.

**Waste handling**: What is done with the ashes?
This has turned out to have a low impact on the overall result, but there might be exceptions, for instance if the ashes need to be transported far distances.

**Combustion:** In what type of plant is the fuel used?
Low ghg emissions: Modern CHP with flue gas condensing. Such plants have high efficiency.
High ghg emissions: Old CHP or heat plants without flue gas condensing. Such plants have a very low efficiency and the emissions/MJ will increase since the MJ will be less.

**Aftertreatment of harvested area:** Is the area reforested?
Low ghg emissions: Yes, as soon as possible after cutting.
High ghg emissions: No, the area is deforested.
Is the forest/land managed in a sustainable way?
Low ghg emissions: Yes, the forestry is certified.
High ghg emissions: No, the production capacity is continuously decreasing.

**Time perspective:** How much earlier do $CO_2$ emissions occur due to combustion of the biofuels compared to a situation where they would not have been used?
Early: fast decomposing matter such as needles and fine branches
Late: Slowly decomposing material, in particular stumps and coarse branches and roots.

Note that the abovementioned questions will have to be amended and the answers are only indicative of the results given in this study and should not be considered as final. For each alternative estimates of greenhouse gas emissions (in g $CO_2$-eq. $MJ^{-1}$) should be given which enables an overall analysis of each possible fuel chain. The combustion, aftertreatment of the harvested area and time perspective needs separate evaluations, which for instance could include radiative forcing calculations.

# 10 Further research

The impact on soil carbon storage of some of the biofuel production chains is not properly known. This needs to be further investigated. This is especially important for the use of stumps since the impact can be significant emissions from the soil. Also for agricultural crops the impact on soil carbon storage can be of importance. This should be investigated for biofuels from the agricultural sector.

Net greenhouse gas emissions and the radiative impact for other biofuel systems, especially energy crops grown on agricultural land should be assessed and compared to our results (which mainly include forest-based solid biofuels).

Greenhouse gas emissions from storage of comminuted wood can be significant, and this has not been included in the estimates made in this study. Future studies should investigate this matter further. Estimates of average storage times, storage conditions etc. should be assessed as well as further estimate of actual emissions from storage heaps.

The question of allocation of emissions between main products ad by products needs further investigation. LCA studies of the greenhouse gas emissions from normal forestry could be used for this purpose (i.e. for pulpwood, timber, forest residues, etc.). In addition an LCA where 100% of the product is used for energy purposes could be used to show the impact of possible future systems and the impact of timing of emissions from a fuel with long rotation period.

To properly compare the greenhouse gas emissions from domestic and imported biofuels, LCA studies need to be conducted using the same system boundaries for all production chains. This is necessary to properly tackle the methodology differences which otherwise severely damage the validity of such comparisons. This is also true for the comparison of domestic fuels.

Furthermore, this report has highlighted that the impact of land use change, especially in tropic regions, can potentially be a major source of greenhouse gas emissions. It is important that future LCAs on biofuel production chains take such matters into account in order to provide a comprehensive view of the greenhouse gas emissions of the whole chain.

International biofuel markets are evolving rapidly and biofuel trade can be expected to experience a significant growth in the coming years. This means that new sources of biofuel supply and new trade patterns will emerge. As has been discussed in this report, the GHG emissions from imported biofuels can vary significantly depending on both the conditions at the site of origin as well as the transportation distance. Therefore, more research on Swedish biofuel import patterns is needed in order to be able to assess the net greenhouse gas emissions and climate impact of imported biofuels.

An amendment to the available studies of reforestation legislation needs to be conducted in order to provide better overview of how the issue is dealt with in different countries. The methodology and the presentation of results applied in UNECE & FAO (2007) could be used. The scope of an amending study should be to include all European countries and all major forest nations in the world.

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