Greenhouse gas calculator for electricity and heat from biomass

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Greenhouse Gas Calculator for Electricity and Heat from Biomass

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Disclaimer

The following disclaimer has been drafted by the Stakeholders Committee. It is advised to read this page before using the GHG calculation tool

GHG calculation tool for electricity and heat from biomass
The Greenhouse gas (GHG) calculation tool has been developed following the GHG calculating methodology for biomass formulated by the project group "Sustainable production of biomass" (Commission Cramer). The tool compares direct GHG emissions of the most commonly used feedstocks for electricity and heat in the Netherlands with GHG emissions of the standard fossil fuels they replace. The method follows the general rules for lifecycle assessments (LCA). Because of uncertainties in the LCA-approach and in the data, the variation in the outcome of the calculation is at best +/-15%[1] (This means that a 45% greenhouse gas emission reduction indicates a reduction between 30% and 60%).

Points of particular interest and risks
The greenhouse gas reduction ratio of biomass chains is one of the sustainability criteria formulated by the Commission Cramer. Other sustainability aspects are for example biodiversity, possible competition with food, environmental effects, impacts on economic development, social well being of employees and local population or smallholders. An evaluation of the sustainability of a specific biomass chain should be based on the complete set of sustainability criteria.

This greenhouse gas calculation tool does not take indirect land use change into account. Production of biofuels on existing agricultural land may lead to a displacement of agricultural production into natural area's. The greenhouse gas emissions of such indirect

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[1] Viewls, an international study on the greenhouse gas performance of biofuel supply chains, let by SenterNovem, indicated an uncertainty of 30% on the total emission, at an average total emission of 50% compared with the fossil reference. The resulting uncertainty is thus 15% points.

land use change may be substantial, but are at this stage not included in the tool. The Commission Cramer recommends to set up an international monitoring system to follow the effects at the macro level.

Suitable purposes for the tool

- The tool is suitable to identify possibilities to improve the GHG performance of biomass production.
- The tool is suitable to compare the GHG performance of biomass produced on non-agricultural land.
- The tool gives a maximum estimation of the greenhouse gas emission reduction of biomass produced on prior agricultural land.

Not or less suitable purposes for the tool

- The tool is less suitable to compare biomass produced from residues or produced on non prior agricultural land (e.g. idle land) with biomass produced on agricultural land, because for the last category the tool only gives a maximum estimation for the greenhouse gas emission reduction, because indirect land use change is not taken into account.
- The tool cannot be used to compare biomass production with other greenhouse gas emission reduction measures like for example more efficient cars, wind mills or planting trees to store carbon.

Summary

This report describes the development of a calculating tool to estimate the greenhouse gas performance of electricity and heat from biomass feedstocks and compare that to a fossil reference. The tool, E-LCA, is intended as a specification of one of the sustainability criteria for biobased energy, as developed by the Commissie Cramer for the Dutch government. In this report, the methodology and data used for the GHG calculator are described and results of the calculations are presented. The calculator itself, consisting of calculating software together with a database, a supporting spreadsheet and a user's guide, is a separate product.

The calculator specifies the total greenhouse gas (GHG) emissions of cradle-to-grave chains of electricity and heat, including feedstock production, transport, production of the fuel (if applicable), and the processes of generating electricity and heat. Included as greenhouse gases are CO_2, CH_4 and N_2O, the latter two are especially relevant for biomass based chains. It compares those chains with a fossil reference, representing a chain of electricity and / or heat from fossil sources. The average Dutch electricity mix was used as the reference in most cases; for specific chains specific other references have been defined, following the choices made in the "Renewable Energy Monitoring Protocol" which offers generally accepted basic data for Dutch energy policy and research. The GHG performance of fossil reference chains is also specified from-cradle-to-grave.

The calculator uses the Life Cycle Assessment (LCA) methodology. Data have been taken from a wide variety of sources. For some chains, especially those related to agricultural residues and municipal waste, uncertainties in data are considerable. Progressive knowledge generation is expected to deliver better and more generally accepted data in due time. Methodological choices in some cases have a large influence on the outcomes of the calculations. These are basically different from data uncertainties: based on choices and not on facts. Methodological choices must be consistent and transparent in view of a level playing field. International harmonization is very important in this respect. For that reason, we have followed the rules for calculation as specified in the EC draft Directive "Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources". The GHG calculator for bio-electricity and heat has been developed alongside the development of a similar GHG calculator for bio-based transport fuels. Throughout the whole period, data and methodological choices have been discussed and harmonized between the two projects.

The draft EC Directive lacks guidance on how to treat energy generation from waste streams. A rather large number of chains of electricity and heat generation from waste is included in the calculator. Therefore, we have developed our own approach to deal with this, in line with the general starting points in the EC Directive.

The results from the calculations show that chains from electricity and heat generally perform better than their fossil equivalents on GHG emissions. Within this general statement, there is still a large variety, ranging from chains that actually perform worse to improvements up to a 100%.

Some general conclusions can be drawn. In the first place, there is a shift in GHG emissions by replacing fossil by biomass-based electricity: CO_2 emissions are considerably less but CH_4 and N_2O emissions generally higher. In some cases, the bio-electricity chains performing worse do so because of this shift. Especially in cases of agriculture on newly converted soils emissions may be very high due to carbon losses from soil and forests. In some cases, the process of producing fuel from feedstock is energy-intensive and therefore limits the overall benefit.

In the second place, chains from organic wastes generally show a very good GHG performance. This is due to the fact that they are considered to deliver two functions: treatment of waste and delivering energy. When looking at these chains as they are, their performance is often not better than the fossil alternative. When accounting for the waste treatment service, their allocated benefits become substantial.

This observation relates to the third general conclusion: it appears that the choice for allocation may have a very large influence on the outcomes. This is especially true for the use of by-products and waste as a feedstock for energy. For example, under the influence of allocation choices the performance of the chain of manure digestion varies between +260% and -110% improvement compared to the fossil reference. This indicates the need for a further careful international debate on this issue.

When using the GHG calculator, it should be kept in mind that this in itself is not indicating the sustainability of bio-based electricity and heat, but just one aspect of it, namely the greenhouse gas performance of cradle-to-grave chains of bio-electricity and heat. Other sustainability aspects such as land and water use, direct or indirect loss of natural ecosystems, other emissions besides GHG, indirect effects on the food market, all kinds of social effects, are not included.

Glossary

Allocation:
(1) approach for dealing with multi-output processes in LCA. Several approaches are indicated: allocation based on energy, economic value, mass or other parameters, substitution, and systems expansion.
(2) all allocation approaches based on distributing environmental burdens over multiple outputs, also known as allocation-by-partitioning.

By-product: any product or service from a cradle-to-grave chain, besides the main product or service.

CHP: combined heat-power installations. CHP installations are available in different sizes.

CFPP: coal fired power plant

Cradle-to-grave chain: chain of processes required to produce a product or service, including all life-cycle stages: mining, production, use, waste management.

Default parameter: a preset parameter that is set as default.

Economic allocation: distributing environmental burdens over multiple outputs based on their market value

Energy allocation: distributing environmental burdens over multiple outputs based on their energy content

Fossil reference: the cradle-to-grave chain of electricity and heat from fossil fuels to be compared with an equivalent chain of electricity and heat from biomass. Several different fossil references are defined.

Functional unit: the product or service delivered by the product system.

GFPP: gas fired power plant

GHG: greenhouse gases

GHG performance: greenhouse gas performance, the total of all emissions of CO_2, CH_4 and N_2O from a cradle-to-grave chain of electricity and heat, except biogenic CO_2, expressed in kg CO_2 equivalents.

Life Cycle Assessment (LCA): an analytic tool to compare equivalent product systems on their potential environmental impacts.

LHV: Lower Heating Value, a measure of the energy content of a fuel. LHV is also known as net calorific value or net CV. The LHV is defined as the amount of heat released by combusting a specified quantity (initially at 25 °C or another reference state) and returning the temperature of the combustion products to 150 °C. The LHV assumes that the latent heat of vaporization of water in the fuel and the reaction products is not recovered. By contrast, the higher heating value (HHV) (a.k.a. gross calorific value or gross CV) includes the heat of condensation of water in the combustion products.

Mass allocation: distributing environmental burdens over multiple outputs based on their mass

PPO: pure plant oil. Oil products from crops such as oil palm, soy or rapeseed.

Predefined chain: a common chain of electricity and heat production from biomass that can be selected in the tool.

Preset parameter: data connected to processes of chains of bio-electricity and heat that are entered in the tool. There are three types of preset parameters: conservative, typical and best practice.

Product system: the total cradle-to-grave chain of processes required to deliver a specified product or service.

RDF: Refuse Derived Fuel, a feedstock for electricity and heat made from municipal solid waste.

Substitution: Allocation approach to account for the credit of by-products avoiding a production process elsewhere, or to account for the credit of using by-products or waste streams avoiding a waste treatment process. Typically substitution is done by subtracting the avoided process from the system.

Swill: organic waste from restaurants

Systems expansion: Allocation approach to account for the credit of by-products expanding the system to include more than one functional units.

VGF: Vegetable, Fruit and Garden waste

Introduction

1.1 *Purpose of the study*

The purpose of the study commissioned by SenterNovem has been to develop a tool to calculate greenhouse gas (GHG) emissions of cradle-to-grave chains of electricity and heat from biomass, and compare those to equivalent chains of fossil energy and heat. This report contains the technical specification of the calculator, E-LCA. In the main report, the methodology is described and the most important data sources are listed, and the results from the calculations are presented. The Appendices contain detailed information on the chains, including process data and methodological choices. E-LCA itself, consisting of calculating software, a database, a supporting spreadsheet and a user guide, is a separate product of this study.

The starting point for this project is the report "Testing Framework for Sustainable Biomass" issued by the Commissie Cramer (SenterNovem, 2007b), and the recommendations and the criteria laid down in this report. The Commissie Cramer has advised the Dutch government on sustainability aspects of the use of biomass as a source of energy. The CO_2 balance is one of those criteria. The methodology to be used in the GHG calculators for biobased electricity and heat and bio-fuels is outlined in the report "The greenhouse gas calculation methodology for biomass-based electricity, heat and fuels" (SenterNovem, 2007a). The following guidelines can be taken from this report:

- Inclusion of cradle-to-grave chains of feedstock production, conversion and use
- Specification of all GHG emissions throughout these chains
- Use of a Life Cycle Assessment (LCA) approach:
    - Defining a functional unit as a starting point and demarcate system boundaries based on this functional unit.
    - Specifying the product system in a quantitative manner, including inputs and outputs of products, materials and energy as well as emissions to and extractions from the environment on a process-by-process basis. The specification of emissions and extractions is limited to greenhouse gases in this case.
    - Adding up GHG emissions throughout each cradle-to-grave chain to determine the GHG performance of that chain, expressed in CO_2-equivalents.
- Comparison of these chains with a fossil fuel based alternative, specified on similar principles. The choice for such alternatives is another methodological issue of high relevance, especially in the case of using waste streams for energy generation.

Since the start of this project, the EC has produced a draft Directive with guidelines for calculation procedures to follow in GHG calculators for biofuels (Commission of the European Communities, 2008). On the whole, the two methodologies conform. Where they differ, we have followed the EC guidelines. This is specified in the report, wherever applicable.

A similar tool has been developed at the same time to assess the GHG performance of cradle-to-grave chains of transport fuels (Hamelinck et al., 2008). Methodological choices and, wherever applicable, data have been discussed throughout the project and have been harmonized.

1.2 *Process*

The project teams of the two projects have been advised by experts, organized in topical groups: the focus groups. The focus groups have met once to discuss the main methodological choices, assumptions, data sources and outcomes for the various chains. Their advice has been followed whenever there was a clear consensus within the groups. The two projects have also been supervised by a Stakeholder Committee of stakeholders, discussing the project with an eye on implications for the use of the GHG calculators in practice. Controversial issues have been put before the Steering group of representatives of the various involved Ministries to decide. Stakeholders were also involved in the field tests of the developed calculators, to assess the usefulness and user friendliness of the tools and advise the project team in that respect. International harmonization has also been attempted by a number of meetings during 2007 with international experts working at similar tools in Germany and the UK. Methodological choices have been revisited in view of a draft Directive of the EC issued in early 2008 (Commission of the European Communities, 2008).

1.3 *Structure of the report*

This report is structured as follows: in Chapter 2, the functional requirements of the calculator are described; Chapter 3 is dedicated to methodological issues; in Chapter 4 data issues, such as the data format and the selection of data to include in the tool, are treated; Chapter 5 describes the different feedstocks and conversion processes included in the calculator are described. In Chapter 6, results from the calculations are presented. Detailed data on the various chains can be found in the Appendices.

Functional requirements

2.1 Output of the GHG calculator for electricity and heat from biomass

The output of E-LCA for the user is the net GHG emissions of cradle-to-grave chains of electricity and heat generation from several biomass feedstocks, in terms of CO_2-equivalents. The calculator also contains net GHG emissions from functionally equivalent cradle-to-grave chains of electricity and heat generation from fossil fuels, to enable a comparison between the bio-based and fossil based alternatives. It is also possible to compare different, functionally equivalent, bio-based routes for the production of electricity and heat.

2.2 Data and calculator

The tool contains preset values for all processes in both bio-based and fossil-based chains. These preset values refer to the economic inputs and outputs of processes, in terms of raw materials (in kg) and energy (in MJ), and to the environmental inputs and outputs, limited in this case to GHG uptake and emissions (in CO_2-equivalents). Both processes of the supply chains of biomass and conversion processes transforming biomass into electricity or heat are included, with preset values. These preset values come in three types:

- a conservative value, i.e. the worst case in the market
- a typical value, i.e. the market average
- a best practice value, i.e. the best in the market.

Unless specifically stated otherwise, the conservative values are used as defaults.

By selecting a functional output, e.g. 1 MJ of electricity from palm oil, generated by the conversion process of co-firing, the tool will generate the process tree, i.e. will combine the relevant processes in the database into a cradle-to-grave chain. It will add up all GHG emissions into a total. The calculator contains a default choice for an allocation procedure. According to the methodology adopted by the Commissie Cramer (2007), the first choice is to use substitution, and to use economic allocation if substitution is not possible. The recent Draft Directive by the EC (EC, 2008) however states a preference for allocation based on the Lower Heating Value (LHV) of the functional outputs. We have adopted this latter starting point, in view of the international harmonization of methods. This will be elaborated in Chapter 3. Other allocation options are included in E-LCA, but the user cannot easily modify the allocation choice. In order to compare the biobased production route with a fossil alternative, a functionally equivalent fossil chain needs to be defined. A limited choice of default reference systems is defined as well and included in the calculator (see Chapter 6).

2.3 User defined input

It is possible for the user to disregard the preset values and use others, if for some reason the preset values are not applicable or not in line with the situation at hand. The availability of more up-to-date, better or more detailed information may also be a reason to deviate from the default assumptions. Users can change feedstock data and process data of their own chain. The choice for the allocation methodology and the choice of reference systems cannot be changed.

Changing values to replace the default chains for policy applications requires suitable proof. If sufficient proof is available, processes can be modified to the user's own specifications. For the time being, "sufficient proof" is defined as "taken from accepted literature". In general this would imply the information comes from trustworthy sources, such as the IPCC or statistical offices. Some of the most generally accepted literature sources are mentioned in this chapter, below in Section 4.2.

2.4 Chain definition

A distinction is made into the production of the feedstock and the electricity or heat generating processes. In general terms, we have:

- Agricultural or forestry production, including fertilizing, crop protection, and harvesting
- Transportation of the crop or waste stream, by boat, truck or lorry
- Conversion of the crop or waste stream into a product suitable for electricity or heat generation, including sawing, pelletising, refining, etc.
- Transportation of the product
- Conversion of the product into electricity or heat.

Each (group of) processes can be subdivided into processes at a more detailed level. Not all five steps are applicable in all cases – e.g. when electricity generation takes place at the local level near the production of feedstock, no transport is required, and the use of waste streams may imply disregarding the feedstock generating processes.

Methodological issues

The methodology to compare options for bio-energy with fossil fuel alternatives and with each other is described in general terms in SenterNovem (2007a), elaborating one of the Commissie Cramer criteria, and in the draft EC Directive (EC, 2008). The approach taken in both is a Life Cycle Assessment (LCA): comparing cradle-to-grave chains on a functional basis. This implies specifying chains from the production of the biomass through the processes of feedstock generation, conversion technology and end-use, including all electricity and transportation required in the chain. The unit processes, specifying economic inputs and outputs (raw materials, products and energy) and environmental inputs and outputs (emissions to and extractions from the environment), are chained together to deliver the function, in this case the generation of heat and/or electricity. The methodological steps of LCA studies are specified in the ISO standard for LCA (ISO, 2000). We followed the LCA Handbook (Guinée et al., 2002), written as a guide to the ISO standard, unless this is not in accordance with the methodological choices issued by the Commissie Cramer, in which case we conformed to the latter. The ISO LCA standard knows the following steps:

- Goal and scope definition
- Inventory
- Impact assessment
- Interpretation.

It is important to notice that ISO specifies LCA as an iterative process: it is recommended to reconsider earlier choices in the light of later outcomes.
The most important steps in the methodology are discussed in the next sections.

1.4 *Defining the functional unit and setting system boundaries*

An LCA study starts by defining the functional unit as part of the Goal and scope definition. In this case, the goal is, comparing the GHG performance of generation of electricity and heat from biomass to that of electricity and heat generation from fossil fuels. The functional unit therefore will have to be in terms of electricity and heat. For electricity, we have used the production of 1 MJ of electricity, low voltage, as a functional unit. An alternative is to use medium voltage, as this is most frequently used by industry. The tool leaves the option open that in future a change may be made to medium voltage electricity. For heat, the functional unit is defined as 1 MJ of heat. Two types of heat are distinguished: high-temperature heat suitable for industrial use, and low-temperature heat suitable for space heating. In combined processes (CHP) heat and electricity are generated in a certain ratio. Both outputs can serve as the functional unit, emissions from the previous chain are allocated over the electricity and heat outputs based on their respective energy contents, in line with the draft EC Directive.

Starting from the functional unit, the product system is defined. This step requires specifying system boundaries: what belongs to the system and what not? There are certain rules for cut-off of capital goods and waste. In this project, the choice was made to exclude capital goods completely. Waste related issues are relevant in this case, because biobased electricity often comes from feedstocks bordering between waste and by-product. For waste as an input, the production chain in front is cut off. When using a by-product, allocation is required (see Section 3.2). Whether or not a certain flow is classified as waste is determined by economic reasoning: the value should be zero or negative, the latter indicating that actors in the chain pay for the treatment or for getting rid of the waste stream. This definition follows the conventions of the LCA community.

1.5 *Specifying the product system and Allocation*

In the Life Cycle Inventory (LCI), the product system is quantified in terms of inputs and outputs of raw materials, energy, products and emissions to and extractions from the environment. The system is built up out of so-called unit processes: standardized process descriptions in LCI format. LCA databases contain large lists of such unit processes. In the product system, starting from the functional unit, these processes are called on and appear in the process tree with inputs and outputs matched to the delivery of the functional unit. For the reference fossil fuel chains, the GHG performance is calculated using data from the Ecoinvent database, a standard LCA database with a good background in energy generation processes.

A methodological issue of great importance is multi-output allocation. When a process has more than one functional output and only one is used for the functional unit, the chain before somehow has to be distributed over the various outputs, or another correction must be made. There are various options to do that, specified in the ISO 14040 standard for LCA studies.

The most straightforward way is partitioning: dividing the previous chain over the outputs. This can be done in different ways again:

- Economic allocation, based on the relative market value of the outputs
- Physical allocation, based on the relative outputs of mass, or on other physical variables such as the carbon content or energy content of the outputs.

Correction of the system is another option. This can also be done in different ways:

- Systems expansion: adding one or more functional units, so the systems becomes a multi-function system. A relevant example is a CHP installation: this produces two outputs, electricity and heat. Systems expansion means that both outputs are taken into consideration. The fossil reference for this system then also must be composed out of both electricity and heat, in the same ratio. This approach is proposed by ISO as the way to avoid allocation according to some sort of partitioning.
- Substitution: keeping the single functional output but correcting the system by subtracting an “avoided process”. This, too, can be regarded as avoiding allocation by partitioning. Substitution is often used in the case of waste or by-

[2].

There is no “right” or “wrong” way to allocate, and all of these options are accorded by ISO. It does, however, make a difference for the outcomes, sometimes even a very large difference, as is already mentioned in the LCA Guide to the ISO standard (Guinée et al., 2002). This makes it a very important and equally difficult and controversial step in the LCA procedure.

In view of the intended use of the GHG calculators, not only scientific “correctness” or accordance with ISO-standards are decisive here, but also robustness and transparency, especially when the tool is used for regulation and interests are at stake. The chosen approach must not be vulnerable for speculative outcomes and must allow for a level playing field to be established. The methodology specified by SenterNovem (2007a) indicates to use the substitution method whenever possible. In light of international developments and especially to conform with the draft EC Directive, this choice has been re-visited and allocation based on energy (the LHV of the functional outputs) is applied.

In case of production of electricity and heat from crops or crop-based fuels, the draft EC Directive offers sufficient guidance on how to handle allocation. GHG emissions are allocated based on the LHV of main products and by-products alike. In some cases, an exception is made: for a number of specified agricultural residues, it is stated that all GHG emissions should be allocated to the main product. In the calculator, we have conformed to these specifications. The draft EC directive does not specify the case of generating energy from waste (i.e. a residue with no economic value). In line with LCA practice, we made the choice in such cases to ignore the previous chain and allocate all GHG emissions to the main, often non-energy related product. The Directive also does not give guidance on how to treat energy generation from the residues mentioned above. Our interpretation of the Directive is, to treat such residues as waste streams. These issues, however, are likely to be debated further in the international arena.

In the case of generating electricity or heat from waste treatment processes, another problem occurs. Such processes are often quite inefficient when compared to electricity generation from fossil fuels. Allocating all GHG emissions from the waste treatment processes to the generated electricity or heat would result in a low or even negative improvement percentage. The EC draft Directive does not specify how to deal with this. It is the question, whether it makes sense to regard these processes as energy generating processes, while in fact they have another main function: the service of waste treatment. Since this service has no LHV it is difficult to attribute part of the emissions to it with the chosen allocation method. We have solved this by using the LHV of the incoming waste-to-be-treated to allocate emissions to the waste treatment service. Other solutions can be imagined, however, these may not conform to allocation based on energy content. In the international debate, this issue will come back.

[2] NB Another way to apply substitution is to consider electricity generated from conventional (fossil) sources as the avoided process. In this case this is not feasible since electricity from fossil sources is already used as a reference for comparison (see section 3.3).

3.3 *Reference systems*

A third issue is the definition of reference systems. A comparison must be made between the biobased electricity and heat chains and comparable fossil chains. The EC Draft Directive leaves open the choice of using a general European reference for electricity, or a more local one. In the calculator, we have specified reference chains for the Dutch situation. In most cases, the Dutch grid mix of heat and/or electricity is used. In some cases, specific reference systems are defined for specific biobased energy chains. The guidelines of the Renewable Energy Monitoring Protocol (SenterNovem, 2006) are followed for the choice of reference systems. This is specified in Chapters 5 and 6.

1.4 *Calculating the GHG performance of chains*

The results of the LCA inventory is a list of GHG emissions of all processes in the chain. These are added up and are translated into CO_2-equivalents by IPCC-defined factors. Greenhouse gases included in the tool are CO_2 (IPCC factor 1) CH_4 (23) and N_2O (296). The LCA approach, methodology and data allow for a wider analysis, including other impact categories as well. This may be of interest at a later stage, when other sustainability criteria will be operationalised.

1.5 *Carbon neutrality of biomass chains*

The production of biomass involves extracting CO_2 from the atmosphere and incorporating it in organic material. Later, when the biomass is used to produce electricity or heat, this CO_2 is emitted once again. Because the moment of extraction is not far removed in time from the moment of emission – depending on the exact feedstock, this ranges from several weeks to several decades – these feedstocks are considered to be carbon neutral. In energy analysis, the common practice is that neither extractions nor emissions are accounted for: they are assumed to eliminate each other and add up to zero beforehand. The standard LCA procedure is that both emissions and extractions are accounted for. In the case of straightforward chains, both ways will lead to the same results and therefore it does not matter. However, when allocation is involved, this may not be the case. Depending on the allocation method, a smaller or larger part of the extractions and/or emissions may be attributed in various extents to co-products of the chain. In this project, a choice was made to follow the convention from the energy analysis field to consider the biomass feedstock as carbon neutral. We must then be aware that results may differ from those of LCA studies “by the book”.

1.6 *Ignoring the fossil part of co-firing processes*

In co-firing processes, biomass is used together with fossil fuels to generate electricity and/or heat. The percentage of biomass being co-fired varies, but is in most cases quite low. The usual practice in LCA methodology is to include processes as they are. In this case, the co-firing process would be included with two feedstocks as inputs: biomass (e.g. wood pellets) and fossil fuels (e.g. coal), and one service as output: electricity or heat. In deviation of that, a distinction is made to the different inputs and the calculations in the tool are confined to the GHG performance of the use of biomass as a feedstock only. The decision to do this has been made in the Stakeholder Committee and also has been applied in the calculator for biobased transport fuels.

1.7 *GHG performance indicator*

After the GHG performance of the chains of electricity and heat generation from biomass feedstocks is specified, we end up with one number per chain: the total GHG emission expressed in kg CO_2-equivalent per 1 kWh of electricity, or per 1 MJ of heat. This number then should be compared with the GHG performance, in similar terms, of the fossil equivalent of this particular chain. In the methodology developed for the Commissie Cramer, the following indicator is proposed:

$(GHG_{fossil} – GHG_{bio}) / GHG_{fossil}$ (in %).

This indicator represents the GHG improvement of the bio-energy chain over the fossil equivalent. In the GHG calculator, this indicator is calculated as one of the outcomes.

Data and calculation procedure

1.8 *Data format*

The data format is taken from the LCA methodology and the Ecoinvent database we use (Ecoinvent Centre, 2006). A distinction is made between economic flows (goods coming from or going to another production or consumption process in society) and environmental flows (extractions from and emissions to the environment). Each process is specified in terms of its economic as well as environmental inputs and outputs in physical terms: kilograms, cubic meters, kWh, piece etc.. Process data from literature in some cases need to be re-calculated to this format. This is reported in the Appendices for the separate chains. Conversions, multiplyers and other factors needed to recalculate literature data into the LCA-format are presented after the process data in spreadsheets.

These basic process data are then used to build process trees of entire chains. To arrive at a total score for GHG performance, emissions (environmental outflows) of CO_2, CH_4 and N_2O are translated into CO_2-equivalents and added up.

In the tool, we keep the foreground process data, referring to the chains of biomass electricity and heat themselves, at the desaggregate level. It is possible to use aggregated chains, but the drawback is that pre-cooked choices for process data, allocation and cut-off cannot be reversed. For background processes, preset values are based on aggregated chains. The user cannot change those. Background processes are e.g. electricity from the grid needed in the chain, or transportation by ship, truck or train.

1.9 *Data sources*

Background data are mostly from the Ecoinvent database. For the foreground data, i.e. the processes related to feedstock production and conversion of feedstocks / fuels into electricity and heat, we used a large variety of data. These are listed in the References at the end of this report, as well as in the Appendices where the chains are described in more detail. For several chains, especially those related to plant based oils and wheat, data have been used from Hamelinck et al. (2008), the report of the parallel project for developing the GHG calculator for biofuels.

Some sources are of an overall-importance because of their standing as internationally accepted literature or their guidance for making choices. These are listed below.

Guiding publications for methodological choices:

- SenterNovem, 2006. Renewable Energy Monitoring Protocol, update 2006. Methodology for calculating and recording amounts of energy produced from renewable sources in the Netherlands. Available at: **http://www.senternovem.nl/mmfiles/protocol2006%20-%20English_tcm24-209344.pdf**

- SenterNovem, 2007a. The greenhouse gas calculation methodology for biomass-based electricity, heat and fuels. Energy Transition, January 2007. Available at: **http://www.senternovem.nl/mmfiles/Toetsingskader%20duurzame%20biomassa_tcm24-221153.pdf**
- SenterNovem, 2007b. Toetsingskader voor duurzame biomassa. Eindrapport van de Projectgroep "Duurzame productie van biomassa". Available at : **http://www.senternovem.nl/mmfiles/Toetsingskader%20duurzame%20biomassa_tcm24-232793.pdf**
- Guinée, J.B., Gorrée M., Heijungs R., Huppes G., Kleijn R., de Koning, A., Oers L. Van, Wegener Sleeswijk A., Suh S., Udo de Haes H.A., de Bruijn H., Duin R. Van & Huijbregts M.A.J, 2002. Life Cycle Assessment, an operational guide to the ISO standard. Springer verlag.

Encompassing valuable studies related to bio-electricity and heat:

- Damen K. & Faaij, A., 2005. Greenhouse Gas Balances of Biomass Import Chains for "Green" Electricity Production in the Netherlands. Available at: **http://www.ieabioenergy-task38.org/projects/task38casestudies/netherlands-brochure.pdf**
- IPCC, 2000. SPM Land Use, Land-Use Change, and Forestry. Intergovernmental Panel on Climate Change, Montreal.
- IPCC, 2006. IPCC Guidelines for National Greenhouse gas Inventories - Agriculture, Forestry and Other Land Uses. Intergovernmental Panel on Climate Change, Hayama.
- Parkhomenko S., 2004. International competitiveness of soybean, rapeseed and palm oil production in major producing regions. Landbauforschung Völkenrode FAL agricultural research, Braunschweig Germany.

Useful statistical sources:

- CBS, 2006. Land- en tuinbouwgegevens 2006.
- Food and Agriculture Organization (FAO), 2004. Fertilizer Use by crop.
- International Energy Agency (IEA), 2007. BIOBIB, A database for biofuels. Available at: **www.vt.tuwien.ac.at/Biobib/fuel300.html**
- KWIN AGV 2006. Kwantitatieve Informatie. Akkerbouw en Vollegrondsgroenteteelt 2006. PPO No. 354, p. 93-94, 126-128
- Milieu en Natuur Compendium, Elektriciteitsproductie en –verbruik, 2007. http://www.mnp.nl/mnc/i-nl-0020.html.
- Seebregts, A.J. & Volkers C.H., 2005. Monitoring Nederlandse Electriciteitscentrales 2000-2004, ECN.

The reports of the studies conducted at the same time on biofuels (SenterNovem, forthcoming and Bauen et al., in prep.) have also been a good source for data, methodology and harmonization.

For the individual chains, data sources have been listed in the Appendices.

1.10 *Combining process data into chains*

The procedure for combining processes into chains starts with the functional unit: in this case, a unit (kWh or MJ) of electricity and/or heat. The process generating this electricity and heat has certain inputs: fuels and equipment. These inputs are made by other processes. In the tool, the processes producing those fuels and equipment as outputs are then added, to the amount that they are required for generating the unit of electricity or heat. These processes in turn also have economic inputs and call on yet other processes, etc. etc., back until every economic input reaches its ultimate extraction from the environment. In this way, the cradle-to-grave chain is built up out of the processes it is composed of.

1.11 *Calculating procedure: E-LCA*

LCA is the theoretical model underlying the computations of the CO_2 calculating tool. This is a model that comprises aspects of data (like the CO_2 emission of a combustion process), choices (such as on allocation), and mathematical equations (e.g., related to the calculation of the system-wide CO_2 release).

The practical implementation of the calculating tool is another issue. For this, there are several options:

- doing the calculations by hand or using a pocket calculator;
- using a spreadsheet to carry out the computations;
- developing or purchasing dedicated software for LCA.

The first option works fine for very small systems, provided no recalculations are needed to account for updates or scenario calculations. The use of a spreadsheet works good for larger systems, and it is also able to process changes easily, but it has the disadvantage that more advanced types of analyses (e.g., contribution analyses, Monte Carlo simulations) are difficult to implement. The use of dedicated software, finally, is from a working point of view superior, but it takes some time to learn to operate such a program, and some of the available programs are quite expensive.

In this project, we have chosen to elaborate on an existing dedicated program for LCA. This program is called CMLCA, an abbreviation of Chain Management by Life Cycle Assessment. CMLCA 5.0 has been the starting point. A fourth view mode has been introduced, dedicated specifically to the requirements of the project. The new version has received a new name: E-LCA, which stands for Energy Life Cycle Assessment. The program, with the database containing the bio-electricity and heat chain data and a user manual, is a separate deliverable of this project. The program can be used to get an overview of the GHG performance of the default chains included in the database and to compare those with their fossil reference. Results are expressed in terms of GHG emissions and as % emission reduction in comparison with their fossil alternatives (the previously mentioned GHG indicator). More detailed analyses are also possible, for example by using the Contribution analysis, which provides insight in the processes in the chain contributing most to the GHG emissions. The user can also modify the user-defined default chains to suit his/her own purpose. How E-LCA is operated, is not described in this report, but in the user manual.

Feedstocks and conversion processes

For the combination of feedstocks and conversion processes many options are available. The current version of the CO_2 tool contains only a limited number. A choice has been made for the chains currently most in use. In future, it is possible to expand the number of options as seems appropriate.

1.12 *Feedstocks*

Feedstocks included in the calculator are

- Wood and woody by-products
- Agricultural crops and products
- Manure
- Organic residues from agriculture
- Organic waste streams from the food industry
- Municipal solid waste (MSW), VFG and Refuse derived fuel (RDF) from MSW
- Sewage sludge from Waste Water Treatment Plants (WWTP)

1.13 *Energy generating processes*

We include the following energy generating processes, some in different variants:

- Co-firing of biomass in a fossil-fuel based electricity plant, generating electricity
- Combined heat and power (CHP) in installations of different sizes, generating electricity as well as heat in the same process, and with different power : heat ratios
- Waste incinerators, generating electricity as a by-product from waste treatment

Other processes are specified to generate a fuel from the feedstock:

- (Co-)gasification of organic matter, converting biomass into syngas which can be used for heating or electricity generation
- (Co-)fermentation or digestion of manure and other organic matter, generating CH_4 (biogas or green gas) which is used for heating and/or electricity generation

These processes are used in combination as well: gasification followed by co-firing, or fermentation followed by small scale CHP.

A description of processes delivering electricity and heat is provided in Appendix A.

1.14 *Combinations*

Not all combinations of the abovementioned feedstocks and conversion processes are included in the tool. The possible combinations of feedstock, scale level and conversion processes are too extensive for that. On the one hand, many different feedstocks can be used. On the other hand, different conversion processes are available, that can in some cases even be used in serial. Therefore, a selection has to be made. We made the following selection, based on our ideas of the most relevant chains:

- Pure plant oils (PPO: palm oil, rape seed oil and soybean oil):
    - Large scale co-firing with gas
    - Large scale CHP
- Wood residues (wood chips, wood pellets and waste wood from construction)
    - Large scale co-firing with coal
    - Large and medium scale CHP
- Agricultural crops
    - Small scale co-digestion with manure followed by CHP (grass, maize)
- Agricultural residues (manure and crop by-products)
    - Small scale manure digestion followed by CHP
    - Small scale manure co-digestion with maize, grass and/or potato residues followed by CHP
    - Large scale biogas production from manure co-digestion
    - Small scale single firing of straw in a grate furnace
- Waste from the food industry
    - Medium and small scale digestion of swill (restaurant waste) followed by CHP
    - Large scale co-firing of animal fat and bone meal with coal
- Municipal solid waste
    - RDF production followed by incineration in cement ovens
    - MSW incineration with energy recovery
    - Large scale biogas production from VFG digestion
    - Landfill gas recovery
- Sewage sludge
    - Large scale biogas production from sewage sludge digestion

In the GHG calculator, the possibility remains open to make different combinations of processes or to enter additional processes or even whole chains.

1.15 *Fossil reference systems*

The choice of reference systems refers to the fossil fuel alternative: the equivalent chain of heat or electricity based on fossil feedstocks. The following choices have been made:

- We use the option given in the EC draft Directive of specifying local, i.e. Dutch, reference systems.
- For electricity, in most cases, the reference is the electricity from the grid, using the Dutch electricity production mix. Following the “Renewable Energy Monitoring Protocol” (SenterNovem, 2006), electricity and heat from renewable sources is excluded, making it a mix of fossil and nuclear energy sources. At present, the difference with the total Dutch production mix is minor. In future, this might be different. A case could be made to take the Western European or EC mix as the reference, since the electricity market is international. However, the tool is presently developed for the Dutch situation and Dutch decision making. Therefore the Dutch mix seems to be the most relevant choice.

- Next to the grid mix, more specific references are defined in addition for the different routes of bio-based energy generation. This allows for a more specific and sometimes more appropriate comparison. These specific references are also in accordance with the "Renewable Energy Monitoring Protocol". In the case of co-firing of biomass in large-scale coal or gas plants, the fossil reference is the large scale coal or gas plant without biomass co-firing. This is calculated by comparing the chain of biomass production and use with the chain of the production and use of the amount of coal or gas that is actually being replaced by the biomass, on a per MJ basis.
- For heat we define two references, industrial use (high temperature) and use for space heating (low temperature). Depending on the heat production process in question, a choice is made for one of them.

System	**Fossil reference**
Co-firing of biomass with coal or gas	• Low voltage electricity from coal/gas fired power plant
Firing in cement ovens (RDF)	• Heat from coal
Heat from biogas / green gas	• High / low temperature heat from natural gas
Other bio-based systems	• Low voltage electricity from Dutch production mix, excluding renewable sources

For the calculation of the GHG performance of the fossil reference chains, Ecoinvent process data have been used. For the composition of the Dutch production mixes, the Renewable Energy Monitoring Protocol (SenterNovem, 2006) has been taken as a source. As for the chains of electricity and heat from biomass, fossil references refer to cradle-to-grave chains. They include mining, refinery, transport, conversion etc., to generate comparable systems. These chains are described in more detail in Appendix A. The values for the fossil references are the following:

GHG emissions of fossil reference chains of electricity and heat, in kg CO_2-eq / kWh (electricity) or kg CO_2-eq / MJ (heat)	Type of chain
0,551	Electricity from gas fired power plant
1,200	Electricity from coal fired power plant
0,715	Dutch electricity production mix ex renewables
0,198	Heat from coal
0,075	Heat, industrial furnace (high temperature heat)
0,071	Heat, gas fired boiler (low temperature heat)

Description of electricity and heat generation chains

1.16 *General aspects*

In this chapter, the default chains and processes with regard to electricity and heat production from biomass are specified. Data as included in the database used by E-LCA and literature sources used are described in the Appendices. In this chapter, the main choices and results are given: in 6.2, PPO chains are described, in 6.3 the chains related to woody waste and by-products and municipal waste are specified, in 6.4 the chains using agricultural residues are presented, 6.5 is dedicated to (co-)digestion processes in relation to manure, and finally in 6.6 chains using MSW are specified. Each section starts with one or more flow diagrams picturing the chain or chains of feedstock/technology combinations involved, followed by a description of more specific choices regarding system boundaries and methodological steps. If necessary, this will be followed by specific information regarding the conservative, typical and best practice processes and with regard to the fossil reference. Finally, some outcomes of the CO_2 calculator will be shown in graphs and will be discussed.

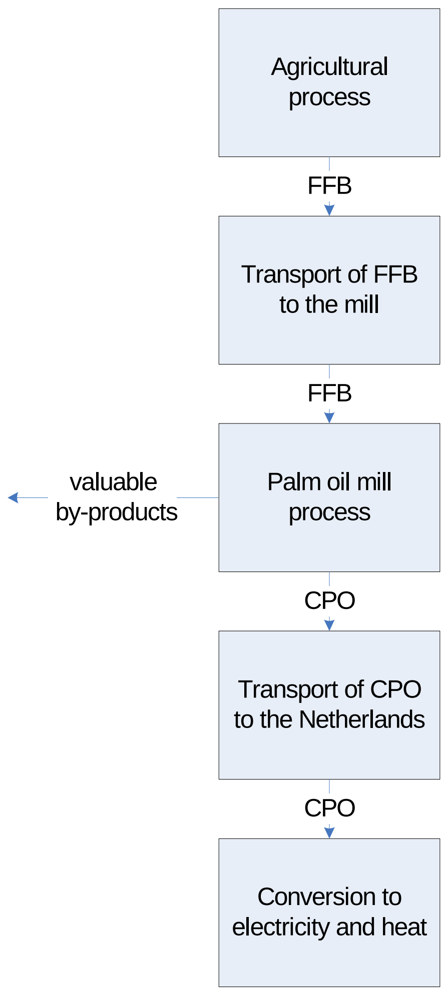
1.17 *Chains of plant based oils*

Three types of plant based oil are included: palm oil, rape seed oil and soybean oil. They are functionally equivalent for the generation of electricity and heat. Their chains, however, look different: the agricultural processes are different and the location is different, which has consequences for the transportation distances. The last part of the chain, the generation of electricity and heat itself, is identical. Co-firing with fossil fuels (gas) and single firing in a CHP (small / medium sized) are included. The chains and their processes are described in detail in Appendices B (palm oil), C (rape seed oil) and D (soybean oil).

1.17.1 Flow charts

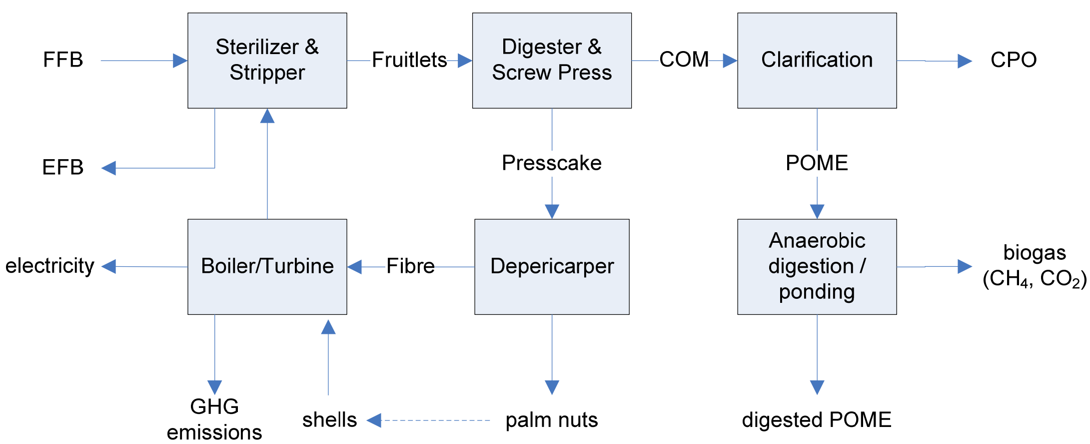
Palm oil

The general flow chart of the chain of electricity generation from palm oil looks as follows:



Palm oil is produced from oil palm fruits, grown at palm plantations mostly in countries in South East Asia and South America. The fresh fruit bunches (FFB) go into a milling process extracting crude palm oil, which is then transported to the Netherlands. Crude palm oil is used directly for electricity generation, but can also go into a refinery process from which refined palm oil is produced that is used by the food industry. Stearine, a by-product from this process, can be used for electricity generation as well. Various boxes in this chain are a summary of a number of processes and the chain has many by-products that can be considered waste streams, but also could be re-used or re-cycled in some way. This makes the palm oil chain rather complicated to address in a methodological correct manner (see Section 6.2.2).

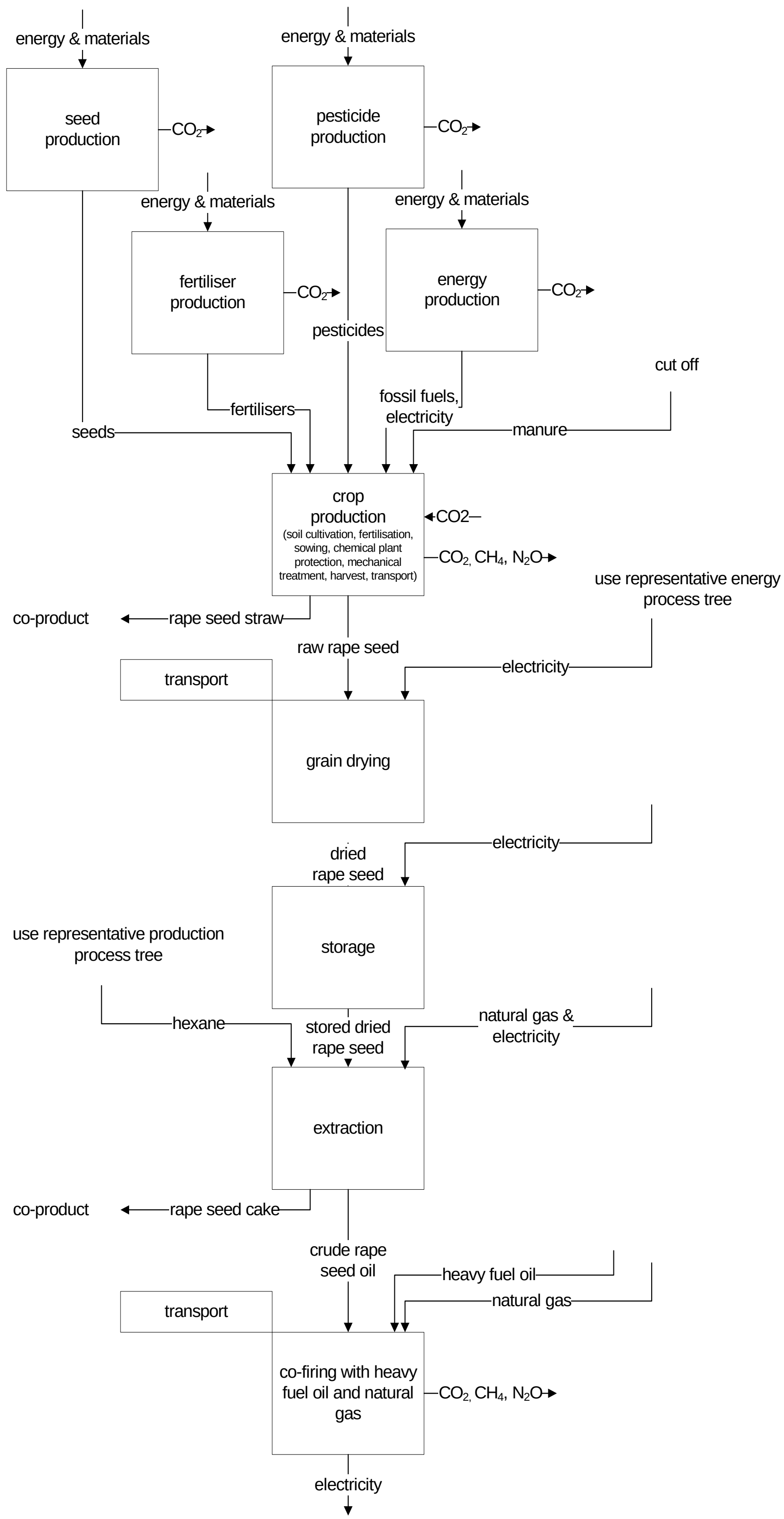
The palm oil mill process as the most complicated one is pictured in more detail below:



This flow chart shows that the milling processes deliver all kinds of co- and byproducts. Most important are the palm nuts which go into a process of extracting palm kernel oil, used in the food and fodder industry. Other by-products are the empty fruit bunches (EFB) which are generally used as an organic fertilizer, various organic wastes like fibres and shells that can be used to produce electricity on-site, and a watery waste stream (POME) which must be treated before emitted into the surface water. During treatment, CH_4 is formed which is generally emitted into the atmosphere but could be, and sometimes is, caught and used as biogas.

Rapeseed oil

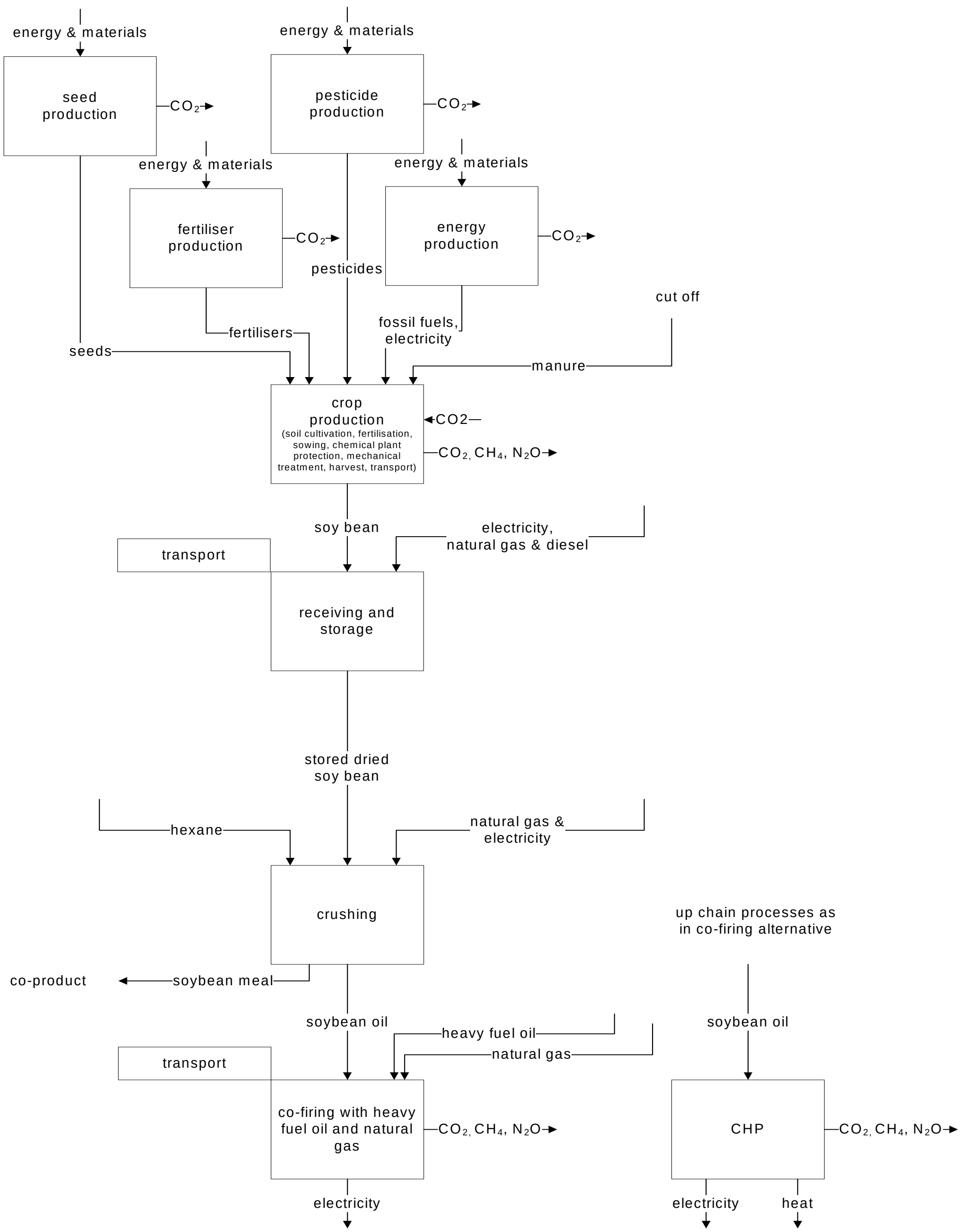
Below, the flow chart of rape seed oil is presented:


energy & materials
seed production
CO2
energy & materials
pesticide production
CO2
energy & materials
fertiliser production
CO2
energy & materials
energy production
CO2
pesticides
cut off
fertilisers
fossil fuels, electricity
seeds
manure
crop production
(soil cultivation, fertilisation, sowing, chemical plant protection, mechanical treatment, harvest, transport)
CO2
CO2, CH4, N2O
use representative energy process tree
co-product
rape seed straw
raw rape seed
transport
electricity
grain drying
electricity
dried rape seed
storage
use representative production process tree
hexane
stored dried rape seed
natural gas & electricity
extraction
co-product
rape seed cake
crude rape seed oil
heavy fuel oil
natural gas
transport
co-firing with heavy fuel oil and natural gas
CO2, CH4, N2O
electricity

Crop production is assumed to take place in Europe. Various options for location and intensity of agriculture are included. Main by-product of this chain are rape seed straw and rape seed cake. Straw is generally used within the agricultural sector, for soil improvement, but could also be used for electricity generation (see 6.4, agricultural by-products). Cake is used in the fodder industry.

Soybean oil

The product system for soybean oil is pictured below:



Soybean production takes place in various parts of the world. Included in the calculations is soybean from South America and soybean from North America. Compared to rapeseed, very little fertilizer is used: soybean, as a leguminose crop, generates its own nitrogen fertilizer. On the other hand, the process of producing soybean oil is more CO_2-intensive. Apparently soybean needs more energy in the drying process. The chains are quite similar for the remainder, including byproduct generation and use.

1.17.2 System boundaries and methodological choices

The systems include cradle-to-grave chains according to the general specification given in Chapter 3. A specific issue for these chains is the allocation method for by-products The PPO used for electricity generation itself is not a by-product. However, there are a number of by-products in the chain which cannot be considered waste, since they are used for a purpose and in most cases have a market price as well. For those, we applied allocation based on the LHV of the outputs.

For palm oil, there is the specific issue of co-production at the plantation – in many cases, other plants are grown alongside the palm trees, for example tea crops. We do not have the data to specify such options and therefore left them out of the calculator.

1.17.3 Conservative / typical / best practice

For palm, rape seed and soybean oil, choices for conservative, typical and best practice values as made in the parallel project on biofuels (Hamelinck et al., 2008) are used.

For the milling process related to palm oil production, choices were made as follows:

- Conservative / typical: CH_4 formed in the treatment of the POME is released into the atmosphere
- Best practice: CH_4 is captured and used to produce electricity

Fibres and nut shells are assumed to be used for electricity generation in all cases; EFB as natural fertilizer at the plantation itself.

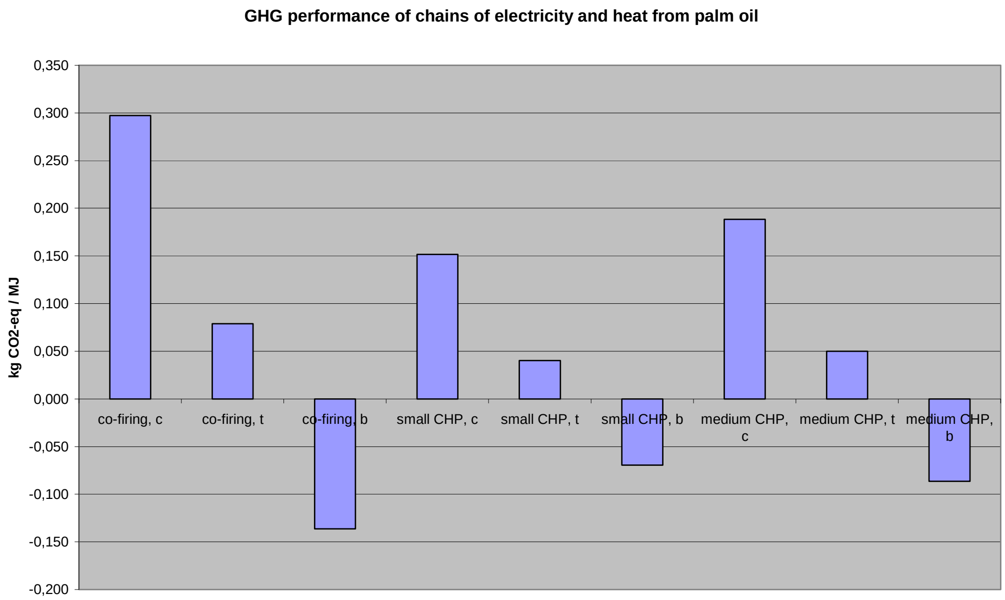
1.17.4 The fossil reference

For the co-firing process, electricity from a gas fired power plant is used as a reference. For illustrative purposes, the more general reference of the Dutch production mix is pictured as well. For the CHP alternatives, the reference is a combined heat-power reference according to the description in Section 6.4.

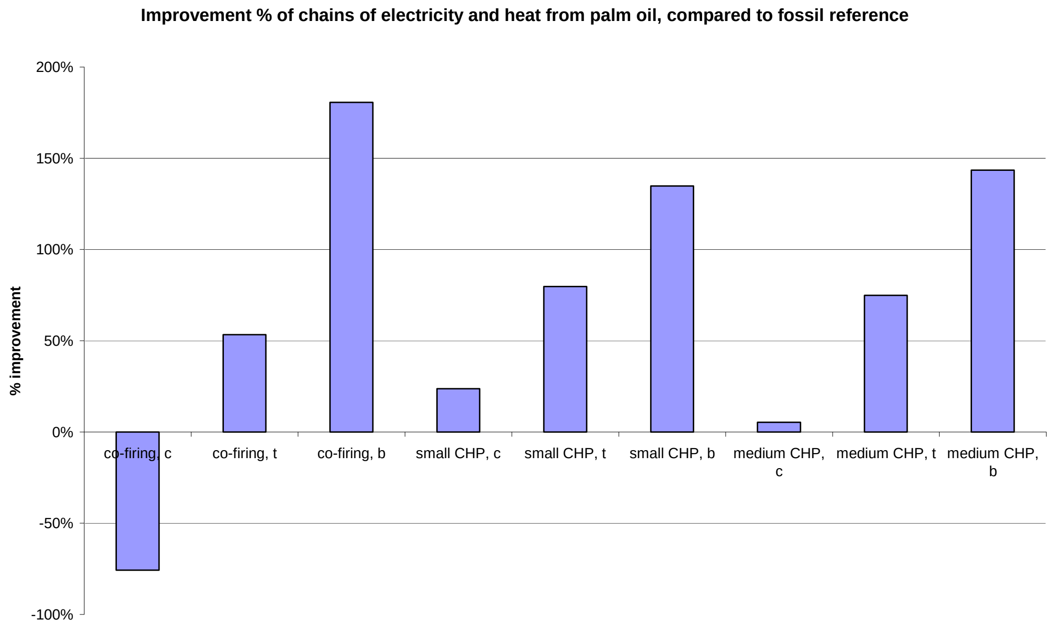
1.17.5 Results

Palm oil

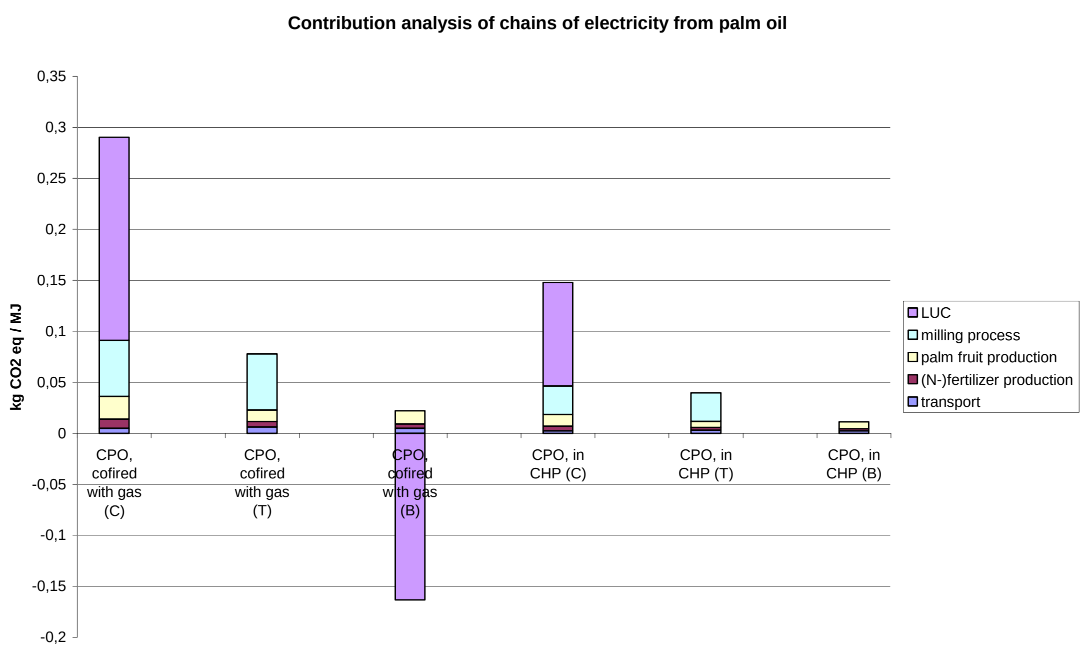
Greenhouse gas emissions from various chains of electricity and heat generation from palm oil are depicted below.



The choice for conservative, typical or best practice processes appears to have a large influence on the GHG performance of palm oil chains. Values range from slightly under 0.3 kg CO_2-eq per MJ to almost – 0,15. Negative values in the "best" alternatives are due to the assumption about land use change: a change from set-aside, degraded or agricultural lands to palm oil plantations leads to a net carbon uptake into the above-ground stock. The indicator, % improvement compared to the fossil reference, looks as follows:



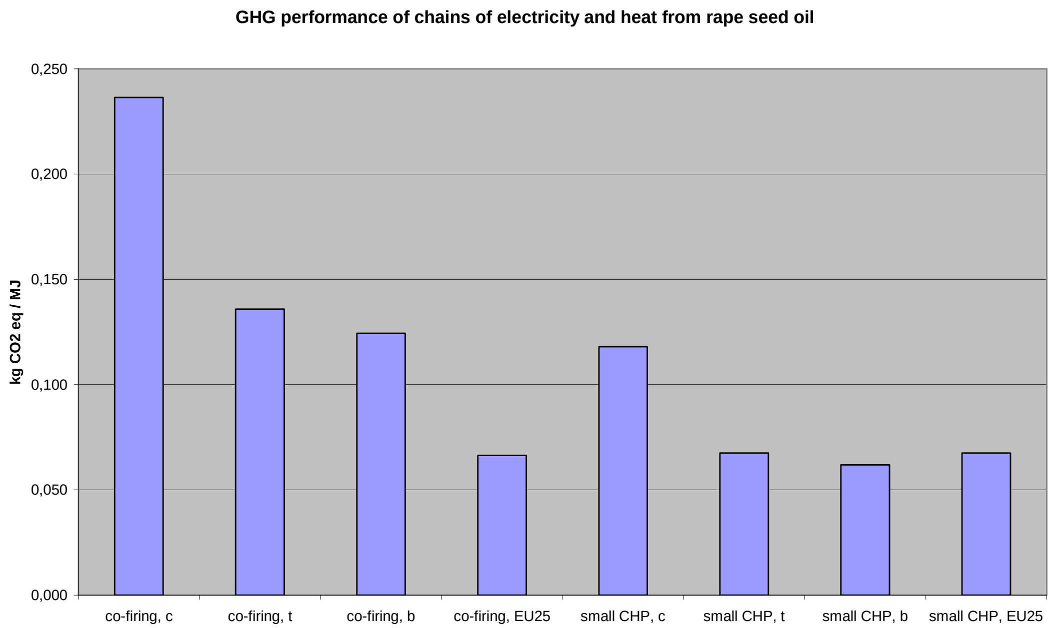
The “conservative” chains, including oil palm plantations on peat, don’t score well. The conservative chain for co-firing even scores negative, implying that its GHG performance is worse than the fossil reference. Other chains show an improvement, ranging from 50% to well over 100%, depending on technology and assumptions regarding typical and best practice systems, and depending on the choice for the fossil reference. Values over 100% indicate a net extraction of CO_2 from the atmosphere. This can only be found in cases of land use change, where the carbon stored in soils and biomass after the change is larger than before. A contribution analysis is performed to obtain more insight in the differences.



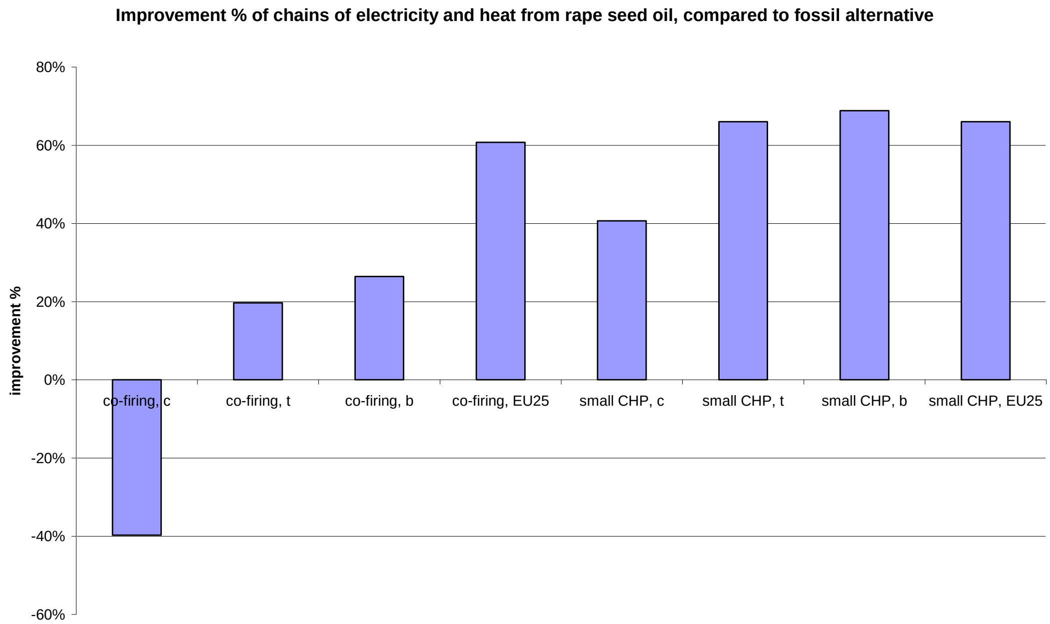
The high score for the conservative chain is for the largest part due to land use changes. For the typical chains, these emissions are absent. Best practice chains assume a net extraction of CO_2 in the aboveground stock of palm trees. In conservative and typical chains, the milling process is also contributing significantly to the GHG emissions. In best practice chains, methane emissions from milling are assumed to be captured and used. The emissions related to agriculture, transport and the industrial process are more or less identical for all three chains.

Rapeseed oil

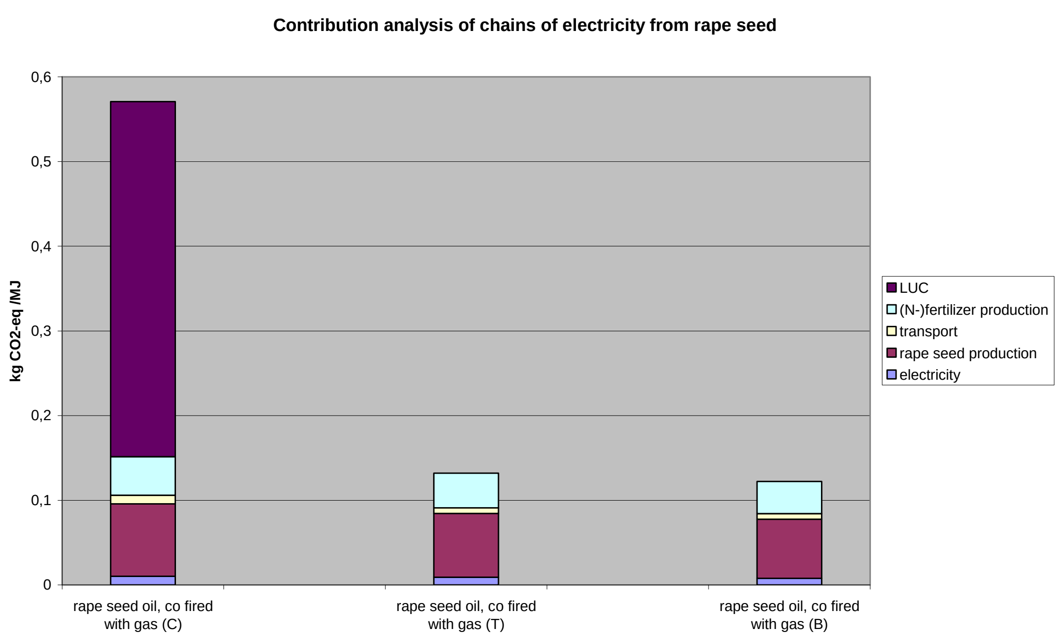
Chains of rape seed oil show less variation than palm oil chains. As the figure below shows, GHG performance varies roughly between 0.24 and 0.06 kg CO_2-eq / MJ.



The Improvement indicator for rape seed chains look as follows:



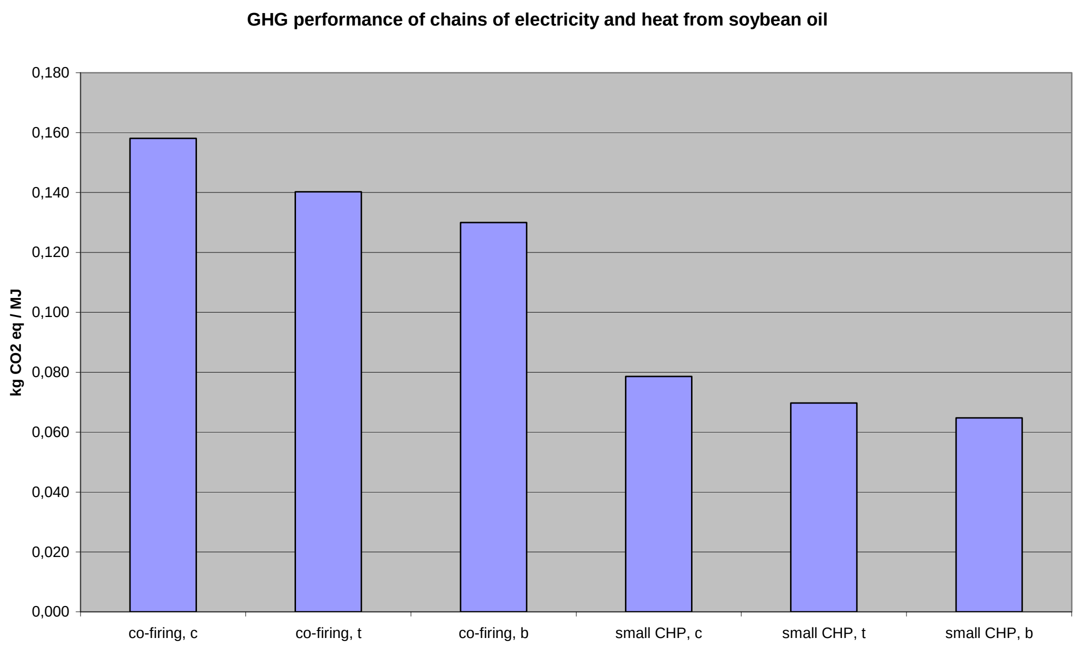
Co-firing chains score low improvement percentages. Their performance is not that much better, especially compared with their reference, gas-fired power plants, which have relatively low GHG emissions. CHP processes have a multiple heat-power output, therefore their improvement percentage is more marked: from 40% to 70%. The main differences between the chains are due to the conservative, typical and best practice assumptions.



In the conservative chain, land use change is the most GHG intensive part of the chain. Agriculture (N_2O emissions) an important process in all three chains, followed by fertilizer production.

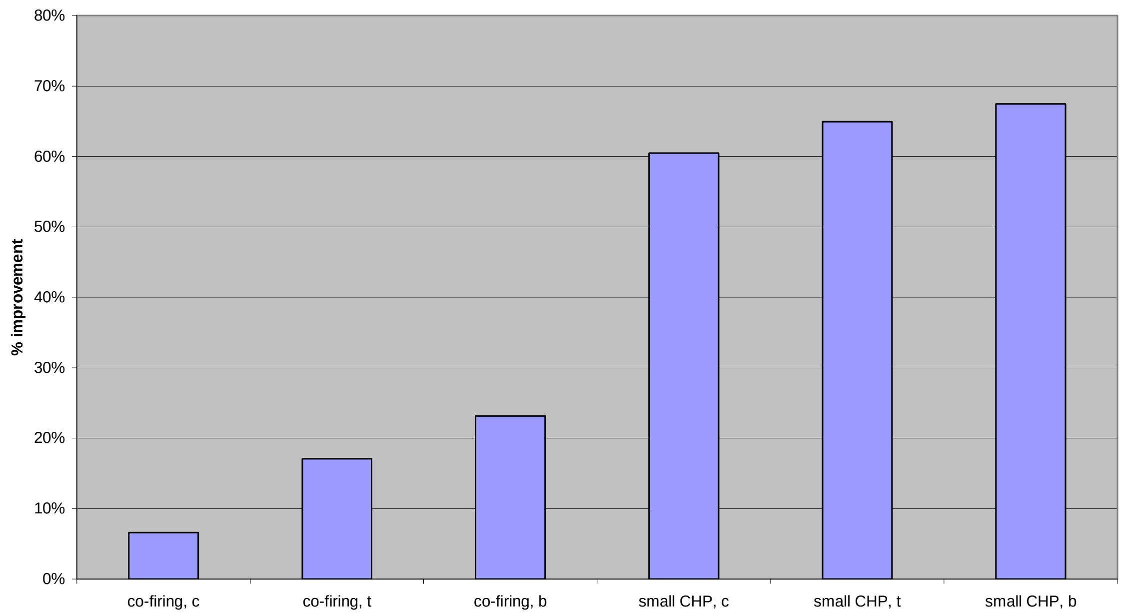
Soybean oil

Chains of soybean oil vary in their GHG performance from 0.06 to 0.16 kg CO_2-equivalent per MJ of electricity.



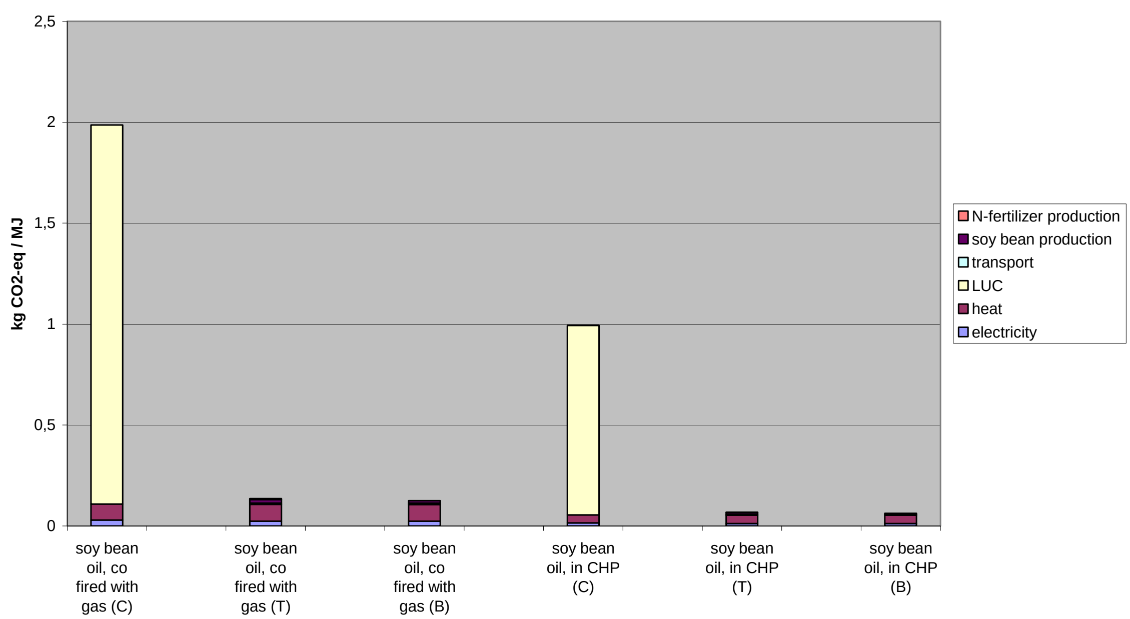
The indicator of improvement compared to the fossil reference is shown below:

Improvement % of chains of electricity and heat from soybean oil, compared to fossil reference



Due to the low GHG emissions of the fossil reference, improvement percentages are small for the co-firing options, and better for the CHP options. A contribution analysis for electricity and heat from soy bean oil is presented below:

Contribution analysis of chains of electricity from soy bean oil



Besides land use change, the industrial processes are most important. This includes both the electricity generating process and the process of preparing soybean oil from crop, the latter one being the more important. Here lies the main difference with the rape seed oil chains, where the agricultural process dominates. This also implies that improvement options are quite different for these two chains. Transportation, even considering long distance freight transport, is not so important. In this case, the contribution analysis refers to soy bean production in the United States of America.

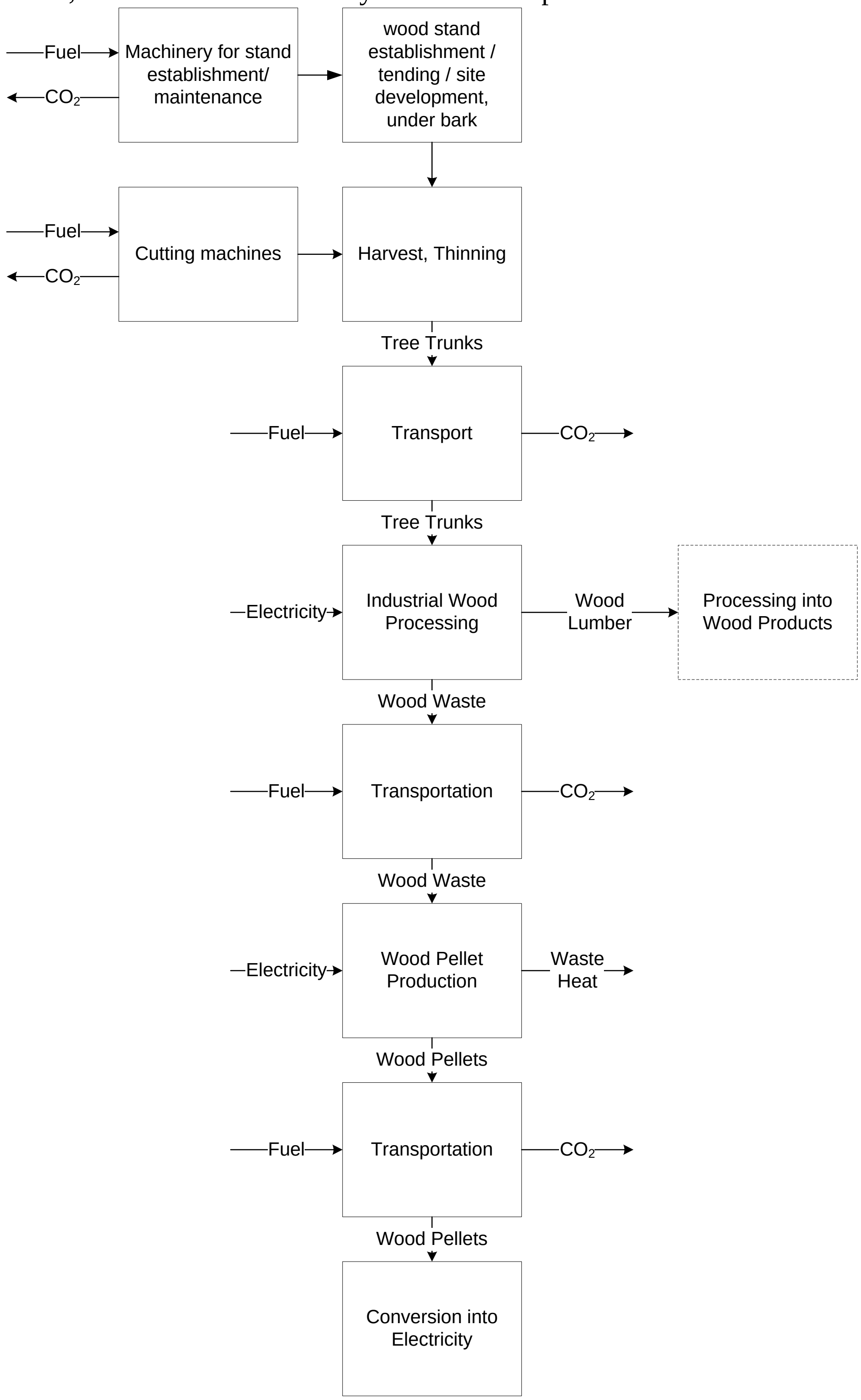
1.18 *Chains of wood residues*

Wood residues from forestry and public green maintenance, from the timber industry and from industries using wood are valuable and very suitable materials for electricity generation from biomass. In this section, we analyse chains of electricity generation from wood chips and from wood pellets. Wood chips are imported from other countries, sometimes over large distances, but are also produced locally, for example from pruning and trimming in public parks. Wood pellets are made from sawdust from the forestry industry. Significant quantities are imported from the Canadian logging industry: we have defined two chains, one from East and one from West Canada, based on the distance of transport. A last wood related feedstock is the use of waste wood from the demolition process. This wood has the advantage that it does not have to be transported over large distances. On the other hand, it is often polluted with paints or wood preservatives. We combined this feedstock production with different conversion processes: co-firing with coal, gasification and co-firing, gasification and single firing, and gasification and CHP.

In Appendices E and F, the chains and processes with regard to electricity and heat generation from wood chips, wood pellets and waste wood are described in more detail.

1.18.1 Flow charts

Below, a flow chart of electricity from wood is pictured.



Wood waste can be converted into pellets or it can be used directly for electricity generation. Wood pellets have certain advantages in use and transport, on the other hand the process of making them involves a little energy. Wood pellets may come from distant origins such as Canada. Within Europe, wood waste is transported as well between countries. Within the Netherlands, waste wood generated in park and greens maintenance can be used as well. The chain involves drying, sometimes pelletising, and transport.

1.18.2 System boundaries and methodological choices

The use of wood residues involves allocation. Wood residues can be regarded as either a waste or a by-product. Which is the case depends on the specific situation. Both are arguable. In the practice of the Canadian timber industry, sawdust often is left in the woods. Sometimes it is used to generate electricity locally. This local energy generation could be increased but since in most cases the situation is far away from more densely populated areas, there is no infrastructure to transport electricity. There are various other options to use the wood residues, such as for fibre board. For this moment, we have opted to treat the wood residues as a waste. This implies the processes related to the timber industry are cut off.

1.18.3 Conservative / typical / best practice

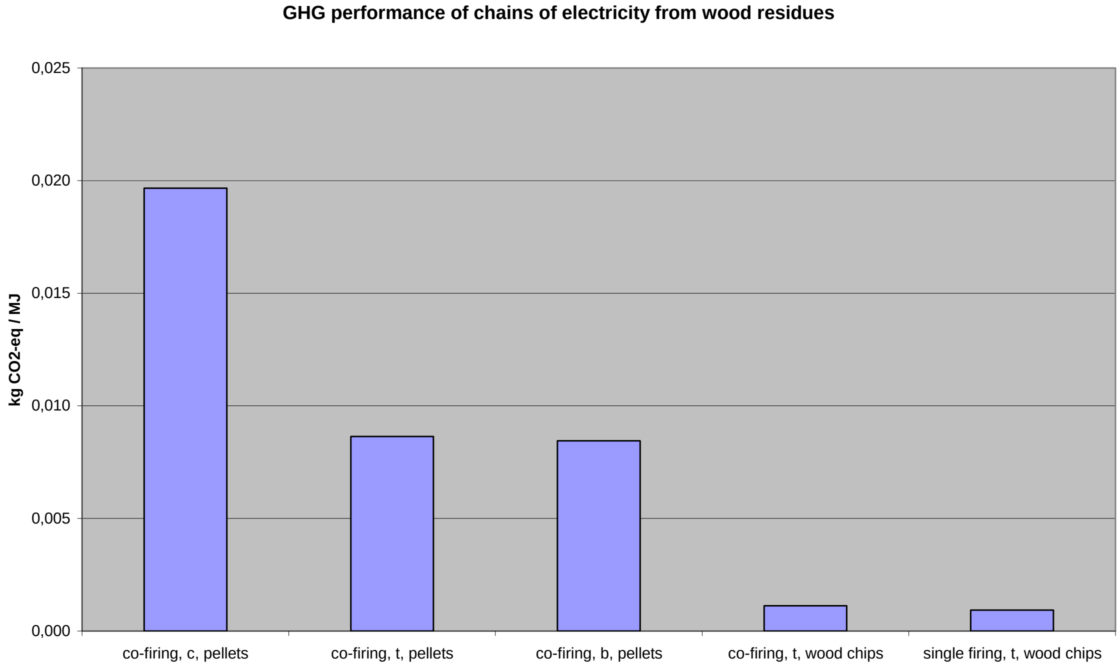
Main choices for conservative, typical and best practice refer to the distance of transportation. Best practice assumes only local transportation, typical an "average" European transportation of 2000 km, and conservative transportation from West Canada over 16500 km. The other process for which the distinction is made, is the drying of wood residues (chips or sawdust). This process can be done with more or less efficiency and with a more or less renewable energy mix. Details can be found in Appendix E.

1.18.4 The fossil reference

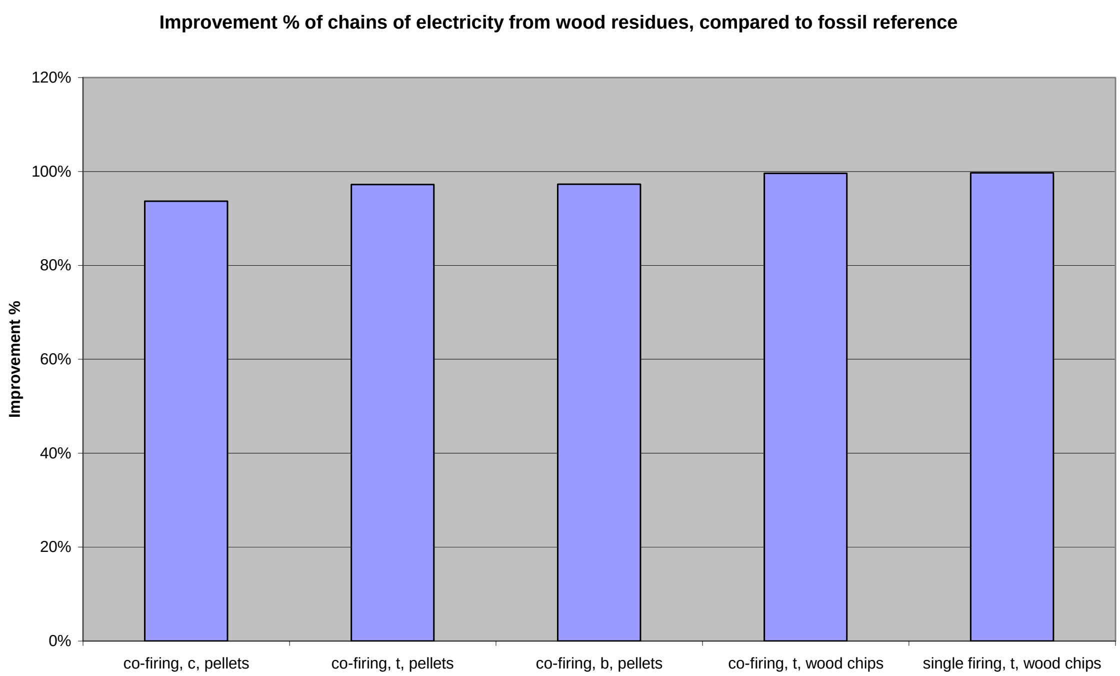
In cases of co-firing with coal, electricity generated in a coal fired power plant is used as the reference. For the CHP processes, the combined heat-power reference is used: 1 kWh of electricity from the Dutch mix with the amount of heat that is co-produced in the CHP, according to the Dutch heat reference, added to that. For single-firing processes, the Dutch fossil mix is used as a reference.

1.18.5 Results

Below, the results of the GHG performance of chains of electricity and heat from wood residues are presented. Note that the co-firing processes refer to the biomass fraction of the process only, in line with Section 3.5.



All chains have a much better performance than the fossil references. The improvement percentages come near 100% as is shown in the picture below.



1.19 *Chains of agricultural residues and by-products*

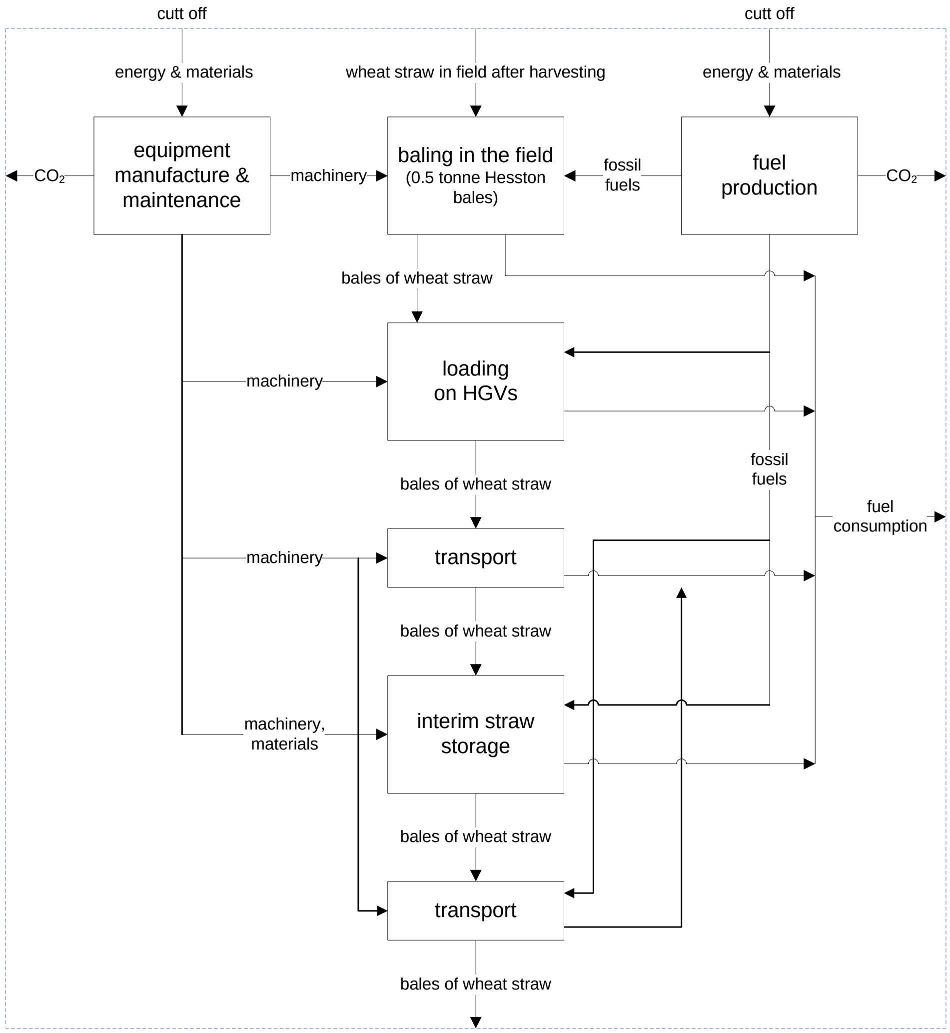
Two examples of agricultural residues are included in the database: wheat straw and animal fats & bone meal. Their chains and processes are described in detail in Appendix G (wheat straw) and H (animal fats). Wheat straw can be used for co-firing, however, in this chapter we only describe the chain of single-firing of wheat straw in a small scale CHP, as is already quite common in Denmark and Germany. For animal fats and bone meal, the chain of co-firing with coal is worked out.

1.19.1 Flow charts

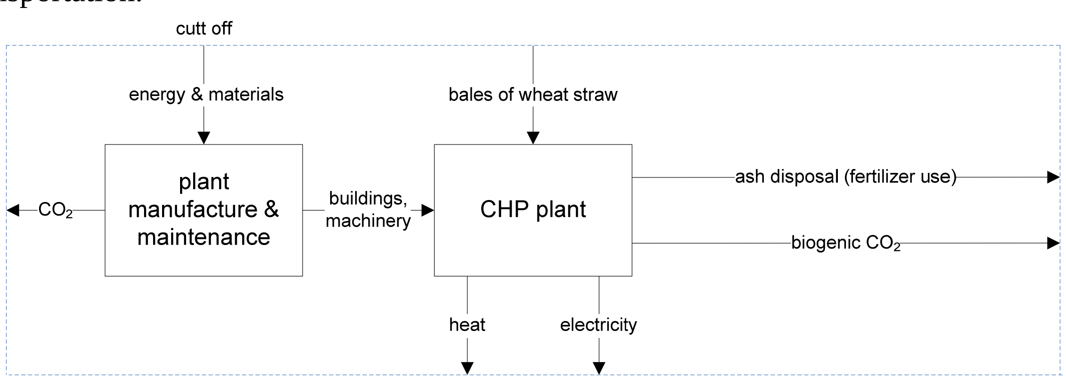
Wheat straw

Wheat straw is an example of an agricultural residue included in the calculator E-LCA. Other residues may be included by using the general supporting spreadsheet, as delivered with the calculator itself. Feedstock production, preparing the feedstock for use, the conversion process and all transportation processes are included in the flows charts below.

Wheat is assumed to be produced in the Netherlands. Capital goods are not included in the process input and output data; fuel use is included.



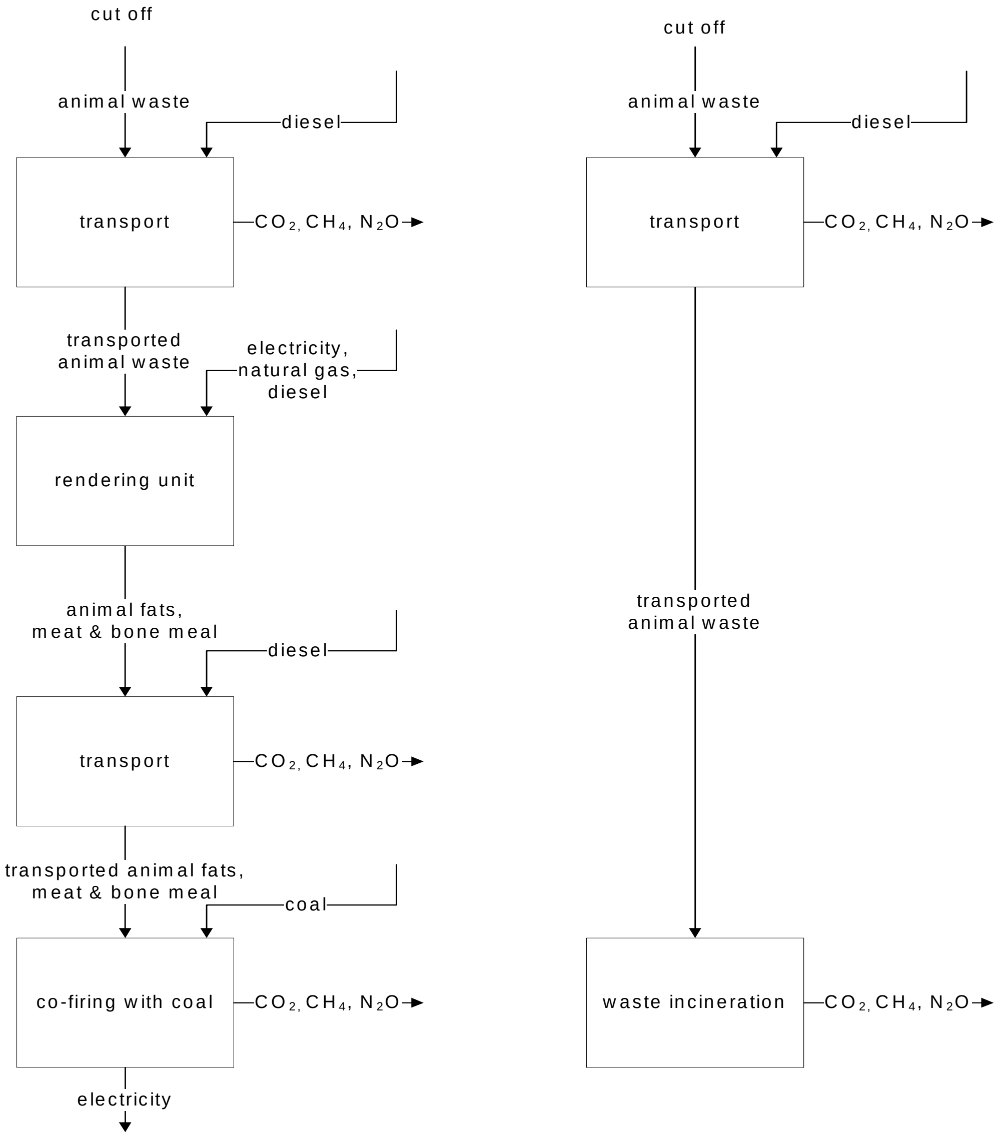
The process of preparing the wheat straw is fairly simple: baling, storage and some transportation.



Transport distances are short, since the wheat straw is assumed to be used in a local CHP installation. Obviously, wheat straw can also be used in larger scale conversion processes. Transport distances then must be modified in E-LCA.

Bone meal and animal fat

For bone meal and animal fat, co-fired with coal, the chain is pictured below. Right next to it, the avoided chain is depicted (see section 6.4.2: allocation).



1.19.2 System boundaries and methodological choices

Again, the main methodological issue is allocation. Agricultural residues are the most complicated feedstocks to address, since they border on the line between waste and by-product. They can be treated as by-products or as waste streams.

If residues are considered by-products, a part of the emissions of the agricultural chain must be attributed. In line with a choice for energy based allocation, the lower heating value can be used. This has the consequence, in many cases, that a rather large share of the GHG emissions from the agricultural chain is attributed to the by-product. Electricity generation from such by-products therefore will score very much worse than when economic allocation or substitution would have been applied. Economic allocation acknowledges the small value of the by-products and attributes emissions according to that. Substitution allows for subtracting an “avoided process” with concurrent “avoided emissions, which can be very favourable for waste feedstocks: for example, in the case of manure digestion the avoided process of conventional manure use on the land can be subtracted, leading to negative GHG emissions. However, such options are not in line with the starting point of allocation based on LHV as specified in the draft EC Directive.

To avoid this problem, a number of such residues have been excepted in the draft EC Directive. We have conformed to those exceptions. For these residues, including among others straw, the previous chain is cut off and all emissions from agriculture go to the main product. Only the processes of generating electricity or heat are then attributable to the chains. As a consequence, there is a difference between residues on this list and residues not on the list. The latter ones will have a worse GHG performance. The difference is not due to the actual processes but to differences in treatment of allocation.

In the case of generating electricity or heat from waste treatment processes, another problem occurs. Such processes are often quite inefficient when compared to electricity generation from fossil fuels. Allocating all GHG emissions from the waste treatment processes to the generated electricity or heat would result in a low or even negative improvement percentage. The problem is, that the waste treatment processes have another main function: the service of waste treatment. Since this service has no LHV it is difficult to attribute part of the emissions to it. We have solved this by using the LHV of the incoming waste-to-be-treated to allocate emissions to the waste treatment service. The EC draft Directive does not specify how to deal with this.

1.19.3 Conservative / typical / best practice

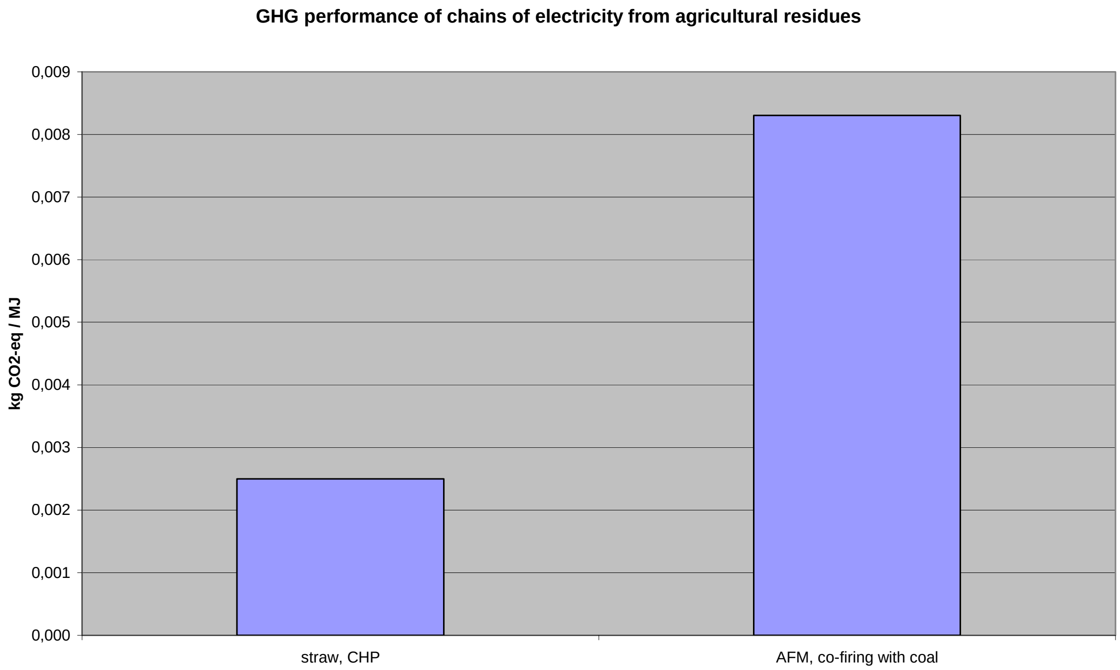
For wheat production, the chain implemented in E-LCA represents the Dutch situation. In line with SenterNovem (forthcoming), this is considered to be best practice due to the high yields. For conservative and typical chains and processes, assumptions are taken from SenterNovem (forthcoming). The difference lies mainly in the yield per hectare (lowest for the conservative chain) and also in the fertilizer use and in the distance of travel (highest for the conservative chain). For bone meal, just one chain is specified.

1.19.4 The fossil reference

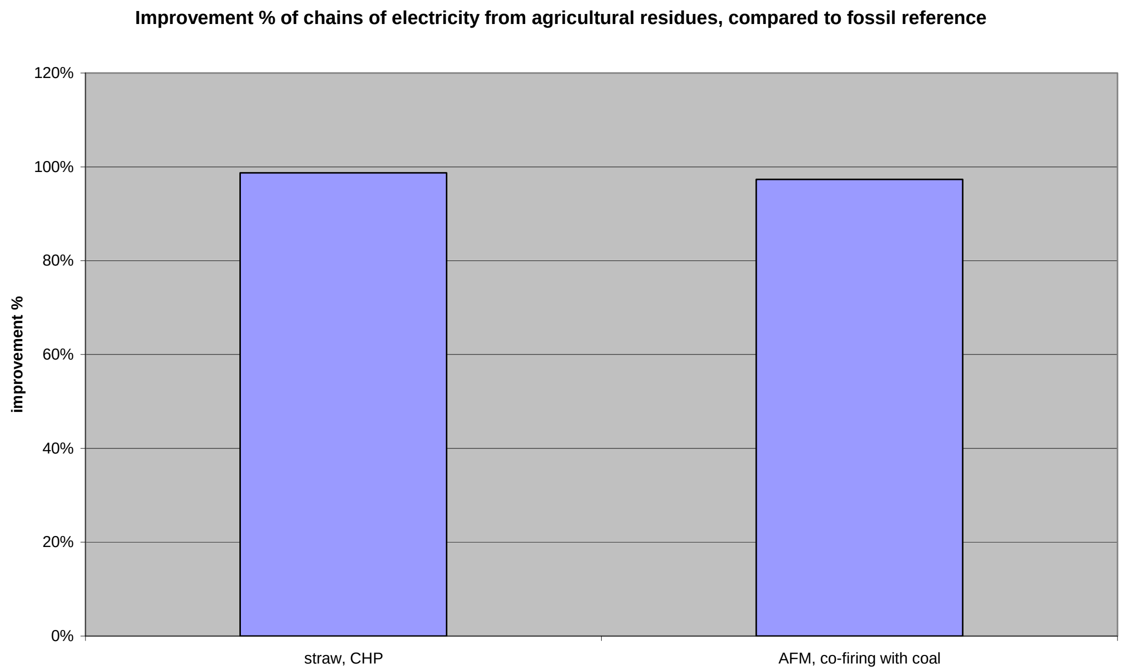
The fossil reference is the reference for CHP conversion processes, i.e. a double reference with 1 kWh of electricity produced according to the Dutch mix, and the parallel amount of heat produced according to the low-temperature natural gas-based heat reference.

1.19.5 Results

Five wheat straw chains have been specified. The three "best practice" chains represent the Dutch wheat production on different soils. All of them are considerably better than the fossil reference. The difference between the chains is not visible under the present choices regarding allocation: according to the guidelines from the draft EC Directive, the previous chain is cut off and therefore differences in agricultural practice do not show. Animal fats and bone meal obviously is a waste stream. Here, emissions are distributed over the product (electricity) and the service (waste treatment) as specified in section 6.4.2. Below, the performance of these chains is pictured.



As GHG emissions are very low, the improvement compared to the fossil alternative is near 100%. This is due to the fact that under the guidelines from the draft EU-Directive the wheat production chain is left out.


Improvement % of chains of electricity from agricultural residues, compared to fossil reference
120%
100%
80%
60%
40%
20%
0%
improvement %
straw, CHP
AFM, co-firing with coal

1.20 *Digestion and co-digestion chains*

The following chains are included:

- Small scale digestion of manure at farm level, followed by electricity and heat generation in a CHP installation
- Idem, co-digestion of manure and grass
- Idem, co-digestion of manure and maize
- Large scale digestion of manure, followed by green gas production, upgraded and delivered to the gas grid, and used for heating
- Large scale digestion of maize and potato waste as co-digestion inputs, followed by green gas production, upgraded and delivered to the gas grid, and used for heating
- Large scale digestion of manure and/or maize and/or potato waste followed by CHP
- Large scale digestion of swill (restaurant waste), followed by CHP

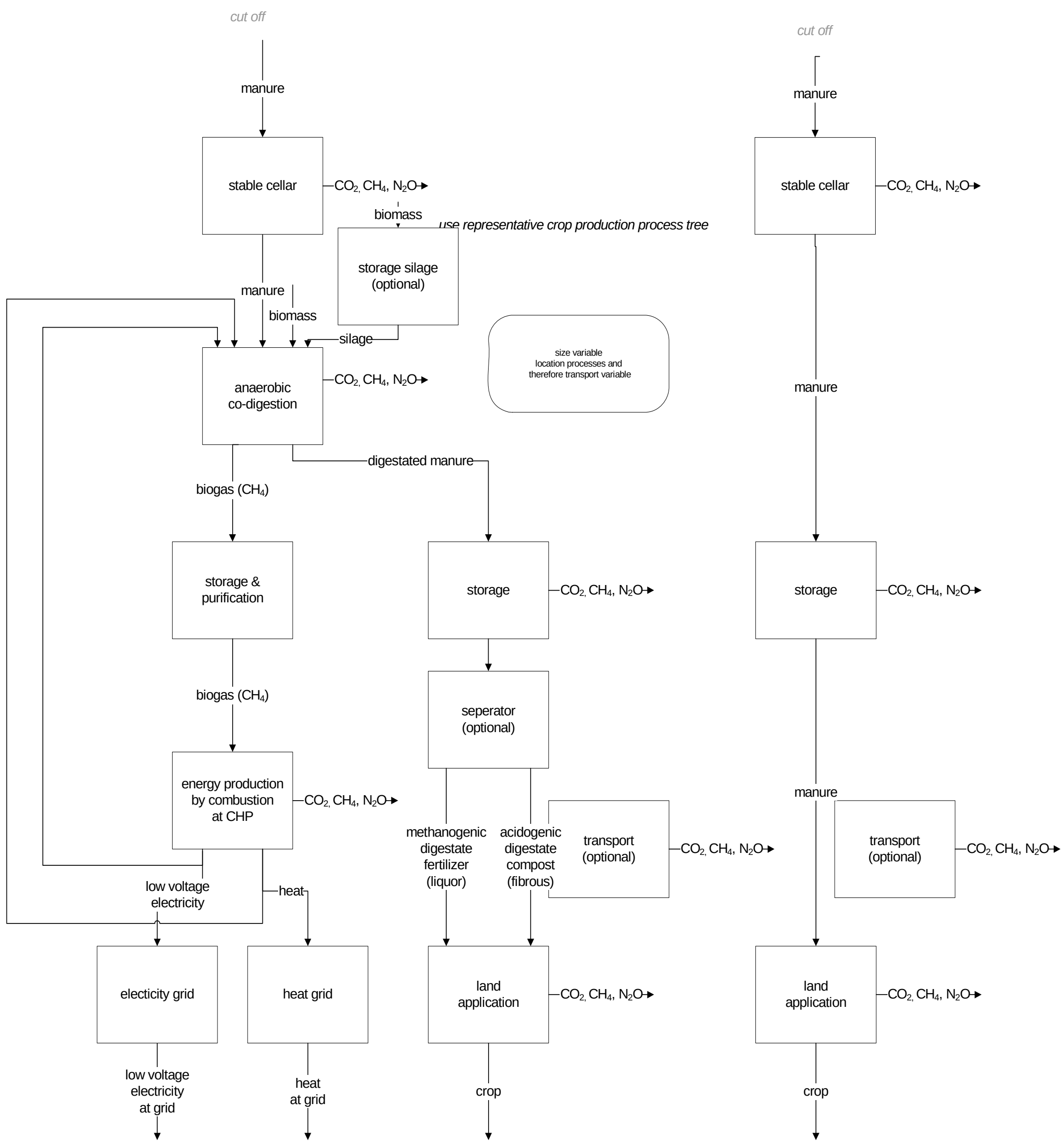
Maize and potato waste are representatives of energy crops and residues/waste streams that can be co-digested. A detailed description of the digestion chains is provided in Appendix I (farm scale digestion) and Appendix J (large scale digestion). In Appendix P, a number of other digestion feedstocks, not included in the GHG calculator, is specified together with their biogas production.

1.20.1 Flow chart

The general flow chart of the process tree for small scale manure (co)digestion is shown below. Manure is collected at farm level and is digested, with or without plant material to be co-digested. The digestate is assumed to be used on the land as manure. The biogas formed in the process goes to a small-scale CHP, converting it into heat and electricity. The heat and part of the electricity generated is fed back into the process. The remainder of the electricity is delivered to the low-voltage grid.

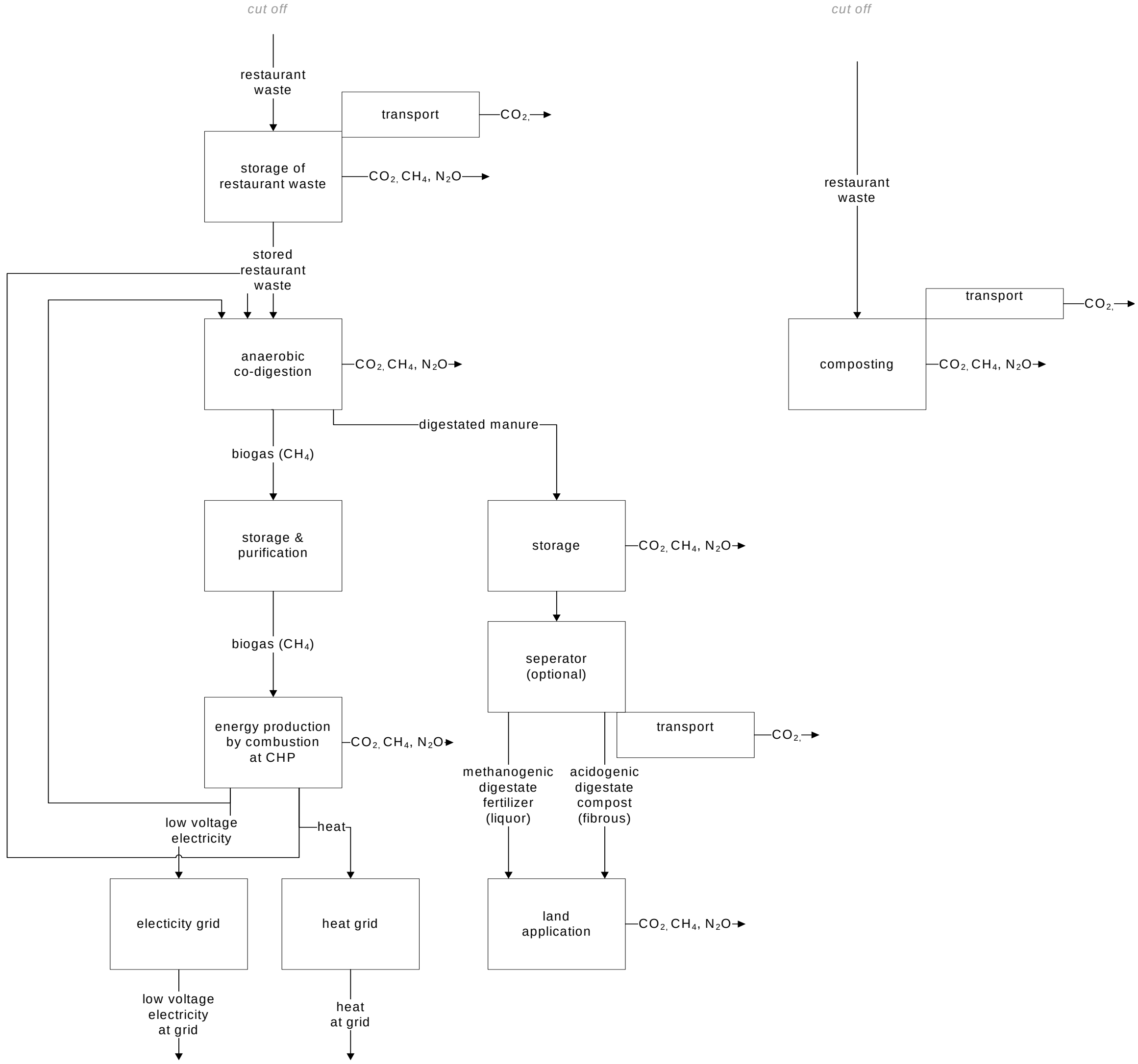
The chains for large scale manure (co-)digestion and medium scale digestion of organic waste are rather similar. For large scale manure (co-)digestion, the produced heat is assumed to be used in the typical and best practice chains, but not in the conservative chains. Swill digestion has a different feedstock, mainly waste from restaurants. This has consequences for the transportation: waste is collected from within a radius of ca. 100 km, while the digestate is transported to Germany, due to the fact that use as a fertilizer in the Netherlands is not allowed.

The efficiency of the digestion process is included in the E-LCA database for each feedstock separately. In case of co-digestion, a linear relation is assumed: the combined efficiency is determined by the individual efficiencies of the various feedstocks, in the ratio of their use in the digester. In Appendix P, the biogas production process efficiencies for a number of energy crops and residues from agriculture and the food industry are given. With these efficiencies, it is possible for E-LCA users to define their own mix in the supporting spreadsheet delivered with the calculator.



cut off
manure
stable cellar
CO2, CH4, N2O
biomass
use representative crop production process tree
storage silage (optional)
manure
biomass
silage
anaerobic co-digestion
size variable
location processes and
therefore transport variable
digestated manure
biogas (CH4)
storage & purification
storage
seperator (optional)
energy production by combustion at CHP
methanogenic digestate fertilizer (liquor)
acidogenic digestate compost (fibrous)
transport (optional)
low voltage electricity
heat
electicity grid
heat grid
land application
low voltage electricity at grid
heat at grid
crop

The flow chart for restaurant waste or swill is pictured below:



1.20.2 System boundaries and methodological choices

When specifying and quantifying the manure chains, choices must be made regarding methodology and data. These are listed below.

- The manure-to-be-digested is considered a waste stream. Reason for this is that is has no market price and farmers have to pay to take it off their hands. The implication of this choice is, that the previous chain of stock breeding can be ignored.
- Maize and grass used for energy crops are assumed to have been grown specifically for that purpose. Therefore, the previous agricultural chain is included as a whole and does not have to be allocated. For the treatment of by-products of those chains, see Section 6.4.

- Potato remains and swill are considered waste. Restaurant owners pay to have their leftovers removed and treated. The chain of food production, of which this waste originates, is therefore left out.
- The digestion process has two economic outputs: a product (biogas) and a service (waste treatment). Allocation based on LHV would assign all emissions to the biogas, since waste treatment as a service has no LHV. This choice would lead to very high GHG emissions for biogas: the process of digestion is not particularly efficient compared to electricity generation in power plants from fossil fuels. In order to acknowledge the fact that this type of digestion also has a waste treatment function, we have allocated emissions to this service based on the LHV of the incoming waste.

Other choices
The use of agricultural residues involved complicated methodological choices, see Section 6.4.2.

CHP process
Heat and electricity are generated in the CHP process from the biogas produced in the digestion step. For the farm-scale digestion processes, the assumption is that all of the heat and part of the electricity are fed back into the digestion process. The net generation of electricity is specified as the output of the process, and indeed of the whole system. Large-scale digestion and CHP is assumed to produce both electricity and heat as outputs.

1.20.3 Conservative / typical / best practice

Digestion process, farm scale
- Conservative: manure only
- Typical: manure with co-digestion of plant material, average efficiency
- Best practice: manure with co-digestion of plant material, high efficiency

Digestion process, large scale
- Conservative: minimum efficiency
- Typical: average efficiency
- Best practice: maximum efficiency

Storage of manure in the stable and with the digestor
- Conservative: emissions from storage according to literature (high value)
- Typical: emissions from storage according to literature (average value)
- Best practice: no emissions from storage

Silage of plant materials
- Data are missing, but this seems to be an important item due to CH_4-formation in silage.
- Conservative / typical: assumed emissions per ton similar as for manure
- Best practice: no emissions from storage

CHP process

- Conservative large-scale and all farm scale digestion processes: no use of heat
- Typical and best practice for the large scale digestion: use of heat.

Transport, farm scale

- Local transport at farm: one value, from Ecoinvent database
- Additional transport, if applicable, by truck, from Eco-invent database

Medium and large scale digestion

The assumption is, that this type of digestion differs from the farm-level digestion in two respects: storage and transportation. Transportation happens over larger distances. Storage cannot happen in a system-integrated manner, therefore, the zero-emission assumption cannot be made. The digestion and CHP processes are assumed to be comparably efficient to the small-scale processes.

1.20.4 The fossil reference

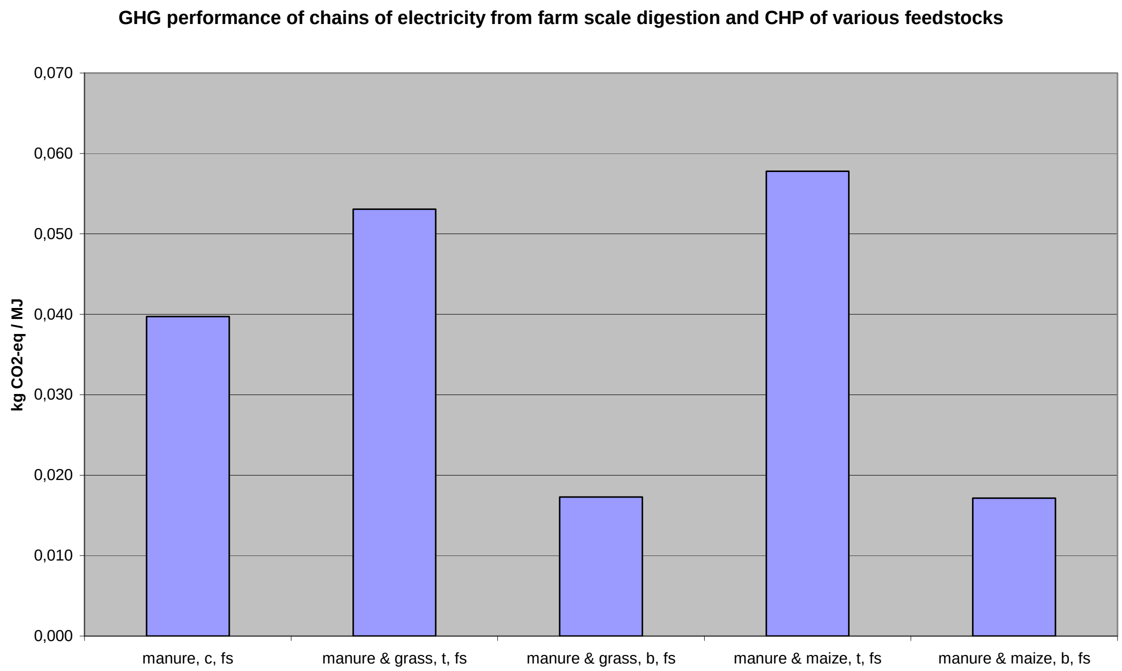
For electricity, the Dutch electricity mix is used as the fossil reference. For heat, small-scale low-temperature heat generation with natural gas is the reference. When benchmarking CHP, a combined heat-power reference is used, composed out of 1 kWh electricity and the amount of heat that corresponds to the heat production in the CHP in question.

1.20.5 Results

Detailed specifications of the digestion chains and the processes, including literature references, can be found in Appendix I. In this section, the results of the LCA are presented: the GHG performance of the various digestion chains, and the contribution analysis.

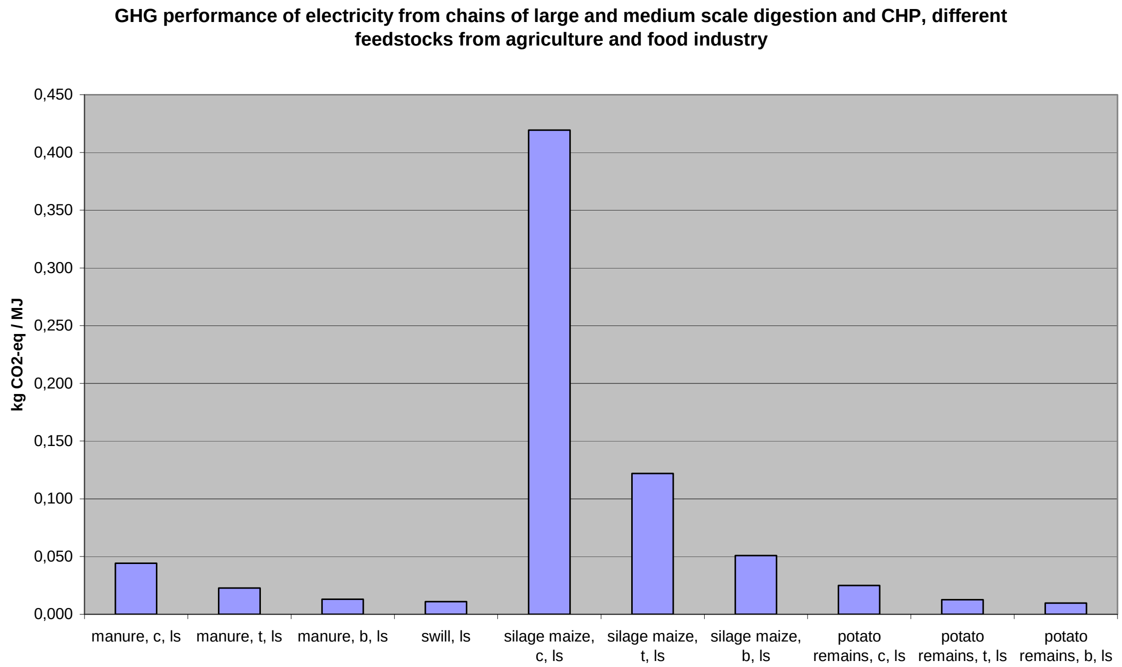
GHG performance of farm-scale digestion chains

The figure below shows the GHG emissions of five total, cradle-to-grave chains of (co-)digestion of manure:



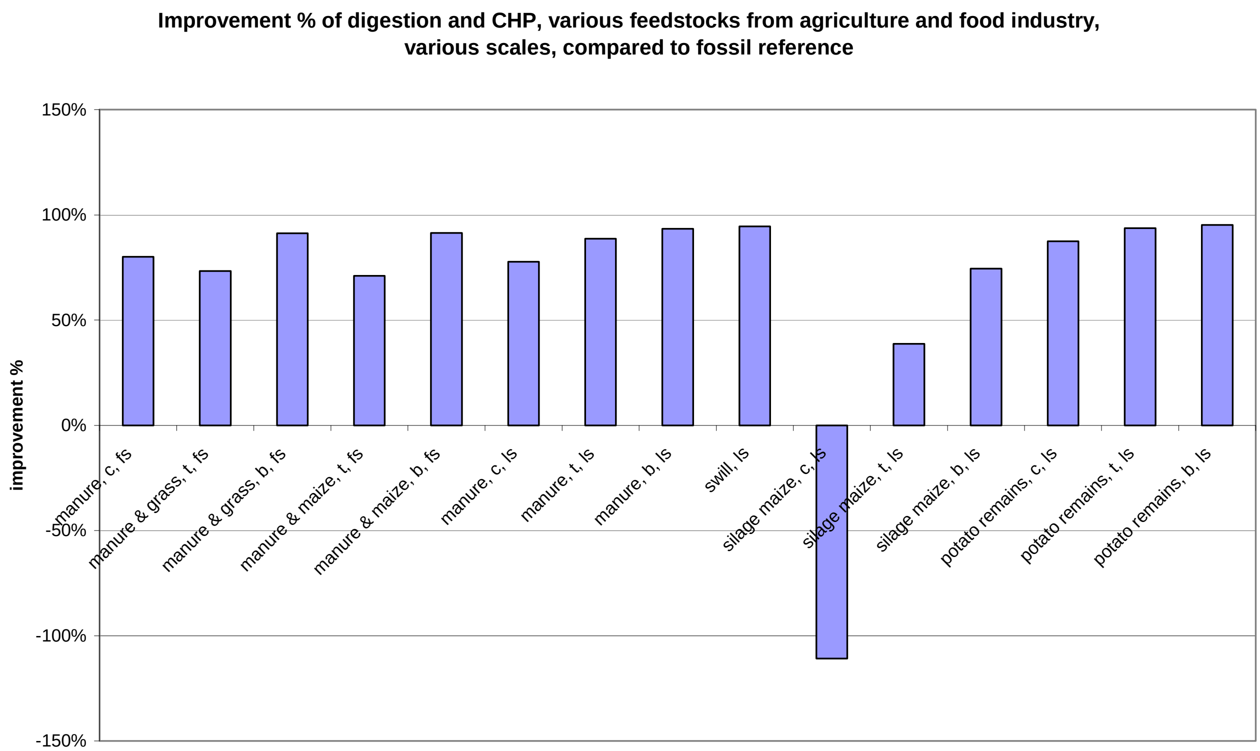
Looking at the digestion chains, co-digestion unexpectedly leads to worse results. This is due to the fact that manure is considered a waste, but the co-digested crops are products. For manure, the previous chain is cut-off, while for maize and grass their production chains are included according to the allocation rules. Best practice chains indeed have least GHG emissions.

The results for large- and medium-scale digestion are pictured below.



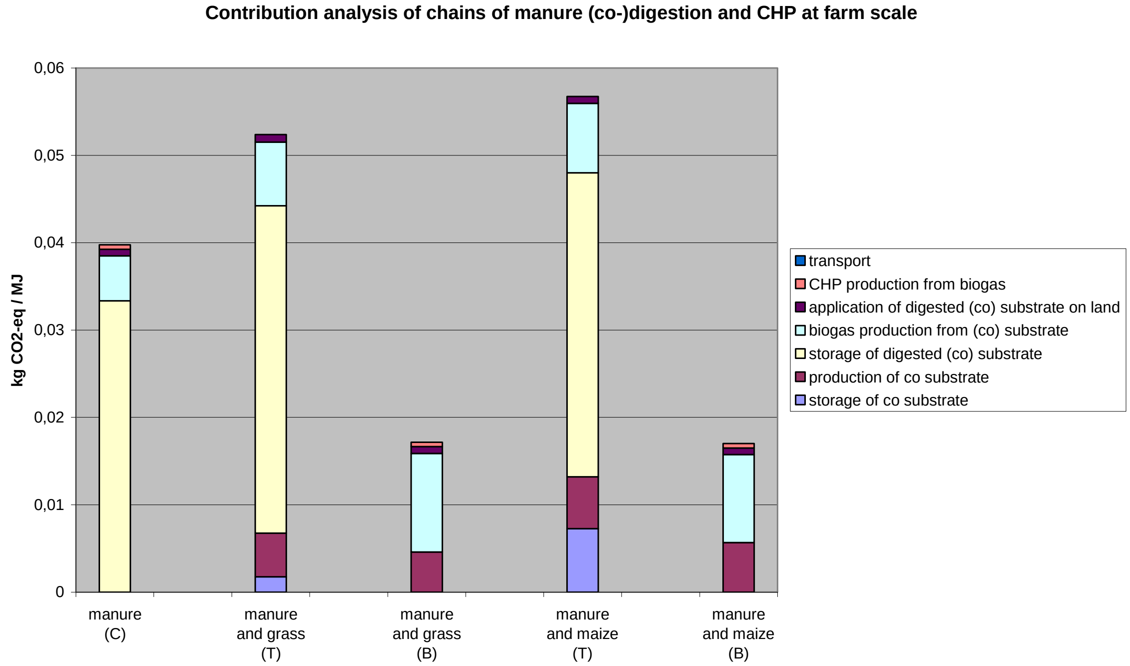
Manure digestion has a good GHG performance in all cases. Emissions are lower than for the farm-scale chains: not just the electricity, but also the heat is assumed to be a useful product. The same is true for swill and potato remains. All of those are considered wastes, therefore the previous chain is cut off. Only maize has high GHG emissions; due to the fact that this is not a waste but an energy crop, emissions from the agricultural process are included. In practice, digestion of maize or potato remains only will not occur: these chains have been included to enable users to define their own mix.

The indicator (% improvement compared to the fossil reference) is shown below. Improvement percentages are high (70 – 90%), with the exception of silage maize.



Contribution analysis

Not just the performance itself, but also the contribution of the various GHG and of the different processes in the chain are interesting, especially for identifying main areas of improvement. Below, the contribution of the three GHG involved to the total performance is shown. In addition to the usual contribution analysis for processes, we show a contribution analysis for the different greenhouse gases, to show this option in E-LCA. Again, the contribution analysis is performed for the unallocated chains.



Storage is the important source of emissions. In the best practice chains, storage emissions are assumed to be zero: this improves performance significantly. Crop cultivation is also important, especially in best practice chains where leaks are closed in the storage system.

1.21 *Chains of municipal solid waste and waste water treatment*

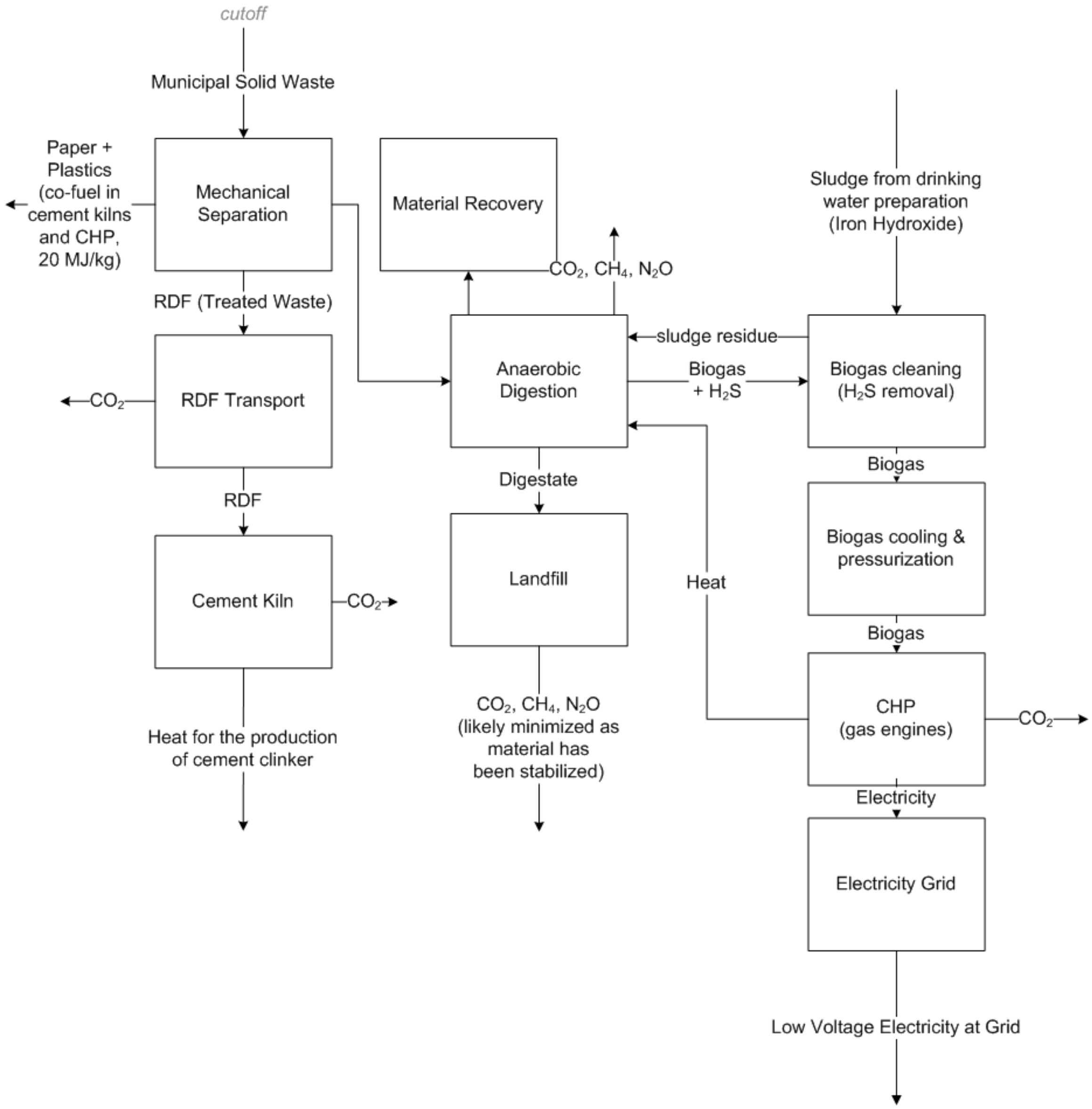
1.21.1 Flow chart

Municipal solid waste, or fractions thereof, can be used to generate electricity and/or heat in various ways:

- Electricity and heat can be generated by incinerating municipal solid waste (MSW) directly, as described in Appendix A. Recovering energy from MSW directly has become standard practice already in the Netherlands. Waste incinerators therefore are sometimes indicated as Waste Fired Power Plants, indicating a different view on waste incineration than just the treatment of waste. Developments towards a higher efficiency are ongoing.
- From MSW, a fuel can be produced from the most suitable fractions of organic waste and plastics: Refuse Derived Fuel (RDF). Various processes are available to make RDF; three of these are described in detail in Appendix M. RDF is mostly used as a fuel in co-firing processes. In the Netherlands, this use does not exist. Dutch RDF is mostly exported. One of the applications is the use of RDF in cement ovens, replacing coal. Firing RDF in a MSW incinerator also happens, but not as a preferred option. The chain of firing RDF in cement ovens is the one we have included in the GHG calculator.
- Organic waste separately collected (VFG, vegetable, fruit and garden waste) can be digested and the produced gas can be used for heat or electricity production.
- Landfill gas can be captured and used for heat or electricity production.
- In addition, sewage sludge from waste water treatment plants (WWTP) can be digested to produce gas, which can be used for heat or electricity production.

Details of the various chains can be found in Appendix K (landfill gas), Appendix L (sewage sludge), Appendix J (VGF) and Appendix M (Waste to Energy and RDF).

Below, a flow chart is shown for the production and co-firing of RDF: the best practice chain. Other processes are available as well. This chain produced RDF by mechanical separation, followed by anaerobic treatment of the waste with co-production of electricity and heat.



1.21.2 System boundaries and methodological choices

When specifying and quantifying the MSW and sewage chains, choices must be made regarding methodology, especially allocation. These are listed below.

- Municipal solid waste and sewage sludge are obviously waste streams. Therefore, all previous processes can be ignored. The production of RDF involves some energy use and therefore some GHG emissions. This is included in the RDF chains.
- The waste treatment processes have two economic outputs: a product (green gas, electricity and/or heat) and a service (waste treatment). According to the procedure described and applied for the chains of manure digestion in 6.5, we have distributed the emissions of the process over the two outputs based on the LHV of the energy product and the LHV of the incoming waste stream,

respectively. General considerations of allocation of residues and waste streams are described in section 6.4.2. Even more complicating is the fact that MSW incinerators often deliver more recovered waste streams as goods to be used. These are, at least for the moment, ignored.

1.21.3 Conservative, typical and best practice

For MSW incineration, the efficiency of the energy recovery determines the choice for conservative, typical and best practice.

- RDF can be produced by combinations of mechanical treatment, aerobic treatment and anaerobic treatment in different orders. For RDF, the chain of RDF from mechanical treatment preceded by anaerobic treatment of wastes, with co-production of electricity and heat, is labeled best practice. Mechanical treatment followed by aerobic treatment is defined as the conservative process. The other two process combinations studied are labeled Typical: RDF production by mechanical treatment followed by aerobic digestion, and RDF production by aerobic digestion followed by mechanical separation.
- For MSW, the conservative process is a waste incinerator with 14% electrical efficiency, typical is 20% and best practice 30%.
- Both typical and best chains have been specified with and without use of the co-produced heat.

For green gas production, electricity production in a CHP has been implemented as well as upgrading the gas to natural gas-quality, delivering it to grid and using it for heat generation. The distinction between conservative, typical and best practice chains has been made based on

- The efficiency of biogas production from feedstock and the process losses
- The efficiency of the upgrading process in case of green gas delivery to the gas grid
- The assumption whether or not heat from the CHP is used internally, only in the case of landfill gas.

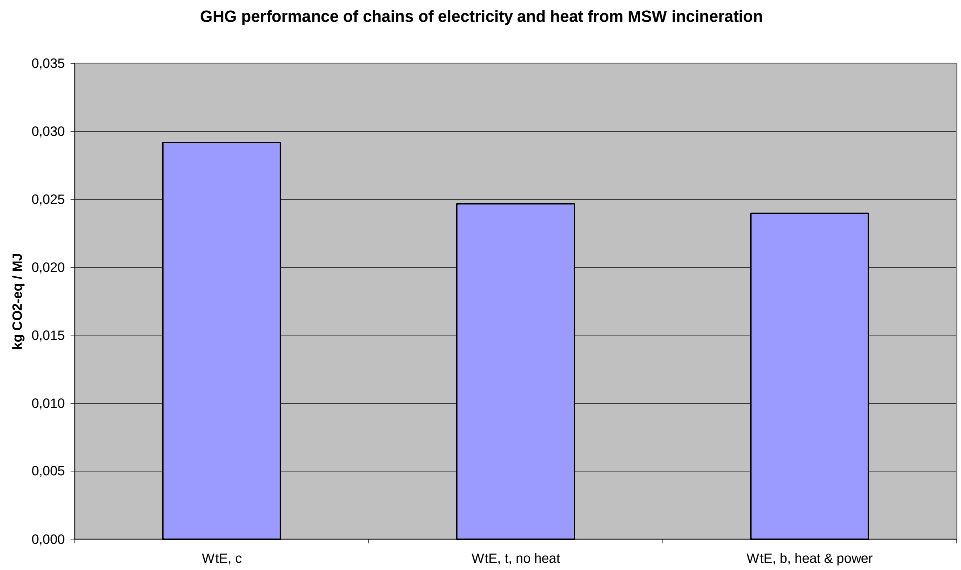
Details can be found in Appendices J, K, and L for green gas production.

1.21.4 The fossil reference

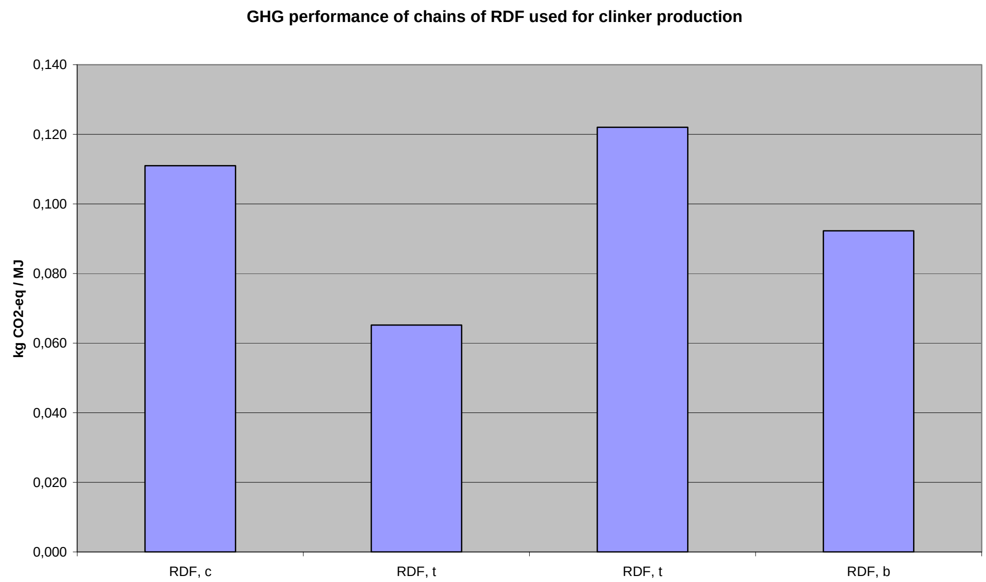
For the MSW chains, the Dutch electricity production mix is the reference. For the RDF chains, heat from coal is used as a reference, since this is what is being replaced by the RDF in that application. For green gas refined to natural gas quality and used for heating, the fossil reference is the use of natural gas from the Dutch grid for the same purpose. For green gas used for electricity generation in a CHP, the Dutch electricity production mix is the reference.

1.21.5 Results

Below, the GHG emissions of chains of electricity from waste are specified in various graphs.

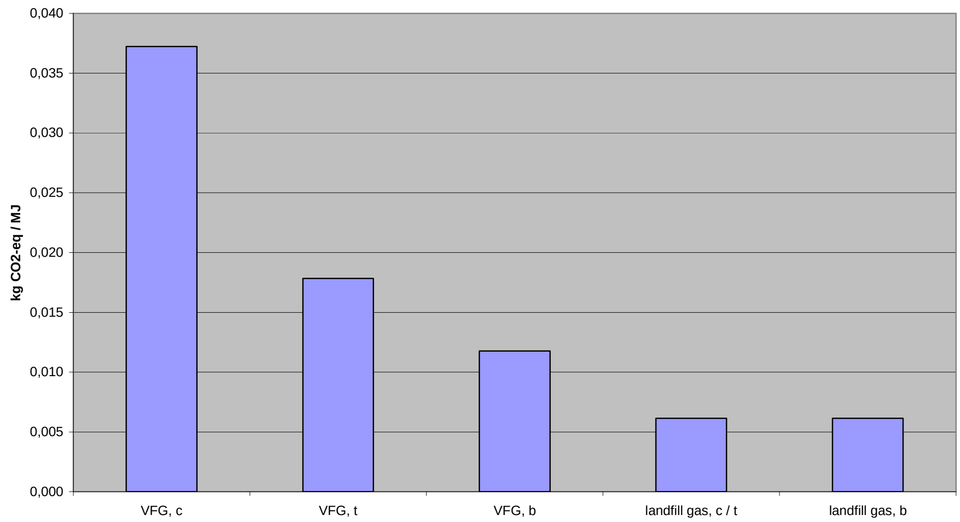


Due to the allocation of part of GHG emissions to the waste treatment service, the performance of the WtE chains is good.



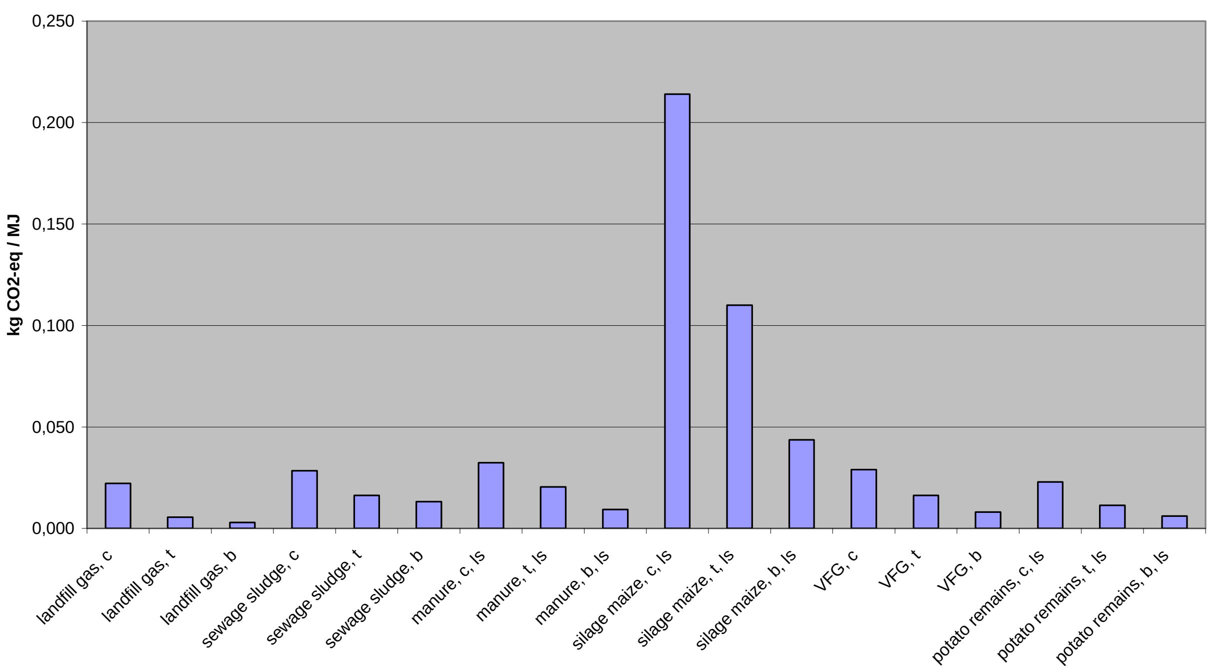
RDF used as fuel in cement ovens also performs well. The alternative where digestion is combined with mechanical separation is the best one.

GHG performance of chains of electricity from digestion of organic waste followed by CHP

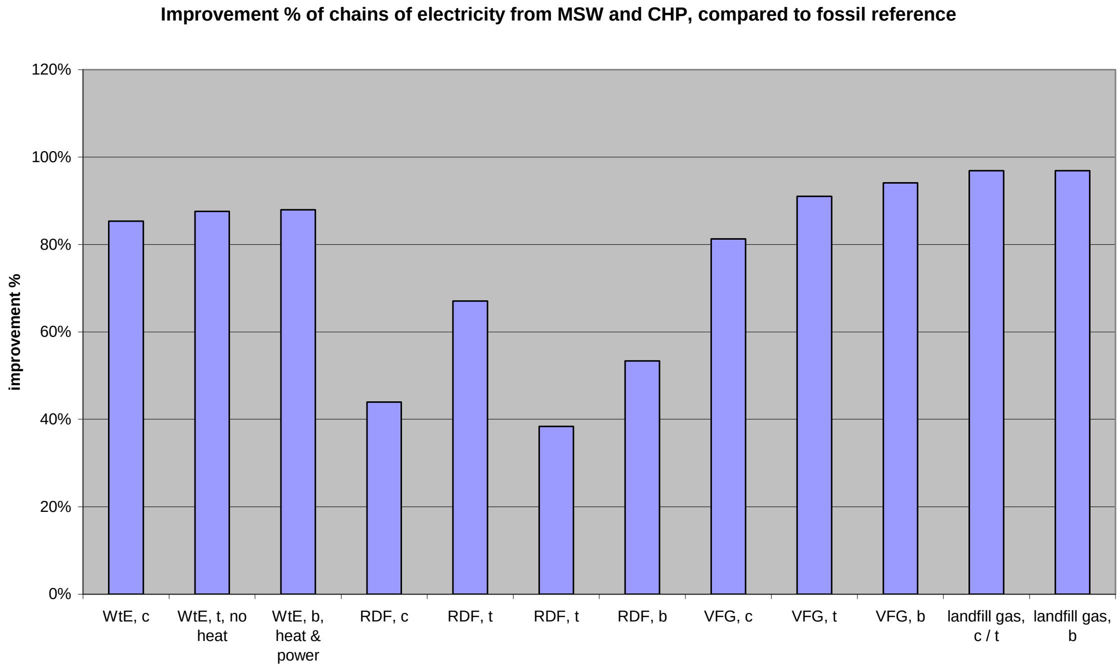


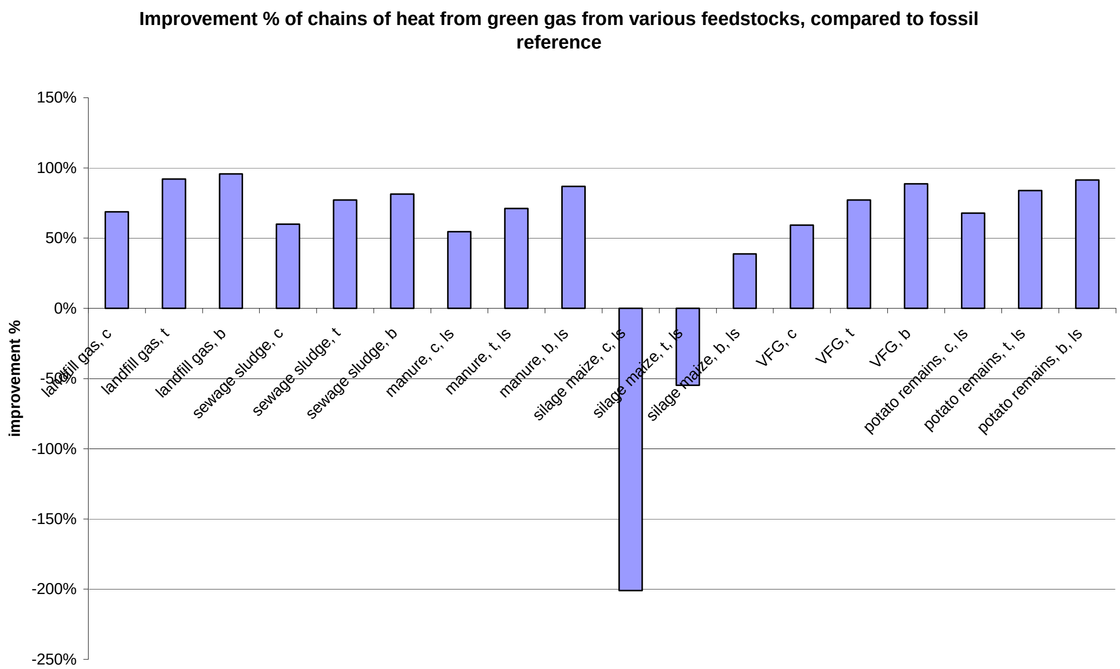
Methane production by digestion of VFG and landfill gas, transformed into electricity by CHP, also has a good GHG performance. CHP also produces heat; results are not pictured but can be found in the overall results tables in Section 6.7. Methane produced by digestion can also be used as green gas for heating purposes, pictured below. For landfill gas, GHG emissions are comparable to those of using it in a CHP. It has to be noted, however, that the assumptions regarding landfill gas extraction are oversimplified, due to lack of data. Emissions of sewage sludge chains are comparable to those of manure digestion. The high emissions from silage maize digestion are due to the inclusion of the agricultural chain, while for wastes the previous chain is cut off.

GHG performance of chains of green gas used for heat from various feedstocks



Below, the improvement percentages are specified for the abovementioned chains.





Improvement percentages for WtE chains and digestion chains are high, from 85 to 97%. Landfill gas improvement percentages are a little higher for use in CHP to make electricity than for use as green gas for heating. This is due to the different fossil references for both systems: electricity from grid vs natural gas for heating.

1.22 Summary of the results

Below, the results of all calculations are summarized in four tables: feedstocks and conversion processes with their GHG performances and improvement percentages, for the conservative (c) typical (t) and best practice (b) chains.

Results tables for all included chains of electricity and heat from biomass

Electricity from plant based oils							
	kg CO2-eq/MJ			**improvement compared to fossil reference**			**fossil reference**
	c	t	b	c	t	b	
Co-firing with natural gas							
rape seed oil, Northern Europe	0.578	0.136	0.124	-242%	20%	26%	electricity at consumer, from natural gas
rape seed oil, EU-25		0.144			15%		electricity at consumer, from natural gas
soy bean oil, USA	2.036	0.140	0.130	-1104%	17%	23%	electricity at consumer, from natural gas
crude palm oil, S-E Asia	0.297	0.079	-0.136	-76%	53%	181%	electricity at consumer, from natural gas
CHP, < 10 MWe							
rape seed oil, Northern Europe	0.289	0.068	0.062	-45%	66%	69%	fossil electricity production mix, NL
rape seed oil, EU-25		0.068			66%		fossil electricity production mix, NL
soybean oil, USA	1.019	0.070	0.065	-413%	65%	67%	fossil electricity production mix, NL
crude palm oil, S-E Asia	0.152	0.040	-0.069	24%	80%	135%	fossil electricity production mix, NL
CHP, 10 - 50 MWe							
crude palm oil, S-E Asia	0.188	0.050	-0.086	5%	75%	143%	fossil electricity production mix, NL

Electricity from wood							
	kg CO2-eq / MJ			**improvement compared to fossil reference**			**fossil reference**
	c	t	b	c	t	b	
Co-firing with coal							
wood pellets	0.020	0.009	0.008	94%	97%	97%	electricity at consumer, from coal
wood chips		0.001			100%		electricity at consumer, from coal
Gasification followed by (co-) firing							
wood pellets, syngas co-firing with coal	0.036	0.018	0.018	88%	94%	94%	electricity at consumer, from coal
wood pellets, syngas single firing	0.043	0.023	0.018	78%	88%	91%	fossil electricity production mix, NL
wood chips, syngas single firing		0.001			100%		fossil electricity production mix, NL

Electricity and heat from manure and agricultural residues							
	kg CO2-eq / MJ			improvement compared to fossil reference			fossil reference
	c	t	b	c	t	b	
Firing in grate furnace							
wheat straw	0.002	0.002	0.002	99%	99%	99%	fossil electricity production mix, NL
Farm scale digestion and CHP, electricity only							
manure (co-)digestion with maize	0.040	0.058	0.017	80%	71%	91%	fossil electricity production mix, NL
manure (co-)digestion with grass	0.040	0.053	0.017	80%	73%	91%	fossil electricity production mix, NL
Large scale digestion and CHP, electricity							
manure	0.044	0.023	0.013	78%	89%	93%	fossil electricity production mix, NL
silage maize	0.419	0.122	0.051	-111%	39%	74%	fossil electricity production mix, NL
potato remains	0.025	0.013	0.010	87%	94%	95%	fossil electricity production mix, NL
Large scale digestion and CHP, heat							
Manure	n.a.	0.022	0.013	n.a.	69%	82%	heat, natural gas, at boiler
silage maize	n.a.	0.117	0.049	n.a.	-65%	31%	heat, natural gas, at boiler
potato remains	n.a.	0.012	0.009	n.a.	83%	87%	heat, natural gas, at boiler
Green gas production used for heat							
Manure	0.032	0.021	0.009	55%	71%	87%	heat, natural gas, at boiler
silage maize	0.214	0.110	0.044	-201%	-55%	39%	heat, natural gas, at boiler
potato remains	0.023	0.011	0.006	68%	84%	92%	heat, natural gas, at boiler

Electricity and heat from waste							
	kg CO2-eq / MJ			**improvement compared to fossil reference**			**fossil reference**
	c	t	b	c	t	b	
Municipal solid waste							
MSW incineration WtE without use of heat	0.029	0.029	0.027	85%	85%	86%	fossil electricity production mix, NL
MSW incineration WtE with use of heat	n.a.	0.025	0.024	85%	88%	88%	fossil electricity production mix, NL
RDF production and use for production of clinker	0.111	0.122	0.092	44%	38%	53%	heat, from hard coal combustion
		0.065			67%		
Co-firing with coal							
animal fat and meal, electricity only		0.008			97%		electricity from coal
Digestion of organic wastes and CHP							
swill, electricity only		0.011			94%		fossil electricity production mix, NL
VGF, electricity	0.022	0.037	0.012	81%	91%	94%	fossil electricity production mix, NL
VGF, heat	n.a.	0.017	0.011	n.a.	76%	84%	heat, natural gas, at boiler
landfill gas, electricity only		0.006	0.006		97%	97%	fossil electricity production mix, NL
Green gas production and use for heating							
VGF	0.029	0.016	0.008	59%	77%	89%	heat, natural gas, at boiler
landfill gas	0.022	0.006	0.003	69%	92%	96%	heat, natural gas, at boiler
sewage sludge	0.028	0.016	0.013	60%	77%	81%	heat, natural gas, at boiler

Conclusions, Discussion and Recommendations

In this report, chains of electricity and heat from various biomass sources and various producing methods have been quantified and assessed. In order to do this, a great many data from different sources were used. Data availability has been a problem in some specific instances, mainly for the chains of manure digestion and chains of electricity and heat from municipal waste and sewage sludge. For these chains, it is recommended to conduct further studies to fill in data gaps. However, data uncertainties also occur in other chains. Specifically data with regard to emissions from agricultural soil and emissions as a result of land use changes are highly uncertain. Estimates from IPCC have been used, which represent the best estimates at this point in time. It is recommended to include progressive results from studies and measurement programs in the GHG calculator. However, we can expect a wide variation even with more precise measurements.

The chains included in this report and in the tool are examples. Many more options are available – most biomass can be used to generate electricity and heat. It was not possible in this project to include all relevant chains. This is especially true for the variety of organic waste streams. Additional effort is needed in this area, to widen the scope of the tool. Some provisions have been made in the supporting spreadsheet to the GHG calculator for the user to include more feedstocks with regard to the already included conversion processes.

Regarding methodology, we conclude that methodological choices are at least as important as data uncertainties, and probably more so. Consequences of methodological choices as specified in Chapter 3 are significant. Most influential is the choice for the allocation methodology to correct the chains for byproducts. This is especially true for the use of by-products and waste as a feedstock for energy. For example, under the influence of allocation choices the performance of the chain of manure digestion varies between +260% and -110% improvement compared to the fossil reference. The very positive result is from using substitution as an allocation method, allowing to subtract "avoided" methane emissions, as a result of using untreated manure, from the chain. The negative result comes from energy allocation, treating manure digestion purely as an energy generating process: a comparison with fossil energy shows that the latter is obviously much more efficient. This indicates the need for a further careful international debate on this issue.

In line with the draft EC Directive, allocation in E-LCA is based on the energy content of the different outputs, more specifically on the Lower Heating Value. We encountered some problems, that require solving:

- One problem refers to the treatment of residues which can be considered by-products, i.e. have a market value. This problem is in fact twofold. Some of those residues are excepted from allocation by the draft Directive while others are not, and therefore not all residues are treated in the same way. Those residues which are not excepted get a rather large share of the GHG emissions because their LHV is not so different from that of the main product, although their market value is considerably less. This leads to counter-intuitive results.

- The second problem refers to the generation of electricity and heat from waste. These processes are often highly inefficient and have high GHG emissions compared to the fossil reference, and therefore score badly from that point of view. Nevertheless, the alternative is treatment of the waste without energy generation. From a GHG reduction point of view, generating energy from waste is in all cases we investigated a good idea. The draft EC Directive does not include these feedstocks. We have outlined an approach to allocate part of these GHG emissions to the waste treatment service, which is actually the main function of the system. Other approaches are possible, although they may not be in line with a the strict application of allocation based on LHV.

One possible solution would be to shift from energy based allocation to economic allocation, based on the market values of the respective outputs, which is applicable to all types of outputs. Another is, in the case of “real” waste streams, to except them from the chosen method of allocation and identify avoided emissions to subtract from the system. A third approach may be to shift the reference and assess these processes not as energy generating chains, but as processes to avoid GHG emissions. These problems and possible solutions need to be discussed in an international setting. The draft EC directive primarily is dedicated to biofuels from dedicated energy crops. In the future, however, biofuels from waste and residues will become more prominent and therefore will be included. The same is true for the generation of electricity and heat from biomass. It is important that present choices allow for a later inclusion of these feedstocks and processes.

Another issue is the fossil reference. Here, we followed the indications of the Dutch “Renewable Energy Monitoring Protocol”, as is allowed by the EC draft Directive. While the choices made in the Protocol are obviously well considered and the result of careful deliberations, still there are some issues. The main problem is that a specific single technology for energy generation is not judged by a single straightforward criterion, but in a manner that is dependent on the actor. The influence of this choice on the outcomes, the improvement percentage indicator, appears to be considerable. For example, co-firing of rape seed oil in a coal fired power plant shows a much higher improvement percentage than co-firing of rape seed oil in a gas fired power plant. This favours the coal fired power plants above the more efficient gas fired power plants. Using a single reference would solve this problem.

When looking at the results of the calculations, an overall conclusion is that in many cases chains of electricity and heat from biomass have a significantly better GHG performance than the fossil alternative. Improvement percentages have a wide range, but go up to over 90%. There are some clear exceptions that are apparent in the results shown in Chapter 6. In general, the influence of transportation even over large distances is not great. Emissions related to agricultural practice are often important contributors to GHG performance. There is a shift from CO_2-emissions in fossil chains to CH_4- and N_2O-emissions in agricultural chains. Since the global warming potential of these gases per kg is very much larger than that of CO_2, we have a clear instance of problem shifting. In case of growing energy crops on newly cultivated land, land use change emissions can be very large contributors to the total score, depending on the type of soil and removed ecosystem.

The GHG tool is not suitable to provide an overall judgment on the sustainability of bio-based electricity and heat, but only on one aspect of that: the GHG performance. Other environmental impact categories, such as acidification, eutrophication etc. can be linked to the GHG tool with relative ease. This has been standard practice in LCA for a long time. Yet other impacts, such as land and water use, and such as social consequences, are highly relevant for a sustainability assessment of bio-energy chains, but cannot be included in the GHG calculator easily.

As has been discussed during the project many times, international harmonisation of the use of such a tool is very important. The energy market is international, therefore it is highly undesirable if such assessments diverge, especially within Europe. We regard the developed tool as a first step: it calculates GHG performance of chains and has had a first check on data and method, but it needs further refinement, development and harmonisation. As a first step, we conformed to the draft EC Directive. However, this Directive is composed for biofuels and does not cover all necessary methodological choices for chains of electricity and heat. Further international debate must take place on those issues.

In its present state, the GHG calculator can be used to obtain a first idea on the benefits of different biomass energy options in terms of GHG emissions. Time for additional data collection, for international harmonisation especially with regard to methodological issues and for gaining experience with the practical use of the tool is needed. Straightforward guidelines for data requirements and the use of the tool by the various actors in the field also have to be developed.

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