Appendices Greenhouse Gas Calculator for Electricity and Heat from Biomass

Appendix A Conversion Processes

This appendix contains information on the conversion processes used for the production of electricity as described in the other appendices. This is meant to provide an overview of the different configurations of technologies used throughout this report. Many of these technologies are able to process a variety of biomass feedstocks, so although the processes may be described using one feedstock, it is in most cases possible to substitute that feedstock with another type.

This appendix is divided into three sections. First a system description is presented of the conversion processes. Generic issues are discussed there and several example systems are described, including the systems used as reference. After that, process descriptions are given of the described systems, in which the used data is reported. The data sources are listed there. This is then followed by an example of the spreadsheet that can be used to calculate the emissions resulting from a technology utilizing a particular feedstock.

A.1 System description

This section contains the description of the systems to produce power (in combined heat and power plants co-produced with heat) on small, medium or large scale, by the combustion of a stream of biomass, sometimes gasified and/or co-fired with coal or gas. An overview of the possible system choices can be found in Figure 1.

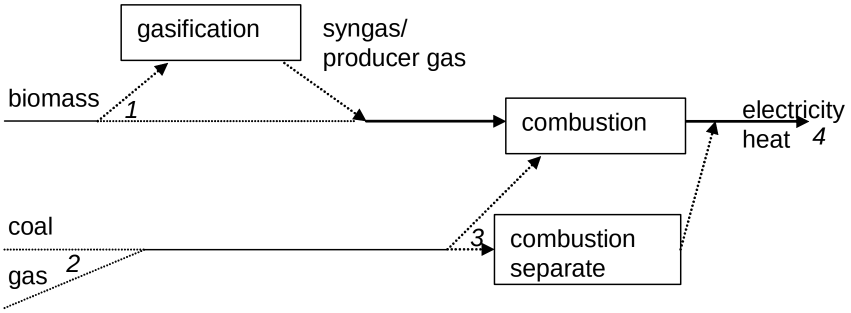

Figure 1 Overview of the system choices for conversion processes for biomass to electricity. 1) Is the biomass stream gasified before combusting? 2) Is the biomass stream co-fired? If yes, with gas or coal? 3) If co-fired, is the combustion of biomass direct, meaning that the combustion chamber is shared? and 4) is heat also considered as a product or is it a waste?

Based on these choices, a set of systems are built which are discussed in more detail (see the next sections). Before going into detail, notions generic to all of these systems are presented.

Functional unit

The functional unit is 1 kWh of electricity. In case a CHP is considered also heat is produced. For heat the functional unit is 1 MJ heat.

System boundaries and cut off

The system is cut off at the delivery of biomass streams. This means that upchain processes from production and transport of biomass are not taken into account here. The emissions by the production of capital goods (in other words, the power plants themselves) are not taken into account. All products but heat and electricity are in the analyses considered wastes, although they might have economic value.

Allocation: energy allocation

The process system “electricity and heat from biomass (and coal/gas)” delivers one or two functions 1) the production of electricity and, in case of a CHP also 2) the production of heat. All other commercial byproducts are considered wastes. In case of a CHP the system delivers two economic outputs, electricity and heat. For the CHP allocation is used based on energy content (LHV: 3.6 MJ/kWh electricity and 1 M/MJ heat).

Conservative, typical and best practice systems

In this project a distinction is made between conservative, typical and best practice systems. A system is defined as a chain of linked processes. The best practice system is defined as the chain of best practice processes. That is the most efficient processes and/or processes with the lowest GHG emission levels. Per system, described in the next sections, conservative, typical and best practice processes are defined.

General process approach

Many different types of biomass can be used to fire, co-fire and gasify. For that reason, we have made the choice to define the processes at a general level. The only thing the “user” must do is specify the carbon content and the energy content of their feedstock. An Excel based calculator then calculates the required feedstock to produce 1 kWh of electricity and the concurrent process emissions. This process description then enters E-LCA and can be used as a part of feedstock-conversion chains.

In instances such as co-firing where biomass is used for electricity production at the same time as fossil fuels, a distinction is made between electricity produced from the fraction of fossil fuels, and electricity produced by the fraction of biofuels. This division is based on energy content, with results calculated by allocation through partitioning. Upstream processes required for energy conversion of both types of fuels are partitioned in this manner. Emissions are split the same way, except for emissions such as fossil CO_2 and biogenic CO_2 where it is clear which feedstock they should be attributed to.

In the remaining part of this Appendix, example calculations have been made using different feedstocks, especially wood chips, wood pellets, waste wood, MSW and RDF. The technologies are described in the order below, and are grouped on the scale they operate on.

Small Scale < 10 MWe

- Single fired CHP with capacity 1.265 MWe. 6.3:1 kWth/kWe
- Single fired CHP with capacity 5 MWe. 2.6:1 kWth/kWe

- Single fired CHP with capacity <10 MWe. 0.208:1 kWth/kWe
- Biogas CHP with capacity 18 kWe. 1.61:1 kWth/kWe
- Biogas CHP with capacity 980 kWe. 0.672:1 kWth/kWe

Medium Scale 10 MWe to 50 MWe

- Single fired CHP with capacity 10-50 MWe. 0.714kWth/kWe
- Single firing of syngas with capacity 36.55 MWe. 0.794kWth/kWe

Large Scale > 50 MWe and Waste to Energy Installations

- Co-firing of syngas in large scale CHP (Amercentrale) with capacity 650 MWe. 0.538kWth/kWe
- Co-firing of biomass in coal-fired power plant with capacity 500 MWe. 0.58kWth/kWe
- Co-firing of biomass in natural gas fired power plant (Clauscentrale) with capacity 1840 MWe. No use of heat.
- Incineration of MSW in a waste incinerator with output 26.2MWe, 0.256:1 kWth/kWe
- Incineration of MSW in a waste incinerator with output 27.2MWe, 2.358:1 kWth/kWe
- Incineration of MSW in a waste incinerator with output 46 MWe, 1.229:1 kWth/kWe
- Incineration of MSW in a waste incinerator with output 37.5 MWe.
- Incineration of MSW in a waste incinerator with output 56.1 MWe.

The Excel based calculator is presented also at the end of this Appendix.

A.1-1 System description "Electricity and heat from single fired CHP with capacity 1.265 MWe. 6.3:1 kWth/kWe"

The described system refers to a small scale centralized electricity production system. Biomass is brought to the power plant as main feedstock. Additionally, amounts of fuel oil are used to ignite the burner. The production of electricity is delivered to the high voltage grid, and finally converted to low voltage electricity grid. The produced heat is considered also considered a product. Below a description is given of the process system according to the flowchart presented in Figure 2.

Electricity and heat are produced in a small scale CHP plant at a heat to power ratio of 6.17 : 1. The process is assumed to have an overall efficiency of 69.9%. The functional unit is defined as the supply of 1 kWh electricity, low voltage, at grid *and* 6.17 kWh of heat, low temperature.

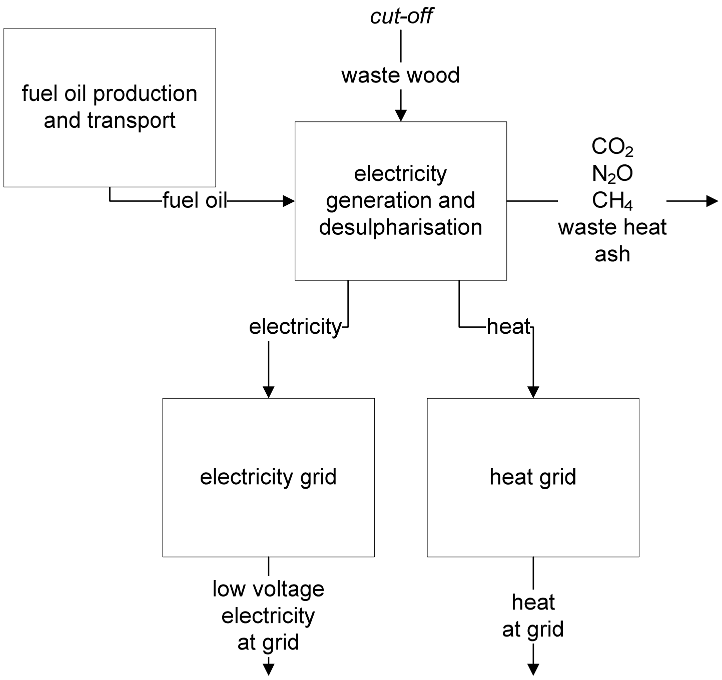

Figure 2 Flowchart of electricity and heat production by single-firing waste wood in a small scale CHP plant.

A.1-2 System description "Electricity and heat from single fired CHP with capacity 5 MWe. 2.6:1 kWth/kWe"

The described system refers to a small scale centralized electricity production system. Wood wastes are brought to the power plant as main feedstock. Additionally, amounts of fuel oil are used to ignite the burner. The production of electricity is delivered to the high voltage grid, and finally converted to low voltage electricity grid. The produced heat is considered also considered a product.

Electricity and heat are produced in a small scale 5 MWe CHP plant at a heat to power ratio of 2.6:1. The process is assumed to have an overall efficiency of 77%. The functional unit is defined as the supply of 1 kWh electricity, low voltage, at grid *and* 6.17 kWh of heat, low temperature at grid. This process is used in Appendix J.

A.1-3 System description "Electricity and heat from single fired CHP with capacity <10 MWe. 0.208:1 kWth/kWe"

The described system refers to a small scale centralized electricity production system. Wood wastes are brought to the power plant as main feedstock. Additionally, amounts of fuel oil are used to ignite the burner. The production of electricity is delivered to the high voltage grid, and finally converted to low voltage electricity grid. The produced heat is considered also considered a product. Below a description is given of the process system.

Electricity is produced by combustion of rapeseed oil in a CHP (Tilburg et al., 2006). Together with electricity also heat is produced. Per kWh about 2.57 MJ heat is produced. This system will be compared to the reference system producing 1 kWh electricity according to the Dutch production mix and 2.57 MJ of heat according to the combustion of natural gas. This process is used in Appendices B,C, D, and I.

A.1-4 System description "Electricity and heat from biogas CHP with capacity 18 kWe. 1.61:1 kWth/kWe"

This process is used in Appendix I. The described system refers to a small scale decentralized production system of electricity based on cattle manure, i.e. production of feedstock, biogas and electricity on a farm level. This means that the processes for feedstock production, conversion and end use are on the same site and therefore transport of feedstock and other materials is minimized. The feedstock for digestion can either be manure or a mixture of manure and biomass (crop, crop residues). The energy consumed by the system, e.g. electricity for chopping and mixing and heating of the digester are supplied internal by the CHP in the system. However there is a net production of electricity by the CHP on the farm that is delivered to the low voltage electricity grid (end use).

The produced heat is used internal in the system to heat up the digester (35-40 degrees C). Also part of the produced electricity (5000 kWh/year) is used within the system for mixing and pumping etc. The exceed electricity is delivered to the low voltage electricity grid (103000 kWh/year). The functional unit is defined as the supply of 1 kWh electricity, low voltage, at grid. There is no profitable use of exceed heat.

A.1-5 System description "Electricity and heat from biogas CHP with capacity 980 kWe. 0.672:1 kWth/kWe"

An example of this process can be seen in Appendix I. The biogas is combusted in a CHP that produces both heat and electricity (capacity 980kW). The produced heat is used internal within the system to heat up the digester (35-40 degrees C). Also part of the produced electricity is used within the system.

The produced heat is used internal in the system to heat up the digester (35-40 degrees C) (assumption 1155 MJ per tonne swill (SenterNovem, forthcoming)). Also part of the produced electricity is used within the system for mixing and pumping etc. (assumption 1619 MJ per tonne swill (SenterNovem, forthcoming)). The exceed electricity is delivered to the low voltage electricity grid. The functional unit is defined as the supply of 1 kWh electricity, low voltage, at grid. Together with electricity also heat is produced. Per kWh about 2.42 MJ heat is produced (see appendix A.2-4C and A.2-7). This system will be compared to the reference system producing 1 kWh electricity according to the Dutch production mix and 2.42 MJ of heat according to the combustion of natural gas.

A.1-6 System description “Electricity and heat from single fired CHP with capacity 10-50 MWe. 0.714kWth/kWe”

This system appears in Appendices B, C, D, and I. The described system refers to a small scale centralized electricity production system. Wood wastes are brought to the power plant as main feedstock. Additionally, amounts of fuel oil are used to ignite the burner. The production of electricity is delivered to the high voltage grid, and finally converted to low voltage electricity grid. The produced heat is considered also considered a product. Below a description is given of the process system.

Electricity is produced by combustion of biomass in a CHP (Tilburg et al., 2006). Together with electricity also heat is produced. Per kWh about 2.57 MJ heat is produced. This system will be compared to the reference system producing 1 kWh electricity according to the Dutch production mix and 0.75 MJ of heat according to the combustion of natural gas as defined by the fossil reference in A.1-16.

A.1-7 System description “Electricity and heat from single firing of syngas with capacity 36.55 MWe. 0.794kWth/kWe”

The described system refers to a medium scale electricity production system. Poplar thinnings are gasified and burned in a gas turbine. The electricity consumed by the gasifier is supplied by the gas turbine in the system. The net production of electricity is delivered to the high voltage grid, and finally converted to low voltage electricity grid. Below a description is given of the process system according to the flowchart presented in Figure 3.

The poplar thinnings are gasified in a gasification unit, based on Dorland et al (1997). Electricity used in this conversion comes from the electricity generation process. The wood pellets are converted to syngas. Electricity is produced in a medium scale coal gas turbine, based on Dorland et al (1997), by combusting the syngas from the gasifier. Part of the produced electricity is used in the gasifier. The rest of the electricity is brought to the electricity grid. The functional unit is defined as the supply of 1 kWh electricity, low voltage, at grid. This process appears in Appendix D.

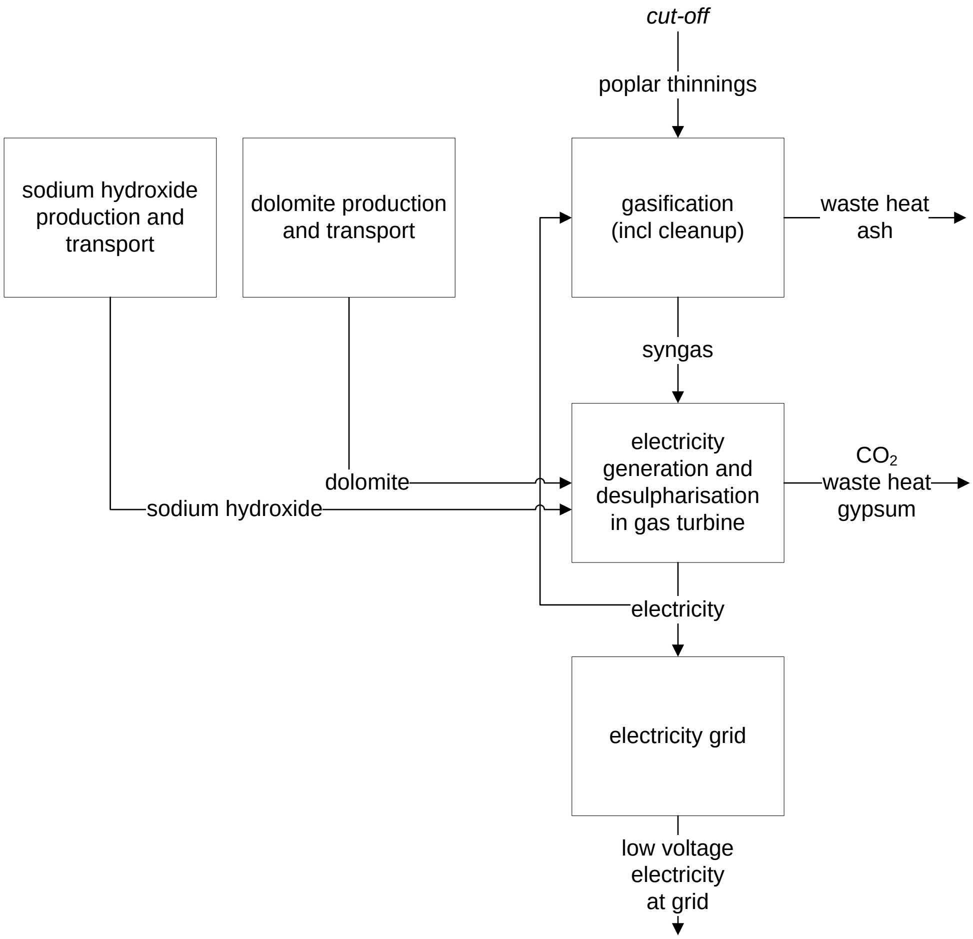

Figure 3 Flowchart of electricity production by co-firing gasified poplar thinnings with coal in a medium scale gas turbine.

A.1-8 System description "Electricity and heat from co-firing of syngas in large scale CHP (Amercentrale) with capacity 650 MWe. 0.538kWth/kWe"

The described system refers to a large scale centralized electricity and heat production system. Coal is mined and transported to the power plant as main feedstock. Additionally, amounts of wood pellets are used. The electricity consumed by the gasifier is supplied by the CHP in the system. The net production of electricity is delivered to the high voltage grid, and finally converted to low voltage electricity grid. The produced heat is delivered to the heat grid. Below a description is given of the process system according to the flowchart presented in Figure 4.

The wood pellets are gasified in a gasification unit, based on Duman et al (2007) and Damen et al (2003). The wood pellets are converted to syngas and steam is coproduced. Heat and electricity are produced in a large scale coal power plant, co-fired with syngas from the gasifier. Also the in the gasifier produced steam is used. Part of the produced electricity is used in the gasifier. The rest of the electricity and all the heat (the heat to power ratio is 1:0.58) are brought to respectively the electricity and heat grid. The functional unit is defined as the supply of 1 kWh electricity, low voltage, at grid *and* 0.58 kWh of heat in the heat grid. This process appears in Appendix E.

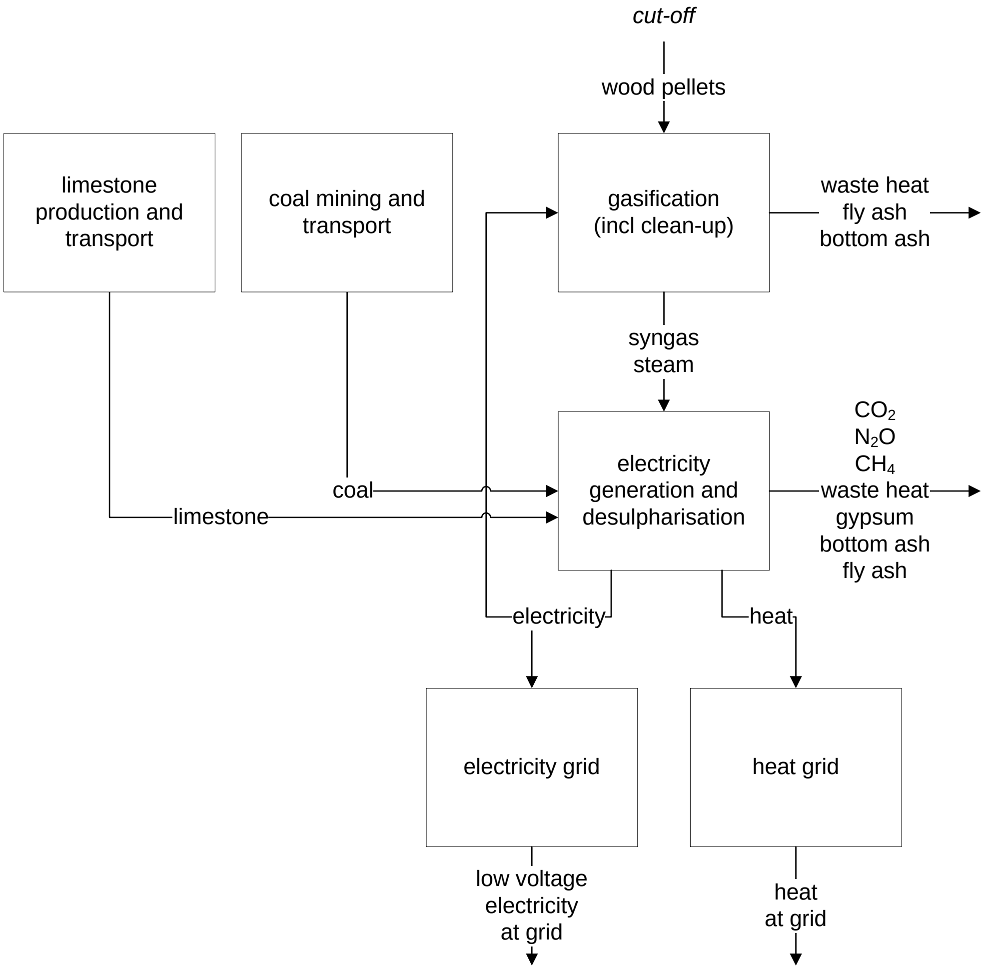

Figure 4 Flowchart of electricity and heat production by co-firing gasified wood pellets with coal in a large scale CHP plant.

A.1-9 System description "Electricity and heat from co-firing of biomass in coal-fired power plant with capacity 500 MWe. 0.58kWth/kWe"

The described system refers to a large scale centralized electricity production system. Coal is mined and transported to the power plant as main feedstock. Additionally, amounts of wood pellets are used. The production of electricity is delivered to the high voltage grid, and finally converted to low voltage electricity grid. Below a description is given of the process system according to the flowchart presented in Figure 5.

Electricity is produced in a large scale coal power plant, directly co-fired 7% (on thermal basis) with wood pellets. The process is assumed to have an electric efficiency of 42%. The functional unit is defined as the supply of 1 kWh electricity, low voltage, at grid. This process appears in Appendices E and F.

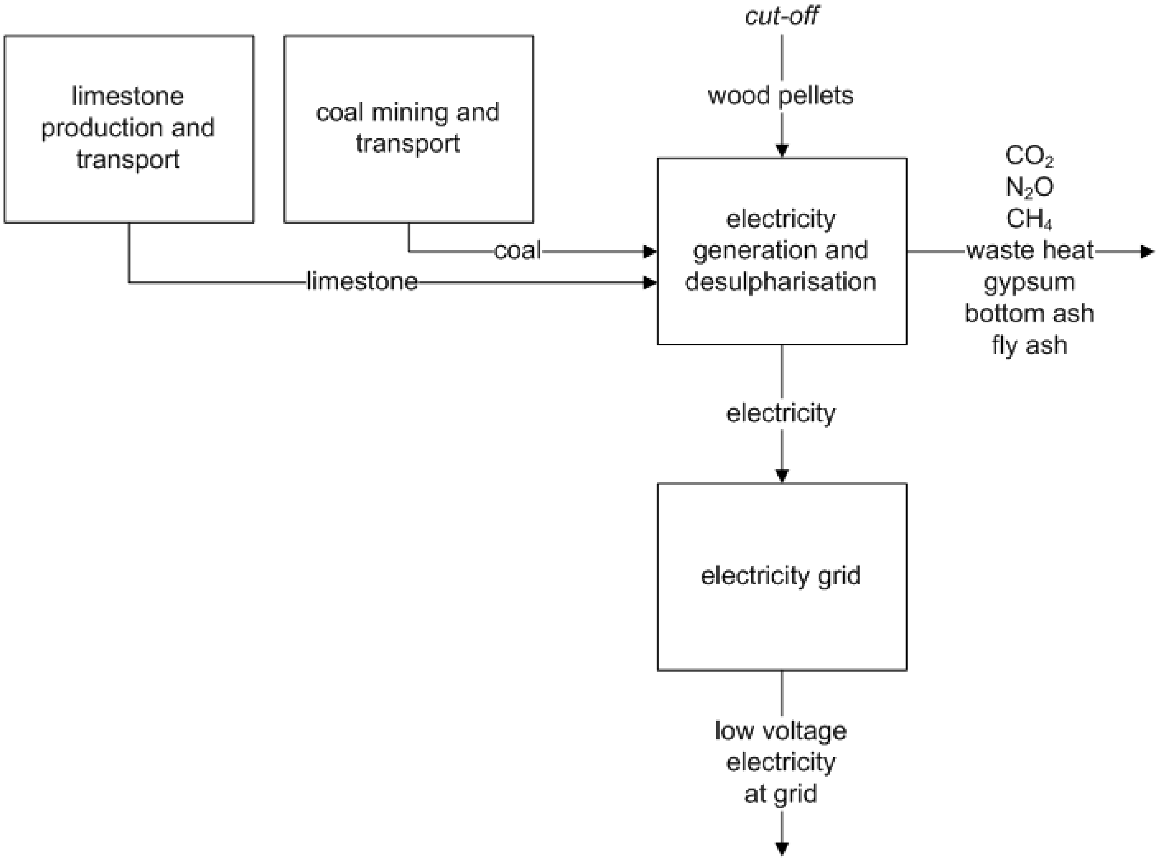

Figure 5 Flowchart of electricity production by co-firing gasified wood pellets with coal in a large scale electricity plant.

A.1-10 System description "Electricity from co-firing of biomass in natural gas fired power plant (Clauscentrale) with capacity 1840 MWe. No use of heat."

System appears in Appendix B.1-1, C.1-1, D.1-1. The functional unit is defined as the supply of 1 kWh electricity, low voltage, at grid. The electricity is produced by co-firing of rape seed oil with heavy oil and natural gas, as Essent used to do in the Claus Power plant in Maasbracht (Essent, 2006). The electricity production of the co-firing process is separated into 3 parts for rapeseed oil, heavy oil and natural gas based on the energy content of the fuels. Only the electricity from rapeseed oil and the accompanying necessary inputs are taken into account. This process appears in Appendices B, C, and D.

A.1-11 System description "Electricity and heat from incineration of MSW in a waste incinerator with output 26.2MWe. 0.256:1 kWth/kWe"

This system is based on an average Dutch waste incinerator that handles 530 kton/yr of MSW, and operates with a net electrical efficiency of 13.9%. For every 1kWh of electricity, 0.256 kWh of residual heat is produced that is then used for industrial purposes. Upstream processes such as collection and delivery of MSW are not included in the calculations as they are assumed to always occur with MSW disposal options.

The functional unit is defined as the supply of 1 kWh electricity, low voltage, at grid, with 0.26 kWh of heat based on the fossil reference described in A.2-16.

A.1-12 System description "Electricity and heat from incineration of MSW in a waste incinerator with output 27.2MWe. 2.358:1 kWth/kWe"

This system is based on a conventional waste incinerator that handles 530 kton/yr of MSW, and operates with a net electrical efficiency of 14.5%. This technology represents the most efficient plants currently in operation. For every 1kWh of electricity, 2.36 kWh of residual heat is produced that is then used for industrial purposes. Upstream processes such as collection and delivery of MSW are not included in the calculations as they are assumed to always occur with MSW disposal options.

The functional unit is defined as the supply of 1 kWh electricity, low voltage, at grid, with 2.36 kWh of heat based on the fossil reference described in A.2-16.

A.1-13 System description "Electricity and heat from incineration of MSW in a waste incinerator with output 46 MWe. 1.229:1 kWth/kWe"

This system is based on an optimized waste incinerator that handles 530 kton/yr of MSW, and operates with a net electrical efficiency of 24.6%. This type of plant represents state of the art technology, with facilities currently being constructed and planned to be operational in 2007. For every 1kWh of electricity, 1.23 kWh of residual heat is produced that is then used for industrial purposes. Upstream processes such as collection and delivery of MSW are not included in the calculations as they are assumed to always occur with MSW disposal options.

The functional unit is defined as the supply of 1 kWh electricity, low voltage, at grid, with 1.23 kWh of heat based on the fossil reference described in A.2-16.

A.1-14 System description "Electricity and heat from incineration of MSW in a waste incinerator with output 37.5 MWe, no use of heat"

This system is based on an optimized waste incinerator that handles 530 kton/yr of MSW, and operates with a net electrical efficiency of 24.6%. This type of plant represents state of the art technology, with facilities currently being constructed and planned to be operational in 2007. For every 1kWh of electricity, 1.23 kWh of residual heat is produced that is then used for industrial purposes. Upstream processes such as collection and delivery of MSW are not included in the calculations as they are assumed to always occur with MSW disposal options.

The functional unit is defined as the supply of 1 kWh electricity, low voltage, at grid, with 1.23 kWh of heat based on the fossil reference described in A.2-16.

A.1-15 System description “Electricity and heat from incineration of MSW in a waste incinerator with output 56.1 MWe, no use of heat”

This system is based on an optimized waste incinerator that handles 530 kton/yr of MSW, and operates with a net electrical efficiency of 24.6%. This type of plant represents state of the art technology, with facilities currently being constructed and planned to be operational in 2007. For every 1kWh of electricity, 1.23 kWh of residual heat is produced that is then used for industrial purposes. Upstream processes such as collection and delivery of MSW are not included in the calculations as they are assumed to always occur with MSW disposal options.

The functional unit is defined as the supply of 1 kWh electricity, low voltage, at grid, with 1.23 kWh of heat based on the fossil reference described in A.2-16.

A.1-16 System description of fossil reference systems for electricity and heat production

The described system refers to the Dutch electricity and heat generation and transport systems. The Dutch domestic non-renewable production mix is used, excluding water, wind and biomass but including nuclear energy, in accordance with the Renewable Energy Monitoring Protocol. The functional unit for electricity is defined as the supply of 1 kWh electricity, low voltage, at grid. For heat, two reference functional units are defined: 1 MJ heat, low temperature, for space heating; and 1 MJ heat, high temperature, for industrial use. Below a description is given of the process system according to the flowchart presented in Figure 6. In the case of CHP processes, a combined heat-power reference is used, according to the heat-power ratio of the CHP in question.

For electricity, losses of transport and distribution grids are taken into account. Also, for the industrial heat reference, a gas-fired industrial furnace is used, without transport and distribution (EcoInvent). Specific references are defined in addition for specific biomass chains based on specific replacement or comparability. For co-fired biomass, depending on the case, coal fired or gas-fired electricity generation is used as the fossil reference.

See the process descriptions of the references (section A.2-16) for more detailed data on the composition of the Dutch electricity mix and the data used.

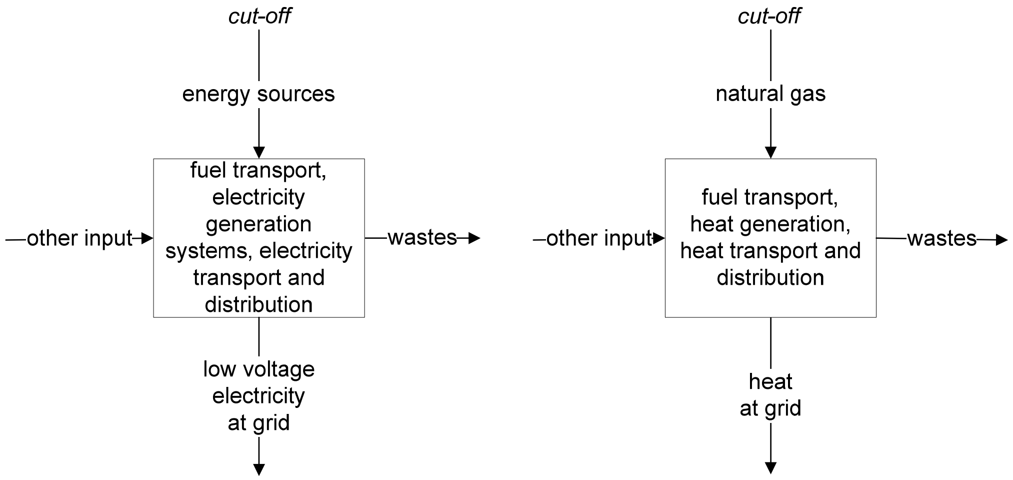

Figure 6 Flowchart of reference systems for electricity and heat production in the Netherlands.

A.1-17 System description "transformation and transport to consumer of electricity, from (….)"

Average transformation and transport losses for the referenced electricity production are 4% (SenterNovem 2006). As a default, also for bio-electricity options this 4% loss is assumed for transformation and transport. However, losses due to transformation and transport will dependent on the type of produced electricity (high, medium or low voltage), the transportation distance and the type of consumed electricity (high, medium or low voltage). For this reason a different loss can be defined in the process named "transformation and transport to consumer of electricity, from (….)" that is available for each bio-electricity chain.

A.2 Process Description

In this appendix for each of the processes in the systems (see appendix C-1) the economic inputs (consumed energy and materials of a process) and economic outputs (produced energy and materials of a process) are summarized together with the environmental inputs (e.g. the fixation of CO_2 in biomass production) and environmental outputs (the emissions of GHGs: CO_2, CH_4 and N_2O) in the unit process tables.

For the quantification of the process data several data sources are used, they are listed in the tables. For now, the focus has been on acquiring conservative data.

A.2-1 Description of the unit processes for *"electricity and heat from single fired CHP with capacity 1.265 MWe. 6.3:1 kWth/kWe"*

Process	**Electricity generation, biomass single fired, CHP** Source: Jungmeier (1998). Remarks: All carbon output of electricity generation is converted to CO_2 and CH_4. CO_2 from biomass is assumed to be biogenic. CO_2 from fuel oil is assumed fossil. The ashes are carbon-free. The system is optimized for total efficiency. An overall efficiency of 69.9% is assumed at a heat to power ratio of 6.17 : 1 (H : P). Biomass input is measured in dry weight.				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
wood chips, 64% C-content dry weight, 13.29 MJ/kg		chemicals	2.7660	kg	C
heavy fuel oil, at regional storage		chemicals	0.0979	kg	C
disposal wood ash mixture, pure, 0% water, to sanitary landfill		waste	0.0805593	kg	C
Economic outflow					
electricity generation, biomass single fired, CHP		electricity	1	kWh	reference
heat from electricity generation, biomass single fired, CHP		energy	6.17	kWh	
Environmental inflow					
Environmental outflow					
methane [air]	74-82-8	air	0.0001650	kg	C
dinitrogen monoxide [air]	10024-97-2	air	0.0000299	kg	C
carbon dioxide [air]	124-38-9	air	0.0004470	kg	C
carbon dioxide biogenic [air]		air	6.4422	kg	C
heat, waste [air]		energy	1.0829	MJ	C, corresponding to 0.3008 kWh

A.2-2 Description of the unit processes for *"Electricity and heat Single fired CHP with capacity 5 MWe. 2.6:1 kWth/kWe"*

This process describes the conversion of straw into heat and electricity, as it is used in Appendix G. Bales of straw are transported into the delivery facility of the CHP plant with the truck-trailer combination and grabbed by a crane that automatically measures the moisture-content with a microwave-measuring system. At the CHP plant are barns to store the straw bales. This gives the plant a fuel buffer for up to four days of operation.

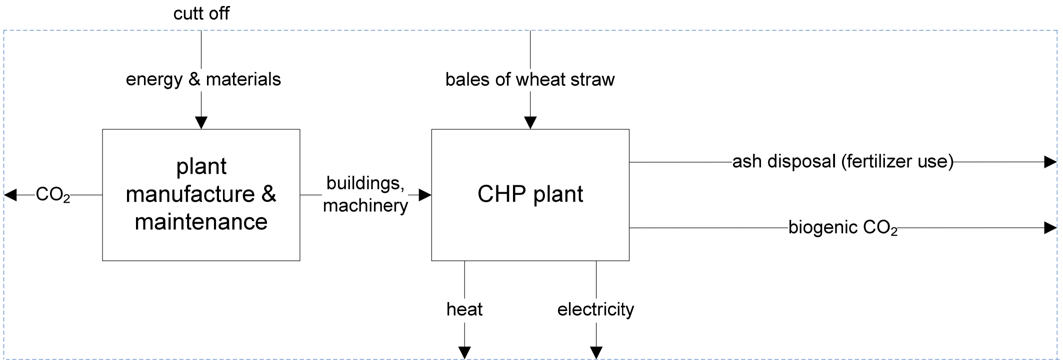

Figure 5. Flowchart of process box: [C] feedstock conversion into fuel.

Process	**Single straw firing with grate furnace in CHP plant**				
name	**code/ CAS-no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
straw		(bio)fuel	1.165	kg	= 0.002329 Hesston bale
Economic outflow					
electricity		energy	1	kWh	[3091 MJ_e/t] / [3.6 MJ/kWh] = 858.61 kWh/t / 2 = 429.31 kWh / Hesston bale → [(1 / 429.31) H.bale/kWh] x [500 kg/H.bale] = 1.165 kg.
heat		energy	9.36	MJ	[electricity (MJ_e/tonne] : [heat (MJ_{th}/tonne] = 1 : 2.6
Environmental inflow					
O_2		air	0.710	kg	44.33 wt.% C, 44/32 O_2
Environmental outflow					
CO_2 (biogenic)		air	1.893	kg	

A.2-3 Description of the unit processes for *“Electricity and heat from single fired CHP with capacity <10 MWe. 0.208:1 kWth/kWe”*

Also see Appendix C.2-2, Alternative 2

Process	**Electricity production from combustion of rape seed oil in CHP (< 10 MWe, 42% electric efficiency, 30% thermic efficiency) (Typical)** Source: (Tilburg, van et al, 2006), see appendix I.4				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Transported crude rape seed oil		biofuel	1000	kg	37.1 GJ/ton
Economic outflow					
electricity		electricity	4.33E+03	kWh	42% electric efficiency
heat		heat	11.13E+3	MJ	30% thermic efficiency
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	air	-		assumption: fuels are completely incinerated (no CH_4 formation)
N_2O	10024-97-2	air	-		assumption: fuels are completely incinerated (no N_2O formation)
CO_2, biogenic	124-38-9 (Biogenic)	air	2.83E+3	kg	own calculations, see appendix I.4

A.2-4 Description of the unit processes for *"Electricity and heat from biogas CHP with capacity 18 kWe. 1.61:1 kWth/kWe"*

Also see Appendix A.2-2

Process	**Combined Heat Power (CHP) production,** **Small scale (Capacity: 29 kW thermal,18 kWh electric),** **cattle manure, biogas option** Source: Kool, Hilhorst & van der Vegte, 2005

name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
1. Biogas (from manure) 2. Biogas (from manure and grass) 3. Biogas (from manure and corn)		biofuel	1	m^3	Alternative 1, 2 or 3 for feedstock, one of the alternatives should be chosen. 63% methane, methane: 0.71 kg/m^3 37% carbon dioxide, CO_2: 1.98 kg/m^3
Economic outflow					
electricity		energy	1.24	kWh	
heat		energy			used on site for heating of digester
Environmental inflow					
Environmental outflow					
CO_2 (Biogenic)	124-38-9 (Biogenic)	air	1.77	kg	calculated based on combustion of natural gas in CHP corrected for heating value natural gas (31.65 MJ/m^3) versus biogas (22 MJ/m^3), see appendix I.5
N_2O	10024-97-2	air	7.19E-06		see CO_2
CH_4	74-82-8	air	9.27E-06		see CO_2

A.2-5 Description of the unit processes for *“Electricity and heat from biogas CHP with capacity 980 kWe. 0.672:1 kWth/kWe”*

Also see Appendix A.2-4

Process	**Electricity production from combustion of biogas from swill in CHP (< 10 MWe, 42% electric efficiency, 30% thermic efficiency) (Typical)** Source: (after Tilburg, van et al, 2006), see appendix I.5				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Biogas (from swill)		biofuel	1	m^3	18.7 MJ/m^3 (55% CH_4)
Economic outflow					
electricity		electricity	2.18 [1]	kWh	42% electric efficiency
heat		heat	5.61 [1]	MJ	30% thermic efficiency
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	air	-		assumption: fuels are completely incinerated (no CH_4 formation)
N_2O	10024-97-2	air	-		assumption: fuels are completely incinerated (no N_2O formation)
CO_2, biogenic	124-38-9 (Biogenic)	air	1.96	kg	own calculations, see appendix I.5

Note 1: The presented production data refer to Gross production.

A.2-6 Description of the unit processes for *“Electricity and heat from single fired CHP with capacity 10-50 MWe. 0.714kWth/kWe”*

Also see Appendix C.2-2, Alternative 3

Process	**Electricity production from combustion of rape seed oil in CHP (10 MWe < 50 MWe, 48% electric efficiency, 10% thermic efficiency) (Typical)** Source: (Tilburg, van et al, 2006)), see appendix I.4				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Transported crude rape seed oil		biofuel	1000	kg	37.1 GJ/ton
Economic outflow					
electricity		electricity	4.95E+03	kWh	48% electric efficiency
heat		heat	3.71E+3	MJ	10% thermic efficiency
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	air	-		assumption: fuels are completely incinerated (no CH_4 formation)
N_2O	10024-97-2	air	-		assumption: fuels are completely incinerated (no N_2O formation)
CO_2, biogenic	124-38-9 (Biogenic)	air	2.83E+3	kg	own calculations), see appendix I.4

Transformation of Medium to Low Voltage Electricity is detailed in A.2-18.

A.2-7 Description of the unit processes for *"Electricity and heat from single firing of syngas with capacity 36.55 MWe. 0.794kWth/kWe"*

Process	**Gasification of wood chips (poplar thinnings)** Source: Dorland (1997) Remarks: It is assumed that there are no leakages between the gasification facility and this process. The heat is assumed not to be used. . The amount of electricity, stated as economic inflow, comes from the electricity generation process after this process. The ashes are carbon-free.				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
wood chips from poplar thinnings		wooden materials	0.00561	m^3	C, corresponding to 1.0930 kg (at 195 kg/m^3, FAO 2004)
electricity, single-fired syngas from wood chips (poplar thinnings) in a gas turbine		electricity	0.3890	kWh	C
disposal wood ash mixture, pure, 0% water, to sanitary landfill		waste	0.0930	kg	C
Economic outflow					
syngas from gasification of wood chips (energy emissions based on poplar thinnings)		chemicals	1	kg	reference
Environmental inflow					
Environmental outflow					
heat, waste [air]		air	0.0334	MJ	C, corresponding to 0.0901 kWh

Process	**Electricity generation, single fired syngas from poplar thinnings in a gas turbine** Source: Dorland (1997) Remarks: It is assumed that there are no leakages between the gasification facility and this process. A part of the electricity produced is used in the gasification process that should be before this process. All carbon output of electricity generation is converted to CO_2. CO_2 from syngas is assumed to be completely biogenic, since the source for syngas is biomass. Since biogenic CO_2 emissions are not listed, the stated CO_2 emissions have a fossil origin. The heat is assumed not to be used.				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
syngas from gasification of wood chips (energy emissions based on poplar thinnings)		chemicals	0.5282	kg	C
dolomite, at plant		chemicals	0.0389	kg	C
sodium hydroxide 50% H_2O production mix at plant		chemicals	0.0001592	kg	C, corresponding to 0.0000796 kg NaOH at 50% H_2O (EcoInvent)
Economic outflow					
electricity, single-fired syngas from wood chips (poplar thinnings) in a gas turbine		electricity	1	kWh	reference
gypsum, mineral, at mine		chemicals	0.0393	kg	C
Environmental inflow					
Environmental outflow					
carbon dioxide biogenic [air]		air	0.9449	kg	C
heat, waste [air]		air	4.9716	MJ	C, corresponding to 1.3810 kWh

Transformation of Medium to Low Voltage Electricity is detailed in A.2-18.

A.2-8 Description of the unit processes for *"Electricity and heat from co-firing of syngas in large scale CHP (Amercentrale) with capacity 650 MWe. 0.538kWth/kWe"*

Process	**Gasification of wood pellets** Source: Duman (2007) and Damen (2003) Remarks: It is assumed that there are no leakages between the gasification facility and this process. The amount of electricity, stated as economic inflow, comes from the electricity generation process after this process. The ashes are carbon-free.				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
wood pellets u=10% at store house		wooden materials	0.00156	m^3	C, corresponding to 1.0142 kg (at 650 kg/m^3, EcoInvent)
electricity generation coal-cofired with 7% syngas, H : P = 1 : 0.58		electricity	0.0352	kWh	C
disposal wood ash mixture, pure, 0% water, to sanitary landfill		waste	0.014220	kg	C
Economic outflow					
syngas from gasification of wood pellets		chemicals	1	kg	reference
steam from gasification of wood pellets		heat	0.7043	kWh	C
Environmental inflow					
Environmental outflow					
heat, waste [air]		air	2.90	MJ	C, corresponding to 0.4578 kWh

Process	**Electricity generation, coal co-fired with 7% syngas, P:H = 1 : 0.58** Source: Duman (2007) and Damen (2003) Remarks: It is assumed that there are no leakages between the gasification facility and this process. All carbon output of electricity generation is converted to CO_2 and CH_4. CO_2 from syngas is assumed to be completely biogenic, since the source for syngas is biomass. The ashes are carbon-free.				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
syngas from gasification of wood pellets		chemicals	0.0355	kg	C
hard coal supply mix [NL]		chemicals	0.3806	kg	C
limestone, milled, loose, at plant		chemicals	0.0106	kg	C
steam from gasification of wood pellets		heat	0.025	kWh	C
disposal, hard coal ash, 0% water, two residual landfill		waste	0.0479	kg	C
Economic outflow					
electricity generation, coal contribution		electricity	0.93	kWh	Since cofiring ratio based on energy contribution, 1 kWh = 0.93 kWh from coal + 0.07 kWh from syngas
electricity generation, syngas contribution		electricity	0.07	kWh	reference
heat from electricity generation, coal-cofired with 7% syngas, H : P = 1 : 0.58		heat	0.9733	kWh	C
gypsum, mineral, at mine		chemicals	0.0184	kg	C
Environmental inflow					
Environmental outflow					

methane [air]	74-82-8	air	0.0000085	kg	C
dinitrogen monoxide [air]	10024-97-2	air	0.0000100	kg	C
carbon dioxide [air]	124-38-9	air	0.8910	kg	C
carbon dioxide biogenic [air]		air	0.0661	kg	C
heat, waste [air]		energy	2.117	MJ	C, corresponding to 0.5833 kWh

Transformation of High to Low Voltage Electricity is detailed in A.2-17.

A.2-9 Description of the unit processes for *“Electricity and heat from co-firing of biomass in coal-fired power plant with capacity 500 MWe. 0.58kWth/kWe”*

Process	**Electricity generation, coal co-fired with 7% wood pellets** Source: Duman et al (2007), Damen et al (2003) and Manninen (1995) Remarks: All carbon output of electricity generation is converted to CO_2 and CH_4. The ashes are carbon-free. The heat is considered a waste and the system is optimized for electric efficiency. An electric efficiency of 42% is assumed.				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
wood pellets		chemicals	3.4E-5	m^3	650 kg/m^3
hard coal supply mix [NL]		chemicals	0.3242	kg	
limestone, milled, loose, at plant		chemicals	0.0106	kg	
gypsum, mineral, at mine		chemicals	0.0184	kg	
disposal wood ash mixture, to sanitary landfill		waste	0.007708	kg	
Economic outflow					
electricity generation, contribution from coal		electricity	0.93	kWh	Since cofiring ratio is based on energy contribution, 1 kWh = 0.93 kWh coal + 0.07 kWh from wood pellets
electricity generation, contribution from wood pellets		electricity	0.07	kWh	reference
Environmental inflow					
Environmental outflow					
methane [air]	74-82-8	air	0.0000085	kg	
dinitrogen monoxide [air]	10024-97-2	air	0.0000100	kg	
carbon dioxide [air]	124-38-9	air	0.891	kg	
carbon dioxide biogenic [air]		air	0.0661	kg	
heat, waste [air]		energy	2.088	MJ	corresponding to 0.5800 kWh

Transformation of High to Low Voltage Electricity is detailed in A.2-17.

A.2-10 Description of the unit processes for *"Electricity from co-firing of biomass in natural gas fired power plant (Clauscentrale) with capacity 1840 MWe. No use of heat."*

See Appendix C.2-2, Alternative 1

Process	**Electricity production from co-firing of rape seed oil with heavy oil and gas (Typical)** Source: Essent, 2006, see appendix C.3 As Essent used to do in the Claus Power plant in Maasbracht allocation energy production based on energy content of fuels (MJ/kg; rape seed oil = 37, natural gas = 37, heavy oil = 41.5)				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Transported crude rape seed oil		biofuel	8.52	kg	
Heavy fuel oil		Fossil fuel	3.81	kg	
Natural gas		Fossil fuel	1.26e3	MJ	
Economic outflow					
Electricity (rape seed part)		electricity	31.68	kWh	
Electricity (heavy oil part)		electricity	15.84	kWh	
Electricity (natural gas part)		electricity	128.48	kWh	
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	air	-		assumption: fuels are completely incinerated (no CH_4 formation)
N_2O	10024-97-2	air	-		assumption: fuels are completely incinerated (no N_2O formation)
CO_2, fossil	124-38-9 (Fossil)	air	84.4	kg	own calculations, see appendix A.3
CO_2, biogenic	124-38-9 (Biogenic)	air	24.1	kg	own calculations, see appendix A.3

Transformation of High to Low Voltage Electricity is detailed in A.2-17.

A.2-11 Description of the unit processes for *"Electricity and heat from incineration of MSW in a waste incinerator with output 26.2MWe. 0.256:1 kWth/kWe"*

Process	**Electricity and heat production from incineration of MSW** Based on average Dutch waste incineration facility. Assume 53% of energy from fossil resources, 47% from biogenic, according to SenterNovem, 2006. Process description derived from Berlo, 2006				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**Remarks**
Economic inflow					
Municipal solid waste			2.57	kg	10 MJ/kg
Economic outflow					
Electricity		electricity	1	kWh	
Heat		Heat	0.92	MJ	
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	Air	0.001796	kg	
CO_2, fossil	124-38-9 (Fossil)	Air	1.174757	kg	
CO_2, biogenic	124-38-9 (Biogenic)	Air	1.009708	kg	

Transformation of High to Low Voltage Electricity is detailed in A.2-17.

A.2-12 Description of the unit processes for *“Electricity and heat from incineration of MSW in a waste incinerator with output 27.2MWe. 2.358:1 kWth/kWe”*

Process	**Electricity and heat production from incineration of MSW** Based on “conventional” Dutch waste incinerator – best practice technology currently in operation. Assume 53% of energy from fossil resources, 47% from biogenic, according to SenterNovem, 2006. Process description derived from Berlo, 2006				
name	**code/ cas- no.**	**class/ compartment**	**Value**	**unit**	**remarks**
Economic inflow					
Municipal solid waste			2.46	kg	10 MJ/kg
Economic outflow					
Electricity		electricity	1	kWh	
Heat		heat	8.48	MJ	
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	air	0.001721	kg	
CO_2, fossil	124-38-9 (Fossil)	air	1.125581	kg	
CO_2, biogenic	124-38-9 (Biogenic)	air	0.967442	kg	

Transformation of High to Low Voltage Electricity is detailed in A.2-17.

A.2-13 Description of the unit processes for *"Electricity and heat from incineration of MSW in a waste incinerator with output 46 MWe, 1.229:1 kWth/kWe"*

Process	**Electricity and heat production from incineration of MSW** Based on optimized Dutch waste incinerator facility – start of the art technology, currently under construction. Assume 53% of energy from fossil resources, 47% from biogenic, according to SenterNovem, 2006. Process description derived from Berlo, 2006				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**Remarks**
Economic inflow					
Municipal solid waste			1.46	kg	10 MJ/kg
Economic outflow					
Electricity		electricity	1	kWh	
Heat		heat	4.42	MJ	
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	air	0.000691	kg	
CO_2, fossil	124-38-9 (Fossil)	air	0.665746	kg	
CO_2, biogenic	124-38-9 (Biogenic)	air	0.58011	kg	

Transformation of High to Low Voltage Electricity is detailed in A.2-17.

A.2-14 Description of the unit processes for *"Electricity and heat from incineration of MSW in a waste incinerator with output 37.5 MWe, no use of heat"*

Process	**Electricity and heat production from incineration of MSW** Based on conventional Dutch waste incinerator. Assume 53% of energy from fossil resources, 47% from biogenic, according to SenterNovem, 2006. Process description derived from Berlo, 2006				
name	**code/ cas- no.**	**class/ compartment**	**Value**	**unit**	**Remarks**
Economic inflow					
Municipal solid waste			1.79	kg	10 MJ/kg
Economic outflow					
Electricity		electricity	1	kWh	
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	air	0.00125	kg	
CO_2, fossil	124-38-9 (Fossil)	air	0.817568	kg	
CO_2, biogenic	124-38-9 (Biogenic)	air	0.702703	kg	

Transformation of High to Low Voltage Electricity is detailed in A.2-17.

A.2-15 Description of the unit processes for *"Electricity and heat from incineration of MSW in a waste incinerator with output 56.1 MWe, no use of heat"*

Process	**Electricity and heat production from incineration of MSW** Based on optimized Dutch waste incinerator. Assume 53% of energy from fossil resources, 47% from biogenic, according to SenterNovem, 2006				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Municipal solid waste			1.199	kg	10 MJ/kg
Economic outflow					
Electricity (fossil)		electricity	0.53	kWh	
Electricity (bio)		electricity	0.47	kWh	
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	air	0.000566	kg	
CO_2, fossil	124-38-9 (Fossil)	air	0.545249	kg	
CO_2, biogenic	124-38-9 (Biogenic)	air	0.475113	kg	

Transformation of High to Low Voltage Electricity is detailed in A.2-17.

A.2-16 Description of the unit processes for *"fossil reference systems for electricity and heat production"*

The fossil reference for electricity is the Dutch production mix, based on fossil fuels and nuclear energy, so without renewable energy. The Dutch electricity mix is defined as follows (based on 2004 CBS data, Milieu en Natuur Compendium 2007, Seebregts 2005, and EcoInvent):

source	**mix** %	**efficiency** %	**remark**
natural gas	52.0	43	
hard coal	43.6	39	
nuclear	4.1		90% pressure water reactor, 10% boiling water reactor
industrial gas	0.1	36	
oil	0.1	44	

The electric efficiencies of the most important energy sources are stated. For coal co-firing, the reference of coal (as displayed in the table above) is used. These data come from the EcoInvent database.

Average transformation and transport losses for the referenced electricity production are 4% (SenterNovem 2006).

References for heat are the following:

- Industrial heat use (burning natural gas in an industrial furnace of 100kW)
- District heating: tap water and house heating (burning natural gas in a boiler of <100kW)

The following properties apply to those references. Note that transport losses are absent in these references, since they are bound to specific situations and no general conclusions can be drawn.

Use	**Efficiency**	**Source**
District heating	95%	EcoInvent and SenterNovem (2006)
Industrial heat use	90%	SenterNovem (2006)

The resulting greenhouse gas emissions, in kg CO_2-eq per kWh rep per MJ, 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
0,071	Heat, gas fired boiler

A.2-17 System description "transformation and transport to consumer of electricity, from (….)"

Average transformation and transport losses for the referenced electricity production are 4% (SenterNovem 2006). As a default, also for bio-electricity options this 4% loss is assumed for transformation and transport. However, losses due to transformation and transport will depend on the type of produced electricity (high, medium or low voltage), the transportation distance and the type of consumed electricity (high, medium or low voltage). For this reason a different loss can be defined in the process named "transformation and transport to consumer of electricity, from (….)" that is available for each bio-electricity chain.

Process	***transformation and transport to consumer of electricity, from (….)*** Average transport losses for the referenced electricity production are 4% (SenterNovem 2006).				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Electricity (High Voltage)		electricity	1.04	kWh	
Economic outflow					
Electricity (Low Voltage)		electricity	1	kWh	
Environmental inflow					
Environmental outflow					

A.3 Example spreadsheet

In this section an example is given of the spreadsheet that can be used to calculate the emissions resulting from a certain technology using a particular mix of feedstocks. The user must fill in the highlighted sections that detail the mix of feedstocks, the energy content of each feedstock, and the electrical conversion efficiency of the technology itself. In addition, the user must specify the percent carbon by weight of each feedstock. For this column, the user must designate whether the carbon is derived from fossil fuels or renewable resources.

Sheet 1

ENERGY BALANCE - CO-FIRING WITH COAL

Fuel	Quantity		Energie content		Input			Elektrisch rendement	Electrical Output				
Coal	3000	kg	29.3	MJ/kg	87900	MJ			36918	MJ		10255	kWh
Wood pellets	0	kg	14	MJ/kg	0	MJ			0	MJ		0	kWh
Syngas	3	kg	6.5	MJ/kg	19.5	MJ			8.19	MJ		2.275	kWh
RDF1	0	kg	10.25	MJ/kg	0	MJ			0	MJ		0	kWh
RDF2	0	kg	11.68	MJ/kg	0	MJ			0	MJ		0	kWh
RDF3	0	kg	16.57	MJ/kg	0	MJ			0	MJ		0	kWh
RDF4	0	kg	14.9	MJ/kg	0	MJ			0	MJ		0	kWh
Palm oil	0	kg	37.1	MJ/kg	0	MJ			0	MJ		0	kWh
rape seed oil	0	kg	37.1	MJ/kg	0	MJ			0	MJ		0	kWh
soy bean oil	0	kg	37.1	MJ/kg	0	MJ			0	MJ		0	kWh
meat and bone meal	89	kg	18.8	MJ/kg	1673.2	MJ			702.744	MJ		195.2067	kWh
animal fat	242	kg	35.6	MJ/kg	8615.2	MJ			3618.384	MJ		1005.107	kWh
other2	0	kg		MJ/kg	0	MJ			0	MJ		0	kWh
other2	0	kg		MJ/kg	0	MJ			0	MJ		0	kWh
total	3334	kg			98207.9	MJ		42.0%	4.12E+04	MJ	equals	1.15E+04	kWh

CARBON BALANCE - CO-FIRING WITH COAL

Fuel	Quantity		Carbon content		Carbon			Carbon dioxide emissions		
			Bio	Fossil	Bio	Fossil		Bio	Fossil	
Coal	3000.00	kg		58.11%	0	1743.3	kg	0	6392.1	kg
Wood pellets	0.00	kg			0	0	kg	0	0	kg
Syngas	3.00	kg	41.30%		1.239	0	kg	4.543	0	kg
RDF1	0.00	kg			0	0	kg	0	0	kg
RDF2	0.00	kg			0	0	kg	0	0	kg
RDF3	0.00	kg			0	0	kg	0	0	kg
RDF4	0.00	kg			0	0	kg	0	0	kg
Palm oil	0.00	kg	77.10%		0	0	kg	0	0	kg
rape seed oil	0.00	kg	77.10%		0	0	kg	0	0	kg
soy bean oil	0.00	kg	77.10%		0	0	kg	0	0	kg
meat and bone meal	89.00	kg	50.10%		44.589	0	kg	163.493	0	kg
animal fat	242.00	kg	50.10%		121.242	0	kg	444.554	0	kg
other1	0.00	kg			0	0	kg	0	0	kg
other2	0.00	kg			0	0	kg	0	0	kg
total	3334.00	kg						total	7.00E+03	kg
								total biogenic	6.08E+02	kg
								total fossil	6.39E+03	kg

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Appendix B Electricity and heat from palm oil by co-firing with heavy oil and natural gas or combustion in CHP

B.1 System description

This section contains the description of the system to produce heat and electricity from palm oil. An overview of the total system can be found in figure G1. Before going into detail of these individual processes, notions generic this system are presented.

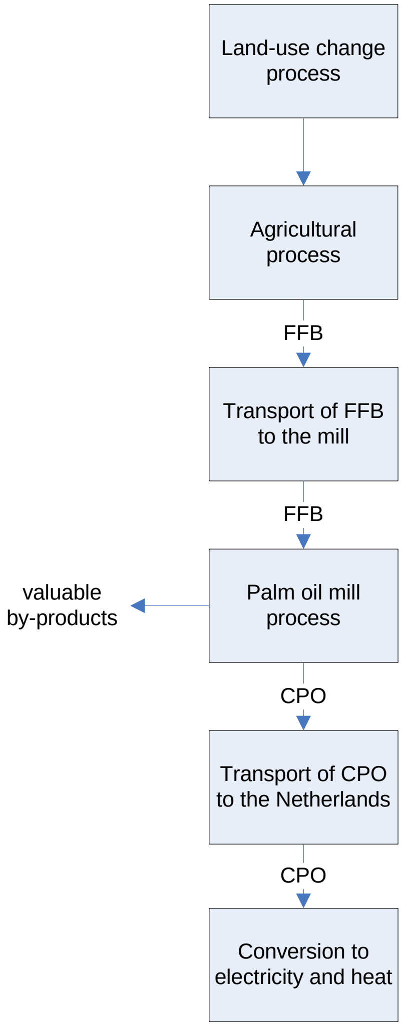


Figure G1 ***production chain of heat and electricity generation from crude palm oil (CPO)***

Functional unit
The functional unit is 1 kWh of electricity or 1 MJ of heat, in case a CHP is considered.

System boundaries
The system of the palm oil production starts at the cultivation of the oil palm trees, including the land-use change process. All the economic and environmental in- and outflows from this point to the final conversion to heat and electricity are taken into account. The emissions by the production of capital goods (in other words, the power plants themselves) are not considered in this analysis.

Allocation: energy allocation
The milling process produces more than one good, i.e. 1) palm oil and 2) Palm kernel. The allocation factor is based on the energy content of the produced materials. The energy content is based on the Lower Heating Value (LHV) (see table). An overview of LHVs of materials as used in this project is given in the appendix.

Lower Heating Values (fresh material)

	MJ/kg
Crude palm oil	36.5
Palm kernel	14

Conservative, typical and best available systems
In this project, a distinction is made between conservative, typical and best available systems. A system is defined as a chain of linked processes. The best available system is defined as the chain of best available processes. That is the most efficient processes and/or processes with the lowest GHG emission levels. Per system, described in the next sections, conservative, typical and best available processes are defined.

B.1-1 System description "production of heat and electricity from crude palm oil"

The system of heat and electricity from crude palm oil starts at the agricultural processes where the fresh fruit bunches (FFB) are cultivated. These FFB are transported to the palm oil mill where crude palm oil (CPO) will be extracted from the fruits. Subsequently, the CPO will be transported to the harbor where it will be loaded on a transoceanic tanker that transports the oil to the Netherlands. Finally, the crude palm oil is, in different ways, converted into heat and electricity. The individual processes can be listed as follows

[A] land-use change process
[B] oil palm cultivation
[C] fresh fruit bunches transportation
[D] crude palm oil extraction
[E] crude palm oil transportation
[F] end use

NOTE: Palm oil and its derivatives are important feed stocks in the food and cosmetic industry. For that reason, crude palm oil is fractionated into palm olein, palm oil stearine and free fatty acids. Palm oil stearine can be used to produce both heat and electricity. When palm oil stearine is considered, the refinery process should be added to the chain. Because the refinery process is a multi-output process, the emissions from the preceding chain should be allocated economically. Since representative information of the in- and outputs of this refinery process is difficult to find, this process should be added manually in E-LCA by the users of the tool.

The individual processes are described in more detail in B.2-1. The environmental and economic in- and outflows are also given in that section of this appendix.

B.2 Process Description

This part of the appendix gives more detailed information on the economic and environmental flows for the processes described in Appendix B.1. For the environmental flows, we are mainly concerned with accounting for the major greenhouse gases CO_2, CH_4, and N_2O. The economic flows described concern the daily operation of the processes. Flows regarding capital goods are excluded as it is assumed their impact is minor.

Here, the processes of the system of *"production of heat and electricity from crude palm oil"* are described in more detail. All the environmental and economic in- and outflows are given for each of these processes.

B.2[A] *land-use change*

Several oil palm plantations (croplands) are located at land that used to be in another land-use category. The land-use change from the original land-use category to cropland results in changes in carbon stocks in biomass, mineral soils and organic soils. In the IPCC's *Guidelines for National Greenhouse Gas Inventories* (2006), three methodologies

- differing in the level of elaboration - are given for the calculation of GHG emissions from these land use changes. The least elaborated and most general methodology, tier 1, is used in this appendix. References to tables and equation in this part of the appendix refer to the IPCC report unless specified otherwise. Further, it is assumed that the carbon stock changes will oxidize completely and will be released as CO_2.

Carbon stored in biomass is considered as biogenic and is - because its global warming potential is set to 0 - not included in this inventory analysis.

Annual carbon stock changes in mineral soils are calculated by determining the difference between the original and final carbon stocks divided by the inventory time (eq. 2.25). The carbon stocks in forestland and grassland are defined as 60 tonnes C ha^{-1} (table 5.10), since the reference carbon stock is found to be 60 tonnes C ha^{-1} (table 2.3). Mineral carbon stocks in cropland are calculated to be 55,2 tonnes C ha^{-1} (table 5.5) and the inventory time is set to 20 yrs. These values will result in an emission of 0,88 tonnes CO_2 ha^{-1} yr^{-1} for the first 20 after land conversion from both grassland and forestland to cropland.

Peat soils contain very much organic carbon that mainly will be released when drained and cultivated. According to the IPCC, the emission factor for the annual carbon loss from drained/cultivated organic soils is 20 tonnes C ha^{-1} yr^{-1} (table 5.6) for the inventory time period. This results in an emissions of 73,33 tonnes CO_2 ha^{-1} yr^{-1} for the first 20 years after conversion from peat soils to cropland.

Since the C:N ratio remains constant in soils, carbon losses in soils will result in mineralization of organic nitrogen. This inorganic nitrogen will induce the microbiological processes of nitrification and denitrification in which N_2O is an intermediate or by-product. Produced N_2O can leak from the microbial cells into the soil and ultimately into the atmosphere. Both carbon losses in mineral soils and carbon losses from drained/cultivated organic soil result in an increase of nitrous oxide emissions.
The direct and indirect (after leaching) nitrogen emissions due to carbon losses in mineral soils are 0,25 kg N_2O ha^{-1} yr^{-1} (eq. 11.1&11.8) and 0,06 kg N_2O ha^{-1} yr^{-1} (eq. 11.8&11.10) respectively. The emission factor for N_2O emissions from drained/managed soils is given as 16 kg N_2O-N ha^{-1} yr^{-1} (table 11.1), which results in an emission of 25,1 kg N_2O ha^{-1} yr^{-1}.

Conservative, typical and best practice

conservative:	The oil palms are cultivated on peat soils that used to be forestland within the last 20 years.
typical:	Emissions due to the land conversion are not allocated to the oil palm cultivation. It is assumed that the land was already in the same land-use category
best practice:	The oil palms are cultivated on land that used to be grassland within the last 20 years.

Land-use change process

Name	Code/ Cas- no.	Class/ Compartment	Value	Unit	Remarks
Economic inflow					
Economic outflow					
Cropland			1,00E+00	ha	
Environmental inflow					
Forestland on peat			1,00E+00	ha	C
Cropland			1,00E+00	ha	T
Grassland			1,00E+00	ha	B
Environmental outflow					
N_2O	10024-97-2	air	2,55E+01	kg	C
			0,00E+00	kg	T
			3,08E-01	kg	B
CO_2, fossil	124-38-9	air	7,44E+04	kg	C
			0,00E+00	kg	T
			8,80E+02	kg	B

B.2[B] *oil palm cultivation*

Palm trees are cultivated on plantations ranging from 1000 to 6000 hectares that contain 120-150 palms per hectare. After three years, the palms start to produce the oil containing fresh fruit bunches (FFB) for 20 to 25 years continuously, which can be harvested every 10 to 21 days. Each fresh fruit bunch weight 10-20 kg and contain many individual fruits. Per hectare, 19,1 tonnes FFB (C; Parkhomenko, 2004) 19,6 tonnes FFB (T; MPOB, 2006), 23,3 tonnes FFB (B; Parkhomenko, 2004) can be harvested annually.

Both organic and inorganic fertilizers are used during the cultivation of oil palms. The empty fruit bunches (EFB), a waste product from the palm oil mill process, are used as organic fertilizer (Hirsinger *et al*., 1995; Yusoff *et al*., 2007). The best available default values for the N and P consumption come from Parkhomenko (2004), for the K consumption, the best available value comes from FAO (2001). The typical values for all fertilizer consumptions come from FAO (2004). The conservative value of the K consumption comes from Parkhomenko (2004) while the N and P consumption values come from Dehue (2006). The emissions from the production of the artificial fertilizers are taken from Eco-Invent.

Dehue (2006) states that 0,5 GJ/tonne palm oil is used, this value is corrected for yield applied used as Conservative, Typical and Best practice value. The applied pesticides also come from Dehue (2006).

The calorific value of Diesel is 45,4 MJ/kg (Jungbluth *et al.* 2004). The emissions from the 1 kg diesel combusted in a lorry is taken from Spielmann *et al.* (2004) and are 3,11 kg CO_2, 0,000204 kg N_2O and 0,000265 kg CH_4.

Due to the human induced net additions of N fertilizers - both organic and inorganic - the managed soil will emit amounts of N_2O. In the IPCC's *Guidelines for National Greenhouse Gas Inventories* (2006), three methodologies - differing in the level of elaboration - are given for the calculation of nitrous oxide emissions from managed soils. The least elaborated and most general methodology, tier 1, is applied in this appendix. References to tables and equation in this part of the appendix refer to the IPCC report unless specified otherwise.

Additions of mineral nitrogen will induce the microbiological processes of nitrification and denitrification. N_2O is an intermediate or by-product of these reaction sequences and can leak into the soils and finally into the atmosphere. The N_2O emissions are calculated by equation 11.1, 11.9 and 11.10. The applied synthetic N fertilizer is 200 kg N $ha^{-1}yr^{-1}$(C), 81,1 kg N $ha^{-1}yr^{-1}$(T) and 114 kg N $ha^{-1}yr^{-1}$(B), respectively. 23% of the FFB weight will be removed as empty fruit bunches (EFB) that has as dry matter content of 35% (Yusoff, 2006) and a nitrogen content of 0,93% (Saletes, 2004). The organic N fertilizer will then be 1,43 kg N $ha^{-1}yr^{-1}$ (C), 1,47 kg N $ha^{-1}yr^{-1}$ (T) and 1,74 kg N $ha^{-1}yr^{-1}$(B). The emissions factors and fraction are taken from table 11.1 and 11.3.

Agricultural Process

Name	Code/ Cas- no.	Class/ Compartment	Value	Unit	Remarks
Economic inflow					
Cropland			1,00E+00	ha	
Pesticides			8,50E+00	kg	C
			8,00E+00	kg	T
			1,04E+01	kg	B
Atificial Fertilizer					
N			2,00E+02	kg	C
			8,11E+01	kg	T
			1,14E+02	kg	B
P			3,78E+01	kg	C
			4,84E+01	kg	T
			1,90E+01	kg	B
K			1,70E+02	kg	C
			1,05E+02	kg	T
			1,77E+02	kg	B
Diesel			2,12E+03	MJ	C
			2,13E+03	MJ	T
			2,59E+03	MJ	B
Economic outflow					

FFB			1,91E+04	kg	C
			1,96E+04	kg	T
			2,33E+04	kg	B
Environmental inflow					
Environmental outflow					
N_2O	10024-97-2	air	4,21E+00	kg	C
			1,73E+00	kg	T
			2,42E+00	kg	B
CH_4	74-82-8	air	1,24E-02	kg	C, T
			1,51E-02	kg	B
CO_2, fossil	124-38-9	air	1,45E+02	kg	C
			1,46E+02	kg	T
			1,77E+02	kg	B

B.2[C] *fresh fruit bunches transportation*

The average distance between the palm plantation and the palm oil mill is 5 km (Damen *et al*., 2003). This distance is as short as possible because the FFB have to be manufactured very soon to prevent free fatty acids formation in the palm fruits, which harms the quality of the palm oil. The average amount of fresh fruit bunches transported is 5 ton (Damen *et al*., 2003). Emissions from the operation of the truck are calculated automatically by CMLCA or E-LCA. Emissions values come from Eco-Invent.

Transport (plantation-mill)

Name	Code/ Cas- no.	Class/ Compartment	Value	Unit	Remarks
Economic inflow					
FFB			2,00E+04	kg	
operation, lorry < 16t			2,00E+01	km	
Economic outflow					
FFB, at mill			2,00E+04	kg	
Environmental inflow					
-					
Environmental outflow					
-					

G-2[D] *crude palm oil extraction* (Yusoff *et al*., 2007; Hirsinger *et al.* 1995)

When delivered at the palm oil mill, the fresh fruit bunches are sterilized with steam. The high temperature of the steam deactivates the enzymes, which break down the oil into free fatty acids. After sterilization, the FFB are sent to a stripper where the individual fruitlets are separated from the stems. In this analysis, it is assumed that the empty fruit bunches (EFB) are transported back to the plantation where they are used as organic fertilizer. In the digester & screw press process, the fruitlets are converted into an oily mash out of which the crude oil mixture (COM) comes. The COM consists of oil, water and fruit solids. The remaining presscake is sent to a depericarper, where the fibre is separated from the nuts.

The fibre is used as fuel to produce the steam and electricity for the process. The nuts are sent to another mill where they are used for the palm kernel oil production. The palm kernel shells that are a waste of the palm kernel oil extraction process are sent back to the palm oil mill and also used to produce steam and electricity (Mahlia *et al.,* 2001; Harimi *et al.* 2005; Yusoff, 2006). In this analysis, it is assumed that the fibers and shell produce enough energy for the extraction process. The moisture content of the fibres and shells are 35% and 10%, respectively. The carbon contents of these fuels are supposed to be 47,2% for fibres and 52,4% for shells (Mahlia, 2001). It is assumed that the oxygen supply is sufficient for complete combustion, so all the carbon will be emitted as CO_2.

The crude oil mixture is clarified where after the product, crude palm oil (CPO), has been produced. Another outflow of this clarification process is the palm oil mill effluent (POME). This POME is digested anaerobicly and released into the river. During this digestion, 28 m^3 biogas[1]/tonne POME is produced (Yacob *et al.*2005). In practice, this biogas is mostly emitted into the air, but project are initiated to collect this biogas for electricity generation, which is used internally. A flowchart of a palm oil mill is shown in figure G2.

From 1 tonne of FFB, 200 kg crude palm oil, 65 kg as palm kernels, 230 kg empty fruit bunches (EFB), 145 kg fibres, 65 kg shells and 0,7 m^3 POME will be obtained.

Conservative, typical, best practice

Conservative and typical: it is assumed that the biogas is released into the air
Best practice: The biogas is captured and used to produce electricity.

---

[1] It is assumed that the biogas contains 50v% methane, 50v% CO_2. This is the mean value of Yacob *et al.* (2006) and earlier reported data (Hirsinger *et al.*, 1995).

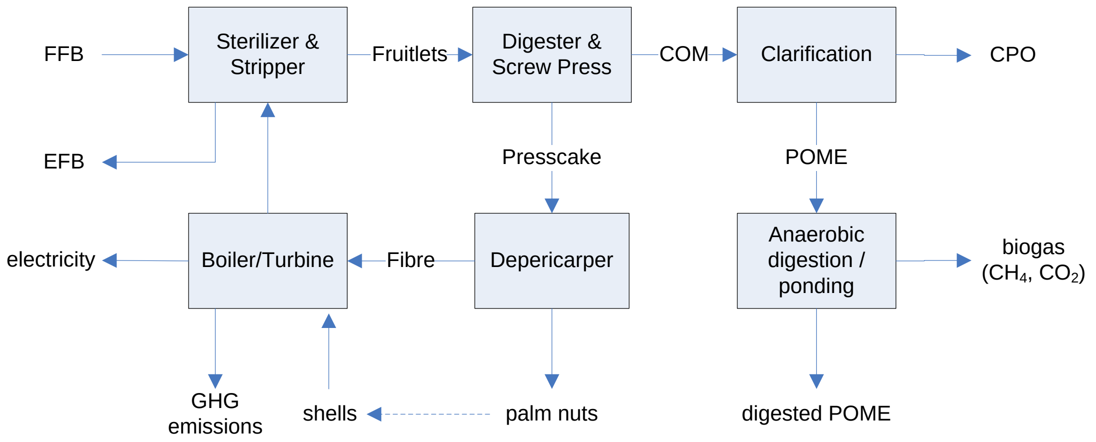


Figure G2 ***Flowchart of a palm oil mill process***

The products (CPO and palm kernel) are allocated based on the energy content of the materials.

Mill process

Name	Code/ Cas- no.	Class/ Compartment	Value	Unit	Remarks
Economic inflow					
FFB			1,00E+03	kg	
Economic outflow					
CPO			2,00E+02	kg	
Palm kernel			6,50E+01	kg	
Environmental inflow					
-					
Environmental outflow					
POME		water	7,00E+02	kg	
CH_4	74-82-8	air	7,01E+00	kg	T
			0,00E+00	kg	B
CO_2, biogenic		air	2,95E+02	kg	T
			3,14E+02	kg	B

B.2[E] *crude oil palm transportation*

The crude palm oil is first transported to the harbor where it will be loaded on a transoceanic tanker, which transports it to the Netherlands. The average distance from the palm oil mill to the harbor is assumed to be 100 km and is transported in a lorry with a capacity of 40t (Damen *et al*., 2003). The distance from the harbor, assumed to be located in South East Asia, to the Netherlands is 16.000 km (www.distances.com). Emissions from the operation of the truck are calculated automatically by CMLCA or E-LCA and come from Eco-Invent.

Transport (mill-harbor)					
Name	**Code/ Cas- no.**	**Class/ Compartment**	**Value**	**Unit**	**Remarks**
Economic inflow					
CPO			4,00E+04	kg	
Operation, lorry 40t, full			1,00E+02	km	
Economic outflow					
CPO [MY]			4,00E+04	kg	
Environmental inflow					
-					
Environmental outflow					
-					

Transport (harbour-NL)					
Name	**Code/ Cas- no.**	**Class/ Compartment**	**Value**	**Unit**	**Remarks**
Economic inflow					
CPO [MY]			1,00E+03	kg	
Operation, transoeanic tanker			1,60E+04	tkm	
Economic outflow					
CPO [NL]			1,00E+03	kg	
Environmental inflow					
-					
Environmental outflow					
-					

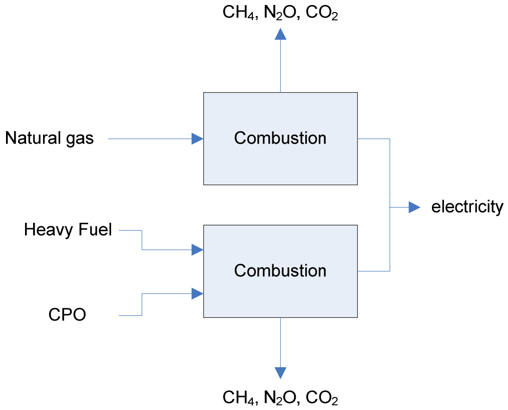
B.2[F] *End use*

The palm oil can be converted into electricity in different ways. In the Netherlands, crude palm oil is mainly co-fired or single fired. The following conversion processes are defined.

- Crude palm oil co-fired with oil and natural gas.
- Single fired medium scale CHP (10-50 MW_e).
- Single fired small scale CHP (<10 MW_e).

Since the fossil part of the co-firing process is ignored, the only difference between the co-firing process and the CHP processes is that the heat generated is counted as either economic or environmental flow. The difference between the two CHP conversion processes is the difference between the electrical and thermal efficiencies.

- *Crude palm oil co-fired with oil and natural gas*

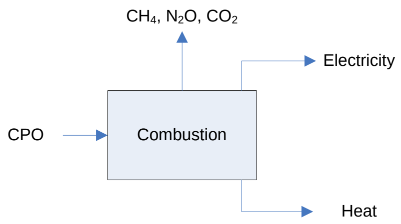


In the Clauscentrale (Maasbracht, Netherlands), Essent used to co-fire palm oil with heavy fuel and natural gas. Because the fossil parts of the co-firing process are ignored in this report, the economic inflows natural gas and heavy oil are omitted in the inventory table.

The average energy content of crude palm oil is 37,1 GJ/ton and the efficiency of the co-firing process is 36,7% (Kema&Essent, 2006). It is assumed that the crude palm oil is completely combusted and thus all the carbon is converted into CO_2. The carbon content of crude palm oil is 77,10% (Kema&Essent, 2006).

Conversion process (co-firing with heavy fuel and natural gas)					
Name	**Code/ Cas- no.**	**Class/ Compartment**	**Value**	**Unit**	**Remarks**
Economic inflow					
CPO			1,00E+03	kg	
Economic outflow					
Electricity, high voltage			3,78E+03	kWh_e	
Environmental inflow					
-					
Environmental outflow					
CO_2, biogenic			2,83E+03	kg	

- *Single fired medium scale CHP (10-50 MW_e).*



Palm oil can be used to produce both heat and electricity in a Combined Heat and Power (CHP) plant. The scale of the CHP influences the efficiencies of the heat- or electricity production. In the medium scale CHP process the thermal efficiency η_{th} is 10,0% and the electrical efficiency is 48,0% (ECN, 2006). The energy and carbon content are, of course, the same as in the co-firing process.

Conversion process (CHP, medium scale)					
Name	**Code/ Cas- no.**	**Class/ Compartment**	**Value**	**Unit**	**Remarks**
Economic inflow					
CPO			1,00E+03	kg	
Economic outflow					
Electricity			4,95E+03	kWh_e	
Heat			3,71E+03	MJ	
Environmental inflow					
-					
Environmental outflow					
CO_2, biogenic			2,83E+03	kg	

- *Single fired small scale CHP (<10 MW_e).*

The electrical and thermal efficiency of a small scale CHP is 30% and 42%, respectively.

Conversion process (CHP, small scale)					
Name	**Code/ Cas- no.**	**Class/ Compartment**	**Value**	**Unit**	**Remarks**
Economic inflow					
CPO			1,00E+03	kg	
Economic outflow					
Electricity			4,33E+03	kWh_e	
Heat			1,11E+04	MJ	
Environmental inflow					
-					
Environmental outflow					
CO_2, biogenic			2,83E+03	kg	

transformation and transport losses of electricity from producer to consumer

Average transformation and transport losses for the referenced electricity production are 4% (SenterNovem 2006). As a default, also for bio-electricity options this 4% loss is assumed for transformation and transport. However, losses due to transformation and transport will dependent on the type of produced electricity (high, medium or low voltage), the transportation distance and the type of consumed electricity (high, medium or low voltage). For this reason a different loss can be defined in the process named "transformation and transport to consumer of electricity, from (….)" that is available for each bio-electricity chain.

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Appendix C Electricity and heat from rapeseed oil by co-firing with heavy oil and natural gas or combustion in CHP

C.1 System description

In this system the electricity production is based on two alternative processes. The first alternative is the process of co-firing of crude rape seed oil with heavy fuel and natural gas, as Essent used to do in the Claus Power plant in Maasbracht (Essent, 2006).
The second alternative is the combustion of rapeseed oil in a CHP producing both electricity and heat (Tilburg et al., 2006).

The description of the system to produce crude rape seed oil from rape seed largely overlaps with the system for the production of biodiesel from rape seed. The latter system is described in the technical specification of the concurrent greenhouse gas calculator for biofuels (SenterNovem, forthcoming). For the process chain from production of the rape seed to production of crude rape seed oil the description and assumptions of SenterNovem (forthcoming) are used, unless otherwise stated. In figure 1 a flowchart is presented that summarizes the different processes of the system and indicates where emissions of green house gasses (GHGs) might occur.

Functional unit
The functional unit is 1 kWh of electricity. In case a CHP is considered also heat is produced. For heat the functional unit is 1 MJ heat.

System boundaries and cut off
The chain includes electricity and heat generation, production of rapeseed oil from crop, and the agricultural process to produce rapeseed.

Allocation: energy allocation
In the process chain there are three processes with possible co-production of products, namely: 1) the production of rapeseed & rapeseed straw; 2) the production of crude rapeseed oil & rapeseed meal and 3) the production of electricity and heat in a CHP. In correspondence with the Draft EU directive (EC, 2008) nothing is allocated to the agricultural residues, i.e. straw. For the extraction process and the CHP allocation is used based on energy content. The LHV used for energy allocation are presented in table 1. The actual allocation factors are based on the LHV of the material and the amount of produced material.

Table 1 LHV, amounts and allocation factors for oil extraction and CHP.

	LHV MJ/kg	**Amount[1] kg**	**Allocation factor[1]**
Production of rapeseed and straw			
Raw rapeseed	21.8	3449	1
Rapeseed straw	14.7	2613	0
Extraction of crude rapeseed oil			
Crude rapeseed oil	37.2	0.33	0.55
Rapeseed meal	15	0.67	0.45
CHP			
electricity	3.6 MJ/kWh	4.33E+03 kWh	0.58
heat	1 MJ/MJ	11.13E+03 MJ	0.42

[1] the amount and allocation factor are given as an example. Figures are different for different conservative, typical and best practice options.

conservative, typical and best practice systems
In this project a distinction is made between conservative, typical and best practice systems. A system is defined as a chain of linked processes. The best practice system is defined as the chain of best practice processes.

C.1-1 System description "electricity from rapeseed oil by co-firing with heavy oil and natural gas or combustion in CHP"

The system description from the production of the rape seed to the production of crude rape seed oil is taken from SenterNovem (forthcoming), unless otherwise stated.
Below a description is given of the process system according to the flowchart presented in figure 1 divided in the phases:

[A] feedstock production
Production of rapeseed and straw in Northern Europe, as SenterNovem (forthcoming), N_2O emissions due to N-fertilizer application 0.033 kg N_2O / kg N.
Production of rapeseed and straw in EU-25 (average), as SenterNovem (forthcoming), N_2O emissions due to N-fertilizer application 0.033 kg N_2O / kg N.

[B] feedstock transport
Transport of raw rape seed, as SenterNovem (forthcoming),

[C] conversion
Drying of rape seed, as SenterNovem (forthcoming),
Storage of rape seed, as SenterNovem (forthcoming),
Extraction of rape seed oil, as SenterNovem (forthcoming).

[D] (biofuel) transport

Biofuel (crude rape seed oil) transport for Northern Europe, as SenterNovem (forthcoming),
Biofuel (crude rape seed oil) transport for EU-25 (average), as SenterNovem (forthcoming),

[E] end use
The functional unit is defined as the supply of 1 kWh electricity at consumer.
In alternative 1 the electricity is produced by co-firing of rape seed oil with heavy oil and natural gas, as Essent used to do in the Claus Power plant in Maasbracht (Essent, 2006). The electricity production of the co-firing process is separated into 3 parts for rapeseed oil, heavy oil and natural gas based on the energy content of the fuels. Only the electricity from rapeseed oil and the accompanying necessary inputs are taken into account.
In alternative 2 the electricity is produced by combustion of rapeseed oil in a CHP (Tilburg et al., 2006). Together with electricity also heat is produced. Per kWh about 2.57 MJ heat is produced. This system will be compared to the reference system producing 1 kWh electricity according to the Dutch production mix and 2.57 MJ of heat according to the combustion of natural gas.

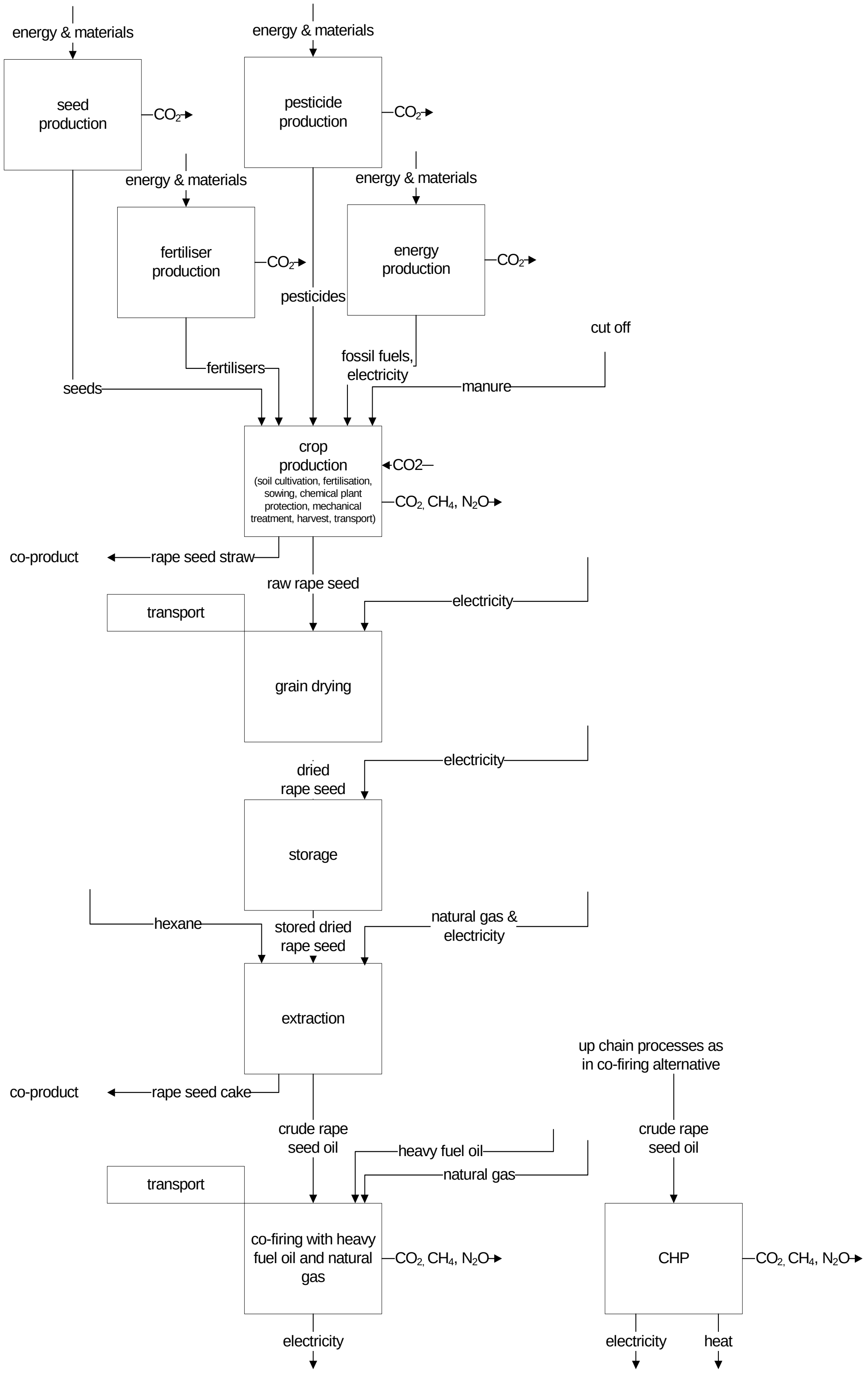

Figure 1 Two alternative flowcharts for the electricity production from crude rape seed oil

C.2 process description

In this appendix for each of the processes in the systems (see appendix H-1) the economic inputs (consumed energy and materials of a process) and economic outputs (produced energy and materials of a process) are summarized together with the environmental inputs (e.g. the fixation of CO_2 in biomass production) and environmental outputs (the emissions of GHGs: CO_2, CH_4 and N_2O) in the unit process tables.

The quantification of the process data is taken from the report on biodiesel from rape seed (SenterNovem, forthcoming), unless otherwise stated.

C.2-1 Definition of conservative, typical and best practice processes and process systems

In the appendix C.2-2 only the Typical version is presented. The E-LCA tool database also contains conservative and best practice values as described by SenterNovem, forthcoming.

C.2-2 Description of the unit processes for electricity from rape seed oil

B = best practice; T = typical; C = conservative
In the appendix given below only the Typical version is presented. The E-LCA tool database also contains conservative and best practice values as described by SenterNovem, forthcoming.

[A] Feedstock production

Process	**Production of rapeseed and straw in Northern Europe (Typical)** Source: SenterNovem, forthcoming				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Diesel combustion in machine		Fossil fuel	3463	MJ	LHV 43.1 MJ/kg, Density 832 kg/m^3
Fertiliser N		agr. means	175	kg	production emissions, see appendix J, table 6
Fertiliser P_2O_5		agr. means	44	kg	
Fertiliser K_2O		agr. means	89	kg	
Economic outflow					
Raw rape seed		agr. product	3449	kg	allocation: all to rape seed
Rape seed straw		agr. product	2613	kg	allocation: nothing to straw
Environmental inflow					
CO_2, biogenic		air	16307		Fixation 2.69 kg CO_2/kg Source: Ecoinvent
Land use change		land use			Set aside rapeseed
Environmental outflow					
CH_4	74-82-8	air			
N_2O	10024-97-2	air	5.775		0.033 kg N_2O / kg N from N fertiliser Source: CE/Ecofys, 2007

Process	**Production of rapeseed and straw in Europe (EU-25 average) (Typical)** Source: SenterNovem, forthcoming				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Diesel		Fossil fuel	2403	MJ	
Fertiliser N		agr. means	167	kg	production emissions, see appendix J, table 6
Fertiliser P_2O_5		agr. means	49	kg	
Fertiliser K_2O		agr. means	38	kg	
Fertiliser CaO		agr. means	20	kg	
Economic outflow					
Raw rape seed		agr. product	3000	kg	
Rape seed straw		agr. product	2272	kg	
Environmental inflow					
CO_2, biogenic		air	14182		Fixation 2.69 kg CO_2/kg Source: Ecoinvent
Land use change		land use			Set aside rapeseed
Environmental outflow					
CH_4	74-82-8	air			
N_2O	10024-97-2	air	5.51		0.033 kg N_2O / kg N from N fertiliser Source: CE/Ecofys, 2007

[B] Feedstock transport

Process	**Transport of feedstock (Typical)** Source: SenterNovem, forthcoming				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Raw rape seed		agr. product	1000	kg	
Transport by truck		transport	150	tkm	distance 150 km
Economic outflow					
Transported raw rape seed		agr. product	1000	kg	
Environmental inflow					
Environmental outflow					

[C] Conversion

Optional

Process	**Drying from moisture content 15% -> 9% (Typical)** Source: SenterNovem, forthcoming				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Transported raw rape seed		agr. product	1	kg	
Fuel oil		Fossil fuel	-	MJ	
Electricity		electricity	0.0186	kWh	
Economic outflow					
Dried rape seed		agr. product	0.94	kg	
Environmental inflow					
Environmental outflow					

Process	**Storage of dried rape seed (Typical)** Source: SenterNovem, forthcoming				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Dried rape seed		agr. product	1	kg	
Electricity		electricity	0.0116	kWh	
Economic outflow					
Stored dried rape seed		agr. product	1	kg	
Environmental inflow					
Environmental outflow					

Alternative 1.

Process	**Cold pressing of crude rape seed oil (Typical)** Source: SenterNovem, forthcoming				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Stored dried rape seed		agr. product	1	kg	
Electricity		electricity	0.126	kWh	
Economic outflow					
Crude rape seed oil		biofuel	0.33	kg	Energy allocation: 37.2 MJ/kg
Rape seed meal		fodder	0.67	kg	Energy allocation: 15 MJ/kg
Environmental inflow					
Environmental outflow					

Alternative 2.

Process	**Extraction of crude rape seed oil (Typical)** Source: SenterNovem, forthcoming				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Stored dried rape seed		agr. product	1	kg	
Electricity		electricity	0.084	kWh	
Heat from Natural gas combustion		Fossil fuel	1.69	MJ	
Hexane		chemical	0.0026	kg	
Economic outflow					
Crude rape seed oil		biofuel	0.4	kg	Economic allocation: 37.2 MJ/kg
Rape seed meal		fodder	0.6	kg	Economic allocation: 15 MJ/kg
Environmental inflow					
Environmental outflow					

[D] Biofuel transport

Process	**Biofuel transport for Northern Europe (Typical)** Source: SenterNovem, forthcoming				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Crude rape seed oil		biofuel	1000	kg	
Transport by truck		transport	150	tkm	distance 150 km
Economic outflow					
Transported crude rape seed oil		biofuel	1000	kg	
Environmental inflow					
Environmental outflow					

Process	**Biofuel transport for Europe-25 (Typical)** Source: SenterNovem, forthcoming				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Crude rape seed oil		biofuel	1000	kg	
Transport by truck		transport	600	tkm	distance 600 km
Economic outflow					
Transported crude rape seed oil		biofuel	1000	kg	
Environmental inflow					
Environmental outflow					

[E] End use

Alternative 1

Process	**Electricity production from co-firing of rape seed oil with heavy oil and gas (Typical)** Source: Essent, 2006, see appendix A.3 As Essent used to do in the Claus Power plant in Maasbracht allocation energy production based on energy content of fuels (MJ/kg; rape seed oil = 37, natural gas = 37, heavy oil = 41.5)				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Transported crude rape seed oil		biofuel	8.52	kg	
Heavy fuel oil		Fossil fuel	3.81	kg	
Natural gas		Fossil fuel	1.26e3	MJ	
Economic outflow					
Electricity (rape seed part)		electricity	31.68	kWh	
Electricity (heavy oil part)		electricity	15.84	kWh	
Electricity (natural gas part)		electricity	128.48	kWh	
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	air	-		assumption: fuels are completely incinerated (no CH_4 formation)
N_2O	10024-97-2	air	-		assumption: fuels are completely incinerated (no N_2O formation)
CO_2, fossil	124-38-9 (f)	air	84.4	kg	own calculations, see appendix C.3
CO_2, biogenic	124-38-9 (b)	air	24.1	kg	own calculations, see appendix C.3

Alternative 2

Process	**Electricity production from combustion of rape seed oil in CHP (< 10 MWe, 42% electric efficiency, 30% thermic efficiency) (Typical)** Source: (Tilburg, van et al, 2006), see appendix C.4				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Transported crude rape seed oil		biofuel	1000	kg	37.1 GJ/ton
Economic outflow					
electricity		electricity	4.33E+03	kWh	42% electric efficiency; energy allocation: 3.6 MJ/kWh
heat		heat	11.13E+3	MJ	30% thermic efficiency; energy allocation: 1 MJ/MJ
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	air	-		assumption: fuels are completely incinerated (no CH_4 formation)
N_2O	10024-97-2	air	-		assumption: fuels are completely incinerated (no N_2O formation)
CO_2, biogenic	124-38-9 (b)	air	2.83E+3	kg	own calculations, see appendix C.4

Alternative 3

Process	**Electricity production from combustion of rape seed oil in CHP (10 MWe < 50 MWe, 48% electric efficiency, 10% thermic efficiency) (Typical)** Source: (Tilburg, van et al, 2006)), see appendix C.4				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Transported crude rape seed oil		biofuel	1000	kg	37.1 GJ/ton
Economic outflow					
electricity		electricity	4.95E+03	kWh	48% electric efficiency; energy allocation: 3.6 MJ/kWh
heat		heat	3.71E+3	MJ	10% thermic efficiency; energy allocation: 1 MJ/kWh
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	air	-		assumption: fuels are completely incinerated (no CH_4 formation)
N_2O	10024-97-2	air	-		assumption: fuels are completely incinerated (no N_2O formation)
CO_2, biogenic	124-38-9 (b)	air	2.83E+3	kg	own calculations), see appendix C.4

transformation and transport losses of electricity from producer to consumer
Average transformation and transport losses for the referenced electricity production are 4% (SenterNovem 2006). As a default, also for bio-electricity options this 4% loss is assumed for transformation and transport. However, losses due to transformation and transport will dependent on the type of produced electricity (high, medium or low voltage), the transportation distance and the type of consumed electricity (high, medium or low voltage). For this reason a different loss can be defined in the process named "transformation and transport to consumer of electricity, from (….)" that is available for each bio-electricity chain.

Appendix C.3

ENERGY BALANCE - CO-FIRING WITH HEAVY FUEL AND NATURAL GAS									
Fuel	**Quantity**		**Energy content**		**Input**		**Electrical efficiency**	**Electrical Output**	
Natural gas	0.00E+00	ton	37	GJ/ton	1.73E+00	GJ	36.7%	6.35E-01	GJ
	3.97E+01	m^3	31.65	MJ/m^3					
Rapeseed oil	8.52E-03	ton	37.1	GJ/ton				1.76E+02	kWh
Heavy Fuel	3.81E-03	ton	41.5	GJ/ton					

CARBON BALANCE - CO-FIRING WITH FUEL AND NATURAL GAS								
Fuel	**Quantity**		**Carbon content**	**Carbon**		**Carbon dioxide emissions**		
Natural gas	3.39E-02	ton	58.11%	1.97E-02	ton	7.23E-02		ton
Rapeseed oil	8.52E-03	ton	77.10%	6.57E-03	ton	2.41E-02		ton
Heavy Fuel	3.81E-03	ton	86.80%	3.30E-03	ton	1.21E-02		ton
						Total	1.09E-01	ton
						biogenic	2.41E-02	
						fossil	8.44E-02	

Conversion process

Name	**Code/ Cas- no.**	**Class/ Compartment**	**Value**	**Unit**	**Remarks**
Economic inflow					
Natural gas			1.26E+03	MJ	
Heavy fuel			3.81E+00	kg	
Rapeseed oil			8.52E+00	kg	
Economic outflow					
Electricity			1.76E+02	kWh	
Environmental inflow					
-					
Environmental outflow					
CH_4					
N_2O					
CO_2, biogenic			2.41E+01	kg	
CO_2			8.44E+01	kg	

Appendix C.4

ENERGY BALANCE - Combined Heat Power <10MW$_e$

Fuel	Quantity		Energy content		Input		Electrical efficiency	Thermal efficiency	Electrical Output		Heat Output	
Rape seed oil	1	ton	37.1	GJ/ton	37	GJ	42.0%	30.0%	15.582	GJ	11.13	GJ
									4.33E+03	kWh		

CARBON BALANCE - Combined Heat and Power <10MW$_e$

Fuel	Quantity		Carbon content	Carbon		Carbon dioxide	
Rape seed oil	1.00E+00	ton	77.10%	7.71E-01	ton	2.83E+00	ton

ENERGY BALANCE - Combined Heat Power 10-50MW$_e$

Fuel	Quantity		Energie content		Input		Elektrisch rendement	Thermisch rendement	Electrical Output		Heat Output	
Rape seed oil	1	ton	37.1	GJ/ton	37	GJ	48.0%	10.0%	1.78E+01	GJ	3.71E+00	GJ
									4.95E+03	kWh		

CARBON BALANCE - Combined Heat and Power 10-50MW$_e$

Fuel	Quantity		Carbon content	Carbon		Carbon dioxide	
Rape seed oil	1.00E+00	ton	77.10%	7.71E-01	ton	2.83E+00	ton

Literature

Ecoinvent Centre, 2006. ecoinvent data v 1.03. Final reports ecoinvent 2000 No 1-15. Swiss Centre for Life Cycle Inventories, Dübendorf, 2006. http://www.ecoinvent.ch/

Essent, 2006. Milieu-effectrapportage. Upgrade eenheid B van de Clauscentrale te Maasbracht. Essent, Maasbracht.

SenterNovem, forthcoming. Technical specification: Greenhouse gas calculator for biofuels.

Tilburg, van X., E.A. Pfeiffer, J.W. Cleijne, G.J. Stienstra & S.M. Lensink, 2006. Technisch-economische parameters van duurzame elektriciteitsopties in 2008. ECN, Petten.

Appendix D Electricity and heat from soybean oil by co-firing with heavy oil and natural gas or combustion in CHP

D.1 System description

In this system the electricity production is based on two alternative processes. The first alternative is the process of co-firing of crude soybean oil with heavy fuel and natural gas, as Essent used to do in the Claus Power plant in Maasbracht (Essent, 2006).
The second alternative is the combustion of soybean oil in a CHP producing both electricity and heat (Tilburg et al., 2006).

The description of the system to produce crude soybean oil from soy bean largely overlaps with the system for the production of biodiesel from soy bean. This latter system is described in the technical specification of the greenhouse gas calculator for biofuels (SenterNovem, forthcoming). For the process chain from production of the soy bean to production of crude soybean oil the description and assumptions of SenterNovem (forthcoming) are used, unless otherwise stated. In figure 1, a flowchart is presented that summarizes the different processes of the system and indicates where emissions of green house gasses (GHGs) might occur.

Functional unit
The functional unit is 1 kWh of electricity. In case a CHP is considered also heat is produced. For heat the functional unit is 1 MJ heat.

System boundaries and cut off
The system includes electricity and heat generation from soy bean, the production of soybean oil from crop, and the crop cultivation itself.

Allocation: energy allocation
In the process chain there are two processes with possible co-production of products, namely: the production of soybean oil & soybean meal and the production of heat and power in a CHP. For these processes energy allocation is used. The LHV used for energy allocation are presented in table 1. The actual allocation factors are based on the LHV of the material and the amount of produced material.

Table 1 LHV, amounts and allocation factors for oil extraction and CHP.

	LHV MJ/kg	**Amount[1] kg**	**Allocation factor[1]**
Extraction of crude soybean oil			
Crude soybean oil	36.6	0.169	0.35
Soybean meal	15	0.76	0.65
CHP			
electricity	3.6 MJ/kWh	4.33E+03 kWh	0.58
heat	1 MJ/MJ	11.13E+03 MJ	0.42

1 the amount and allocation factor are given as an example. Figures are different for different conservative, typical and best practice options.

conservative, typical and best practice systems
In this project a distinction is made between conservative, typical and best practice systems. A system is defined as a chain of linked processes. The best practice system is defined as the chain of best practice processes.

D.1-1 System description "electricity from soybean oil by co-firing with heavy oil and natural gas or combustion in CHP"

The system description from the production of the soy bean to the production of crude soybean oil is taken from SenterNovem (forthcoming), unless otherwise stated.
Below a description is given of the process system according to the flowchart presented in figure 1 divided in the phases:

[A] feedstock production
Production of soybean in United States of America, as SenterNovem (forthcoming), N_2O emissions due to N-fertilizer application 0.033 kg N20 / kg N.

[B] feedstock transport
Transport of soybean, as SenterNovem (forthcoming),

[C] conversion
Receiving and Storage of soybean, as SenterNovem (forthcoming),
Extraction of soybean oil, as SenterNovem (forthcoming)

[D] (biofuel) transport
Biofuel (crude soybean oil) transport from USA to Europe, as SenterNovem (forthcoming),

[E] end use
The functional unit is defined as the supply of 1 kWh electricity at consumer.
In alternative 1 the electricity is produced by co-firing of soybean oil with heavy oil and natural gas, as Essent used to do in the Claus Power plant in Maasbracht (Essent, 2006). The electricity production of the co-firing process is separated into 3 parts for soybean oil, heavy oil and natural gas based on the energy content of the fuels. Only the electricity from soybean oil and the accompanying necessary inputs are taken into account.
In alternative 2 the electricity is produced by combustion of soybean oil in a CHP (Tilburg et al., 2006). Together with electricity also heat is produced. Per kWh about 2.57 MJ heat is produced. This system will be compared to the reference system producing 1 kWh electricity according to the Dutch production mix and 2.57 MJ of heat according to the combustion of natural gas.

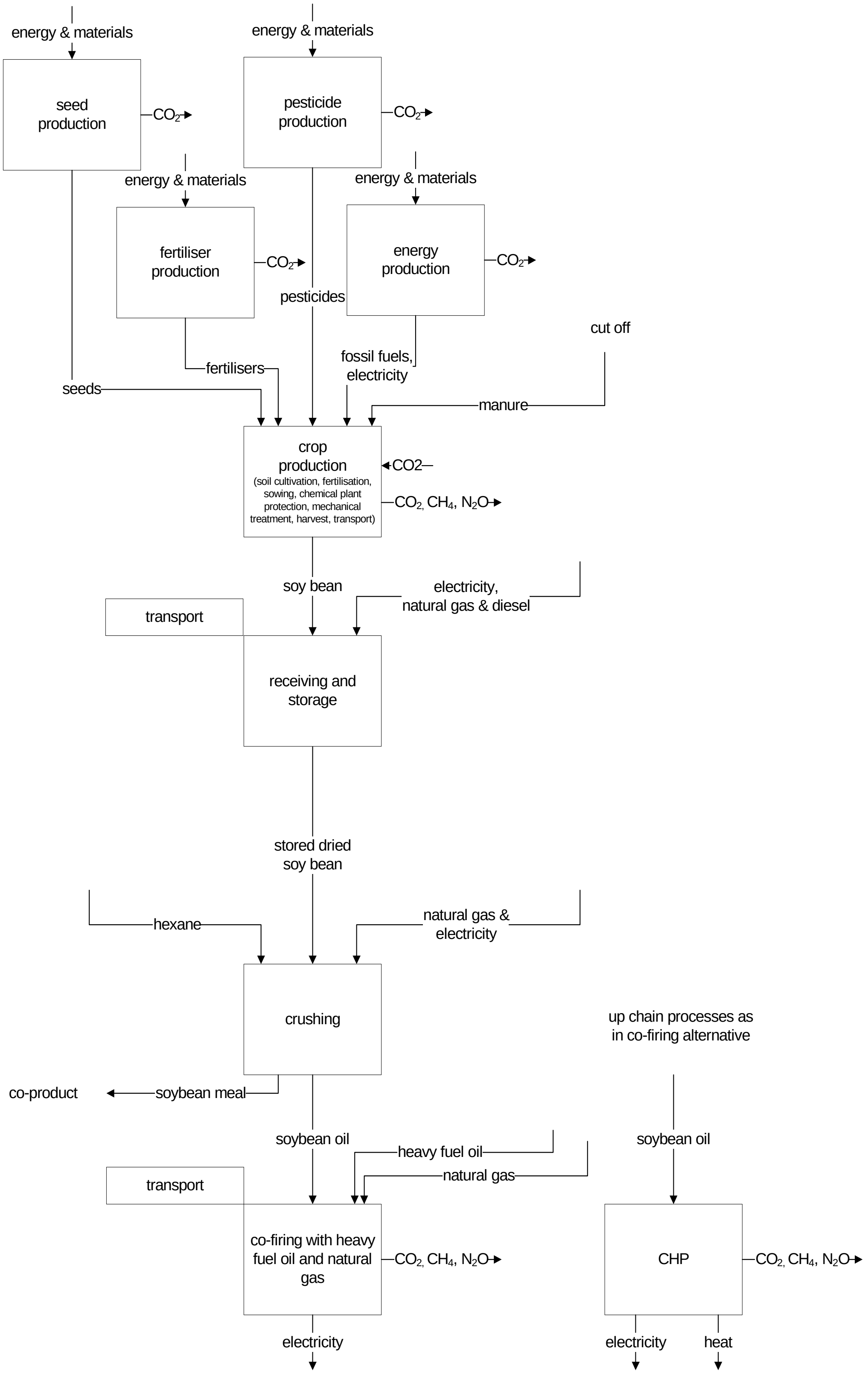

Figure 1 Two alternative flowcharts for the electricity production from soybean oil

D.2 process description

In this appendix for each of the processes in the systems (see appendix I-1) the economic inputs (consumed energy and materials of a process) and economic outputs (produced energy and materials of a process) are summarized together with the environmental inputs (e.g. the fixation of CO_2 in biomass production) and environmental outputs (the emissions of GHGs: CO_2, CH_4 and N_2O) in the unit process tables.

The quantification of the process data is taken from the report on biodiesel from soy bean (SenterNovem, forthcoming), unless otherwise stated.

D.2-1 Definition of conservative, typical and best practice processes and process systems

In the appendix D.2-2 only the Typical version is presented. The E-LCA tool database also contains conservative and best practice values as described by SenterNovem, forthcoming.

D.2-2 Description of the unit processes for electricity from soy bean oil

B = best practice; T = typical; C = conservative
In the appendix given below only the Typical version is presented. The E-LCA tool database also contains conservative and best practice values as described by SenterNovem, forthcoming.

[A] Feedstock production

Process	**Production of soy bean in the United States of America (Typical)** Source: SenterNovem, forthcoming				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Diesel combustion in machine		Fossil fuel	2360	MJ	LHV 43.1 MJ/kg, Density 832 kg/m^3
Electricity		electricity	11.4	kWh	
Heat from Natural gas combustion		Fossil fuel	0.18	MJ	
Fertiliser N		agr. means	4.8	kg	production emissions, see appendix J, table 6
Fertiliser P_2O_5		agr. means	13	kg	
Fertiliser K_2O		agr. means	19.2	kg	
Economic outflow					
Soy bean		agr. product	2400	kg	
Environmental inflow					
CO_2, biogenic		air	6456	kg	Fixation 2.69 kg CO_2/kg Source: Ecoinvent
Land use change		land use			Set aside
Environmental outflow					
CH_4	74-82-8	air			
N_2O	10024-97-2	air	0.1584	kg	0.033 kg N_2O / kg N from N fertiliser Source: CE/Ecofys, 2007

[B] Feedstock transport

Process	**Transport of feedstock (Typical)** Source: SenterNovem, forthcoming				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Soy bean		agr. product	1000	kg	
Transport by truck		transport	50	tkm	distance 50 km
Economic outflow					
Transported soy bean		agr. product	1000	kg	
Environmental inflow					
Environmental outflow					

Soy oil is transported to Europe by ship see biofuel transport

[C] Conversion

Process	**Receiving and storage (Typical)** Source: SenterNovem, forthcoming				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Transported soy bean		agr. product	1	kg	
Heat from Natural gas combustion		Fossil fuel	1.114	MJ	
Electricity		electricity	0.02135	kWh	
Economic outflow					
Stored dried soy bean		agr. product	1	kg	
Environmental inflow					
Environmental outflow					

Process	**Soy bean crushing (Typical)** Source: SenterNovem, forthcoming				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Stored dried soy bean		agr. product	1	kg	
Electricity		electricity	0.257	kWh	
Heat from Natural gas combustion		Fossil fuel	6.080	MJ	
Hexane		chemical	0.0119	kg	
Economic outflow					
Degummed soy bean oil		biofuel	0.169	kg	36.6 MJ/kg Energy allocation
Soy bean meal		fodder	0.760	kg	15 MJ/kg Energy allocation
Environmental inflow					
Environmental outflow					

[D] Biofuel transport

Process	**Biofuel transport from United States of America (Typical)** Source: SenterNovem, forthcoming				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Crude soybean oil		biofuel	1000	kg	
Transport by ship		transport	5500	tkm	distance 5500 km
Transport by truck		transport	50	tkm	distance 50 km
Economic outflow					
Transported crude soybean oil		biofuel	1000	kg	
Environmental inflow					
Environmental outflow					

[E] End use

Alternative 1

Process	**Electricity production from co-firing of soybean oil with heavy oil and gas (Typical)** Source: Essent, 2006, see appendix A.3 As Essent used to do in the Claus Power plant in Maasbracht allocation energy production based on energy content of fuels (MJ/kg; soybean oil = 37, natural gas = 37, heavy oil = 41.5)				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Transported crude soybean oil		biofuel	8.52	kg	
Heavy fuel oil		Fossil fuel	3.81	kg	
Natural gas		Fossil fuel	1.26e3	MJ	
Economic outflow					
Electricity (soy bean oil part)		electricity	31.68	kWh	
Electricity (heavy oil part)		electricity	15.84	kWh	
Electricity (natural gas part)		electricity	128.48	kWh	
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	air	-		assumption: fuels are completely incinerated (no CH_4 formation)
N_2O	10024-97-2	air	-		assumption: fuels are completely incinerated (no N_2O formation)
CO_2, fossil	124-38-9 (Fossil)	air	84.4	kg	own calculations, see appendix D.3
CO_2, biogenic	124-38-9 (Biogenic)	air	24.1	kg	own calculations, see appendix D.3

Alternative 2

Process	**Electricity production from combustion of soybean oil in CHP (< 10 MWe, 42% electric efficiency, 30% thermic efficiency) (Typical)** Source: (Tilburg, van et al, 2006), see appendix A.4				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Transported crude soybean oil		biofuel	1000	kg	37.1 GJ/ton
Economic outflow					
electricity		electricity	4.33E+03	kWh	42% electric efficiency Energy allocation: 3.6 MJ/kWh
heat		heat	11.13E+3	MJ	30% thermic efficiency Energy allocation: 1 MJ/MJ
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	air	-		assumption: fuels are completely incinerated (no CH_4 formation)
N_2O	10024-97-2	air	-		assumption: fuels are completely incinerated (no N_2O formation)
CO_2, biogenic	124-38-9 (b)	air	2.83E+3	kg	own calculations, see appendix D.4

Alternative 3

Process	**Electricity production from combustion of soybean oil in CHP** **(10 MWe < 50 MWe, 48% electric efficiency, 10% thermic efficiency)** **(Typical)** Source: (Tilburg, van et al, 2006)), see appendix A.4				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Transported crude soybean oil		biofuel	1000	kg	37.1 MJ/kg
Economic outflow					
electricity		electricity	4.95E+03	kWh	48% electric efficiency Energy allocation: 3.6 MJ/kWh
heat		heat	3.71E+3	MJ	10% thermic efficiency Energy allocation: 1 MJ/MJ
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	air	-		assumption: fuels are completely incinerated (no CH_4 formation)
N_2O	10024-97-2	air	-		assumption: fuels are completely incinerated (no N_2O formation)
CO_2, biogenic	124-38-9 (b)	air	2.83E+3	kg	own calculations), see appendix D.4

transformation and transport losses of electricity from producer to consumer
Average transformation and transport losses for the referenced electricity production are 4% (SenterNovem 2006). As a default, also for bio-electricity options this 4% loss is assumed for transformation and transport. However, losses due to transformation and transport will dependent on the type of produced electricity (high, medium or low voltage), the transportation distance and the type of consumed electricity (high, medium or low voltage). For this reason a different loss can be defined in the process named “transformation and transport to consumer of electricity, from (….)” that is available for each bio-electricity chain.

Appendix D.3

ENERGY BALANCE - CO-FIRING WITH HEAVY FUEL AND NATURAL GAS									
Fuel	**Quantity**		**Energie content**		**Input**		**Elektrisch rendement**	**Electrical Output**	
Natural gas	0.00E+00	ton	37	GJ/ton	1.73E+00	GJ	36.7%	6.35E-01	GJ
	3.97E+01	m^3	31.65	MJ/m^3					
Soybean oil	8.52E-03	ton	37.1	GJ/ton				1.76E+02	kWh
Heavy Fuel	3.81E-03	ton	41.5	GJ/ton					

CARBON BALANCE - CO-FIRING WITH FUEL AND NATURAL GAS								
Fuel	**Quantity**		**Carbon content**	**Carbon**		**Carbon dioxide emissions**		
Natural gas	3.39E-02	ton	58.11%	1.97E-02	ton	7.23E-02		ton
soybean oil	8.52E-03	ton	77.10%	6.57E-03	ton	2.41E-02		ton
Heavy Fuel	3.81E-03	ton	86.80%	3.30E-03	ton	1.21E-02		ton
						Total	1.09E-01	ton
					biogenic		2.41E-02	
					fossil		8.44E-02	

Conversion process

Name	Code/ Cas- no.	Class/ Compartment	Value	Unit	Remarks
Economic inflow					
Natural gas			1.26E+03	MJ	
Heavy fuel			3.81E+00	kg	
Soybean oil			8.52E+00	kg	
Economic outflow					
Electricity			1.76E+02	kWh	
Environmental inflow					
-					
Environmental outflow					
CH_4					
N_2O					
$CO_{2,}$ biogenic			2.41E+01	kg	
CO_2			8.44E+01	kg	

Appendix D.4

ENERGY BALANCE - Combined Heat Power <10MW$_e$

Fuel	Quantity		Energie content		Input		Elektrisch rendement	Thermisch rendement	Electrical Output		Heat Output	
Soy bean oil	1	ton	37.1	GJ/ton	37	GJ	42.0%	30.0%	15.582	GJ	11.13	GJ
									4.33E+03	kWh		

CARBON BALANCE - Combined Heat and Power <10MW$_e$

Fuel	Quantity		Carbon content	Carbon		Carbon dioxide	
Soy bean oil	1.00E+00	ton	77.10%	7.71E-01	ton	2.83E+00	ton

ENERGY BALANCE - Combined Heat Power 10-50MW$_e$

Fuel	Quantity		Energie content		Input		Elektrisch rendement	Thermisch rendement	Electrical Output		Heat Output	
Soy bean oil	1	ton	37.1	GJ/ton	37	GJ	48.0%	10.0%	1.78E+01	GJ	3.71	GJ
									4.95E+03	kWh		

CARBON BALANCE - Combined Heat and Power 10-50MW$_e$

Fuel	Quantity		Carbon content	Carbon		Carbon dioxide	
Soy bean oil	1.00E+00	ton	77.10%	7.71E-01	ton	2.83E+00	ton

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Appendix E Electricity and heat from wood chips and wood pellets by gasification, co-firing and / or CHP

E.1 System description

The system described here documents several different routes through which waste wood can be converted into wood pellets and then used as a feedstock for electricity production.

Functional unit
The functional unit is 1 kWh of electricity. In case a CHP is considered also heat is produced. For heat the functional unit is 1 MJ heat.

System boundaries and cut off
The system extends upstream to the point where wood residue is generated at a saw mill. The residue is considered a waste, and emissions resulting from the operation of the saw mill are not attributed to the wood residue. In addition, production of capital goods is not considered in the LCA, as their impact is considered to be minimal.

Allocation: Energy allocation
In the process chain there is one process with possible co-production of products, namely: the wood pellets production which delivers the functions of waste treatment and pellet production. For this processes energy allocation is used. The LHV used for energy allocation are presented in table 1. The actual allocation factors are based on the LHV of the material and the amount of produced material.

Table 1 LHV, amounts and allocation factors for wood pellet production

	LHV MJ/kg	**Amount[1] kg**	**Allocation factor[1]**
Wood pellet production			
Wood waste	16.54	650	0.5
Wood pellet	17.27	650	0.5

1 the amount and allocation factor are given as an example. Figures are different for different conservative, typical and best practice options

Not considered in this report are implications of the Mountain Pine Beetle infestation in British Columbia. This infestation has resulted in a very significant amount of dead standing wood, which has a definite impact on carbon cycling in the area. Bradley (2006) details the implications of this in regard to life cycle analysis of wood pellets produced in that region.

Conservative, Typical and Best practice Systems
In this project a distinction is made between conservative, typical and best practice systems. A system is defined as a chain of linked processes. The best practice system is defined as the chain of best practice processes. That is the most efficient processes and/or processes with the lowest GHG emission levels.

For the case of electricity generation from wood pellets, it is useful to extend this distinction further to the level of certain processes. In particular, there are three processes for which a range of values for efficiencies and GHG emissions exist. These relate to the electricity requirements of the pellet drying process (coupled with the amount of renewable electricity present in the consumed electricity mix) and the distance of the wood pellet transportation.

For the production of wood pellets the following systems are defined:

Conversion

Conservative:	Highest electricity requirements for pelletization process, electricity mix with low renewable percentage
Typical:	Average electricity requirements for pelletization process, electricity mix with average renewable percentage
Best practice:	Lowest electricity requirements for pelletization process, electricity mix with high renewable percentage

BioFuel Transport

Conservative:	Pellets transported 16500km from Western Canada.
Typical:	Pellets transported 5000km from Eastern Canada.
Best practice:	Pellets transported 2000km from Northern Europe.

E.*1-1 System description “Production of wood pellets for use as feedstock in electricity generation”*

This section details the emissions occurring during the life cycle of wood pellets that are utilized for the generation of electricity. The bio-electricity production chain is separated into the five stages listed below:

[A] Feedstock production
[B] Feedstock transport
[C] Conversion
[D] (Biofuel) transport
[E] End use

Feedstock production involves the growth and harvesting of trees used for the production of various wood products. Next, the trees are transported via lorry to a lumber mill where they are processed. During the processing, sawdust and other wood waste is produced. This waste wood is then pressed into wood pellets, either on-site or at another location. The produced pellets are then shipped by truck to a harbor and loaded onto a transoceanic ship, which transports the pellets to a harbor in the Netherlands. The pellets are then transported by truck or barge to a power plant where they are used as a feedstock for electricity production.

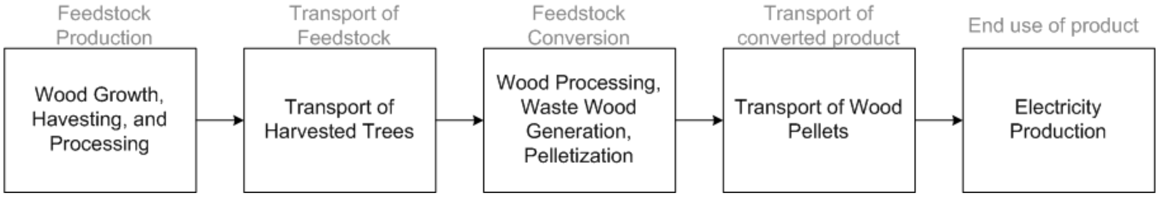

Figure 2 -- System Flowchart

E.1-1[A] feedstock production

Feedstock production involves the growth and harvesting of trees used for the production of various wood products. This is outside the system boundaries.

E.1-1[B] feedstock transport

Trees are transported via lorry to a lumber mill where they are processed. This is outside the system boundaries.

E.1-1[C] conversion

During the processing, wood waste such as sawdust and shavings are produced. This waste wood is then dried and pressed into wood pellets, either on-site or at another location 75 km away. Drying is accomplished using electricity or by burning a portion of the waste wood in a furnace used for heating.

E.1-1[D] biofuel transport

The produced pellets are then shipped by truck to a harbor and loaded onto a transoceanic ship, which transports the pellets to a harbor in the Netherlands. Three different possible origins are specified for the transoceanic ship: Western Canada, Eastern Canada, and Northern Europe. In this report, the distance from these ports to Rotterdam is specified to be 16,500 km, 5,000 km, and 2,000 km respectively. Once in the Netherlands, the pellets are then transported by truck or barge to a power plant.

E.1-1[E] End use

This is covered in the “Conversion Processes” appendix.

E.*1-2 System description “conventional use of waste wood”*

Waste wood conventionally is sent to a landfill where much of it then degrades into methane. With awareness of the role of methane as a greenhouse gas, some are choosing to combust waste wood or convert it into fuels.

E.2 Process Description

This appendix gives more detailed information on the economic and environmental flows for the processes described in Appendix A.1. For the environmental flows, we are mainly concerned with accounting for the major greenhouse gases CO_2, CH_4, and N_2O. The economic flows described concern the daily operation of the processes. Flows regarding capital goods are excluded as it is assumed their impact is minor.

The wood pellet systems described below are based primarily on those detailed within Damen & Faaij 2003 and Bradley 2006. The Damen & Faaij report details wood pellets sourced from Halifax, Nova Scotia on the eastern side of Canada, and follows them to their gasification at the Amer-9 plant in the Netherlands. The Bradley report investigates wood pellets sourced from the Vancouver, British Columbia on the western side of Canada and follows them to a coal burning plant that co-fires the pellets. An illustration of the system can be seen in figure 2 below. As can be seen, the wood used for pellets is a waste product from lumber manufacturing. Also, the transportation of the waste wood to a site for pellet production is optional, as the production of waste wood and the pellet production process may occur at the same site.

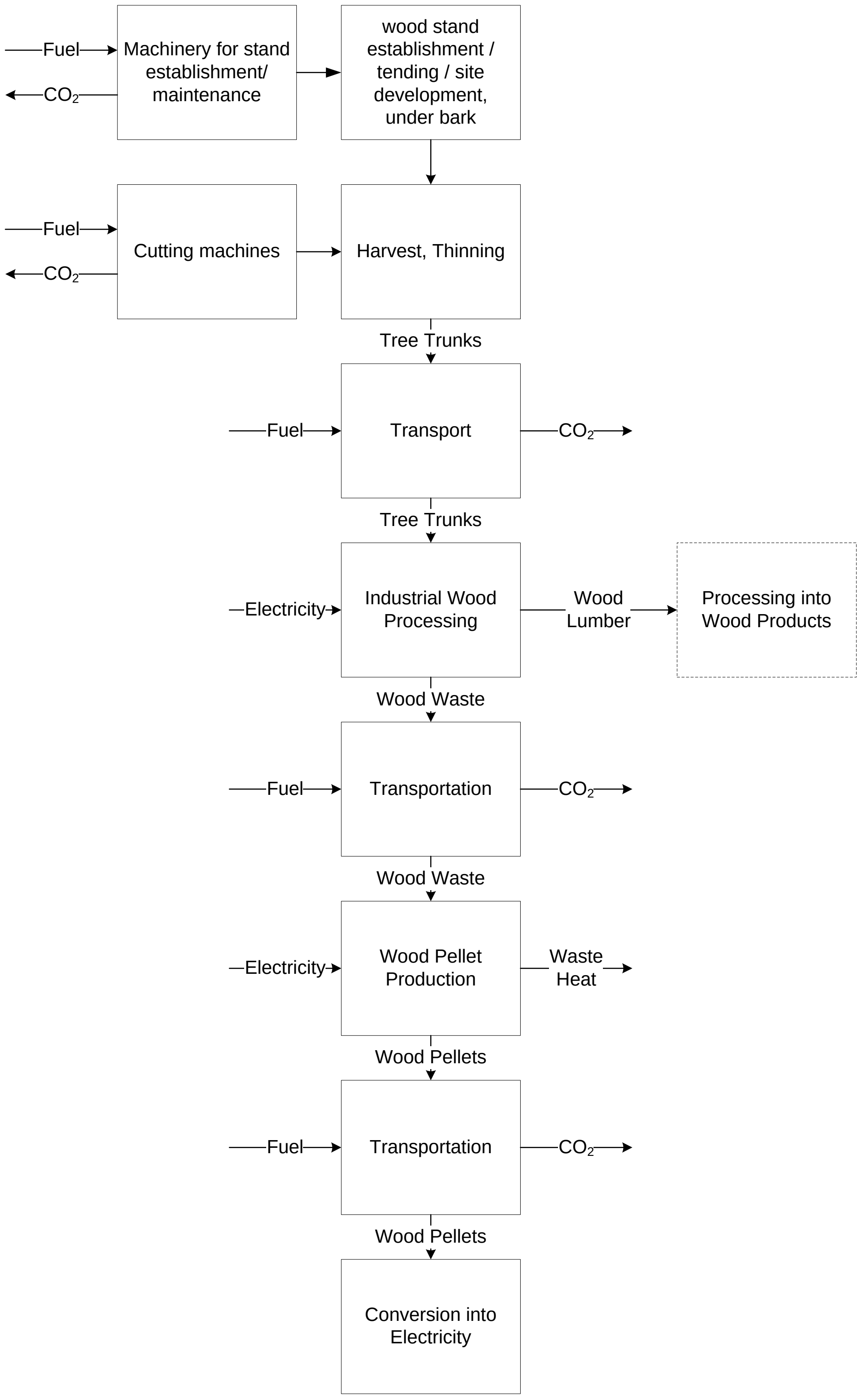

Figure 2: System Description of Wood Pellet Bio-Electricity Production

E.2-1 Definition of conservative, typical and best practice processes and process systems

The table below shows some of the values encountered in literature that were used to designate conservative, typical, and best practice processes.

Table 1 - Definition of conservative, typical and best practice systems for production of wood pellets for use as feedstock in electricity production

Stage	Best practice	Typical	Conservative	Unit
Electricity Requirement for Pellet production (4)(5)	80	115	150	kWh
Biofuel Transport transoceanic freighter	2000 (1)	5000 (2)	16500 (3)	km

(1) Distance to ports in Northern Europe from Rotterdam
(2) Distance to Halifax, Nova Scotia in Eastern Canada
(3) Distance to Vancouver, British Columbia in Western Canada
(4) Several different Estimates of electricity consumption were found within the literature. Damen & Faaij (2005) quote 125 kWh/tonne, while Bradley (2006) uses 150 kWh/tonne. Pastre (2002) cites a wide range from 55-535 kWh/tonne, but notes that most values fall within the range from 80 to 130 kWh/tonne.
(5) For this report, an average Canadian electricity production mix was assumed, as cited in Damen & Faaij 2003 (quoting the "el-generation-mix-Can" entry in the GEMIS database). Statistics Canada (2006) gives a detailed breakdown of electricity production in each province, which shows that some provinces produce nearly all of their power through hydroelectricity, while others are nearly completely fossil-based.

E.2-2 System description "Electricity generation using wood pellets"

E.2-2[A] Feedstock production

Outside system boundaries

E.2-2[B] Feedstock transport

Transportation of wood from the forest to the saw mill is outside of the system boundaries. Once waste wood is produced at the saw mill, we assume that the residues are transported 75km to a plant for pelletization (Damen & Faaij, 2003). For this process we use the specifications on transport by lorry available within the EcoInvent database ("operation, lorry, 28t").

E.2-2[C] Conversion

For the processes defined below, the difference between the wood pellet manufacturing in Europe and that in Canada relates to the electricity used. Each of these locations have different amounts of renewable electricity present in their electricity production mixes.

Process	**Wood pellet manufacturing in Europe**

name	**code/ cas- no.**	**class/ compartment**	**value**	**Unit**	**Remarks**
Economic inflow					
transport, lorry 28t[CH]			62.6	tkm	75km transport for total 1.285 m^3 of input waste wood
electricity, medium voltage, production UCTE, at grid[UCTE]			74.75	kWh	
(waste) softwood			0.925	m^3	Energy allocation: 16.54 MJ/kg
(waste) hardwood			0.36	m^3	Energy allocation: 16.54 MJ/kg
Economic outflow					
Wood pellets, manufactured in Europe			1	m^3	650kg/m^3 Energy allocation: 17.27 MJ/kg
Environmental inflow					
Environmental outflow					
Heat, waste[air]		air	591	MJ	

Process	**Wood pellet manufacturing in Canada**				
name	**code/ cas- no.**	**class/ compartment**	**value**	**Unit**	**Remarks**
Economic inflow					
transport, lorry 28t[CH]			62.6	tkm	75km transport
Electricity - Canadian production mix			74.75	kWh	
(waste) softwood			0.925	m^3	Energy allocation: 16.54 MJ/kg
(waste) hardwood			0.36	m^3	Energy allocation: 16.54 MJ/kg
Economic outflow					
Wood pellets, manufactured in Canada			1	m^3	650kg/m^3 Energy allocation: 17.27 MJ/kg
Environmental inflow					
Environmental outflow					
Heat, waste[air]		air	591	MJ	

Process	**Electricity production mix, Canada** Damen & Faaij 2003, based on GEMIS “el-generation-mix-Can” Assumes >50% renewable due to hydroelectricity. See Appendix 2.1 for more discussion				
Name	**code/ cas- no.**	**class/ compartment**	**value**	**Unit**	**Remarks**
Economic inflow					
Economic outflow					
Electricity – Canadian production mix		electricity	1	kWh	
Environmental inflow					
Environmental outflow					
CO_2 (fossil)	124-38-9	air	0,223	kg	
CH_4	74-82-8	air	0,00031	kg	
N_2O	10024-97-2	air	0,00001	kg	

E.2-2[D] Biofuel transport

Transport of wood from the forest to the processing plant and to the harbor is done by lorry. We assume a representative distance of 60km, as used by Damen & Faaij (2003). Shipment of the pellets from Canada to the Netherlands is accomplished through a 9000 tonne transoceanic freighter. Depending on where the wood is sourced, this may originate from Vancouver on the western side of Canada, Halifax on the eastern side, or from Scandinavia. This can be significant as the journey from Vancouver to Rotterdam is 16,500 km (through the Panama Canal), while Halifax and Scandinavia are only 5000 and 2000 km away respectively.

Once in the Netherlands, transport may be by lorry or by barge. A co-gasification plant such as Amer-9 is 52 km away from the harbor, and could be feasibly serviced by a 2000 tonne barge.

Entries in the EcoInvent database are used to characterize transport by lorry, transoceanic freighter, and by barge. The following three entries are used:

- operation, transoceanic freight ship
- operation, barge
- operation, lorry, 28t

E.2-2[E] End use

This is covered in the “Conversion Processes” Appendix. Suitable processes can be found in A.1-6, A.1-7, A.1-8, A.1-9, and A.1-10.

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Appendix F Electricity and heat from Demolition Wood Chips

F.1 System description

System boundaries and cut off
Production of capital goods are not considered in the LCA, as their impact is considered to be minimal. Transportation of demolition wastes to a processing facility is excluded, as this is assumed to occur normally.

Allocation: energy allocation
In the process chain there is one process with possible co-production of products, namely: the wood chips production which delivers the functions of waste treatment and chip production. For this processes energy allocation is used.

It should also be noted that part of demolition wood waste stream is currently recycled for board or paper production (Gielen et al. 2000). When demolition wood is processed, it is separated into three grades (A,B, and C) based on its level of contamination. This is determined by if it is clean, or contains paint and wood preservatives. Grade A wood is most attractive for recycling into new wood products. This grade of wood is also attractive for energy production as it contains fewer pollutants, although all grades may be used for energy given sufficient emissions control.

conservative, typical and best practice systems
In this project a distinction is made between conservative, typical and best practice systems. A system is defined as a chain of linked processes. The best practice system is defined as the chain of best practice processes. That is the most efficient processes and/or processes with the lowest GHG emission levels.

For the production of electricity from demolition wood the following systems are defined:

Conservative:	high processing needs for demolition chips
Typical:	average processing needs for demolition chips
Best practice:	demolition chips can be directly gasified with minimal pre-treatment

The processing needs relate directly to electricity requirements. Depending on the end use of the demolition wood, the wood may only need to be chipped, or it may have to be run through a hammer mill to reduce its size, combined with processes intended to separate out metals and other inert materials.

F.1-1 System description **"Production of Demolition Wood Chips for use as Feedstock in Electricity Geneneration"**

This section details the emissions occurring during the life cycle of demolition wood chips that are utilized for the generation of electricity. The bio-electricity production chain is separated into the five stages listed below:

[A] Feedstock production
[B] Feedstock transport
[C] Conversion
[D] (Biofuel) transport
[E] End use

The system described is based on processes used for the processing of demolition wastes and for the gasification of wood chips. Figure 1 summarizes the basic system that is detailed within this document.

Figure 1 -- System Flowchart

F.1-1[A] Feedstock production

Feedstock is produced during demolition of buildings. Some sorting may occur on site, which aids in simplifying the conversion process by removing unwanted materials not suitable for combustion.

F.1-1[B] Feedstock transport

The feedstock is transported by lorry to a demolition waste processing facility.

F.1-1[C] Conversion

Conversion takes place in existing demolition waste processing facilities, and it is assumed that no modifications are necessary as the wood is separated out normally. Wood from a processing facility is separated into three grades. Grade A is clean wood such as construction wastes. Grade B is painted wood, while Grade C wood has been treated with chemical preservatives.

F.1-1[D] Biofuel transport

Transport occurs by lorry, with an average range of 50km used.

F.1-1[E] End use

This is covered in the "Conversion Processes" appendix.

F.1-2 System description “conventional use of demolition wood”

This system involves the incineration of demolition wood at a municipal solid waste incineration facility. Transportation requirements will be similar as for the previous systems defined above, although very little feedstock conversion may take place aside from the mechanical separation of the wood from inert fraction of the waste stream.

F.2 Process Description

This appendix gives more detailed information on the economic and environmental flows for the processes described in Appendix F.1. For the environmental flows, we are mainly concerned with accounting for the major greenhouse gases CO_2, CH_4, and N_2O. The economic flows described concern the daily operation of the processes. Flows regarding capital goods are excluded as it is assumed their impact is minor.

F.2-1 Definition of conservative, typical and best practice processes and process systems

Conservative:	high processing needs for demolition chips
Typical:	average processing needs for demolition chips
Best practice:	demolition chips can be directly gasified with minimal pre-treatment

Additional distinctions may be made based on the processing methods of demolition wastes. Material and energy flow information for these processes, as they relate to the Dutch situation, is difficult to find. Furthermore, it is assumed that the processing of demolition wastes always occurs regardless of the end use.

F.2-2 Description of the unit processes for processing of demolition wood for use as fuel

Figure 4 below shows the processes used for processing demolition wastes into wood chips, followed by gasification. Other end uses besides gasification are possible. This particular diagram is applicable to gasifiers that operate at different scales. As seen by the box surrounded by the dashed line, additional processing of the demolition wood chips is sometimes necessary as in the case of Buggenum. Here the gasifier requires a very consistent input made up of fine particles. For some smaller scale gasifiers, the chips can be fed in directly, provided that the chips have had some pretreatment to prevent contamination with metal fragments.

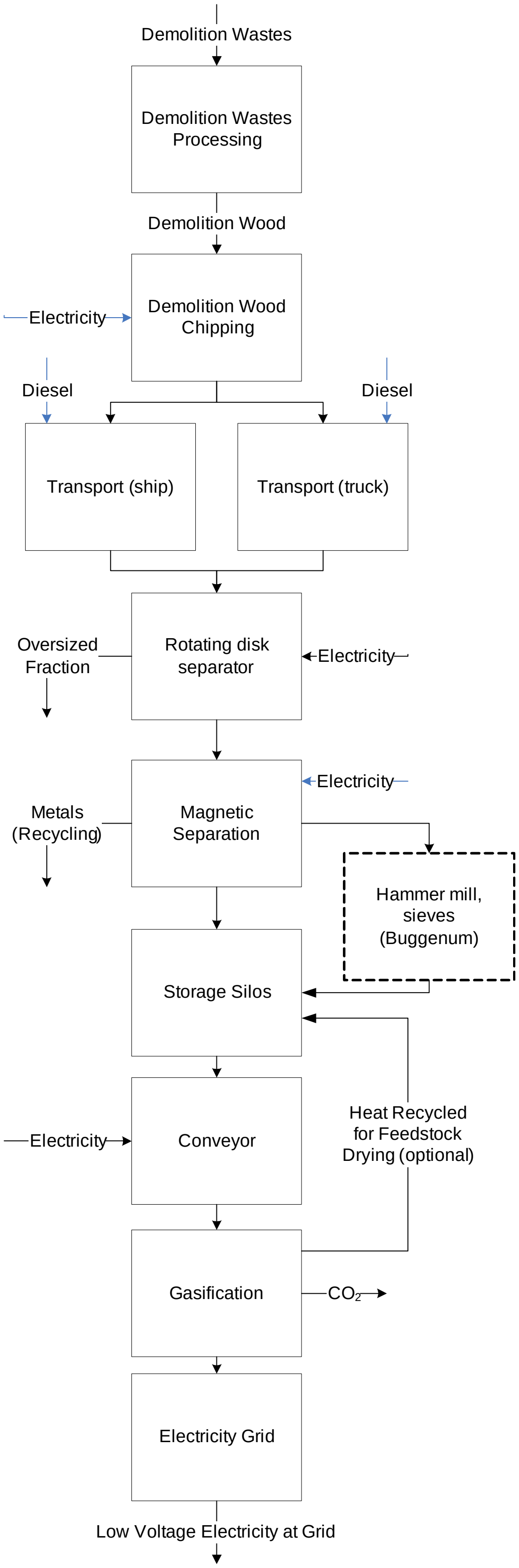

Figure 2 - Flowchart of demolition wood processing combined with gasification

[A] Feedstock production

Outside system boundaries.

[B] Feedstock transport

Outside system boundaries.

[C] Conversion

The level of processing of the demolition chips will depend on the type end use that occurs. In the case of gasification, for a smaller scale circulating fluidized bed reactor, the chips may be used directly after processing steps that remove rocks and metal. For larger gasifiers that use entrained flow beds, the wood chips may need to pass through a hammer mill to further reduce their size.

For conversion, the Demolition Wood Chipping process will always occur, and will be followed either by “Magnetic separation of metals from chipped wood” or “Wood powder production from chipped wood”, depending on the requirements of the electricity conversion process. The magnetic separation process is intended to remove nails and other fasteners from the demolition wood. The wood powder process is much more thorough, and includes not only metal separation, but other sieving and size reduction processes as well.

Process	**Demolition Wood Chipping**				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Demolition Wood			1000	kg	
Electricity			47.2 – 102.5	kWh	Gevers, et al. 2002, pg 64. Also Beeks et al 2006 (Table 14)
Economic outflow					
Demolition Wood Chips			1000	kg	
Environmental inflow					
Environmental outflow					

Process	**Magnetic separation of metals from chipped wood** This process is used for situations where wood chips can be gasified directly. Some types of gasifiers may need the chips to be made into a power form. See **Wood powder production from chipped wood** for a more comprehensive process, which includes magnetic separation in the energy balance.				
Name	**code/ cas- no.**	**class/ compartment**	**value**	**Unit**	**Remarks**
Economic inflow					
Demolition Wood chips			1000	kg	
Electricity		electricity	0.8 – 2.8	kWh	Data applies to MSW production. Wallman & Fricke 2002 (quoted by den Boer et al. 2005) give range of 0.8 – 2.8.
			0.44 – 0.75	kWh	Caputo & Pelaggo 2002 give range of 0.44 to 0.75 kWh based on equipment capacity
Economic outflow					
Demolition Wood Chips with metal removed			1000	kg	
Environmental inflow					
Environmental outflow					

Process	**Wood powder production from chipped wood** Wood powder production is not always necessary, depending on the type of gasifier used. The process described here consists of magnetic separation, a windsifter, hammer mill, screens, cyclones, mills, etc. (Beekes et al 2006, Figure 2)				
Name	**code/ cas- no.**	**class/ compartment**	**value**	**Unit**	**remarks**
Economic inflow					
Demolition Wood chips			1000	kg	

Electricity	172,4	kWh	(Beekes et al. 2006, Table 14, Figure 2)
Economic outflow			
Wood powder	1000	kg	
Environmental inflow			
Environmental outflow			

[D] Biofuel transport

Biofuel transport is done by lorry. A distance of 50 km is used with the entry “operation, lorry 28t” found in the EcoInvent database.

[E] End use

This is covered in the “Conversion Processes” appendix.

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Appendix G Electricity and heat from wheat straw by combustion in CHP

G.1 System description

The system description of using wheat straw as a fuel to generate heat and electricity can be roughly divided into three processes, presented in the figure below.

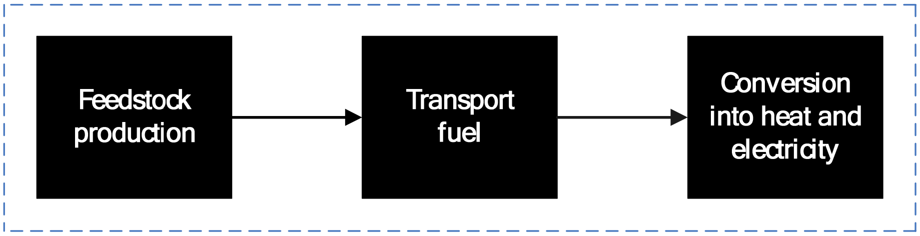

Figure 1. The three process boxes of the total life cycle system.

The three process boxes from *figure 1* are labelled as follows:

[A] Feedstock production
[B] Transport fuel
[C] Conversion into heat and electricity

All three process boxes will be described in this appendix, in order from left to right in *figure 1*. For each of the three process boxes the following two descriptions are made:

[1] Flowchart descriptions;
[2] Inventory tables of processes within the three process boxes.

Winter wheat straw is the feedstock, Hesston bales are the fuel and single firing of bales in a grate furnace of a combined heat power (CHP) plant forms the conversion step. This conversion process of straw to heat and electricity is the most conventional one, already operational in Denmark, Spain and England (BERK 2004) and therefore chosen as a starting point of this LCA study.

Functional unit

Since the single firing of straw is connected to a CHP[2], there are multiple outputs: heat (MJ_{th}) and electricity (kWh_e). The functional unit of the system is one kWh of electricity or 1 MJ of heat.

System boundaries and cut-off

Wheat straw is considered a by-product from wheat production. Therefore the agricultural process of the combined wheat-straw production, the harvesting an baling of straw, and the CHP process are all included in the system. Three alternatives are considered, based on wheat production in the Netherlands, dependent on the soil type.

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[2] 5 MW_e + 13 MW_{th}, 91% load factor, 77% efficiency, 46428 tonnes/yr. (Grant, J.F. *et al*. 1995)

Allocation
In the process chain there are two processes with possible co-production of products, namely: 1) the production of wheat & wheat straw; 2) the production of electricity and heat in a CHP. In correspondence with the Draft EU directive (EC, 2008) nothing is allocated to the agricultural residues, i.e. straw. For the production of electricity and heat in a CHP allocation is used based on energy content (LHV: 3.6 MJ/kWh for electricity; 1 MJ/MJ for heat).

In the crop production process from *figure 3*, carbon dioxide fixation by the wheat plants takes place. The fixated carbon in straw is eventually released into the atmosphere again during combustion. This carbon dioxide flow is labelled ‘biogenic’ and considered neutral, because the assumption of zero biogenic carbon dioxide accumulation in the total life cycle system is made. The biogenic CO_2 flows of wheat grains and straw are shown in the crop production inventory table [G.2.3].

Conservative, typical and best practice
The systems described in this appendix represent three varieties of the best practice system. The conservative and typical systems are the same except for the process of production of the crop. For this process the description is used as defined by SenterNovem (forthcoming).

G.1-1 Feedstock production

The wheat straw production chain, with its upstream processes, is presented in the flowchart of *figure 3*. Only the upstream processes ‘seed production’, ‘fertiliser production’ and ‘energy production’ are taken into account for the production of straw, since pesticide and infrastructure production are suppose to have an insignificant contribution to the overall GHG emissions of the feedstock production. The data on seed, fertiliser and fuel use in the Netherlands are from KWIN (2006). The KWIN data are imported into the Ecoinvent database to get the GHG emissions of the Dutch straw production chain. In the KWIN (2006) report there is made a distinction between three different soil types in the Netherlands for winter wheat production, namely (1) southwest clay grounds (IJsselmeerpolders included), (2) sand grounds and (3) clay grounds in the north of the Netherlands. All three soil types are included in the CMCLA calculations.

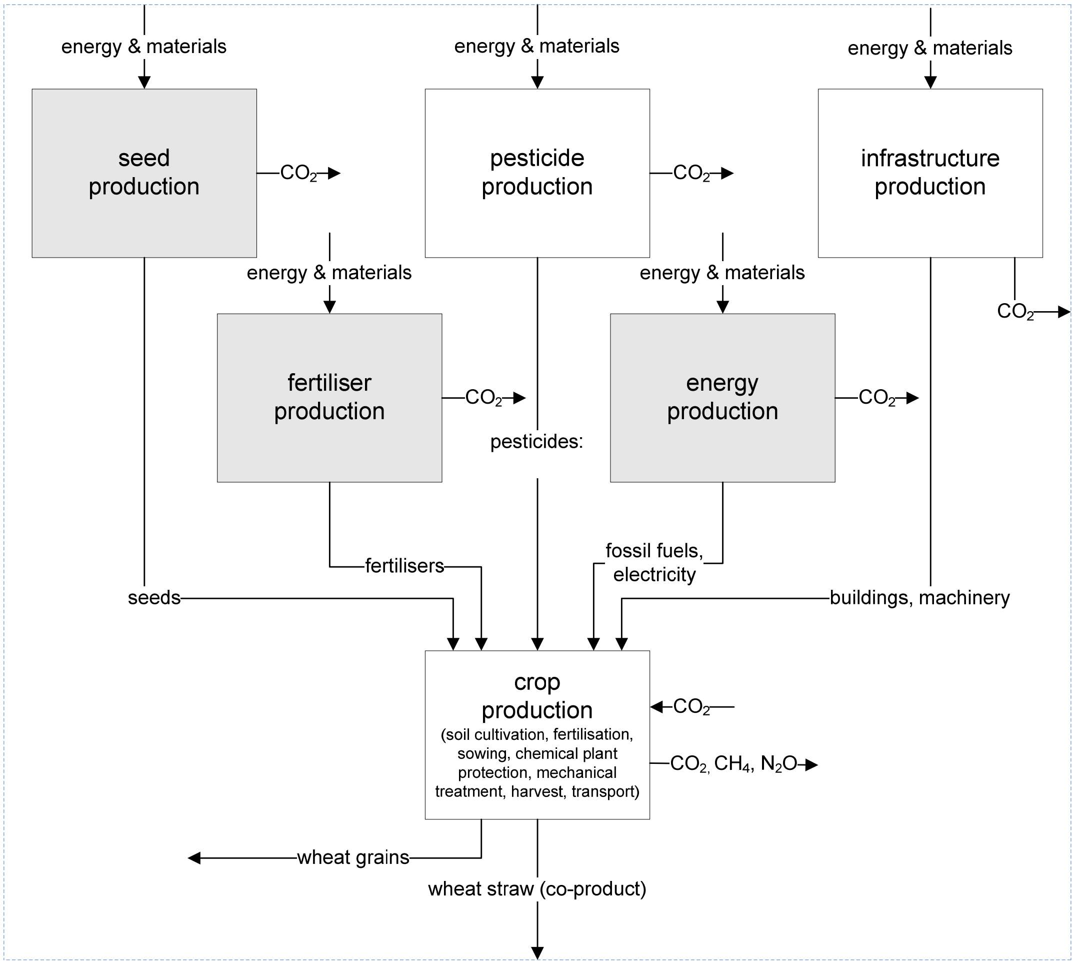

Figure 3. Flowchart of process box: [A] Feedstock production.

As becomes clear from *figure 3* there are multiple outflows in the crop production process: wheat grains and the co-product wheat straw. This means that there has to be an allocation method to calculate the contribution of wheat straw in the overall GHG emissions of the feedstock production.

G.1-2 Feedstock transport

The flowchart of the 'feedstock transport' process box is shown in *figure 7*. The grey shaded process boxes are included in the LCA study; capital goods like equipment manufacture and maintenance are excluded. The process 'fuel production' is integrated in the processes baling, (un)loading and transport by the consumption of diesel, which is linked to upstream processes in the Ecoinvent database. The nomenclature of the discussed processes is as follows:

[B.2.1]	Baling in the field
[B.2.2]	Loading Hesston bales + Transport to interim storage
[B.2.3]	Interim storage + Transport to CHP plant

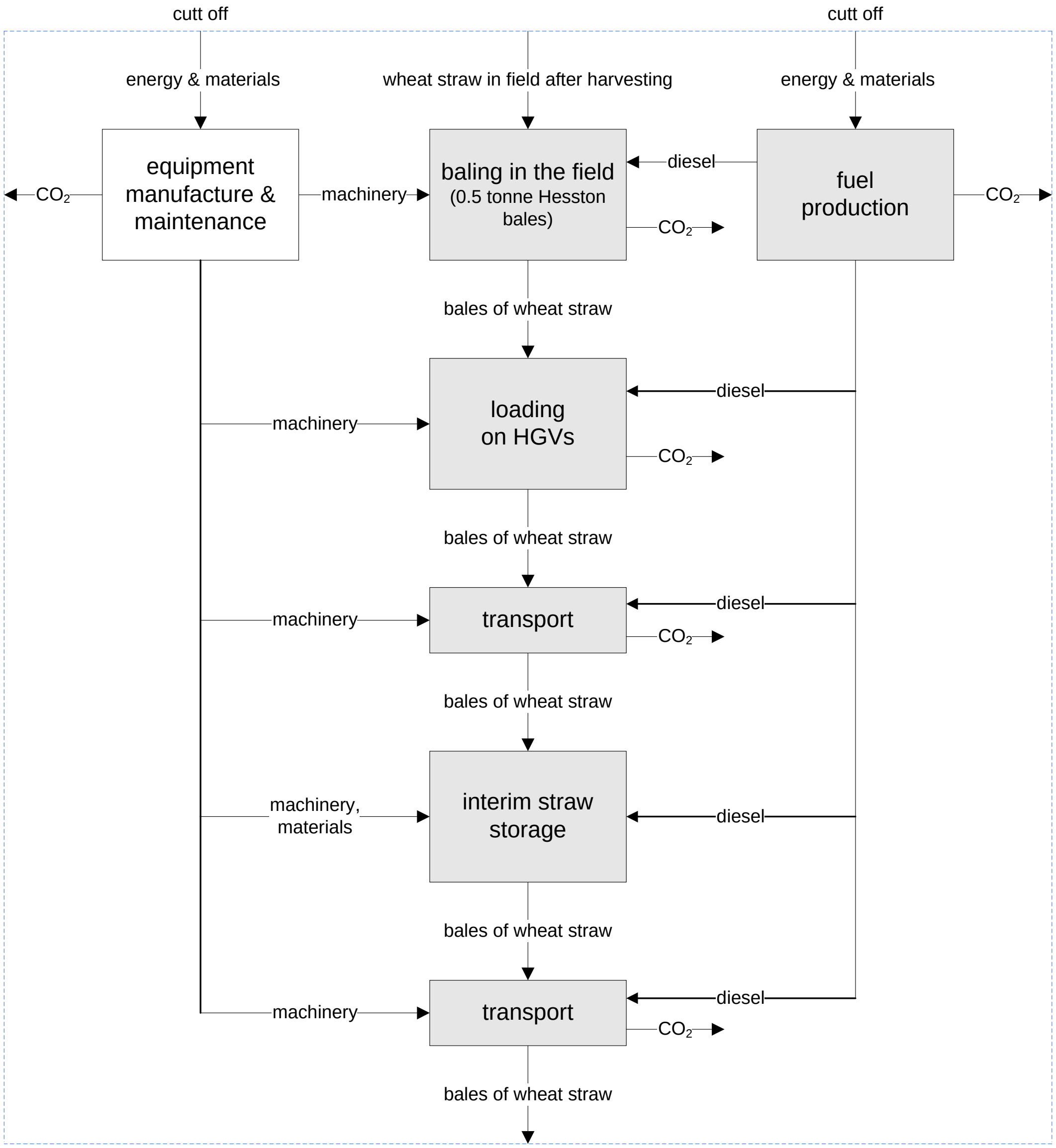

Figure 7. Flowchart of process box: [B] feedstock transport.

G.1-3 Conversion into heat and electricity

The last process box of the total system described is the conversion of straw into heat and electricity (*figure 8*). Bales of straw are transported into the delivery facility of the CHP plant with the truck-trailer combination and grabbed by a crane that automatically measures the moisture-content with a microwave-measuring system. At the CHP plant are barns to store the straw bales. This gives the plant a fuel buffer for up to four days of operation.

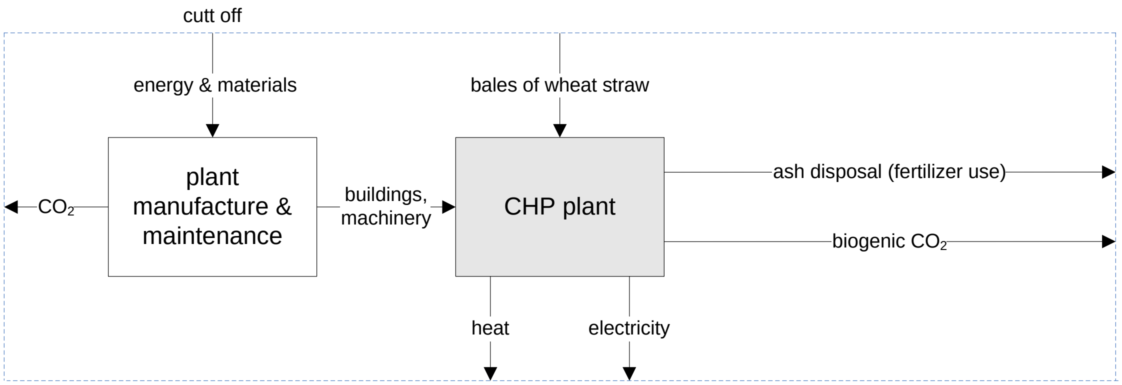

Figure 8. Flowchart of process box: [C.1] Conversion into heat and electricity

G.2 Process descriptions

The life cycle inventory tables, with all the economic and environmental in- and outputs, of the three grey shaded process boxes from *figure 3* are discussed in this appendix and have the following nomenclature:

The seed production process of wheat seed is very similar as the commercial crop production, but it requires higher quality standards for all inputs in the seed production process (fertilizers, pesticides, weed control etc.). The average seed-crop yield that meets the quality requirements and thus can be used as seed is 80%[3]. The other assumptions of seed production are stated in the remarks-column of the life cycle inventory table [A.2.1].

Process	**Wheat seed production, Ecoinvent – [P2677]** Source: Ecoinvent, *Life Cycle Inventories of Agricultural Production Systems*, 2004. Appendix A11 Chapter 11 (Seed), p. 103-109 and 228				
name	**code/ CAS-no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
lorry 32t		capital good (transport)	0.13	tkm	*primarily domestic production*: transport field to seed-processing centre: 30 km; transport seed-processing centre to regional storehouse: 100 km (no import) [RER]
electricity		energy	0.024	kWh	[G910]: electricity, low voltage, at grid NL, for seed processing: pre-cleaning, cleaning, chemical seed dressing and bag filling.
wheat grains		agricultural production	1	kg	winter wheat grains, conventional farming, at farm [NL]
difenoconazole		chemical	0.0001	kg	$C_{19}H_{17}Cl_2N_3O_3$, (diphenylether-compounds), at regional storehouse[RER]
Economic outflow					
wheat seed			1	kg	conventional farming, at regional storehouse [NL]
Environmental inflow					
Environmental outflow					
heat		waste/air	0.0864	MJ	

Table 1. Inventory table for the process seed production [A.2.1].

The seed requirements for the production of one hectare of wheat on the different soil types in the Netherlands are listed in *table 2*.

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[3] Ecoinvent 2004, Chapter 11: Seed, p. 104

1	Southwest clay grounds	160 kg
2	Sand grounds	150 kg
3	North clay grounds	175 kg

Table 2. Seed requirements for the three different soil types in the Netherlands (KWIN 2006).

G.2-2 Fertiliser production

The average mineral fertiliser use per ha in the Netherlands, distinguishing three soil types, for 2000-2005 is presented in *table 3, 4 and 5* (KWIN 2006).

Winter wheat, southwest clay grounds in the Netherlands, IJsselmeerpolders		
Mineral fertiliser	**Quantity**	**Unit**
N	205	kg N
P_2O_5	0	kg P_2O_5
K_2O	0	kg K_2O

Table 3. Mineral fertiliser use per ha on the southwest clay grounds in the Netherlands.

Winter wheat, sand grounds in the Netherlands		
Mineral fertiliser	**Quantity**	**Unit**
N	165	kg N
P_2O_5	20	kg P_2O_5
K_2O	94	kg K_2O

Table 4. Mineral fertiliser use per ha on the sand grounds in the Netherlands.

Winter wheat, clay grounds in the north of the Netherlands		
Mineral fertiliser	**Quantity**	**Unit**
N	205	kg N
P_2O_5	0	kg P_2O_5
K_2O	0	kg K_2O

Table 5. Mineral fertiliser use per ha on the clay grounds in the north of the Netherlands.

To calculate the CO_2 equivalent emissions as a result of fertiliser use, presented in the tables above, the specific CO_2, N_2O and CH_4 emission parameters most be known. The parameters are shown in *table 6*, grey shaded. There is made a distinction between direct (usage of fertilisers) and indirect (production and delivery of the fertiliser) energy use or GHG emissions. The data in *table 6* are from the technical specification report of Ecofys and CE for the CO_2 tool project. For the N-fertiliser production the capital goods are excluded, using Mortimer N.D. *et al.* (2002).

Specific CO_2 equivalent emissions for mineral fertilisers								
Sources: Ecofys and CE, Technical specification: greenhouse gas calculator for biofuels, Annex F, p. 69. Elsayed M.A. *et al.*, Carbon and Energy Balances for a Range of Biofuels Options, Resources Research Unit, Sheffield Hallam University, United Kingdom, March 2003. Mortimer N.D. *et al.*, Evaluation of the Comparative Energy, Environmental, and Social Costs and Benefits of Biodiesel. Resources Research Unit, Sheffield Hallam University, United Kingdom, November 2002.								
	Energy use		**CO_2 emission**		**N_2O emission**		**CH_4 emission**	
	Direct	**Indirect**	**Direct**	**Indirect**	**Direct**	**Indirect**	**Direct**	**Indirect**
Fertilisers	(MJ/kg)	(MJ/kg)	(kg CO_2/kg)	(kg CO_2/kg)	(kg N_2O/kg)	(kg N_2O/kg)	(kg CH_4/kg)	(kg CH_4/kg)
N	-	36.825	-	1.72	0.033	0.01467	-	0.0037
P_2O_5	-	15.8	-	0.70	-	-	-	-
K_2O	-	9.3	-	0.453	-	-	-	-

Table 6. Specific CO_2 equivalent emissions for mineral fertilisers.

Winter wheat, southwest clay grounds in the Netherlands, IJsselmeerpolders					
Mineral fertiliser	**Quantity (kg/ha)**	**Indirect CO_2 emission (kg CO_2/kg)**	**Indirect N_2O emission (kg N_2O/kg)**	**Indirect CH_4 emission (kg CH_4/kg)**	**Total CO_2 equivalent (kg CO_2 eq.)**
N	205	352.60	3.00735	0.7585	1260.22
P_2O_5	0	0	-	-	0
K_2O	0	0	-	-	0

Table 7. GHG emissions per hectare on the southwest clay grounds in the Netherlands.

Winter wheat, sand grounds in the Netherlands					
Mineral fertiliser	**Quantity (kg/ha)**	**Indirect CO_2 emission (kg CO_2/kg)**	**Indirect N_2O emission (kg N_2O/kg)**	**Indirect CH_4 emission (kg CH_4/kg)**	**Total CO_2 equivalent (kg CO_2 eq.)**
N	165	283.80	2.42055	0.6105	1014.32
P_2O_5	20	14.00	-	-	14.0
K_2O	94	42.58	-	-	42.58

Table 8. GHG emissions per ha on the sand grounds in the Netherlands.

Winter wheat, sand grounds in the Netherlands					
Mineral fertiliser	**Quantity (kg/ha)**	**Indirect CO_2 emission (kg CO_2/kg)**	**Indirect N_2O emission (kg N_2O/kg)**	**Indirect CH_4 emission (kg CH_4/kg)**	**Total CO_2 equivalent (kg CO_2 eq.)**
N	205	352.60	3.00735	0.7585	1260.22
P_2O_5	0	0	-	-	0
K_2O	0	0	-	-	0

Table 9. GHG emissions per ha on the clay grounds in the north of the Netherlands.

The CO_2, N_2O, and CH_4 emissions from *table 7, 8* and *9* are also presented in the crop production inventory tables of [A.2.3].

(De)nitrification of mineral N-fertiliser

For the determination of the nitrous oxide (N_2O) emissions during the application of mineral fertilisers it is important to look at the N-fertiliser use per hectare of wheat production, because nitrous oxide is an intermediate in the denitrification and a by-product in the nitrification process. To calculate the N_2O emissions per hectare for the different soil types in the Netherlands, the specific direct N_2O emission from *table 6 (yellow shaded)* is used.

	unit	**southwest clay grounds**	**sand grounds**	**north clay grounds**
Fertiliser use	kg N	205	165	205
Direct N_2O emissions	**kg N_2O/ha**	**6.765**	**5.445**	**6.765**

Table 10. Direct N_2O emissions during the application of N-fertiliser.

Multiplying the specific direct N_2O emission of 0.033 kg/ha by the mineral fertiliser use on the different soil types in the Netherlands, give the results stated in *table 10*. These direct N_2O emissions can also be found in the crop production inventory tables [A.2.3].

Direct and indirect GHG emissions from application of manure

In this appendix for the production of wheat also an inventory is made of the emissions of GHG due to the application of manure. The data are presented in the tables below. However, for other crops that are relevant for the production of bio-energy, like soy bean and rape seed, no such inventory is made (SenterNovem, forthcoming). So for reasons of consistency within the development of the CO_2-tool, the application of manure and the GHG emissions are not taken into account.

Since there is only data available on the liquid manure use in the Netherlands for the years 2001-2002, calculations of direct and indirect field emissions due to the application of organic fertiliser are based on the data presented in *table 11*.

	kg N/ha	**kg P_2O_5/ha**	**kg org. P_2O_5**	**kg K_2O/ha**	**kg org. K**	**Year**
CH[4]:	140	66	-	59	-	-
NL[5]:	218	30	26	52	44	2001
	223	34	31	63	55	2002
Average	**220.5**	**32**	**28.5**	**57.5**	**49.5**	

Table 11. Mineral and organic fertilizer use in CH and NL per hectare wheat production.

Nutrient quantity liquid manure	kg/tonne (cow)	kg/tonne (pig)
N-total	4.4	7.2
P_2O_5	1.6	4.2
K_2O	6.2	7.2

Table 12. N-, P_2O_5- and K_2O-nutrient quantity in liquid manure from cows and pigs (Voort et al. 2006).

The average quantity of organic nutrient fertiliser (labelled 'org.') for P_2O_5 and K_2O are given in *table 11*, grey shaded. The ratio [28.5 kg org. P_2O_5] / [49.5 kg org. K_2O] is equal as the ratio [4.2 kg P_2O_5/ton] / [7.2 kg K_2O/ton] for pig manure in *table 12*. This means that solely pig manure is used for fertilisation the wheat crop in the Netherlands.

To calculate the actual quantity of liquid manure used on the Dutch fields, the ratio:
[49.5 kg org K_2O] / [7.2 kg/tonne] = **6.875** tonnes liquid manure, is used. The assumption is made that the average quantity of liquid manure used on the Dutch fields of 2001 and 2002 is representative for the period 2000-2005.

In inventory *tables 14, 15* and *16* the GHG emissions of the upstream processes (storage of manure in silo, storage in stable cellar and excreted manure on land) from the application of 6.875 tonne manure per hectare on the fields are stated. These emissions can also be found in the crop production inventory table [A.2.3].

Emissions from diesel combustion

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[4] Ecoinvent 2004, Tab. 14.2, p.127

[5] Dijk, T.A. *et al*. 2002 and 2003

Process	**Storage of manure in stable cellar (conventional), NL**				
Source	CMLCA database [P63], small scale (3000 m^3 manure/year), cattle manure, conventional treatment of manure; "De Marke"demo project: Kool, Hilhorst & van der Vegte, 2005				
Name	**code/ CAS-no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
manure (excreted in stable)		waste	6896	kg	6.875 t manure / ha * (1000/997)
Economic outflow					
manure (stored in stable cellar)		waste	6896	kg	1000 kg manure stored in stable cellar / 1000 kg excreted in stable
Environmental outflow					
CH_4		air	1.379	kg	**0.2 kg CH_4** * (1000/997) * 6.875

Process	**Storage of manure in silo (conventional), NL**				
Source	CMLCA database [P64], small scale (1400 m^3 silo), cattle manure, conventional treatment of manure; "De Marke" demo project: Kool, Hilhorst & van der Vegte, 2005				
Name	**code/ CAS-no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
manure (stored in stable cellar)		waste	6896	kg	6.875 t manure / ha * (1000/997)
Economic outflow					
manure (stored in silo)		waste	6875	kg	997 kg manure stored in silo / 1000 kg manure stored in stable cellar
Environmental outflow					
CH_4		air	21.239	kg	**3.08 kg CH_4** * (1000/997) * 6.875

The emission of CO_2, N_2O and CH_4 from diesel consumption of the field work process machinery is calculated with the emission factors from *table 13* and presented in the crop production inventory table [A.2.3].

Substance	Value	Unit
CO_2	3120	g CO_2 / kg diesel
N_2O	0.120	g N_2O / kg diesel
CH_4	0.129	g CH_4 / kg diesel

Table 13. Emission factors of GHGs.[6]

Table 14. CH_4 emissions due to the storage of manure in stable cellar.

Table 15. CH_4 emissions due to the storage of manure in silo.

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[6] Ecoinvent, 2004 ‘Life Cycle Inventories of Agricultural Production Systems’, Tab. 7.1, p.61

Table 16. CO_2*,* N_2O *and* CH_4 *emissions due to the application of manure on land.*

Process	**Application of manure on land (conventional), NL**				
Source	CMLCA database [P65], cattle manure, conventional treatment of manure; own assumptions CO_2 emissions based on C-balans; Amon et al., 2006				
Name	**code/ CAS-no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
manure (stored in silo)		waste	6875	kg	6.875 tons of manure / ha
Economic outflow					
manure (applied on land)		waste	6875	kg	1000 kg manure applied on land / 1000 kg manure stored in silo
Environmental outflow					
CO_2		air	577.50	kg	**84 kg CO_2** * 6.875 t/ha
N_2O		air	0.0261	kg	**0.0038 kg N_2O** * 6.875 t/ha
CH_4		air	0.0089	kg	**0.0013 kg CH_4** * 6.875 t/ha

G.2-3 Crop production (1)

Process	**Crop production (winter wheat, southwest clay grounds in the Netherlands, IJsselmeerpolders)** KWIN AGV 2006				
Name	**code/ CAS-no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
diesel		fuel	118	kg	[G561] diesel, at regional storage [RER]
wheat seed		material	160	kg	[G2954], wheat seed, at regional storehouse [NL]
N-fertiliser		material	205	kg	[G2950] mineral N-fertiliser
manure		waste	6875	kg	[P2660] liquid manure
Economic outflow					
wheat grains		main product	9000	kg	per ha, 15% moisture allocation: all to grains
wheat straw		co-product	4500	kg	per ha, 15% moisture allocation: nothing to straw
Environmental inflow					
CO_2, biogenic (wheat grains)		air	12434.57	kg	wheat grains CO_2-fixation, 66.67% of total fixation
CO_2, biogenic (wheat straw)		air	6217.28	kg	wheat straw CO_2-fixation, 33.33% of total fixation
Environmental outflow					
CO_2		air	368.16	kg	3.120 kg CO_2 / kg diesel
N_2O		air	0.0142	kg	0.120 g N_2O / kg diesel
CH_4		air	0.0152	kg	0.129 g CH_4 / kg diesel
CO_2 (biogenic)		air	577.50	kg	84 kg CO_2 / 1 t manure
N_2O		air	0.0261	kg	liquid manure, table 14-16
CH_4		air	22.627	kg	liquid manure, table 14-16
N_2O		air	6.765	kg	direct: 0.033 kg N_2O / kg N
CO_2		air	352.60	kg	indirect: 1.72 kg CO_2 / kg N
N_2O		air	3.007	kg	" : 0.01467 kg N_2O / kg N
CH_4		air	0.759	kg	" : 0.0037 kg CH_4 / kg N

Table 17. Inventory table for the process crop production [A.2.3].

Environmental outflow totals		
Substance	**Value**	**Unit**
CO_2 (biogenic)	577.500	kg
CO_2	720.760	kg
N_2O	9.81264	kg
CH_4	23.4005	kg

Table 18. Environmental outflow totals of table 17.

G.2-4 Crop production (2)

Process	**Crop production (winter wheat, sand grounds in the Netherlands)** KWIN AGV 2006				
Name	**code/ CAS-no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
diesel		fuel	115	kg	[G561] diesel, at regional storage [RER]
wheat seed		material	150	kg	[G2954], wheat seed, at regional storehouse [NL]
N-fertiliser		material	165	kg	[G2950] mineral N-fertiliser
P_2O_5-fertiliser		material	20	kg	[G2951] P_2O_5-fertiliser
K_2O-fertiliser		material	94	kg	[G2952] K_2O-fertiliser
manure		waste	6875	kg	[P2660] liquid manure
Economic outflow					
wheat grains		main product	7800	kg	per ha, 15% moisture allocation: all to grains
wheat straw		co-product	4000	kg	per ha, 15% moisture allocation: nothing to straw
Environmental inflow					
CO_2, biogenic (wheat grains)		air	10776.62	kg	wheat grains CO_2-fixation, 66.10% of total fixation
CO_2, biogenic (wheat straw)		air	5526.47	kg	wheat straw CO_2-fixation, 33.90% of total fixation
Environmental outflow					
CO_2		air	358.80	kg	3.120 kg CO_2 / kg diesel
N_2O		air	0.0138	kg	0.120 g N_2O / kg diesel
CH_4		air	0.0148	kg	0.129 g CH_4 / kg diesel
CO_2 (biogenic)		air	577.50	kg	84 kg CO_2 / 1 t manure
N_2O		air	0.0261	kg	liquid manure, table 14-16
CH_4		air	22.627	kg	liquid manure, table 14-16
N_2O		air	5.445	kg	direct: 0.033 kg N_2O / kg N
CO_2		air	283.80	kg	indirect: 1.72 kg CO_2 / kg N
CO_2		air	14.00	kg	” : 0.70 kg CO_2 / kg P_2O_5
CO_2		air	42.58	kg	” : 0.453 kg CO_2 / kg K_2O
N_2O		air	2.421	kg	” : 0.01467 kg N_2O / kg N
CH_4		air	0.611	kg	” : 0.0037 kg CH_4 / kg N

Table 19. Inventory table for the process crop production [A.2.3].

Environmental outflow totals		
Substance	**Value**	**Unit**
CO_2 (biogenic)	577.500	kg
CO_2	699.182	kg
N_2O	7.90548	kg
CH_4	23.2521	kg

Table 20.
Environmental outflow totals of table 19.

G.2.5 Crop production (3)

Process	**Crop production (winter wheat, clay grounds in the north of the Netherlands)** KWIN AGV 2006				
Name	**code/ CAS-no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
diesel		fuel	87	kg	[G561] diesel, at regional storage [RER]
wheat seed		material	175	kg	[G2954], wheat seed, at regional storehouse [NL]
N-fertiliser		material	205	kg	[G2950] mineral N-fertiliser
manure		waste	6875	kg	[P2660] liquid manure
Economic outflow					
wheat grains		main product	8400	kg	per ha, 15% moisture allocation: all to grains
wheat straw		co-product	4400	kg	per ha, 15% moisture allocation: nothing to straw
Environmental inflow					
CO_2, biogenic (wheat grains)		air	11605.59	kg	wheat grains CO_2-fixation, 65.62% of total fixation
CO_2, biogenic (wheat straw)		air	6079.12	kg	wheat straw CO_2-fixation, 34.38% of total fixation
Environmental outflow					
CO_2		air	271.44	kg	3.120 kg CO_2 / kg diesel
N_2O		air	0.0104	kg	0.120 g N_2O / kg diesel
CH_4		air	0.0112	kg	0.129 g CH_4 / kg diesel
CO_2 (biogenic)		air	577.50	kg	84 kg CO_2 / 1 t manure
N_2O		Air	0.0261	kg	liquid manure, table 14-16
CH_4		Air	22.627	kg	liquid manure, table 14-16
N_2O		Air	6.765	kg	direct: 0.033 kg N_2O / kg N
CO_2		Air	352.60	kg	indirect: 1.72 kg CO_2 / kg N
N_2O		Air	3.007	kg	” : 0.01467 kg N_2O / kg N
CH_4		air	0.759	kg	” : 0.0037 kg CH_4 / kg N

Table 21. Inventory table for the process crop production [A.2.3].

Environmental outflow totals		
Substance	**Value**	**Unit**
CO_2 (biogenic)	577.500	kg
CO_2	624.040	kg
N_2O	9.80892	kg
CH_4	23.3965	kg

Table 22. Environmental outflow totals of table 21.

G.2-6 Baling in the field

To estimate the diesel consumption for the baling of Hesston bales the conversion factor of [500 kg / 160 kg], namely 3.125 is used. The fuel consumption for baling round bales of 160 kg is 6.8 L/h.[7] The specific weight of diesel is assumed to be 0.84 kg/L.[8] The operation time for baling is 0.23 times 'silage baling' (0.13 h/bale) in Ecoinvent.[9]

Process	**Baling, Ecoinvent** Source: Ecoinvent, *Life Cycle Inventories of Agricultural Production Systems*, 2004. Appendix A7 Chapter 7 (Agricultural Field Work Processes), Tab. A11, p. 186				
Name	**code/ CAS-no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
diesel		fuel	0.534	kg	at regional storage, [RER]
wheat straw		material	500	kg	500 kg / Hesston bale: 2.4 m. x 1.2 m. x 1.2 m.
Economic outflow					
Hesston bale			1	unit	0.84 kg/L x (0.13 h/bale x 0.23) x 6.8 L/h x (500/160) = 0.534 kg/Hesston bale
Environmental inflow					
Environmental outflow (due to fuel consumption)					
CO_2		air	1.665	kg	3.120 kg/kg diesel
N_2O		air	0.0640	g	0.120 g/kg diesel
CH_4		air	0.0688	g	0.129 g/kg diesel

Table 23. Inventory table for the process baling in the field [B.2.1].

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[7] Ecoinvent 2004, Appendix A7, Tab. A 10, p.181

[8] Ecoinvent 2004, Chapter 7.2.4, p. 57

[9] Ecoinvent 2004, Appendix A7, Tab. A 9, p.181

G.2-7 Loading Hesston bales + Transport to interim storage

Loading

In the process ‘loading bales’ round bales of 160 kg produced in the baling process are loaded onto a 2-tyre-trailer of max 8t loading capacity each with a tractor in front. So the total capacity of the tractor trailer combination is 16 tonne. For the loading of Hesston bales the conversion factor of [500 kg / 160 kg] is used again. The unloading of the bales at the interim storage is not included in the inventory table below, but included in [B.2.3].

Transport to interim storage

The assumption of field-farm distance plus the distance that the tractor trailer combination drives in the field per hectare during loading of the Hesston bales is 2.5 km. The distance farm-interim storage is assumed to be 5 km.

Process	**Loading Hesston bales + transport to interim straw storage** Source: Grant, J.F. *et al*. 1995 ‘Energy and carbon analysis of using straw as a fuel, Appendices, ETSU B/M4/00487/01/REP/A’, Harwell (United Kingdom), Appendix J.				
Name	**code/ CAS-no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
loading bales		transport	3.125	unit	500 kg straw / Hesston bale 160 kg / unit loading bale 500 kg/ 160 kg = 3.125 unit
tractor and trailer 16t		transport	3.75	tkm	tractor and trailer [CH]: 2.5 km in the field: 50% loaded 5 km to interim storage: 100% loaded = 3.75 tkm
Hesston bale		material	1	unit	
Economic outflow					
Hesston bale			1	unit	Hesston bale: loaded and transported to interim straw storage.
Environmental inflow					
Environmental outflow					

Table 24. Inventory table for the process loading Hesston bales + transport to interim storage [B.2.2].

G.2-7 Interim storage + Transport to CHP plant

Before the bales are fed into the CHP plant, they are stored in a so-called interim straw storage facility. When the Hesston bales arrive at the interim storage they first must be unloaded from the tractor trailer combination with a telescopic handler. The fuel consumption during unloading of the Hesston bales into the stack and the loading from the stack is [32.9 MJ/Hesston bale][10] / [38.739 MJ/L][11] x [0.84 kg/L][12] = 0.713 kg diesel per Hesston bale. The sheeting of the stack is made of low density polypropylene, with an approximate sheet thickness of 1 mm and a density of 920 kg/m^3.[13] And the assumption of 22 km average distance between storage and CHP plant is made.[14]

Process	**Interim storage + Transport to CHP plant** Source: Grant, J.F. *et al*. 1995 'Energy and carbon analysis of using straw as a fuel, Appendices, ETSU B/M4/00487/01/REP/A', Harwell (United Kingdom), Appendix A.				
Name	**code/ CAS-no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
lorry 16t		transport	11	tkm	16,000 kg x 22km / 1000 kg = 352 tkm / 32 Hesston bale = 11 tkm / Hesston bale
diesel		fuel	0.713	kg	unloading + telescopic handler
polyethylene		material	0.9936	kg	LDPE, stack: 2000 H.bales 20x20x5 bales = 12m high, 24m long and 24m wide, 25% extra material. [4* (24m * 12m) + 2* (24m * 24m) = 1728 m^2 * 1.25 = 2160m^2 * 0.001m = 2.16m^3 * 920 kg/m^3 = 1987.2 kg / 2000 Hesston bales = 0.9936 kg / Hesston bale.]
Hesston bale		material	1.10	unit	10 losses during straw storage (pests, diseases, accidental fires, etc.)
Economic outflow					
Hesston bale			1	unit	Hesston bale: ready for combustion in the CHP
Environmental inflow					
Environmental outflow (due to fuel consumption)					
CO_2		air	2.226	kg	3.120 kg/kg diesel
N_2O		air	0.0856	g	0.120 g/kg diesel
CH_4		air	0.0920	g	0.129 g/kg diesel

Table 25. Inventory table for the process interim storage + transport to CHP plant [B.2.3].

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[10] Grant, J.F. *et al*. 1995. (Appendices) Appendix L: p. 71

[11] Grant, J.F. *et al*. 1995. (Appendices) Appendix A: p. 1

[12] Ecoinvent 2004, Chapter 7.2.4, p. 57

[13] Grant, J.F. *et al*. 1995. (Appendices) Appendix L: p. 69

[14] Grant, J.F. *et al*. 1995. p. 61

The GHG emissions from the process 'plant manufacture & maintenance' (capital goods) and the ash disposal from *figure 8* are not taken into account.

Table 26. Inventory table for the process conversion into heat and electricity [C.2].

Process	**Single straw firing with grate furnace in CHP plant** Grant, J.F. *et al*. 1995				
name	**code/ CAS-no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
wheat straw		(bio)fuel	1.165	kg	= 0.002329 Hesston bale 15% moisture content
Economic outflow					
electricity		energy	1	kWh	[3091 MJ$_e$/t] / [3.6 MJ/kWh] = 858.61 kWh/t / 2 = 429.31 kWh / Hesston bale → [(1 / 429.31) H.bale/kWh] x [500 kg/H.bale] = 1.165 kg.
heat		energy	9.36	MJ	[electricity (MJ$_e$/tonne] : [heat (MJ$_{th}$/tonne] = 1 : 2.6
Environmental inflow					
O_2		air	0.604	kg	44.33 wt.% C, 44/32 O_2
Environmental outflow					
CO_2 (biogenic)		air	1.610	kg	carbon content: 44.33wt.%[15] 44/12 CO_2

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[15] IEA, BIOBIB (wheat straw) 2007.

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Appendix H Electricity from animal fat and meat meal by co-firing with coal

H.1 System description

Electricity production is based on co-firing of animal wastes in a coal fired power plant. The rendering products, animal fat and meat meal, are produced from category 1 and 2 materials. According to EU directives for destruction of animal wastes these materials have to be discharged to a render company (e.g. Rendac BV in the Netherlands) and the resulting products may not be used for feed or food applications. In figure 1 a flowchart is presented that summarizes the different processes of the system and indicates where emissions of green house gasses (GHGs) might occur.

Functional unit
The functional unit is 1 kWh of electricity. In case a CHP is considered also heat is produced. For heat the functional unit is 1 MJ heat.

System boundaries and cut off
Category 1 and 2 materials are considered wastes (negative economic value). The system is therefore cut off at the production of meat. This means that up-chain processes from livestock husbandry are not taken into account and the systems starts with transportation of animal wastes from farms (cadavers) and slaughterhouses (contaminated parts). All data refer to the Dutch situation of 2006 (Rendac, 2006).

Allocation: energy allocation
The process “rendering” in the process system “electricity from co-firing of animal fat and meat meal with coal” delivers two functions 1) the production of fuel[16] and 2) the service waste treatment of animal waste materials (cat. 1 and 2). For this processes energy allocation is used. The LHV used for energy allocation are presented in table 1. The actual allocation factors are based on the LHV of the material and the amount of produced material.

Table 1 LHV, amounts and allocation factors for waste processing of animal waste

	LHV MJ/kg	**Amount kg**	**Allocation factor**
Animal waste processing			
Animal waste	17.95	1000	0.72
Meat&bone meal (fuel)	21.5	331	0.28

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[16] Technically the rendering process produces two products, animal fat (31 MJ/kg) and meat meal (18 MJ/kg). However, in this project it is assumed that both materials are co-fired with coal to produce electricity. Thus allocation is only necessary between the services fuel production for co-firing and waste treatment.

conservative, typical and best practice systems
In this project for this case no distinction is made between conservative, typical and best practice systems. Only a Typical system is defined.

H.*1-1* ***System description*** “electricity from co-firing of animal fat and meat meal with coal”

Below a description is given of the process system according to the flowchart presented in figure 1 divided in the phases:

[A] feedstock production
Not applicable

[B] feedstock transport
The transport from cadavers and slaughter waste to the rendering unit is assumed to be 75 km.

[C] conversion
The cadavers and slaughter waste are converted into animal fat and meat and bone meal. Both can be used as fuel for co-firing with coal. The conversion process requires some energy (electricity, natural gas and diesel).

[D] (biofuel) transport
The animal fats and meat meal are transported to the power plant to be co-fired with coal. A transportation distance of 150 km is assumed, using transportation in 30 ton trucks.

[E] end use
The functional unit is defined as the supply of 1 kWh electricity at consumer.
The electricity is produced by co-firing of a mixture of animal fat and meat meal with coal. The electricity production of the co-firing process is separated into 2 parts for a mixture of animal fat and meat meal and for coal based on the energy content of the fuels. Only the electricity from the mixture and the accompanying necessary inputs are taken into account.

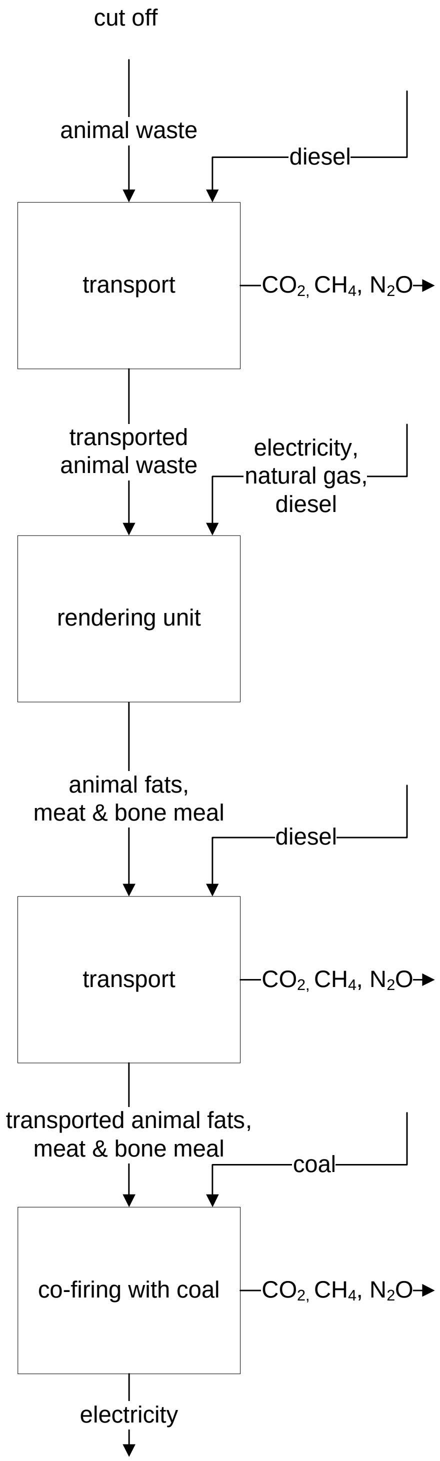

Figure 1 Flowcharts for the electricity production by co-firing with coal from rendering products of animal waste.

H.2 process description

In this appendix for each of the processes in the systems (see appendix B-1) the economic inputs (consumed energy and materials of a process) and economic outputs (produced energy and materials of a process) are summarized together with the environmental inputs (e.g. the fixation of CO_2 in biomass production) and environmental outputs (the emissions of GHGs: CO_2, CH_4 and N_2O) in the unit process tables.

The quantification of the process data is taken from Blonk (2006).

H.2-1 Definition of conservative, typical and best practice processes and process systems

For the process system on “electricity production by co-firing with coal of rendering products of animal waste” only a typical version is implemented.

H.2-2 Description of the unit processes for electricity from co-firing of animal fat and meat meal with coal

B = best practice; T = typical; C = conservative

[A] Feedstock production

Not applicable

[B] Feedstock transport

Process	**Transport of animal waste, to rendering unit (bio-electricity option) (Typical)** Source: Blonk, 2006				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Animal waste (cadavers and slaughter waste)		waste	1000	kg	
Transport by truck		transport	75	tkm	distance 75 km
Economic outflow					
Transported animal waste (bio-electricity option)		waste	1000	kg	
Environmental inflow					
Environmental outflow					

[C] Conversion

Process	**Production of animal fat and meat and bone meal from animal waste (category 1 and 2) in a rendering unit** Source: Blonk, 2006				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Transported animal waste (bio-electricity option)		waste	1000	kg	
energy from diesel combustion		Fossil fuel	3.868	MJ	0.1 liter diesel 38.68 MJ/l 45MJ/kg
energy from Natural gas combustion		Fossil fuel	322.83	MJ	10.2 m^3 Natural gas 31.65 MJ/m^3
Electricity		electricity	87	kWh	Dutch production mix
Economic outflow					
Animal fat, meat meal and bone meal (bio-electricity option)			331	kg	89 kg animal fat, 242 kg meal, all used as biofuel for co-firing
Environmental inflow					
Environmental outflow					

[D] Biofuel transport

Process	**Transport of animal fat, meat meal and bone meal (biofuel)(Typical)** Source: Blonk, 2006				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Animal fat, meat meal and bone meal (bio-electricity option)		biofuel	1000	kg	
Transport by truck		transport	150	tkm	distance 150 km
Economic outflow					
Transported animal fat, meat meal and bone meal (bio-electricity option)		biofuel	1000	kg	
Environmental inflow					
Environmental outflow					

[E] End use

Process	**Electricity production from co-firing of animal fat, meat meal and bone meal with coal (Typical)** see appendix H.3 allocation energy production based on energy content of fuels (MJ/kg; coal = 23, animal fat and meal mix = 31)				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Transported animal fat, meat meal and bone meal (bio-electricity option)		biofuel	331	kg	
coal		Fossil fuel	3000	kg	
Economic outflow					
Electricity (animal fat and meal part)		electricity	1200	kWh	
Electricity (coal part)		electricity	10255	kWh	
Environmental inflow					
Environmental outflow					
CO_2, fossil	124-38-9 (Fossil)	air	6390	kg	
CO_2, biogenic	124-38-9 (Biogenic)	air	608	kg	

transformation and transport losses of electricity from producer to consumer
Average transformation and transport losses for the referenced electricity production are 4% (SenterNovem 2006). As a default, also for bio-electricity options this 4% loss is assumed for transformation and transport. However, losses due to transformation and transport will dependent on the type of produced electricity (high, medium or low voltage), the transportation distance and the type of consumed electricity (high, medium or low voltage). For this reason a different loss can be defined in the process named “transformation and transport to consumer of electricity, from (….)” that is available for each bio-electricity chain.

Appendix H.3 Example of spreadsheet to calculate inputs and outputs of electricity production

ENERGY BALANCE - CO-FIRING WITH COAL

Fuel	Quantity		Energie content		Input		Elektrisch rendement	Electrical Output	
Coal	3000	kg	29.3	MJ/kg	87900	MJ			
Palm oil	0	kg	37.1	MJ/kg	0	MJ			
rape seed oil	0	kg	37.1	MJ/kg	0	MJ			
soy bean oil	0	kg	37.1	MJ/kg	0	MJ			
meat and bone meal	89	kg	18.8	MJ/kg	1673.2	MJ			
animal fat	242	kg	35.6	MJ/kg	8615.2	MJ			
other2	0	kg		MJ/kg	0	MJ			
other2	0	kg		MJ/kg	0	MJ			
total	3331	kg			98188.4	MJ	42.0%	4.12E+04	MJ

CARBON BALANCE - CO-FIRING WITH COAL

Fuel	Quantity		Carbon content	Carbon			Carbon dioxide emissions	
Coal	3000.00	kg	58.11%	1.74E+03	kg		6.39E+03	kg
Palm oil	0.00	kg	77.10%	0.00E+00	kg		0.00E+00	kg
rape seed oil	0.00	kg	77.10%	0.00E+00	kg		0.00E+00	
soy bean oil	0.00	kg	77.10%	0.00E+00	kg		0.00E+00	
meat and bone meal	89.00	kg	50.10%	4.46E+01	kg		1.63E+02	
animal fat	242.00	kg	50.10%	1.21E+02	kg		4.45E+02	
other1	0.00	kg		0.00E+00	kg		0.00E+00	
other2	0.00	kg		0.00E+00	kg		0.00E+00	
total	3331.00	kg				total	7.00E+03	kg
						total biogenic	6.08E+02	kg
						total fossil	6.39E+03	kg

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Appendix I Electricity and heat from biogas by digestion of manure and biomass and combustion in CHP (farm scale)

I.1 System description

In this appendix mainly two systems are described:

a) small scale, decentralized systems for co-digestion of manure and biomass
b) larger scale, centralized systems for digestion of restaurant waste ("swill")

The description of the system to produce biogas from manure and biomass, and electricity from biogas in a CHP (Combined Heat Power installation) are based on the description given for the digestion of cattle manure at the demonstration project of "De Marke" (Kool et al., 2005). In figure 1 a flowchart is presented that summarizes the different processes of the system and indicates where emissions of green house gasses (GHGs) might occur. The system for the centralized digestion of restaurant waste more or less resembles this system, but includes more transport and likely also makes profitable use of the heat produced in the CHP (see figure 2).

Functional unit

The functional unit is 1 kWh of electricity. In case a CHP is considered also heat is produced. For heat the functional unit is 1 MJ heat.

System boundaries and cut off

Manure is considered a waste stream. The system is cut off at the production of manure. This means that up-chain processes from livestock husbandry are not taken into account. Also waste from restaurants are cut off and so up chain processes from food industry and agriculture are not taken into account

The system is also cut off after the application of the (digested) manure. It is assumed that the alternative systems are not different for the delivered function of soil fertilization and improvement. At the moment there is insufficient scientific evidence that digested manure will lead to higher mineral nitrogen availability for the crops (Kool et al., 2005) and therefore may lead to a higher yield or a reduced fertilizer consumption. Future investigations may prove differently.

Allocation: energy allocation

In the process chain there are two processes with possible co-production of products, namely: the digestion process delivers the functions 1) waste treatment, and 2) biogas production. The CHP delivers both 1) electricity and 2) heat. For these processes energy allocation is used. The LHV used for energy allocation are presented in table 1. The actual allocation factors are based on the LHV of the material and the amount of produced material.

Table 1 LHV, amounts and allocation factors for digestion and CHP

	LHV MJ/kg	**Amount[1] kg**	**Allocation factor[1]**
Manure digestion			
Manure (cattle)	5.09	1000	0.91
Biogas (65% CH4)	23.45 MJ/m3	22.5 m3	0.09
Swill digestion			
Swill	10.62	1000	0.75
Biogas (55% CH4)	19.84 MJ/m3	175 m3	0.25
CHP			
electricity	3.6 MJ/kWh	2.36 kWh	0.5
heat	1 MJ/kWh	8.08 MJ	0.5

1 the amount and allocation factor are given as an example. Figures are different for different conservative, typical and best practice options.

conservative, typical and best practice systems
In this project a distinction is made between conservative, typical and best practice systems. A system is defined as a chain of linked processes. The best practice system is defined as the chain of best practice processes. These are the most efficient processes and/or processes with the lowest GHG emission levels. For the process system “electricity from manure and biomass” this distinction is made, see table 1. For the process system on “electricity from restaurant waste” only one version is implemented.

Table 1 Definition of conservative, typical and best practice systems

	feedstock	efficiency biogas production	GHG emission levels
conservative	cattle manure only	average	average
typical	cattle manure and grass	average	average
	manure and maize	average	average
best practice	cattle manure and grass	high (“de Marke”)	zero, low (“de Marke”)
	cattle manure and maize	high (“de Marke”)	zero, low (“de Marke”)

For a detailed description of the conservative, typical and best practice processes is referred to appendix I.2-1 and I.2-2.

I.*1-1 System description “electricity from manure and biomass (small scale/decentralized)”*

The described system refers to a small scale decentralized production system of electricity based on cattle manure, i.e. production of feedstock, biogas and electricity on a farm level. This means that the processes for feedstock production, conversion and end use are on the same site and therefore transport of feedstock and other materials is minimized. The feedstock for digestion can either be manure or a mixture of manure and biomass (crop, crop residues). The energy consumed by the system, e.g. electricity for chopping and mixing and heating of the digester are supplied internal by the CHP in the system. However there is a net production of electricity by the CHP on the farm that is delivered to the consumer (end use). Below a description is given of the process system according to the flowchart presented in figure 1 divided in the phases:

[A] feedstock production
[B] feedstock transport
[C] conversion
[D] (biofuel) transport
[E] end use

I.1-1[A] feedstock production

This phase of the system includes the excretion of manure in the stable (3000 m^3/yr) and the production and storage of co substrate (silage grass, silage maize) on the farm.

The manure is mixed and part of it is transported daily to the digester. Because of the mixing and daily transport a long retention time of the manure in the stable is avoided. Therefore also spontaneous biogas formation and emissions of methane (CH_4) from manure stored in the stable cellar are minimized.

Fixation and emissions related to the production of biomass (grass/corn/silage etc. on farm) will be based on the Ecoinvent system and process descriptions (Ecoinvent Centre, 2006, see appendix) In Zwart et al., 2006 it is assumed that crops grown for co-substrate may be stored on the site as silage. Because this silage may be stored over a long period of time emissions may occur from the storage of this fermenting biomass.

I.1-1[B] feedstock transport

Feedstock production of manure and biomass for co-digestion are assumed to be produced on site. So there is no transport of feedstock.

I.1-1[C] conversion

This phase of the system includes the anaerobic digestion of the manure and biomass, the combustion of the biogas in a CHP, the storage of the digested manure and the application of the digested manure on the farmland.

The manure and biomass are transported to a mixing barrel (10 m^3) where the biomass is chopped and mixed with the manure. After that the substrate is digested in the digester (1400 m^3, 35-40 degrees C, 2 to 3 months). The digester produces biogas and a waste flow called “digested manure”. The biogas and the digested manure are stored together in a manure bag (1500 m^3). The biogas (63% methane) is purified, i.e. condensation of waterdamp in drip-trap, the condens is transported back to digested manure and H_2S removed by bacteria, the water and sulphur (S) is transported back to the digested manure. The biogas is combusted in a CHP that produces both heat and electricity (capacity 18 kW electric, 29 kW thermal). The produced heat is used internal within the system to heat up the digester (35-40 degrees C). Also part of the produced electricity is used within the system. The digested manure is applied on the farmland for fertilizing and soil improvement. An intermediate step separation of the digested manure into a liquid fertilizer fraction “methanogenic digestate” and a fibrous compost fraction “acidogenic digestate” is optional. However this process is not further analyzed in this study.

Note that the digested manure that is applied on the land will lead to emissions of green house gases. Depending on the efficiency of the biogas production in the digester the digested manure may contain more or less readily digestible organic matter. The digestion of this organic matter on the land will lead to dinitrogenoxide, carbon dioxide and/or methane emissions depending on the aerobic conditions of the soil. In literature not much information can be found on emissions after application of the manure and digested manure and often information is ambiguous (Amon et al., 2006, Clemens et al., 2006, Kool et al., 2005, Bosker & Kool, 2004, Kool en de Ruiter, 2004), see also appendix I.7. Within another project for the development of a CO_2-tool for biofuels a model is developed by CE (SenterNovem, forthcoming). However, this model is not applicable for (co-)digestion of biomass. So, at this moment there is not a broad excepted model approach to solve the problem of emissions after application of manure or digestate. As stated in Van der Hoek & Schijndel (2006); “In the case that biogas production from animal manure increases in the Netherlands in the near future, the method for calculating methane emissions from manure management has to be extended to include effects of biogas production. Focus should also be placed on N_2O emissions when digested manure is applied to the soil”.

In appendix I.4 an example is given of the calculation of carbon dioxide emissions from the digestion of (digested) manure after application on the land. In this example it is assumed that due to aerobic conditions on the land all readily digestible organic matter will be digested into carbon dioxide. However, part of the organic matter might well be digested under anaerobic conditions and lead to methane emissions.

It can be concluded therefore that the reported emissions of methane and dinitrogenoxide after application of manure or digestate are very uncertain.

I.1-1[D] (biofuel) transport

The biogas is produced and combusted in the CHP on site. The digested manure is applied on the farm level. Transport is therefore non-existent or very local, and is ignored.

I.1-1[E] end use

The produced heat is used internally in the system to heat up the digester (35-40 degrees C). Also part of the produced electricity (5000 kWh/year) is used within the system for mixing and pumping etc. The excess electricity is delivered to the consumer (103000 kWh/year). The functional unit is defined as the supply of 1 kWh electricity at consumer. There is no profitable use of excess heat.

I.*1-2 System description "electricity from biomass (i.e. waste from restaurants "Swill") (larger scale/centralized)"*

I.1-2[A] feedstock production

Food residues from restaurants ("swill") are considered wastes. Therefore the system is cut off and up-chain processes for the production of the food are not taken into account.

I.1-2[B] feedstock transport

It is assumed that "swill" will be supplied from different locations all over the Netherlands. Therefore a transport distance of 100 km is assumed, using 28t trucks.

I.1-2[C] conversion

This phase of the system includes the anaerobic digestion of the biomass, the combustion of the biogas in a CHP and the storage of the swill and digested swill.

The "swill" is digested in two vessels (1900 m^3 each). The conditions are mesofiel (ca. 35-40 degrees Celcius). The retention time of the biomass is about 70 days. The resulting production of biogas is about 175-200 m^3 biogas per ton swill. The methane content of the biogas is 55% (data refer to BeWa, Moerdijk).

The biogas is combusted in a CHP that produces both heat and electricity (capacity 980kW). The produced heat is used internal within the system to heat up the digester (35-40 degrees C). Also part of the produced electricity is used within the system.

In the Netherlands the digested biomass is not allowed to be applied on the land as a fertilizer. The digestate is exported (to Germany). An intermediate step separation of the digested biomass into a liquid fertilizer fraction "methanogenic digestate" and a fibrous compost fraction "acidogenic digestate" is optional. However this process is not further analyzed in this study.

I.1-2[D] (biofuel) transport

The biogas is produced and combusted in the CHP on site. So there is no transport of biofuel.. However, there is transport of (waste) materials. In the Netherlands the digested biomass is not allowed to be applied on the land as a fertilizer. The digestate is exported (to Germany). For this an average transport distance of 100 km is assumed, using 28t trucks.

I.1-2[E] end use

The produced heat is used internal in the system to heat up the digester (35-40 degrees C) (assumption 1155 MJ per tonne swill (SenterNovem, forthcoming)). Also part of the produced electricity is used within the system for mixing and pumping etc. (assumption 1619 MJ per tonne swill (SenterNovem, forthcoming)). The exceed electricity is delivered to the electricity grid. The functional unit is defined as the supply of 1 kWh electricity at consumer. Together with electricity also heat is produced. Per kWh about 2.42 MJ heat is produced (see appendix I.2-4C and I.2-7). This system will be compared to the reference system producing 1 kWh electricity according to the Dutch production mix and 2.38 MJ of heat according to the combustion of natural gas.

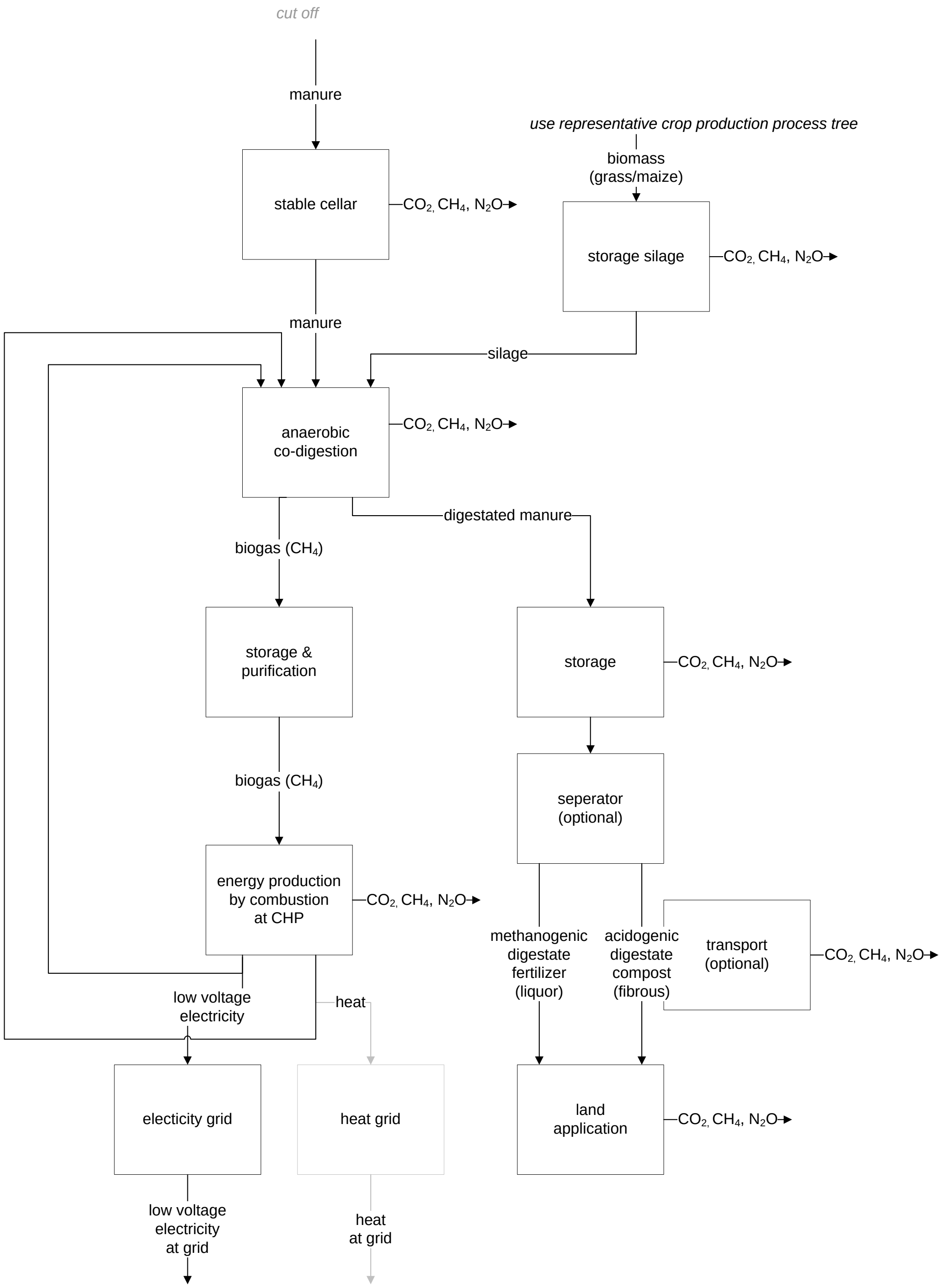

Figure 1 Flowcharts of the system for bio-electricity and "avoided" conventional waste treatment a) electricity production from manure and biomass and b) conventional treatment of manure.

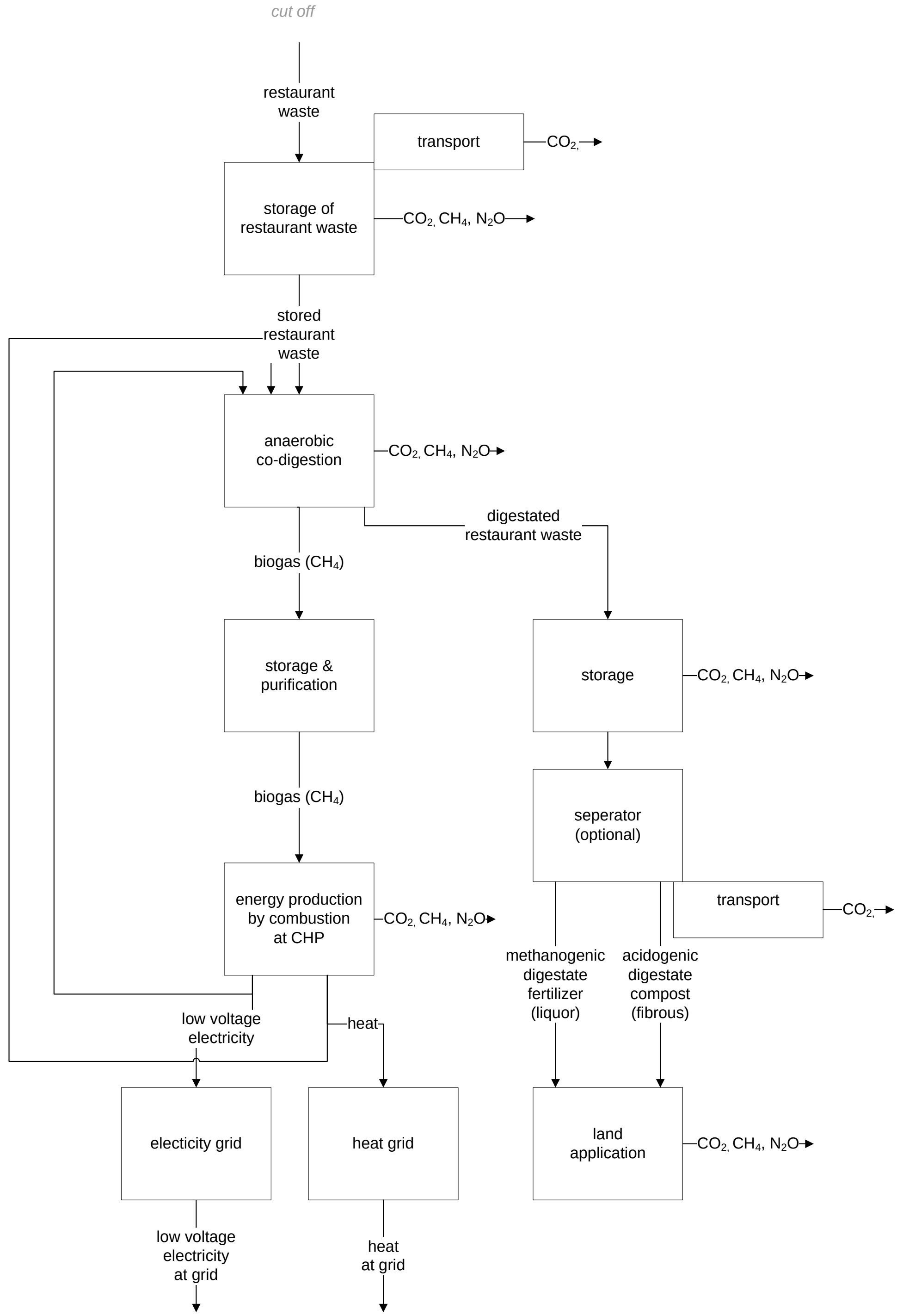

Figure 2 Flowcharts of the system for bio-electricity and “avoided” conventional waste treatment a) electricity production from restaurant waste and b) composting of restaurant waste.

I.2 process description

In this appendix for each of the processes in the systems (see appendix A-1) the economic inputs (consumed energy and materials of a process) and economic outputs (produced energy and materials of a process) are summarized together with the environmental inputs (e.g. the fixation of CO_2 in biomass production) and environmental outputs (the emissions of GHGs: CO_2, CH_4 and N_2O) in the unit process tables.

For the quantification of the process data mainly the demonstration project “realization of manure digestion at De Marke”(Kool et al., 2005) is used. However also other literature sources are consulted (Amon et al., 2006; Clemens et al., 2006; Dooren et al., 2005; Dumont, 2004; Kuikman et al., 2000; Lent & van Dooren, 2001; Tijmensen et al., 2002; Zwart et al., 2006) and listed in the remarks of the process format.

I.2-1 Definition of conservative, typical and best practice processes and process systems

The operational system “electricity from manure and biomass” of the demonstration farm “De Marke” can be considered an optimized system. The digestion process is proceeding very well, with substantially higher than average biogas yields (30 m^3 biogas per m3 manure instead of 21 m^3 biogas per m^3 manure based on literature, see appendix I.3). Possible explanations are the long retention time of the manure in the digester (2 to 3 months), subsequent fermentation, high temperature and rationing of the dairy cattle. The co-digestion of a crop with the manure will even improve the biogas yield.

All in all the data from the different literature sources are used to define the system of digestion of manure and biomass and subsequent combustion in CHP in three classes representing a conservative, typical and best practice system (see table 2).

For the process system on “electricity from biomass (e.g.food remains from restaurants, i.e. Swill) (larger scale/centralized)” only a typical version is implemented.

Table 2a Definition of conservative, typical and best practice systems for digestion of manure and crop and subsequent combustion in CHP (small scale, decentralized)

			conservative De Marke data for manure only, adjusted (based on other (more average data) from other literature sources	typical De Marke data for manure + grass, adjusted based on (more average) data from other literature sources	best practice De Marke data for manure + grass	typical De Marke data for manure + maize, adjusted based on (more average) data from other literature sources	best practice De Marke data for manure + maize
stable	CH4 emissions	kg/1000 kg substrate	0.09	0.09	0	0.09	0
	N2O emissions	kg/1000 kg substrate	0.0002	0.0002	0	0.0002	0
storage co substrate	CH4 emissions	kg/1000 kg substrate	-	3.1	0	3.1	0
	N2O emissions	kg/1000 kg substrate	-	0.014	0	0.014	0
digester	biogas production	m3/1000 kg substrate	22.5	28	47	33	43
	CH4 emissions	kg/1000 kg substrate	0.23	0.29	0.49	0.34	0.45
storage digestate	CH4 emissions	kg/1000 kg substrate	1.00	1.00	0.00	1.00	0.00
	N2O emissions	kg/1000 kg substrate	0.04	0.04	0.00	0.04	0.00
CHP	CH4 emissions	kg/m3 biogas	9.27E-06	9.27E-06	9.27E-06	9.27E-06	9.27E-06
	N2O (biogenic) emissions	kg/m3 biogas	7.19E-06	7.19E-06	7.19E-06	7.19E-06	7.19E-06
	CO2 (biogenic) emissions	kg/m3 biogas	1.77	1.77	1.77	1.77	1.77
digestate application	CH4 emissions	kg/m3 digestate	0.002	0.002	0.002	0.002	0.002
	N2O (biogenic) emissions	kg/m3 digestate	0.0027	0.0027	0.0027	0.0027	0.0027
	CO2 (biogenic) emissions	kg/m3 digestate	48	37	0	27	8

Table 2b Definition of conservative, typical and best practice systems for digestion of manure and crop and subsequent combustion in CHP (per kWh electricity) (small scale, decentralized)

			conservative	typical	best practice	typical	best practice
			De Marke data for manure only, adjusted (based on other (more average data) from other literature sources	De Marke data for manure + grass, adjusted based on (more average) data from other literature sources	De Marke data for manure + grass	De Marke data for manure + maize, adjusted based on (more average) data from other literature sources	De Marke data for manure + maize
stable	CH4 emissions	kg/kWh	0.0032	0.0026	0.0000	0.0022	0.0000
	N2O emissions	kg/kWh	7.17E-06	5.76E-06	0.00E+00	4.89E-06	0.00E+00
storage co substrate	CH4 emissions	kg/kWh	-	8.93E-02	0.00E+00	7.58E-02	0.00E+00
	N2O emissions	kg/kWh	-	4.03E-04	0.00E+00	3.42E-04	0.00E+00
digester	biogas production	m3/kWh	0.8065	0.8065	0.8065	0.8065	0.8065
	CH4 emissions	kg/kWh	0.0084	0.0084	0.0084	0.0084	0.0084
storage digestate	CH4 emissions	kg/kWh	0.0358	0.0288	0.0000	0.0244	0.0000
	N2O emissions	kg/kWh	0.0014	0.0012	0.0000	0.0010	0.0000
CHP	CH4 emissions	kg/kWh	7.48E-06	7.48E-06	7.48E-06	7.48E-06	7.48E-06
	N2O (biogenic) emissions	kg/kWh	5.80E-06	5.80E-06	5.80E-06	5.80E-06	5.80E-06
	CO2 (biogenic) emissions	kg/kWh	1.43E+00	1.43E+00	1.43E+00	1.43E+00	1.43E+00
digestate application	CH4 emissions	kg/kWh	7.17E-02	5.76E-02	3.43E-02	4.89E-02	3.75E-02
	N2O (biogenic) emissions	kg/kWh	9.68E-02	7.78E-02	4.63E-02	6.60E-02	5.06E-02
	CO2 (biogenic) emissions	kg/kWh	1.72E+03	1.07E+03	0.00E+00	6.60E+02	1.50E+02
	manure	kg/kWh	35.8422939	28.801843	17.158545	24.437927	18.754688
	biogas	m3/kWh	0.80645161	0.8064516	0.8064516	0.8064516	0.8064516
	electricity	kWh	1	1	1	1	1

For a detailed description of all the data in all the processes is referred to unit process tables that are described below. Note the avoided conventional manure treatment for different biogas yields, see appendix I.6.

I.2-2 Description of the unit processes for digestion of manure and biomass to biogas and combustion in CHP

B = best practice; T = typical; C = conservative

[A] Feedstock production

Process	**Storage of manure in stable cellar , small scale (3000 m^3 manure/year), cattle manure, biogas option** Source: Kool, Hilhorst & van der Vegte, 2005				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
manure excreted in stable (cattle)		waste from cattle husbandry	1000	kg	density: 1000kg/m^3
electricity		energy		kWh	for mixing and pumping, internal supply from CHP
Economic outflow					
manure stored in stable cellar (cattle, biogas option)		waste from cattle husbandry	1000	kg	density: 1000kg/m^3
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	air	0	kg	B: no emission because of frequent transport of manure to digester (no storage in between)
CH_4	74-82-8	air	0.09		C,T: Zwart et al., (2006)
N_2O	10024-97-2	air	0		B: no emission because of frequent transport of manure to digester (no storage in between)
N_2O	10024-97-2	air	0.0002		C,T: Zwart et al., (2006)

- definition in CMLCA: manure is a waste, the processing of manure is a waste process

- electricity consumption: optional to add if in CHP electricity is given as gross production

In Zwart et al., 2006 it is assumed that crops grown for co-substrate may be stored on the site as silage. Because this silage may be stored over a long period of time emissions may occur from the storage of this fermenting biomass. In Zwart et al., (2006) it is assumed that emission might have the same magnitude as emissions from stored manure in silos. There is not much information on the emission of methane and dinitrogenoxide from silage. It is assumed that the emission factor is somewhere between the emission from cattle and pigs manure.

Process	**Storage of co substrate (silage), , biogas option** Source: Zwart et al., 2006				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
silage			1000	kg	density: 1000kg/m^3
Economic outflow					
stored silage			997	kg	density: 1000kg/m^3
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	air	0	kg	B; own assumption
CH_4	74-82-8	air	3.1	kg	T: Zwart et al., (2006)
N_2O	10024-97-2	air	0	kg	B: own assumption
N_2O	10024-97-2	air	0.014	kg	T: Zwart et al., (2006)

[B] Feedstock transport

N/A

[C] Conversion

Three alternative feedstock mixtures

The efficiency of the biogas production depends on the feedstock mixture. Production of Biogas is distinguished in Biogas (from manure), Biogas (from manure and grass), Biogas (from manure and corn). The biogas has been given different names to enable alternative choices in inputs for the CHP (see CHP). The characteristics of the digested manure is assumed to be the same for the different alternative biogas production processes. So no discriminating nomenclature is applied.

Alternative 1 Conservative

Process	**Biogas production from manure, small scale (1400m^3), Temperature range 35-40 degrees Celsius, cattle manure, biogas option** Source: Kool, Hilhorst & van der Vegte, 2005 adapted				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
manure stored in stable cellar (cattle, biogas option)		waste from cattle husbandry	1000	kg	density: 1000kg/m^3
heat		energy		kW	internal supply from CHP
Economic outflow					
digested manure (cattle)		waste from cattle husbandry	988	kg	calculated based on manure minus biogas
Biogas (from manure)		biofuel	22.5	m^3	Zwart et al., (2006) 63% methane, methane: 0.71 kg/m^3 37% carbondioxide, CO_2: 1.98 kg/m^3
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	air	0.23	kg	kg CH4 emission per ton digested substrate, biogas leakage is ca. 2% of produced biogas

Alternative 2a Typical

Process	**Biogas production from manure and grass, small scale, Temperature range 35-40 degrees Celsius, cattle manure, biogas option** Source: Kool, Hilhorst & van der Vegte, 2005 adapted				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
manure stored in stable cellar (cattle, biogas option)		waste from cattle husbandry	850	kg	density: 1000kg/m^3
grass		fodder	150	kg	internal supply “De Marke”, upchain processes taken from Ecoinvent database
heat		energy		kW	internal supply from CHP at “De Marke”
Economic outflow					
digested manure (cattle)		waste from cattle husbandry	985	kg	calculated based on manure minus biogas
Biogas (from manure and grass)		biofuel	28	m^3	Tijmensen et al., (2002) 63% methane, methane: 0.71 kg/m^3 37% carbondioxide, CO_2: 1.98 kg/m^3
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	air	0.29	kg	kg CH4 emission per ton digested substrate, biogas leakage is ca. 2% of produced biogas

Alternative 2b Typical

Process	**Biogas production from manure and maize, small scale, Temperature range 35-40 degrees Celsius, cattle manure, biogas option** Source: Kool, Hilhorst & van der Vegte, 2005 adapted				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
manure stored in stable cellar (cattle, biogas option)		waste from cattle husbandry	900	kg	density: 1000kg/m^3
maize		fodder	100	kg	internal supply “De Marke”, upchain processes taken from Ecoinvent database
heat		energy		kW	internal supply from CHP at “De Marke”
Economic outflow					
digested manure (cattle)		waste from cattle husbandry	982	kg	calculated based on manure minus biogas
Biogas (from manure and grass)		biofuel	33	m^3	Tijmensen et al., (2002) 63% methane, methane: 0.71 kg/m^3 37% carbondioxide, CO_2: 1.98 kg/m^3
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	air	0.34	kg	kg CH4 emission per ton digested substrate, biogas leakage is ca. 2% of produced biogas

Alternative 3a Best practice

Process	**Biogas production from manure and grass, small scale, Temperature range 35-40 degrees Celsius, cattle manure, biogas option** Source: Kool, Hilhorst & van der Vegte, 2005				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
manure stored in stable cellar (cattle, biogas option)		waste from cattle husbandry	850	kg	density: 1000kg/m^3
grass		fodder	150	kg	internal supply “De Marke”, upchain processes taken from Ecoinvent database
heat		energy		kW	internal supply from CHP at “De Marke”
Economic outflow					
digested manure (cattle)		waste from cattle husbandry	975	kg	calculated based on manure minus biogas
Biogas (from manure and grass)		biofuel	47	m^3	63% methane, methane: 0.71 kg/m^3 37% carbondioxide, CO_2: 1.98 kg/m^3
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	air	0.49	kg	kg CH4 emission per ton digested substrate, biogas leakage is ca.2% of produced biogas

- definition in CMLCA: manure and digested manure are wastes; biogas is a product; the conversion of manure into biogas serves two functions, i.e. waste treatment of manure and production of biogas, all flows are allocated to biogas

Alternative 3b Best practice

Process	**Biogas production from manure and maize, small scale, Temperature range 35-40 degrees Celsius, cattle manure, biogas option** Source: Kool, Hilhorst & van der Vegte, 2005				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
manure stored in stable cellar (cattle, biogas option)		waste from cattle husbandry	900	kg	density: 1000kg/m^3
grass		fodder	100	kg	internal supply “De Marke”, upchain processes taken from Ecoinvent database
heat		energy		kW	internal supply from CHP at “De Marke”
Economic outflow					
digested manure (cattle)		waste from cattle husbandry	977	kg	calculated based on manure minus biogas
Biogas (from manure and maize)		biofuel	43	m^3	63% methane, methane: 0.71 kg/m^3 37% carbondioxide, CO_2: 1.98 kg/m^3
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	air	0.45	kg	kg CH4 emission per ton digested substrate, biogas leakage ca. 2% of produced biogas

All the same for Conservative, Typical , Best practice

Process	**Combined Heat Power (CHP) production, Small scale (Capacity: 29 kW thermal,18 kWh electric), cattle manure, biogas option** Source: Kool, Hilhorst & van der Vegte, 2005				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
1. Biogas (from manure) 2. Biogas (from manure and grass) 3. Biogas (from manure and corn)		biofuel	1	m^3	Alternative 1, 2 or 3 for feedstock, one of the alternatives should be chosen. 63% methane, methane: 0.71 kg/m^3 37% carbondioxide, CO_2: 1.98 kg/m^3
Economic outflow					
electricity		energy	1.24	kWh	
heat		energy			used on site for heating of digester
Environmental inflow					
Environmental outflow					
CO_2 (Biogenic)	124-38-9 (Biogenic)	air	1.77	kg	calculated based on combustion of natural gas in CHP corrected for heating value natural gas (31.65 MJ/m^3) versus biogas (22 MJ/m^3), see appendix I.5
N_2O	10024-97-2	air	7.19E-06		see CO_2
CH_4	74-82-8	air	9.27E-06		see CO_2

Process	**Storage of digested manure,** **cattle manure, biogas option** Source: Kool, Hilhorst & van der Vegte, 2005				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
digested manure (cattle)		waste from cattle husbandry	1000	kg	density: 1000kg/m^3
Economic outflow					
digested manure stored (cattle)		waste from cattle husbandry	1000	kg	density: 1000kg/m^3
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	air	0	kg	B: assumption, no leakage from stored digested manure in manure bag
CH_4	74-82-8	air	1	kg	C,T: Clemens et al. (2006) reports emissions of 0.6 kg/m^3, Amon et al. (2006) reports emissions of 1.3 kg/m^3
N_2O	10024-97-2	air	0	kg	B: assumption, no leakage from stored digested manure in manure bag
N_2O	10024-97-2	air	0.04	kg	C,T: Clemens et al. (2006) reports emissions of 0.05 kg/m^3, Amon et al (2006) reports emissions of 0.03 kg/m^3

Process	**Application of digested manure on land, cattle manure, biogas option** Source: own assumptions, Amon et al., 2006 Data reported in literature are ambiguous, see also appendix I.7.				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
digested manure stored (cattle)		waste from cattle husbandry	1000	kg	density: 1000kg/m^3
Economic outflow					
digested manure applied on land		waste from cattle husbandry	1000	kg	Injection
Environmental inflow					
Environmental outflow					
N_2O	10024-97-2	air	0.0027	kg	C, T, B: Amon et al., 2006 Very much depends on soil type, crop type, application type
CH_4	74-82-8	air	0	kg	B: assumption: all easily digestible organic matter is 100% digested so no CH_4 emissions after application
CH_4	74-82-8	air	0.002	kg	C,T: Amon et al., 2006
CO_2 (biogenic)	124-38-9 (Biogenic)	air	0	kg	B (co digestion grass): assumption: all easily digestible organic matter is 100% digested so no CO_2 emissions after application
CO_2 (biogenic)	124-38-9 (Biogenic)	air	37	kg	T (co digestion grass): assumption: only part of the all easily digestible organic matter is digested so the remaining is emitted as CO_2 after application, see appendix I.4

CO_2 (biogenic)	124-38-9 (Biogenic)	air	8	kg	B (co digestion maize): assumption: all easily digestible organic matter is 100% digested so no CO_2 emissions after application
CO_2 (biogenic)	124-38-9 (Biogenic)	air	27	kg	T (co digestion maize): assumption: only part of the all easily digestible organic matter is digested so the remaining is emitted as CO_2 after application, see appendix I.4
CO_2 (biogenic)	124-38-9 (Biogenic)	air	48	kg	C: assumption: only part of the all easily digestible organic matter is digested so the remaining is emitted as CO_2 after application, see appendix I.4

- definition in CMLCA: stored manure (w) en applied manure (w);

[D] Biofuel transport

N/A

[E] End use

transformation and transport losses of electricity from producer to consumer

Average transformation and transport losses for the referenced electricity production are 4% (SenterNovem 2006). As a default, also for bio-electricity options this 4% loss is assumed for transformation and transport. However, losses due to transformation and transport will dependent on the type of produced electricity (high, medium or low voltage), the transportation distance and the type of consumed electricity (high, medium or low voltage). For this reason a different loss can be defined in the process named "transformation and transport to consumer of electricity, from (….)" that is available for each bio-electricity chain.

I.2-3 Description of the unit processes for centralized digestion of biomass (food remains from restaurant “swill”) to biogas and combustion in CHP

Only a Typical (T) version is implemented

[A] Feedstock production

Not applicable

[B] Feedstock transport

Process	**Transport of “swill” from restaurants to centralized digester (bio-electricity option)(Typical)** Source: BEWA, Moerdijk				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Transport by 28t truck			100	tkm	Distance 100 km
Swill at restaurants		waste	1000	kg	
Economic outflow					
Transported swill at digester		waste	1000	kg	
Environmental inflow					
Environmental outflow					

[C] Conversion

Process	**Storage of swill (bio-electricity option)(Typical)**				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Transported swill at digester		waste	1000	kg	
Economic outflow					
Stored swill at digester		waste	1000	kg	
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	air	3.1	kg	T: Zwart et al., (2006) Assumption: same emissions as for silage
N_2O	10024-97-2	air	0.014	kg	T: Zwart et al., (2006) Assumption: same emissions as for silage

Process	**Biogas production from swill,** **scale (2x 1900m^3), Temperature range 35-40 degrees Celsius,** **(bio-electricity option)(Typical)** Source: BEWA, Moerdijk				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Stored swill at digester			1000	kg	
heat		energy		kW	internal supply from CHP
Economic outflow					
digested swill		waste	907	kg	calculated based on manure minus biogas
Biogas (from swill)		biofuel	175	m^3	55% methane, methane: 0.71 kg/m^3 45% carbondioxide, CO_2: 1.98 kg/m^3
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	air	1.8	kg	leakage from biogas motor assumption: same relative emissions as in manure options

Process	**Electricity production from combustion of biogas from swill in CHP (< 10 MWe, 42% electric efficiency, 30% thermic efficiency) (Typical)** Source: (after Tilburg, van et al, 2006), see appendix I.5				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Biogas (from swill)		biofuel	1	m^3	18.7 MJ/m^3 (55% CH_4)
Economic outflow					
electricity		electricity	2.18[1]	kWh	42% electric efficiency
heat		heat	5.61[1]	MJ	30% thermic efficiency
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	air	-		assumption: fuels are completely incinerated (no CH_4 formation)
N_2O	10024-97-2	air	-		assumption: fuels are completely incinerated (no N_2O formation)
CO_2, biogenic	124-38-9 (Biogenic)	air	1.96	kg	own calculations, see appendix I.5

Note 1: The presented production data refer to Gross production. Below a simple energy balance is given to calculate the net production

Energy balance				
175.00	m3 biogas per tonne swill		CH4 content	55%
production energy per tonne swill				
electricity	1374.45	MJ		
heat	981.75	MJ		
internal use per tonne swill				
electricity	60.00	MJ	(SenterNovem, forthcoming)	
heat	110.00	MJ	(SenterNovem, forthcoming)	
external supply per tonne swill				
electricity	1314.45	MJ		
heat	871.75	MJ		
external supply per m3 biogas				
electricity	7.51	MJ	2.09	kWh
heat	4.98	MJ		

Process	**Storage of digested restaurant waste, biogas option** Assumption: Same data as for manure are used Source: Kool, Hilhorst & van der Vegte, 2005				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
digested swill		waste	1000	kg	
Economic outflow					
digested swill stored		waste	1000	kg	
Environmental inflow					
Environmental outflow					
CH_4	74-82-8	air	0	kg	B: assumption, no leakage from stored digested manure in manure bag
CH_4	74-82-8	air	1	kg	C,T: Clemens et al. (2006) reports emissions of 0.6 kg/m^3, Amon et al. (2006) reports emissions of 1.3 kg/m^3
N_2O	10024-97-2	air	0	kg	B: assumption, no leakage from stored digested manure in manure bag
N_2O	10024-97-2	air	0.04	kg	C,T: Clemens et al. (2006) reports emissions of 0.05 kg/m^3, Amon et al (2006) reports emissions of 0.03 kg/m^3

Process	**Transport of “digested swill” from centralized digester to Germany (bio-electricity option)(Typical)** Source: BEWA, Moerdijk				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
Transport by 28t truck			100	tkm	distance 100 km
Stored digested swill		waste	1000	kg	
Economic outflow					
Transported digested swill		waste	1000	kg	
Environmental inflow					
Environmental outflow					

Process	**Application of digested restaurant waste on land,** Assumption: same data as for manure are used Source: own assumptions, Amon et al., 2006 Data reported in literature are ambiguous, see also appendix I.7.				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**remarks**
Economic inflow					
digested manure stored (cattle)		waste from cattle husbandry	1000	kg	density: 1000kg/m^3
manure injection			…..		See ecoinvent
Economic outflow					
digested manure applied on land		waste from cattle husbandry	1000	kg	Injection
Environmental inflow					
Environmental outflow					
N_2O	10024-97-2	air	0.0027	kg	C, T, B: Amon et al., 2006 Very much depends on soil type, crop type, application type
CH_4	74-82-8	air	0	kg	B: assumption: all easily digestible organic matter is 100% digested so no CH_4 emissions after application
CH_4	74-82-8	air	0.002	kg	C,T: Amon et al., 2006
CO_2 (biogenic)	124-38-9 (Biogenic)	air	0	kg	B (co digestion grass): assumption: all easily digestible organic matter is 100% digested so no CO_2 emissions after application
CO_2 (biogenic)	124-38-9 (Biogenic)	air	37	kg	T (co digestion grass): assumption: only part of the all easily digestible organic matter is digested so the remaining is emitted as CO_2 after

					application, see appendix I.4
CO_2 (biogenic)	124-38-9 (Biogenic)	air	8	kg	B (co digestion maize): assumption: all easily digestible organic matter is 100% digested so no CO_2 emissions after application
CO_2 (biogenic)	124-38-9 (Biogenic)	air	27	kg	T (co digestion maize): assumption: only part of the all easily digestible organic matter is digested so the remaining is emitted as CO_2 after application, see appendix I.4
CO_2 (biogenic)	124-38-9 (Biogenic)	air	48	kg	C: assumption: only part of the all easily digestible organic matter is digested so the remaining is emitted as CO_2 after application, see appendix I.4

- definition in CMLCA: stored swill (w) en applied swill (w);

[D] Biofuel transport

Not applicable

[E] End use

transformation and transport losses of electricity from producer to consumer

Average transformation and transport losses for the referenced electricity production are 4% (SenterNovem 2006). As a default, also for bio-electricity options this 4% loss is assumed for transformation and transport. However, losses due to transformation and transport will dependent on the type of produced electricity (high, medium or low voltage), the transportation distance and the type of consumed electricity (high, medium or low voltage). For this reason a different loss can be defined in the process named “transformation and transport to consumer of electricity, from (….)” that is available for each bio-electricity chain.

I.3 biogas production yields in literature

Biogas production of several substrates (manure and crops)

	dry weight %			organic matter %			biogas m3 / ton substrate	biogas m3 / ton organic matter			CH4 %
	range		average	range		average	average	average	range		
cattle manure	8	13	11	6	9	8	22.50	300	200	400	60
pigs manure	6	9	8	5	6	6	19.25	350	200	500	60
maize	25	35	30	20	30	25	143.75	575	400	650	55
rye (silage)	33	45	39	30	40	35	157.50	450	300	600	55
barley (silage)	30	35	33	25	33	29	182.70	630	230	1100	60

source: Zwart et al., 2006

an extensive overview of sources reporting biogas production of materials is given in the appendix 3 of the report of Zwart et al., 2006

pig manure			8			5	18	0.35
sugar beet leaves			12			8	85	0.69
potato leaves			15			12	109	0.69
maize			32			26	222	0.69
verge grass							192	0.60

source: Tijmensen et al., 2002

an extensive overview of sources reporting biogas production of materials is given in the appendix 2 of the report of Tijmensen et al., 2002

see also: Feedstocks for anaerobic Digestion (Steffen et al., 1998)

mixtures	manure	co-fermentate	manure	co-fermentate	biogas production	
	fresh weight		dry weight			
	ton/yr	ton/yr	ton/yr	ton/yr	m3/yr	m3/ton mixture
pig manure	21400		1600		343800	16
sugar beet leaves	21400	9200	1600	1600	738400	24
potato leaves	21400	8000	1600	1600	830600	28
maize	21400	4300	1600	1600	843600	33
verge grass	21400	4000	1600	1600	716500	28

source: Tijmensen et al., 2002

	% CH4	m3 CH4/kg o.m.	m3 biogas/ kg o.m.	m3 CH4/m3 manure	m3 biogas/ m3 manure	m3 biogas/kg d.w.
cattle						
average	62.00	0.17	0.30	13.20	20.50	0.16
minimum	50.00	0.02	0.14	7.00	12.00	0.11
maximum	73.00	0.45	0.85	28.00	43.00	0.21
standard deviation	6.60	0.07	0.13	7.30	9.00	0.07
pigs						
average	68.00	0.29	0.46	15.10	15.40	0.32
minimum	64.00	0.13	0.18	6.60	10.10	0.28
maximum	80.00	0.66	0.93	21.50	20.00	0.37
standard deviation	4.60	0.15	0.20	5.40	5.00	0.05

source: Lent, van & van Dooren, 2001

I.4 calculation of CO_2 emissions after application of manure, based on C-balance

assumption:

all easily digestable organic matter will be digested either in a digester or in the stable, storage or on the land after application of the manure

assumption for digestion route:

In the best practice case (biogas production: 47m3/m3 substrate) digestion of easily digestible organic matter in digester is 100%:

produced as biogas	21.0231	kg CH4/ 1000 kg manure	15.767325	kg C/ 1000 kg manure
	34.4322	kg CO2/ 1000 kg manure	9.3906	kg C/ 1000 kg manure
emitted	0.31	kg CH4/ 1000 kg manure	0.2325	kg C/ 1000 kg manure
total			25.390425	kg C/ 1000 kg manure

there are no emissions of CH4 and CO2 in stable, storage and after application of digested manure

assumption for conventional route:

emission stable	0.2	kg CH4/ 1000 kg manure	0.15	kg C/ 1000 kg manure
emission storage	3.08	kg CH4/ 1000 kg manure	2.31	kg C/ 1000 kg manure
emission application	0.0013	kg CH4/ 1000 kg manure	0.000975	kg C/ 1000 kg manure
total			2.460975	kg C/ 1000 kg manure

carbon available in easily digestible organic matter is	25.390425	kg C/ 1000 kg manure
minus	2.460975	kg C/ 1000 kg manure
	22.92945	kg C/ 1000 kg manure

The remaining easily digestible organic matter will lead to a CH4 and/or CO2 emission after application on the land.
The ratio anaerobic and aerobic digestion is unknown, if all is assumed to be emitted as CO2 the amount will be

84.07465 kg CO2/ 1000 kg manure

47	m3 biogas/1000 kg substrate	Manure and grass, best practice case
63	% methane	
37	% carbondioxide	
0.71	kg/m3 for methane	
1.98	kg/m3 for carbondioxide	

In the typical and conservative case only part of the easily digestable organic matter is digested into CH4.
It is assumed that the remaining carbon is emitted as CO2 after application of the digested manure on the land.

I.5 emissions of biogas combustion in CHP

emissions based on Ecoinvent data on combustion of natural gas (see below), corrected for heating value natural gas versus biogas

natural gas			***biogas***			
heating value	31.65	MJ/m3	22	MJ/m3		
combustion	1	MJ natural gas	1	MJ biogas	1	m3 biogas
emission	0.056	kg CO2	0.080563636	kg CO2	1.7724	kg CO2
	0.000005	kg N2O	7.19318E-06	kg N2O	7.19E-06	kg N2O
	0.00008	kg CH4	0.000115091	kg CH4	9.27E-06	kg CH4

emissions based on methane and carbondioxide content of biogas

1	m3 biogas			
63	% CH4 in biogas			
37	% CO2 in biogas			
0.71	kg/m3 methane			
1.98	kg/m3 carbon dioxide			
0.7326	kg carbondioxide			
0.4473	kg methane		mol weight	12+4
combustion methane		1 CH4 : 1 CO2		
0.335475	kg C			
1.230075	kg carbondioxide	from methane	mol weight	12+32
kg CO2 total	1.962675			

emissions based on methane and carbondioxide content of natural gas

31.65	MJ/m3	natural gas	1 MJ		
81	% CH4		0.031596	m3	natural gas
3.6	% hydrocarbons		0.018171	kg methane	
0.4	% H2S		0.009384	kg CO2	
	% N2		0.013628	kg C	
15	% CO2	own assumption	0.049969	kg CO2	from methane
0.833	kg/m3 natural gas		0.059353	kg CO2 total	
			1.878525	kg CO2/m3 natural gas	

biogas	65	%	CH4	Tijmensen et al., 2002
	35	%	CO2	

Biogas	composition	
CH4	55.00	%
CO2	45.00	%

ENERGY BALANCE - Combined Heat Power (Gross production)

Fuel	Quantity		Energie content		Input		Elektrisch rendement	Thermisch rendement	Electrical Output		Heat Output	
biogas	1	m3	18.7	MJ/m3	2.E+01	MJ	42.0%	30.0%	7.854	MJ	5.61	MJ
								equals	2.1816667	kWh		

ENERGY BALANCE - Combined Heat Power and digester (nett production)

	Electrical Output		Heat Output	
	7.51	MJ	4.98	MJ
equals	2.09	kWh		

CARBON BALANCE - Combined Heat and Power

Fuel	Quantity		Carbon content	Carbon		Carbon dioxide	
biogas	1	m3		5.35E-01	kg	1.96E+00	kg

Basic data

substance	density kg/m3	energy content MJ/m3	carbon content kg/kg
CH4	0.71	34	0.75
CO2	1.98		0.27

calculation energy demand digester and net energy production CHP

biogas production per ton organic waste

175.00	m3 biogas	CH4 content	55.00	%

gross energy production per tonne organic waste

electricity	1374.45	MJ
heat	981.75	MJ

internal energy consumption per tonne organic waste

electricity	60.00	MJ	(SenterNovem, forthcoming)
heat	110.00	MJ	(SenterNovem, forthcoming)

nett energy production per tonne organic waste

electricity	1314.45	MJ
heat	871.75	MJ

nett energy production per m3 biogas

electricity	7.51	MJ	equals	2.09	kWh
heat	4.98	MJ			

I.6 Calculation of manure per kWh electricity

Manure + grass based on data for "De Marke" (kool et al., 2006)

Digester							***Best practice***
In	1000	kg	manure	17.15854	kg	manure	
Out	47	m3	biogas	0.806452		biogas	
CHP							
In	1	m3	biogas	0.806452	m3	biogas	
Out	1.24	kWh	electricity	1	kWh	electricity	
	xxx	kW	heat	xxx	kW	heat	internal use for digester

Manure + maize based on data for "De Marke" (kool et al., 2006)

Digester							***Best practice***
In	1000	kg	manure	18.75469	kg	manure	
Out	43	m3	biogas	0.806452		biogas	
CHP							
In	1	m3	biogas	0.806452	m3	biogas	
Out	1.24	kWh	electricity	1	kWh	electricity	
	xxx	kW	heat	xxx	kW	heat	internal use for digester

Manure + grass adjusted data for "De Marke" (kool et al., 2006), based on (more average) data from other literature sources

Digester							***Typical***
In	1000	kg	manure	28.80184	kg	manure	
Out	28	m3	biogas	0.806452		biogas	
CHP							
In	1	m3	biogas	0.806452	m3	biogas	
Out	1.24	kWh	electricity	1	kWh	electricity	
	xxx	kW	heat	xxx	kW	heat	internal use for digester

Manure + maize adjusted data for "De Marke" (kool et al., 2006), based on (more average) data from other literature sources

Digester							***Typical***
In	1000	kg	manure	24.43793	kg	manure	
Out	33	m3	biogas	0.806452		biogas	
CHP							
In	1	m3	biogas	0.806452	m3	biogas	
Out	1.24	kWh	electricity	1	kWh	electricity	
	xxx	kW	heat	xxx	kW	heat	internal use for digester

Manure only adjusted data for "De Marke" (kool et al., 2006), based on (more average) data from other literature sources

Digester							***Conservative***
In	1000	kg	manure	35.84229	kg	manure	
Out	22.5	m3	biogas	0.806452		biogas	
CHP							
In	1	m3	biogas	0.806452	m3	biogas	
Out	1.24	kWh	electricity	1	kWh	electricity	
	xxx	kW	heat	xxx	kW	heat	internal use for digester

Manure only based on data for "De Marke" (kool et al., 2006)

Digester							
In	1000	kg	manure	26.88172	kg	manure	
Out	30	m3	biogas	0.806452		biogas	
CHP							
In	1	m3	biogas	0.806452	m3	biogas	
Out	1.24	kWh	electricity	1	kWh	electricity	
	xxx	kW	heat	xxx	kW	heat	internal use for digester

I.7

reduction factors for emissions, application of digested manure versus non digested manure

	manure type	**soil type**	**application type**	**factor**	**source**
methane (CH4)					
application	cattle		unspecified	0,60	Clemens et al., 2006
application	cattle		unspecified	1,54	Amon et al., 2006
application	cattle	pasture	sleepstang techniek	0,4	Wulf et al., 2002 in Bosker T. & A. Kool, 2004
application	cattle	arable land	sleepstang techniek	0,5	Wulf et al., 2002 in Bosker T. & A. Kool, 2004
dinitrogen oxide (N2O)					
application	cattle		unspecified	1,05	Clemens et al., 2006
application	cattle		unspecified	0,71	Amon et al., 2006
application	cattle	pasture	sleepstang techniek	1,9	Wulf et al., 2002 in Bosker T. & A. Kool, 2004
application	cattle	arable land	sleepstang techniek	0,9	Wulf et al., 2002 in Bosker T. & A. Kool, 2004
application	cattle	laboratory	bovengronds	0,2	Clemens & Huschka, 2001 in Bosker T. & A. Kool, 2004
application	pigs	sand	unspecified	0,7	Velthof et al., 2002 in Bosker T. & A. Kool, 2004
application	pigs	clay	unspecified	0,8	Velthof et al., 2002 in Bosker T. & A. Kool, 2004

I.8 GHG emissions from production of grass and maize based on Ecoinvent data

Process = [P271] grass intensive IP, at farm[CH]

Description = Refers to 1 kg dry matter of grass from intensive integrated production. The net dry matter yield is 13095 kg/ha.

Author = ecoinvent

Date = 2005-06-28T08:56:52

Economic inflows

Label	Name	Value	Unit	Uncertainty	Meta-information

Economic outflows

Label	Name	Value	Unit	Uncertainty	Meta-information
[G149]	hay intensive IP, at farm[CH]	1	kg	-	

Environmental resources

Label	Name	Value	Unit	Uncertainty	Meta-information
[E5]	Carbon dioxide (biogenic)[air__]	1.65	kg	-	

Environmental emissions

Label	Name	Value	Unit	Uncertainty	Meta-information
[E1]	Carbon dioxide[air]	0.0827	kg	-	
[E2]	Dinitrogen monoxide[air]	0.000404	kg	-	
[E4]	Methane[air]	0.000147	kg	-	

Process = [P272] silage maize IP, at farm[CH]

Description = Inventory refers to the production of 1 kg silage maize IP, at farm with a moisture content of 72 %. Fresh matter yield at 72 % moisture: 61536 kg/ha.
Author = ecoinvent

Date = 2005-06-28T08:54:09

Economic inflows

Label	Name	Value	Unit	Uncertainty	Meta-information

Economic outflows

Label	Name	Value	Unit	Uncertainty	Meta-information
[G150]	silage maize IP, at farm[CH]	1	kg	-	

Environmental resources

Label	Name	Value	Unit	Uncertainty	Meta-information
[E5]	Carbon dioxide (biogenic)[air__]	0.482	kg	-	

Environmental emissions

Label	Name	Value	Unit	Uncertainty	Meta-information
[E1]	Carbon dioxide[air]	0.0199	kg	-	
[E2]	Dinitrogen monoxide[air]	0.000129	kg	-	
[E4]	Methane[air]	3.59E-05	kg	-	

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Appendix J Electricity and heat from biogas by digestion of manure and biomass (large scale, incl. green gas production)

J.1 System description

In this appendix mainly two systems are described:

a) Co-production of electricity and heat by combustion of biogas[17] in a CHP
b) Production of heat by combustion of green gas[18] in an industrial furnace

Both described systems are representative for large scale, centralized (co-)digestion of manure and biomass.

In figure 1 a flowchart is presented that summarizes the different processes of the system for the production of electricity and heat from combustion of biogas in a CHP (efficiency 70%). It is assumed that both excess electricity and heat are profitable used. An indication is given where emissions of green house gasses (GHGs) might occur.

The system for heat from green gas for a large part resembles the previous system. However, the biogas primary is used to be upgraded to green gas that can be a substitute for natural gas. It is assumed that all electricity and heat that is necessary for digestion and upgrading of the biogas to green gas are supplied by a CHP that runs on biogas (see figure 2). The green gas is combusted in a furnace (efficiency 90%) to produce heat.

Functional unit
For bioelectricity the functional unit is 1 kWh of electricity at the consumer.
For heat the functional unit is 1 MJ of heat at the consumer.

System boundaries and cut off
If the substrate for digestion is a waste, i.e. outputs with no positive economic value that must be disposed of, the system is cut off at the production of the waste. This means that up-chain processes are not taken into account. For example manure, VFG (GFT) and restaurant waste are considered to be wastes, so emissions of GHG from livestock husbandry, agricultural production and food industry are not considered to be part of the production of electricity and heat from biomass.

The system is also cut off after the application of the (digested) manure. It is assumed that the alternative systems are not different for the delivered function of soil fertilization and improvement. At the moment there is insufficient scientific evidence that digested manure will lead to higher mineral nitrogen availability for the crops (Kool et al., 2005) and therefore may

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[17] Biogas: gas produced by digestion of biomass (e.g. manure, crops etc), typical composition: methane (55%-65%) and carbondioxide (45%-35%)

[18] Green gas: general term for processed biogas, SNG and gas from landfill, produced as a substitute for natural gas; reference composition as substitute for natural gas: methane (88%) and carbondioxide (12%)

lead to a higher yield or reduced fertilizer consumption. Future investigations may prove differently.

Allocation: energy allocation

In the systems there are processes that deliver more than one function[19]. For example, in the case a waste is digested in an anaerobic digester the process delivers the function of 1) waste treatment and 2) production of biogas[20]. Another multifunctional process is the combustion of biogas in a CHP that delivers both 1) (excess) electricity and 2) (excess) heat. The allocation factor is based on the energy content of the produced materials or energy. The energy content is based on the Lower Heating Value (LHV). An overview of LHVs of materials as used in this project is given in appendix N. The LHV used for energy allocation are presented in table 1. The actual allocation factors are based on the LHV of the material and the amount of produced material.

Table 1 LHV, amounts and allocation factors for biomass digestion and CHP.

	LHV MJ/kg	**Amount[1] kg**	**Allocation factor[1]**
Digestion of biomass waste, manure			
Manure	5.09	1000	0.91
Biogas (CH4: 65%)	23.45 MJ/m3	22.5 m3	0.09
Digestion of biomass waste, VFG			
VFG	5.89	1000	0.77
Biogas (CH4: 55%)	19.84 MJ/m3	90 m3	0.23
Digestion of biomass waste, potato remains			
Potato remains	12.8	1000	0.83
Biogas (CH4: 55%)	19.84 MJ/m3	111 m3	0.17
CHP			
electricity	3.6 MJ/kWh	2.36 kWh	0.58
heat	1 MJ/MJ	6.06 MJ	0.42

[1] the amount and allocation factor are given as an example. Figures are different for different conservative, typical and best practice options.

conservative, typical and best practice systems

In this project a distinction is made between conservative, typical and best practice systems. A system is defined as a chain of linked processes. The best practice system is defined as the chain of best practice processes. These are the most efficient processes and/or processes with the lowest GHG emission levels, see table 2.

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19 A process may deliver more than one function. A function may be the production or transport of a good or the proper disposal of a waste. In this case the inputs (e.g. goods and resources) and outputs (e.g. waste and emissions) of a process should be allocated to the different functions delivered by the process.

[20] The produced digestate is considered a produced waste, therefore nothing is allocated to the digestate.

Table 2 Definition of conservative, typical and best practice systems

	efficiency biogas production	GHG emission levels from storage, digestion and CHP	Efficiency CHP % electricity, % heat	Profitable use of excess heat from CHP	CH4 emission % of produced green gas
conservative	low	average	42,30	No	3%
typical	average	average	42,40	Yes	1%
best practice	high	zero, low	42,40	Yes	0.5%

For a detailed description of the conservative, typical and best practice processes is referred to appendix J.2.

J.1-1 System description "electricity and heat by combustion in a CHP of biogas from manure and biomass (large scale/centralized)"

The described system refers to a large scale centralized production system of electricity and heat based on different feedstocks (substrate to be digested). This means that the processes for feedstock production, conversion and end use are situated on different sites and therefore transport of substrate, digested substrate and energy is taken into account. The feedstock for digestion can either be manure, energy crops or green waste (VFG) or a mixture of substrates. The energy consumed by the system, e.g. electricity for chopping and mixing and heating of the digester are supplied internal by the CHP in the system. However, there is a net production of electricity and heat by the CHP that can be delivered to the consumer (end use).

Below a description is given of the process system according to the flowchart presented in figure 1 divided in the phases:

[A] feedstock production
[B] feedstock transport
[C] conversion
[D] (biofuel) transport
[E] end use

J.1-1[A] feedstock production

In this project the GHG emissions of the system are calculated for four different feedstocks:

1) Manure: cattle manure
2) Green waste:
   a) VFG (GFT) and
   b) potato residues
3) Energy crops: maize

Manure and green waste are considered wastes. Therefore the up chain processes are cut off, which means that GHG emissions in these up chain processes are not taken into account.

However, in case the substrate that is digested is an (energy) crop the emissions related to the production of the biomass (e.g. maize, potato, grass etc.) should be taken into account. In these cases the emissions during the production of the substrate are based on the Ecoinvent system and process descriptions (Ecoinvent Centre, 2006, see appendix O).

J.1-1[B] feedstock transport

In the case of a centralized digester it is assumed that the substrate for digestion will be supplied from different locations all over the Netherlands. Therefore a transport distance of 100 km is assumed, using 28t trucks.

J.1-1[C] conversion

The conversion from feedstock to energy (fuel) is divided in several processes:
1) storage of substrate in a silo
2) digestion of the substrate
3) storage of the digested substrate (digestate)
4) application of the digestate on the land, including transport to Germany
5) production of electricity and heat in a CHP

Storage of substrate

In Zwart et al., 2006 it is assumed that (co-)substrate may be stored on the site. Because this substrate may be stored over a long period of time emissions may occur from the storage of this fermenting biomass. Emissions during storage of substrate are taken from Zwart et al., 2006, see table 3. The original emissions are representative for storage of pig manure. It is assumed that these emission factors are also applicable for all other substrates.

Table 3 Emissions from storage of substrate (kg substance / ton substrate)

methane	3.1
dinitrogen oxide	0.014

Digestion

In this project the biogas production by digestion of biomass is calculated for four different feedstocks:
1) Manure: cattle manure
2) Green waste:
   a) VFG
   b) potato residues
3) Energy crops: maize

The substrate is assumed to be digested in anaerobic mesophilic conditions (temperatures about 30-40 ° Celsius) for about 2 to 3 months. The Conservative, Typical and Best practice values for the production of biogas (CH4 content 55%-60%) are based on minimum, average and maximum values that are given for each of the feedstocks in literature (Steffen et al., 1998; Tijmensen et al., 2002; Zwart et al., 2006; SenterNovem, 2008), see table 8. An overview of literature data on biogas production of other feedstocks may be found in the appendix P. These figures can be used as a first estimate to define a digestion process for an alternative feedstock in the CO2 calculator.

The biogas production is calculated for the separate digestion of a feedstock. However, in practice often co-digestion of combinations of substrates is applied. It is assumed that to calculate biogas production of co-digestion of substrates one might assume a linear relationship between the amount of biogas production and amount of digested substrates (see for example Zwart et al., 2008). In other words the biogas production of the digestion of a combination of substrates is the sum of the biogas production of the digestion of the separate substrates. In the spreadsheet "supporting calculations for E-LCA" the biogas production can be estimated given a user specified mixture of substrates. Data for a number of feedstocks can be found in Appendix P.

This assumption is a simplification of reality. For example if the materials are very different in composition of readily degradable matter this linear relationship might not hold. However, if the retention time of the material in the digester is large one might assume that the potential biogas production may be reached. In these cases the assumption of a linear relationship might be acceptable (comment. Kor Zwart, Alterra).

The digester is assumed to be representative for a large scale system. Table 4 gives the energy consumption of a digester for two different scale levels (Zwart et al., 2006).

Table 4 Energy use of a digester
(MJ / ton substrate)

	heat	electricity
farm scale	250	33
large scale	110	60

During digestion part of the produced biogas will be emitted. This emission is assumed to be 1% of the produced biogas (CH4 content 55%-60%).

The digested substrate that is produced is considered a waste.

Storage of the digested substrate
Emissions of methane and dinitrogen oxide are taken from Clemens et al. (2006) and Amon et al. (2006), see table 5. The original emissions are representative for storage of digested cattle manure. It is assumed that these emission factors are applicable for all types of digested substrates.

Table 5 Emissions from storage of digested substrate
(kg substance / ton digested substrate)

	average	range
methane	1	0.6 – 1.3
dinitrogen oxide	0.04	0.03 – 0.05

application of the digestate on the land, including transport to Germany

In the Netherlands the digestate from organic waste like restaurant waste is not allowed to be applied on the land as a fertilizer. The digestate is exported (to Germany). For this an average transport distance of 100 km is assumed, using 28t trucks.

Note that the digested manure that is applied on the land will lead to emissions of green house gases. Depending on the efficiency of the biogas production in the digester the digested manure may contain more or less readily digestible organic matter. The digestion of this organic matter on the land will lead to dinitrogenoxide, carbon dioxide and/or methane emissions depending on the aerobic conditions of the soil. In literature not much information can be found on emissions after application of the manure and digested manure and often information is ambiguous (Amon et al., 2006, Clemens et al., 2006, Kool et al., 2005, Bosker & Kool, 2004, Kool en de Ruiter, 2004), see also appendix P. Within another project for the development of a CO_2-tool for biofuels a model is developed by CE (SenterNovem, forthcoming). However, this model is not applicable for (co-)digestion of biomass. So, at this moment there is not a broad excepted model approach to solve the problem of emissions after application of manure or digestate. As stated in Van der Hoek & Schijndel (2006); “In the case that biogas production from animal manure increases in the Netherlands in the near future, the method for calculating methane emissions from manure management has to be extended to include effects of biogas production. Focus should also be placed on N_2O emissions when digested manure is applied to the soil”. It can be concluded therefore that the reported emissions of methane and dinitrogenoxide after application of manure or digestate are very uncertain. Table 6 shows the GHG emissions from digestate applied on land that are used in this project. Emissions are taken from Amon et al., 2006.

Table 6 Emissions after application of digestate on land (kg substance / 1000 kg digestate)

methane	0.002
dinitrogen oxide	0.0027

production of electricity and heat in a CHP

The CHP is assumed to be representative for a large scale system. Table 7 gives the energy efficiency of a CHP for two different scale levels. In this project for the Conservative option the efficiency of the joint scale plant of 42% electric and 30% heat is used. For the Typical and Best practice option the efficiency of 42% electric and 40% heat is used.

Table 7 Energy efficiency of a CHP (%)

	heat	electricity	source
farm scale plants (100-200 kWe)	52	26	(lca food: www.lcafood.dk)
	35	35	(Zwart et al., 2008)
joint scale plants (500 kWe)	30	42	(Tilburg, van et al, 2006)
	40	42	General Electric[21]
	48	37	(lca food: www.lcafood.dk)
	30	42	(Tilburg, van et al, 2006)

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[21] http://www.ge-energy.com/prod_serv/products/recip_engines/en/cogen_systems/cogen_system.htm

During combustion part of the consumed biogas will be emitted. This emission is assumed to be 1% of the consumed biogas (CH4 content 55%-60%).

For the Typical en Best practice option it is assumed that both electricity and heat are profitable used, that is the process is allocated to electricity and heat. If the heat is not profitable used the heat output is set zero (Conservative option).

J.1-1[D] (biofuel) transport

The biogas is produced and combusted in the CHP on site. Transport is therefore non-existent or very local, and is ignored.

J.1-1[E] end use

The produced heat is used internally in the system to heat up the digester. Also part of the produced electricity is used within the system for mixing and pumping etc. The excess electricity is delivered to the consumer. The functional unit is defined as the supply of 1 kWh electricity at consumer. Also a profitable use of excess heat is assumed. The functional unit is defined as the supply of 1 MJ heat at consumer.

Average transformation and transport losses for the referenced electricity production are 4% (SenterNovem 2006). As a default, also for bio-electricity options this 4% loss is assumed for transformation and transport. However, losses due to transformation and transport will dependent on the type of produced electricity (high, medium or low voltage), the transportation distance and the type of consumed electricity (high, medium or low voltage). For this reason a different loss can be defined in the process named “transformation and transport to consumer of electricity, from (….)” that is available for each bio-electricity chain.

J.1-2 System description “heat by combustion of green gas from upgraded biogas from manure and biomass (large scale/centralized”

J.1-2[A] feedstock production
See J.1-1[A]

J.1-2[B] feedstock transport
See J.1-1[B]

J.1-2[C] conversion
See J.1-1[C]

Green gas production
The system resembles the system described in J.1-1[C]. However, the biogas (CH4 content 55%-60%), is primary used to be upgraded to green gas (CH4 content 88%, as a reference to natural gas). During the process of upgrading not all the biogas will end up in the green gas, depending on the technology of upgrading this “leak” of biogas might be 3% (VPSA and cryogen system) to 20% (membrane system) (Welink et al., 2007). In case the biogas is

produced by digestion this “leak” of biogas can be made profitable. Namely, by combustion of the biogas to heat up the digester. In case of the membrane technology this “leak” of biogas is sufficient. In case of the VPSA and Cryogene technology the “leak” of biogas is not sufficient and additional biogas is used to heat up the digester. The amount of methane necessary to heat up the digester is about 15% of the produced methane (Welink et al., 2007), see also table 3. Furthermore, the digestion and upgrading process also needs electricity. In this project it is assumed that the heat and electricity that is necessary for the digestion and upgrading process is produced by combustion of biogas in a CHP (see table 8). So in the end for all systems the efficiency is more or less the same, about 20% of the produced methane is used internal for production of electricity and heat

Table 8 Energy use of a digester and green gas production

	heat	electricity	
Digester, large scale	110	60	MJ / ton substrate
Green gas production	-	1.1	MJ / m3 green gas (88% CH4)

During green gas production part of the methane will be emitted. For respectively the Conservative, Typical and Best practice option this emission is assumed to be 3, 1 and 0.5% of the produced green gas (CH4 content 88%).

The biogenic carbondioxide that is separated during the upgrading of the biogas to green gas is assumed to be emitted. So no net fixation and/or profitable use of the biogenic carbondioxide is assumed.

J.1-2[D] (biofuel) transport

The green gas is delivered to the low pressure network. No electricity consumption for compression is taken into account because green gas is delivered to low pressure network.

J.1-2[E] end use

The functional unit is defined as the supply of 1 MJ heat at consumer. For the combustion an efficiency is assumed of 90% (0.9 MJ heat from 1 MJ LHV green gas).

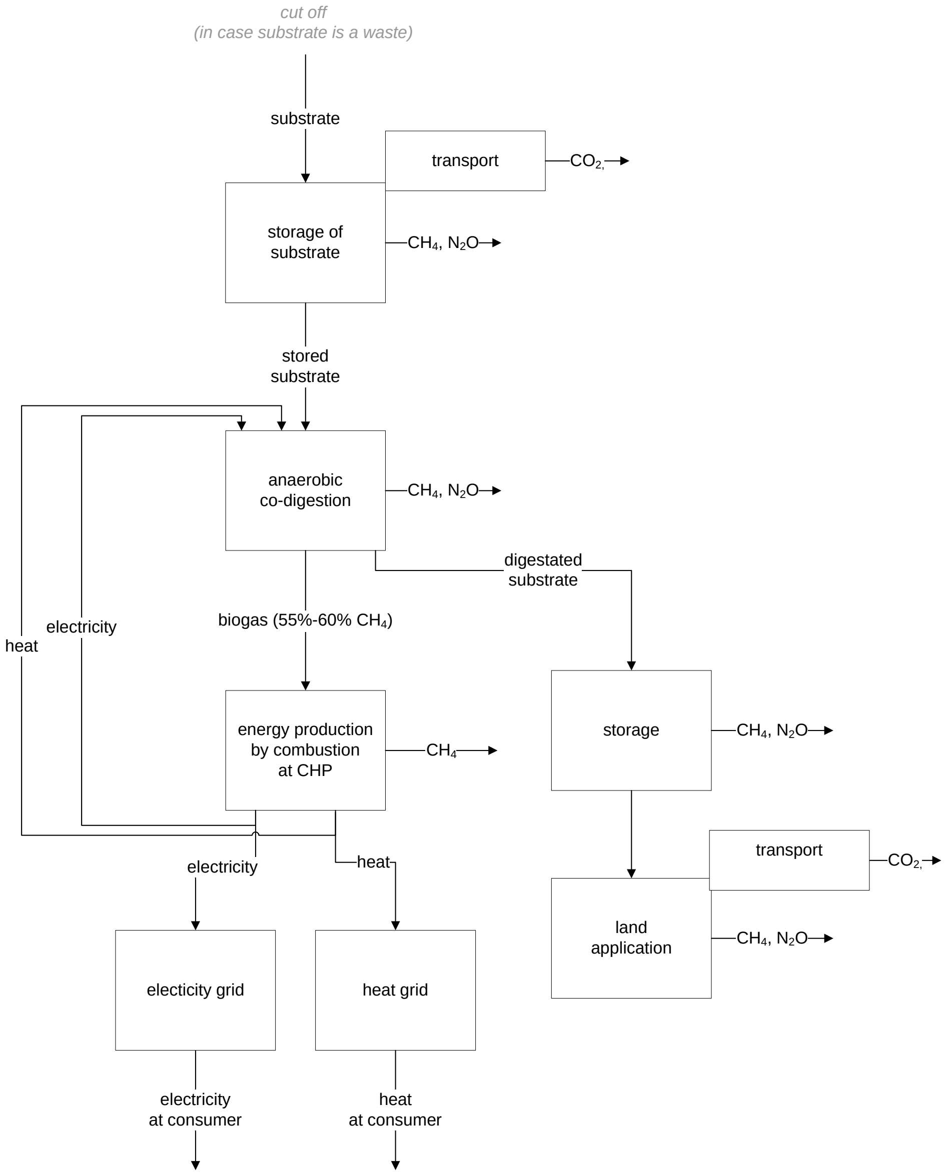

Figure 1 Flowchart of the system for bio-electricity and heat by combustion in CHP of biogas from (co-)digestion of substrate (e.g. (combinations of) manure, energy crops and green waste)

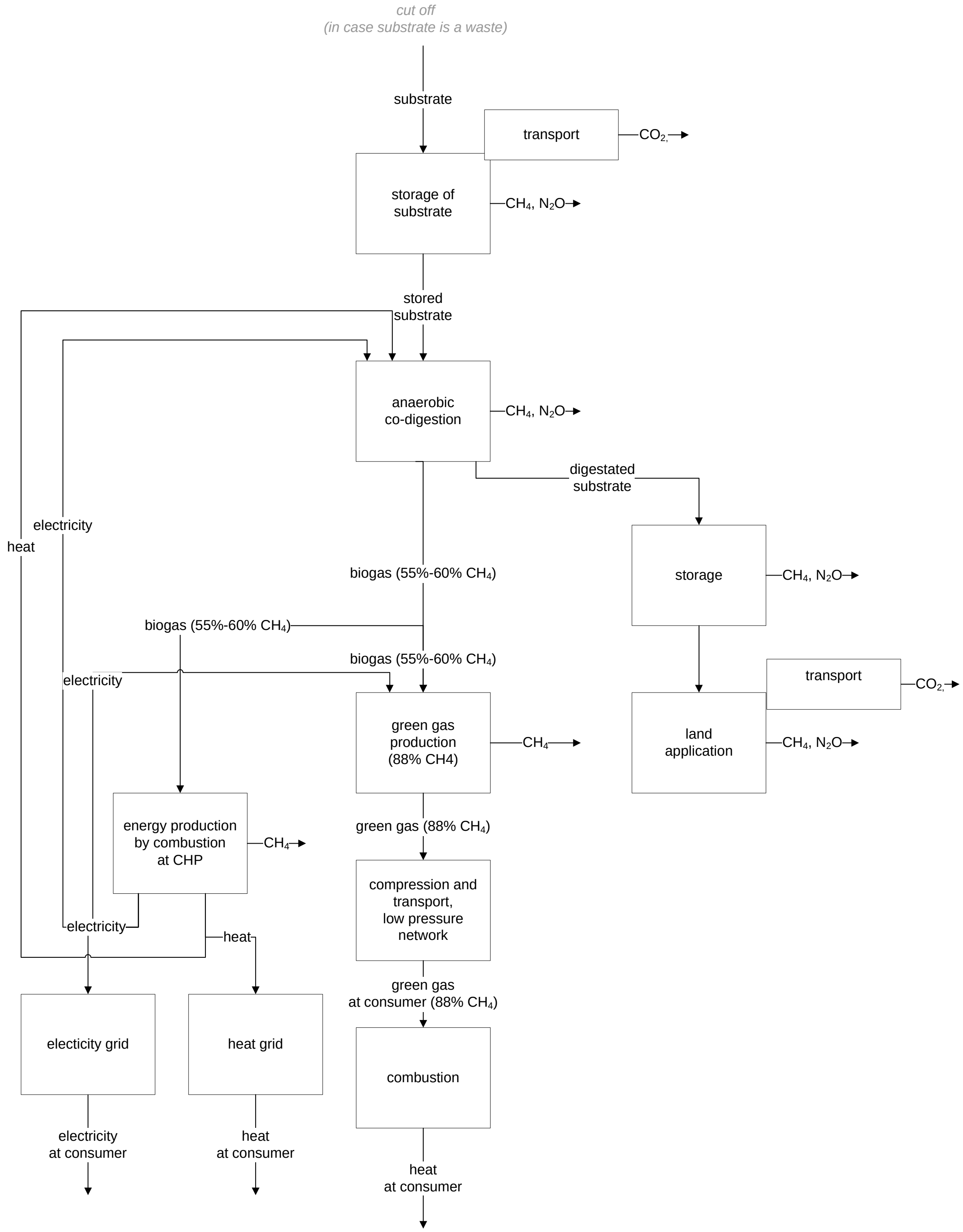

Figure 2 Flowchart of the system for heat from the combustion in an industrial furnace of green gas from upgraded biogas from (co-)digestion of substrate (e.g. (combinations of) manure, energy crops and green waste).

J.2 process description

In this appendix for each of the processes in the systems (see appendix J.1) the economic inputs (consumed energy and materials of a process) and economic outputs (produced energy and materials of a process) are summarized together with the environmental outputs (the emissions of GHGs: CO_2, CH_4 and N_2O).

Table 9 Process data for conservative, typical and best practice processes

feedstock			manure, cattle			maize			GFT			potato remains		
scale CHP and digester			large joint scale			large joint scale			large joint scale			large joint scale		
			C	T	B	C	T	B	C	T	B	C	T	B
stable	CH4 emissions	kg/1000 kg substrate	0.09	0.09	0									
	N2O emissions	kg/1000 kg substrate	0.0002	0.0002	0									
transport of substrate	28t trucks	km/1000 kg substrate	100	100	100	100	100	100	100	100	100	100	100	100
storage co substrate	CH4 emissions	kg/1000 kg substrate	3.1	3.1	0	3.1	3.1	0	3.1	3.1	0	3.1	3.1	0
	N2O emissions	kg/1000 kg substrate	0.014	0.014	0	0.014	0.014	0	0.014	0.014	0	0.014	0.014	0
digester	electricity consumption	MJ/1000 kg substrate	60	60	60	60	60	60	60	60	60	60	60	60
	heat consumption	MJ/1000 kg substrate	Intern. supply	110	110	Intern. supply	110	110	Intern. supply	110	110	Intern. supply	110	110
	biogas production	m3/1000 kg substrate	16	22.5	36	80	143.75	195	30	90	150	55	111	160
	digestate	kg/1000 kg substrate	992	988	982	960	928	903	985	955	925	973	945	920
	CH4 emissions	kg/1000 kg substrate	0.07	0.10	0.15	0.31	0.56	0.76	0.12	0.35	0.59	0.23	0.47	0.68
storage digestate	CH4 emissions	kg/1000 kg substrate	1	1	0.00	1	1	0.00	1	1	0.00	1	1	0.00
	N2O emissions	kg/1000 kg substrate	0.04	0.04	0.00	0.04	0.04	0.00	0.04	0.04	0.00	0.04	0.04	0.00
transport of digestate	28t trucks	km/1000 kg digestate	100	100	100	100	100	100	100	100	100	100	100	100
digestate application	CH4 emissions	kg/1000 kg digestate	0.0027	0.0027	0.0027	0.003	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027
	N2O (biogenic) emissions	kg/1000 kg digestate	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
CHP	CH4 emissions	kg/m3 biogas	0.0043	0.0043	0.0043	0.004	0.0039	0.0039	0.0039	0.0039	0.0039	0.0043	0.0043	0.0043
(efficiency C: 42% electricity, 30% heat)	CO2 (biogenic) emissions	kg/m3 biogas	2.04	2.04	2.04	1.95	1.95	1.95	1.95	1.95	1.95	1.95	1.95	1.95
(efficiency T,B: 42% electricity, 40% heat)	electricity produced	kWh/m3 biogas	2.36	2.36	2.36	2.16	2.16	2.16	2.16	2.16	2.16	2.36	2.36	2.36
	heat produced	MJ/m3 biogas	excess heat not used	8.08	8.08	excess heat not used	7.41	7.41	excess heat not used	7.41	7.41	excess heat not used	8.08	8.08
transformation and transportation losses	electricity consumption	kWh/kWh produced	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04

feedstock			manure, cattle			maize			GFT			potato remains		
scale CHP and digester			large joint scale			large joint scale			large joint scale			large joint scale		
			C	T	B	C	T	B	C	T	B	C	T	B
green gas (CH4 88%) production	biogas consumption (CH4 55%)	m3/m3 green gas	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
	biogas consumption (CH4 60%)	m3/m3 green gas	1.47	1.47	1.47	1.47	1.47	1.47	1.47	1.47	1.47	1.47	1.47	1.47
	electricity consumption	MJ/m3 green gas	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
	CH4 emission	Kg/ m3 green gas	0.019	0.0062	0.0032	0.019	0.0062	0.0032	0.019	0.0062	0.0032	0.019	0.0062	0.0032
green gas combustion (efficiency: 90% heat)	heat produced	MJ/m3 green gas	26.9	26.9	26.9	26.9	26.9	26.9	26.9	26.9	26.9	26.9	26.9	26.9
	methane content biogas	%	60	60	60	55	55	55	55	55	55	60	60	60

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Appendix K Electricity and heat from landfill gas

K.1 System description

In this appendix mainly two systems are described:

a) Co-production of electricity and heat by combustion of landfill gas in a CHP
b) Production of heat by combustion of green gas[22] from landfill gas in an industrial furnace

In figure 1 a flowchart is presented that summarizes the different processes of the system for the production of electricity and heat from combustion of landfill gas in a CHP (efficiency 70%). It is assumed that both excess electricity and heat are profitable used. An indication is given where emissions of green house gasses (GHGs) might occur.

The system for heat from green gas for a large part resembles the previous system. However, the landfill gas primary is used to be upgraded to green gas that can be a substitute for natural gas. Electricity that is necessary for upgrading of the landfill gas to green gas can be supplied by either a conventional electricity mix (Conservative) or by a CHP that runs on landfill gas (Typical, Best) (see figure 2). The green gas is combusted in a furnace (efficiency 90%) to produce heat.

Functional unit
For bioelectricity the functional unit is 1 kWh of electricity at the consumer.
For heat the functional unit is 1 MJ of heat at the consumer.

System boundaries and cut off
The system is cut off at the production of landfill gas from the landfill site. This means that up-chain processes, like collection of the waste and disposal with emissions from the landfill site are not taken into account in the bio-energy options.

Allocation: energy allocation
In the system the combustion of landfill gas in the CHP delivers more than one function[23]. A CHP delivers both 1) electricity and 2) heat. The allocation factor is based on the energy content of the produced materials or energy. The energy content is based on the Lower Heating Value (LHV). An overview of LHVs of materials as used in this project is given in appendix N. The LHV used for energy allocation are presented in table 1. The actual allocation factors are based on the LHV of the material and the amount of produced material.

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[22] Green gas: general term for processed biogas, SNG and gas from landfill, produced as a substitute for natural gas; reference composition as substitute for natural gas: methane (88%) and carbondioxide (12%)

23 A process may deliver more than one function. A function may be the production or transport of a good or the proper disposal of a waste. In this case the inputs (e.g. goods and resources) and outputs (e.g. waste and emissions) of a process should be allocated to the different functions delivered by the process.

Table 1 LHV, amounts and allocation factors for oil extraction and CHP.

	LHV	**Amount[1]**	**Allocation factor[1]**
CHP			
electricity	3.6 MJ/kWh	2.16 kWh	0.51
heat	1 MJ/MJ	7.41 MJ	0.49

[1] the amount and allocation factor are given as an example. Figures are different for different conservative, typical and best practice options.

conservative, typical and best practice systems

In this project a distinction is made between conservative, typical and best practice systems. A system is defined as a chain of linked processes. The best practice system is defined as the chain of best practice processes. These are the most efficient processes and/or processes with the lowest GHG emission levels, see table 2.

Table 2 Definition of conservative, typical and best practice systems

	Electricity consumption of green gas production	Use of landfill gas	CH4 emission % of produced green gas
conservative	Conventional electricity mix	80%[24] used in green gas, 20% flared	3%
typical	Bio electricity from CHP	80% used in green gas, 20% used in CHP	1%
best practice	Bio electricity from CHP	97% used in green gas, 3% used in CHP	0.5%

For a detailed description of the conservative, typical and best practice processes is referred to appendix K.2.

K.*1-1 System description "electricity and heat by combustion in a CHP of landfill gas"*

K.1-1[A] feedstock production

Not applicable

The feedstock of bio energy from landfill gas is the organic matter in Municipal Solid waste (MSW). In this project the bio energy system is cut off at the production of landfill gas that is produced at the landfill site by anaerobic digestion of organic matter in MSW. This means that up-chain processes, like collection of the waste and disposal with emissions from the landfill site are not taken into account in the bio-energy options. After

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[24] In the calculations the low efficiency will not result in higher GHG intensity because the system is cut off at the production of landfill gas and so emissions of GHG from landfill site are not attributed to the landfill gas.

all, the landfill site is primary a final waste disposal and not a facility to produce bio energy.

K.1-1[B] feedstock transport

Not applicable, see B.1-1[A].

K.1-1[C] conversion

The conversion from feedstock to energy (fuel) is divided in several processes:
1) digestion on the landfill site of the organic matter in Municipal Solid waste
2) production of electricity and heat in a CHP by combustion of landfill gas

Digestion
Not applicable, see B.1-1[A] .

production of electricity and heat in a CHP
The CHP is assumed to be representative for a large scale system. Table 3 gives the energy efficiency of a CHP for two different scale levels. In this project for the Conservative option the efficiency of the joint scale plant of 42% electric and 30% heat is used. For the Typical and Best practice option the efficiency of 42% electric and 40% heat is used.

Table 3 Energy efficiency of a CHP (%)

	heat	electricity	source
farm scale plants (100-200 kWe)	52	26	(lca food: www.lcafood.dk)
	35	35	(Zwart et al., 2008)
joint scale plants (500 kWe)	30	42	(Tilburg, van et al, 2006)
	40	42	General Electric[25]
	48	37	(lca food: www.lcafood.dk)
	30	42	(Tilburg, van et al, 2006)

During combustion part of the consumed landfill gas will be emitted. This emission is assumed to be 1% of the landfill gas (CH4 content 55%).

It is assumed that both electricity and heat are profitable used, that is the process is allocated to electricity and heat. If the heat is not profitable used the heat output should be set zero.

K.1-1[D] (biofuel) transport

The landfill gas is produced and combusted in the CHP on site. Transport is therefore non-existent or very local, and is ignored.

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[25] http://www.ge-energy.com/prod_serv/products/recip_engines/en/cogen_systems/cogen_system.htm

K.1-1[E] end use

The functional unit is defined as the supply of 1 kWh electricity at consumer. Also a profitable use of excess heat is assumed. The functional unit is defined as the supply of 1 MJ heat at consumer.

Average transformation and transport losses for the referenced electricity production are 4% (SenterNovem 2006). As a default, also for bio-electricity options this 4% loss is assumed for transformation and transport. However, losses due to transformation and transport will dependent on the type of produced electricity (high, medium or low voltage), the transportation distance and the type of consumed electricity (high, medium or low voltage). For this reason a different loss can be defined in the process named "transformation and transport to consumer of electricity, from (….)" that is available for each bio-electricity chain.

K.*1-2 System description "heat by combustion of green gas from upgraded landfill gas"*

K.1-2[A] feedstock production
See K.1-1[A]

K.1-2[B] feedstock transport
See K.1-1[B]

K.1-2[C] conversion

Green gas production
The system resembles the system described in B.1-1. However, the landfill gas (CH4 content 55%), is primary used to be upgraded to green gas (CH4 content 88%, as a reference to natural gas).

During the process of upgrading not all the landfill gas will end up in the green gas, depending on the technology of upgrading this "leak" of landfill gas might be 3% (VPSA and cryogen system) to 20% (membrane system) (Welink et al., 2007). In the calculations the low efficiency will not result in higher GHG intensity because the system is cut off at the production of landfill gas and so emissions of GHG from the landfill site are not attributed to the landfill gas.

The upgrading process also needs electricity. For the conservative calculations it is assumed that this electricity is supplied by the conventional electricity mix and so will lead to emissions of fossil CO2. For the Typical and Best practice calculations it is assumed that this electricity is supplied internal by the CHP that runs on landfill gas.

Table 4 Energy use for green gas production (Welink et al., 2007)

	heat	electricity	
Green gas production	-	1.1	MJ / m3 green gas (88% CH4)

During green gas production part of the methane will be emitted. For respectively the Conservative, Typical and Best practice option this emission is assumed to be 3, 1 and 0.5% of the produced green gas (CH4 content 88%).

The biogenic carbondioxide that is separated during the upgrading of the biogas to green gas is assumed to be emitted. So no net fixation and/or profitable use of the biogenic carbondioxide is assumed.

K.1-2[D] (biofuel) transport

The green gas is delivered to the low pressure network. No electricity consumption for compression is taken into account because green gas is delivered to low pressure network.

K.1-2[E] end use

The functional unit is defined as the supply of 1 MJ heat at consumer. For the combustion an efficiency is assumed of 90% (0.9 MJ heat from 1 MJ LHV green gas).

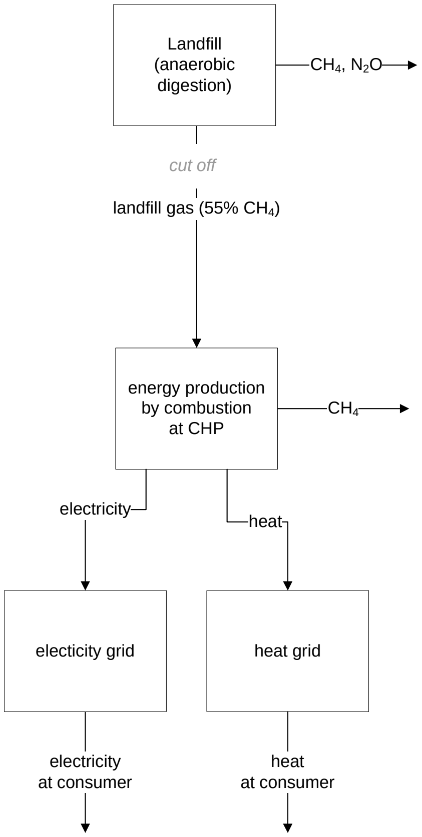

Figure 1 Flowchart of the system for bio-electricity and heat by combustion in CHP of landfill gas.

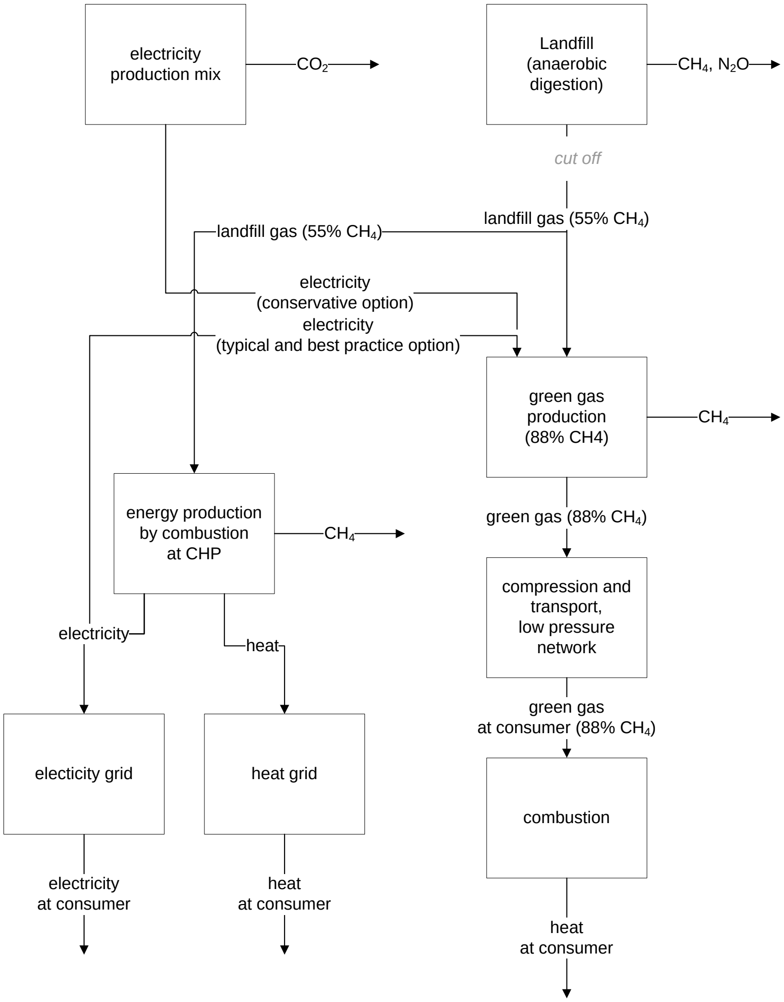

Figure 2 Flowchart of the system for heat from the combustion in an industrial furnace of green gas from upgraded landfill gas.

K.2 process description

In this appendix for each of the processes in the systems (see appendix K.1) the economic inputs (consumed energy and materials of a process) and economic outputs (produced energy and materials of a process) are summarized together with the environmental outputs (the emissions of GHGs: CO_2, CH_4 and N_2O).

Table 5 Process data for conservative, typical and best practice processes

feedstock			landfill waste		
			C	T	B
landfill site	biogas production	m3/1000 kg waste	25	25	25
	CH4 emissions	kg/1000 kg substrate	0.10	0.10	0.00
CHP (efficiency: 42% electricity, 40% heat)	CH4 emissions	kg/m3 biogas		0.0039	0.0039
	electricity produced	kWh/m3 biogas		2.16	2.16
	heat produced	MJ/m3 biogas		7.41	7.41
transformation and transportation losses	electricity consumption	kWh/kWh produced		1.04	1.04
green gas (CH4 88%) production	biogas consumption (CH4 55%)	m3/m3 green gas	1.9	1.6	1.6
	electricity consumption from CHP	MJ/m3 green gas		1.1	1.1
	electricity consumption (fossil)	MJ/m3 green gas	1.1		
	CH4 emission	kg/m3 green gas	0.019	0.0062	0.0032
green gas combustion (efficiency: 90% heat)	heat produced	MJ/m3 green gas	26.9	26.9	26.9
	methane content biogas	%	55	55	55

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Appendix L Heat from green gas based on biogas from sewage sludge digestion

L.1 System description

In this appendix the system is described for the production of heat in an industrial furnace by combustion of green gas[26] from biogas from sewage sludge digestion.

In figure 1 a flowchart is presented that summarizes the different processes of the system. The digested sewage sludge is assumed to be incinerated. It is assumed that all electricity and heat that is necessary for digestion and upgrading of the biogas to green gas are supplied by a CHP that runs on biogas. The green gas is combusted in a furnace (efficiency 90%) to produce heat. An indication is given where emissions of green house gasses (GHGs) might occur.

Functional unit
For heat the functional unit is 1 MJ of heat at the consumer.

System boundaries and cut off
The system is cut off at the production of the thickened sewage sludge (typical dry weight thickened sewage sludge 22%; typical dry weight fresh sewage sludge 5%). This means that up-chain processes, like collection and treatment of the sewage and thickening of the sewage sludge are not taken into account in the bio-energy options.

Allocation: energy allocation
In the systems there are processes that deliver more than one function[27]. The process of anaerobic digestion delivers the function of 1) waste treatment and 2) production of biogas[28]. Another multifunctional process is the combustion of biogas in a CHP that delivers both 1) electricity and 2) heat. The allocation factor is based on the energy content of the produced materials or energy. The energy content is based on the Lower Heating Value (LHV). An overview of LHVs of materials as used in this project is given in appendix N. The LHV used for energy allocation are presented in table 1. The actual allocation factors are based on the LHV of the material and the amount of produced material.

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[26] Green gas: general term for processed biogas, SNG and gas from landfill, produced as a substitute for natural gas; reference composition as substitute for natural gas: methane (88%) and carbondioxide (12%)

27 A process may deliver more than one function. A function may be the production or transport of a good or the proper disposal of a waste. In this case the inputs (e.g. goods and resources) and outputs (e.g. waste and emissions) of a process should be allocated to the different functions delivered by the process.

[28] The produced digestate is considered a produced waste, therefore nothing is allocated to the digestate.

Table 1 LHV, amounts and allocation factors sludge digestion and CHP.

	LHV MJ/kg d.w.	**Amount[1] kg d.w.**	**Allocation factor[1]**
Sewage sludge digestion			
Thickened Sewage sludge (d.w. 22%)	14.0	1	0.7
Biogas (CH4: 60%)	21.64 MJ/m3	0.275 m3	0.3
CHP			
electricity	3.6 MJ/kWh	2.36 kWh	0.51
heat	1 MJ/MJ	8.08 MJ	0.49

[1] the amount and allocation factor are given as an example. Figures are different for different conservative, typical and best practice options.

conservative, typical and best practice systems

In this project a distinction is made between conservative, typical and best practice systems. A system is defined as a chain of linked processes. The best practice system is defined as the chain of best practice processes. These are the most efficient processes and/or processes with the lowest GHG emission levels, see table 2.

Table 2 Definition of conservative, typical and best practice systems

	Biogas production from sludge (m3/1000 kg fresh sludge)	Efficiency CHP % electricity, % heat	Profitable use of excess heat from CHP	CH4 emission % of produced green gas
conservative	10	42,30	No	3%
typical	10	42,40	Yes	1%
best practice	12	42,40	Yes	0.5%

For a detailed description of the conservative, typical and best practice processes is referred to appendix L.2.

L.*1-1 System description "heat by combustion of green gas based on upgraded biogas from digestion of sewage sludge"*

L.1-1[A] feedstock production

Not applicable

The feedstock of biogas from sewage sludge is the organic matter in sludge. In this project the bio energy system is cut off at the production of the sewage sludge. This means that up-chain processes, like collection and treatment of the sewage are not taken into account in the bio-energy options. After all, the sewage treatment is primary a final waste treatment and not a facility to produce bio energy.

L.1-1[B] feedstock transport

Not applicable, see C.1-1[A].

L.1-1[C] conversion

The conversion from feedstock to energy (fuel) is divided in several processes:
1) digestion of the sewage sludge
2) incineration of the digested sewage sludge
3) production of electricity and heat in a CHP by combustion of biogas
4) green gas production

Digestion of the sewage sludge
The sewage sludge is assumed to be digested in anaerobic mesophilic conditions (temperatures about 30-40 ° Celsius). The biogas production from digestion of sewage sludge is assumed to be 0.275 to 0.33 m3 per 1 kg sewage sludge (dry weight)(sewage treatment plant Beverwijk; Coenen *et al*., 2004).

The biogas production is calculated for the separate digestion of a feedstock. However, in practice often co-digestion of combinations of substrates is applied. It is assumed that to calculate biogas production of co-digestion of substrates one might assume a linear relationship between the amount of biogas production and amount of digested substrates (see for example Zwart et al., 2008). In other words the biogas production of the digestion of a combination of substrates is the sum of the biogas production of the digestion of the separate substrates.

This assumption is a simplification of reality. For example if the materials are very different in composition of readily degradable matter this linear relationship might not hold. However, if the retention time of the material in the digester is large one might assume that the potential biogas production may be reached. In these cases the assumption of a linear relationship might be acceptable (mond. med. Kor Zwart).

The digester is assumed to be representative for a sewage treatment plant. For digestion energy is required for mixing of the sludge and heating of the digester, see table 3. The energy demand of the digester is assumed to be supplied by a CHP that runs on biogas from the digester.

Table 3 Energy consumption of digester in sewage treatment plant (Ecoinvent, version 2.0; Ecoinvent, 2007)

	heat	electricity	
Digester, sewage treatment plant	4	0.9	MJ / m3 produced biogas
	1.1	0.25	MJ / kg thickened sewage sludge (dw.)

During digestion part of the produced biogas will be emitted. This emission is assumed to be 1% of the produced biogas (CH4 content 60%).

The digested sewage sludge that is produced is considered a waste.

incineration of the digested sewage sludge

There are several routes for treatment of the digested sludge, like for example:

1. route with final incineration in a sludge incinerator
2. route with final incineration in a cement oven
3. route with final incineration in a electricity power station

In the Netherlands most of the sludge is incinerated in sludge incinerators (48%). About 32% is incinerated in either a cement oven or a power station. In sludge treatment chains with an efficient use of the energy content of the sludge in the final sludge treatment (i.e. cementoven, power station), the anaerobic digestion can have a negative effect on the energy saldo of the total sludge treatment chain (STOWA, 2005). In this project it is assumed that the sludge is finally incinerated in a sludge incinerator.

The GHG emissions for combustion of the sludge are taken from “slibketenstudie” (STOWA, 2005). Data are based on the incineration of sludge. Table 4 gives the emissions for the combustion of 1 kg of digested sludge (dry weight).

Table 4 Emissions of GHG for the combustion of 1 kg of digested sewage sludge (d.w.)(kg substance / 1 kg d.w. sludge)

carbondioxide	0.12

production of electricity and heat in a CHP

The CHP is assumed to be representative for a large scale system. Table 5 gives the energy efficiency of a CHP. In this project for the Conservative option the efficiency of the joint scale plant of 42% electric and 30% heat is used. For the Typical and Best practice option the efficiency of 42% electric and 40% heat is used.

Table 5 Energy efficiency of a CHP (%)

	heat	electricity	source
joint scale plants (500 kWe)	30	42	(Tilburg, van et al, 2006)
	40	42	General Electric[29]
	48	37	(lca food: www.lcafood.dk)
	30	42	(Tilburg, van et al, 2006)

During combustion part of the consumed biogas will be emitted. This emission is assumed to be 1% of the consumed biogas (CH_4 content 55%-60%).

For the Typical en Best practice option it is assumed that both electricity and heat are profitable used, that is the process is allocated to electricity and heat. If the heat is not profitable used the heat output is set zero (Conservative option).

Green gas production

The biogas (CH_4 content 60%) is used to be upgraded to green gas (CH_4 content 88%, as a reference to natural gas).

During the process of upgrading not all the biogas will end up in the green gas, depending on the technology of upgrading this “leak” of biogas might be 3% (VPSA and cryogen system) to 20% (membrane system) (Welink et al., 2007). However, the biogas that does not end up in the green gas is assumed to be profitable used in the CHP.

The upgrading process also needs electricity. It is assumed that this electricity is supplied internal by the CHP that runs on biogas from the digestion of sewage sludge.

Table 6 Energy use for green gas production (Welink et al., 2007)

	electricity	
Green gas production	1.1	MJ / m3 green gas (88% CH_4)

During green gas production part of the methane will be emitted. For respectively the Conservative, Typical and Best practice option this emission is assumed to be 3, 1 and 0.5% of the produced green gas (CH_4 content 88%).

The biogenic carbondioxide that is separated during the upgrading of the biogas to green gas is assumed to be emitted. So no net fixation and/or profitable use of the biogenic carbondioxide is assumed.

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[29] http://www.ge-energy.com/prod_serv/products/recip_engines/en/cogen_systems/cogen_system.htm

L.1-1[D] (biofuel) transport

The green gas is delivered to the low pressure network. No electricity consumption for compression is taken into account because green gas is delivered to low pressure network.

L.1-1[E] end use

The functional unit is defined as the supply of 1 MJ heat at consumer. For the combustion an efficiency is assumed of 90% (0.9 MJ heat from 1 MJ LHV green gas).

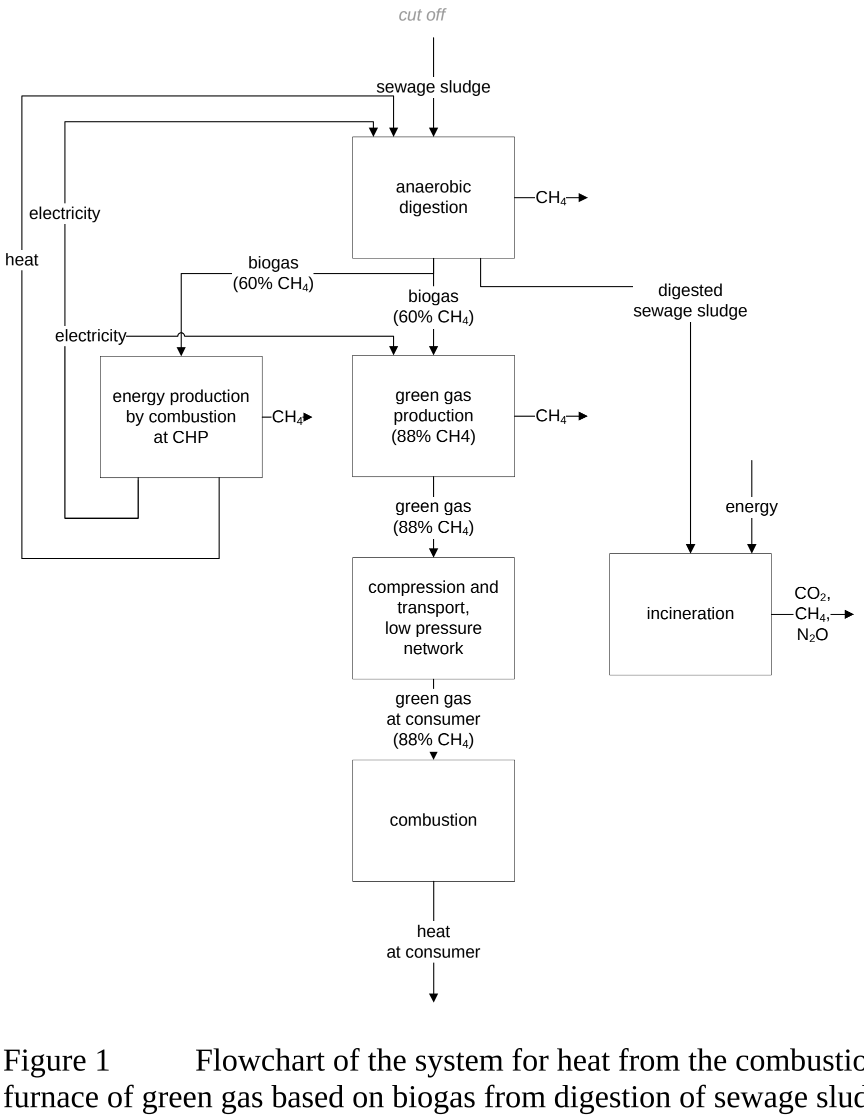

Figure 1 Flowchart of the system for heat from the combustion in an industrial furnace of green gas based on biogas from digestion of sewage sludge.

L.2 process description

In this appendix for each of the processes in the systems (see appendix L.1) the economic inputs (consumed energy and materials of a process) and economic outputs (produced energy and materials of a process) are summarized together with the environmental outputs (the emissions of GHGs: CO_2, CH_4 and N_2O).

Table 7 Process data for conservative, typical and best practice processes

feedstock			sewage sludge		
			C	T	B
anaerobic digestion	electricity consumption	kWh/1 kg thick. sludge (dw.)	0.069	0.069	0.069
	heat consumption	MJ/1 kg thick. sludge (dw.)	Internal supply	1.1	1.1
	biogas production	m3/1 kg thick. sludge (dw.)	0.275	0.275	0.33
	digested sewage sludge	kg (dw.)/kg thick. sludge (dw)	0.80	0.80	0.76
	CH4 emissions	kg/1 kg thick. sludge (dw.)	0.00165	0.00165	0.00198
incineration of digested sewage sludge	CO2 emissions	kg/kg digested sludge (dw.)	0.12	0.12	0.12
CHP (efficiency T,B: 42% electricity, 40% heat)	CH4 emissions	kg/m3 biogas	0.0043	0.0043	0.0043
	electricity produced	kWh/m3 biogas	2.36	2.36	2.36
(efficiency C: 42% electricity, 30% heat)	heat produced	MJ/m3 biogas	excess heat not used	8.08	8.08
green gas (CH4 88%) production	biogas consumption (CH4 60%)	m3/m3 green gas	1.76	1.51	1.51
	electricity consumption (fossil)	MJ/m3 green gas	1.1	1.1	1.1
	CH4 emission	kg/mr green gas	0.019	0.0062	0.0032
green gas combustion (efficiency: 90% heat)	heat produced	MJ/m3 green gas	26.9	26.9	26.9
	methane content biogas	%	60	60	60

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Appendix M Electricity and heat from Municipal Solid Waste

M.1 System description

The system described here documents several different routes through which municipal solid waste can be converted through various means into a fuel, which is then used as a feedstock for electricity and/or heat production. The conversion techniques detailed differ in the type and order of mechanical and biological treatments that are used to stabilize, dry, and sort the municipal solid waste into a form more suitable for fuel use. Additional processes are included for direct use of MSW as a fuel without treatment in a waste incinerator.

System boundaries and cut off

The system is cut off at the collection of municipal solid waste. This means that this process and all processes upstream are not accounted for. Also, one of the RDF (Refuse Derived Fuel) production processes (Alternative 1) produces digestate from anaerobic digestion, which is then used as a landfill cover. Emissions during landfilling are not included as this material is assumed to already be stabilized, with most emissions occurring during the digestion stage. For this same process, sludge sourced from a nearby drinking water preparation process that is used to remove H_2S from the biogas. The sludge is then sent to the digester. This is excluded from the system as well. Implications of materials recovery are not examined, although these will have an impact in offsetting raw material extraction.

Allocation: energy allocation

The process system “heat from combustion of RDF for production of cement clinker” delivers two functions 1) production of heat and 2) the treatment of municipal solid waste. Allocation is based on energy content. The LHV used for energy allocation are presented in the appendix N. The actual allocation factors are based on the LHV of the material and the amount of produced material (see table 1).

Table 1 LHV, amounts and allocation factors.

	LHV MJ/kg	**Amount[1] kg**	**Allocation factor[1]**
Production of RDF from MSW			
MSW	14.37	1000	0.65
RDF	13.23	600	0.35

[1] the amount and allocation factor are given as an example. Figures are different for different conservative, typical and best practice options.

Conservative, Typical and Best Practice Systems

In this project a distinction is made between conservative, typical and best practice systems. A system is defined as a chain of linked processes. The best practice system is defined as the chain of best practice processes. That is the most efficient processes and/or processes with the lowest GHG emission levels.

For this system, this distinction was decided by finding the lowest greenhouse gas emissions per unit of energy. This was deduced by determining the greenhouse gas emissions resulting from the production of 1 kg of RDF for each of the different conversion processes. The values for CH_4, CO_2, and N_2O were aggregated into a single figure for each process according to the GWP100 categorization. This value was then divided by the energy content (in MJ/kg) that is present in the RDF produced by each process. This provides a value indicating the kg of CO_2 equivalents emitted for each MJ of RDF utilized. The RDF production process with the lowest greenhouse gas emissions per MJ is considered the best practice process, while the process with the highest greenhouse gas emissions is considered the conservative estimate. The two middle values were labeled typical. Table 1 below shows how each of the RDF production alternatives was categorized. Table 2 lists the designation assigned for Waste to Energy processes. For this table, the labels are related to the calculation of greenhouse gases per kWh, with credit given to avoided emissions resulting from the production of heat.

Label	**Alternative**	**Description**
Best practice	1	RDF from Mechanical Treatment, Wastes Processed by Anaerobic Digestion, Electricity and Heat produced onsite from biogas.
Typical	2	RDF from Mechanical Treatment, Wastes Processed by Aerobic Digestion
	3	RDF produced by Aerobic Digestion, followed by Mechanical Treatment
Conservative	4	RDF produced by Mechanical Treatment, followed by Aerobic Digestion

Table 1: Conservative, Typical and Best Practice process designation for RDF Production

Label	Alternative	Description
Best Practice	1	WtE Optimized 56.1 MWe, no heat
	2	WtE Optimised heat & power 46 MWe, 1.229:1 kWth/kWe
Typical	3	WtE Conventional heat & power 27.2 MWe, 2.358:1 kWth/kWe
	4	WtE Conventional 37.5 MWe, no heat
Conservative	5	WtE Average 26.2 MWe, 0.256:1 kWth/kWe

Table 2: Conservative, Typical and Best Practice process designation for Waste to Energy.

For more information about the conservative, typical, and best practice processes, refer to Appendix M.2-1

M.*1-1 System description "heat from combustion of RDF for production of cement clinker"*

The description of the bio-electricity production chain is separated into the following five stages:

[A] Feedstock production
[B] Feedstock transport
[C] Conversion
[D] (Biofuel) transport
[E] End use

The system outline is further illustrated in Figure 1, the system outline can be seen. Feedstock production and transport of feedstock are assumed to be essentially the same as the current MSW collection infrastructure. The feedstock is assumed to be household MSW, without industrial wastes. Several different RDF production routes are detailed. These generally involve a mix of mechanical and biological treatments. The mechanical treatments serve to reduce the size of materials and separate out materials that may be recycled or have very little energy content. The biological treatments serve to stabilize the organic fraction and drive off excess water.

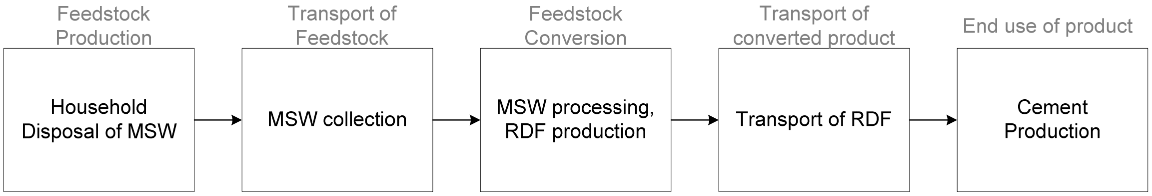

Figure 1 -- System flowchart

M.1-1[A] Feedstock production

Feedstock production involves the production of municipal solid waste at a household level. This is outside the system boundaries since it will happen regardless of the MSW treatment system that is used.

M.1-1[B] Feedstock transport

Feedstock transport involves the collection of municipal solid waste with a garbage lorry. This is outside the system boundaries since it will happen regardless of the MSW treatment system that is used.

M.1-1[C] Conversion

Four different alternatives for RDF production processes are defined. All of them employ various forms of mechanical treatments in order to reduce the size of wastes. This treatment is also used in some processes to separate out recyclable materials or inert fractions that have minimal energetic value. Additionally, biological treatment is employed by three of the processes. This takes the form of aerobic and anaerobic digestion, which serves to stabilize the organic fraction of the municipal solid waste.

Alternative 1: "RDF from Mechanical Treatment, Wastes Processed by Anaerobic Digestion"

During this process, municipal solid waste first goes through a mechanical treatment process that reduces its size and separates out inert materials and an organic fraction. The organic fraction of the waste stream is sent to an anaerobic digester, with the inorganic fraction then pressed into pellets or left as a “fluff”. The anaerobic digestion then produces biogas which is used in turn to provide heat and power for the plant. Only 1/3 of the electricity produced is needed for the operation of the plant, with the remaining 2/3 sold to the grid. It is assumed that the biogas is completely derived from organic materials, and thus contains only biogenic carbon.

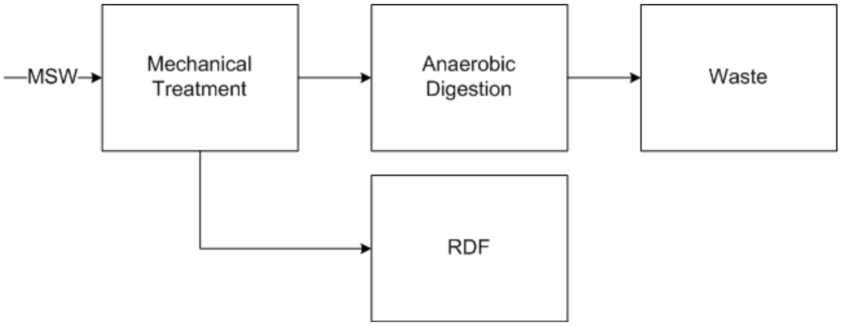

Figure 3 - RDF from Mechanical Treatment,Wastes Processed by Anaerobic Digestion

Alternative 2: "RDF produced by Mechanical Treatment, followed by Aerobic Digestion"

This conversion process is similar to Alternative 2, except that the organic fraction of the municipal solid waste is included in the final RDF. Here the entire stream is aerobically digested, with the produced heat helping to reduce the moisture content of the resulting RDF, and increasing its energy density. Electricity for the process also comes from the grid and is not generated on-site.

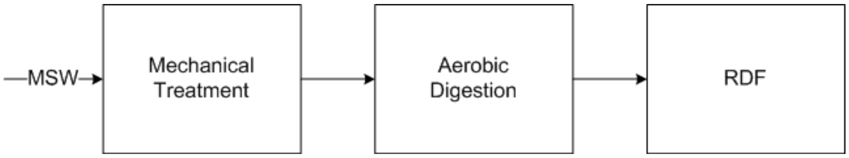

Figure 3 - RDF produced by Mechanical Treatment, followed by Aerobic Digestion

Alternative 3: "RDF produced by Aerobic Digestion, followed by Mechanical Treatment"

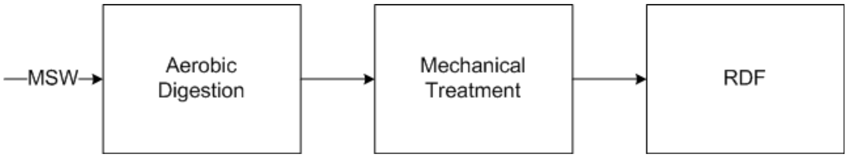

Figure 4 - RDF produced by Aerobic Digestion, followed by Mechanical Treatment

This conversion process is similar to that described in I.1-3, with the exception that aerobic digestion occurs before mechanical treatment. This may be desirable since the aerobic digestion drives off much of the water present in the MSW and can make mechanical treatment and separation much more effective since the materials are not as prone to stick to each other.

M.1-1[D] (Biofuel) transport

Transportation of the RDF is assumed to occur via lorry, with an average distance of 50 km. The entry provided in the EcoInvent database is used.

M.1-1[E] End use

The RDF will be used in the production of heat in cement kilns. In these kilns, high temperatures are needed to transform calcium carbonate to a mix of calcium silicates known as clinker. Fossil fuels are the primary source of heat, although various waste materials can be used as the conditions in the kiln are favorable for the disposal of even certain types of hazardous materials.

M.*1-2 System description "Conventional treatment of Municipal Solid Waste"*

The conventional treatment of municipal solid waste, without conversion to RDF, is assumed to occur at a Waste to Energy plant where the MSW is incinerated and the resulting ash is landfilled. No feedstock conversion is considered to occur. Five different types of plants have been documented in the chapter on "Conversion Processes", sections A.1-11 through A.1-15.

M.*2 Process descriptions*

This section gives more detailed information on the economic and environmental flows for the processes described in Appendix M.1. For the environmental flows, we are mainly concerned with accounting for the major greenhouse gases CO_2, CH_4, and N_2O. The economic flows described concern the daily operation of the processes. Flows regarding capital goods are excluded as it is assumed their impact is minor.

The RDF conversion processes are detailed in two sources. Alternative 1 is based on the SBI Friesland and Grontmij processes detailed by Juniper Consultancy Services Ltd, 2005. Alternatives 2, 3 and 4 correspond to the b, c, and d systems investigated by Consonni et al, 2005. The production of electricity from RDF is described more fully in Duman et al (2007), Damen et al (2003) and Manninen (1995)

M.2-1 Definition of conservative, typical and best practice processes and process systems

Table 3 below shows the calculations performed in order to determine the Conservative, Typical, and Best practice systems. This is based on the four alternatives described for the RDF conversion process. At the top of the table is an accounting of emissions resulting from the production of 1 kg of RDF. These values were calculated using the CMLCA tool.

In the next section of the table, the three greenhouse gases are scaled according to the GWP100 characterization factor, with each greenhouse gas value represented in terms of CO_2 equivalents, according to its contribution to global warming. The last line in this section sums the total global warming potential (GWP) for each alternative. The third section lists the energy content for the RDF as stated in the literature. When the total GWP listed in the second section is divided by the energy content, this results in a number that represents how much each alternative contributes to global warming, per unit of energy (MJ) contained in the fuel.

	Alternative 1	Alternative 3	Alternative 4	
CO_2 (fossil)	0.00E+00	1.80E-01	7.03E-02	Emissions (kg/kg RDF)
N_2O	0.00E+00	5.14E-06	2.75E-03	Emissions (kg/kg RDF)
CH_4	2.73E-04	1.74E-04	7.50E-05	Emissions (kg/kg RDF)
CO_2 (fossil)	0.00E+00	1.80E-01	7.03E-02	Emissions (kg CO_2 eq/kg RDF)
N_2O	0.00E+00	1.52E-03	8.14E-01	Emissions (kg CO_2 eq/kg RDF)
CH_4	6.28E-03	4.00E-03	1.73E-03	Emissions (kg CO_2 eq/kg RDF)
total GWP	6.28E-03	1.86E-01	8.86E-01	Emissions (kg CO_2 eq/kg RDF)
	Energy content of RDF in each alternative			
	10.25	16.57	14.9	MJ/kg
	GHG scaled to energy content			
	6.13E-04	1.12E-02	5.95E-02	kg CO_2 eq/MJ
	Best practice	*Typical (2)*	*Conservative*	

Table 3 – Calculations used to determine Conservative, Typical and Best practice system.

M.*2-2 Description of the unit processes for converting MSW into RDF*

[A] Feedstock Production

This is outside the system boundaries. It involves production of MSW at the household level.

[B] Feedstock Transport

This is outside the system boundaries. It involves transportation of MSW to a MSW processing facility as is currently common practice.

[C] Conversion

Municipal solid waste is a complex combination of numerous materials. Each of the four conversion processes detailed below handles this stream differently, separating out different amounts of recyclable and inert materials. As a result, each process produces different amounts of RDF from the same input of MSW. Another result is that the RDF produced by one process will not have the same energy density (measured in MJ/kg) as the RDF produced by another process. This is related to the moisture content of the produced RDF and the percentage of the waste fractions present. For example, paper and plastics have a high energy density, and if they are diverted to recycling, then this will reduce the energy density of the final RDF.

Alternative 1: Process description "RDF from Mechanical Treatment, Wastes Processed by Anaerobic Digestion"

This process is distinguished from the other alternatives in that it generates its own heat and power on-site. This is accomplished by combusting biogas generated from the anaerobic digestion process in a combined heat and power turbine. This alternative is actually a net electricity generator, with 1/3 of the power used on-site, and 2/3 exported to the grid. The biogas is assumed to be completely of biogenic origin, so no fossil CO_2 emissions are assumed to occur from the power production. Leakage of CH_4 from the anaerobic digestion process is assumed to be around 1%. As seen in Table 2, this alternative is labeled as “best practice” and this designation is directly related to these process characteristics.

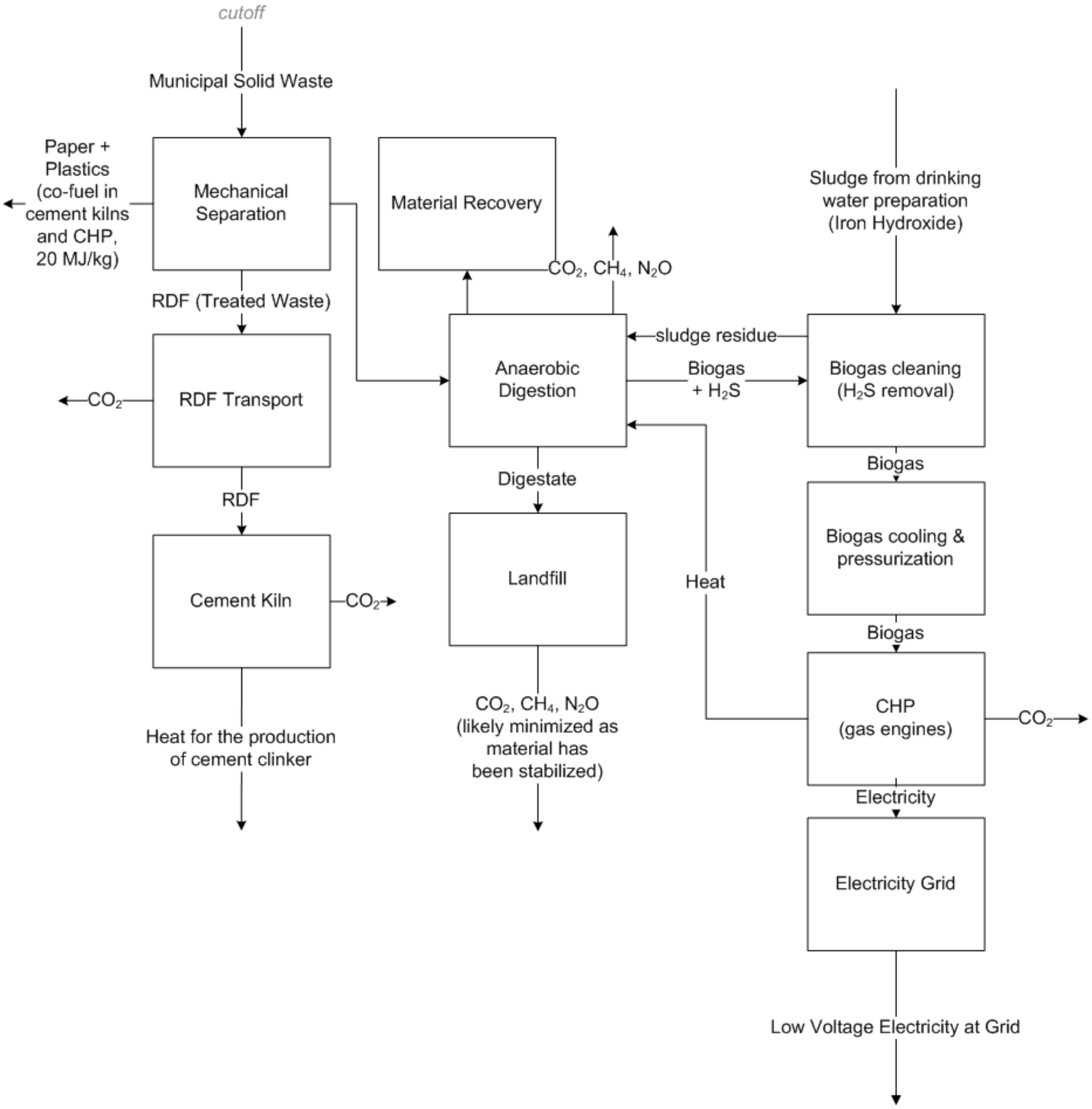

Figure 5 – Configuration 1: RDF production combined with anaerobic digestion (SBI Friesland & Grontmij).

Process	**Configuration 1: MSW processing with RDF production and anaerobic digestion of residuals** Electricity and Heat for this process are generated on-site from biogas generated from this process. This description is based on the SBI Friesland and Grontmij processes described in Juniper Consultancy Services 2005				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**Remarks**
Economic inflow					
Municipal Solid Waste		waste management	1000	kg	
transport, lorry 28t		transport systems	9.49	tkm	EcoInvent 2003, based on numbers for MSW incineration
transport, freight, rail		transport systems	13.9	tkm	
Economic outflow					
Refuse Derived Fuel		waste management	420	kg	9 – 11.5 MJ/kg (Grontmij numbers)
Electricity		electricity	19	kWh	Only accounts for electricity exported to the grid.
Ferrous + non-ferrous metals		waste management	30	kg	Recycled
Paper + plastic		waste management	150 – 160	kg	Used as a co-fuel in cement kilns and CHP. Exact mix not known, but Juniper 2005 indicates near 50/50 mix in Figure D103
Coarse Inerts		waste management	80	kg	Recycled or landfilled
Sand		waste management	40	kg	Recycled or landfilled
Digestate		waste management	100 - 160	kg	Used as landfill permanent cover
Environmental inflow					
Environmental outflow					
CO_2	124-38-9	air	78.56	kg	Only considers CO_2 from combustion of biogas. From Juniper, 2005 describing SBI-Friesland process. 1 tonne MSW input to plant results in 40 Nm^3 of biogas, 55-60% CH_4 composition
CH_4	74-82-8	air	0.000273	kg	Assume 1% escape of methane during digestion.

Alternative 2: Process description "RDF produced by Mechanical Treatment, followed by Aerobic Digestion"

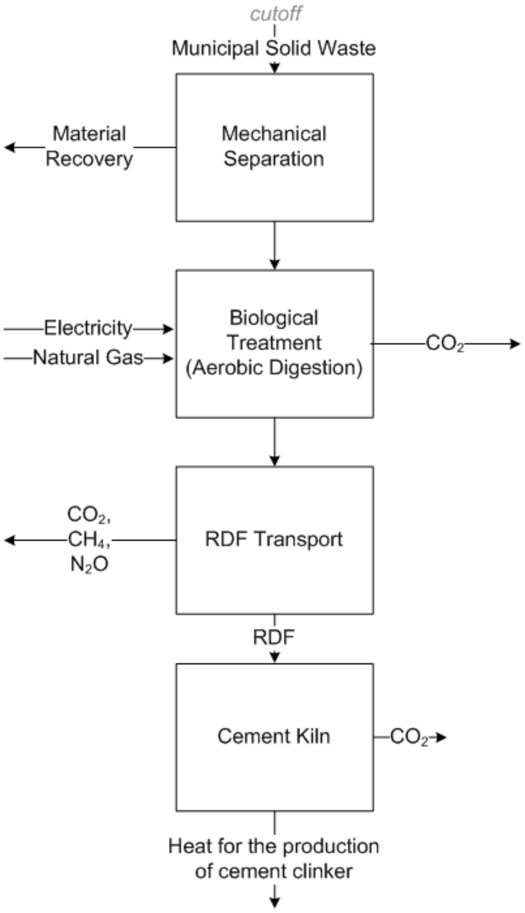

Figure 6 -- RDF Production Scenario 3 - Mechanical separation followed by aerobic digestion

Process	**RDF production with biological stabilization before mechanical treatment** **Scenario 3 from Consonni et al 2004** Based on the Herhof process, involves biological stabilization of MSW (aerobic digestion) before mechanical treatment (separation into waste fractions)				
Name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**Remarks**
Economic inflow					
MSW			1000	kg	
Electricity			118	kWh	
Natural Gas			10.3	m^3	
Economic outflow					
RDF			533	kg	LHV: 16.57 MJ/kg Moisture: 12.9% Ash: 11.4%
Environmental inflow					
Environmental outflow					
CO_2 (fossil)	124-38-9	air	13.72	kg	
CO_2 (non-fossil)	124-38-9	air	91.7	kg	
N_2O	10024-97-2	air	0	kg	
Inert materials to landfill		landfill	150	kg	
Water		air	300	kg	Released during drying process

Alternative 3: Process description "RDF produced by Aerobic Digestion, followed by Mechanical Treatment"

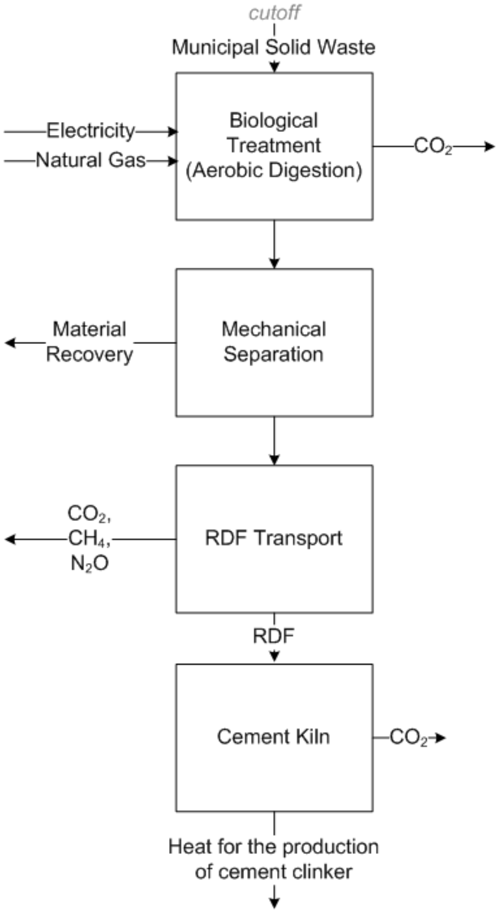

Figure 7 -- RDF Production Scenario 4 - Aerobic digestion followed by mechanical separation

Process	**RDF production with mechanical treatment before biological stabilization.** **Scenario 4 from Consonni et al 2004** Based on EcoDeco process, involves mechanical separation of MSW then bio-stabilization through aerobic digestion				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**Remarks**
Economic inflow					
MSW			1000	kg	
Electricity			60	kWh	
Economic outflow					
RDF			600	kg	LHV: 14.90 MJ/kg Moisture: 20.4% Ash: 9.8%
Environmental inflow					
Environmental outflow					
CO_2 (fossil)	124-38-9	air	0	kg	
CO_2 (non-fossil)	124-38-9	air	28.8	kg	
N_2O	10024-97-2	air	1.65	kg	
SOF to landfill		landfill	150	kg	

[D] Biofuel transport

Transport of the RDF is considered to be by lorry. We use the entry provided in the EcoInvent database and assume an average transportation distance of 50km.

[E] End use

This is covered in the “Conversion Processes” appendix, Appendix A.

M.*2-3 Description of the unit process for incineration of MSW in Waste to Energy facilities*

The process descriptions for five alternatives for Waste to Energy facilities are listed in the chapter on “Conversion Processes” in sections A.2-11 through A.2-15.

M.*2-4 Process description "Combustion of RDF in Cement Kiln"*

The combustion of RDF in a cement kiln is presented below, along with the fossil alternative where hard coal is used in its place to deliver the same amount of heat for the production of clinker. The values for RDF energy and C content are taken from a single example of RDF. These values will vary based on the specific RDF production method and the components of the source MSW.

Process	**Combustion of RDF in Cement Kiln** Assume 44% efficiency, European Commission, 2003. 1kg RDF = 1.067 kg CO_2, 66.8% Renewable (Banks, n.d.)				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**Remarks**
Economic inflow					
Refuse Derived Fuel			0.152	kg	15 MJ/kg
Economic outflow					
Heat applied to clinker			1	MJ	44% efficiency
Environmental inflow					
Environmental outflow					
CO_2, fossil	124-38-9 (Fossil)	Air	0.0538	kg	Assume 66.8% Renewable CO_2
CO_2, biogenic	124-38-9 (Biogenic)	Air	0.1083	kg	

Process	**Combustion of Hard Coal in Cement Kiln** Assume 44% efficiency, European Commission, 2003. 1kg RDF = 1.067 kg CO_2, 66.8% Renewable (Banks, n.d.)				
name	**code/ cas- no.**	**class/ compartment**	**value**	**unit**	**Remarks**
Economic inflow					
Refuse Derived Fuel			0.0811	kg	28 MJ/kg
Economic outflow					
Heat applied to clinker			1	MJ	44% efficiency
Environmental inflow					
Environmental outflow					
CO_2, fossil	124-38-9 (Fossil)	Air	0.1785	kg	Assume coal 60% C by weight (Damen, 2003)

M.3 *Calculation of Carbon Emissions from RDF utilization*

In order to find the CO_2 emissions that result from utilization of RDF, three different levels must be known: the energy density of the RDF, the composition of the waste fractions in the RDF, and the percentage of biogenic & fossil carbon in each of those waste fractions present. When combined, these numbers can be used to calculate the amounts of biogenic and fossil carbon that are released per 1 kWh.

The actual energy content of RDF will depend on the treatment method. As seen in Table 4, unprocessed MSW has the lowest energy density, while higher density fuels can be produced through additional waste processing steps. The RDF with the highest energy density will generally consist of only consist of paper and plastic residues.

Processing RDF to a higher energy density involves a tradeoff as energy must be used in order to get more useable energy out of the MSW. This treatment generally involves the removal of water, but also may remove some components with a lower energy density. So while the RDF will then have a higher energy density, the total amount of energy available may be lower due to this diverted stream.

Table 4 -- Energy content of various fuels from waste (European Commission, 2003)

	Untreated MSW	**RDF from mixed MSW**	**RDF from source-separated MSW**
Energy Content (MJ/kg)	8 – 11	13	20 – 23

Further differences will arise based on the actual composition of the RDF. Paper, plastic, and wood may be recycled, or may be separated from the RDF stream due to their high energy density, for use in combustion in another process. The actual composition of RDF in use in the Netherlands is not well documented. For data that was found, many of the categories are vague and do not aid further analysis. Data may not also reflect the final composition of the RDF, such as for the Grontmij process listed below, where the only numbers available were for the RDF stream before the paper/plastics removal step.

Table 5 -- Composition of Different RDF Samples

	(Flemish Region)[30]		
Waste Fraction	**Sorting Process %**	**Mechanical Biological Treatment %**	**Grontmij (MBT) %[31]**
Plastic	31	9	15-20
Paper/cardboard	13	64	20-25
Wood	12	25	
Textile	14		
Others	30		
Undesirable material (glass, stone, metal)		2	
Glass/Coarse Inerts			5
Metals			<1
Organics			10-15
Other combustible			30
Other non-combustible			5

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[30] European Commission, 2003

[31] Juniper Consultancy Services Ltd, 2005. Data is before paper/plastics removal process

Calculations of CO_2 emissions through the utilization of RDF must consider the origin of the carbon in each of the components that make up the stream. A selection of the available data is shown in Table 6 below.

Table 6 -- Carbon content of different waste fractions of RDF

	Carbon Content	
Waste Fraction	**Biogenic Carbon Content (% by weight)**	**Fossil Carbon Content (% by weight)**
Paper and cardboard	31.87 (2) - 37.6 (1)	
Wood	37.6 (1)	
Plastic		55.5 (1)
Plastic (dense)		54.83 (2)
Plastic (film)		47.81 (2)
Glass and inert metal	0.28 (2)	1.0 (1)
Metals		1.0 (1)
Organic fraction	9.6 (1)	
Kitchen waste	13.46 (2)	
Green waste	17.17 (2)	
Fines	6.88 (2) - 12.3 (1)	6.88 (2) - 8.2(1)
Textiles	19.93 (2)	19.93 (2)
Miscellaneous Combustibles	19.2 (2)	19.2 (2)
Miscellaneous Noncombustibles	3.5 (2)	3.5 (2)

(1) Consonni, et al. 2005

(2) Defra 2006, quoting ERM & Environment Agency Data (2003-2005)

As has been demonstrated, literature values on the energy density and carbon composition of RDF vary widely. For the most accurate calculations, it is best to find this type data from one manufacturer of RDF, and then calculate the resulting emissions by using the two formulas below (VROM, 2006). This formula iterates over each component waste fraction to find the total weight of carbon, and the resulting CO_2 emissions from each waste fraction.

$$\text{Fossil } CO_2 = \sum_i (\text{quantity}_{\text{component } i} * \%\text{Fossil } C_{\text{component } i} * C \text{ content}_{\text{component } i}) * 44/12 \text{ (ton } CO_2/\text{ton C)}$$

$$\text{Biogenic } CO_2 = \sum_i (\text{quantity}_{\text{component } i} * \%\text{Biogenic } C_{\text{component } i} * C \text{ content}_{\text{component } i}) * 44/12 \text{ (ton } CO_2/\text{ton C)}$$

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Appendix N Allocation details

ENERGY CONTENT OF MATERIALS USED TO CALCULATE ALLOCATION FACTORS

				Energetic allocation			Economic allocation	Substitution
scenario				Present version CO2 tool			Previous version CO2 tool	
Full name	Kind	IN/ OUT	Unit	LHV OS (MJ)	Water content (%)	energy allocation in CO2 tool	Price (EUR	
rape seed								
raw rape seed	good	OUT	kg	21.8	16.2	YES	0.282	
rape seed straw	good	OUT	kg	14.7	11.8	NO	0.029	
crude rape seed oil	good	OUT	kg	37.2	0	YES	0.598	
rape seed meal	good	OUT	kg	15	18.6	YES	0.127	
soy bean								
soybean seed	good	OUT		17	13.3	YES		
soybean residues	good	OUT		13	20.5	NO		
degummed soybean oil	good	OUT	kg	36.6	0	YES	0.467	
Soy bean meal	good	OUT	kg	15	18.6	YES	0.177	
palm oil								
crude palm oil	good	OUT	kg	36.5	0	YES	0.396	
Palm kernel	good	OUT	kg	14	20.5	YES	0.258	
straw								
wheat grains	good	OUT	kg	13.7	16.9	YES	0.1	
wheat straw	good	OUT	kg	13.3	19.8	NO	0.05	
manure								
manure (cattle)	waste	IN	kg	5.09	47.10	YES		conventional storage and application on farmland
biogas (65% methane)	good	OUT	m3	23.45	0.00	YES		
digestate	waste	OUT	kg			NO		

manure + gras			kg					conventional storage and application on farmland
manure (cattle)	waste	IN	kg	5.09	47.10	YES		
biogas (65% methane)	good	OUT	m3	23.45	0.00	YES		
digestate	waste	OUT	kg			NO		
manure + corn			kg					conventional storage and application on farmland
manure (cattle)	waste	IN	kg	5.09	47.10	YES		
biogas (65% methane)	good	OUT	m3	23.45	0.00	YES		
digestate	waste	OUT	kg			NO		
restaurant waste								
Swill	waste	IN	kg	10.62	36.60	YES		conventional storage and composting
biogas (55% methane)	good	OUT	m3	19.84	0.00	YES		
digestate	waste	OUT	kg			NO		
animal wastes								
animal residues	waste	IN	kg	17.95	5.10	YES		incineration of animal waste
animal fat	good	OUT	kg	30.86	16.80	YES		
meat&bone meal	good	OUT	kg	18.05	2.80	YES		
wood								
wood waste	waste	IN	kg	16.54	9.60	YES		burning of wood in beehive
wood pellets	good	OUT	kg	17.27	8.00	YES		
RDF from waste								
MSW	waste			14.37	15.10	YES		
RDF	good	OUT	kg	13.23	27.30	YES		
MSW								
waste incineration	waste	IN	kg	14.37	15.10	YES		conventional waste inc wit elec and heat generation
electricity	good	OUT	MJ			YES		

VFG (GFT								
GFT	waste	IN	kg	5.89	54.10	YES		
biogas (55% methane)	good	OUT	m3	19.84		YES		
digestate	waste	OUT	kg			NO		
Starch								
starch	waste	IN	kg	12.80	16.80	YES		
biogas (55% methane)	good	OUT	m3	19.84		YES		
digestate	waste	OUT	kg			NO		
Sewage sludge (RWZI)								
sewage sludge	waste	IN	kg	12.40		YES		
biogas (60% methane)	good	OUT	m3	21.64		YES		

LHV OS: Lower heating value of the original substance, considering the given water content, also sometimes called LHVar (as received)

LHV values taken from:

1) Phyllis, database for biomass and waste, http://www.ecn.nl/phyllis, Energy research Centre of the Netherlands
LHVos (or LHVas received) are based on LHVdaf given in Phyllis. LHVar is calculated from LHVdaf by formulas given on website, see Definitions used in Phyllis

2) Greenhouse Gas Balances for the German Biofuels Quata Legislation. Methodological Guidance and Default values. Fehrenbach, Horst, Jürgen Giegrich, Sven Gärtner, Dr. Guido Reinhardt & Nils Rettenmaier, 2007. IFUE, Heidelberg.

Appendix O GHG emissions from background processes

GHG emissions in kg CO2 equivalents based on Ecoinvent process data, version 1.3 (Ecoinvent, 2008)

transport, lorry 28t	0.221	per tkm
transport, lorry 32t	0.164	per tkm
transport, freight, rail	0.0135	per tkm
transport, barge	0.0456	per tkm
transport, transoceanic freight ship	0.0105	per tkm
heat, light fuel oil, at industrial furnace 1MW	0.0924	per MJ
diesel, burned in machine	0.0903	per MJ
electricity, medium voltage, production UCTE, at grid	0.482	per kWh
pesticide unspecified, at regional storehouse	7.33	per kg
grass at farm	0.206	per kg (dry weight)[1]
silage maize IP, at farm	0.0588	per kg
N-fertilizer, mineral	6.15	per kg
P2O5-fertilizer, mineral	0.7	per kg
K2O-fertilizer, mineral	0.453	per kg

[1] moisure content grass: 80% of fresh weight

Ecoinvent Centre, 2006. ecoinvent data v 1.03. Final reports ecoinvent 2000 No 1-15. Swiss Centre for Life Cycle Inventories, Dübendorf, 2006. http://www.ecoinvent.ch/

Appendix P Overview of biogas production for several feedstocks and procedure to calculate mixes of feedstocks for digestion

biogas production from digestion of (co) substrates

substrate **manure**	dry weight %	organic matter % of dry weight	biogas production m3 / ton fresh matter	biogas content vol. %	Ref.
cattle manure (slurry)	8-11	75-82	20-30	60	1)
cattle manure (slurry)	9		21	55	2)
pig manure (slurry)	7	75-86	20-35	60-70	1)
pig manure (slurry)	6		20	60	2)
cattle manure	25	68-76	40-50	60	1)
pig manure	20-25	75-80	55-65	60	1)
poultry manure	32	63-80	70-90	60	1)
poultry manure	15		56	65	2)
agricultural products					
maize silage	20-35	85-95	170-200	50-55	1)
rye silage, total crop	30-35	92-98	70-220	55	1)
rye grain	87		597	52	2)
wheat grain	87		598	53	2)
wheat chaff	89		262	51	2)
grain, total crop	40		195	52	2)
sugar beet	23	90-95	170-180	53-54	1)
sugar beet, fresh	23		147	51	2)
sugar beet leafs	16		85	54	2)
beet leafs	16	75-80	70	54-55	1)
beet residues (bieten puntjes)	17		96	52	2)
fodder beet	12	75-85	75-100	53-54	1)
fodder beet	15		90	51	2)
grass silage (1. cut)	40		202	54	2)
grass silage (all cuts)	35		182	54	2)
meadow grass	18		98	54	2)
hay	86		404	53	2)
maize silage	28		155	52	2)
maize silage	33		185	52	2)
maize silage	35		202	52	2)
barley straw	86		312	51	2)
potato raw, high starch content	26		177	51	2)
potato raw, medium starch content	22		150	52	2)
whey, fresh	5		34	53	2)
milk, fresh, low fat	9		58	58	2)
cabbage, green	12		63	54	2)
CCM (corn cob maize)	65		426	53	2)
by products food industry					
beer dregs	20-25	70-80	105-130	59-60	1)

grain slop, alcohol production	6-8	83-88	30-50	58-65	1)
fruit slop, alcohol production	2-3	95	39741	58-65	1)
potato slop, alcohol production	6-7	85-95	36-42	58-65	1)
potato slop, fresh	6		35	56	2)
pulp (fresh), potato starch production	13	90	80-90	52-65	1)
fruit water, potato starch production	4	70-75	50-56	50-60	1)
process water, potato starch production	2	65-90	55-65	50-60	1)
rape seed meal, press residue, 15% oil	91		579	63	2)
melasse, sugar production	80-90	85-90	290-340	70-75	1)
press residues, sugar production	22-26	95	60-75	70-75	1)
apple dregs	25-45	85-90	145-150	65-70	1)
fruit dregs	25-45	90-95	250-280	65-70	1)
wine dregs	40-50	80-90	250-270	65-70	1)
glycerine	100		846	50	2)
organic waste					
old bread	65		482	53	2)
old frying fat	95		874	68	2)
baking waste	88		651	53	2)
cheese waste	79		674	68	2)
Vegetable waste	15		57	56	2)
Vegetable Fruit Garden waste	40-75	50-70	80-120	58-65	1)
foods	9-37	80-98	50-480	45-61	1)
foods, low fat	18		127	62	2)
market waste	5-20	80-90	45-110	60-65	1)
fat	2-70	75-93	11-450	60-72	1)
fat waste	5		45	68	2)
stomach content (pigs)	12-15	75-86	20-60	60-70	1)
guts content	11-19	80-90	20-60	58-62	1)
slaughter waste	5-24	80-95	35-280	60-72	1)
potato raw, peel waste	11		68	51	2)
cut back garden waste					
cut back garden waste	12	83-92	150-200	55-65	1)

1) Handreichung Biogasgewinnung- und -nutzung (FNR, 2005) table 4-25
2) Handreichung Biogasgewinnung- und -nutzung (FNR, 2005) table 10-9
Fachagentur Nachwachsende Rohstoffe e.V. (FNR), Gülzow

http://www.unendlich-viel-energie.de/uploads/media/Biogasgewinnung_und_-nutzung.pdf

These data can be used to compose a mix of feedstocks for digestion. The supporting spreadsheet can be used to calculate GHG emissions from the mix, which in turn can be used as process data in E-LCA. In the section containing the digestion chains of manure and agricultural residues and crops, there is a user-defined option to specify a mix. The data from this appendix are provided in the supporting spreadsheet as well. The amount in tonnes has to be filled into the yellow cells in the worksheet “biogas production co digestion”. The biogas production in m3 per ton of feedstock, from the table above, must be entered in the mint green cells. The spreadsheet then calculates the data that must be entered into E-LCA (blue and red). In addition, the LHV is needed for the allocation in E-LCA. For a number of feedstocks, the LHV is specified in Appendix N. If the feedstock in question is not included in Appendix N, the user must find his or her own data, or use that of another feedstock as an approximation.