



NL Agency
Ministry of Economic Affairs, Agriculture and
Innovation

Methodology CO₂-tool for electricity, gas and heat from biomass

>> Focus on energy and climate change

Methodology CO₂-tool for electricity, gas and heat from biomass

This document gives background information on the methodology and data sources used in the CO₂ tool. Practical instructions on how to use the CO₂ tool can be found in the user manual that accompanies this tool.

Contact information

This CO₂-tool was developed by Ecofys by order of NL Agency. For information on this tool please contact:

Har van Himbergen, NL Agency, Har.vanHimbergen@agentschapnl.nl

Ella Lammers, NL Agency, Ella.Lammers@agentschapnl.nl

Version

1.0

Date

May 2011

Disclaimer

No rights may be derived from this publication, nor may NL Agency be held liable for the consequences arising from the use thereof.

Table of contents

1	Introduction & background	1
1.1	What can I do with the CO ₂ -tool?.....	1
1.2	Relevant legislation on CO ₂ -calculations.....	1
1.3	CO ₂ -tools.....	2
1.4	How to use this document.....	3
2	Methodology of greenhouse gas calculations	4
2.1	Introduction.....	4
2.2	System boundaries.....	5
2.3	The greenhouse gas emission of the pathway.....	7
2.4	Greenhouse gas emission reduction.....	8
3	The predefined pathways	12
3.1	Predefined pathways.....	12
3.2	Electricity and heat from wood pellets by boiler, CHP and Co-firing.....	13
3.3	Electricity and heat from wood chips by boiler, CHP and Co-firing.....	17
3.3.1	Electricity from torrefied wood pellets by cofiring in coal plant.....	18
3.3.2	Heat from wood chips by combustion in boiler.....	20
3.3.3	Electricity and heat from demolition wood by combustion in CHP.....	21
3.4	Green gas production from biogas by mono-digestion of manure, maize, potato remains, sugar beet remains, glycerine and organic waste.....	22
3.5	Jatropha oil, ready to be used for the production of electricity and/or heat by means of an diesel engine.....	31
3.6	Rape seed oil, ready to be used for the production of electricity and/or heat by means of an diesel engine.....	34
3.7	Animal fats, ready to be used for the production of electricity and/or heat by means of an diesel engine.....	38
3.8	Used frying oils, ready to be used for the production of electricity and/or heat by means of an diesel engine.....	40
	Reference sources	41
	Appendix A Abbreviations and definitions	43

1 Introduction & background

1.1 What can I do with the CO₂-tool?

Biomass can be converted into final energy in the form of electricity, heat or biofuels. This final energy is considered 'green' since it does not result in the release of CO₂ with 'fossil carbon'. However, several steps in producing this final energy from biomass do generate fossil carbon emission. Examples are: Cultivation and harvesting (tractors using diesel), transport (trucks, ships using diesel), drying (often natural gas is used for drying), size reductions (often electricity use), etc. The reduction in greenhouse gas (GHG) emission compared to final energy from a fossil fuel is therefore less than 100%. How much less than 100% depends on the type of biomass, the transport distance and the processing steps. The diversity in biomass, conversion technologies, ways of transport and the geographical spread of both biomass sources and the energy demand, result in numerous possible biomass-to-energy pathways. Each of these pathways has a different GHG emission performance. The calculation of the total GHG-emission from a specific pathway is time-consuming. The CO₂-tool is software to make these calculations easier.

1.2 Relevant legislation on CO₂-calculations

Renewable Energy Directive

In 2009 the Renewable Energy Directive (RED) [1] and the Fuel Quality Directive set sustainability criteria for liquid biofuels. One of the criteria is a minimum greenhouse gas saving compared to fossil fuels. Annex V of the RED gives the methodology and rules to calculate this. This Annex includes a list of typical and default greenhouse gas emission savings for about 35 biofuel production pathways. The Annex gives for some of these pathways also the disaggregated emissions (g CO_{2eq}/MJ) per step (cultivation, processing, transport, etc.).

Report on solid biomass for electricity, heating and cooling

For electricity, heating and cooling from solid and gaseous biomass, there is no directive that compares to the RED. However, there is a 2010 report from the European Commission on sustainability requirements for electricity, heating and cooling from solid and gaseous biomass [2]. In contrast with the RED, this report is not binding. Annex I of this report gives the methodology and rules to calculate the greenhouse gas saving compared to fossil fuels. This methodology is analogous to Annex V of the RED. This Annex includes a list of typical and default greenhouse gas emission (g CO_{2eq}/MJ) for about 30 pathways. However, the Annex gives no disaggregated result like Annex V of the RED.

NTA 8080

The NTA 8080 is a Netherlands Technical Agreement on sustainability criteria for energy purposes [3]. The NTA 8080 refers to the CO₂-tool as instrument to determine the greenhouse performance. Since there is the wish to apply the NTA 8080 in the near future for the Dutch renewable energy subsidy scheme SDE, it is important that the CO₂-tool is transparent, unambiguous and user friendly.

1.3 CO₂-tools

Dutch CO₂-tools

A greenhouse gas calculation tool is a software instrument to calculate the greenhouse gas saving from biomass-to-energy pathways compared to fossil comparators. These tools are often simple called 'CO₂-tool'. In 2006 – 2007, two CO₂-tools were developed in order by Agentschap NL: one for liquid biofuels for transport from biomass and one for electricity and heat from biomass.

The Biograce project

The Biograce project (www.biograce.net) develops Excel-based spreadsheets to calculate the greenhouse gas saving of most of the biofuel production pathways that are given in Annex V of the RED. The calculations are based on the disaggregated emissions per step (as given in the Annex V) and standard conversion factors that are used to calculate the default values in the Annex V of the RED. The spreadsheet calculations give therefore by definition the same saving compared to fossil comparators as reported in the RED.

The present CO₂-tool

The present CO₂-tool is an update of the tool for electricity and heat from biomass as was developed in 2006 – 2007. However, the format and part of the calculation methodology is changed drastically. The software environment of the original tool is abandoned. The Biograce spreadsheet calculation format is the basis of the present CO₂-tool. Despite the fact that the present tool looks and functions like the Biograce calculation sheets, there are differences compared to Biograce. The most important are:

- 1** Since Biograce deals with liquid biofuels, there is in each pathway only one final biofuel (ethanol, biodiesel). In the present tool, many pathways result in both electricity and heat. This has consequences in the calculation methodology;
- 2** The final emission saving that is calculate in the Biograce sheets (a percentage) is exactly the default greenhouse gas emission saving as listed in Annex V of the RED. This is possible since most of the parameters that are required for the calculation of the reduction are known (see also section 1.2). Since the parameters required for the pathways in the present tool are mostly unknown (see again section 1.2), it is currently not possible to prepare calculation sheets that exactly result in the default greenhouse gas emissions that are listed in

Annex I of the report on sustainability requirements for electricity, heating and cooling from solid and gaseous biomass.

1.4 How to use this document

This document is the methodology document that accompanies the tool (Excel-file) and the user manual. The first chapter explains what you can do with the tool, what legislation formed the basis of the development of the tool and gives some backgrounds on the history of the CO₂-tool. Chapter 2 describes the calculation methodology. The main part of this document is chapter 3 where all pre-defined pathways are explained in detail. These pathway descriptions are well documented and referenced.

Besides the tool and this methodology document, there is a user manual that gives practical information on how to use the tool.

2 Methodology of greenhouse gas calculations

2.1 Introduction

There are many choices to make in GHG-calculations. The most important are:

- How the complete pathway is build up. Which steps can be identified? For example: cultivation, harvesting, transport, processing, digestion, biogas combustion generating electricity and heat.
- The pathway specific parameters to use. For example: What is the yield of a certain energy crop (ton/ha)? What is the electric efficiency of a gas engine?
- The general parameters. For example: the GHG-emission from the use of fossil fuels in processing or transportation steps, the GHG-emissions resulting from the use of fertilizer.
- How to distribute the GHG-burden. For example: when wheat is harvested, there are two products: wheat grains and straw. How to distribute the CO₂-burden from the cultivation among those two products? This is often referred to as allocation.

In previous CO₂-tools, these choices were made by the developers. Some used strict rules from Life Cycle Analysis while others used more pragmatic approaches. This resulted in different choices and subsequently different outcomes of calculations. Since then, some choices were made, resulting in 'calculation rules' and more consistency in GHG-calculations and outcomes. These rules are given in the Renewable Energy Directive (RED) and the communication 'on sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling', both discussed in section 1.2. Next to these documents from the European Commission, there are other sources that we use in the development of the current tool. Table 2 - 1 gives all sources, in order of preference in use.

Table 2 - 1 Sources used for methodological choices and parameter selection

	Source	Comment
1	European Commission: 'on sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling' (2010) [2]	
2	Renewable Energy Directive (2009) [1]	This is on biofuels for transport and electricity and heat from bioliquids only
3	Biograce calculation tool (2010) [3]	This is on biofuels for transport only
4	CO ₂ -tool for electricity and heat (2006 - 2008) [5]	The tool and accompanying document as prepared by CML
5	Peer-reviewed literature	Mostly scientific literature
6	Other sources	For example: data from existing installations.

2.2 System boundaries

The pathway

We consider the complete biomass-to-energy pathways. This means from cultivation from biomass until the final energy. This final energy can be:

- 1 Electricity
- 2 Heat
- 3 Green gas (upgraded biogas)

The pathway is cut off at the produced final energy. Losses in transport to the consumer are not included. This is also not included in the fossil comparator. The process of bringing the final energy on specifications is included in the pathway. This is for example transformation of electricity to the electricity grid voltage or pressurizing upgraded biogas to the pressure of the (local) grid pressure.

By-products

By-products are products that are formed in the process from biomass to energy, other than the final energy or a precursor of the final energy. For example: after harvesting, wheat is processed into wheat grain and wheat straw. When the wheat straw is converted to electricity, wheat grain is a by-product. On the other hand, when wheat grains are fermented and the ethanol is fed to an engine that produces electricity, wheat straw is a by-product.

Allocation to by-products

Where a pathway produces (besides the energy carrier for which emissions are being calculated) one or more co-products, greenhouse gas emissions up to the step where the co-product is formed are distributed among the energy carrier (main product) and the co-product in proportion to their energy content. Part of the CO₂-burden is allocated to the co-product in this way. This allocation takes only place for by-products and not for wastes.

(By-)product or waste?

Since part of the CO₂-burden allocates to by-products and not to wastes, it is important to distinguish by-products and wastes. The communication [2] of the EC is guiding, but not comprehensive in this. Also the RED [1] and the NTA 8080 [3] are guiding.

Wastes

When the starting material for a pathway is a waste, the greenhouse gas emissions up to the point of collection of the starting material is considered zero ([2], Annex I, point 16, third paragraph). In other words: the pathway is considered only from the point of

collection; the steps before that are irrelevant and therefore not included in the CO₂-tool.

Allocation in case of CHP

Biofuels for transport pathways (RED, Biograce) always result in a single product: the biofuel (ethanol, biodiesel). The greenhouse gas emission saving is in that case the ratio between the total greenhouse gas emission from the pathway divided by the pathway of the fossil comparator. Pathways of solid biomass used for electricity, heating and cooling are different in this aspects. In CHP-pathways more than one final product is formed, often electricity and heat. The greenhouse gas emission are in these cases distributed among the energy carriers. The allocation factors for electricity and heat are (see Annex I, point 1b and 15 of [2]):

- Allocation factor for electricity $= \frac{C_{el} \times \eta_{el}}{C_{el} \times \eta_{el} + C_h \times \eta_h}$
- Allocation factor for heat $= \frac{C_h \times \eta_h}{C_{el} \times \eta_{el} + C_h \times \eta_h}$

Where:

C_{el} Fraction of exergy in the electricity (=1)

C_h Fraction of exergy in the heat (Carnot efficiency):

For $T_h \geq 150^\circ\text{C}$: $1 - (273/T_h)$

For $T_h < 150^\circ\text{C}$: 0.3546 (=Carnot efficiency at 150°C)

T_h Temperature of useful heat at point of delivery as final energy (K)

η_{el} Electric efficiency

η_h Heat efficiency

In the calculation of the thermal efficiency, only 'useful heat' is accounted for. This excludes heat that is used within the energy generation installation self (parasitic load) and heat that is destroyed or lost. The efficiency is based on annual useful heat output divided by annual energy input.

Parasitic load

Every energy generation installation uses part of the energy produced to maintain the processes: the parasitic load. Examples of this are: electricity for flue gas cleaning equipment, pumps, fans and heat for maintaining the optimum digestion temperature. The parasitic load varies and depends on the type of installation. The parasitic load makes the difference between gross and net energy production. In accordance with the Communication ([2], Annex I), the efficiencies are based on net energy production, so excluding parasitic load. The energy production input numbers in the CO₂-tool are therefore net energy productions in any case.

Final products

The tool contains two types of pathways:

- 1 solid or gaseous biomass → electricity and/or heat and green gas
- 2 biomass → biofuels / bioliquids

We calculate the first type of pathways according Annex I of Communication [2]; the second type according Annex V of the Renewable Energy Directive (RED) [1]. This is because the RED covers (a) biofuels for transport and (b) bioliquids used in other sectors (electricity, heating and cooling) (see [1], Introduction, first sentence). A consequence is that the final product with type 1 is electricity and heat, while the final product in type 2 is a fuel. After all, the RED deals only with biofuels and bioliquids as final product of the pathways (see Annex V of [1], section C, point 2). This is in contrast with the analogous Annex I of [2], point 2). Another consequence is that other fossil comparators are used (see section 2.4 under 'Fossil comparators').

2.3 The greenhouse gas emission of the pathway

According to RED, greenhouse gas emissions from the production of solid and gaseous biomass fuels, before conversion into electricity and heat are calculated as (as given in [2], Annex I, point 1a):

- $E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr}$

Where:

E	total emissions from the production of the fuel before energy conversion
e_{ec}	emissions from the extraction or cultivation of raw materials
e_l	annualised emissions from carbon stock changes caused by land use
e_p	emissions from processing
e_{td}	emissions from transport and distribution
e_u	emissions from the fuel in use, that is green house gases emitted during the combustion of solid and gaseous biomass
e_{sca}	emission savings from soil carbon accumulation via improved agricultural management
e_{ccs}	emission savings from carbon capture and geological storage
e_{ccr}	emission savings from carbon capture and replacement

Emissions from the manufacture or machinery and equipment is not taken into account in the methodology.

The final step is the calculation of the total greenhouse gas emissions from the final energy commodity (as given in [2], Annex I, point 1b):

- a single commodity: $EC_i = \frac{E}{\eta_i}$

Where:

EC_i	total greenhouse gas emissions from the final energy commodity I
--------	--

η_i (electricity or heat)
The efficiency of the conversion ($=\eta_{el}$ or η_h or η_c)

- more than one commodity (CHP): $EC_i = \frac{E}{\eta_i} \left(\frac{C_i \times \eta_i}{C_{el} \times \eta_{el} + C_h \times \eta_h} \right)$

The greenhouse gasses taken into account are carbon dioxide (CO₂), methane (CH₄) and nitrogen dioxide (N₂O). The total greenhouse gas emission is expressed in g CO_{2eq} per MJ of final commodity. The CO₂ equivalents are:

- 1 g CO₂ = 1 g CO_{2eq}
- 1 g CH₄ = 25 g CO_{2eq}
- 1 g N₂O = 298 g CO_{2eq}

Note that these global warming potentials are slightly different from the ones prescribed in [2] (23 and 296 instead of 25 and 296). We use these values because these were used by the European Commission in calculating the default values in the RED [1]. It is expected that these values will be used in future European legislation.

Emissions from combustion

Emissions of greenhouse gases from the combustion of the final fuel are assumed zero according [2], Annex 1, point 12 and the definition of e_u in abovementioned definition of E.

2.4 Greenhouse gas emission reduction

Fossil comparators

The fossil comparators are:

- 198 g CO_{2eq} / MJ electricity (from [2], solid and gaseous biomass)
- 87 g CO_{2eq} / MJ heat (from [2], solid and gaseous biomass)
- 91 g CO_{2eq} / MJ fuel in electricity production (from [1], bioliquids)
- 77 g CO_{2eq} / MJ fuel in heat production (from [1], bioliquids)
- 85 g CO_{2eq} / MJ fuel incogeneration (from [1], bioliquids)

The communication [2] reports no fossil comparators for biogas and green gas. In the present tool we use:

- 67.59 g CO_{2eq} / MJ green gas¹

Calculation of emission reduction

The greenhouse gas emission reduction is the total greenhouse gas emission of the pathway, divided by the total greenhouse gas emission of the pathway of the fossil comparator (as given in [2], Annex I, point 1b):

- SAVING of i = $1 - \frac{EC_i}{\text{fossil comparator of i}}$

where i is the final commodity (electricity, heat).

In case of the production of both electricity and useful heat in a CHP, the saving will be expressed in both commodities;

- SAVING for heat = $1 - \frac{EC_{heat}}{87}$
- SAVING for electricity = $1 - \frac{EC_{electricity}}{198}$

In order to get a single value that can be compared with other CHP's, the tool computes an overall GHG emission reduction (this is not part of the calculation methodology in [1] and [2]). This overall GHG emission reduction is the weighted average of the saving for heat and the saving for electricity, with the allocation factors for electricity and heat as weighting factors. For example: when a pathway gives an emission reductions of 90% for heat and 87% for electricity and allocation factors of 20% for heat and 80% for electricity, the overall GHG emission reduction is: 20% x 90% + 80% x 87% = 88%.

General calculation methodology

The CO₂-tool calculates the total greenhouse gas emissions from a number of pathways. The calculations are based on two types of numbers:

- Input numbers → default values in tool; can be changed by user
- Standard values → fixed values in tool; cannot be changed by user

Table 2 - 2 gives the most important of these numbers.

9/47

¹ This is the emission factor used in Biograce for 'Natural gas (4000 km, EU Mix quality)'. This is 16% higher than the 56.7 emission factor from natural gas as commonly used in the Netherlands and is reported in among others [6]. However, the latter value includes only the combustion emissions and not the emissions from transport and extraction.

Table 2 - 2 Input numbers and standard values

Type	Sub-type	Examples
Input numbers	Energy use	The production of one ton wood pellets from sawdust requires 414 MJ electricity.
	Material use	Per hectare maize, 185 kg N-fertilizer is used for cultivation.
	Yield / moisture content	One kg of wet sewage sludge gives 44 g of dried sewage sludge.
Standard values	GHG emission factors	One MJ of natural gas gives 63 g CO ₂ , 0.20 g of CH ₄ and 0.00022 N ₂ O.
	Lower heating values	The heating value at 0% moisture of wood pellets is 17.1 MJ/kg.
	Global warming potentials (GWP)	The GWP of N ₂ O is 296 on mass basis.
	Transport efficiencies	The fuel efficiency of a dry bulk diesel truck is 0.94 MJ/ ton / km
	Transport exhaust gas emissions	A dry bulk diesel truck produces 0.005 g CH ₄ per ton per km.

The user manual of the CO₂-tool explains in detail how this calculation methodology is implemented in the CO₂-tool.

Co-digestion pathways

Co-digestion is the digestion of manure and co-substrates in the same installation with a single reactor. Since the ratio between manure and co-substrate varies and more than one co-substrate can be used in a digester, there are more variables in co-digestion pathways compared to other pathways such as the combustion of solid biomass. In order to maintain the general structure and format used in the CO₂-tool, the co-digestion pathways are split in separate pathways on separate calculation sheets. An example of a feed (mass-%) to a co-digester is: 30% pig manure, 15% cattle manure, 5% chicken litter, 40% maize and 10% crude glycerine. In this case, the calculation consists of three pathways: for manure (one sheet for all types), for maize and for crude glycerine. Each of these pathways is according the general structure and format. However, the pathways are rather different. Manure is a waste and the pathway starts therefore with the collection of manure while the maize pathway starts with the cultivation and harvesting of maize. Finally, there is a single sheet for the co-digestion pathways. In this calculation sheet, the user fills in the composition of the feed only. This sheet calculates the greenhouse gas emission from the co-digestion by taking the data from the sheets of each of the fees streams (in the example: manure, maize and crude glycerine). The weighting factor is the amount of biogas arising from the substrate. For the example, this means that the only 10% of crude glycerine in the feed, contributes more to the final result than the 50% manure

since the specific biogas yield of crude glycerine is about 40 times higher than manure (see Table 3 - 11 on page 29).

It is important to notice that the separate sheets for the co-substrates are based on co-digestion. These sheets should not be used for calculating a mono-digestion of that co-substrate.

Land use change (LUC)

A land use change (LUC) occurs when the carbon stock per hectare is different for the biomass crop and the reference situation. Therefore, LUC does not occur in pathways based on wastes. Annual emissions from carbon stock changes due to land use change are calculated by spreading the total emissions over twenty years. The carbon stock change is calculated in a separate sheet in the tool that is accessible from the sheets with the pathways. This calculation sheet is based on the sheet within the Biograce project [4] and fully in accordance with the "Commission decision of 10 June 2010 on guidelines for the calculation of land use carbon stocks for the purpose of Annex V of the Directive 2009/28/EC". Indirect LUC is not included in [1], [2], [4] and the current tool.

3 The predefined pathways

3.1 Predefined pathways

The CO₂-tool includes a number of predefined pathways. These pathways are defined by:

- Input blocks (see user manual) for each of the steps in the pathway;
- Default values for the input values in the blocks (see user manual; these values can be changed by the user, but when unknown, the pre-filled-in values can be used).
- Pre-defined Standard values

Currently the following pathways are predefined in the CO₂-tool:

- 1** Heat from wood pellets by combustion in boiler
- 2** Electricity from torrefied wood pellets by cofiring in coal plant
- 3** Electricity from wood pellets by cofiring in coal plant
- 4** Electricity and heat from wood pellets by combustion in CHP
- 5** Electricity and heat from demolition wood by combustion in CHP
- 6** Heat from wood chips by combustion in boiler
- 7** Electricity and heat by combustion of biogas from mono-digestion of manure
- 8** Electricity and heat by combustion of biogas from mono-digestion of maize
- 9** Electricity and heat by combustion of biogas from mono-digestion of organic waste
- 10** Electricity and heat by combustion of biogas from mono-digestion of glycerine
- 11** Electricity and heat by combustion of biogas from mono-digestion of potato remains
- 12** Electricity and heat by combustion of biogas from mono-digestion of sugar beet remains
- 13** Electricity and heat by combustion of biogas from co-digestion of manure + co-substrate (co-substrates to select from 8 , 10 , 11 and 12 by user)
- 14** Green gas from manure by mono-digestion
- 15** Green gas from silage maize by mono-digestion
- 16** Green gas from organic waste by mono-digestion
- 17** Green gas from glycerine by mono-digestion
- 18** Green gas from potato remains by mono-digestion
- 19** Green gas from sugar beet remains by mono-digestion
- 20** Green gas from manure + co-substrate by co-digestion (co-substrates to select from 15 , 17 , 18 and 19 by user)
- 21** Rape seed oil, ready to be used for the production of electricity and/or heat by means of an diesel engine
- 22** Jatropha oil, ready to be used for the production of electricity and/or heat by means of an diesel engine

- 23** Animal fats, ready to be used for the production of electricity and/or heat by means of an diesel engine
- 24** Used frying oils, ready to be used for the production of electricity and/or heat by means of an diesel engine

The coming paragraphs detail these predefined pathways. The pathways that are strongly related with each other are described together in one paragraph. These are the pathways of wood pellets and wood chips for the production of electricity and/or heat and the pathways of digestion with different substrates. Every paragraph starts with a block diagram of the pathway, including all inflows (feedstock, material use, energy use, GHG emissions and commodities). A detailed description of each of the blocks follows the block diagram. This description includes the default input numbers, a motivation why a number was selected and for each number a reference to the (literature) source.

The abovementioned pathways 21 - 24 are pathways of liquid biomass. The methodology is therefore completely analogous to Biograce (see also 'Final products' in section 2.2).

3.2 Electricity and heat from wood pellets by boiler, CHP and Co-firing

Process description

The system described here documents routes through which sawdust is converted into wood pellets that are used as feedstock for electricity and heat production through three different conversion technologies, i.e. combustion in boiler, combustion in CHP and co-firing in a coal-fired power plant. The flowchart of the process is illustrated in Figure 3 - 1.

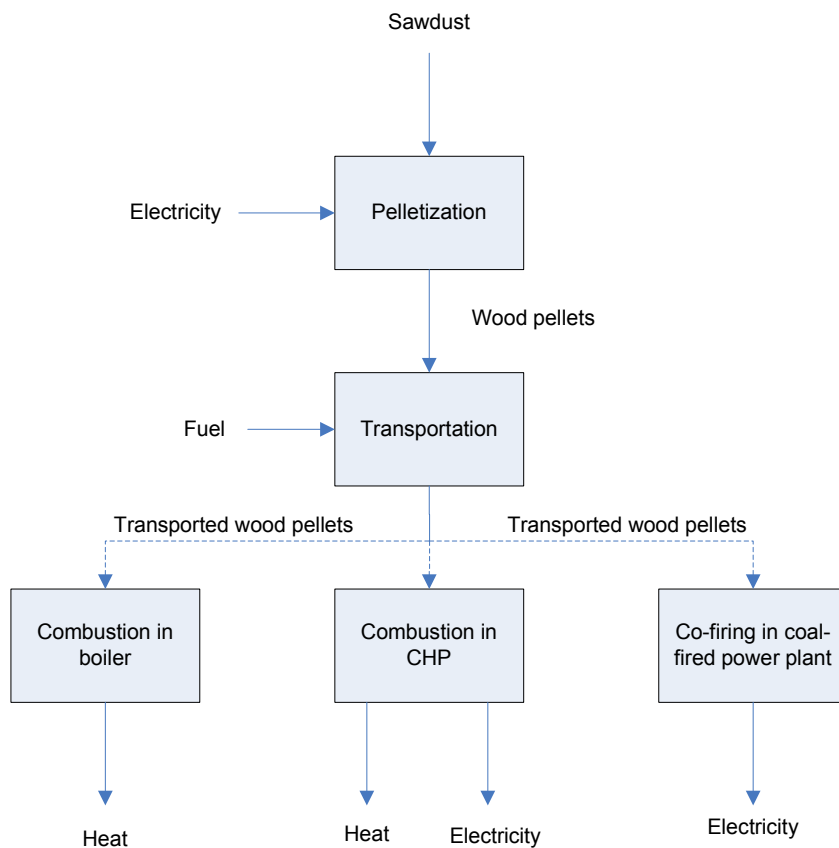


Figure 3 - 1 Flowchart of pathway of electricity and heat production from combustion of wood pellets in CHP, boiler and coal plant (co-firing)

The electricity production pathway is separated into the three stages listed below:

- Pelletization
- Transportation of wood pellets
- Combustion in boiler, CHP or coal plant (co-firing)

The sawdust from wood processing is pressed to wood pellets in Canada. We assume that the production of sawdust and the pellet production occurs at the same site. The produced pellets are then shipped by truck to a harbour and loaded onto a transoceanic ship, which transports the pellets to a harbour in the Netherlands (Rotterdam harbour). The pellets are then transported through road transport to a power plant where they are used as a feedstock for electricity and heat production through different means.

Typically, wood pellets are used in 3 different appliances; combustion in boiler for the production of heat, combustion in CHP for the combined production of electricity and heat and co-combustion in a large coal-fired power plant. Direct emission of CO₂ from the combustion of wood pellets can be neglected as CO₂ is assumed to be biogenic. Other emissions from wood pellet combustion are also neglected following the calculation methodology in Annex I of [2].

The wood used for pellets is a waste product from lumber manufacturing. Therefore, 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. We assume there are no losses in collection of sawdust.

Pelletization

During the processing, wood waste such as sawdust and shavings are produced with a moisture content of around 40% [8]. This waste wood is then dried and pressed into wood pellets on-site. Drying can be accomplished using electricity or by burning a portion of the waste wood in a furnace used for heating. We assume that the pelletization process uses only electricity. Wood pellets typically have 6% moisture content. Assuming a material loss of 1%, the yield of wood pellets will be around 0.632 ton pellets per ton of sawdust (this is: $(1-0.4)/(1-0.06)*0.99 = 0.632$).

For the processes defined above, the difference between the wood pellet manufacturing in Europe and that in Canada relates to the electricity used. Each of these locations has different amounts of renewable electricity present in their electricity mix. We assume that the pellets are produced in Canada, which has a much lower emission factors due to a larger share of renewable energy in electricity production (>50% renewable due to hydroelectricity). The electricity emission factors for Canadian mix are taken from [5]. The electricity requirement for pellet production is typically 115 kWh per ton pellets [5].

Transportation of wood pellets

The produced pellets are then transported by truck to a harbour and loaded onto a transoceanic ship, which transports the pellets to a harbour in the Netherlands. Transport from the processing plant to the harbour is done by lorry. We assume a representative distance of 60 km, as reported in [5]. Further, we assume that the shipment of the pellets from Canada to the Netherlands is accomplished through a 9,000 ton transoceanic freighter using HFO as fuel. The distance between Eastern Canada to Rotterdam is typically reported to be 5,000 km [5].

Once in the Netherlands, transport of the wood pellets will be done by lorry. A local combustion plant would be 100 km away from the harbour, and could be feasibly serviced by a 28t lorry. Consequently, the total distance for transportation of wood pellets equals 160 km. The transport losses are assumed to be 1%.

Combustion in boiler

The typical application of wood pellets in the CO₂-tool is the combustion in a small scale decentralized heat production system with a thermal capacity of <1 MW_{th}. Wood pellets are brought to the plant as main feedstock. Possible small amounts of fuel oil used to ignite the burner are neglected. The process is assumed to have an efficiency

of 90%, which is typical for small combustion systems for heat production. The functional unit is defined as the supply of low temperature heat (90°C). We assume there is no loss of pellets. The user should fill in the actual performance parameters of the boiler. The example values in the tool are given in Table 3 - 1.

Table 3 - 1 Example values conversion step in pathway wood pellet boiler (basis is ≈ 750 kW boiler @ 8500 h/year)

Parameter	Starting value	Unit
Useful heat	23225	GJ _{heat} / year
Temperature	90	°C
Input	1500	ton _{Transported pellets} / year

Combustion in CHP

The described system refers to a medium scale centralized electricity production system with a net power output of 5 MW_e. Wood pellets are brought to the power plant as main feedstock. Amounts of fuel oil are used to ignite the burner are neglected. The production of electricity is delivered to the high voltage grid, and finally converted to low voltage electricity grid. The produced heat is also considered a product. The user should fill in the actual performance parameters of the CHP. The example starting values in the tool are given in Table 3 - 2.

Table 3 - 2 Example values conversion step in pathway wood pellet CHP (basis is ≈ 5 MW_e CHP @ 8000 h/year)

Parameter	Starting value	Unit
Electricity	40000	MWh _{electricity} / year
Useful heat	250000	GJ _{heat} / year
Temperature	90	°C
Input	33000	ton _{Transported pellets} / year

Combustion in coal plant (co-firing)

Electricity is produced in a large scale centralized coal-fired power plant. Wood pellets are directly co-fired with coal. Coal is mined and transported to the power plant as main feedstock. The electricity production of the co-firing process is separated into 2 parts: for wood pellets and for coal, based on the energy content of the fuels. Only the electricity from wood pellets and the accompanying necessary inputs are taken into account. The heat is considered a waste and the system is optimized for electric efficiency [5].

The user should fill in the actual performance parameters of the CHP. The example starting values in the tool are given in Table 3 - 3.

Table 3 - 3 Example values conversion step in pathway wood pellet co-firing (basis is $\approx 850 \text{ MW}_e$ power plant @ 8760 h/year and 10% co-firing)

Parameter	Starting value	Unit
Electricity	750	$\text{GWh}_{\text{electricity}} / \text{year}$
Useful heat	0	$\text{TJ}_{\text{heat}} / \text{year}$
Temperature	0	$^{\circ}\text{C}$
Input	400	$\text{kton}_{\text{Transported pellets}} / \text{year}$

3.3 Electricity and heat from wood chips by boiler, CHP and Co-firing

Process description

The system described here documents routes through which wood waste (from wood processing) or demolition wood (wood after use) is converted into wood chips and then used as a fuel for electricity and heat production through three different conversion technologies, i.e. combustion in boiler, combustion in CHP and co-firing in a coal plant as torrefied wood pellets. The flowchart of the processes is illustrated in Figure 3 - 2.

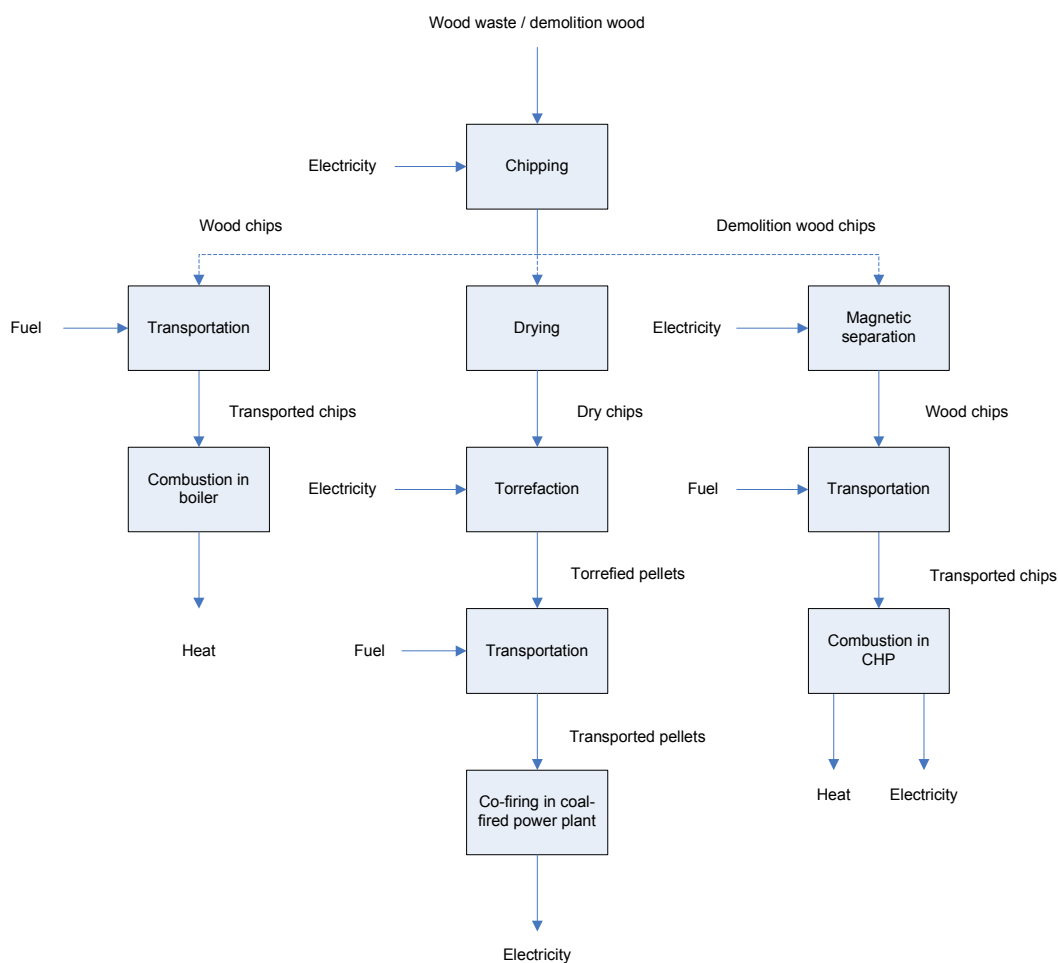


Figure 3 - 2 Flowchart of pathway of electricity and heat production from combustion of wood chips in CHP, boiler and coal plant (co-firing after torrefaction)

We assume that all pretreatment steps (chipping, torrefaction, etc.) take place at the same site as where the waste comes available. The produced fuel is then transported to the power plant where it is used for electricity and/or heat production. The systems described in this section extend upstream to the point where wood residue is generated.

As stated before, emission of CO₂ from any combustion of wood can be neglected as CO₂ is assumed to be biogenic. Other emissions from wood combustion are also neglected following the calculation methodology in Annex I.

3.3.1 Electricity from torrefied wood pellets by cofiring in coal plant

This section describes the pathway of using torrefied wood chips for co-firing in a coal-fired power plant. Torrefaction of wood is a process through which the woody feedstock is converted into a product that has increased energy density and

characteristics that make it easy to handle and transport and therefore become suitable to co-fire in existing coal-fired power plants at high co-firing percentages.

The wood is assumed to originate from Canada, where it is chipped, dried, torrefied and pelletized at the same site as where the wood processing residues become available. The resulting torrefaction pellets are combusted in a Dutch coal-fired power plant after transportation by ship to the Netherlands. The pathway through which electricity is produced by co-firing torrefaction pellets consists of five:

- Chipping of wood waste
- Drying of wood chips
- Torrefaction of wood chips and pelletization to torrefaction pellets
- Transportation of torrefaction pellets
- Co-firing of torrefaction pellets in coal-fired power plant

Chipping of wood waste

The wood used for chipping is a waste product from lumber manufacturing in the Canada. The initial moisture content of wood waste approximates 50%. If the wet wood is allowed to dry for a few months in the air the moisture content is lowered to about 30%. With the assumption of 1% wood loss during chipping, the yield of wood chips will be around 0.707 ton chips per ton wood waste (this is: $(1-0.5)/(1-0.3) * 0.99 = 0.707$). The average electricity consumption during the chipping process is reported to be 75 kWh per ton wood waste [5].

Drying of wood chips

The biomass should be dried a further 15% to 10% in order it to be suitable for the torrefaction process [14]. This is one of the most important steps in the total torrefaction process, as evaporation of water is very energy consuming. The energy for the drying is generated by a furnace that is fuelled with a part of the wood chips. We assume this requires 15% of the total wood chips. Therefore, no fossil fuel is required for the drying process. Because of the weight loss during the drying process, the dry chips yield will be 0.778 ton per ton fresh chips (this is: $(1-0.3)/(1-0.1)$). Since 15% is used for the drying, this is 0.661 ton per ton fresh chips.

Torrefaction of wood chips

Torrefaction is a thermal pre-treatment technology performed at atmospheric pressure in the absence of oxygen. The dried wood chips are brought into the torrefaction reactor that operates at around 250°C. It is assumed that heat for the process is supplied by the 'tor gas' from the torrefaction process itself. The wood chips will convert into a solid uniform product with very low moisture content and a high calorific value compared to fresh biomass. Torrefied biomass typically contains 70% of its initial weight (the mass yield) and 90% of the original energy content [14]. After torrefaction, it is common to pelletize the material. This is seen as part of the torrefaction process here. The LHV of torrefied wood pellets is in the range of 18-23 MJ/kg [14] at 97% dry substance. Based on this, it is assumed to use an average LHV

of 21.13 MJ/kg for dry torrefied pellets. The electrical input to the system is reported to be 102 kWh per ton wood input (including size reduction and pelletization) [14].

Transportation of torrefied wood

The transportation route of torrefied wood pellets is similar to the transportation route of wood pellets from Canada described in section 3.2, i.e. 5000 km ocean shipping and 160 km road transport with a material loss of 1% during transportation.

Combustion in coal plant (co-firing)

This process is the same process as the coal-fired power plant described in section 3.2. Thus, the system is optimized for electric efficiency without the utilization of heat. The user should fill in the actual performance parameters of the coal-fired power plant. The example values in the tool are given in Table 3 - 4.

Table 3 - 4 Example values conversion step in pathway torrefied wood pellets co-firing (basis is \approx 850 MW_e power plant @ 8760 h/year and 10% co-firing)

Parameter	Starting value	Unit
Electricity	750	GWh _{electricity} / year
Useful heat	0	TJ _{heat} / year
Temperature	0	°C
Input	335	kton _{Transported pellets} / year

3.3.2 Heat from wood chips by combustion in boiler

The system described in this section represents a small scale combustion plant using fresh wood chips from the Netherlands as feedstock. Wood chip boilers can be used to provide central heating or process heating. They can be installed alongside, or to replace, existing gas, coal, or oil boilers. This system includes the next processes:

- Chipping of wood waste
- Transportation of wood chips
- Combustion in boiler

Chipping of wood waste

The starting material are prunings and trimmings. The initial moisture content of this woody waste approximates 50%. If the wet wood is allowed to dry for a few months in the air the moisture content is lowered to about 30%. We assume 1% wood loss during chipping. The resulting yield of wood chips is then 0.707 ton chips per ton wood waste (this is $(1-0.5)/(1-0.3) * 0.99$).

The average electricity consumption during the chipping process is reported to be 75 kWh per ton wood waste [5].

Transportation of wood chips

Transport of wood chips will be by lorry. A local biomass conversion plant is assumed to be 100 km away from wood chips production site and could be feasibly serviced by a 28t lorry. The transport losses are neglected.

Combustion in boiler

The typical application of wood chips in the CO₂-tool is the combustion in a small scale decentralized heat production system with a thermal capacity of <1 MW_{th}. Wood pellets are brought to the combustion installation as main feedstock. Possible small amounts of fuel oil used to ignite are neglected. The process is assumed to have an efficiency of approximately 90%, which is typical for small combustion systems for heat production. The functional unit is defined as the supply of low temperature heat (90°C). The user should fill in the actual performance parameters of the boiler. The example values in the tool are given in Table 3 - 1.

Table 3 - 5 Example values conversion step in pathway wood chips boiler (basis is ≈750 kW boiler @ 8500 h/year)

Parameter	Starting value	Unit
Useful heat	23225	GJ _{heat} / year
Temperature	90	°C
Input	2000	ton _{Transported pellets} / year

3.3.3 Electricity and heat from demolition wood by combustion in CHP

Demolition wood produced during demolition of buildings is another feedstock that can be used for the production of electricity and heat. The pathway does not differ much from the system of combustion of wood chips in a boiler described in section 3.3.2. The only difference is the source of the feedstock and an additional separation process to separate woody biomass from inert fraction such like metals and other contaminations. The system consists of the following processes:

- Chipping of demolition wood
- Magnetic separation
- Transportation of wood pellets
- Combustion in CHP

Chipping of demolition wood

The moisture content of demolition wood approximates 12% [13]. When neglecting wood losses during chipping, the yield of wood chips will be around 1 ton chips per ton wood waste as the moisture content of wood will be the same after the chipping process. The average electricity consumption during the chipping process is reported to be 75 kWh per ton wood waste [5].

Magnetic separation

The magnetic separation process is intended to remove nails and other fasteners from the demolition wood. This process takes place at the same location as chipping. The electricity requirement for this process is reported to be 0.6 kWh average per ton wood chips [5]. We assume a 1% loss by the removed materials.

Transportation of demolition wood chips

The chipped demolition wood is transported to the plant by truck. A local biomass conversion plant is assumed to be 50 km away from wood chips production site [5]. The transport losses are neglected.

Combustion in CHP

The described system refers to a medium scale centralized direct combustion power plant with a net capacity of 5 MW_e. The system burns chipped and cleaned demolition wood directly in boilers that supply steam for the same kind of steam-electric generators used to burn fossil fuels. A small amounts of fuel oil are possibly used to ignite the burner are neglected. The production of electricity is delivered to the high voltage grid, and finally converted to low voltage electricity grid. The produced heat is considered as a product. The user should fill in the actual performance parameters of the CHP. The example values in the tool are given in Table 3 - 2.

Table 3 - 6 Example values conversion step in pathway demolition wood chips CHP (basis is ≈5 MW_e CHP @ 8000 h/year)

Parameter	Starting value	Unit
Electricity	40000	MWh _{electricity} / year
Useful heat	250000	GJ _{heat} / year
Temperature	90	°C
Input	33000	ton _{Transported pellets} / year

3.4 Green gas production from biogas by mono-digestion of manure, maize, potato remains, sugar beet remains, glycerine and organic waste

Process description

The system described here documents routes through which 6 different substrates, i.e. manure, maize, organic waste (in Dutch: GFT), potato remains, sugar beet remains and glycerine can be used as a feedstock for the production of biogas through anaerobic mono-digestion which subsequently will be upgraded to green gas. Green gas is upgraded biogas with 88 volume-% methane. Apart from the pathway for maize, all pathways of the substrates do not include a cultivation phase as they are waste streams. Therefore, the pathways for all the substrates are identical except the pathway for maize which includes an additional cultivation phase. The flowchart of the process is illustrated in Figure 3 - 3.

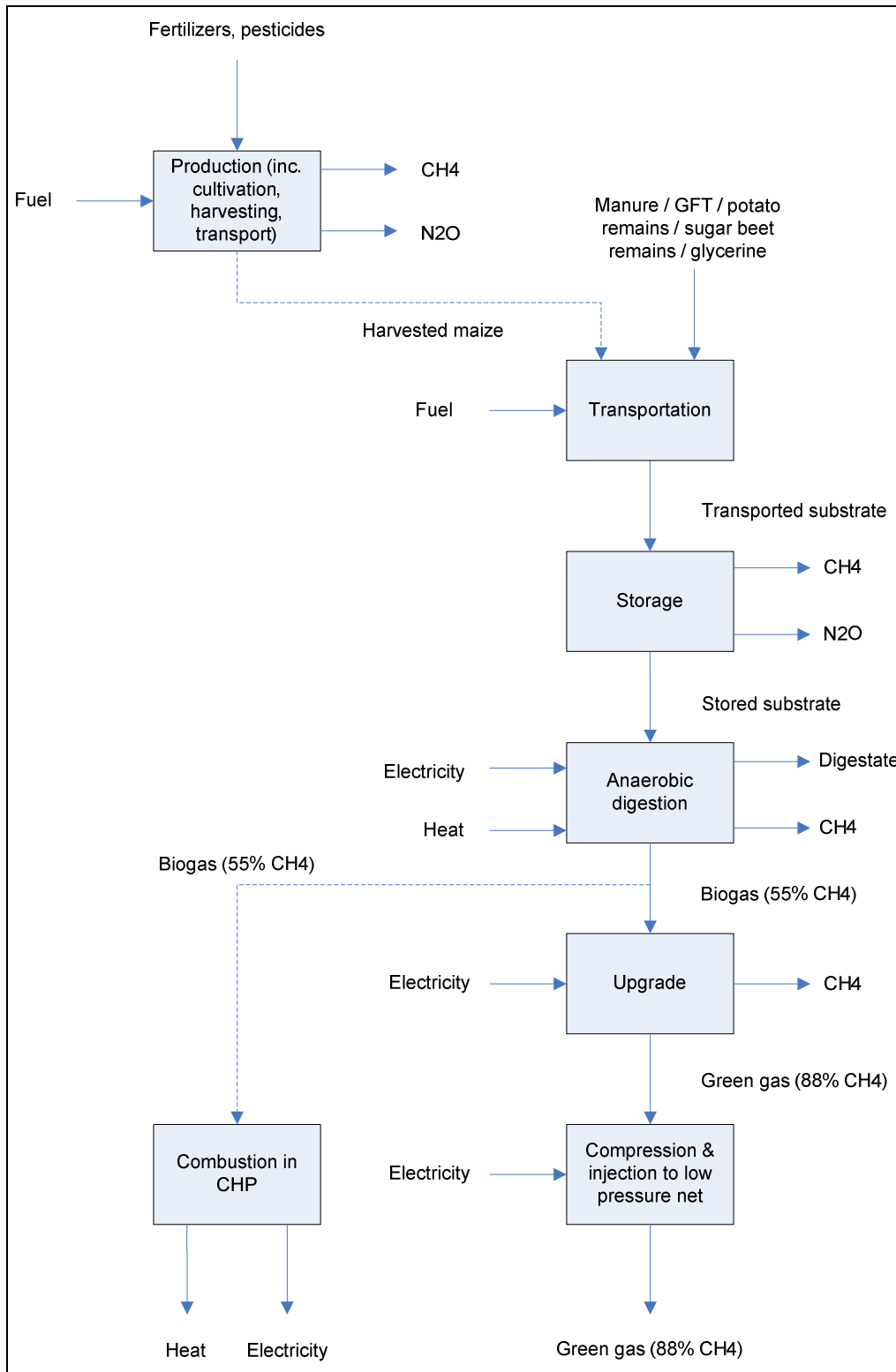


Figure 3 - 3 Flowchart of pathway of green gas production from mono-digestion of different substrates and electricity and heat production from combustion of biogas

The green gas production pathway includes the five stages listed below:

- Transport of substrate
- Storage of substrate

- Anaerobic mono-digestion of substrate
- Biogas upgrade
- Compression of green gas and injection to the net

For the production of electricity and heat, the system includes a CHP process instead of upgrading and compression processes. The system processes will then be:

- Transport of substrate
- Storage of substrate
- Anaerobic mono-digestion of substrate
- Combustion in CHP

The described system refers to a large scale centralized system (typically 1.5 – 5 MW_e in case of a CHP configuration). This means that the processes for feedstock production, conversion and end use are situated on different sites and therefore transport of substrate, digestate (digested substrate) and energy is taken into account. In CHP-configurations, part of the produced electricity and heat is used for the operation of the digester (heat for the digestion tanks and electricity for pumps etc.) In the case of green gas as final commodity, part of the produced biogas is used for heating the digestion tanks. Electricity is purchased from the grid. It is important that net electricity and heat production is filled in the tool instead of gross values.

Manure, organic waste (GFT), potato remains, sugar beet remains and glycerine are considered waste streams which means that emissions of GHG from livestock husbandry, agricultural production and food industry are not considered part of the production of green gas. Therefore, the system is cut off at the production of these substrates and that upstream processes are not taken into account. Silage maize is considered an energy crop. Therefore, the system starts at the production of maize which includes cultivation, harvesting, mechanical treatment and transportation. The downstream processes for maize are identical to other pathways.

The emissions from the storage of digested substrate up to the application of it on land will be excluded from the system as the produced digestate is considered a produced waste. Therefore, nothing is allocated to the digestate. Emissions from the digestate storage are not included, according to the biogas pathways in Biograce [4].

Greenhouse gases will be emitted during the combustion of biogas. However, as stated before, the emissions from the fuel in use emitted during the combustion of solid and gaseous biomass should be neglected according to the calculation methodology in Annex I of [2].

The heating values and the moisture contents of substrates are the important parameters that influence the GHG emissions. An overview these parameters per substrate and the source of the numbers is given Table 3 - 7.

Table 3 - 7 Moisture contents of the substrates

	Lower heating value LHV (dry) [MJ/kg]	Source LHV	Moisture content [%]	Source moisture content
Manure	10.0	[4]	92	[4]
Maize	18.5	[4]	70	[20]
Potato remains	5.0	[15]	22	[5]
Sugar beet remains	6.5	[15]	17	[5]
Organic waste (GFT)	10.9	[5]	54	[5]
Glycerine	16.0	[4]	0	[5]

Mono-digestion and co-digestion

The six substrates that are mentioned in this section are not all suitable or likely to be used for mono-digestion or co-digestion. This is indicated in Table 3 - 8.

Table 3 - 8 Possible use of substrates in mono- and co-digestion

	Mono-digestion	Co-digestion with manure
Manure	yes	Not applicable
Maize	Yes	Yes
Potato remains	No	Yes
Sugar beet remains	No	Yes
Organic waste (GFT)	Yes	No
Glycerine	No	Yes

The main reason that municipal organic waste (Dutch: GFT) is not co-digested with manure is that the digested material from organic waste can be composted. Compost is a more valuable material than digestate (digested manure). The parameters that describe the pathway of organic waste digestion are similar to the other pathways. For this reason, organic waste is treated alike the co-substrates in this section.

How the GHG emission savings in co-digestion pathways are calculated in the tool, can be found in the accompanying user manual.

Cultivation of maize

The production, including cultivation, harvesting and transportation, of silage maize occurs off site. Because maize is an (energy) crop, the emissions related to the production of maize should be taken into account. In this case, the emissions during the production of maize are based on KWINDATA for silage maize cultivated on sandy soil in southern and eastern part of the Netherlands [20]. These regions are known as the most important cultivation zones for silage maize in the Netherlands. Silage maize will be produced with a yield of 13,060 kg dry substance per hectare with a moisture

content of 70%. This corresponds to a wet yield of 44 ton per hectare. For the cultivation of silage maize, 185 kg of N-fertiliser and 150 kg of K₂O-fertiliser per hectare is required. Besides that, 50 litre of diesel (equal to 1,793 MJ) per hectare is required for harvesting and transport of the product. This equals to 1,793 MJ diesel per hectare. The field N₂O emission during the production of silage maize in sandy soil in the Netherlands is reported to be 1.92 kg N₂O per hectare [21].

Transport of substrate

It is assumed that manure will be collected from local farms. Therefore a transport distance of 10 km is assumed, using 28t trucks [4]. Maize, potato remains and sugar beet remains will be transported to the site over a distance of 50 km, using 28t lorries [4]. For organic waste (GFT), an average transportation of 100 km is assumed to the site [5].

There are a few biodiesel plants in Netherlands that produce glycerine. Therefore, it is likely that crude glycerine is imported from European (mainly Germany) biodiesel plants through road transport. It is assumed that glycerine will be transported to the site over a distance of 150 km, using a 28t lorry. It is assumed that there will be no loss of substrates during the transportation from production location to the site.

An overview of the assumed transportation distances is given in Table 3 - 9.

Table 3 - 9 Assumed transportation distances

	Assumed transportation distance to the site [km]
Manure	10
Maize	50
Potato remains	50
Sugar beet remains	50
Organic waste (GFT)	100
Glycerine	150

Storage of substrate

Maize, potato remains, sugar beet remains, organic waste (GFT) and glycerine is assumed to be stored on site over a longer period compared to manure. Therefore, emissions may occur from the storage of this biomass. In the tool as developed by CML [5], the GHG emissions are reported to be 3.1 kg CH₄ and 0.014 kg N₂O per tonne of manure, maize, organic waste or potato remains [5] as conservative and typical values (for all these substrates the same). The 'best available' values are zero. In Biograce, only biogas from manure and organic waste pathways are included. Here, the emissions from storage are neglected. CML [5] extracted the values from Alterra report [19]. In this report, storage is assumed in the form of silage (Dutch: inkuilen). The reported emission factors (that are adopted by CML) are based on this type of

storage. However, based on the characteristics of potato remains, sugar beet remains and organic waste (GFT) we know that storage of these products is not done by silage. Moreover, the mentioned materials are waste products and subsequently not stored for the purpose of digestion only. When these materials are not digested, they are stored to be used as animal feed. The numbers reported by CML are therefore not applicable for these materials. Therefore we adopt the zero-emission assumption of Biograce and the also zero 'best available' value of CML. Since glycerine is stored in tanks, zero emissions are assumed there.

Ensilage is applicable to maize. This suggests to use the 3.1 kg CH₄ and 0.014 kg N₂O per tonne for the storage of maize. Reviewing the assumptions in the Alterra report [19], we notice that the authors assume that these emissions from cosubstrates is the average of pig and cattle manure (average of 1.8 and 4.65 ≈ 3.1) because of the lack of actual numbers. This makes the value of 3.1 for maize questionable as well. Since in silages the material is covered by plastic to avoid aerobic degradation of the material (loss of material and quality), the formation of 3.1 kg methane (=4.7 m³) per tonne of maize would be noticeable. In practice, this is not observed. Therefore we reject this value.

Finally, the Alterra report [19] states that 95% of the reported maximum emissions from the storage of manure can be avoided by minimizing the storage period. Based on the typical storage capacity of digesters that are in operation in the Netherlands, we can conclude that the storage period (on site) is short. For this reason we assume an emission from manure storage of 5% of 3.1 and 0.014, which is 0.155 kg methane per tonne of manure and 0.0007 kg N₂O per tonne of manure. This is based on 50% pig and 50% cattle manure.

An overview of the assumed GHG emissions during the storage of the substrates is given in Table 3 - 10.

Table 3 - 10 Emissions during storage per substrate

	CH ₄ [kg/ton substrate]	N ₂ O [kg/ton substrate]
Manure	0.155	0.0007
Maize	0	0
Potato remains	0	0
Sugar beet remains	0	0
Organic waste (GFT)	0	0
Glycerine	0	0

Anaerobic mono-digestion of substrate

This step in the pathway includes the anaerobic digestion of the substrate. Typical values for the biogas yield and the methane content of the produced biogas from

different substrates are given in Table 3 - 11. We assume that 1% of the produced biogas will be emitted during the digestion process [5]. This is for example for manure: $21 \text{ m}^3 \text{ biogas} / \text{ton manure} \times 1\% \text{ leakage} \times 55\% \text{ methane} \times 0.71 \text{ kg methane/m}^3 \text{ methane} = 0.082 \text{ kg} / \text{ton manure}$. The methane leakage is also given in Table 3 - 11.

The energy consumption of a large scale decentralised digester is reported as 110 MJ and 16.7 kWh per ton substrate respectively for heat and electricity [5]. This is assumed to be equal for all substrates. In the Green Gas pathways, we assume that a small CHP-installation is used to generate heat and electricity. For this reason, the net biogas yield in the calculation sheet is reduced by this internal use. For example: When 1 ton of manure gives 21 Nm^3 biogas (see Table 3 - 11) with a LHV of 19.5, the net biogas yield is $21 - (110+60)/19.5 = 15.4 \text{ Nm}^3/\text{ton manure}$ (see Table 3 - 12). In general this is:

$$\text{Net biogas yield} = \text{Gross biogas yield} - \frac{\text{Specific parasitic load}}{\text{LHV biogas}}$$

$$\text{For manure this is: } 21 \frac{\text{m}^3}{\text{ton}} - \frac{170 \frac{\text{MJ}}{\text{ton}}}{0.55 \frac{\text{m}^3 \text{CH}_4}{\text{m}^3 \text{Biogas}} \times 0.71 \frac{\text{kgCH}_4}{\text{m}^3 \text{CH}_4} \times 50 \frac{\text{MJ}}{\text{kgCH}_4}} = 12.3 \frac{\text{m}^3}{\text{ton}}$$

Please note that in the CHP calculation sheet, the total amount of biogas is fed to the CHP. In the above example, this means that the value of the biogas yield in that case is $21 \text{ Nm}^3/\text{ton}$.

Table 3 - 11 Digester data for different substrates in CHP-pathways

	Gross biogas yield [m ³ /ton substrate] [5]	Methane content [%] [5]	Usage of natural gas [MJ/ton substrate] [5]	Usage of electricity [kWh/ton substrate] [5]	Methane leakage [kg/ton substrate]
Manure	21	55	110	16.67	0.082
Maize	143.75	55	110	16.67	0.56
Potato remains ²	150	52	110	16.67	0.55
Sugar beet remains	96	52	110	16.67	0.35
Organic waste (GFT)	90	55	110	16.67	0.35
Glycerine	846	50	110	16.67	3.00

Table 3 - 12 Calculated net biogas yields for different substrates in green gas pathways

	Net biogas yield for green gas pathways[m ³ /ton substrate]
Manure	12.3
Maize	135.0
Potato remains	140.8
Sugar beet remains	86.8
Organic waste (GFT)	81.3
Glycerine	836.4

Biogas upgrade

Biogas with a typical methane percentage of between 50% and 65% CH₄ will be processed to green gas with an approximate CH₄ content of 88% (as Dutch natural gas). We assume that for the upgrading process, a cryogenic system is used. During the process of upgrading not all biogas will end up in the green gas. For cryogen systems, the methane "leak" will be typically around 1 % of produced green gas [5]. The volumetric green gas yield can then be calculated by dividing the percentage methane in biogas (50%-65%) by the percentage of methane in green gas (88%) and correct for the loss of green gas (1%) during upgrading. For example: Biogas with a methane content of 55% that is upgraded to green gas, gives a yield of $0.55 / 0.88 * (1-0.01) = 0.619$ m³ green gas per m³ biogas. The volumetric yields of green gas per substrate and the methane emissions per substrate are given in Table 3 - 13.

² Medium starch content

The upgrading process 1.1 MJ electricity per m³ green gas (88% CH₄) [5]. The electricity requirement in kWh per m³ biogas per substrate is given in Table 3 - 13 as well.

Table 3 - 13 Data for biogas upgrading for different substrates

	Green gas yield [m ³ / m ³ biogas]	Methane leakage [kg/m ³ biogas]	Electricity use [kWh/m ³ biogas]
Manure	0.619	0.0039	0.19
Maize	0.619	0.0039	0.19
Potato remains	0.585	0.0037	0.18
Sugar beet remains	0.585	0.0037	0.18
Organic waste (GFT)	0.619	0.0039	0.19
Glycerine	0.563	0.0035	0.17

The biogenic carbon dioxide 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 carbon dioxide are assumed.

Compression of green gas and injection to the net

The green gas is delivered to the local low pressure network of 8 bar. The electricity consumption for compression is calculated to be 0.13 kWh per m³ green gas. This number is based on the theoretical electricity consumption for the compression of methane as ideal gas at atmospheric conditions to 8 bar with considering 90% compression efficiency.

The green gas might also be injected to the high pressure network of 40 bar. The calculated theoretical compression energy will then be 0.25 kWh per m³ green gas with the same assumptions as for the low pressure network. An overview of the compression energies are summarized in Table 3 - 14.

Table 3 - 14 Compression energies

	Network pressure [bar]	Compression efficiency	Compression energy [kWh/m ³]
Low pressure network	8	90%	0.13
High pressure network	40	90%	0.25

The example values in the sheets are the ones for the 8 bar network.

Combustion of biogas in CHP

The biogas is combusted in a $\approx 1 \text{ MW}_e$ CHP that produces both heat and electricity with a gross electric efficiency of 42% [5]. and a thermal efficiency of 0% (no external heat utilization) This resembles a typical CHP with an electrical capacity of $<10 \text{ MW}_e$ operating for around 8000 hours a year. A part of the produced heat is used internally to heat up the digester (35-40°C). Also part of the produced electricity is used within the system for mixing and pumping etc.: the parasitic load. On average, 16,67 kWh (= 60 MJ) electricity and 110 MJ heat per ton substrate is consumed by internal processes [5]. The remaining electricity is delivered to the low voltage electricity grid. The excess heat around 90°C is considered as waste and will not be applied for external use. This means that the thermal efficiency of the installation equals zero. It is important to fill in the net electricity production, so excluding the parasitic load.

During combustion in CHP, part of the consumed biogas will be emitted (methane slip). This emission is assumed to be 1% of the consumed biogas [5].

The user should fill in the actual performance parameters of the CHP. The example values in the tool are given in Table 3 - 15. It should be noted that these values are all based on 42% gross electric efficiency. The differences in net electric efficiencies are caused by the differences in biogas yields. Since the electric parasitic load depends on the feed in mass, a feedstock with a low biogas yield, consumes a relative large portion of the electricity produced from the biogas. For example: when the 1 MWe CHP is in operation for 8000 hours per year, the gross electricity production is 8000 MWh. To produce this from manure, the plant requires 167,230 tons of manure (based on 21 m³ biogas per ton manure with 55% methane and a gross CHP efficiency of 42%). However, the plant itself needs $167230 * 16,67 / 1000 = 2,788 \text{ MWh}$ to process the manure. The net efficiency, based on a net production of $8000 - 2,788 = 5,212 \text{ MWh}$, is then 27.4%. The example values in Table 3 - 15 are calculated in the same way.

Table 3 - 15 Example values in digestion pathways (based on a 1 MWe CHP plant and 8000 hours per year)

	Net electricity yield [MWh/year]	Net electrical efficiency CHP [%] (calculated value)	Input materials [ton/year]
Manure	5212	27.4	167237
Maize	7592	39.9	24431
Potato remains	7587	39.8	24764
Sugar beet remains	7355	38.8	38583
Organic waste (GFT)	7349	38.6	39022
Glycerine	7923	41.6	4566

3.5 Jatropha oil, ready to be used for the production of electricity and/or heat by means of an diesel engine

Process description

Jatropha oil is a relatively new vegetable oil. The jatropha plant can be cultivated on marginal lands. The oil is recovered by crushing the seeds of the plant. The oil is transported to Europe where it is used as fuel for the generation of electricity and/or heat. We assume a jatproha plantation in (North) East India. All numerical data on yields and transports are taken from a study by Ecofys for D1 oils in 2008 [16]. The pathway consists of the following processes:

- Cultivation of jatropha
- Transport of seeds
- Extraction of oil
- Oil transport
- Oil refinery
- Transport of PVO (Pure Vegetable Oil)

The flowchart of the process is illustrated in Figure 3 - 4.

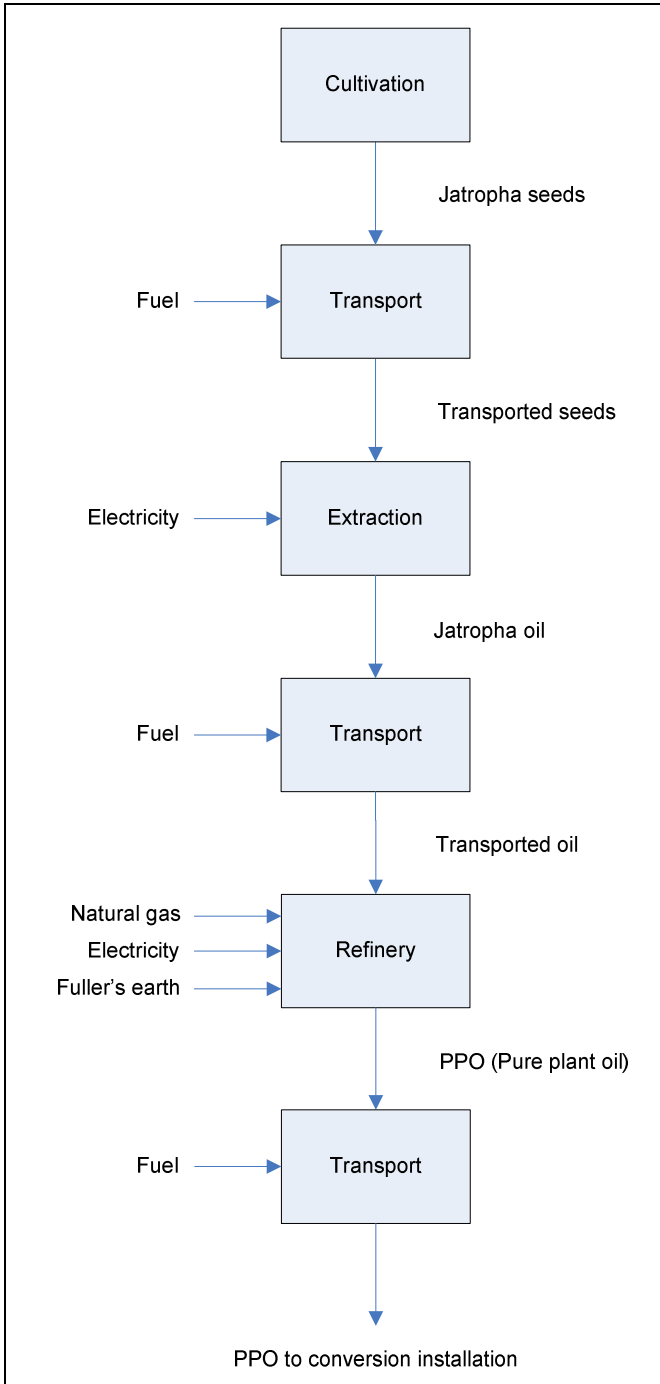


Figure 3 - 4 Flowchart of pathway of PPO production from jatropha

Cultivation

Since this plant is known from its ability to grow on marginal lands, we assume cultivation without the use of agro-chemicals (fertilizer, compost, pesticides). We use a yield of 4.5 tonnes of seeds per ha (so this excludes the hulls from the fruit). This estimate is based on cultivation without agro-chemicals. We assume a manual harvesting without the use of fuels. The seeds are dried in the sun.

Transport of seeds

The sun-dried seeds are transported over 150 km by a truck to an oil extraction facility. We assume a zero loss of seeds.

Extraction of oil

In the oil extraction facility, the shells and kernels are separated and the oil is extracted from the kernels with an overall efficiency of 0.25 kg extracted oil and 0.50 kg press cake (jatropha meal) per kg sundried seeds. This corresponds to 0.4348 MJ extracted oil and 0.4478 press cake per MJ jatropha seed. The electricity use of this step is 6 kWh per tonne oil which corresponds to 0.0006 MJ electricity per MJ crude vegetable oil.

Oil transport

The extracted, unrefined, oil is transported by 750 km by truck and 15.000 km by ship to a refinery in Europe. We assume a zero loss of crude vegetable oil during the transportation. The transportation over the ocean will be carried out by ship / product tanker 50kt using HFO as fuel.

Oil refinery

The oil is refined to a PVO (Pure Vegetable Oil) quality that can be used in stationary diesel engines that can be used in CHP's. It is important to know that there is no transesterification to biodiesel and also not a hydrogenation to HVO (Hydrogenated Vegetable Oil). The refinery of the oil is a simple cleaning step. We assume that this refinery step is the same as refining rape seed oil. All data from this refining step is from Version 3.4 (January 2011) of the Biofuels GHG Calculator by Agentschap NL [17]. The refining requires per GJ refined oil: 0.8 MJ electricity, 11.5 MJ steam and 0.2 MJ Fuller's earth (a claylike material used for the refining). The steam is produced by a NG boiler with a natural gas input of 1.11 MJ and an electricity input of 0.02 MJ per MJ steam. The efficiency is 0.96 MJ refined oil per MJ transported extracted oil. The refined oil is the final fuel that is ready to be used in adapted diesel engines (CHP).

Transport of refined oil to CHP

The final step is the transport of refined oil to the CHP where it will be used. We assume a transport of 300 km by truck [4] [17] using diesel as fuel. We assume a zero loss of refined oil during the transportation.

3.6 Rape seed oil, ready to be used for the production of electricity and/or heat by means of an diesel engine

Process description

Rapeseed is typically cultivated in Europe. After harvesting, the raw rapeseed is dried and the oil is extracted. The pathway includes the next processes:

- Cultivation of rape seed
- Drying of rape seed
- Transport of dried rape seed
- Extraction of oil
- Oil refinery
- Transport of PVO (Pure Vegetable Oil)

The flowchart of the process is illustrated in Figure 3 - 5.

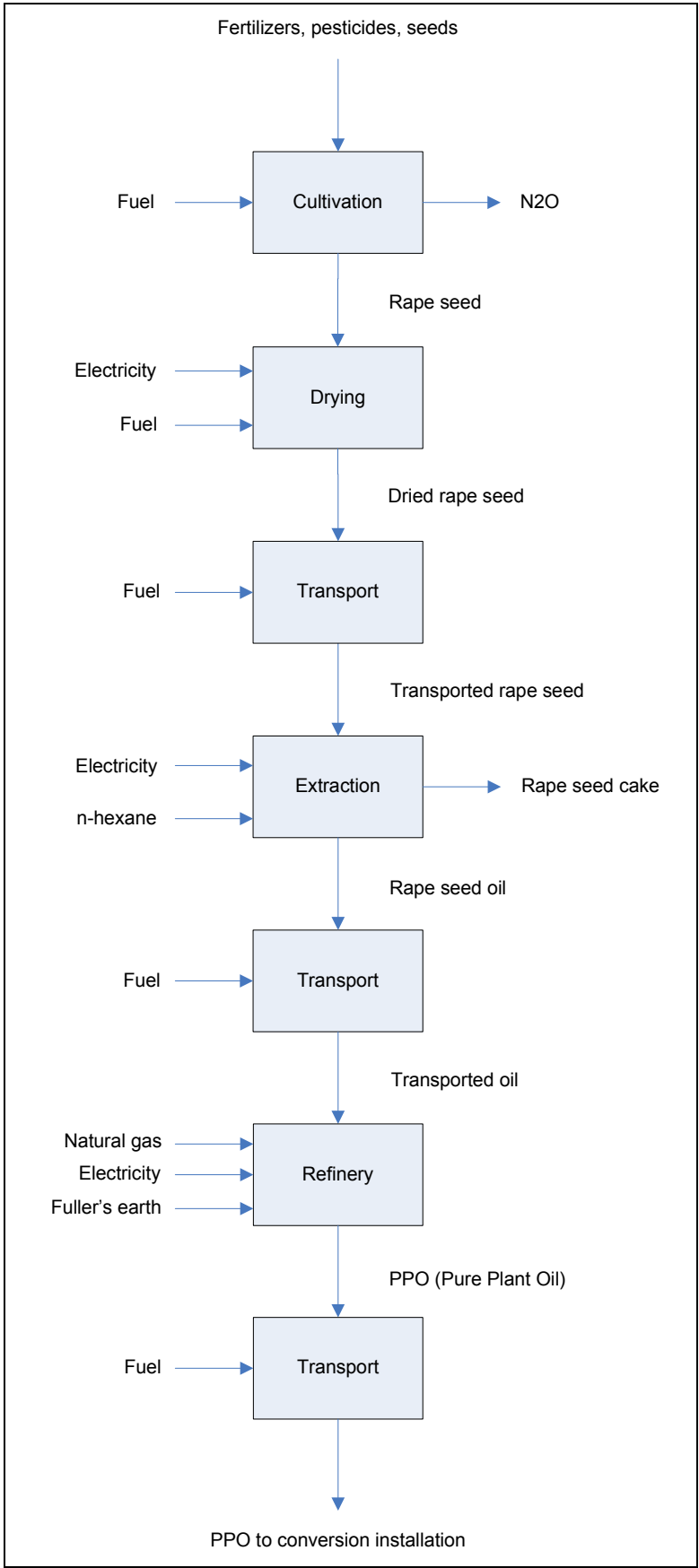


Figure 3 - 5 Flowchart of pathway of PPO production from rape seed

Cultivation

The yield of raw rapeseed in Europe at 10% moisture content is 3,113 kg per hectare. The cultivation and harvesting requires per hectare: 2,963 MJ diesel, 137.4 kg N-fertilizer, 19 kg CaO fertilizer, 49.46 kg K₂O-fertilizer, 33.67 kg P₂O₅-fertilizer, 1,230 kg pesticides and 6,000 kg seeding material. The field N₂O-emissions are 3.1 kg/ha/yr [4] [17].

Rapeseed drying

The rapeseed is dried using 0.181 MJ diesel and 3.079 MJ electricity per GJ dried rapeseed [4] [17].

Transport of dried rapeseed

The dried rapeseed is transported to a central extraction facility. We assume a transport distance of 50 km by truck a loss of material of 1% by energy content [4] [17].

Extraction of oil

Crude rapeseed oil is extracted from the dried rapeseed by a hexane extraction resulting in 0.613 MJ crude oil and 0.387 MJ rapeseed cake from 1 MJ dried rapeseed. Per GJ crude rapeseed oil is required: 11.8 MJ electricity, 55.7 MJ steam and 4.3 MJ n-hexane. The steam is produced by a NG boiler with a natural gas input of 1.11 MJ and an electricity input of 0.02 MJ per MJ steam.

Oil refinery

The oil is refined to a PVO (Pure Vegetable Oil) quality that can be used in stationary diesel engines that can be used in CHP's. It is important to know that there is no transesterification to biodiesel and also not a hydrogenation to HVO (Hydrogenated Vegetable Oil). The refinery of the oil is a simple cleaning step. All data from this refining step is from Version 3.4 (January 2011) of the Biofuels GHG Calculator by Agentschap NL [17]. The refining requires per GJ refined oil: 0.8 MJ electricity, 11.5 MJ steam (natural gas boiler) and 0.2 MJ Fuller's earth (a claylike material used for the refining). The efficiency is 0.96 MJ refined oil per MJ transported extracted oil. The refined oil is the final fuel that is ready to be used in adapted diesel engines (CHP).

Transport of refined oil to CHP

The final step is the transport of refined oil to the CHP where it will be used. We assume a transport of 150 km by truck [4] [17].

3.7 Animal fats, ready to be used for the production of electricity and/or heat by means of a diesel engine

Process description

Waste animal fat (also called tallow; often Category 1 according to the Regulation (EC) 1192/2006 / (EC) 1774/2002) is used to produce secondary fuels for stationary CHP's consisting of a diesel engine. An example of such a fuel is Bioline from the company Ecoson [18]. Examples of bio-CHP's using such a fuel are those of swimming pool Calluna in Ermelo and TNT's headquarter building in Hoofddorp. The main step in producing such a standardized fuel for waste animal fat is deacidification to remove the high content (compared to vegetable oils) of free fatty acids (FFA). FFA can damage engines. This step is similar to the first step in making biodiesel from waste animal fats since the transesterification from fat to biodiesel is also hindered by the high content of free fatty acids. The FFA content of raw rapeseed is about 1%, in used frying oils (UFO) about 7% and in tallow category 1 about 15%.

The process at Ecoson in the Netherlands is [18]: In a first step, the fat is cleaned by centrifuges to remove solids. The next step is a washing with water. In a settle tank, water with impurities is removed from the bottom and cleaned fat is removed from the top. The next step is deacidification. In this step, the fat is heated to approximately 250°C. The FFA evaporate and are released from the fat (stripping / distillation). The deacidified fat is ready for use in an adapted diesel engine (or can be used as feedstock for biodiesel production) [18]. There are also alternative processes to remove FFA of which esterification of FFA is the most important. The pathway includes the next processes:

- Transport of animal fats
- Cleaning of animal fats
- Transport of cleaned fats

The simplified flowchart of the process is illustrated in Figure 3 - 6. We present this flowchart in a simplified format because the energy and material uses in the abovementioned sub-steps are not known.

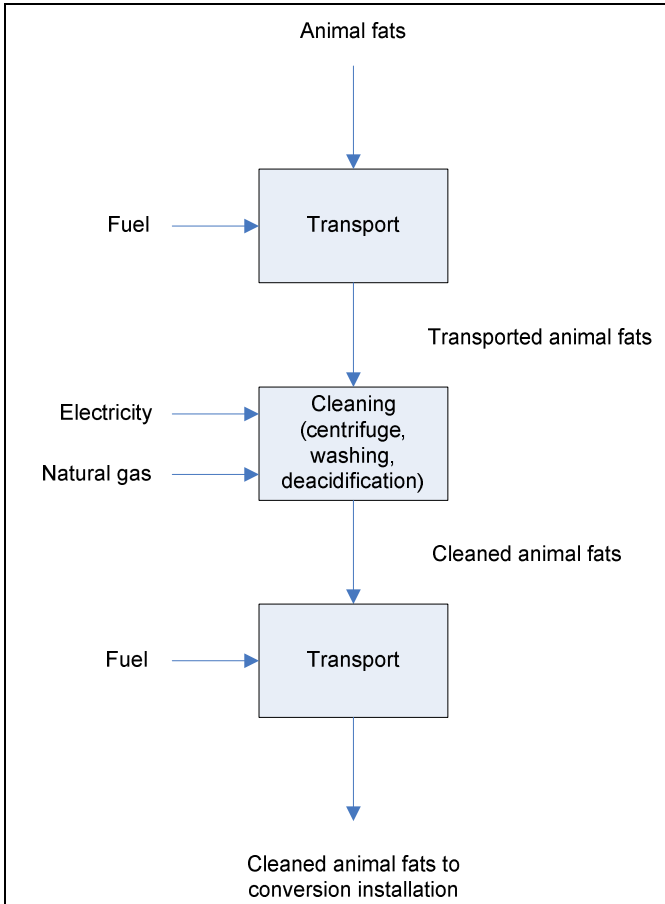


Figure 3 - 6 Flowchart of pathway of animal fat fuel

Transport of animal fats

We consider animal fat as a waste. Therefore, the first step in the pathway is de collection of animal fat. We assume a 75 km transport by truck [5].

Cleaning of animal fats

There is little specific information on the energy and material consumption at the cleaning of animal fat. Therefore, we use the data from Biograce [4] and the GHG-tool [17] on the cleaning step in the pathway of producing biodiesel from waste animal fat. Since in both processes (making the fat suitable for a diesel engine and the transesterification to biodiesel) require the removal of free fatty acids, this is a valid assumption. This results in a steam use of 0.0115 MJ per MJ refined oil and 0.0008 MJ electricity per MJ refined oil. For the steam generation we assume a natural gas boiler as this is common in the Netherlands. The boiler performance parameters are taken from Biograce [4].

Transport of cleaned oil to CHP

The final step is the transport of cleaned oil to the CHP where it will be used. We assume a transport of 300 km by truck [4].

3.8 Used frying oils, ready to be used for the production of electricity and/or heat by means of an diesel engine

The pathway of used frying oils (UFO) is very similar to the pathway of animal fats. Frying oil consists of a mixture of vegetable oils. Although the free fatty acid content in UFO is typically lower (typically about 7%, but ranging from 1% - 20%) than in animal fat, the content is still high compared to common raw vegetable oils (typical FFA content of < 1% up to a few percent). The FFA content of UFO is higher than in the vegetable oils because the FFA are formed during cooking when water reacts with the fat (triglycerides). The FFA content in UFO differs over a wide range from 1 to 20% because of the different frying conditions (water content of product fried, how long is the oil used, etc.).

Generally speaking, physical refining (vacuum distillation using steam) is preferred to esterification when the FFA is high. Distillation is therefore for both UFO and animal fat the cleaning technology that is selected for the CO₂-tool. For this reason, all inputs are the same as in the pathway of animal fats.

The flowchart of the process is illustrated in Figure 3 - 7.

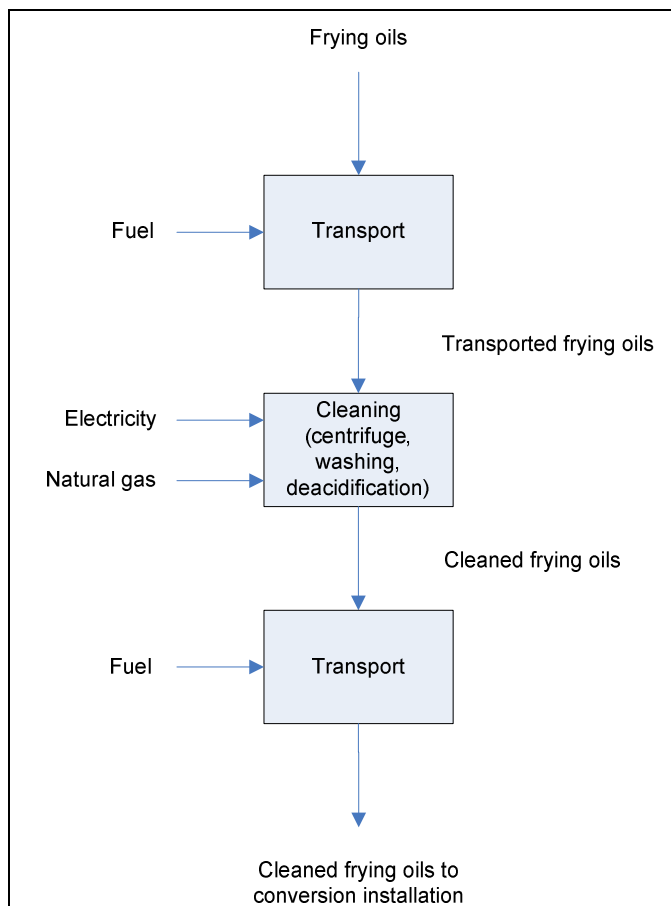


Figure 3 - 7 Flowchart of pathway of used frying oil fuel

Reference sources

- [1] Directive 2009/28/EC of the European Parliament and the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directive 2007/77/EC and 2003/30/EC
- [2] Report from the commission to the Council and the European Parliament on sustainability requirements for the use of solid and gaseous biomass resources in electricity, heating and cooling; Brussels, 25-02-2010; COM(2010) final
- [3] Nederlands Normalisatie-instituut, Nederlands Technical Agreement (NTA) 8080: 2009, on sustainability criteria for energy purposes, 2009
- [4] Biograce project: www.biograce.net
- [5] CO₂-tool developed by CML by order of SenterNovem, available from: http://www.senternovem.nl/duurzameenergie/infotheek/publicaties/publicaties_bio-energie/co2_tool.asp, January 2011
- [6] Agentschap NL, Protocol monitoring hernieuwbare energie – Update 2010, Publicatienummer 2 DENB1013
- [7] Agentschap NL, Afvalverwerking in Nederland, Gegevens 2009, available from: http://www.senternovem.nl/mmfiles/1AFVA1005_Afvalverwerking_in_Nederland_gegevens_2009h_tcm24-344045.pdf, August 2010
- [8] Magelli 2009, An environmental impact assessment of exported wood pellets from Canada to Europe
- [9] WBL, Technologisch jaarverslag WBL 2009, available from: http://www.wbl.nl/upload/algemeen/technologisch%20jaarverslag%20WBL%202009_tekst.pdf
- [10] STOWA, Compendium slibdroging, available from: <http://edepot.wur.nl/119054>
- [11] HVC, Slibverbranding Dordrecht, Milieujaarverslag 2009, available from: http://www.hvcgroep.nl/uploads/Downloads_downloadFile_31c1fdf0feee1f320d3cbcc11a420180.pdf
- [12] Nachwachsende-rohstoffen, 2009, Biogas-Messprogramm 2, 61 biogasanlagen im Vergleich, available from: http://www.biogasrat.de/index.php?option=com_docman&task=doc_download&gid=34&Itemid=129
- [13] Nico A. Leek, 2009, De markt van gebruikt hout en resthout in 2007, available from: http://www.probos.nl/home/pdf/Rapport_De_markt_van_gebruikt_hout_en_rest_hout_in_2007.pdf
- [14] Uslu, 2008, Pre-treatment technologies, and their effect on international bioenergy supply chain logistics
- [15] Koppejan, 2009, Beschikbaarheid van Nederlandse biomassa voor elektriciteit en warmte in 2020, available from: http://www.senternovem.nl/mmfiles/Beschikbaarheid%20Biomassa%20in%202020_tcm24-320154.pdf
- [16] Dehue and Hettinga, GHG performance Jatropha biodiesel, commissioned by D1 Oils. Available on www.d1plc.com

- [17] Biofuel GHG-tool, Version 3.4 (Januari 2011), available from www.senternovem.nl/gave_english/ghg_tool/index.asp (March 2011)
- [18] Ecoson, personal contact and website www.ecoson.nl
- [19] Zwart et a., *Duurzaamheid co-vergisting van dierlijke mest*, Alterra, 2006
- [20] WUR, *Kwantitatieve informatie (KWIN), Akkerbouw en Vollegrondsgroenteteelt 2009*
- [21] *Plant Soil* 263, 101-111, 2004, Nitrous oxide emissions from silage maize fields under different mineral nitrogen fertilizer and slurry applications
- [22] Commission decision of 10 June 2010 on guidelines for the calculation of land use carbon stocks for the purpose of Annex V of the Directive 2009/28/EC, Document C(2010) 3751

Appendix A

Abbreviations and definitions

Biogas	Gas produced by anaerobic digestion containing about 55% methane and 45% CO ₂
CHP	Combined heat and power
FFA	Free fatty acid
GFT	Groente- fruit en tuinafval (English: organic waste from households)
GHG	Greenhouse gas
Green gas	Upgraded biogas containing 88% methane and 12% CO ₂ . Upgraded so it can be injected in natural gas grids.
HFO	Heavy fuel oil
PVO	Pure vegetable oil
UCO	Used cooking oil
UFO	Used frying oil

This is a publication from:

NL Agency
NL Energy and Climate change
Croeselaan 15
Postbus 8242 | 3503 RE Utrecht
t 088 602 92 00
www.agentschapnl.nl/duurzameenergie

© NL Agency | May 2011
Publication no. 2DENB1110

No rights may be derived from this brochure, or from any of the examples contained herein, nor may NL Agency be held liable for the consequences arising from the use thereof.

NL Agency is an agency of the Ministry of Economic Affairs, Agriculture and Innovation. NL Agency pursues policies for various ministries when it concerns sustainability, innovation and international affairs. NL Agency is the ultimate point of contact for businesses, knowledge institutions and authorities. For information and advice, financing, networks and legislation.

The NL Energy and Climate change unit strengthens society by working on the energy and climate solutions of the future.