December 2003 ECN-C--03-088

BIOFUEL PRODUCTION CHAINS

Background document for modelling the EU biofuel market using the BIOTRANS model

E. van Thuijl
R. van Ree
T.J. de Lange

Preface
This report was published within the framework of the European Commission-supported project 'Clear Data Clean Fuels' (NNE5-2001-00619), which was later re-named 'Clear Views on Clean Fuels', or in short, 'VIEWLS'. The overall objectives of this project are to provide structured and clear data on the availability and performance of biofuels and to identify the possibilities and strategies towards large scale sustainable production, use and trading of biofuels for the transport sector in Europe, including Central and Eastern European countries (CEEC).

The VIEWLS project is co-ordinated by the Dutch Agency for Energy and the Environment (Novem). Together with Novem, ECN and the Department of Science, Technology and Society of the University of Utrecht (UU-STS) are the technical co-ordinators of the project. In total, 19 organisations from Western and Eastern Europe, and North America are involved in the project.

This report was written in preparation of the development of the BIOTRANS model in Work Package 5 of the VIEWLS project. The purpose of this report was to identify all relevant biofuel conversion routes that should be included in the BIOTRANS model, together with the resulting data requirements.

This report is published under the responsibility of ECN. The publication of this report is registered at ECN under project number 7.7530.01.01. For questions regarding this report you may contact Ms. E. van Thuijl via e-mail: vanthuijl@ecn.nl, or by telephone: +31.224.568263.

The authors would like to thank Sabine Host, Manfred Wörgetter, Goran Berndes and Gerfried Jungmeier for their valuable comments on this report.

The authors would like to emphasise that the main purpose of the information presented was to serve as a basis for the definition of the data requirements for the modelling activities in Work Package 5 of the VIEWLS project. This report shows the current status of information and insights. These may be subject of discussion or may be modified further in the process of model development and analysis within the VIEWLS project.

Abstract
This report was published within the framework of the European Commission-supported project 'VIEWLS'. The main purpose of this report is to determine the data requirements of the BIOTRANS model that will be developed in Work Package 5 of the VIEWLS project. The report includes a classification system for biomass resources, which serves as a basis for the resource definition in the BIOTRANS model. The relevant biofuel conversion routes to be included in the BIOTRANS model are described and outlined in schematic representations. The biofuel conversion routes or chains are defined by subprocesses, which are linked together. These subprocesses - including their inputs, outputs, and (internationally transportable) intermediate products - represent the level of detail on which the BIOTRANS model will be designed. In the report, the part of the biomass resource classification system that will be modelled in the BIOTRANS model is presented. This classification system is limited to the different classes and types of resources and leaving out the details on the specific resources. In the final chapter, the explicit data requirements are defined.

CONTENTS

1. INTRODUCTION

This report was written in preparation within the framework of the European Commission-supported project 'VIEWLS' (Clear Views on Clean Fuels). The overall objectives of this project are to provide structured and clear data on the availability and performance of biofuels and to identify the possibilities and strategies towards large scale sustainable production, use and trading of biofuels for the transport sector in Europe, including Central and Eastern European countries (CEEC).

The VIEWLS project is divided into seven Work Packages, of which Work Package 5 is the responsibility of ECN. The main objectives of this Work Package are to provide an analytical tool, i.e. the BIOTRANS model including necessary data sets, to conduct quantitative analyses on the costs of the European Directive on the promotion of the use of biofuels in transport (2003/30/EC, 8 May 2003), the resulting physical biofuel trade flows and their costs and environmental impacts, the effect of different burden sharing rules and 'biofuel certificate' trading.
Furthermore, Work Package 5 aims at analysing the impacts on the national economies (including the accession countries) and agricultural activities, and possible systems to implement trading in 'bio fuel certificates', its advantages and restrictions, impacts on the promotion of the use of biofuels for transport, and policy recommendations. Finally, the Work Package will provide a specific assessment of the effects and impacts of large-scale trade from the CEECs to Western Europe, including employment and greenhouse gas emissions.

The main purpose of this report is to identify all relevant biofuel conversion routes that should be included in the BIOTRANS model, together with the resulting data requirements. This document contains the following chapters:

- Chapter 2 gives the classification system for biomass resources. We derived this classification system from different studies and use it as a basis for the resource definition in the BIOTRANS model.
- Chapter 3 gives an overview of all conversion routes that will be included in the BIOTRANS model. The chains are defined by subprocesses, which are linked together. These subprocesses are considered in the design of the BIOTRANS model.
- In Chapter 4 the explicit data requirements are defined, for biomass resources, subprocesses and products that may be transported on national level.

In order to provide a better insight in the modelling approach, Figures 1.1 and 1.2 might be useful. Figure 1.1 gives a general impression of the different modules that will be developed. Figure 1.2 provides more information on the way (inter) national transportation is dealt with.

The BIOTRANS model determines the economically most favourable combinations of resources and conversion technologies, taking into account costs for production and transportation, to cover a demand for biofuels determined by a (policy) target for consumption of biofuels. This will be done for the year 2000 (base year), up to 2050, but with a main focus on the period up to 2020. A change of the policy-context over the years as well as a change in production costs (e.g. a change in production costs for biomass crops or a reduction in technology investment costs as a result of technological learning, conversion efficiency improvements or economies of scale) can be included. Thus the model also provides insight in the impact of future changes on the most favourable technological routes, future trade flows between countries, economic costs and benefits for individual countries, the average equilibrium price for biofuels on the European market, the impact of different policies/incentives, etc.

The modelling will be done on country-level for the different production chains. The countries included in the BIOTRANS model are all EU Member States and the CEECs, but also scenarios with large-scale imported streams from outside this group of countries can be analysed.

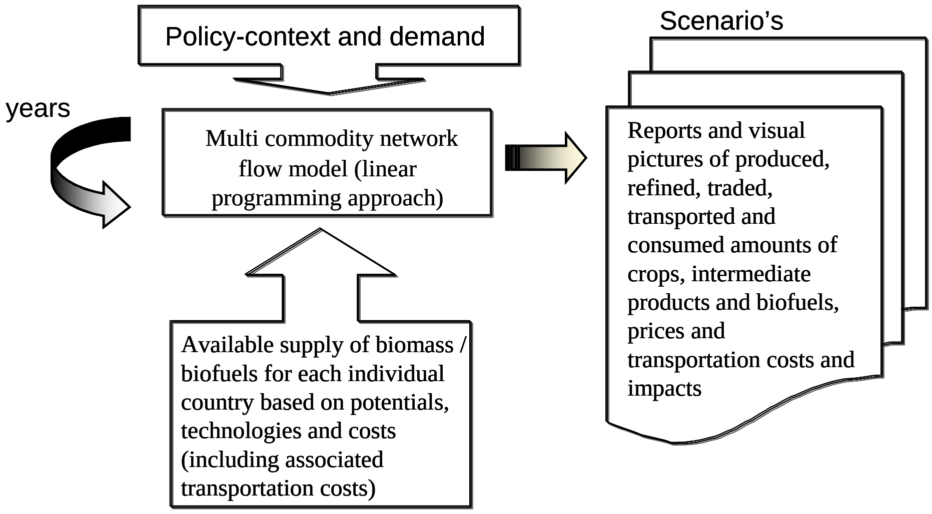


Figure 1.1 *Schematic overview of the different modules of the BIOTRANS model*

The different possible conversion routes for the production of different types of biofuels play a central role in the model. These conversion routes are defined by interlinked subprocesses, which are defined by input and output. Between two subprocesses, transportation of intermediate products may take place, possibly also including storage (this is indicated by arrows between subprocesses).

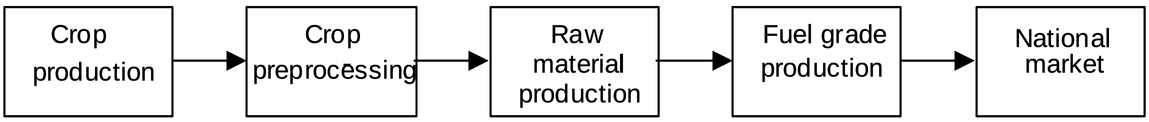


Figure 1.2 *General outline of conversion route definition for the BIOTRANS model*

A number of guiding principles are important to mention. Crop production denotes the production of biomass and biomass residues from agriculture, forestry and industry. The pre-processing of the crop may consist of several pre-treatment steps. After pre-processing of the biomass, it is converted into a raw material (for example bio-crude or raw ethanol), which serves as an input for the production of fuel grade biofuels. Both raw material production and fuel grade production may consist of several conversion processes. Finally, the produced biofuels are transported to the national market, where distribution to end-consumers takes place (in either pure form or blends with conventional automotive fuels). National transportation of input products and output products (including intermediate products) are treated separately in the BIOTRANS model in case it is expected that the subprocesses be not on the same geographical location. From the national market, biofuels may also be exported to another country. This also applies to biomass crops and intermediate products, as they may also be traded internationally. Therefore, the possibility of international transportation of input products, output products and intermediate products is also included in the BIOTRANS model.

This is shown in Figure 1.3, which represents the example of cellulosic ethanol production. In case of international transportation it is assumed that the products are transported to the border (national transportation) before being transported to another country. Also in the importing country the product is assumed to be transported to the related subprocess.

National transportation flows will be defined in terms of an average distance and average costs, without distinguishing different modalities of transport. For international transportation different modalities will be regarded.

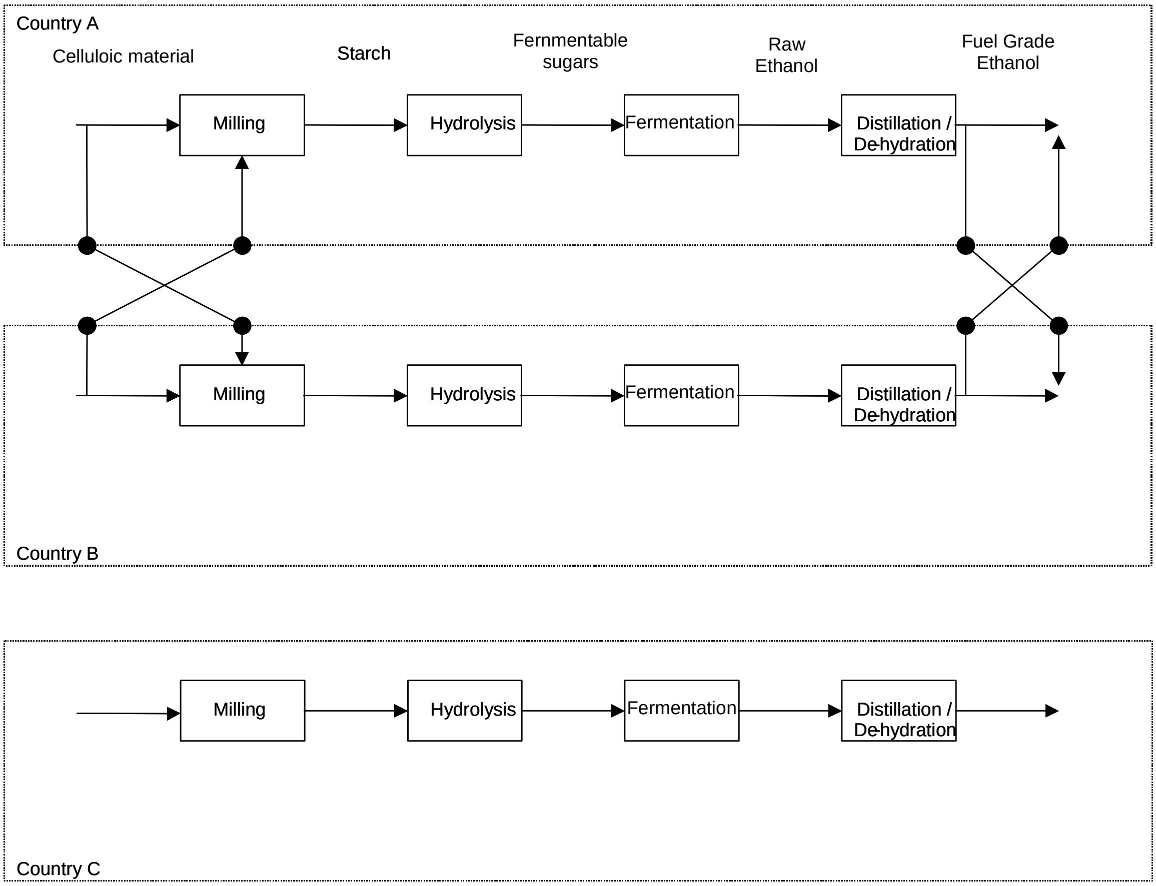


Figure 1.3 *Example of biofuel conversion route including (inter)national transportation*

2. BIOMASS CLASSIFICATION USED TO DETERMINE RELEVANT BIOMASS RESOURCES

This chapter gives the classification system for biomass resources. We derived this classification system from different studies and use it as a basis for the resource definition in the BIOTRANS model. In principle, the first two columns of this table, e.g. ‘classification’ and ‘type of resource’ will be used as input for biofuel conversion routes in the model. If a more detailed approach proves necessary, for example due to substantial differences in relevant biomass characteristics within ‘type of resource’ categories, we can use a further differentiation of these categories. This differentiation is given in the third column of the table.

Table 2.1 *Classification of biomass resources*

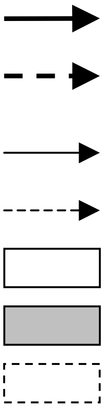
Classification	Type of resource	Resource
Energy Crops	Lignocellulosic crops	Poplar
		Willow
		Eucalyptus
	Oil crops	Sunflower seeds (conventional)
		Sunflower seeds (High-oleic)
		Soybean
		Rapeseed
		Olive-kernel
		Calotropis procera
	Herbaceous lignocellulosic crops	Miscanthus
		Switchgrass
		Common reed
		Reed canarygrass
		Giant reed
		Cynara cardunculus
	Sugar crops	Sugar beet
		Cane beet
		Sweet sorghum
		Jerusalem Artichoke
		Sugar millet
	Starch crops	Maize
		Wheat
		Corn (cob)
		Barley
		Potatoes
		Amaranth
	Other	Flax
		Hemp
		Tobacco stems
		Cotton stalks
		Kenaf
	Aquatic plants	Lipids (from algae)
Residues	Forestry residues	Wood residues
		Thinning wood
	Agricultural residues	Straw (maize)
		Straw (cereal)
		Straw (rapeseed)
		Straw (flax/hemp)
		Straw (grass seed hay)
		Straw (rice)
		Straw (oats)

Classification	Type of resource	Resource
		Straw (amaranth) Sugar beet leaves Residue flows from bulb sector Fruit sector/orchard residues (prunings)
	Wood processing residues	Wood chips Sawdust Residue wood
	Construction residues	Demolition wood
	Food industry residues	Swill Residue flows from food and luxury products industry Tallow/Yellow grease
	Roadside hay	Grass
Manure	Solid manure	Chicken manure
	Liquid manure	Cattle manure Pig manure Sheep manure
Sewage sludge		
Waste	Garden, fruit and vegetable waste Organic waste (dry) Organic waste (wet)	

3. CONVERSION CHAINS AND TRANSPORTATION OPTIONS TO BE MODELLED IN THE BIOTRANS MODEL

This chapter gives an overview of all conversion routes that will be included in the BIOTRANS model. Subprocesses that are linked together define these chains. These subprocesses represent the level of detail on which the BIOTRANS model will be designed. The chapter also gives an overview of the products (input, output, intermediate products) that play a role in the different chains. Furthermore, it gives information on whether these are physically transported on national or international level. It also shows the way transportation is dealt with in the BIOTRANS model.

Legend



= product related national transportation

= product related international transportation

= process internal product flow

= secondary product

= process

= optional process

= product

For most subprocesses an input of electricity and/or heat is required. Sometimes, an amount of heat is released in a subprocess. In the schematic representations of the biofuel conversion routes, only production of electricity and heat by a Combined Heat and Power (CHP) unit will be included in case a certain by-product (e.g. fuel gas, lignin) does not have any other commercial value and the only way to use it economically is use as a fuel for electricity and/or heat production. Otherwise, these energy flows will not be included in the schematic representations. However, they will be included in the model and therefore in the datasheet as well.

For some process, various input categories can be used that undergo a pre-treatment process. It should be noted that not all biomass types listed in ‘input categories’ are suitable for all pre-treatment processes mentioned. This may differ in individual cases.

3.1 Pure vegetable oil

Pure vegetable oil is obtained by extracting vegetable oils from oil seeds, such as rapeseed, sunflower seeds, and soybean. This process is similar to the production of vegetable oils for the food industry, which is a well-established process. Solvent extraction, cold pressing, or a combination of both can do oil extraction. Here, seed cakes are produced as a secondary product. Finally, distillation takes place, where the solvent is recycled. Pure vegetable oil can be used directly in automotive engines without using additives or changing the molecular structure.

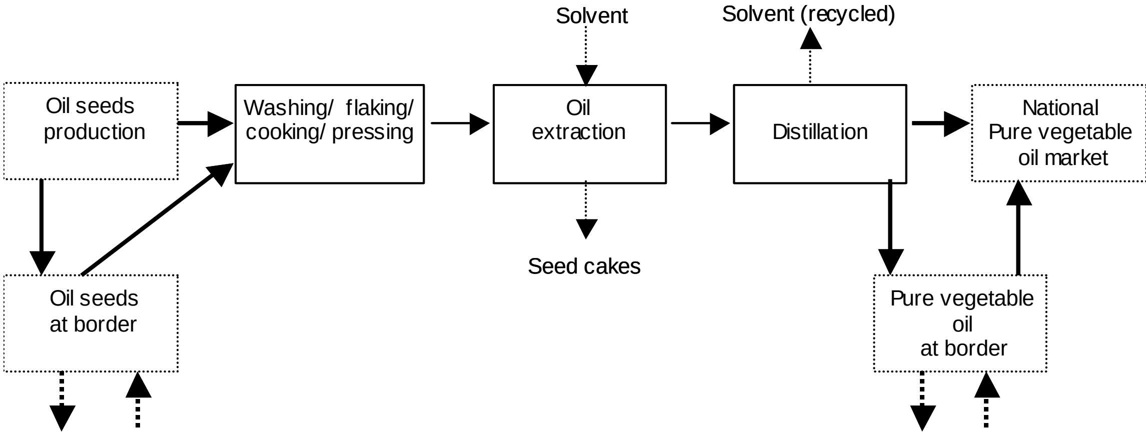


Figure 3.1 *Conversion route for pure vegetable oil*

3.2 Biodiesel

Biodiesel is produced from pure vegetable oil (see section 3.1), derived from oil seeds, e.g. Rapeseed Methyl Ester, Sunflower Methyl Ester, and Soybean Methyl Ester. This is shown in Figure 3.2. It is also possible to convert used fats (tallow, yellow grease) into biodiesel, see Figure 3.3.

3.2.1 Biodiesel from vegetable oils

Pure vegetable oils can be used directly as diesel engine fuels (see Paragraph 3.1). However, their fuel properties (i.e. low cetane number, high viscosity) are less advantageous for this application. To overcome these problems, pure vegetable oil is often converted to biodiesel. Biodiesel has a higher cetane number and a lower viscosity, which makes it a more suitable fuel for diesel engines.

In the biodiesel production process, the large, branched molecule structures of pure vegetable oil are transformed into smaller straight-chained molecules called methyl esters. This transesterification process requires methanol in order to remove glycerine from the vegetable oil. Both methanol and glycerine are recovered from the process. The methanol can be re-used and the glycerine can be sold to the cosmetic and pharmaceutical industry. The biodiesel can be sold to the fuel market for end-use in diesel engines.

Figure 3.2 presents the conversion process for biodiesel produced from pure vegetable oil. Here, transesterification with a homogeneous catalyst is presumed. Another technology, heterogeneous catalyst technology, is expected to be used on an industrial scale on the short term. This technology will enable both process simplification and higher products purity compared to homogeneous catalyst technology. Biodiesel produced through this process will be almost 100% pure [> 99.9%]. In the case of heterogeneous transesterification, neutralisation by means of mineral acid is eliminated. Moreover, no by-product results from methanol recovery to obtain crude glycerine. In this way, the crude glycerine can be up to 98-99.5 % pure. The heterogeneous transesterification process will only be included in the BIOTRANS model if there is a substantial difference between process data for the homogeneous and heterogeneous catalyst process.

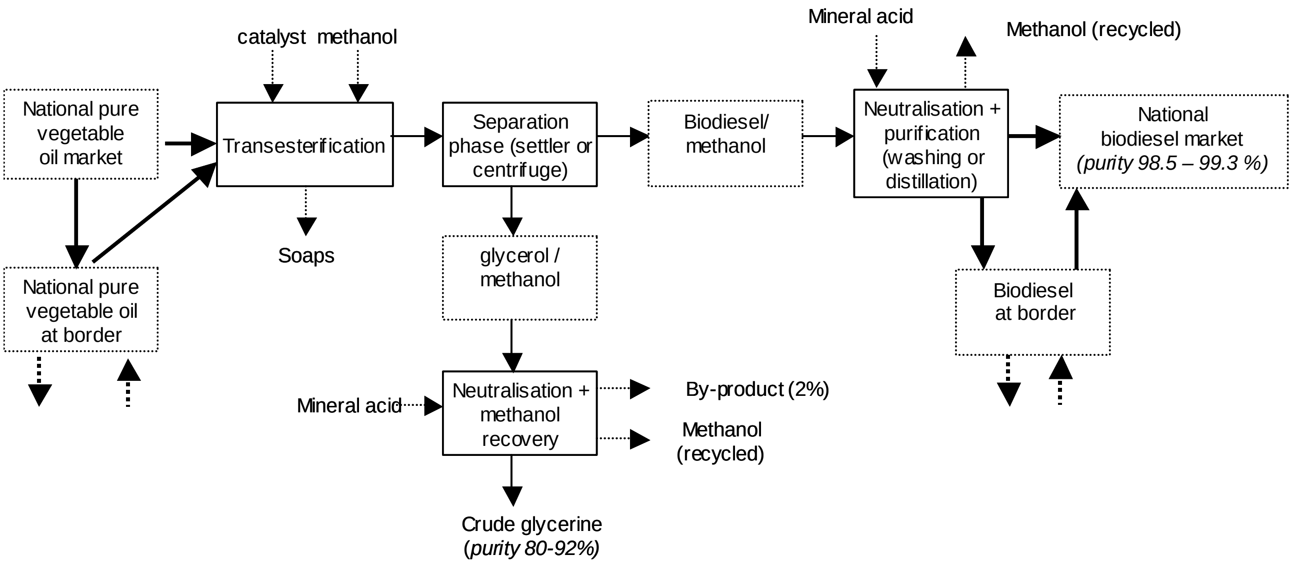


Figure 3.2 *Conversion process for biodiesel produced from pure vegetable oil*

3.2.2 Biodiesel from used fats

This conversion route of biodiesel produced from used fats (Fatty Acid Methyl Ester, FAME) is similar to that of biodiesel produced from pure vegetable oils. However, before the transesterification step takes place, the used fats (tallow/yellow grease) must be refined and filtered first. The conversion route for biodiesel produced from used fats is presented in Figure 3.3.

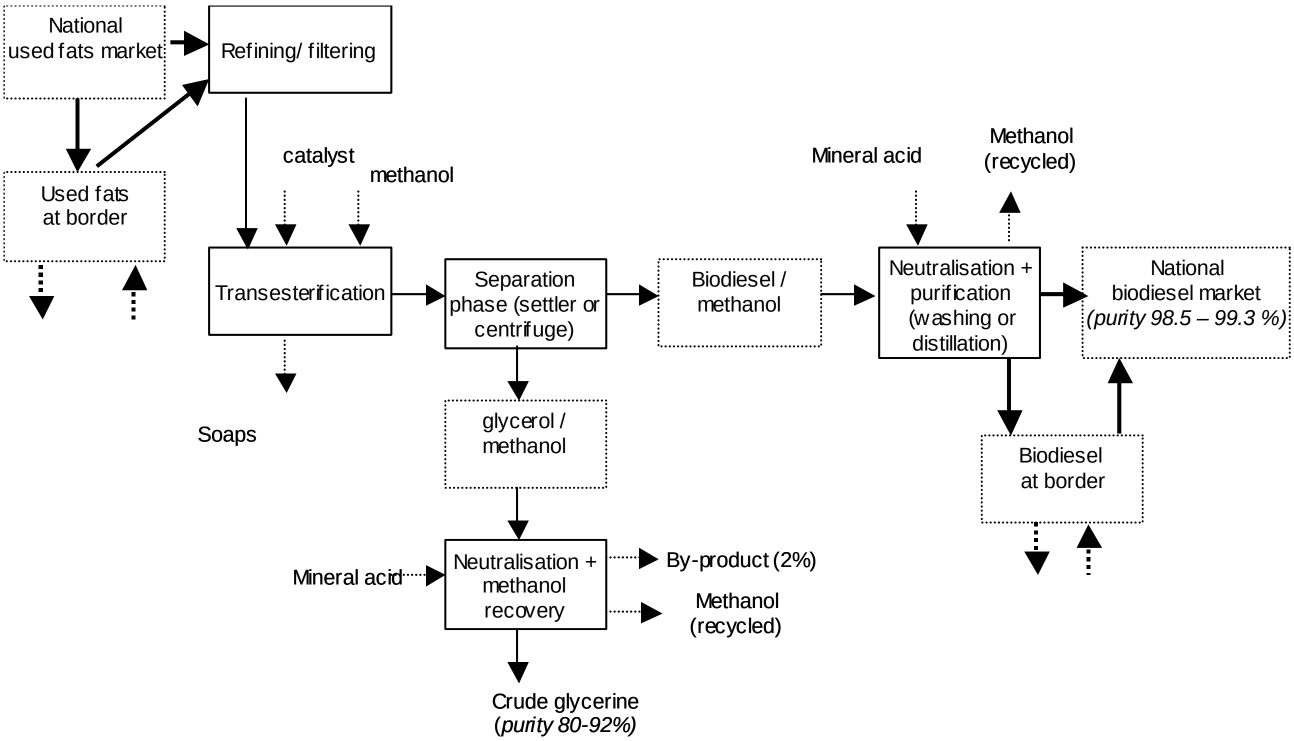


Figure 3.3 *Conversion process for biodiesel produced from used fats*

3.3 Bio-ETBE and Bio-MTBE

Both ETBE (Ethyl tertiary butyl ether) and MTBE (Methyl tertiary butyl ether) are used as oxygenating fuel additives in regular petrol. Oxygenates raise the oxygen content of petrol. Oxygen helps the fuel burn more completely, thus reducing toxic exhaust pipe emissions. The higher oxygen content in the fuel also increases the octane number of the fuel and thus improves its knock resistance.

The conversion routes for the production of bio-ETBE and bio-MTBE are similar. They are produced by the chemical reaction of bioethanol (for ETBE) or biomethanol (for MTBE) and iso-buthylene in the presence of heat over a catalyst. Figures 3.4 and 3.5 show the conversion routes for bio-ETBE and bio-MTBE.

As both the (m) ethanol and the iso-buthylene used for the production of bio-ETBE and bio-MTBE may be produced from either biomass or fossil sources, it is unclear which part of these fuels should be counted as biofuel. In the EU Directive on the promotion of the use of biofuels or other renewable fuels for transport (2003/30/EC, 8 May 2003), the biofuel-part of these fuels is calculated based on the volume-percentage of bioethanol or biomethanol, i.e. 47 vol-% for ETBE and 36 vol-% for MTBE. However, this is subject of discussion. A better way would be to determine the biofuel-part of ETBE and MTBE based on the energetic biomass-derived part (i.e. ethanol and methanol). This results in the following biofuel percentages: 33% for ETBE and 20% for MTBE. For the time being, the percentages in the EU Directive will be used in the BIOTRANS model.

3.3.1 Bio-ETBE

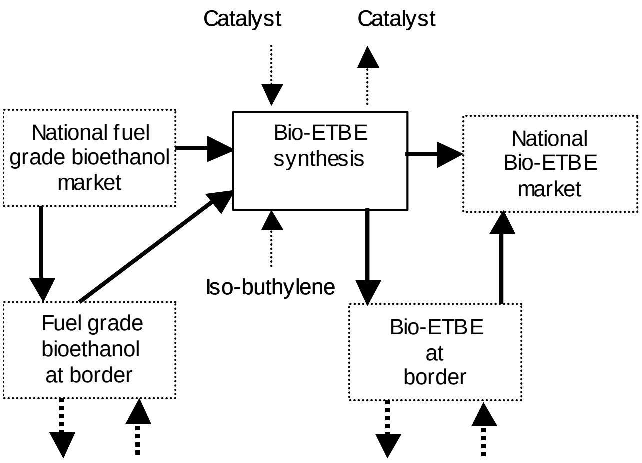


Figure 3.4 *Conversion process for bio-ETBE*

3.3.2 Bio-MTBE

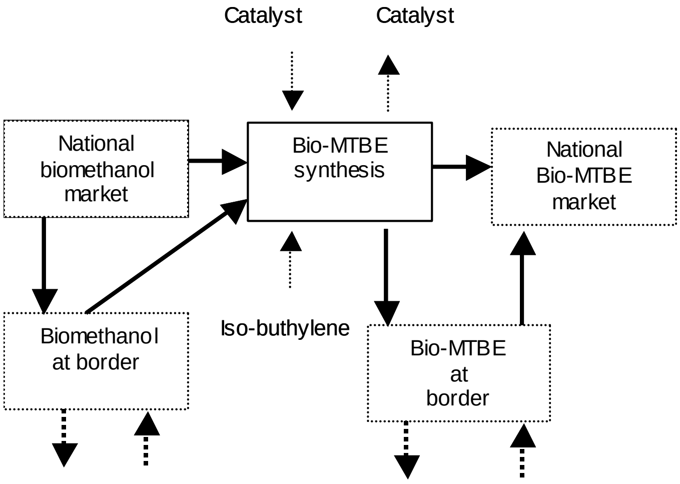


Figure 3.5 *Conversion process for bio-MTBE*

3.4 Conventional bioethanol

Currently, bioethanol is mainly produced from agricultural crops, i.e. sugar crops such as sugar beet and sweet sorghum (Figure 3.6) or starch crops, for example grains and potatoes (Figure 3.7).

3.4.1 Conventional bioethanol from sugar crops

Sugar crops contain simple sugars that can easily be separated and made available to the yeast in the fermentation process. This separation is done by extraction or crushing. In the case of sugar beet a diffusion process is operated. In the next step, the sugars are fermented to raw bioethanol. Subsequently, the raw bioethanol is purified through a series of distillation and dehydration steps in order to obtain fuel grade bioethanol. Bioethanol can be used as an automotive fuel or it may serve as a raw material for the production of the fuel additive bio-ETBE (see Section 3.3).
By-products like pulp, bagasse, and vinasses can be sold commercially. Therefore, they are not used for the production of electricity and/or heat within the process.

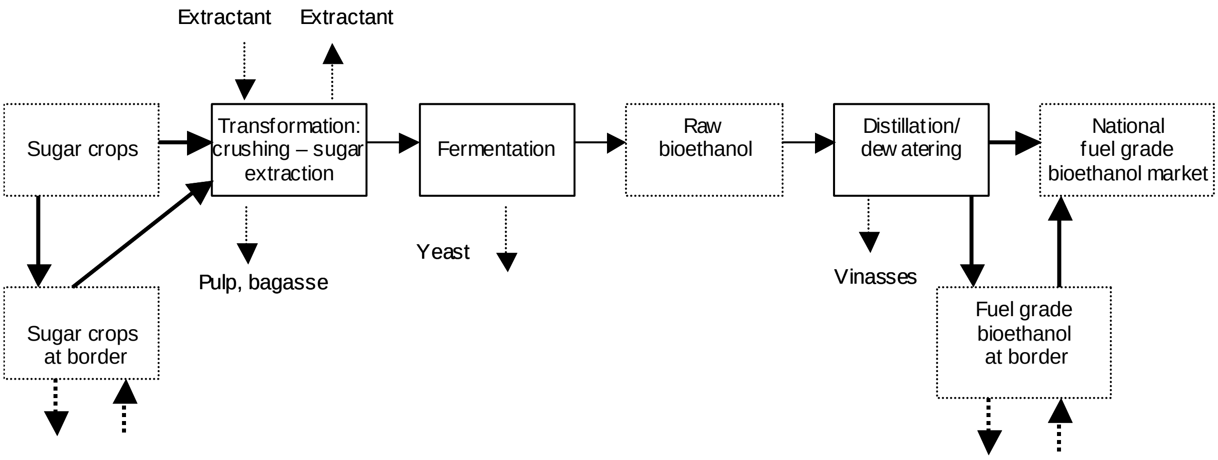


Figure 3.6 *Conversion process for bioethanol produced from sugar crops*

3.4.2 Conventional bioethanol from starch crops

The use of starch crops for the production of bioethanol requires more extensive processing of the material, before it can be fermented to raw bioethanol. This is due to the fact that starch crops contain larger and more complex carbohydrate molecules that have to be broken down to simple sugars first. In an additional process step, the crushed material is heated to dissolve all the water-soluble starches. Simultaneously, the starch is converted to sugars by enzymes or acid hydrolysis. The following process steps are the same as those for the production of bioethanol from sugar crops. By-products such as milling residues and dry distiller residues can be sold commercially, for example as animal feed. Therefore, they are not used for the production of electricity and/or heat within the process.

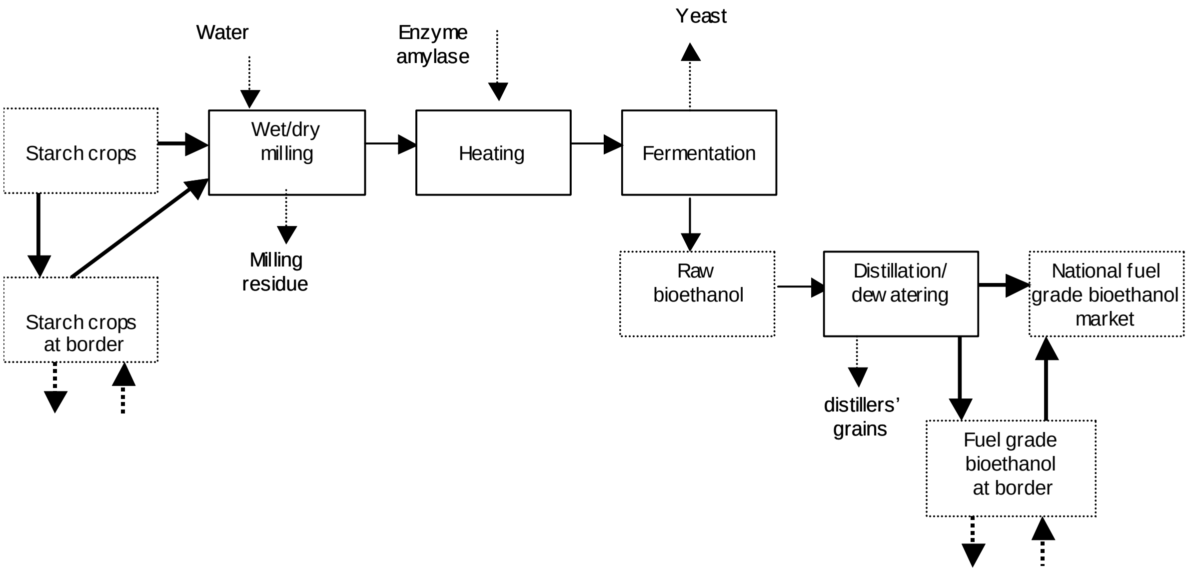


Figure 3.7 *Conversion process for bioethanol produced from starch crops*

3.5 Cellulosic bioethanol

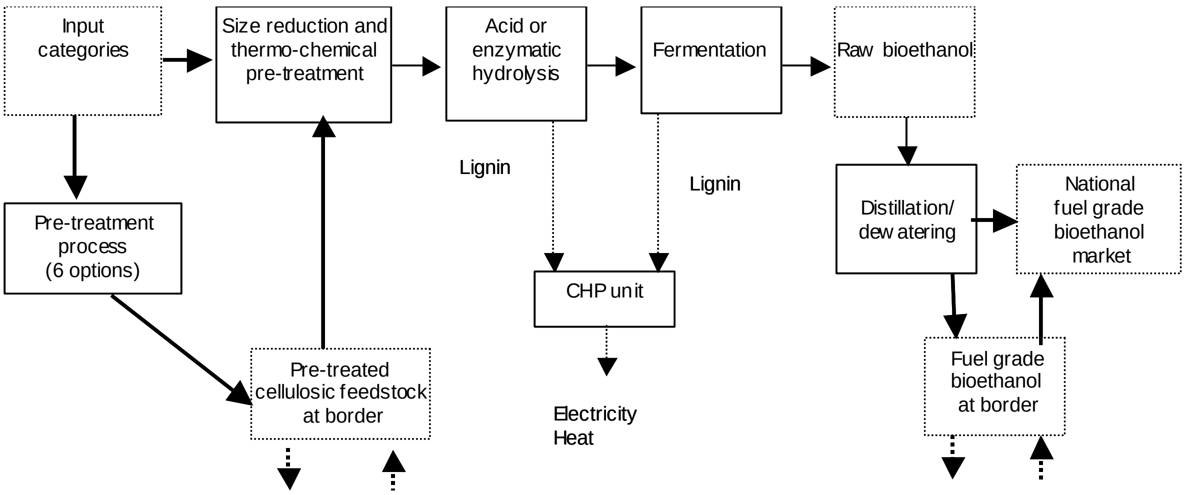
Cellulosic bioethanol is produced from lignocellulosic biomass. Lignocellulosic biomass is composed of mainly cellulose, hemicellulose, and lignin. Both cellulose and hemicellulose are potential sources of sugars that can be fermented to ethanol. The remaining fraction called lignin cannot be fermented but it can be used as a fuel for electricity and/or heat generation. This electricity and/or heat can be used internally or the electricity can be exported to the electricity grid.

Deriving fermentable sugars from lignocellulosic biomass is more difficult compared to sugar or starch crops (see section 3.4). Suitable pre-treatment and hydrolysis steps are required. Pre-treatment of the biomass consists of milling or chipping for size reduction and opening up of the material for further treatment, and thermo-chemical pre-treatment. This thermo-chemical pre-treatment step enables mobilisation of the lignin and (hemi) cellulose fractions. Structural components of the material are broken down further to optimise access for enzymes in the hydrolysis step.

In the hydrolysis step, acid is added to the material to produce a liquid stream of sugar oligomers. Then saccharification takes place, i.e. enzymatic hydrolysis of the sugar oligomers to fermentable monomeric sugars, mainly glucose and xylose. Then these sugars are fermented to ethanol. The lignin can be separated either in the hydrolysis process or in the fermentation step[1]. This 'raw bioethanol' is distilled and dehydrated to obtain fuel grade ethanol.

[1] The optimal choice of where the lignin should be separated in the process is a subject of research.

The conversion route described above is not available on a commercial scale yet. Currently, several technological options are under development. First of all, the National Renewable Energy Laboratory (NREL) in the USA is working on a process that uses a combination of steam pre-treatment and mild acid hydrolysis of the hemicellulose fraction and subsequent enzymatic hydrolysis of the cellulose. Cellulose hydrolysis and fermentation of xylose and glucose monomers occur in the same reactor. Secondly, the BCI (BC International Corporation) process uses a two-stage acid hydrolysis, releasing the hemicellulose and cellulose sugars, respectively. The process developed by Iogen Corporation uses steam explosion with dilute acid for releasing hemicellulose sugars and subsequent hydrolysis of cellulose (Zessen et al, 2003).



Input categories
Lignocellulosic crops
Herbaceous lignocellulosic crops
Forestry residues
Other energy crops
Agricultural residues
Wood processing residues
Construction residues
Organic waste (dry)
Organic waste (wet)
Other organic waste
Roadside hay

Pre-treatment processes
Separation, dewatering, drying and size reduction (chips)
Separation, dewatering, drying and densification (briquettes/pellets)
Separation, dewatering, drying and torrefaction (torrified biomass)
Separation, dewatering, drying and carbonisation (char)
Separation, dewatering, drying and fast pyrolysis (pyrolysis oil)
Separation, dewatering, drying and hydrothermal treatment (biocrude)

Figure 3.8 *Conversion process for bioethanol produced from cellulosic biomass*

3.6 Fischer-Tropsch diesel (synthetic biofuel)

The conversion process for Fischer-Tropsch diesel starts with the pre-treatment of biomass. Figure 3.9 shows the conversion route of the production of Fischer-Tropsch diesel through gasification of various types of biomass.

The combination of size reduction/crushing and drying as pre-treatment of the biomass only appears on the national level. Other pre-treatment options may be applied for international transport of the cellulosic feedstock. This distinction also applies to biomethanol, biodimethylether (bio-DME), Substitute Natural Gas (SNG), and biohydrogen, which will be described further in this Chapter.

The biomass is converted through a gasification process. This results in a mixture of combustible gases, called synthesis gas or syngas. The gas mainly consists of hydrogen (H_2) and carbon monoxide (CO). From this gas, various liquid biofuels can be produced by means of a synthesis process. This process requires the reactants H_2 and CO to be available in the syngas in a certain ratio. For Fischer-Tropsch, this ratio is 2:1. The composition of the final product depends on the type of catalyst and reactor used and the process conditions, such as temperature and pressure. The production process of Fischer-Tropsch diesel usually aims at obtaining waxes (long-chain hydrocarbons), followed by a process called hydro cracking in order to produce diesel fractions. This results in a higher yield of diesel fractions compared to the production of diesel fractions directly from the synthesis gas.

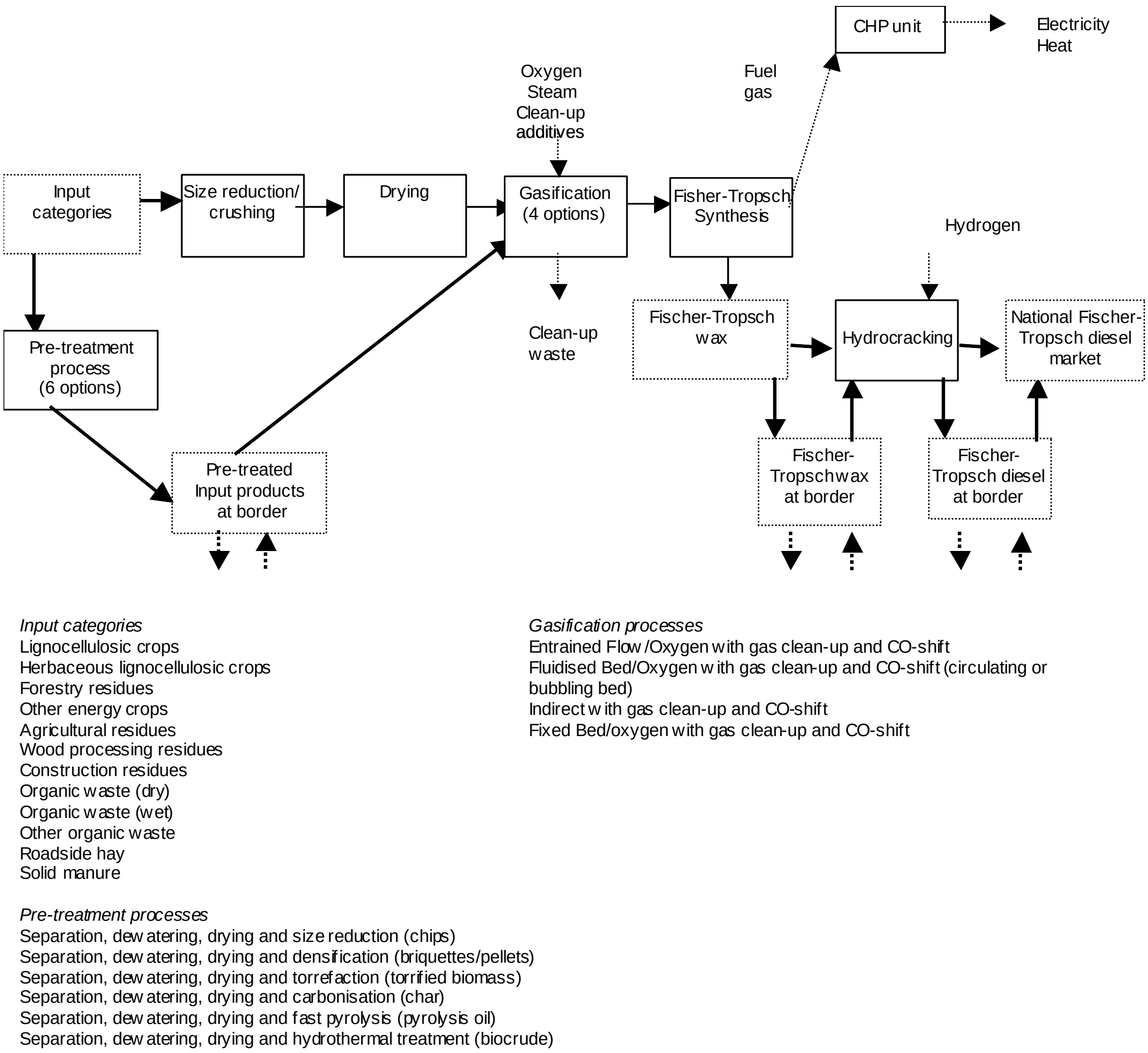


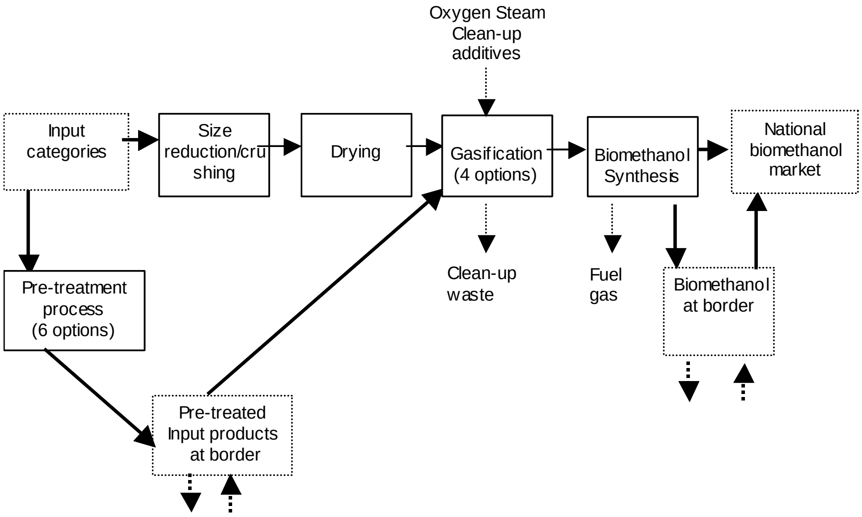
Figure 3.9 *Conversion process for Fischer-Tropsch diesel by gasification*

3.7 Biomethanol

Like Fischer-Tropsch diesel, biomethanol is also produced through a gasification and synthesis process. This conversion route is shown in Figure 3.10. The pre-treatment steps for biomass and biomass products are similar to the Fischer-Tropsch conversion route. Biomethanol production process also requires a H_2/CO ratio of 2:1 in the syngas. However, process conditions, reactors, and catalysts used differ, compared to the Fischer-Tropsch synthesis process.

Conventional methanol reactors operate in the gas phase. Processes under development are mainly slurry technologies, for example the liquid phase process. Here, the reactants H_2 and CO, the product methanol, and the catalyst are suspended in a liquid. This is advantageous in some respects, for example it results in a higher conversion yield per pass compared to conventional methanol reactors.

(Bio-)methanol has a broad range of possible applications, besides as an automotive fuel. It may also be used for the production of the fuel additive bio-MTBE (see section 3.3) or as a chemical feedstock, extractive agent, or solvent.



Input categories
Lignocellulosic crops
Herbaceous lignocellulosic crops
Forestry residues
Other energy crops
Agricultural residues
Wood processing residues
Construction residues
Organic waste (dry)
Organic waste (wet)
Other organic waste
Roadside hay
Solid manure

Gasification processes
Entrained Flow /Oxygen with gas clean-up and CO-shift
Fluidised Bed/Oxygen with gas clean-up and CO-shift (circulating or bubbling bed)
Indirect with gas clean-up and CO-shift
Fixed Bed/oxygen with gas clean-up and CO-shift

Pre-treatment processes
Separation, dewatering, drying and size reduction (chips)
Separation, dewatering, drying and densification (briquettes/pellets)
Separation, dewatering, drying and torrefaction (torrified biomass)
Separation, dewatering, drying and carbonisation (char)
Separation, dewatering, drying and fast pyrolysis (pyrolysis oil)
Separation, dewatering, drying and hydrothermal treatment (biocrude)

Figure 3.10 *Conversion process for biomethanol by gasification*

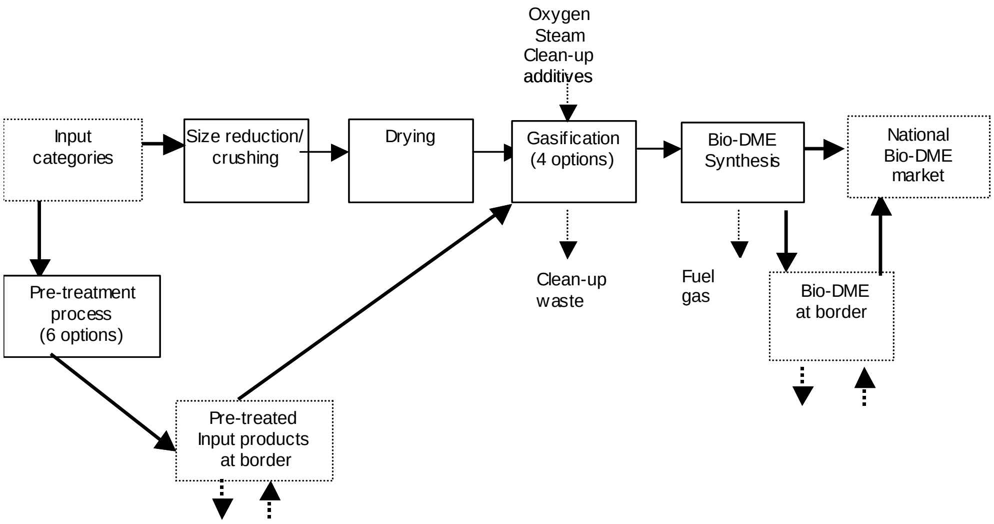
3.8 Biodimethylether (bio-DME)

Before being used as an automotive fuel, DME was mainly used as a substitute propellant for CFCs in spray cans. This still is its primary application. It is also used as an ignition improver in methanol engines.

The conversion process of bio-DME is very similar to that of biomethanol. It also consists of a gasification and synthesis process. However, process conditions are different. There are two possible routes for the production of bio-DME. These will be described in this section.

3.8.1 Bio-DME by gasification

In the first route, DME is produced directly from synthesis gas, for example in a slurry phase reactor. This is shown in Figure 3.11.



Input categories
Lignocellulosic crops
Herbaceous lignocellulosic crops
Forestry residues
Other energy crops
Agricultural residues
Wood processing residues
Construction residues
Organic waste (dry)
Organic waste (wet)
Other organic waste
Roadside hay
Solid manure

Pre-treatment processes
Separation, dewatering, drying and size reduction (chips)
Separation, dewatering, drying and densification (briquettes/pellets)
Separation, dewatering, drying and torrefaction (torrified biomass)
Separation, dewatering, drying and carbonisation (char)
Separation, dewatering, drying and fast pyrolysis (pyrolysis oil)
Separation, dewatering, drying and hydrothermal treatment (biocrude)

Gasification processes
Entrained Flow /Oxygen with gas clean-up and CO-shift
Fluidised Bed/Oxygen with gas clean-up and CO-shift (circulating or bubbling bed)
Indirect with gas clean-up and CO-shift
Fixed Bed/oxygen with gas clean-up and CO-shift

Figure 3.11 *Conversion process for bio-DME by gasification*

3.8.2 Bio-DME by catalytic dehydration of biomethanol

The second route produces bio-DME from pure biomethanol by means of a process called catalytic dehydration, see Figure 3.12. This is a process in which water is chemically separated from the methanol to form DME. Often the production of methanol and DME is combined in one process. This conversion route is only of interest in case biomethanol is internationally imported.

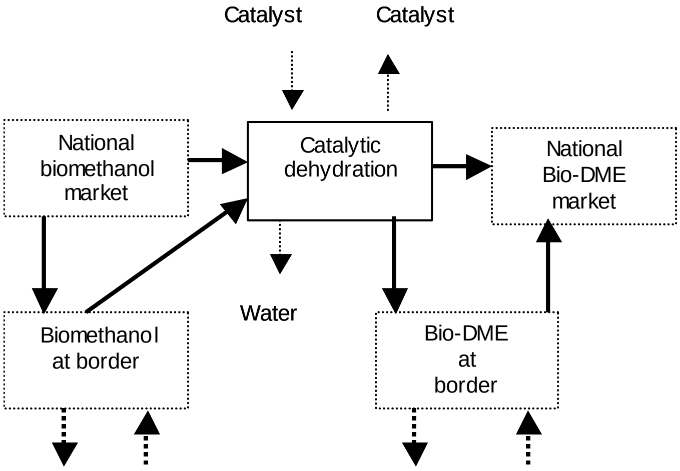


Figure 3.12 *Conversion process for bio-DME by catalytic dehydration of biomethanol*

3.9 SNG (synthetic biofuel)

Three conversion routes for Substitute Natural Gas (SNG) will be discussed in this section. In all chains, SNG is produced from biomass. The generic term SNG usually refers to methane produced by (subcritical) gasification followed by methanation.

SNG can be fed into the (national) natural gas infrastructure for pipeline transportation. After pipeline transport, or directly at the production side, it can be converted to: a) Compressed Substitute Natural Gas (CSNG) by compression to about 200 bar or b) Liquefied Substitute Natural Gas (LSNG) by liquefaction (long-distance intercontinental transport by bulk carriers). Both CSNG and LSNG can be used at filling stations for fuelling cars.

3.9.1 SNG by gasification and methanation

In this conversion route, SNG is produced by means of gasification of biomass in the presence of steam. The synthesis gas consists of a mixture of mainly H_2, CH_4, CO, CO_2 and H_2O. This gas is fed to a methanation reactor. Here, residual carbon oxides are converted to methane and water using a small part of the hydrogen present in the gas. Then the water is removed from the raw SNG. Finally, the remaining CO_2 is removed which leaves SNG that is similar to natural gas.

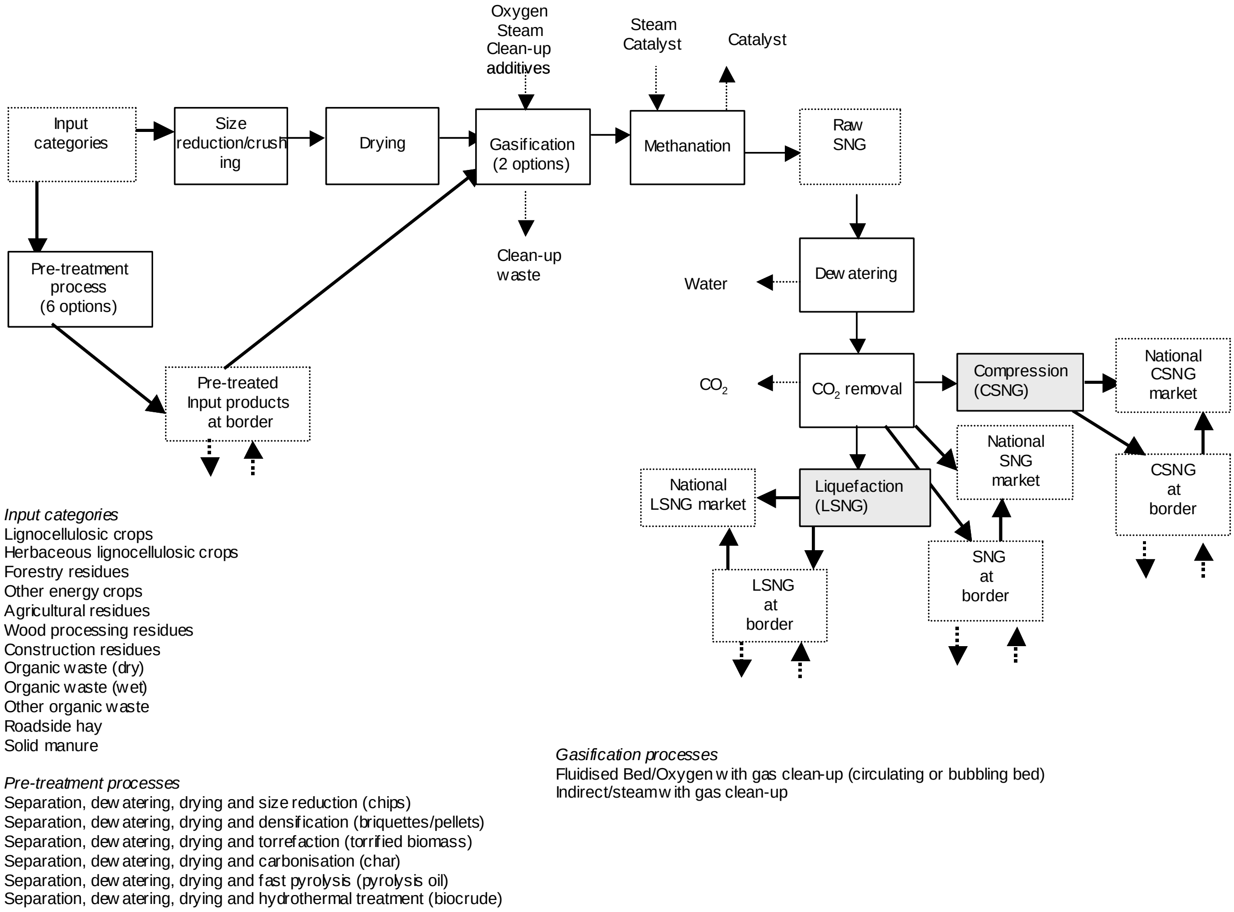


Figure 3.13 *Conversion process for SNG by gasification and methanation (optional compression or liquefaction)*

3.9.2 Biogas/SNG by digestion with CO_2 removal

A second route to produce SNG or biogas is called (anaerobic) digestion. In this process, biomass is biologically degraded by microorganisms in a wet environment, at relatively low temperature, and without the presence of oxygen. The temperature range depends on the kind of microorganisms used. The process consists of several phases, i.e. hydrolysis, fermentation, and formation of acetic acid and methane. In the figure below they are all included in the ‘digestion’ step. The digestion process results in three products, namely biogas (50-70% methane and 30-45% CO_2), a dry fraction, and a wet residual. For application as an automotive fuel the biogas has to be upgraded to a composition of 98% methane (CH_4) and 2% CO_2. This is similar to the composition of natural gas. Removing CO_2 and water from the gas at high pressure does this upgrading.

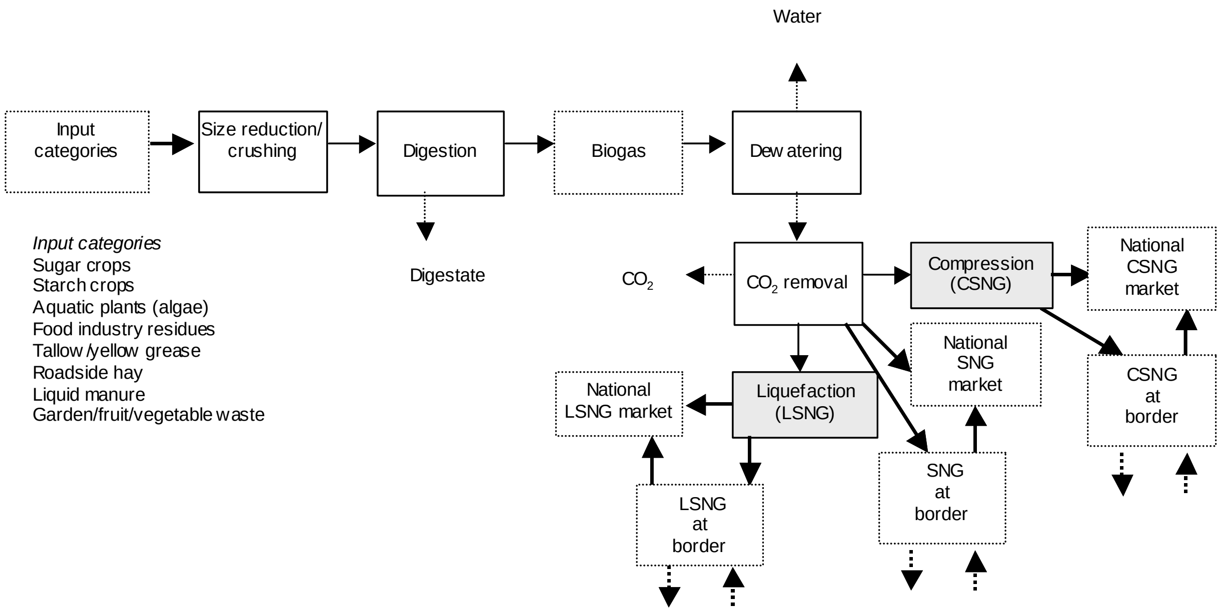


Figure 3.14 *Conversion process for biogas by digestion and CO_2 removal (optional compression or liquefaction)*

3.9.3 SNG by sub critical gasification

SNG can also be produced by subcritical gasification. The gasification step produces a gas mixture that consists of mainly CH_4, H_2, CO, H_2O and CO_2. By methanation, the methane (CH_4) content of the gas is further increased. Water and CO_2 is then removed from the raw SNG, which leaves fuel grade SNG.

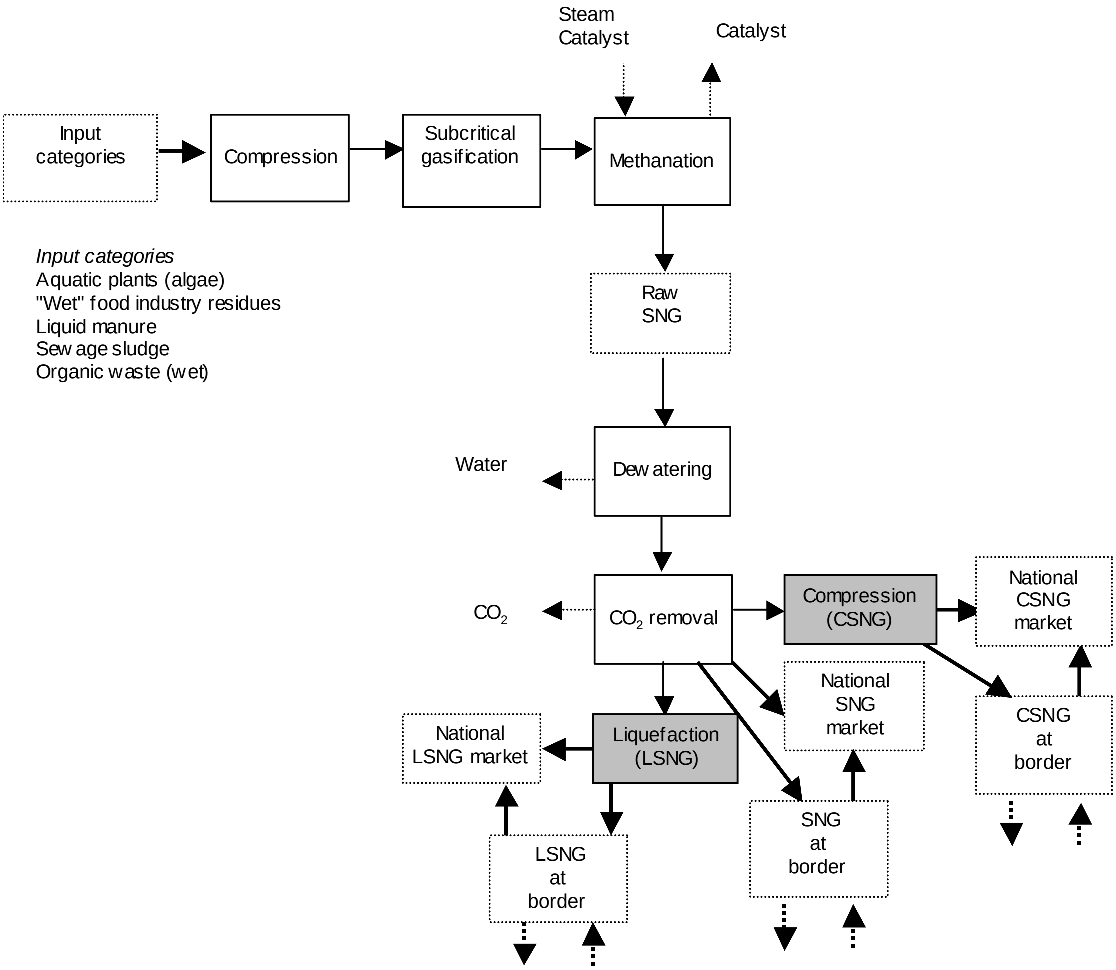


Figure 3.15 *Conversion process for SNG by subcritical gasification (optional compression or liquefaction)*

3.10 Biohydrogen

Three conversion routes for biohydrogen will be discussed in this section, i.e. gasification, digestion and steam reforming, and supercritical gasification. In all routes, compression of hydrogen is included as an optional process step, before the hydrogen is transported to the border or the national biohydrogen market.

3.10.1 Biohydrogen by gasification

Figure 3.16 shows the conversion route for biohydrogen by gasification. This process is similar to the conversion chain for Fischer-Tropsch diesel and biomethanol. First, biomass is gasified to produce synthesis gas. The synthesis gas is then processed further in a steam-reforming step to produce H_2 by the water-gas-shift reaction ($CO + H_2O \Leftrightarrow H_2 + CO_2$). After this water-gas-shift reaction, H_2 is produced by CO_2 removal. The biohydrogen may be compressed first before further transportation.

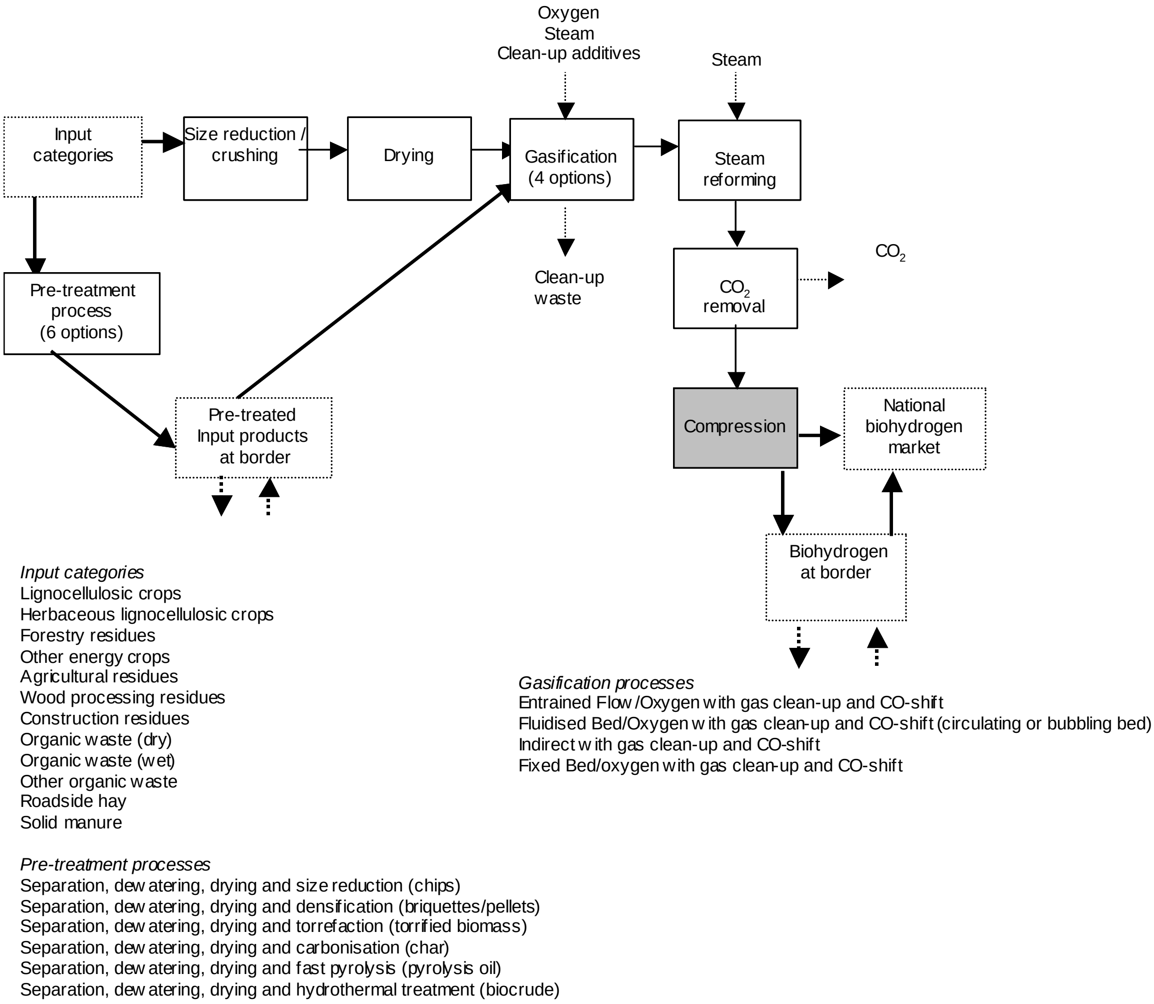


Figure 3.16 *Conversion process for biohydrogen by gasification (optional compression)*

3.10.2 Biohydrogen by digestion and steam reforming

A second route for the production of hydrogen from biomass is the digestion route. This route contains a digestion step, just like the conversion route for biogas (see section 3.9.2). In the process of (anaerobic) digestion, a gas is formed. This is a mixture of primarily CH_4 and CO_2. In order to produce H_2, this gas needs to be converted. This is done by means of a thermo chemical process called steam reforming. After reforming, the CO_2 is removed from the gas, which leaves H_2. The biohydrogen may be compressed first before further transportation.

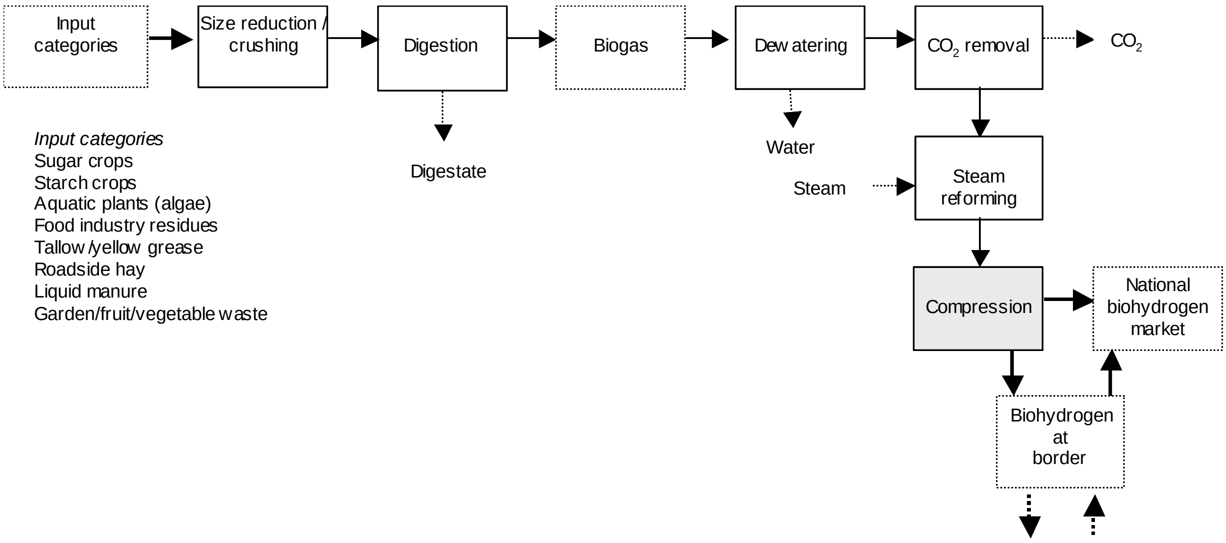


Figure 3.17 *Conversion process for biohydrogen by digestion and steam reforming (optional compression)*

3.10.3 Biohydrogen by supercritical gasification

Another possible route for the production of biohydrogen is supercritical. In contrast to subcritical gasification, the process is optimised to produce a maximum concentration of H_2. The supercritical gasification process results in a gas mixture of mainly H_2, CH_4, CO, H_2O and CO_2. Steam reformer increases the H_2 content further. After CO_2 removal, only H_2 remains, which may be compressed before further transportation.

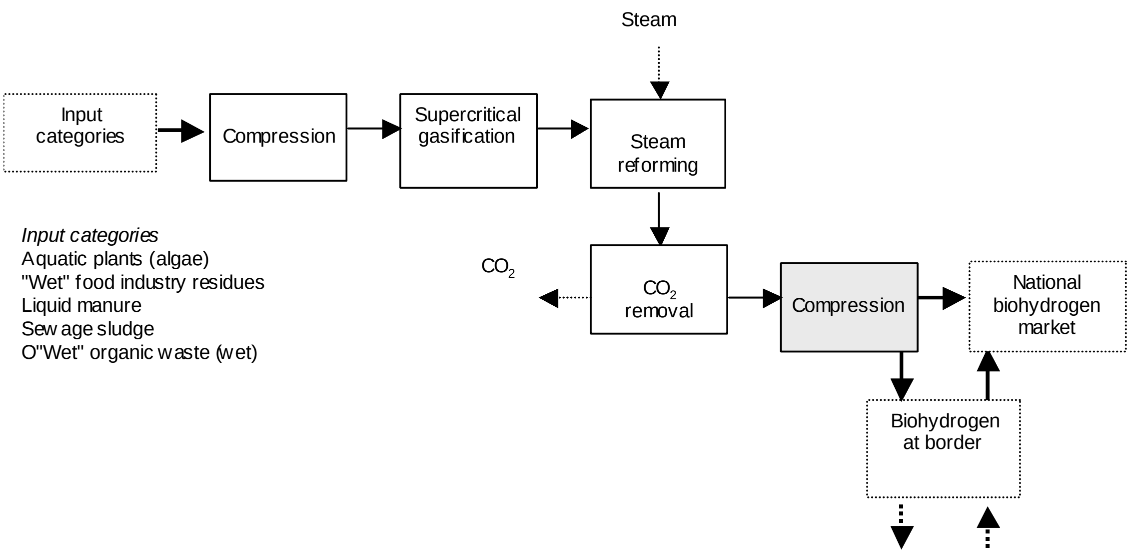
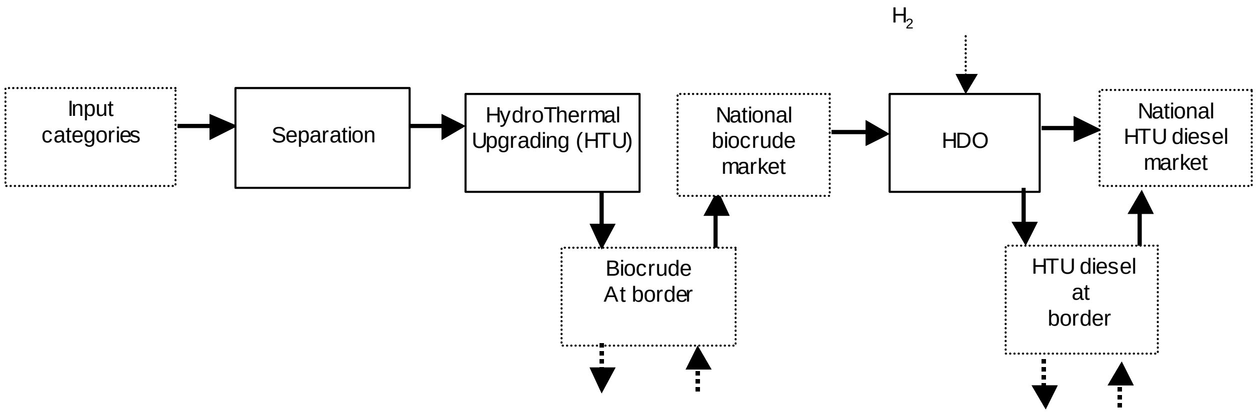


Figure 3.18 *Conversion process for biohydrogen by supercritical gasification (optional compression)*

3.11 HTU-diesel (synthetic biofuel)

The HydroThermalUpgrading (HTU) process can be used for the conversion of a broad range of biomass feedstocks. The process was especially designed for wet biomass. In the HTU process biomass reacts in liquid water at high pressure and relatively low temperature. The main product of this reaction is a liquid consisting of various kinds of hydrocarbon, a ‘biocrude’. It is similar to fossil oil and not mixable with water. The lighter fractions of this biocrude can be upgraded to diesel fuel components. HTU diesel is produced by means of a process called HydroDeOxygenation (HDO). In this process, oxygen is removed from the biocrude by adding hydrogen. The upgrading of the biocrude to diesel fuel may be done at the same location as the production of the biocrude or the biocrude may be transported to other locations, followed by local upgrading to HTU diesel.



Input categories
Aquatic plants (algae)
"Wet" food industry residues
Liquid manure
Sewage sludge
O"Wet" organic waste (wet)

Pre-treatment processes
Separation and hydrothermal treatment (biocrude)

Figure 3.19 *Conversion process for HTU diesel*

4. DATA REQUIREMENTS

In this Chapter, the data requirements for the BIOTRANS model will be identified, based on the biofuel conversion chains defined in Chapter 3. The data requirements will be defined in terms of parameters, units and time frame for the different levels on which the data are needed.

The definition of data requirements starts with a biomass resource classification system, which is given in Appendix A. This system is to define the different classes and types of resources and leaving out the details on the specific resources. The data requirements for biomass resources are presented in Table 4.1. They are to be collected for all EU Member States and CEECs.

Table 4.1 *Data requirements on biomass resources*

Level 1	Level 2	Level 3	Parameter	Unit	Time frame
Country			total area	[ha]	-
			agricultural land (incl. cattle breeding)	[ha]	2000 - 2050
			agricultural production land (excl. cattle breeding, pastures etc.)	[ha]	2000 - 2050
			agricultural production land for non-food purposes	[ha]	2000 - 2050
			forest	[ha]	2000 - 2050
Country	Energy crops	For each individual type[2]			
			productivity	[tonne/ha]	2000
			expected change in productivity	[%/year] (+ or -)	2000 - 2050
			production costs	[€/tonne]	2000
			expected change in production costs	[%/year] (+ or -)	2000 - 2050
			energy content	[GJ/tonne wet material]	-
			moisture content	[%/tonne]	-
			production	[tonne/year]	2000
Country	Residues, Manure, Sludge, Waste	For each individual type[3]			
			cost	[€/tonne] (+ or -)	2000
			change in costs	[%/year] (+ or -)	2000 - 2050
			energy content	[GJ/tonne wet material]	-
			moisture content	[%/tonne]	-
			availability	[tonne/year]	2000
			change in availability	[%/year] (+ or -)	2000 - 2050

In Chapter 3, a large number of biofuel conversion chains consisting of several subprocesses have been identified. All subprocesses and their inputs and outputs are listed in Appendix B. Since these will be the biofuel conversion chains that will be included in the BIOTRANS model, data need to be collected for each subprocess, again country-specific data for all EU Member States and CEECs. Table 4.2 shows the data requirements on subprocesses.

2 The following types should be considered: lignocellulosic crops, oil seeds, herbaceous lignocellulosic crops, sugar crops, starch crops, other energy crops, aquatic plants (algae) (see Appendix A Data: Biomass resources).

3 The following types should be considered: 1. forestry residues, 2. agricultural residues, 3. wood processing residues, 4. construction residues, 5. food industry residues, 6. tallow/yellow grease, 7. roadside hay, 8. solid manure, 9. liquid manure, 10. sewage sludge, 11. garden, fruit and vegetable waste, 12. organic waste (dry), 13. organic waste (wet) (see Appendix A Data: Biomass resources).

Table 4.2 *Data requirements on subprocesses*

Level 1	Level 2	Parameter	Unit	Time frame
Country independent				
		investments in hardware	[€/GJ_{input}]	2000
		change in investments in hardware	[%/year] (+ or -)	2000 - 2050
		external electricity demand	[kWh/GJ_{input}]	2000
		external heat demand	[GJ/GJ_{input}]	2000
	Country dependent			
		Project development costs	[€/GJ_{input}]	2000
		change in project development costs	[%/year] (+ or -)	2000 - 2050
		costs for secondary processing materials	[€/GJ_{input}]	2000
		change in costs for secondary processing materials	[%/year] (+ or -)	2000 - 2050
		costs for external electricity	[€/kWh]	2000
		costs for external heat	[€/GJ]	2000
		O&M costs, except for secondary processing materials, or external electricity and heat	[€/GJ_{input}]	2000
		change in O&M costs	[%/year] (+ or -)	2000 - 2050
		existing production capacity	[GJ_{input}]	2000
		costs for product storage	[€/GJ_{input}]	2000
		conversion factor	[GJ_{output}/GJ_{input}]	2000
		increase in conversion factor	[%/year]	2000 - 2050
		energy content output	[GJ/tonne output]	-
		specific weight of output	[tonne/ m^3 output]	-
		CO_2 emission	[tonne CO_2/GJ_{input}]	2000

Between two subprocesses, the intermediate product may be transported on national level. All products that may be transported nationally are listed in Appendix C. In Table 4.3 the data requirements on national transportation are indicated. Again, these data need to be collected for all EU Member States and CEECs.

Table 4.3 *Data requirements on national transportation*

Level 1	Level 2	Parameter	Unit	Time frame
Product				
		transportation costs	[€/tonne·km]	2000
		change in transportation costs	[%/year] (+ or -)	2000 - 2050
		CO_2 emission	[kg/km]	2000
		change in emission	[%/year] (+ or -)	2000 - 2050
	from process - to process			
		average distance	[km]	-

There are also a number of products that may be transported on international level, see Table 4.4. These data will be collected from Work Package 3 and 4 of the VIEWLS project.

Table 4.4 *Products for international transportation*

Biomass	Pre-treated biomass	Intermediate products	Biofuels
Oil seeds	Chips	Pyrolysis oil	Pure vegetable oil
Tallow/yellow grease	Briquettes/pellets	Biocrude	Biodiesel
Sugar crops	Torrified biomass	Fischer-Tropsch wax	Fuel grade bioethanol
Starch crops	Char		Biomethanol
Lignocellulosic crops			Bio-ETBE
Herbaceous Lignocellulosic crops			Bio-MTBE
Forestry residues			Bio-DME
Other energy crops			Fischer-Tropsch diesel
Agricultural residues			SNG
Wood processing residues			LSNG
Construction residues			CSNG
Organic waste (dry)			Biohydrogen
Organic waste (wet)			
Roadside hay			HTU diesel
Solid manure			

REFERENCES

Thuijl, E. van, C.J. Roos and L.W.M. Beurskens (2003). *An overview of biofuel technologies, markets and policies in Europe*. ECN report ECN-C--03-008. Energy research Centre of the Netherlands, Petten, the Netherlands.

Zessen, E. van, et al. (2003). *Lignocellulosic ethanol: a second opinion*. Energy research Centre of the Netherlands, the Agrotechnological Research Institute (ATO), and Royal Nedalco.

APPENDIX A DATA: BIOMASS RESOURCES

Table A.1 presents the biomass resources that are considered in defining the conversion processes in Chapter 3. This list is based on the classification of biomass resources given in Table 2.1.

Table A.1 *Biomass resources*

Classification	Type of resource
Energy crops	Lignocellulosic crops
	Oil seeds
	Herbaceous lignocellulosic crops
	Sugar crops
	Starch crops
	Other energy crops
	Aquatic plants (algae)
Residues	Forestry residues
	Agricultural residues
	Wood processing residues
	Construction residues
	Food industry residues
	Tallow/yellow grease
	Roadside hay
Manure	Solid manure
	Liquid manure
Sludge	Sewage sludge
Waste	Garden, fruit and vegetable waste
	Organic waste (dry)
	Organic waste (wet)

APPENDIX B DATA: SUBPROCESSES AND PRODUCT FLOWS

Table B.1 *Subprocesses*

Input	Process	Output
Oil seeds	Washing/flaking/cooking/pressing	Pre-treated oil seeds
Pre-treated oil seeds	Oil extraction	Raw vegetable oil
Raw vegetable oil	Distillation	Pure vegetable oil
Pure vegetable oil	Transesterification	Methyl esters
Methyl esters	Separation	Biodiesel+methanol
Biodiesel+methanol	Neutralisation+purification	Biodiesel
Tallow/yellow grease	Refining/filtering	Refined used fats
Refined used fats	Transesterification	Methyl esters
Fuel grade bioethanol	Bio-ETBE synthesis	Bio-ETBE
Biomethanol	Bio-MTBE synthesis	Bio-MTBE
Sugar crops	Transformation: crushing – sugar extraction	Juice/syrup
Juice/syrup	Fermentation	Raw bioethanol
Raw bioethanol	Distillation/dewatering	Fuel grade bioethanol
Starch crops	Wet/dry milling	Crushed starch crops
Crushed starch crops	Heating	Sugars
Sugars	Fermentation	Raw bioethanol
Lignocellulosic crops Herb. lignocellulosic crops Forestry residues Other energy crops Agricultural residues Wood processing residues Construction residues Organic waste (dry) Organic waste (wet) Roadside hay	Size reduction and thermo-chemical pre-treatment	Small sized cellulosic material
Small sized cellulosic material	Acid or enzymatic hydrolysis	Fermentable sugars
Fermentable sugars	Fermentation	Raw bioethanol
Lignocellulosic crops Herb. lignocellulosic crops Forestry residues Other energy crops Agricultural residues Wood processing residues Construction residues Organic waste (dry) Organic waste (wet) Roadside hay	Separation, dewatering, drying and size reduction	Chips
Lignocellulosic crops Herb. lignocellulosic crops Forestry residues Other energy crops Agricultural residues Wood processing residues Construction residues Organic waste (dry) Organic waste (wet) Roadside hay	Separation, dewatering, drying and densification	Briquettes/pellets

Input	Process	Output
Lignocellulosic crops Herb. lignocellulosic crops Forestry residues Other energy crops Agricultural residues Wood processing residues Construction residues Organic waste (dry) Organic waste (wet) Roadside hay	Separation, dewatering, drying and torrefaction	Torrified biomass
Lignocellulosic crops Herb. lignocellulosic crops Forestry residues Other energy crops Agricultural residues Wood processing residues Construction residues Organic waste (dry) Organic waste (wet) Roadside hay	Separation, dewatering, drying and carbonisation	Char
Lignocellulosic crops Herb. Lignocellulosic crops Forestry residues Other energy crops Agricultural residues Wood processing residues Construction residues Organic waste (dry) Organic waste (wet) Roadside hay	Separation, dewatering, drying and fast pyrolysis	Pyrolysis oil
Lignocellulosic crops Herb. Lignocellulosic crops Forestry residues Other energy crops Agricultural residues Wood processing residues Construction residues Organic waste (dry) Organic waste (wet) Roadside hay	Separation, dewatering, drying and hydrothermal treatment	Biocrude
Chips Briquettes/pellets Torrified biomass Char Pyrolysis oil Biocrude	Size reduction and thermo-chemical treatment	Small sized cellulosic material
Lignocellulosic crops Herb. Lignocellulosic crops Forestry residues Other energy crops Agricultural residues Wood processing residues Construction residues Organic waste (dry) Organic waste (wet) Roadside hay Solid manure Sugar crops Starch crops Aquatic plants (algae) Food industry residues Tallow/yellow grease Garden/fruit/vegetable waste	Size reduction/crushing	Small sized input products

Input	Process	Output
Small sized input products	Drying	Dry small sized input products
Dry small sized input products Chips Briquettes/pellets Torrified biomass Char Pyrolysis oil Biocrude	Entrained Flow/Oxygen with gas clean-up and CO shift	Synthesis gas
Dry small sized input products Chips Briquettes/pellets Torrified biomass Char Pyrolysis oil Biocrude	Fluidised/Oxygen with gas clean-up and CO shift	Synthesis gas
Dry small sized input products Chips Briquettes/pellets Torrified biomass Char Pyrolysis oil Biocrude	Indirect with gas clean-up and CO shift	Synthesis gas
Dry small sized input products Chips Briquettes/pellets Torrified biomass Char Pyrolysis oil Biocrude	Fixed bed/Oxygen with gas clean-up and CO shift	Synthesis gas
Synthesis gas	Fischer-Tropsch synthesis	Fischer-Tropsch wax
Fischer-Tropsch wax	Hydrocracking	Fischer-Tropsch diesel
Synthesis gas	Biomethanol synthesis	Biomethanol
Synthesis gas	Bio-DME synthesis	Bio-DME
Biomethanol	Catalytic dehydration	Bio-DME
Dry small sized input products Chips Briquettes/pellets Torrified biomass Char Pyrolysis oil Biocrude	Fluidised Bed/oxygen with gas clean-up	Synthesis gas for SNG
Dry small sized input products Chips Briquettes/pellets Torrified biomass Char Pyrolysis oil Biocrude	Indirect/steam with gas clean-up	Synthesis gas for SNG
Synthesis gas for SNG	Methanation	Raw SNG
Raw SNG	Dewatering	Dewatered raw SNG
Dewatered raw SNG	CO_2 removal	SNG
SNG	Compression (CSNG)	CSNG
SNG	Liquefaction (LSNG)	LSNG
Small sized input products	Digestion	Biogas
Biogas	Dewatering	Dewatered raw SNG
Aquatic plants (algae) 'Wet' food industry residues Liquid manure Sewage sludge Organic waste (wet)	Compression2	Compressed input products

Input	Process	Output
Compressed input products	Subcritical gasification	Gas mixture
Gas mixture	Methanation	Raw SNG
Synthesis gas	Steam reforming	Raw biohydrogen
Raw biohydrogen	CO_2 removal	Compressible biohydrogen
Compressible biohydrogen	Compression	Biohydrogen
Biogas	Dewatering	Dewatered biogas
Dewatered biogas	CO_2 removal	Biogas for steam reforming
Biogas for steam reforming	Steam reforming	Compressible hydrogen
Compressed input products	Supercritical gasification	Gas mixture2
Gas mixture2	Steam reforming	Raw biohydrogen
Aquatic plants (algae) 'Wet' food industry residues Liquid manure Sewage sludge Organic waste (wet)	Separation	Separated input products
Separated input products	HydroThermalUpgrading (HTU)	Biocrude

APPENDIX C DATA: NATIONAL TRANSPORTATION

Table C.1 *Transportation on national level*

Product	From process	To process
Oil seeds	Oil seeds production site	Washing/flaking/cooking/pressing
Oil seeds	Oil seeds production site	Oil seeds at border
Oil seeds	Oil seeds at border	Washing/flaking/cooking/pressing
Pure vegetable oil	Distillation	Pure vegetable oil at border
Pure vegetable oil	Distillation	National pure vegetable oil market
Pure vegetable oil	Pure vegetable oil at border	National pure vegetable oil market
Pure vegetable oil	National pure vegetable oil market	Pure vegetable oil at border
Pure vegetable oil	National pure vegetable oil market	Transesterification
Pure vegetable oil	Pure vegetable oil at border	Transesterification
Biodiesel	Neutralisation+purification	National biodiesel market
Biodiesel	Neutralisation+purification	Biodiesel at border
Biodiesel	Biodiesel at border	National biodiesel market
Tallow/yellow grease	National used fats market	Refining/filtering
Tallow/yellow grease	National used fats market	Used fats at border
Tallow/yellow grease	Used fats at border	Refining/filtering
Fuel grade bioethanol	National fuel grade bioethanol market	Bio-ETBE synthesis
Fuel grade bioethanol	National fuel grade bioethanol market	Fuel grade bioethanol at border
Fuel grade bioethanol	Fuel grade bioethanol at border	Bio-ETBE synthesis
Bio-ETBE	Bio-ETBE synthesis	National bio-ETBE market
Bio-ETBE	Bio-ETBE synthesis	Bio-ETBE at border
Bio-ETBE	Bio-ETBE at border	National bio-ETBE market
Biomethanol	National biomethanol market	Bio-MTBE synthesis
Biomethanol	National biomethanol market	Biomethanol at border
Biomethanol	Biomethanol at border	Bio-MTBE synthesis
Bio-MTBE	Bio-MTBE synthesis	National bio-MTBE market
Bio-MTBE	Bio-MTBE synthesis	Bio-MTBE at border
Bio-MTBE	Bio-MTBE at border	National bio-MTBE market
Sugar crops	Sugar crops production site	Transformation: crushing – sugar extraction
Sugar crops	Sugar crops production site	Sugar crops at border
Sugar crops	Sugar crops at border	Transformation: crushing – sugar extraction
Fuel grade bioethanol	Distillation/dewatering	National fuel grade bioethanol market
Fuel grade bioethanol	Distillation/dewatering	Fuel grade bioethanol at border
Fuel grade bioethanol	Fuel grade bioethanol at border	National fuel grade bioethanol market
Starch crops	Starch crops production site	Wet/dry milling
Starch crops	Starch crops production site	Starch crops at border
Starch crops	Starch crops at border	Wet/dry milling
Lignocellulosic crops Herb. lignocellulosic crops Forestry residues Other energy crops Agricultural residues Wood processing residues Construction residues Organic waste (dry) Organic waste (wet) Roadside hay Solid manure Sugar crops Starch crops Aquatic plants (algae)	Production site	Size reduction/crushing

Product	From process	To process
Food industry residues Tallow/yellow grease Liquid manure Garden/fruit/vegetable waste		
Lignocellulosic crops Herb. lignocellulosic crops Forestry residues Other energy crops Agricultural residues Wood processing residues Construction residues Organic waste (dry) Organic waste (wet) Roadside hay	Production site	Size reduction and thermo-chemical pre-treatment
Lignocellulosic crops Herb. lignocellulosic crops Forestry residues Other energy crops Agricultural residues Wood processing residues Construction residues Organic waste (dry) Organic waste (wet) Roadside hay Solid manure	Production site	Separation, dewatering, drying and size reduction
Lignocellulosic crops Herb. lignocellulosic crops Forestry residues Other energy crops Agricultural residues Wood processing residues Construction residues Organic waste (dry) Organic waste (wet) Roadside hay Solid manure	Production site	Separation, dewatering, drying and densification
Lignocellulosic crops Herb. lignocellulosic crops Forestry residues Other energy crops Agricultural residues Wood processing residues Construction residues Organic waste (dry) Organic waste (wet) Roadside hay Solid manure	Production site	Separation, dewatering, drying and torrefaction
Lignocellulosic crops Herb. lignocellulosic crops Forestry residues Other energy crops Agricultural residues Wood processing residues Construction residues Organic waste (dry) Organic waste (wet) Roadside hay Solid manure	Production site	Separation, dewatering, drying and carbonisation
Lignocellulosic crops Herb. lignocellulosic crops Forestry residues Other energy crops Agricultural residues Wood processing residues	Production site	Separation, dewatering, drying and fast pyrolysis

Product	From process	To process
Construction residues Organic waste (dry) Organic waste (wet) Roadside hay Solid manure		
Lignocellulosic crops Herb. lignocellulosic crops Forestry residues Other energy crops Agricultural residues Wood processing residues Construction residues Organic waste (dry) Organic waste (wet) Roadside hay Solid manure	Production site	Separation, dewatering, drying and hydrothermal treatment
Chips	Separation, dewatering, drying and size reduction	Pre-treated cellulosic feedstock at border
Briquettes/pellets	Separation, dewatering, drying and densification	Pre-treated cellulosic feedstock at border
Torrified biomass	Separation, dewatering, drying and torrefaction	Pre-treated cellulosic feedstock at border
Char	Separation, dewatering, drying and carbonisation	Pre-treated cellulosic feedstock at border
Pyrolysis oil	Separation, dewatering, drying and fast pyrolysis	Pre-treated cellulosic feedstock at border
Biocrude	Separation, dewatering, drying and hydrothermal treatment	Pre-treated cellulosic feedstock at border
Chips Briquettes/pellets Torrified biomass Char Pyrolysis oil Biocrude	Pre-treated cellulosic feedstock at border	Size reduction and thermo-chemical pre-treatment
Chips Briquettes/pellets Torrified biomass Char Pyrolysis oil Biocrude	Pre-treated input products at border	Entrained Flow/Oxygen with gas clean-up and CO shift
Chips Briquettes/pellets Torrified biomass Char Pyrolysis oil Biocrude	Pre-treated input products at border	Fluidised/Oxygen with gas clean-up and CO shift
Chips Briquettes/pellets Torrified biomass Char Pyrolysis oil Biocrude	Pre-treated input products at border	Indirect with gas clean-up and CO shift
Chips Briquettes/pellets Torrified biomass Char Pyrolysis oil Biocrude	Pre-treated input products at border	Fixed bed/Oxygen with gas clean-up and CO shift
Chips	Separation, dewatering, drying and size reduction	Pre-treated input products at border
Briquettes/pellets	Separation, dewatering, drying and densification	Pre-treated input products at border

Product	From process	To process
Torrified biomass	Separation, dewatering, drying and torrefaction	Pre-treated input products at border
Char	Separation, dewatering, drying and carbonisation	Pre-treated input products at border
Pyrolysis oil	Separation, dewatering, drying and fast pyrolysis	Pre-treated input products at border
Biocrude	Separation, dewatering, drying and hydrothermal treatment	Pre-treated input products at border
Fischer-Tropsch wax	Fischer-Tropsch synthesis	Fischer-Tropsch wax at border
Fischer-Tropsch wax	Fischer-Tropsch synthesis	Hydrocracking
Fischer-Tropsch wax	Fischer-Tropsch wax at border	Hydrocracking
Fischer-Tropsch diesel	Hydrocracking	National Fischer-Tropsch diesel market
Fischer-Tropsch diesel	Hydrocracking	Fischer-Tropsch diesel at border
Fischer-Tropsch diesel	Fischer-Tropsch diesel at border	National Fischer-Tropsch diesel market
Biomethanol	Biomethanol synthesis	National biomethanol market
Biomethanol	Biomethanol synthesis	Biomethanol at border
Biomethanol	Biomethanol at border	National biomethanol market
Bio-DME	Bio-DME synthesis	National bio-DME market
Bio-DME	Bio-DME synthesis	Bio-DME at border
Bio-DME	Bio-DME at border	National bio-DME market
Biomethanol	Biomethanol at border	Catalytic dehydration
Biomethanol	National biomethanol market	Catalytic dehydration
Bio-DME	Catalytic dehydration	National bio-DME market
Bio-DME	Catalytic dehydration	Bio-DME at border
Chips Briquettes/pellets Torrified biomass Char Pyrolysis oil Biocrude	Pre-treated input products at border	Fluidised Bed/oxygen with gas clean-up
Chips Briquettes/pellets Torrified biomass Char Pyrolysis oil Biocrude	Pre-treated input products at border	Indirect/steam with gas clean-up
SNG	CO_2 removal	National SNG market
SNG	SNG at border	National SNG market
SNG	CO_2 removal	SNG at border
LSNG	Liquefaction	National LSNG market
LSNG	LSNG at border	National LSNG market
LSNG	Liquefaction	LSNG at border
CSNG	Compression	National CSNG market
CSNG	CSNG at border	National CSNG market
CSNG	Compression	CSNG at border
Biohydrogen	Compression	National biohydrogen market
Biohydrogen	Biohydrogen at border	National biohydrogen market
Biohydrogen	Compression	Biohydrogen at border
Aquatic plants (algae) 'Wet' food industry residues Liquid manure Sewage sludge Organic waste (wet)	Production site	Compression2
Aquatic plants (algae) 'Wet' food industry residues Liquid manure Sewage sludge Organic waste (wet)	Production site	Separation

Product	From process	To process
Separated input products	Separation	HydroThermalUpgrading (HTU)
Biocrude	HydroThermalUpgrading (HTU)	National biocrude market
Biocrude	Biocrude at border	National biocrude market
Biocrude	HydroThermalUpgrading (HTU)	Biocrude at border
Biocrude	National biocrude market	HDO
HTU diesel	HDO	National HTU diesel market
HTU diesel	HDO	HTU diesel at border
HTU diesel	HTU diesel at border	National HTU diesel market