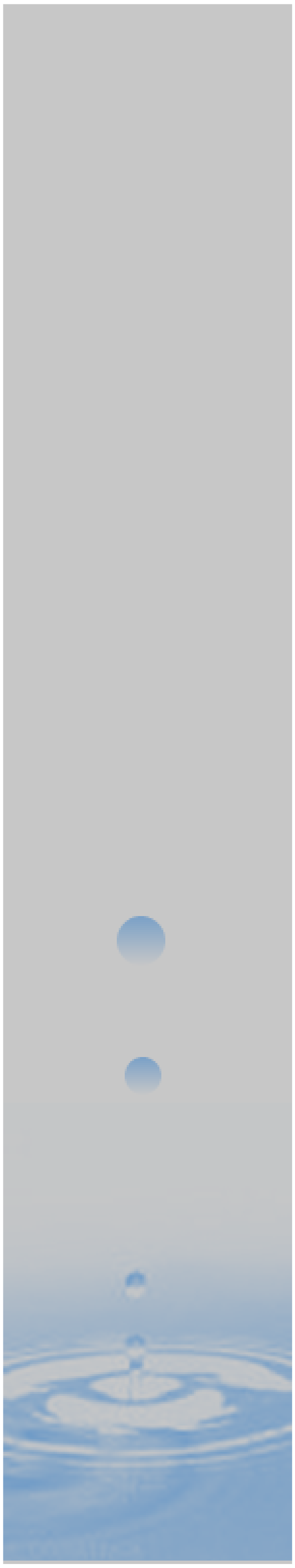
IEA Bioenergy Task 39
Commercializing 1st- and 2nd- Generation Liquid Biofuels from Biomass



Status of 2nd Generation Biofuels Demonstration Facilities in June 2010

A REPORT TO IEA BIOENERGY TASK 39

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wordle, representing the most frequently used words in this report

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Glossary

liquid or gaseous biofuels for transportation	fuels derived from biomass use in engines to provide a transportation service
lignocellulosic biomass	feedstock consisting mainly of cellulose, hemicellulose, and lignin, such as woody materials, grasses, and agricultural and forestry residues
biochemical conversion	Conversion technology based on enzymatic or microbiological processes
thermochemical conversion	Conversion technology based on processes using heat (partly also pressure)
biochemical and thermochemical conversion	combination of biochemical and thermochemical conversion technologies
pilot facility	facility, which does not operate continuously; facility not embedded into a entire material logistic chain; only the feasibility of selected technological steps is demonstrated; the product might not be marketed
demonstration facility	facility demonstrating the capability of the technology for continuous production (operated mainly continuously); the facility covering the entire production process or embedded into an entire material logistic chain; the product is being marketed; facility may not be operated under economical objectives
commercial facility	facility operated continuously with high level of availability; facility operated under economical objectives; he product is being marketed
planned	plans are made but financing is still open
announced	financing is secured
under construction	erection of the production facility has started
under commissioning	erection of the production facility is completed, but regular production has not started
operational	erection and start-up are complete, regular production has started

Executive Summary

Driven by the need to partly replace fossil transport fuels and by food versus fuel and highest possible GHG mitigation considerations, large efforts are dedicated to the development of technologies for the production of biofuels from lignocellulosic raw materials. A high number of projects are being pursued, but only few facilities in the demonstration scale are actually operating. The technologies applied vary widely, as do the raw materials of choice.

This report gives an overview on 66 projects that are being pursued currently, and provides details on the facility size, feedstock in use and technology applied. About 50 companies have provided data on their projects directly to the authors.

The report shows that currently many facilities in the demonstration scale are under construction and will hopefully successfully demonstrate biofuels production from lignocellulosic raw materials in the near future. Plans exist to build larger commercial facilities and thus rapidly increase the production capacities. Despite the possibly fast development, the volumes of lignocellulosic biofuels to be produced in the next five years will be small as compared to the current production of conventional biofuels. High efforts still need to be made to pursue these and more demonstration activities and to quickly multiply facilities when technologies have proven their technical and economic feasibility.

While this report gives an overview on the status by mid 2010, all data on these projects is also available in the internet (http://biofuels.abc-energy.at/demoplants/) and will be updated and expanded to new projects throughout the years to come.

1 Introduction

Currently, large efforts are dedicated to the production of biofuels from lignocellulosic raw materials. While only few production facilities are operational yet, many projects are under construction or planned.

IEA Bioenergy Task 39 has commissioned an overview on pilot and demonstration facilities for the production of biofuels from lignocellulosic raw materials. IEA Bioenergy Task 39 has members in 15 countries or regional associations and is therefore well suited to elaborate a global overview. The task delegates from these 15 countries and the delegates to IEA Bioenergy Task 33 were asked to list 2nd generation biofuel projects in their countries and so produced a list of >150 projects. The respective project owners were then asked to provide detailed information, such as type of product, type of conversion technology, production capacity, current status of the project, project owner and location.

The scope of projects under investigation comprises:

	Scope of Projects
Product	facilities for the production of liquid or gaseous biofuels for transportation
Raw Material	from lignocellulosic biomass
	applying either
Conversion Technology	biochemical or thermochemical or biochemical and thermochemical conversion technologies
	representing either
Type of Facility	pilot or demonstration or commercial facilities
	being either
Status	planned or announced or under construction or under commissioning or operational
	and for which the project owner has provided at least the following data:
Minimum Data	project owner location of the production facility type of technology raw material product output capacity type of facility status and contact information
Optional Data	Additionally, project owners are asked to provide more detailed information, including brief technology description, flow sheets and pictures etc.

Table 1: Scope of Projects under investigation

All information was inserted into a database and is displayed in an interactive map. The map can be viewed at http://biofuels.abc-energy.at/demoplants/. All information displayed was provided by the project owners themselves. Projects, for which no information has been provided by the project owner, are not visible in the map.

The interactive map allows the user to quickly obtain an overview on ongoing lignocellulosic biofuel projects, and to find detailed information on specific projects.

The report in hands summarises the information gathered for the database and displayed in the interactive map. Additionally, an outline of the main technologies applied in the production of biofuels from lignocellulosic raw materials is given, and the vast data available is summarised in the final chapter.

2 Technology Options: Lignocellulosics to Biofuels

2.1 Introduction

The categorization of the biofuels used in this report is as follows:

1st Generation Biofuels: are produced from (parts of) agricultural crops with high energy density like oil seeds or fruits using vegetable oil, sugar or starch as feedstock. The typical representatives of 1st generation biofuels are: biodiesel, bio-ethanol, vegetable oil and biogas.

2nd Generation Biofuels: are made from the overall ligno-cellulosic biomass (ligno-cellulosis = material containing lignin, cellulose and hemi-cellulose). The typical representatives of 2nd generation process are ligno-cellulosic ethanol, Biomass to Liquid (BtL) and bio-synthetic natural gas (bio-SNG).

In alternative categorizations also upgraded biogas, hydro-treated vegetable oil or similar are denoted as 2nd generation biofuels. When multiple products are derived from biomass conversion processes like fuel, power and value added chemicals, this is often referred to as a biorefinery.

The principle ways of processing 2nd generation biofuels are shown in figure below:

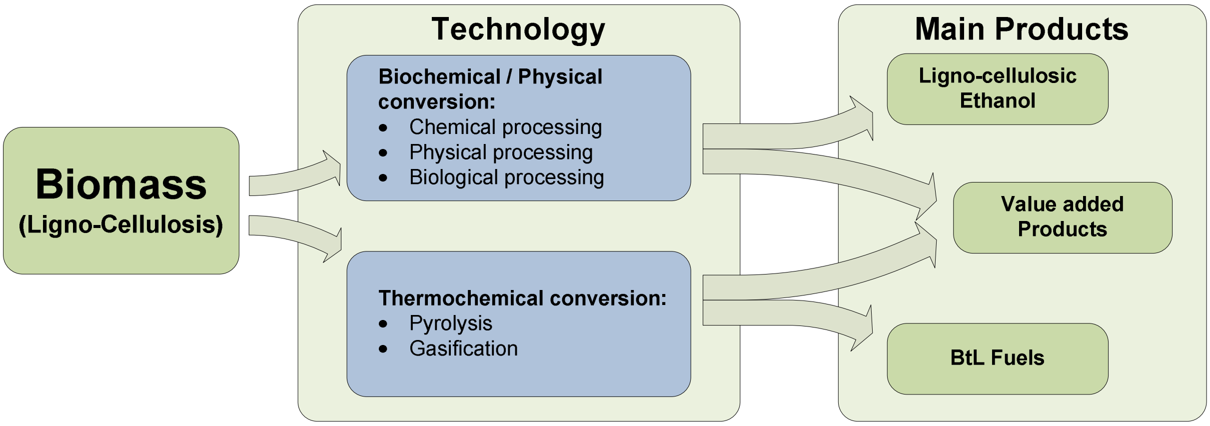

Figure 1: Principle Ways of Processing 2nd Generation Biofuels

2.2 Lignocellulosic Ethanol

2.2.1 Introduction

In contrast to the traditional bio-ethanol production from sugar and starch, the production based on ligno-cellulosic material requires additional processing steps. The reason is that the cellulose (source of C_6 sugars such as glucose) as well as hemi-cellulose (mainly source of C_5 sugars such as xylose) is not accessible to the traditional bio-ethanol producing micro-organisms.

Following processing steps may be found in a general ligno-cellulose to bio-ethanol production process:

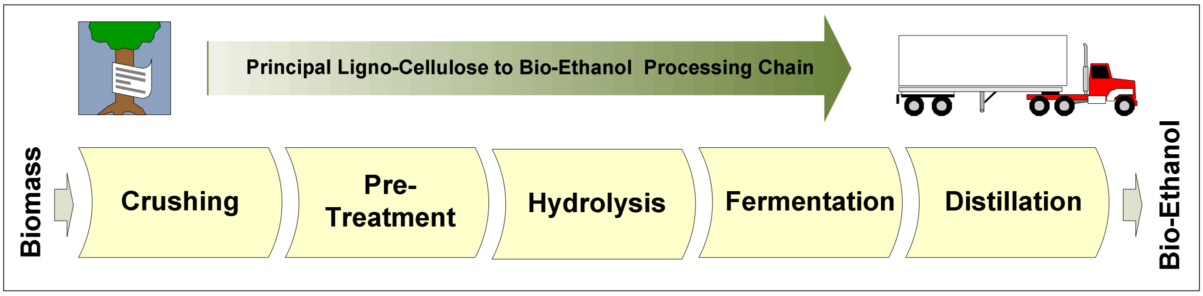

Figure 2: Processing Steps in Lignocellulose to Bioethanol Production

2.2.2 Size reduction

Within the size reduction step the biomass is milled or chipped. This straightforward step is performed by various types of mills in order to increase the accessibility of the processed material for the pre-treatment step.

2.2.3 Pre-Treatment

The main purpose of the pretreatment is to destroy the lignin shell protecting the cellulose and hemi-cellulose material, to decrease the crystallinity of the cellulose and to increase the porosity of the material. Only after breaking this shell the sugar containing materials become accessible for hydrolysis.

The products of this processing step are the released cellulose, hemi-cellulose and fragments of lignin. In dependance of the intensity of the pre-treatment various undesired side-products may be obtained (such as phenol-compounds from lignin or organic acids, anorganic salts) often inhibiting the consecutive micro-biological hydrolysis and/or fermentation processing steps. Under harsh conditions (such as observable in the concentrated acid pre-treatment) a general material degradation may be observed. This again leads to inhibition in the consecutive processing steps but also to general material losses.

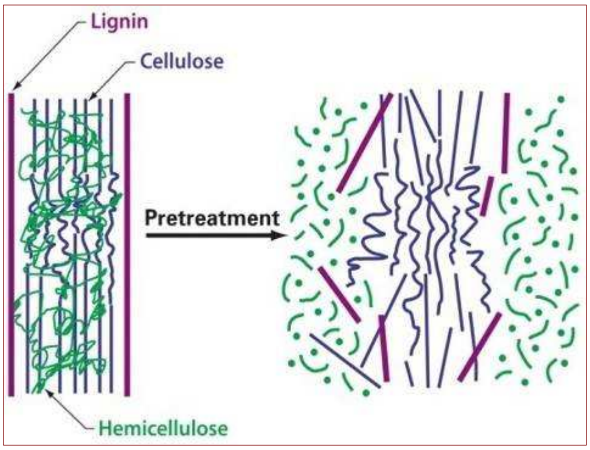

Figure 3: Breakdown of Lignin,
Cellulose and Hemicellulose. Source: Genome Management Information System ORNL

A general classification of the pre-treatment methods into three groups may be undertaken: chemical, physical und biological pre-treatment methods.

Chemical pre-treatment of ligno-cellulose			
Pre-treatment Type	**Example of the Chemical used**	**Conditions**	**Advantages and Disadvantages**
Concentrated Acid	H_2SO_4, HCl	Concentrated acid Low temperature	Well known and already used High yields Hydrolysis is mainly included Corrosion problems Material loss due to degradation High demand for chemicals Environmental issues
Diluted Acid	H_2SO_4	w = 0,5-2% T > 160℃	Well known and already used Corrosion problems Low yields Material loss due to degradation
ARP Ammonia Recycled Percoration	Ammonia	w = 15% T = ~ 170℃	Research topic Media recoverable Environmental issues due to ammonia
Lye	NaOH, $Ca(OH)_2$	w = 0,5M T = ~ 80℃	Research topic Media not recoverable
Organosolv	Ethanol-Water, Butanol-Water, Ethylene-Glycol	T = 150-200℃	Costs of solvent Media recoverable
Ionic Liquids		T = ~ 110℃	Research topic Media recoverable Low energy consumption

Table 2: Chemical Pre-treatment Methods

Physical pre-treatment of ligno-cellulose		
Pre-treatment Type	**Conditions**	**Advantages and Disadvantages**
Steam-Explosion	p = 2,5-7 MPa T = 180-280℃	Well known and already used High yields No corrosion problems Undesired side-products possible High energy demand
LHW - Liquid Hot Water	T = 170-230℃	Research topic High yields Less side-products than in steam explosion No corrosion problems
CO_2 Explosion	p > 7,3 MPa T > 31,1℃ super critical CO_2	Research topic High costs expected Low environmental impact
AFEX Ammonia Fiber Explosion	Liq. Ammonia T = 90-100℃	Low inhibitor formation Media recoverable Environmental issues due to ammonia

Table 3: Physical Pre-treatment Methods

Biological pre-treatment of ligno-cellulose		
Pre-treatment Type	**Examples of organism**	**Advantages and Disadvantages**
Pre-treatment with funghi	White-rot fungi Brown-rot fungi Soft-rot fungi	Research topic Slow conversion Low energy requirements No chemicals required Mild environment conditions
Pre-treatment with bacteria	Sphingomonas paucimobilis, Bacillus circulans	Research topic Slow conversion Low energy requirements No chemicals required Mild environment conditions

Table 4: Biological Pre-treatment Methods

2.2.4 Hydrolysis

The main purpose of the hydrolysis is the splitting of the polymeric structure of lignin-free cellulosic material into sugar monomers in order to make them ready for fermentation. At this stage one should distinguish between the hydrolysis of the C_5 dominated hemi-celluloses and the hydrolysis of the C_6 dominated celluloses.

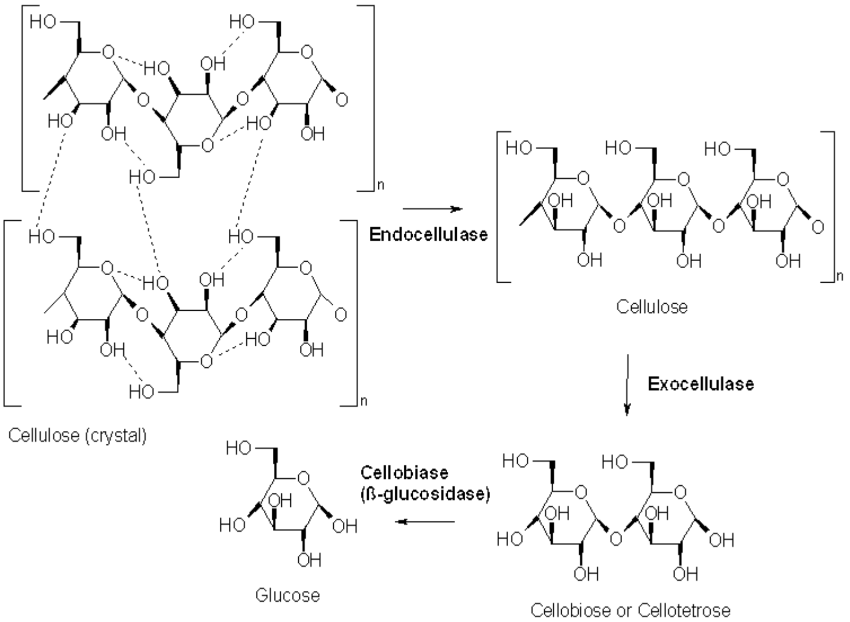

Figure 4: Example of the three stages of the cellulose hydrolysis by cellulase enzyme complex. Source:PD - Wikipedia

<u>Hydrolysis of the Celluloses:</u>
Although acid hydrolysis of the celluloses is possible and has been applied previously, the current state-of-art method is enzymatic hydrolysis by cellulase enzyme complex produced for example by the fungus Trichoderma Reesei.

Ligno-cellulose, similar to starch consists of glucose units. The main difference between starch and ligno-cellulose is the following: Starch consists of α-D-glucose linked together by (1→4) glucosidic bonds into long chains. Ligno-cellulose consists of β-D-glucose linked together in the same way, via (1→4) glucosidic bonds. However, the resulting chains are weakly bound into a 3D crystalline structure. This “minor” difference plays a significant role in hydrolysis. In contrast to starch, cellulose is chemically very stable and extremely insoluble. While starch is hydrolyzed with amylase enzyme, the enzyme complex called cellulase is used for the hydrolysis of cellulose. The cellulase enzyme complex consists of three types of enzymes. The first one is called endocellulase and is capable of breaking up the crystalline structure hereby producing shorter chain fragments. The second type of enzyme, the exocellulase, cuts-off the disaccharide cellobiose (or sometimes also tetrasaccharides) from the chain fragments produced previously by the endocellulase. The last enzyme type, the cellobiase splits the β-glucosidic bound in the cellobiose into to two glucose molecules.

Hydrolysis of the Hemi-Celluloses:

In contrast to the crystalline structure of cellulose, hemi-cellulose has a mainly amorphous structure. This results in a significantly easier way of hydrolysis. The hydrolysis of hemi-celluloses may be performed by diluted acids, bases or by appropriate hemi-cellulase enzymes. In several process set-ups the hydrolysis already happens in the pre-treatment step.

2.2.5 Fermentation:

The fermentation of the C_5 and C_6 sugars obtained from pretreatment and hydrolysis of ligno-cellulose faces several challenges:

- Inhibition from various by-products of pretreatment and hydrolysis such as acetates, furfural and lignin. The impact of these inhibitors is even larger on the C_5 sugar processing.
- Inhibition from the product itself = inhibition from bio-ethanol leading to low titer (ethanol concentration)
- Low conversion rates for C_5 sugars

The mentioned difficulties lead to higher investment costs, high energy and process water demand (due to low titer) as well as to demand for expansive enzymes.

For comparison: the technologies based on the processing of starch to bio-ethanol using high-performance yeasts provide conversion rates of ~90% at convenient rates of 1,5-2,5 g/(l.h) leading to high titers of 10-14%$^m/_m$. In contrast, in case of simultaneous conversion of C_5 and C_6 sugars, modified microorganisms are used (such as modified yeasts, E.coli KO11 or Zymomonas mobilis) which lead to low ethanol titers of 5-6%$^m/_m$ at significantly lower rates than found in the case of starch.

Currently there are two basic R&D strategies in the field of fermentation: either ethanologens like yeasts are used and the ability to utilize C_5 sugars is added to them, or organisms capable of utilizing mixed sugars (such as E. coli or Z. mobilis) are modified in their fermentation pathway in order to produce bio-ethanol. Further research activities focus on the increase of robustness towards inhibition as well as fermentation temperature.

2.2.6 Distillation:

The upgrading of ethanol from lower concentrations in beer to the required 98,7%$^{m}/_{m}$ is performed using the following known and widely applied technological steps:

- Evaporation of ethanol from beer: in this step the first evaporation of ethanol is performed in order to obtain 'crude' ethanol with concentration ~45%$^{V}/_{V}$.
- Rectification: in rectification the ethanol concentration is increased to ~96%$^{V}/_{V}$
- Dehydration: by dehydration the remaining azeotropic water is removed in order to obtain the fuel bio-ethanol with concentration 98,7%$^{m}/_{m}$[1] and water content below 0,3% $^{m}/_{m}$[1] .

2.2.7 Overall process integration:

Typical process integrations in the ligno-cellulose ethanol production.

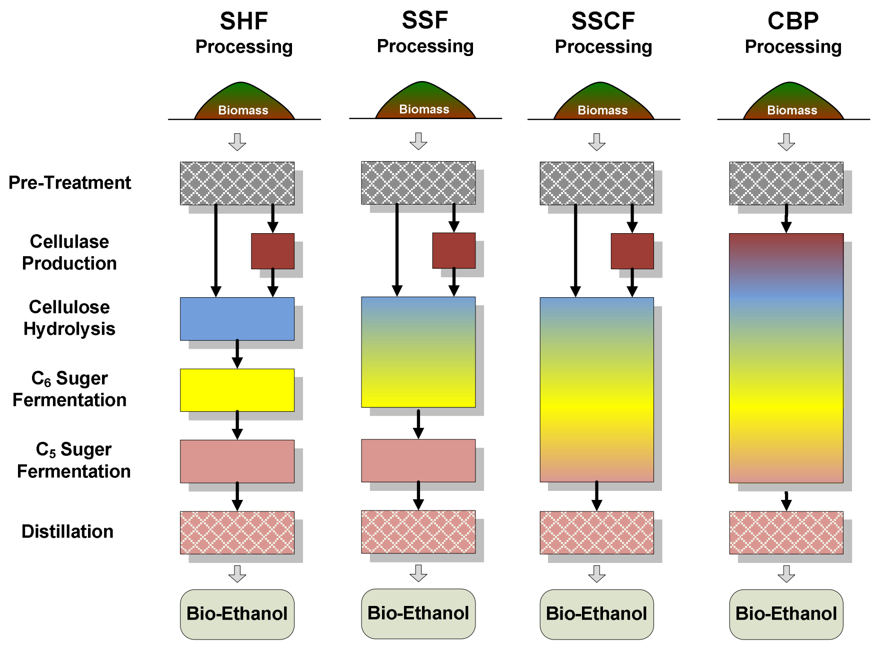

Figure 5: Typical Process Integration in Ligno-cellulose Ethanol Production

Particularly in case of enzymatic hydrolysis various overall process integrations are possible. In all cases a pre-treatment is required. The subsequent processing steps differ in the alignment of the hydrolysis C_5 fermentation and C_6 fermentation steps. It is clear, that in the practical implementation there will be various modifications to the mentioned methods, however, in order to characterize the currently available technologies in the demonstration plants the typical process integration set-ups are described briefly:

<u>SHF – Separate Hydrolysis and Fermentation</u>

In the SHF set-up the (historical) acid hydrolysis is replaced by the cellulase enzyme hydrolysis. In general two strategies are possible. In the first processing variant the C_5 and C_6 fermentation is performed sequentially, i.e. the entire material is first subjected to enzymatic hydrolysis, then the C_6 fermentation is performed, followed by ethanol evaporation; continued by the C_5 fermentation. In the second variant the soluble C_5 sugars are already separated during hemi-cellulose hydrolysis (i.e. shortly after pre-treatment), then C_5 and C_6 fermentation are performed in parallel, and finally both beers are distilled in a common beer distillation.

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[1] According to EN 15376

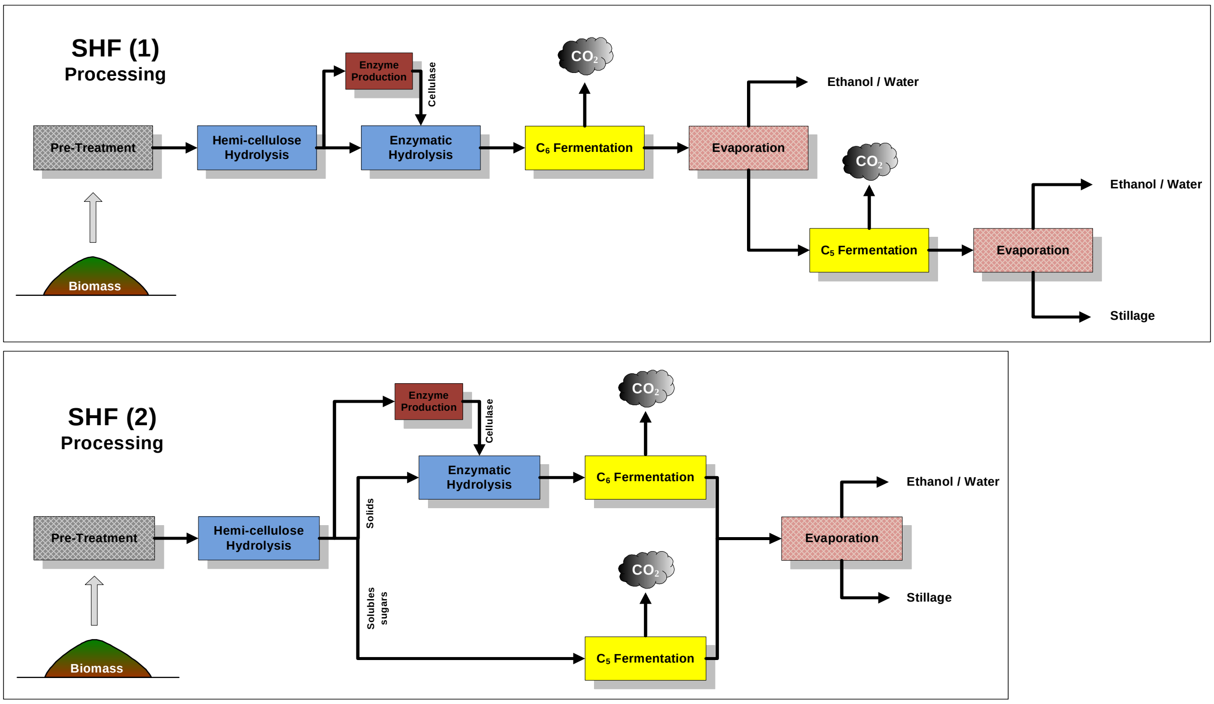


Figure 6: Two basic variants in the SHF process integration.

SSF – Simultaneous Saccharification and Fermentation

For the SSF process integration it is characteristic that the C_6 hydrolysis und C_6 fermentation are performed in one common step. Beside this a hemi-cellulose hydrolysis (if not integrated in the pre-treatment step) and the C_5 fermentation are performed (independently from the C_6 processing). The C_5 fermentation may be situated ahead of the C_6 treatment and is “independent” from the C_6 processing. The obtained beer from both fermentation steps is distilled together in the process end of the process.

SSCF - Simultaneous Saccharification and Co-Current Fermentation

The SSCF set-up is currently the best developed ligno-cellulose processing method and has already been tested in pilot scale. In the SSCF strategy, directly after the pre-treatment the saccharification of C_5 and C_6 sugars as well as the co-current fermentation of both is performed. For the co-current fermentation modified organisms are required, such as genetically modified Zymomonas mobilis. Such a set-up leads to significant technology simplification, hereby reducing investment costs.

CBP - Consolidated BioProcessing

The CBP - Consolidated BioProcessing (previously also called DMC - Direct Microbial Conversion) designates the unification of cellulase production, C_5 and C_6 hydrolysis and C_5 and C_6 fermentation in a single processing step. This is only possible by “creating” a suitable organism community providing the required enzymes directly within the reactor. Hence, the processing focus is shifted from an enzymatic towards a microbial approach. Therefore better understanding of the fundamentals of microbial cellulose utilization is required. From today’s point of view, the establishment of CBP as the consolidation of the four mentioned steps within the biomass to bio-ethanol conversion would mark a significant step forward, in terms of efficiency and simplicity of the process.

2.2.8 Literature:

Taherzadeh M.J. and Karimi K.: Int.J.Mol.Sci.: “Pretreatment of Lignocellulosic Wastes to Improve Ethanol and Biogas Production: A Review”; (9), 2008, 1621-1651

Hamelinck C.N., Hooijdonk G. and Faaij A.P.C: „Prospects for ethanol from lignocellulosic biomass: Techno-economic performance as development progresses“; November 2003

DOE/SC-0095: “A Research Roadmap Resulting from the Biomass to Biofuels Workshop”; June 2006

prEN 15376:2006: “Automotive fuels – Ethanol as blending component for petrol – Requirements and test methods”

Aden A. et.al.: Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizating Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover; NREL/TP-510-32438

Lynd L.R., Weimer P.J., Zyl, W.H. and Pretorius I.S.: Microbiology and Molecular Biology Reviews: Microbial Cellulose Utilization – Fundamentals and Biotechnology; (66), 2002, 506-577

Zhao H. et al.: “Regeneration cellulose from ionic liquids for an accelerated enzymatic hydrolysis”; J.Biotechnol. 2008 (doi: 10.1016/j.jbiotec.2008.08.009)

2.3 Synthetic Biofuels

2.3.1 Introduction

The production of biofuels using the thermo-chemical route differs significantly from the ligno-cellulosic ethanol production. Within this production scheme the biomass is first thermally fragmented to synthesis gas consisting of rather simple molecules such as: hydrogen, carbon monoxide, carbon dioxide, water, methane... Using this gaseous material the BtL fuels may be re-synthesized by catalytic processes. Alternatively methanation may be performed in order to obtain bio-SNG as substitute for natural gas.

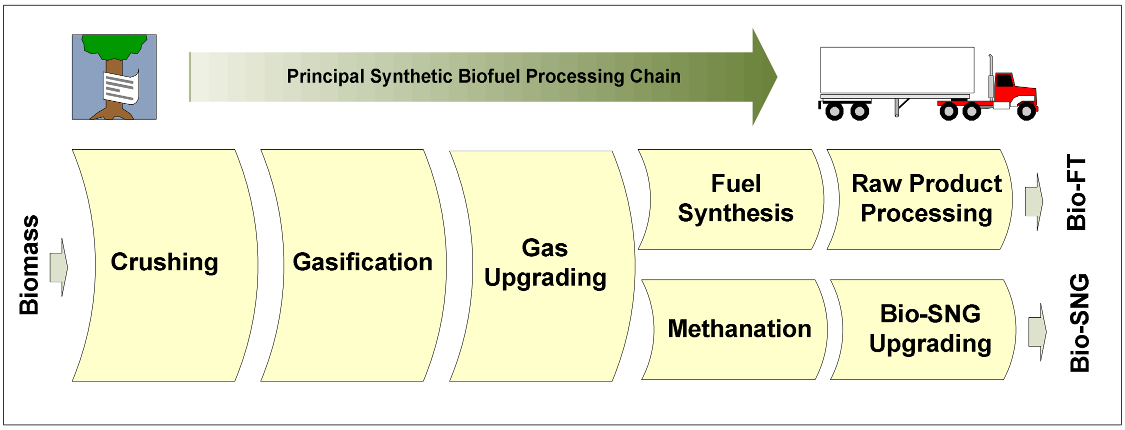


Figure 7: Principal Synthetic Biofuel Processing Chain

2.3.2 Size reduction

Before the biomass material enters the gasifier it has to be broken-down to a suitable size. The size is strongly dependant on the type of gasification.

2.3.3 Gasification

Gasification differs significantly from combustion as well as from pyrolysis and liquefaction. Combustion takes place with excess of air ($\lambda > 1$) and at high temperatures, resulting in heat production and exhaust gas and ashes, both with heating value of zero (i.e. complete oxidation).

Gasification takes place with shortage of oxygen (typically $\lambda = 0{,}2\text{-}0{,}5$), and the two obtained products are product gas and solid by-product (either char or ashes). The product gas has a positive heating value, and, if char is produced, this also has a positive heating value. By reducing the amount of available oxygen we obtain processes called Pyrolysis and Liquefaction (these processes are not discussed further in this work). An overview of the mentioned processes may be found in the figure below.

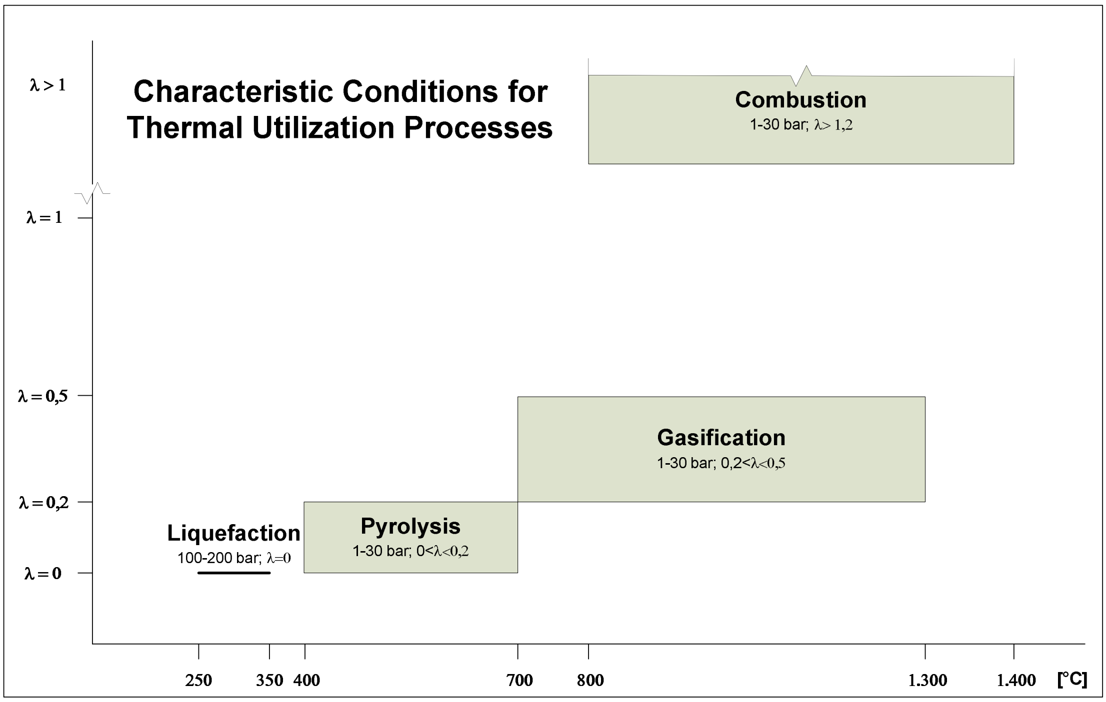


Figure 8: Characteristic Conditions for Thermal Utilization Processes

The gasification processes may be distinguished according to the used gasification agent and the way of heat supply. Typical gasification agents are: oxygen, water, and air (carbon dioxide and hydrogen are also possible). In dependence of the heat supply we distinguish between two process types. In autotherm processes the heat is provided through partial combustion of the processed material in the gasification stage. In the second type of processes, the allotherm processes, the heat is provided externally via heat exchangers or heat transferring medium. In these processes the heat may come from combustion of the processed material (i.e., combustion and gasification are physically separated) or from external sources.

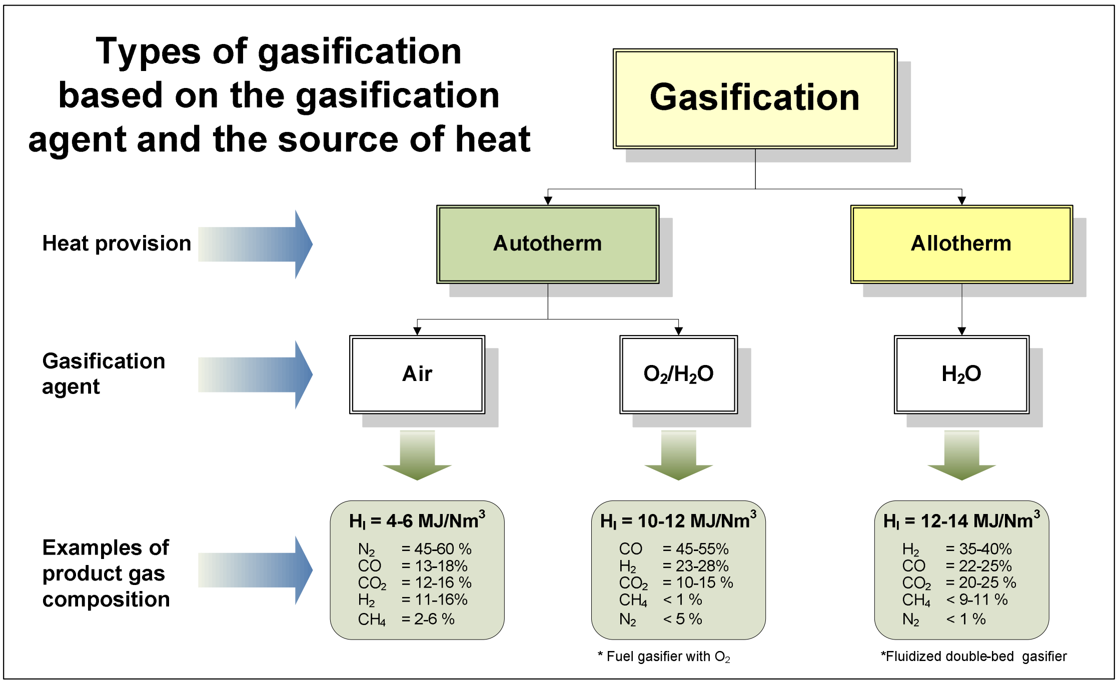


Figure 9: Classification of Gasification Technologies

The choice of the gasification agent is based on the desired product gas composition. In case the product gas is used for a consequent fuel synthesis, the use of air as gasification agent is not favorable (due to the high N_2 content in the product gas).

Types of gasifiers:

The gasifier types can be classified according to the way how the fuel is brought into contact with the gasification agent. There are three main types of gasifiers:

- Fixed-bed gasifier
    - Updraft gasifier
    - Downdraft gasifier
- Fluidized bed gasifier
    - Stationary fluidized bed (SFB) gasifier
    - Circulating fluidized bed (CFB) gasifier
- Entrained Flow Gasifier

Fixed-bed gasifiers: updraft gasifier

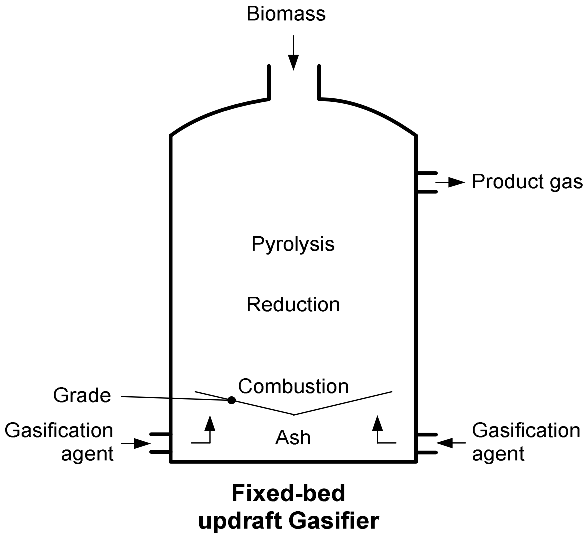


Figure 10: Fixed-bed Updraft Gasifier

The simplest type of gasifier is the fixed-bed gasifier (also called countercurrent gasifier). The processed material enters the reactor at top, the gasification agent at the bottom. As the biomass moves downward (countercurrent to the gas movement) first a drying of the material takes place. In the next step the upward flowing product gas decomposes the solid material into volatile gases and solid char (pyrolysis). Within the reduction zone the main gasification reaction takes place leading to CO and H_2 as main components of the product gas. In the combustion zone the remaining char material is combusted. This combustion process provides heat, CO_2 and H_2O for the reaction in the reduction zone.

There are several advantages and disadvantages of the fixed-bed updraft gasifier. The main advantage is the simplicity of the technology, the high burn-out of the material, the possibility to use material with high moisture content and the low temperature of the product gas. The main disadvantages are the high amount of pyrolysis products in the final gas. For use in engines this implies the requirement for an extensive gas cleaning.

Fixed-bed gasifiers: downdraft gasifier

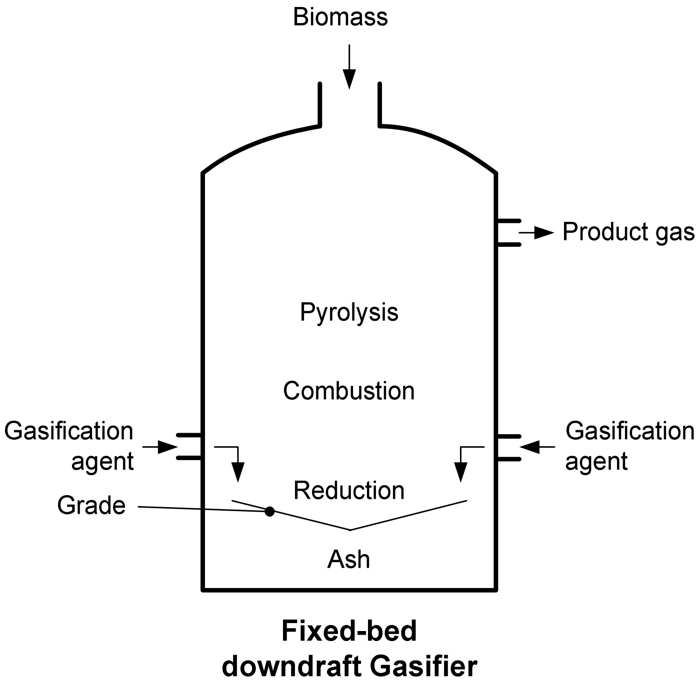


Figure 11:Fixed-bed Downdraft Gasifier

In this gasifier type the processed material enters the reactor from the top. The gasification agent enters at top or at sides while the product gas is dismissed at the bottom and moves in the same direction as the gasification agent. The set-up lead it the exchange of the combustion and reduction zone. After the processed material passes the drying and pyrolysis zone it enters the combustion zone, where a part of the char is burned (providing the required heat for the drying and pyrolysis by convection and radiation). In the reduction zone the remaining of the char as well as the product of the combustion are reduced to CO and H_2.
The main advantage of this technological solution is a product gas with low concentration of tar and other pyrolysis products suitable for engines (however a tar-free gas is in practice not achievable). Disadvantages are: ash and dust content and high temperature of the product gas at the exit and the stricter requirements on the feedstock quality in terms of size and moisture content.

Fixed-bed gasifiers: Other types

Beside the two main types of fixed-bed gasifiers discussed previously there are additional types such as cross-draft gasifier and open-core gasifier as well as various sub-types and particular implementation. The cross-draft gasifier is used mainly for the gasification of charcoal. Extremely high temperatures in the combustion zone (1.500℃ or even higher) are associated with this gasifier, resulting in material selection challenges. However, this type of gasifier may be implemented at small scales (under $10kW_{el}$), hence it is suitable for de-central implementation. The Open-Core gasifier is designed to gasify materials with low bulk density (e.g. rice husks)

Fluidised-bed gasifier: Stationery fluidized bed (SFB) gasifier

In general the fluid-bed gasifier has been developed in order to overcome the shortages of the fixed-bed set-up. The main technological improvement is the introduction of a bed material (for example sand bed). The bed material behaves like a highly turbulent fluid leading to a fast mixing of the fuel material with the bed material resulting in a rapid pyrolysis and uniform processing conditions within the reactor (no reaction zones as typical for the fixed-bed reactors are observable for fluidized bed gasifiers).

In first instance the fluid-bed gasifier can better process materials with higher ash-content as typical for biomass and in general this type of gasifiers is better suitable for large-scale operations (typically above10 MW_{th}). The further difference lies in the temperature within the combustion zone: while fixed-bed gasifiers operate at 1.200℃ (or in case of charcoal above 1.500℃) fluid-bed gasifiers run at 750℃-900℃. Du e to the low processing temperatures the tar-conversion rates are not very high (other measures have to be taken in order to produce a tar-free gas).

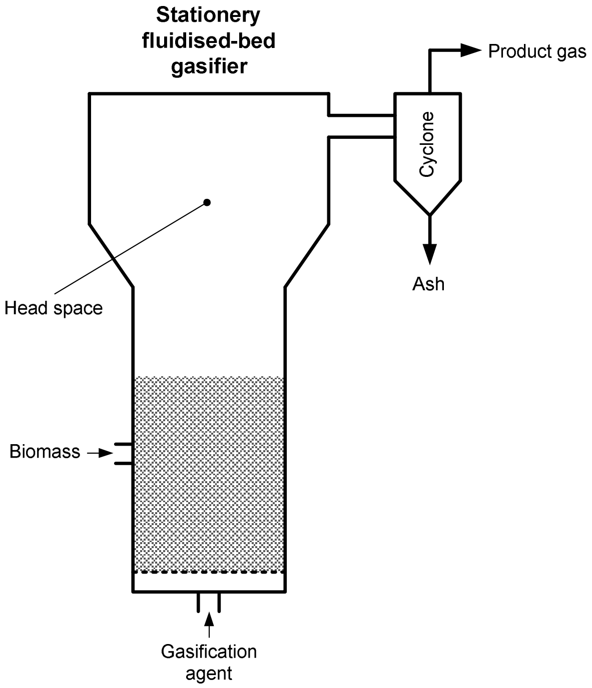


Figure 12: Stationary Fluidised-bed Gasifier

In a stationery fluid-bed gasifier the bed material (for example quartz sand with grain of 0,5-1,0 mm) forms a suspended “bubbling” highly turbulent fluidized bed. The gasification agent enters the reactor at the bottom with speeds high enough to the set the bed material into fluidized conditions, but low enough not to carry away the bed material. Due to these conditions the processed material (typically entering the reactor from the side) is optimally mixed with the hot bed material, leading to a fast pyrolysis as well as uniform conditions in the reactor. The pyrolysis gases together with the ash particles leave from the head space. Due to high temperatures, additional homogenous and heterogeneous reactions take place. The larger the head space is designed, the lower the amount of tar in the product gas. From the head space the gas enters the attached cyclone, where the ash and char particles are separated form the product.

The main advantages of this set-up are the intensive mixing in the bed, leading to uniform conditions in the reactor (is of significance in case of scale-ups), flexibility towards changes in moisture and ash in the processed material as well as the possibility to process materials with low ash melting point. A disadvantage is the high tar and dust content in the product gas requiring an appropriate gas cleaning, possibly incomplete char burn-out as well as high temperature of the product gas. For biomass feedstock with low ash melting point (below the processing temperature) the use of fluidized bed gasifiers is not suitable due to a possible clustering of the bed material with ash.

Fluid-bed gasifier: Circulating fluidized bed (CFB) gasifier

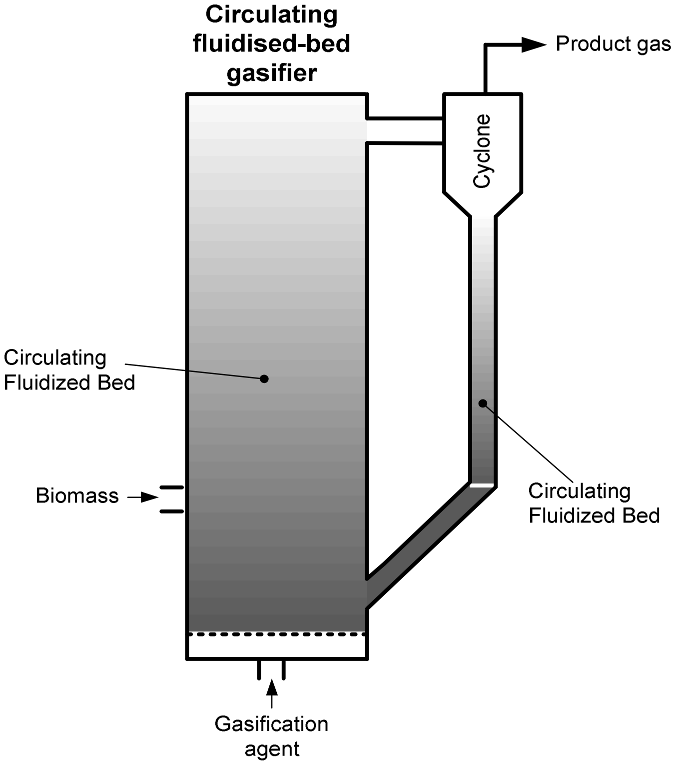


Figure 13: Circulating Fluidised-bed Gasifier

The set-up of the circulating fluid-bed gasifier is similar to the stationary fluid-bed gasifier with the main difference that the gasification agent enters the reactor in velocities leading to carry away of the bed material. The bed material consists of particles with grain of 0,2-0,4mm). Comparing to the SFB gasifiers, there is no bed surface observable. The bed material is distributed in the complete reactor with higher densities in bottom sections. The bed material as well as the ash are separated from the product gas in the cyclone stage and recycled back to the reactor.

The main advantages and disadvantages of the CFB gasifier are similar to the SFB gasifiers. Beside this, the CFB has a higher cross-sectional capacity leading to even better up-scale capabilities of this technology.

Fluid-bed gasifier: Circulating fluidized two-bed gasifier

In the circulating fluidized two-bed gasifier the circulating bed material is used as heat carrier. In this set-up the gasification is performed in one fluidized bed and the bed material is transferred into the second bed, where the necessary gasification heat is generated by combustion of a part of the processed material or of external material. The heated-up bed material is transferred back to the gasification bed. The main advantages of this system are the possibility to optimize the combustion and gasification part separately. Due to the separation of the two reaction spaces it is possible to run the combustion with air, while the gasification can be performed with an appropriate gasification agent, leading to better quality products than from air gasification. This set-up is the basis of several allothermal implementations of fluidized bed gasifiers.

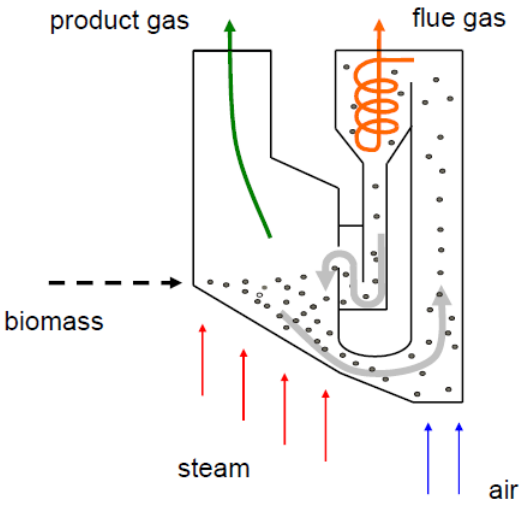


Figure 14: Circulating Fluidised two-bed Gasifier

<u>*Entrained Flow Gasifier*</u>

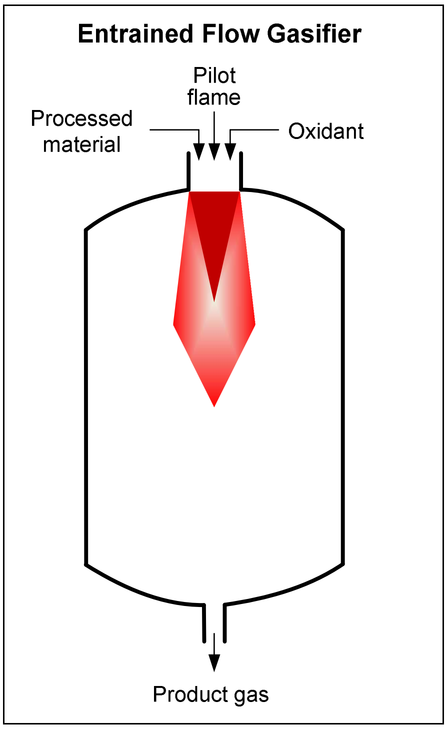


Figure 15: Entrained Flow Gasifier

The entrained flow gasifier differs significantly from the gasifier types described previously. The processed material enters the gasifier at the top, together with the gasification agent. In contrast to other gasifiers there is an additional pilot flame providing the initial energy demand. Typically the entrained flow gasifier is operated at high pressure (up to 100bar) and at high temperatures (up to 1.200℃ or even higher). Due to these conditions the gasification process takes place rapidly and the product gas is low in tar and methane content. The slag and the ash proceeding from the top of the reactor build up a protection film preventing the inner reactor surface from corrosion. Beside this, due to the high operation temperatures (above the ash melting point), the ash may be removed in liquid form. However, typically the ash removal takes place after a cooling down of the product gas in water. Due to this feature the entrained flow gasifier may be used for biomass feedstock with low ash melting point.

The entrained flow gasifier is typically used for the gasification of fossil sources (crude oil, natural gas and charcoal). However, in combination with an upstream low-temperature pyrolysis step this process may be applied to biomass material as well (otherwise a suitable extern pilot flame feed is required). In this setup, the pyrolysis gas from the low temperature step is used as pilot flame fuel and the pyrolysis char is the processed material (see the Carbo-V process from CHOREN for details).

The advantages of the entrained flow gasifier are the rapid flow rate within the reactor (typically retention times in seconds) and the high-quality product gas. The disadvantages are the requirement for a pilot flame fuel of sufficient high quality, the requirement to pulverize the processed material (typically ~ 100µm, alternatively liquid or gaseous feed may be used) and to cool down the product gas for ash removal.

2.3.4 Product gas

The main components of the product gas may be summarized as:

- Combustible gases, mainly: hydrogen (H_2), carbon monoxide (CO), methane (CH_4) and short chain hydrocarbons
- Inert gases, mainly: nitrogen (N_2), carbon dioxide (CO_2) and steam (H_2O)
- Impurities –depending on the temperature:
    - Solid: ash, dust, bed material, alkali salts
    - Gaseous: sulfur (e.g. CS, H_2S) , nitrogen (e.g. NH_3, HCN,…) and halogenide compounds
    - Liquid: at low temperature tar, at high temperature ash

The composition of the product gas is a truly multi dimensional problem: In the following paragraphs a selection of the main parameters and their (general!) key influences on the product gas composition is given.

<u>Gasification temperature:</u>

The increase of the gasification temperature leads to an increase of the reaction rates (= faster reach of the chemical equilibrium). Further, increasing the temperature will in general lead to a shift in the gas composition towards higher H_2 concentration and lower CO and CH_4 content. The CO_2 concentration is typically not influenced by the temperature. At high temperatures typically low tar concentrations are observed.

<u>Gasification pressure:</u>

Increase of the pressure will lead to an increase of the concentration of the 3 and 4 atomic molecules (CO_2 and CH_4) and a decrease of the H_2 and CO concentrations.

<u>Gasification agent:</u>

The use of air as gasification agent will lead to (usually unwanted) presence of nitrogen in the product gas, diluting the gas and reducing its heating value. The highest concentrations of H_2 may be achieved using steam as gasification agent. Hence by variation of the steam/O_2 ratio an influence on the H_2/CO ratio may be achieved.

<u>Type of gasification reactor and the tar concentration:</u>

As the type of gasification reactor usually determines the reaction conditions, the above mentioned tendencies in terms of temperature and pressure may be observed. Beside this, the “alignment” of the reaction zones as well as the temperature in the reactor will determine the tar concentration. The highest tar concentrations are typically obtained in updraft gasifiers (see also corresponding section for explanation). Downdraft gasifiers (due to alignment of the reaction zones) as well as the entrained flow gasifiers (due to high reactor temperature) in general provide a product gas with low tar concentration. The tar concentration in the product gas of fluid-bed gasifiers will be intermediate.

<u>Type of biomass used as fuel:</u>

Keeping all process parameters constant, the type of biomass used as fuel will have no or only a minor influence on the main product gas composition.

This is not true for the content of impurities: If the biomass feedstock contains for example nitrogen or sulfur, we will find these elements in the product gas in form of NO_x, SO_x, H_2S, NH_3,… In this case a suitable gas cleaning system has to be applied.

The ash melting point (or ash softening point) of the feedstock will influence the selection of the appropriate gasification technology. For example: using a fluid-bed gasifier with a temperature range above the ash melting point would lead to clumping of the bed material; hence a careful analysis of the feedstock prior to its gasification has to be performed.

After leaving the gasifier, the product gas has to be cleaned and in dependence on the further processing steps upgraded. In the following we will focus only on the typical requirements for the gas upgrading as required by the bio-fuels production.

2.3.5 Gas cleaning

Reasons for gas cleaning are prevention of corrosion, erosion and deposits in the process lines as well as prevention of poisoning of catalysts. Following typical impurities can be found in the product gas.

Dust and alkali metal compounds

Dust, ashes, bed material and alkali metal compounds are removed from the product gas using cyclones and filter units.

Tar

Tars are high-boiling and highly viscous organic compounds, condensating at ~300 – 400℃. The tar removal is performed using physical methods, by cooling down the gas and performing a gas wash with special solvents (such as biodiesel) or using a condensation in a wet electro filter. Currently under development are catalytic tar removal processes where the tar is converted to gaseous compounds such as H_2, CO.

Sulfur compounds

The removal of sulfur compounds is crucial due to its catalyst poisonous effects. Typical tolerances are 1<ppm. The sulfur removal can be performed by known methods such as Amine gas treating, Benfield process or similar.

Nitrogen and chloride (halogenide) compounds

Nitrogen and halogenide compounds may cause corrosion and / or act as catalyst poisons, hence an efficient removal using for example wet washing is required.

The amount of the mentioned impurities is strongly dependant on the applied gasification technology, obviously the best strategy to minimize their amount is the application of favorable process conditions.

2.3.6 Gas upgrading

Several processes are subsumed under the term gas upgrading:

Water-gas-shift (WGS) reaction:

Using the (reversible) water-gas-shift reaction:

$CO + H_2O \leftrightarrow CO_2 + H_2$

the CO / H_2 ratio may be modified in order to obtain the typically reguired ratio of H_2 / CO = 1,5-3,0

Gas reforming:

Using the gas reforming reactions, the short-chain organic molecules may be converted to CO and H_2 by the following endothermic reaction (example for methane):

$CH_4 + H_2O \leftrightarrow CO + 3\ H_2$

Removal of inert gas fractions – mainly CO_2:

CO_2 is on one hand inert in the subsequent reactions, however, it will increase the requirements for apparatuses and energy demand (for example for compression steps), hence a removal is advantageous. The CO_2 removal can be performed by

- physical methods: absorption to water or other solvents such as polyethylene-glycole (trade name "selexol") or cold methanol (trade name "Rectisol").
- chemical methods: chemical glycol or ethanolamine based absorbents
- other methods such as Pressure Swing Adsorption or Temperature Swing Adsorption

2.3.7 Fuel synthesis

Starting from the synthesis gas (=the cleaned und upgraded product gas from the gasification) several fuel processing pathways are possible. The application of (thermo-) chemical processes such as Fischer-Tropsch (providing diesel / gas like biofuel) or methanol synthesis as well as biotechnological processing towards alcohols is possible.

Fischer-Tropsch (FT) Synthesis

The most widely used fuel synthesis process is the FT process invented in the 1920-ties by the German engineers Franz Fischer and Hans Tropsch. Currently the FT reaction is successfully used for fuel production from coal (CtL = Coal-to-Liquid) or natural gas (GtL = Gas-to-Liquid). Mainly the GtL process becomes increasingly attractive and provides high-quality fuels which can be sold as premium quality fuel enhancers.

Synthesis:

The simplest form of the FT reaction may be summarized by following reactions:

Production of alkanes: $n\,CO + (2n+1)\,H_2 \leftrightarrow C_nH_{2n+2} + n\,H_2O$

Production of alkenes: $n\,CO + (2n)\,H_2 \leftrightarrow C_nH_{2n} + n\,H_2O$

Beside this a number of side reactions take place, where the synthesis gas is degraded to carbon, CO_2 and metal carbides (beside other compounds). The reaction is performed in fixed bed or in slurry reactors.

Based on the reaction temperatures and pressures, there are two process types used for the FT synthesis:

- HTFT – High Temperature Fischer-Tropsch Synthesis:
  The typical HTFT process conditions are temperatures of 300-350℃ and pressures of 20-40 bar. The products obtained at this temperature have "light" character, i.e. this process may be used for the production of basic petrochemical materials (ethylene, propylene,…) as well as gas production.
- LTFT – Low Temperature Fischer-Tropsch Synthesis:
  The low temperature FT – counterpart takes place at temperatures of 200-220℃ and pressures below 20 bar. This technology provides higher-boiling products, hence is more suitable for diesel production.

The FT synthesis is catalyzed by various catalysts based on iron, cobalt, ruthenium, nickel. Due to economic reasons currently only iron (HTFT) and cobalt (HTFT & LTFT) are widely used. Nonetheless, the selection of the appropriate catalyst determines the main product of the FT process, and the life-time of the catalyst affects the overall economy of the production.

Upgrading of the raw FT Product:

The raw Fischer-Tropsch product as provided by the synthesis consists of a distribution of molecules, ranging from gaseous compounds, through liquid fractions ending with a solid wax fraction (at room temperature). Hence, the direct use as fuel is not possible. Even the amount of the desired fraction (petrol or diesel) may be significantly increased through a suitable process control; following additional upgrading steps may be required:

- Distillation: using distillation the obtained raw FT product is split into fractions, the fractions may be further processed as required
- Hydration and isomerization C_5-C_6 fraction (for petrol use): in order to increase the octane number the mainly linear alkanes are isomerized
- Reforming C_7-C_{10} fraction (for petrol use): is used to increase the octane number (as well as the content of aromatics)
- (Hydro- / fluid catalytic) cracking: converting long-chain fractions into petrol and diesel fraction by application of hydrogen under high pressure

Bio-SNG production

The product gas obtained by the gasification may be alternatively used to produce bio-SNG (synthetic natural gas). Starting from the product gas the first step to be performed is the methanation reaction:

Methanation and upgrading:

The methanation is a highly exothermal reaction, thus – in order to achieve a high conversion rate – the reaction heat has to be removed. In this process the carbon monoxide and the hydrogen are reacting to methane and water:

$CO + 3 H_2 \leftrightarrow CH_4 + H_2O$ (reverse to the steam methane reforming reaction)

$CO_2 + 4 H_2 \leftrightarrow CH_4 + 2 H_2O$

The reaction is catalyzed typically by nickel oxide catalysts in a set of reactors (typically three) under pressure of 20-30 bar. The formation of carbon (coking) is a possible undesired side reaction of this process.

The cleaning and upgrading of obtained gas is particularly required for increasing the methane content and reaching natural gas quality, which consists of 98 % methane. For this upgrading primarily the drying, desulphurisation and the separation of methane and carbon dioxide are necessary.

Drying

In order to prevent abrasion and destruction of the gas processing aggregates, the water vapor content has to be separated from the raw SNG. Through chilling of the gas (usually within the gas pipeline) a part of the water vapor is condensed. With the help of a gradient in the gas pipe and an installed condensate separator the water is collected.

Removal of Carbon Dioxide (Methane Accumulation)

With the removal of CO_2 from the raw SNG the methane content is enriched and thus the energy value is enhanced. The following CO_2 removal processes are most common:

- **Water scrubbing:**
  In this physical absorption process the gas is pressurized and fed to the bottom of a packed column where water is fed on the top and so the absorption process is operated counter-currently. Water scrubbing can also be used for selective removal of hydrogen sulfide since it is more soluble than CO_2 in water.
- **Pressure Swing Adsorption (PSA):**
  In this process the raw gas is compressed to 4 – 7 bar. The compressed gas is then streamed into an adsorption column of zeolites or activated carbon molecular sieves.

The adsorption material adsorbs hydrogen sulfide irreversibly and is thus poisoned by hydrogen sulfide. For this reason a hydrogen sulfide removing step is often included in the PSA process.

Aggregates for these rather complex upgrading processes are currently produced in fewer quantities and thus are relatively expensive.

Gas Compression

The pressure of the SNG as provided by the production plant depends on the last processing step. For injection of the SNG into the natural gas grid the respective pressure level of the grid needs to be reached (up to 20 bar).

For the use as vehicle fuel or storage in compressed gas cylinders a more intense compression up to 200 bar is necessary to obtain adequate energy densities. In the latter case the targeted pressure can only be achieved by multistage compression units.

Ethanol and higher Alcohols Produced via Gasification

Starting from a suitably upgraded product gas it is possible to synthesize alcohols as main products as well. Two processing pathways are possible:

- Thermo-chemical pathway
- Microbiological pathway

Thermo-chemical production of alcohols via gasification:

The thermo-chemical production of alcohols describes the catalytic production of mixed C_2-C_6 range alcohols from syngas (=HAS – higher alcohol synthesis). The main processing steps are analogous to the BtL production process: synthesis of gas via gasification, gas cleaning und upgrading, catalytic alcohol synthesis and product upgrading. For example the ethanol synthesis follows the reaction:

$$3\,CO + 3\,H_2 \leftrightarrow C_2H_5OH + CO_2$$

This way of ethanol production may be seen as alternative to the ligno-cellulosic ethanol production.

The gas production via gasification is basically independent from the further use. The gas cleaning is determined by the requirements of the catalyst used for the alcohol synthesis. Various catalysts are used for the synthesis: One group consists of modified high pressure (alkali-doped ZnO/Cr_2O_3 at 125-250bar) or low pressure (alkali-doped Cu/ZnO or $Cu/ZnO/Al_2O_3$ at 50-100bar) and methanol catalysts (operation temperature 250-425 °C). Second group is based on modified FT catalysts (alkali-doped $CuO/CoO/Al_2O_3$; at 50-100bar and 260-320 °C). Further molybdenum and ZrO_2 based catalysis have been investigated as well.

The catalytic HAS transformation of the syngas to alcohols is typically performed in fixed bed reactors. Due to the fact, that the HAS process is highly exothermic, the optimization of the heat removal is of particular interest. Beside fixed bed reactors, there are for example multiple reactor systems (such as double bed type) under investigation, where in separate beds particular processes may be optimized. For example methanol production at lower temperature is performed in the first bed and higher alcohol synthesis at higher temperature in the second bed. In case higher alcohols are in the focus of the process, slurry reactors may be used. This reactor type is particularly suitable for reaction heat removal.

The product upgrading of the obtained alcohol mixture consists typically of de-gassing, drying and separation into 3 streams: methanol, ethanol and higher alcohols.

Microbiological production of alcohols via gasification:
The microbiological production of alcohols is a fermentative process based on the utilization of hydrogen, carbon monoxide and carbon dioxide. Beside alcohols such as ethanol and butanol other chemicals such as organic acids and methane can be obtained.

The main advantage of the microbiological process is the mild process conditions (similar to biogas production). Due to the lower sensitivity of the used microorganisms towards sulfur, the gas cleaning costs may be significantly reduced. Finally, there typically is a higher reaction specificity for a product than in case of inorganic catalysts which is combined with the high tolerance towards the CO/H_2 ratio (no gas shift reaction is needed). The main disadvantage is the limited gas-to-liquid mass transfer rate requiring specific reactor designs.

2.3.8 Literature:

Fürnsinn S. and Hofbauer H.: Synthetische Kraftstoffe aus Biomasse: Technik, Entwicklung, Perspektiven; Chem.Ing.Tech. 79(5), 2007, 579-590
Aadesina A.A.: Hydrocarbon synthesis via Fischer-Tropsch reaction: Travails and triumphs; Appl. Cat. A: 138, 1996, 345-367
Dry M.E.: The Fischer-Tropsch process: 1950-2000; Catal.Today 71(3-4). 2002, 227-241
NREL / Nexat Inc. – Equipment Design and Cost Estimation for Small Modular Biomass Systems, Synthesis Gas Cleanup, and Oxygen Separation Equipment; Task 9: Mixed Alcohols From Syngas – State of Technology, May 2006; NREL/SR-510-39947
Phillips S., Aden A., Jechura J, Dayton D. And Eggeman T.: Thermochamical Ethanol via Indirect Gasification and Mixed Alcohol Synthesis of Lignocellulosic Biomass, April 2007; Nrel/TP-510-41168
Biotechnol.Prog.: Reactor Design Issues for Synthesis-Gas Fermentation; (15), 1999, 834-844

3 List of Facilities

In this section the main data for all projects that are currently visible in the online map (http://biofuels.abc-energy.at/demoplants/) is listed.

3.1 Biochemical Technologies

Company	Location	Country	Input Material	Product	Output	Unit	Type	Status	Start-up Year
Abengoa Bioenergy Biomass of Kansas, LLC	Hugoton	United States		ethanol;	34 000	t/a	commercial	under construction	2011
Abengoa Bioenergy New Technologies	York	United States		ethanol;	75	t/a	pilot	operational	2007
Abengoa Bioenergy, Biocarburantes Castilla y Leon, Ebro Puleva	Babilafuente, Salamanca	Spain	steam explosion, wheat/wheat straw, corn stover	ethanol;	4 000	t/a	demo	under construction	2010
AE Biofuels	Butte	United States	switchgrass, grass seed, grass straw and corn stalks	ethanol;	500	t/a	pilot	operational	2003
BBI BioVentures LLC	Denver	United States	pre-collected feestocks that require little or no pretreatment	ethanol;	13 000	t/a	commercial	planned	2010
BioGasol	Aakirkeby, Bornholm	Denmark	various grasses, garden waste, straw	ethanol; biogas; lignin; hydrogen;	4 000	t/a	demo	planned	2016
BioGasol / AAU	Ballerup	Denmark	flexible	ethanol; biogas; cellulose; hemicelluloses; lignin;	10	t/a	pilot	planned	2010
Borregaard Industries LTD	Sarpsborg	Norway	sulfite spent liquor (SSL, 33% dry content) from spruce wood pulping	ethanol;	15 800	t/a	commercial	operational	1930
DDCE DuPont Danisco Cellulosic Ethanol	Vonore	United States	corn stover, cobs and fibre; switchgrass	ethanol;	750	t/a	pilot	operational	2010
EtanolPiloten i Sverige AB	Örnsköldsvik	Sweden	primary wood chips and sugarcane bagasse	ethanol;	80	t/a	pilot	operational	2004
Frontier Renewable Resources	Kincheloe	United States	wood chip	ethanol; lignin;	60 000	t/a	commercial	planned	

Biochemical Technologies continued

Company	**Location**	**Country**	**Input Material**	**Product**	**Output**	**Unit**	**Type**	**Status**	**Start-up Year**
Inbicon (DONG Energy)	Kalundborg	Denmark	wheat straw	ethanol; c5 molasses; solid biofuel;	4 300	t/a	demo	operational	2009
Inbicon (DONG Energy)	Fredericia	Denmark		ethanol; c5 molasses; solid biofuel;	several	t/h	pilot	operational	2005
Inbicon (DONG Energy)	Fredericia	Denmark	straw	ethanol; c5 molasses; solid biofuel;	several	t/h	pilot	operational	2003
Iogen Corporation	Ottawa	Canada	wheat, barley and oat straw	ethanol;	1 600	t/a	demo	operational	2004
Iogen Corporation	Birch Hills	Canada	wheat straw, etc.	ethanol;	70 000	t/a	commercial	planned	2011
Iowa State University	Boone	United States	grains, oilseeds, vegetable oils, glycerin	ethanol; FT-liquids; biodiesel; pyrolysis oils;	200	t/a	pilot	operational	2009
KL Energy Corporation	Upton	United States	wood waste, including cardboard and paper	ethanol;	4 500	t/a	demo	operational	2007
Lignol Energy Corporation	Burnaby	Canada	hardwood & softwood residues	ethanol; lignin;	80	t/a	pilot	operational	2010
Mascoma Corporation	Rome	United States	Wood Chips, Switchgrass and other raw materials	ethanol; lignin;	500	t/a	demo	operational	2003
Mossi & Ghisolfi - Chemtex Italia	Tortona	Italy	corn stover, straw, husk, woody biomass	ethanol;	50	t/a	pilot	operational	2009
Mossi & Ghisolfi - Chemtex Italia	Piedmont	Italy		ethanol;	40 000	t/a	demo	planned	2011
M-real Hallein AG	Hallein	Austria	sulfite spent liquor (SSL) from spruce wood pulping	ethanol;	12 000	t/a	demo	planned	2016
Pacific Ethanol	Boardman	United States	wheat straw, corn stover, poplar residuals	ethanol; biogas; lignin;	8 000	t/a	demo	planned	2010
POET	Scotland	United States	corn fiber, corn cobs and corn stalks	ethanol;	60	t/a	pilot	operational	2008
POET	Emmetsburg	United States	corn cobs, agricultural residues, biochemical processing; 100 mgy corn etoh + 25 mgy LC etoh	ethanol;	75 000	t/a	commercial	planned	2011

Biochemical Technologies continued

Company	**Location**	**Country**	**Input Material**	**Product**	**Output**	**Unit**	**Type**	**Status**	**Start-up Year**
PROCETHOL 2G	POMACLE	France		ethanol;	2 700	t/a	demo	under construction	2016
Queensland University of Technology	Mackay	Australia	Sugarcane bagasse & other lignocellulosics	ethanol;	several	t/h	pilot	under construction	2010
SEKAB	Örnsköldsvik	Sweden	wood chips or sugarcane bagasse, depending on location	ethanol;	50 000	t/a	demo	planned	2014
SEKAB	Örnsköldsvik	Sweden		ethanol;	120 000	t/a	commercial	planned	2016
SEKAB Industrial Development AB	Örnsköldsvik	Sweden	flexible for wood chips and sugarcane bagasse	ethanol;	4 500	t/a	demo	planned	2011
Southern Research Institute	Durham	United States	Cellullulosics, Municipal wastes, coal/biomass, syngas	FT-liquids; mixed alcohols;	3 500	t/a	pilot	operational	2003
Technical University of Denmark (DTU)	Lyngby	Denmark	wheat straw, corn fibre	ethanol; biogas; lignin;	10	t/a	pilot	operational	2006
Terrabon	Bryan	United States	municipal solid waste, sewage sludge, manure, agricultural residues and non-edible energy crops	ethanol; mixed alcohols; various chemicals;	254	t/a	demo	operational	2009
Verenium	Jennings	United States	Sugar cane bagasse, energy cane	cellulosic ethanol;	150	t/a	pilot	operational	2007
Verenium	Jennings	United States	Sugarcane bagasse, dedicated energy crops, wood products and switchgrass	cellulosic ethanol;	4 200	t/a	demo	operational	2009
Weyland AS	Blomsterdalen	Norway	concentrated acid; coniferous wood sawdust	ethanol;	158	t/a	pilot	under construction	2010

Table 5: List of Projects applying the Biochemical Pathway, by alphabetical order of the company name

3.2 Thermochemical Technologies:

Company	**Location**	**Country**	**Input Material**	**Product**	**Output**	**Unit**	**Type**	**Status**	**Start-up Year**
Chemrec AB	Pitea	Sweden	SSL	DME;	1 800	t/a	pilot	under construction	2010
Chemrec AB	Örnsköldsvik	Sweden	SSL	methanol; DME;	95 000	t/a	demo	planned	2013
CHOREN Fuel Freiberg GmbH & Co. KG	Freiberg	Germany	dry wood chips from recycled wood and residual forestry wood; additionally in the future fast growing wood from short-rotation crops	FT-liquids;	14 000	t/a	commercial	under construction	2010
CHOREN Industries GmbH	Schwedt	Germany	dry wood chips from recycled wood; fast growing wood from short-rotation crops	FT-liquids;	200 000	t/a	commercial	planned	2016
CTU - Conzepte Technik Umwelt AG	Güssing	Austria	syngas from gasifier	SNG;	576	t/a	demo	operational	2008
Cutec	Clausthal-Zellerfeld	Germany	Straw, wood, dried silage, organic residues	FT-liquids;	several	t/a	pilot	operational	1990
ECN	Alkmaar	Netherlands		SNG;	28 800	t/a	demo	planned	2016
ECN	Petten	Netherlands		SNG;	346	t/a	pilot	under construction	2011
Enerkem	Sherbrooke	Canada	20 types of feedstock tested	ethanol;	375	t/a	pilot	operational	2003
Enerkem	Westbury	Canada	Creosoted electricity poles	ethanol;	4 000	t/a	demo	under construction	2010
Enerkem	Edmonton	Canada	MSW	ethanol;	30 000	t/a	commercial	planned	2016
Flambeau River Biofuels LLC	Park Falls	United States	Forest residuals, non-merchantable wood	FT-liquids;	51 000	t/a	pilot	planned	2012
Forschungszentrum Karlsruhe GmbH	Karlsruhe	Germany		diesel; gasoline type fuel;	608	t/a	pilot	under construction	2016

Thermochemical Technologies continued

Company	**Location**	**Country**	**Input Material**	**Product**	**Output**	**Unit**	**Type**	**Status**	**Start-up Year**
GTI Gas Technology Institute	Des Plaines	United States	forest residues, stump material, and bark in both pellet and chip form that will be delivered in super sacks. Moisture content will be about 10 wt% or less and will not require additional drying.	FT-liquids;	26	t/a	pilot	under construction	2010
Iowa State University	Boone	United States	grains, oilseeds, vegetable oils, glycerin	ethanol; FT-liquids; biodiesel; pyrolysis oils;	200	t/a	pilot	operational	2009
NSE Biofuels Oy, a Neste Oil and Stora Enso JV	Varkaus	Finland	forest residues	FT-liquids;	656	t/a	demo	operational	2009
NSE Biofuels Oy, a Neste Oil and Stora Enso JV	Varkaus	Finland	forest residues	FT-liquids;	100 000	t/a	commercial	planned	2016
Range Fuels, Inc.	Soperton	United States	Wood and wood waste from nearby timber harvesting operations	ethanol; methanol;	300 000	t/a	commercial	under construction	2010
Range Fuels, Inc.	Denver	United States	Georgia pine and hardwoods and Colorado beetle kill pine	mixed alcohols;	several	t/a	pilot	operational	2008
Research Triangle Institute	Research Triangle Park	United States		FT-liquids; mixed alcohols;	22	t/a	pilot	planned	2016
Southern Research Institute	Durham	United States	Cellullulosics, Municipal wastes, coal/biomass, syngas	FT-liquids; mixed alcohols;	3 500	t/a	pilot	operational	2003
Tembec Chemical Group	Temiscaming	Canada	spent sulphite liquor feedstock	ethanol;	13 000	t/a	demo	operational	2003
Vienna University of Technology	Güssing	Austria	syngas from gasifier	FT-liquids;	several	t/a	pilot	operational	2005

Table 6: List of Projects applying the Thermochemical Pathway, by alphabetical order of the company name

3.3 Hybrid Technologies:

Company	**Location**	**Country**	**Input Material**	**Product**	**Output**	**Unit**	**Type**	**Status**	**Start-up Year**
Coskata	Warrenville	United States	various	ethanol;	several	t/d	pilot	operational	2003
Coskata	Madison	United States	wood chips, natural gas	ethanol;	120	t/a	demo	operational	2009
Coskata	Clewiston	United States	sugarcane waste, others	ethanol;	300 000	t/a	commercial	planned	2016
Iowa State University	Boone	United States	grains, oilseeds, vegetable oils, glycerin	ethanol; FT-liquids; biodiesel; pyrolysis oils;	200	t/a	pilot	operational	2009
Southern Research Institute	Durham	United States	Cellullulosics, Municipal wastes, coal/biomass, syngas	FT-liquids; mixed alcohols;	3 500	t/a	pilot	operational	2003
ZeaChem	Boardman	United States	poplar trees, sugar, wood, chips	ethanol; mixed alcohols; various chemicals;	4 500	t/a	pilot	under construction	2010

Table 7: List of Projects applying Hybrid Technologies, by alphabetical order of the company name

3.4 Other Innovative Technologies

Company	Location	Country	Input Material	Product	Output	Unit	Type	Status	Start-up Year
Amyris Crystalsev Biofuels	Sertaozinho	Brazil	fermentable sugars	hydrocarbons;	several	t/a	commercial	planned	2010
Amyris-Crystalsev Biofuels	Campinas	Brazil	fermentable sugars, sugarcane	hydrocarbons;	Several	t/a	pilot	under construction	2009
Amyris-Crystalsev Biotechnologies, Inc.	Emeryville	United States	fermentable sugars, sugarcane	hydrocarbons;	several	t/a	pilot	operational	2008
BFT Bionic Fuel Technologies AG	Aarhus - odum	Denmark	straw pellets	diesel; hydrocarbons;	200	t/a	demo	operational	2008
BioMCN	Farmsum	Netherlands	crude glycerine, torrified wood gasification, others	methanol;	800 000	t/a	commercial	planned	2012
BioMCN	Farmsum	Netherlands	from biodiesel and oleochemicals	methanol;	200 000	t/a	commercial stage 1	operational	2009
BioMCN	Farmsum	Netherlands	glycerine	methanol;	20 000	t/a	pilot	operational	2008
Butamax Advanced Biofuels LLC	Hull	United Kingdom	various feedstocks	biobutanol;	15	t/a	demo	planned	2010
Dynamic Fuels LLC	Geismar	United States	hydrotreatment of animal fats, used cooking greases	diesel;	210 000	t/a	commercial	under construction	2010
LanzaTech New Zealand Ltd	Parnell	New Zealand	Any gas containing Carbon Monoxide	ethanol;	90	t/a	pilot	operational	
Neste Oil	Porvoo	Finland	hydrotreatment of oils and fats	diesel;	170 000	t/a	commercial	operational	2009
Neste Oil	Rotterdam	Netherlands	hydrotreatment of oils and fats	diesel;	800 000	t/a	commercial	under construction	2011
Neste Oil	Singapore	Singapore	hydrotreatment of oils and fats	diesel;	800 000	t/a	commercial	under construction	2010
Neste Oil	Porvoo	Finland	hydrotreatment of palm oil, rapeseed oil and animal fat	diesel;	170 000	t/a	commercial	operational	2007
SynGest Inc.	Menlo	United States	corn cobs	ammonia;	50 000	t/a	demo	planned	2011

4 Detailed Descriptions

in alphabetical order of company names

Project Owner	Abengoa Bioenergy New Technologies
Project Name	pilot
Location	York, Nebraska, United States
Technology	biochemical
Raw Material	lignocellulosics;
Input	330 t/a
Product	ethanol;
Output Capacity	75 t/a; 0,02 mmgy
Facility Type	pilot
Partners	NREL, Auburn University
Funding	35 500 000 USD
Status	operational
Start-up Year	2007
Contact Person	Quang Nguyen qnguyen@bioenergy.abengoa.com
Web	http://www.abengoabioenergy.com

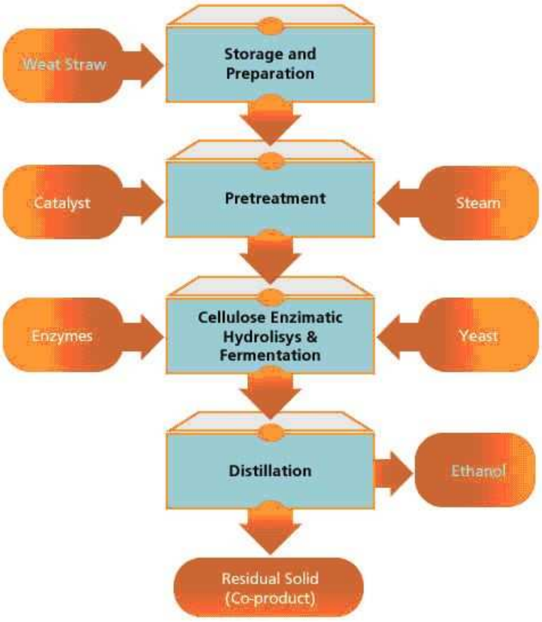
Table 8: Abengoa Bioenergy New Technologies - pilot

Highly versatile pilot facility. Possibility of testing various process configurations (i.e batch vs continuos steam explosion, different levels and techniques for biomass fractionation, separate C5/C6 fermentation or cofermentation…)

Project Owner	Abengoa Bioenergy, Biocarburantes Castilla y Leon, Ebro Puleva
Project Name	demo
Location	Babilafuente, Salamanca, Spain
Technology	biochemical
Raw Material	lignocellulosics; steam explosion, wheat/wheat straw, corn stover
Input	25 000 t/a
Product	ethanol;
Output Capacity	4 000 t/a; 1,32 mmgy
Facility Type	demo
Partners	CIEMAT, University of Lund
Funding	4 000 000 EUR
Status	under construction
Start-up Year	2010
Contact Person	Pablo Gutierrez Gomez pablo.gutierrez@bioenergy.abengoa.com
Web	http://www.abengoabioenergy.com

Table 9: Abengoa Bioenergy – demo

Figure 16: Picture of the Abengoa Bioenergy Plant in Salamanca, Spain



Steam explosion, no fractionation

Figure 17: Process Diagram Abengoa Bioenergy

Project Owner	Abengoa Bioenergy Biomass of Kansas, LLC
Project Name	commercial
Location	Hugoton, Kansas, United States
Technology	biochemical
Raw Material	lignocellulosics;
Input	363 000 t/a
Product	ethanol;
Output Capacity	34 000 t/a; 11,3 mmgy
Facility Type	commercial
Funding	76 000 000 USD
Status	under construction
Start-up Year	2011
Contact Person	Robert Wooley robert.wooley@bioenergy.abengoa.com
Web	http://www.abengoabioenergy.com

Table 10: Abengoa Bioenergy Biomass of Kansas - commercial

Steam explosion coupled with biomass fractionation, C5/C6 fermentation, distillation for ethanol recovery. Heat and power is provided by means of biomass gasification

Project Owner	AE Biofuels
Project Name	pilot
Location	Butte, Montana, United States
Technology	biochemical
Raw Material	lignocellulosics; switchgrass, grass seed, grass straw and corn stalks
Product	ethanol;
Output Capacity	500 t/a; 0,16 mmgy
Facility Type	pilot
Status	operational
Start-up Year	2003
Contact Person	Andy Foster afoster@americanethanol.com
Web	www.aebiofuels.com

Table 11: AE Biofuels

ambient temperature cellulose starch hydrolysis

Project Owner	BBI BioVentures LLC
Project Name	commercial
Location	Denver, Colorado, United States
Technology	biochemical
Raw Material	lignocellulosics; pre-collected feestocks that require little or no pretreatment
Input	52 000 t/a
Product	ethanol;
Output Capacity	13 000 t/a; 4,5 mmgy
Facility Type	commercial
Partners	Fagen
Investment	32 000 000 Fagen
Status	planned
Start-up Year	2010
Contact Person	Mark Yancey myancey@bbibioventures.com
Web	www.bbibioventures.com

Table 12: BBI BioVentures

Project Owner	BioGasol / AAU
Project Name	Maxiflex
Location	Ballerup, Denmark
Technology	biochemical
Raw Material	lignocellulosics; flexible
Input	0,5 t/h
Product	ethanol; biogas; cellulose; hemicelluloses; lignin;
Output Capacity	10 t/a; 40 l/d
Facility Type	pilot
Partners	Aalborg University
Investment	30 000 000 DKK
Funding	15 000 000 DKK
Status	planned
Start-up Year	2010
Contact Person	Rune Skovgaard-Petersen rsp@biogasol.com
Web	www.biogasol.com

Table 13: BioGasol - pilot

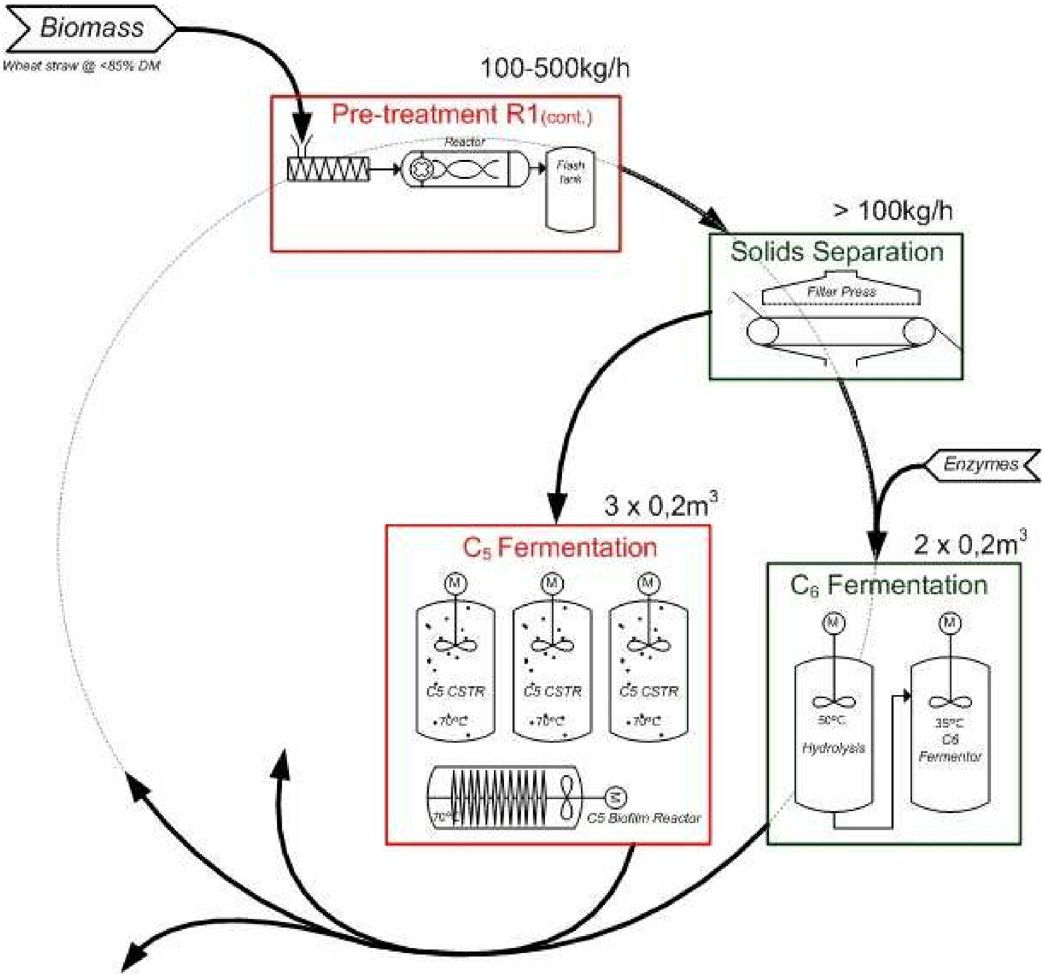


Figure 18: Process Diagram BioGasol - pilot

Project Owner	BioGasol
Project Name	BornBioFuel
Location	Aakirkeby, Bornholm, Denmark
Technology	biochemical
Raw Material	lignocellulosics; various grasses, garden waste, straw
Input	3,4 t/h
Product	ethanol; biogas; lignin; hydrogen;
Output Capacity	4 000 t/a; 5,2 Ml/a
Facility Type	demo
Partners	Siemens, Alfa Laval, Grundfos, Ostkraft, Agro Tech, nne pharmaplan
Investment	35 000 000 EUR
Funding	10 400 000 EUR
Status	planned
Start-up Year	2016
Contact Person	Rune Skovgaard-Petersen rsp@biogasol.com
Web	www.biogasol.com

Table 14: BioGasol - demo

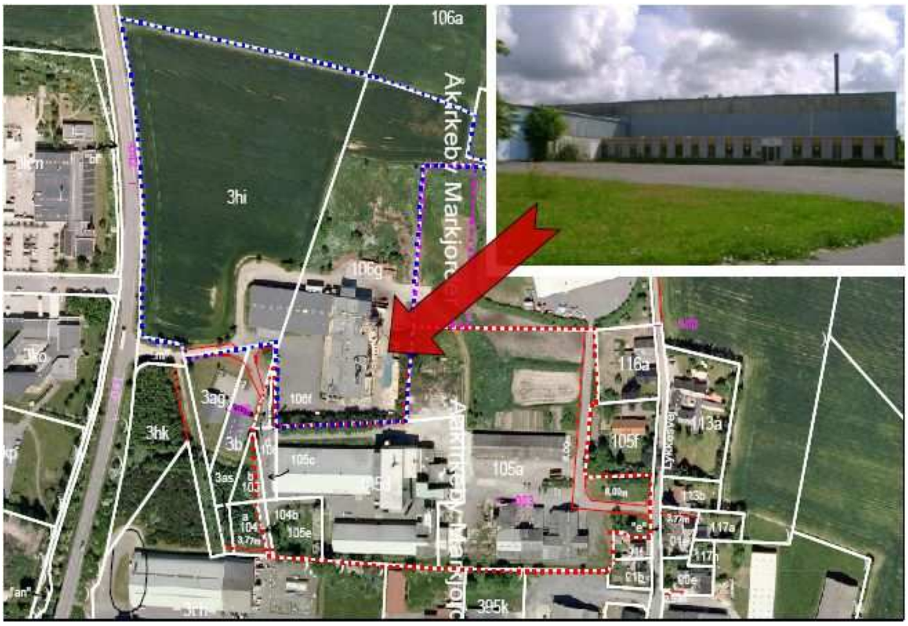


Figure 19: Picture of BioGasol Plant in Bornholm, Denmark

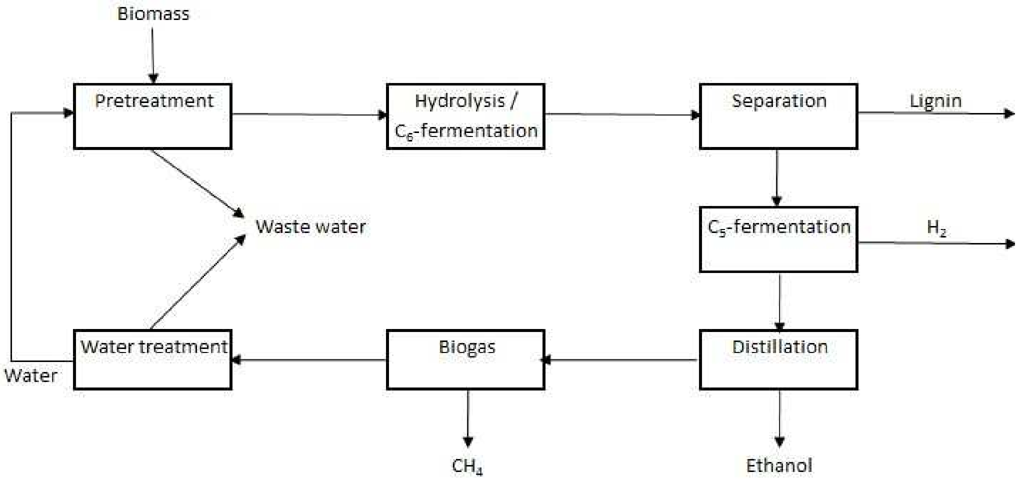
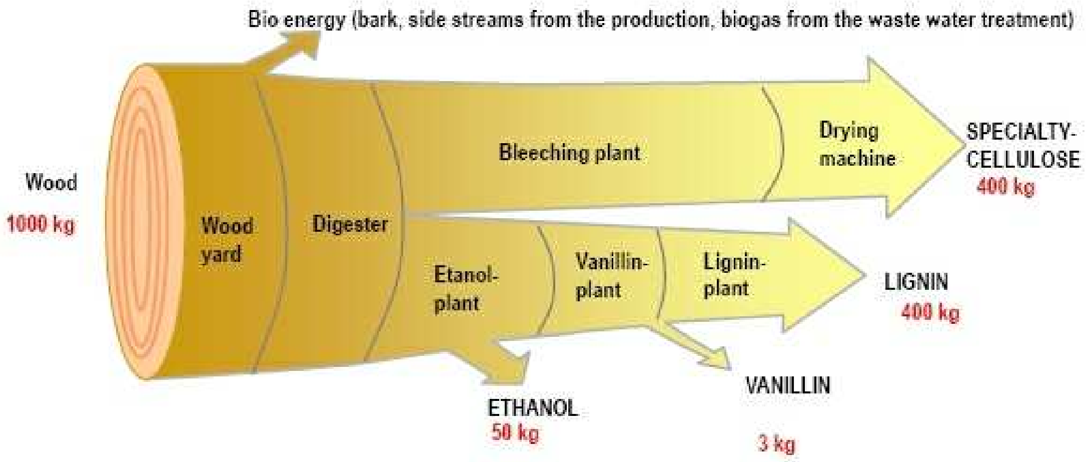


Figure 20: Process Diagram BioGasol - demo

Project Owner	Borregaard Industries LTD
Project Name	ChemCell Ethanol
Location	Sarpsborg, Norway
Technology	biochemical
Raw Material	lignocellulosics; sulfite spent liquor (SSL, 33% dry content) from spruce wood pulping
Input	500 000 t/a
Product	ethanol;
Output Capacity	15 800 t/a; 20 Ml/a
Facility Type	commercial
Status	operational
Start-up Year	1930
Contact Person	Gisle Lohre Johansen, Vice President NBD and R&D, gisle.l.johansen@borregaard.com
Web	www.borregaard.com

Table 15: Borregaard Industries

Figure 21: Picture of Borregaard Industries Plant in Sarpsborg, Norway



Applications (end products)

Cellulose
- Construction materials
- Cosmetics
- Food
- Tablets
- Textiles
- Filters
- Paint / varnish

Lignin
- Concrete additives
- Animal feed
- Dyestuff
- Batteries
- Briquetting
- Mining

Vanillin
- Food
- Perfumes
- Pharmaceuticals

Ethanol
- Car care
- Paint/ varnish
- Pharmaceutical industry
- Bio Fuel

Figure 22: Process Diagram Borregaard Industries

Pulp for the paper mill is produced by cooking spruce chips with acidic calcium bisulfite cooking liquor. Hemicellulose is hydrolyzed to various sugars during the cooking process. After concentration of the SSL, the sugars are fermented and ethanol is distilled off in several steps. A part of the 96% ethanol is dehydrated to get absolute ethanol.

CHEMREC

Project Owner	Chemrec AB
Project Name	BioDME
Location	Pitea, Sweden
Technology	thermochemical
Raw Material	lignocellulosics; Black liquor gasification
Input	20 t/d
Product	DME;
Output Capacity	1 800 t/a; 12 000 mmgy
Facility Type	pilot
Partners	AB Volvo, Haldor-Topsoe, Preem, Total, Delphi, ETC
Investment	28 500 000 EUR
Status	under construction
Start-up Year	2010
Contact Person	Patrik Lownertz patrik.lownertz@chemrec.se
Web	www.chemrec.se

Table 16: Chemrec - pilot

Figure 23: Picture (digitally modified to display planned pilot plant) of Chemrec Plant in Pitea, Sweden

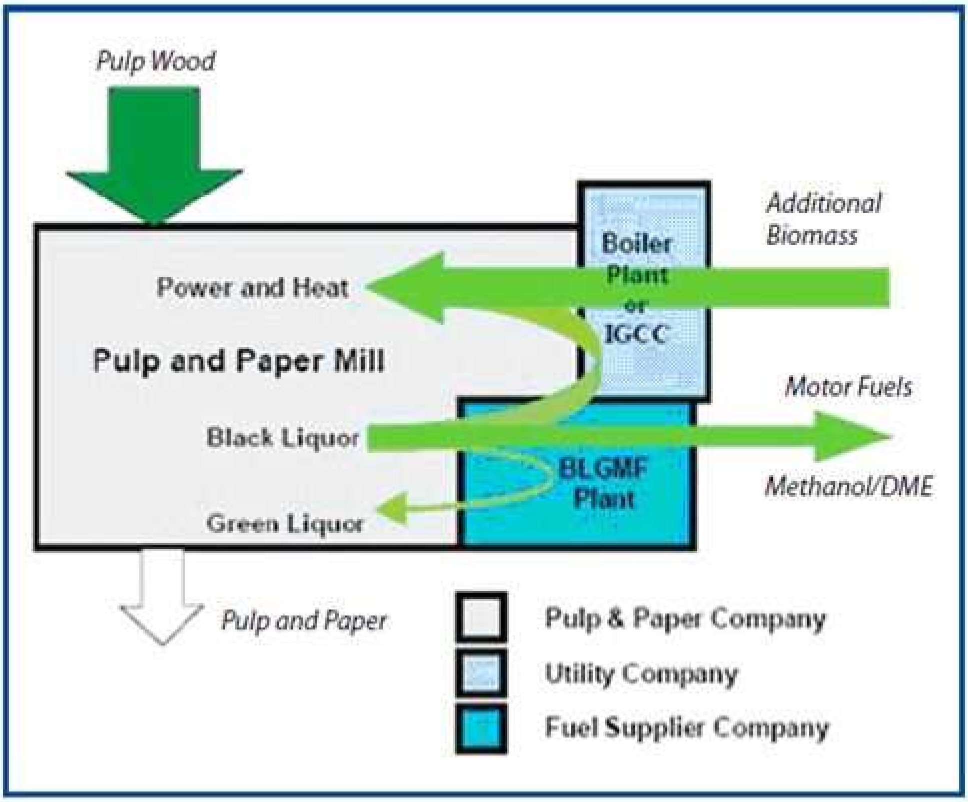


Figure 24: Process Diagram Chemrec

The recovery boiler in the paper mill is replaced or supplemented by a gasification based fuel generating and pulp mill cooking chemicals recovery system. The BioDME pilot is an integrated part of heavy DME fuelled vehicle fleet trials.

CHEMREC

Project Owner	Chemrec AB
Project Name	Domsjoe Biorefinery
Location	Örnsköldsvik, Sweden
Technology	thermochemical
Raw Material	lignocellulosics; Black liquor gasification
Input	380 000 t/a
Product	methanol; DME;
Output Capacity	95 000 t/a;
Facility Type	demo
Partners	Domsjoe Fabriker AB
Investment	250 000 000 EUR
Status	planned
Start-up Year	2013
Contact Person	Patrik Lownertz ; patrik.lownertz@chemrec.se
Web	http://www.chemrec.se

Table 17: Chemrec - demo

The recovery boilers in this dissolving cellulose mill are replaced by a gasification based fuel generating and pulp mill cooking chemicals recovery system.

Project Owner	CHOREN Fuel Freiberg GmbH & Co. KG
Project Name	beta plant
Location	Freiberg, Germany
Technology	thermochemical
Raw Material	lignocellulosics; dry wood chips from recycled wood and residual forestry wood; additionally in the future fast growing wood from short-rotation crops
Product	FT-liquids;
Output Capacity	14 000 t/a; 18 Ml/a
Facility Type	commercial
Investment	100 000 000 EUR
Status	under construction
Start-up Year	2010
Contact Person	info@choren.com +49 3731 2662 0
Web	www.choren.com

Table 18: CHOREN - commercial

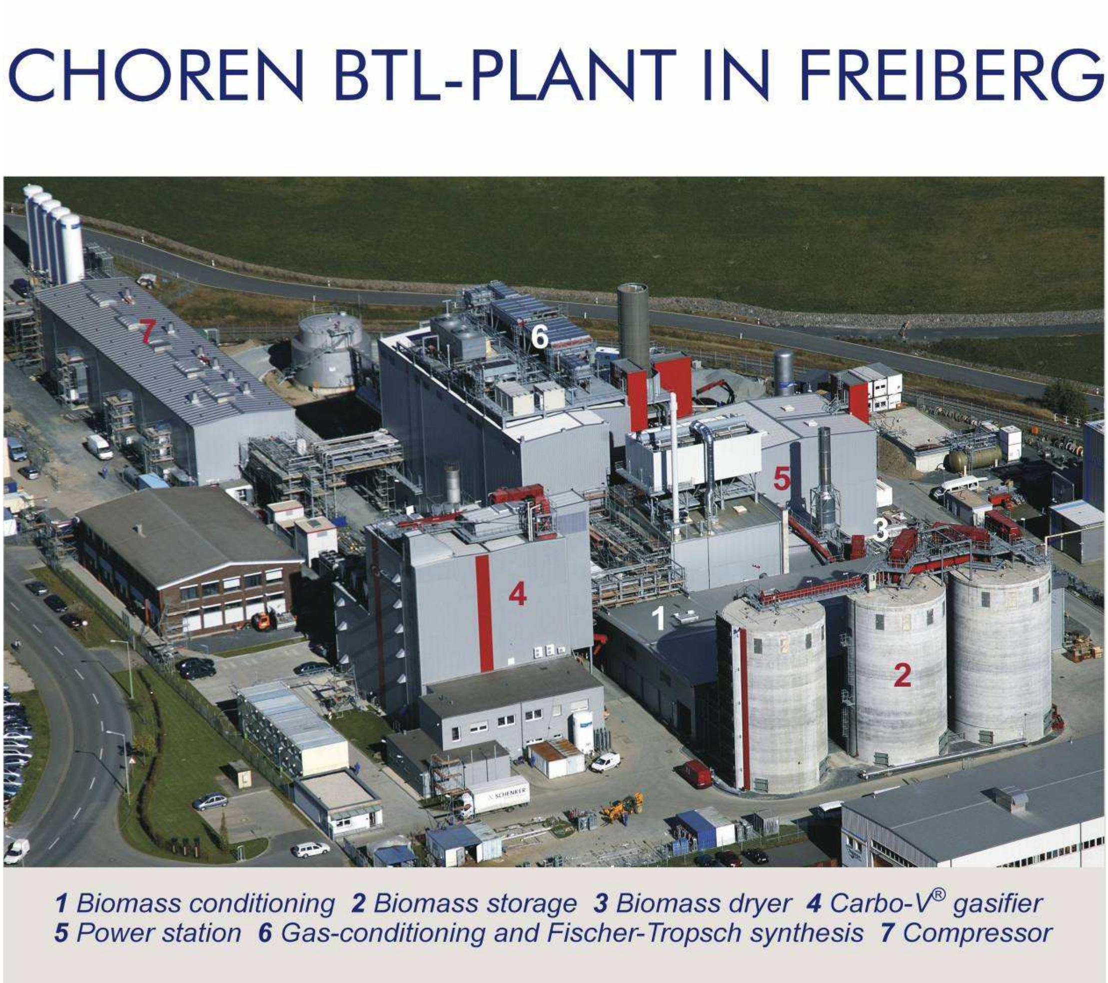


Figure 25: Picture of CHOREN Plant in Freiberg, Germany

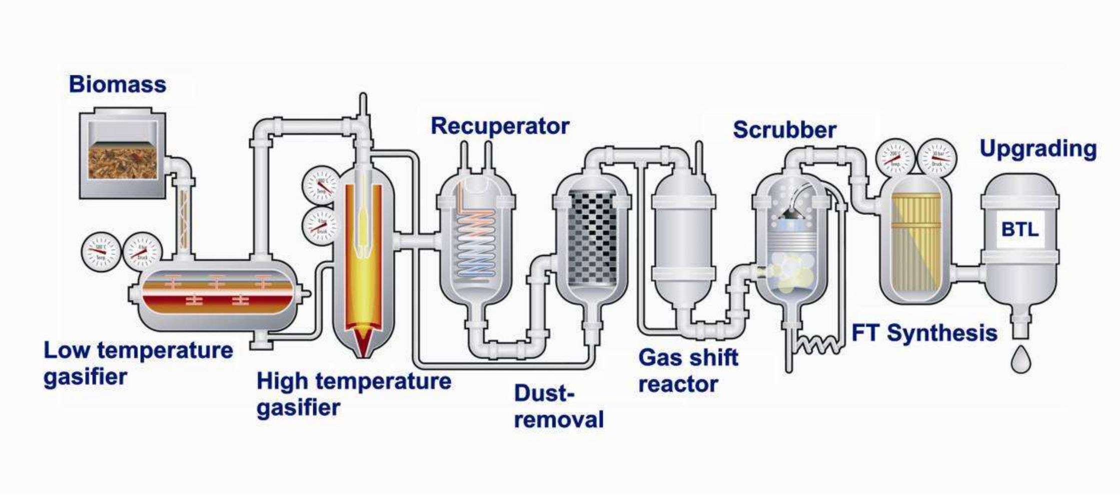


Figure 26: Process Diagram CHOREN

The Carbo-V process, developed by CHOREN, is used to convert dry wood chips into an extremely pure synthetic gas, consisting primarily of CO and H2, containing no tar and little methane.

The first sub-process in this three-stage gasification process is low-temperature gasification. The wood chips are continuously carbonized at a temperature between 400 and 500 ℃, i.e. decomposed into gas containing hydrocarbons (volatile components) and solid carbon (char).

During the following high-temperature gasification the hydrocarbon gas is further oxidized in a combustion chamber above the melting point of the fuel ash with air and/or oxygen to create hot gasification agent.

In the third stage of the process, the char, ground to a combustible dust, is blown into the hot gasification agent. The combustible dust and the gasification agent react endothermically to create raw synthetic gas.

Then the gas is treated using classic techniques for gas purification and preparation (cooling, mechanical dust removal, various washing stages, CO conversion and ultra-fine cleaning). In the last step the gas is converted into a liquid fuel using the Fischer-Tropsch (FT) technology. Now the gas (CO and H2) react in a catalytic converter to generate hydrocarbons. In order to maximize the fuel yield, wax generated in the FT synthesis is further processed by hydrocracking. The diesel and light hydrocarbon (naphtha) products are separated by distillation.

Project Owner	CHOREN Industries GmbH
Project Name	sigma plant
Location	Schwedt, Germany
Technology	thermochemical
Raw Material	lignocellulosics; dry wood chips from recycled wood; fast growing wood from short-rotation crops
Product	FT-liquids;
Output Capacity	200 000 t/a; 270 Ml/a
Facility Type	commercial
Status	planned
Start-up Year	2016
Contact Person	info@choren.com +49 3731 2662 0
Web	www.choren.com

Table 19: CHOREN – commercial planned

Project Owner	Coskata
Project Name	pilot
Location	Warrenville, Illinois, United States
Technology	hybrid
Raw Material	lignocellulosics; various
Product	ethanol;
Output Capacity	several t/d;
Facility Type	pilot
Status	operational
Start-up Year	2003
Contact Person	Doug Williams dwilliams@coskata.com
Web	www.coskata.com

Table 20: Coskata - pilot

Figure 27: Picture of Coskata facility in Warrenville, USA

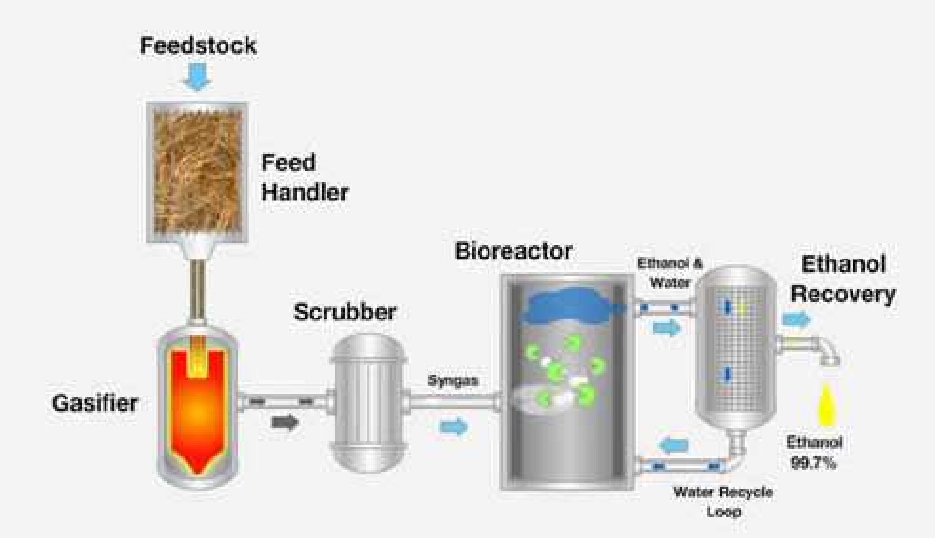


Figure 28: Process Diagram Coskata

Project Owner	Coskata
Project Name	Lighthouse
Location	Madison, Pennsylvania, United States
Technology	hybrid
Raw Material	lignocellulosics; wood chips, natural gas
Product	ethanol;
Output Capacity	120 t/a; 0,04 mmgy
Facility Type	demo
Status	operational
Start-up Year	2009
Contact Person	Doug Williams dwilliams@coskata.com
Web	www.coskata.com

Table 21: Coskata – demo

The plant will employ the Plasma Center's gasifier to superheat raw materials at temperatures up to 1700 degrees Fahrenheit (1000℃), then release the resulting synthetic gas, or "syngas", into a bioreactor, where it will become food for microorganisms that convert it into ethanol.

Coskata has an efficient, affordable, and flexible three-step conversion process:
1. Incoming material converted to synthesis gas (gasification)
2. Fermentation of synthesis gas into ethanol (bio-fermentation)
3. Separation and recovery of ethanol (separations)

Ethanol can be manufactured using this cutting edge technology at a variable cost of under US$1.00 per gallon - the lowest cost of manufacture in the industry. During gasification, carbon-based input materials are converted into syngas using well-established gasification technologies. After the chemical bonds are broken using gasification, Coskata's proprietary microorganisms convert the resulting syngas into ethanol by consuming the carbon monoxide (CO) and hydrogen (H2) in the gas stream. Once the gas-to-liquid conversion process has occurred, the resulting ethanol is recovered from the solution using pervaporation technology.

Coskata's proprietary microorganisms eliminate the need for costly enzymatic pretreatments, and the bio-fermentation occurs at low pressures and temperatures, reducing operational costs. In addition, the Coskata process has the potential to yield over 100 gallons of ethanol per ton of dry carbonaceous input material, reducing both operational and capital costs. Coskata's exclusively licensed separation technology dramatically improves the separations and recovery component of ethanol production, reducing the required energy by as much as 50%. The entire process includes a gasifier, gas clean-up, fermentation, and separation (both distillation and membrane separation) similar to what is in the process illustration.

Project Owner	Coskata
Project Name	commercial
Location	Clewiston, Florida, United States
Technology	hybrid
Raw Material	lignocellulosics; sugarcane waste, others
Product	ethanol;
Output Capacity	300 000 t/a; 100 mmgy
Facility Type	commercial
Investment	400 000 000 USD
Status	planned
Start-up Year	2016
Contact Person	Doug Williams dwilliams@coskata.com
Web	www.coskata.com

Table 22: Coskata – commercial

The plant will employ the Plasma Center's gasifier to superheat raw materials at temperatures up to 1700 degrees Fahrenheit (1000°C), then release the resulting synthetic gas, or "syngas", into a bioreactor, where it will become food for microorganisms that convert it into ethanol.

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Project Owner	CTU - Conzepte Technik Umwelt AG
Project Name	SNG demo
Location	Güssing, Austria
Technology	thermochemical
Raw Material	lignocellulosics; syngas from gasifier
Input	350 Nm3/h
Product	SNG;
Output Capacity	576 t/a; 100 Nm3/h
Facility Type	demo
Partners	Vienna University of Technology, Austria; Paul Scherrer Institute, Switzerland; Repotec, Austria
Status	operational
Start-up Year	2008
Contact Person	Martin Schaub martin.schaub@ctu.ch
Web	www.ctu.ch

Table 23: CTU

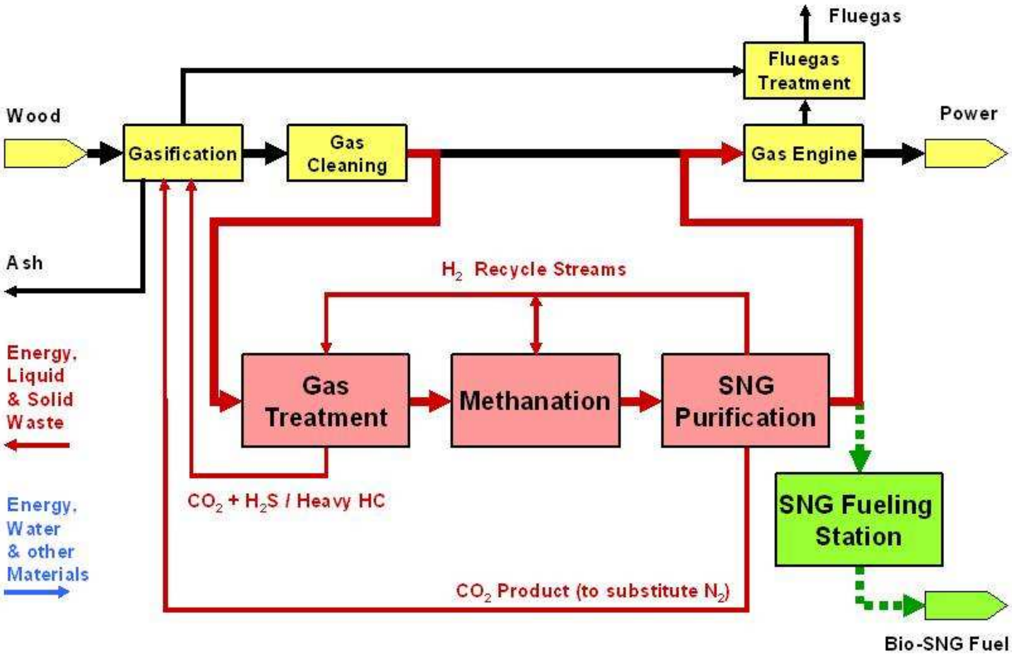


Figure 29: Process Diagram CTU

After lab testing in a scale of 10 kW during the last few years, the pilot and demonstration unit (PDU) with an outout of 1 MW of SNG was inaugurated in June 2009. The plant uses a side stream of the existing Güssing gasifier. The syngas is further purifed before entering the catalysis reactor, where the conversion to methane takes place.

The plant has been designed to work in a fairly wide pressure (1-10 bar) and temperature range (300-360℃) in order to optimize the efficiency of the system. SNG upgrading downstream of the reactor is focussed at reaching H-Gas quality in order to meet the feed in conditions for natural gas pipelines. Achieved peformance of the plant is above expectation and the CNG filling station has beed supplied with high quality H-gas. CNG cars have been run successfully with the gas produced.

Figure 30: Picture of CTU Plant in Güssing, Austria

Project Owner	Cutec
Project Name	pilot
Location	Clausthal-Zellerfeld, Germany
Technology	thermochemical
Raw Material	lignocellulosics; Straw, wood, dried silage, organic residues
Product	FT-liquids;
Output Capacity	several t/a;
Facility Type	pilot
Status	operational
Start-up Year	1990
Contact Person	Stefan Vodegel stefan.vodegel@cutec.de
Web	www.cutec.de

Table 24: CUTEC

Figure 31: Picture of CUTEC Plant in Clausthal-Zellerfeld, Germany

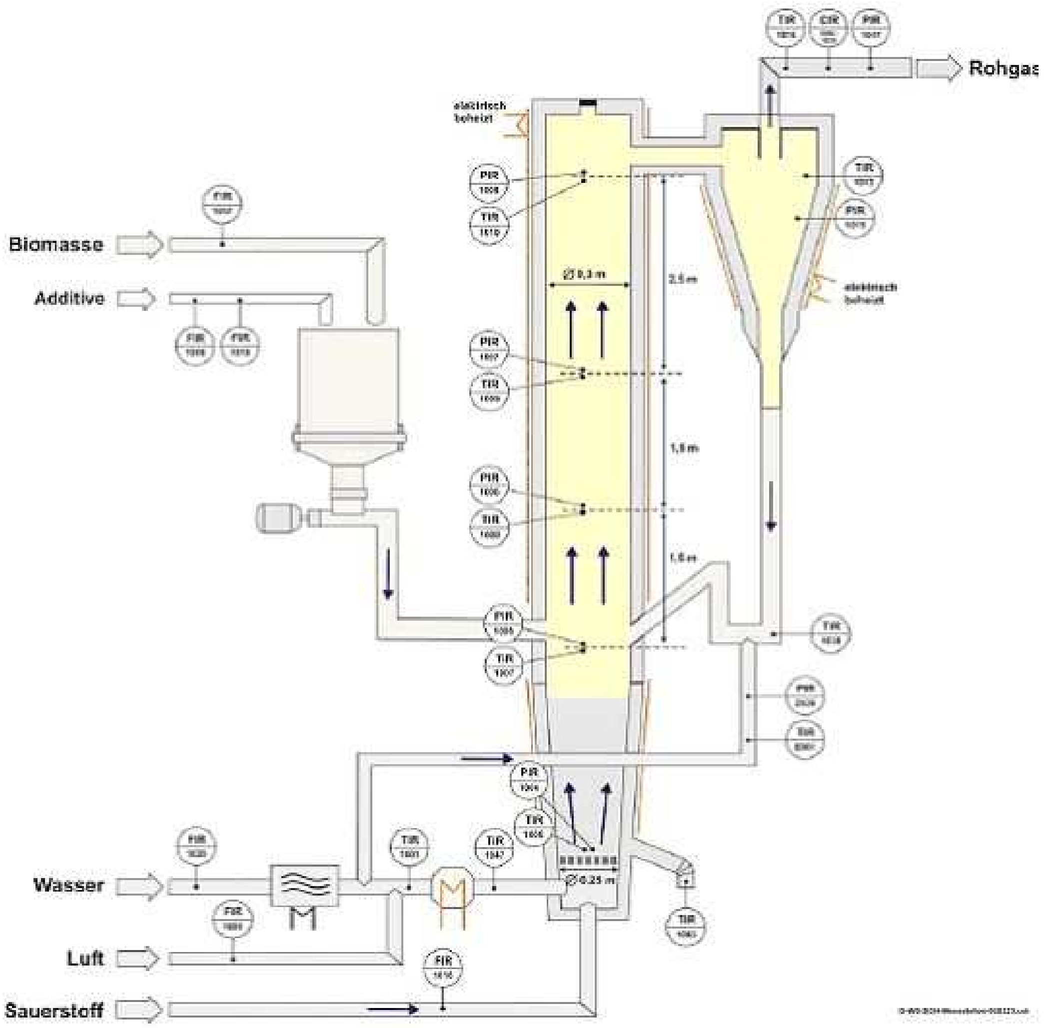
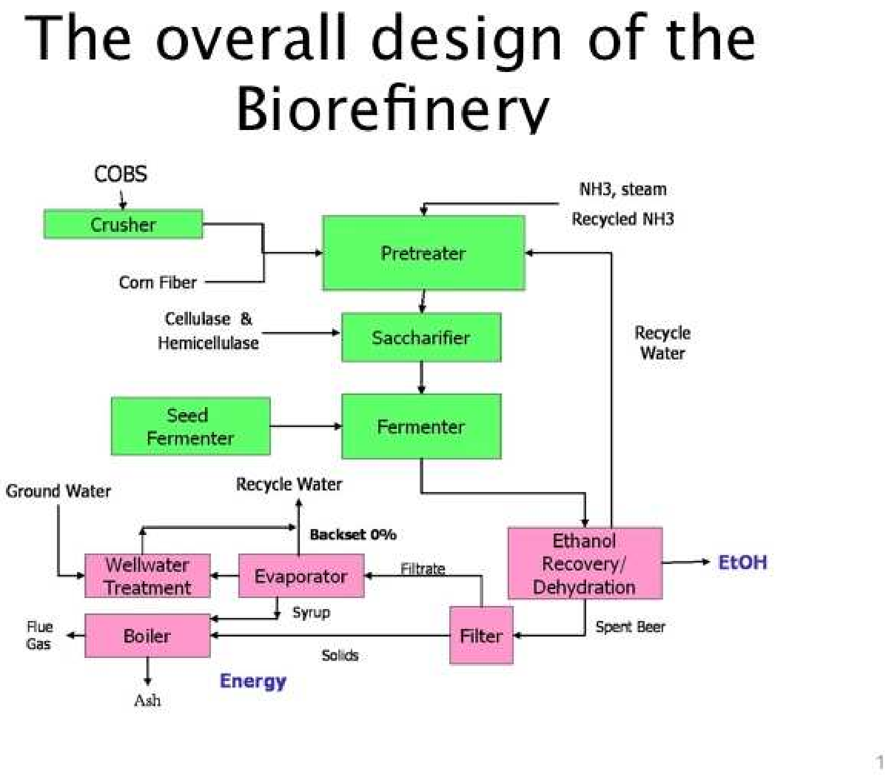


Figure 32: Process Diagram CUTEC

DDCE
DuPont Danisco Cellulosic Ethanol LLC

Project Owner	DDCE DuPont Danisco Cellulosic Ethanol
Project Name	pilot
Location	Vonore, Tennessee, United States
Technology	biochemical
Raw Material	lignocellulosics; corn stover, cobs and fibre; switchgrass
Product	ethanol;
Output Capacity	750 t/a; 0,25 mmgy
Facility Type	pilot
Partners	Genera Energy, University of Tennessee
Status	under construction
Start-up Year	2010
Contact Person	Jack Huttner jack.huttner@ddce.com
Web	http://www.ddce.com/

Table 25: DDCE DuPont Danisco Cellulosic Ethanol



The overall design of the Biorefinery

Figure 33: Process Diagram DDCE

enzymatic hydrolysis

Project Owner	ECN
Project Name	pilot
Location	Petten, Netherlands
Technology	thermochemical
Raw Material	lignocellulosics;
Input	1 800 t/a
Product	SNG;
Output Capacity	346 t/a; 60 Nm3/h
Facility Type	pilot
Status	under construction
Start-up Year	2011
Contact Person	Ruben Smit r.smit@ecn.nl
Web	www.ecn.nl

Table 26: ECN – pilot

Production of Substitute Natural Gas from woody biomass using MILENA gasification, OLGA tar removal, gas cleaning, gas upgrading and methanation

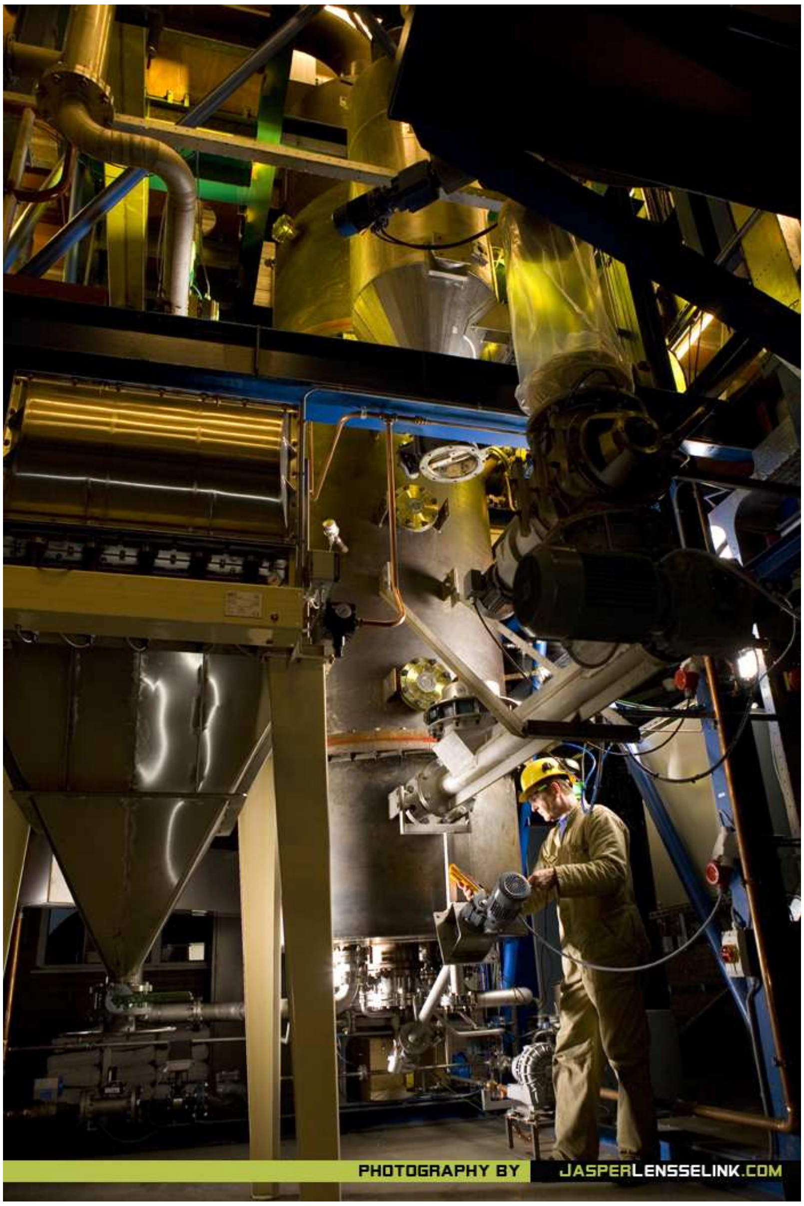


Figure 34: Picture of ECN Plant in Petten, Netherlands

Project Owner	ECN
Project Name	demo
Location	Alkmaar, Netherlands
Technology	thermochemical
Raw Material	lignocellulosics;
Product	SNG;
Output Capacity	28 800 t/a; 50 MW
Facility Type	demo
Partners	HVC
Status	planned
Start-up Year	2016
Contact Person	Ruben Smit r.smit@ecn.nl
Web	www.ecn.nl

Table 27: ECN - demo

Project Owner	Enerkem
Project Name	pilot
Location	Sherbrooke, Quebec, Canada
Technology	thermochemical
Raw Material	lignocellulosics; 20 types of feedstock tested
Product	ethanol;
Output Capacity	375 t/a; 0,47 Ml/a
Facility Type	pilot
Status	operational
Start-up Year	2003
Contact Person	Vincent Chornet vchornet@enerkem.com
Web	http://www.enerkem.com/index.php?module=CMS&id=10&newlang=eng

Table 28: Enerkem - pilot

Figure 35: Picture of Enerkem Facility in Sherbrooke, Canada

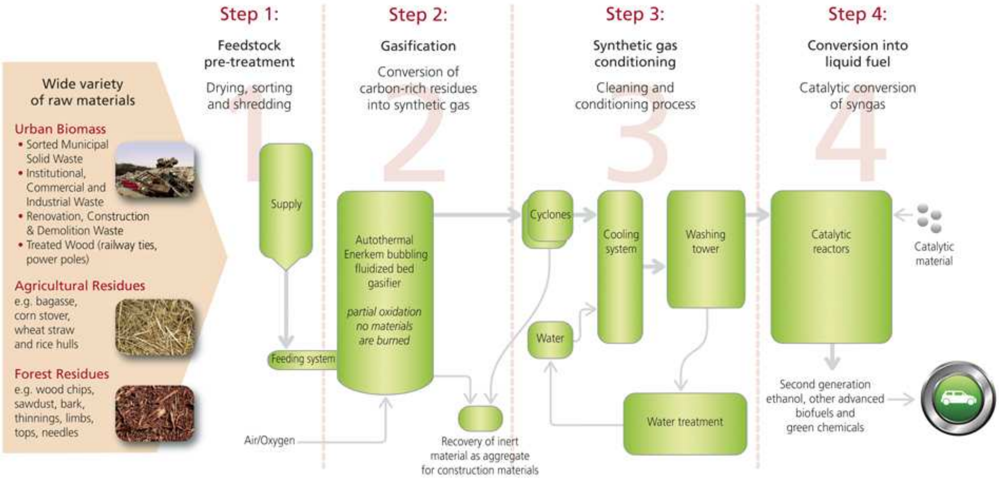


Figure 36: Process Diagram Enerkem

Project Owner	Enerkem
Project Name	demo
Location	Westbury, Quebec, Canada
Technology	thermochemical
Raw Material	lignocellulosics; Creosoted electricity poles
Input	12 000 t/a
Product	ethanol;
Output Capacity	4 000 t/a; 5 Ml/a
Facility Type	demo
Status	under construction
Start-up Year	2010
Contact Person	Vincent Chornet vchornet@enerkem.com
Web	http://www.enerkem.com/index.php?module=CMS&id=11&newlang=eng

Table 29: Enerkem - demo

Figure 37: Picture of Enerkem Plant in Westbury, Canada

Enerkem's gasification, sequential gas conditioning and catalysis technology converts sorted municipal solid waste,agricultural and forest residues into cellulosic ethanol and other biofuels.

Project Owner	Enerkem
Project Name	commercial
Location	Edmonton, Alberta, Canada
Technology	thermochemical
Raw Material	lignocellulosics; MSW
Input	100 000 t/a
Product	ethanol;
Output Capacity	30 000 t/a; 36 Ml/a
Facility Type	commercial
Partners	Greenfield Ethanol
Investment	70 000 000 CAD
Funding	20 000 000 CAD
Status	planned
Start-up Year	2016
Contact Person	Vincent Chornet vchornet@enerkem.com
Web	www.edmontonbiofuels.ca

Table 30: Enerkem - commercial

Enerkem's gasification, sequential gas conditioning and catalysis technology converts sorted municipal solid waste,agricultural and forest residues into cellulosic ethanol and other biofuels.

Project Owner	EtanolPiloten i Sverige AB
Project Name	pilot
Location	Örnsköldsvik, Sweden
Technology	biochemical
Raw Material	lignocellulosics; primary wood chips and sugarcane bagasse, but other raw materials will be studied such as wheat, corn stover, energy grass, recycled waste etc
Product	ethanol;
Output Capacity	80 t/a; 300 l/d
Facility Type	pilot
Partners	University of Umea, Technical University of Lulea, SEKAB E-technology AB
Investment	2 000 000 SEK
Status	operational
Start-up Year	2004
Contact Person	info@sekab.com +46 660 758 00
Web	www.sekab.com

Table 31: EtanolPiloten I Sverige AB – (SEKAB) pilot

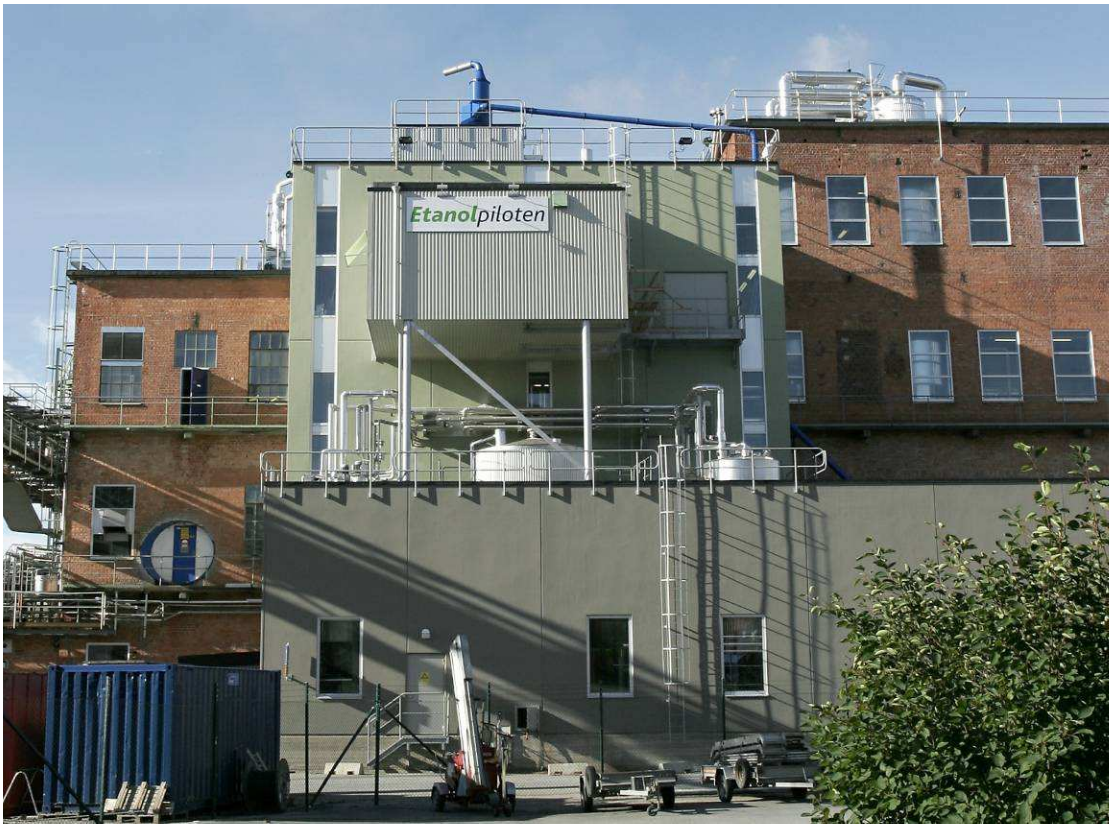


Figure 38: Picture of EtanolPiloten I Sverige Plant in Örnsköldsvik, Sweden

2 step diluted acid + enzyme hydrolysis

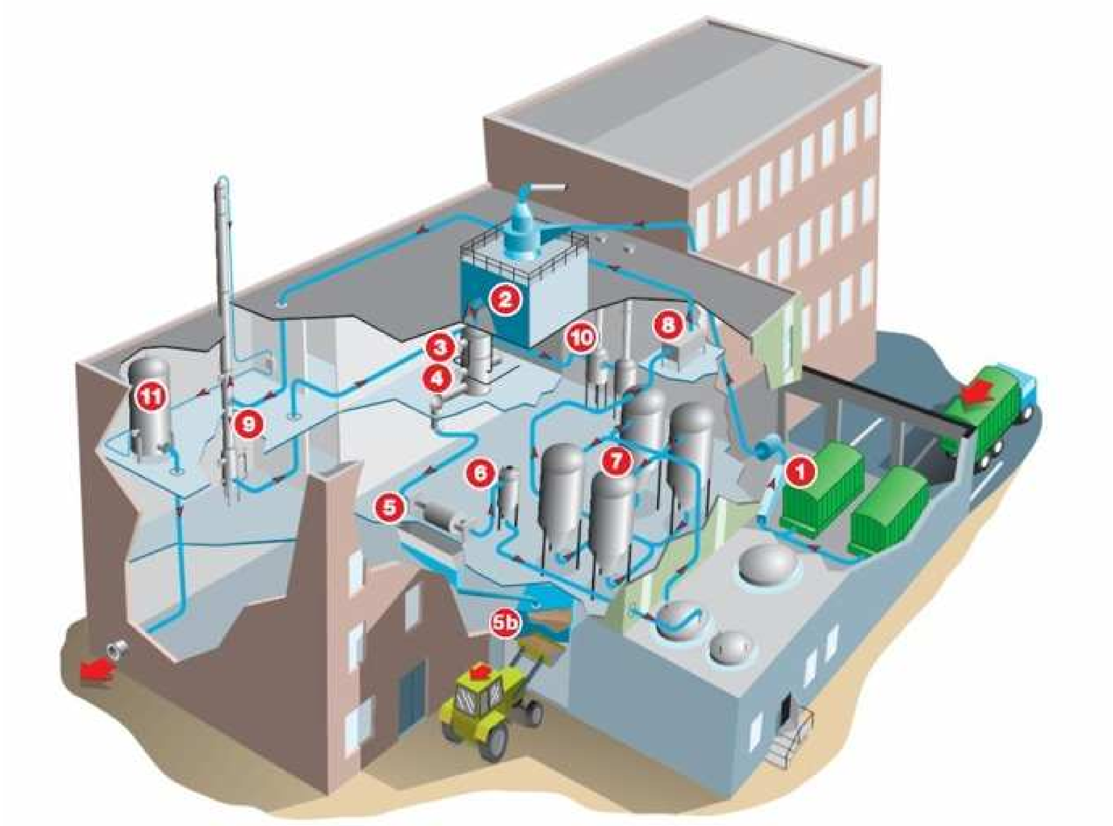


Figure 39: Process Diagram EtanolPiloten I Sverige

Project Owner	Flambeau River Biofuels LLC
Project Name	Project Trixie
Location	Park Falls, Wisconsin, United States
Technology	thermochemical
Raw Material	lignocellulosics; Forest residuals, non-merchantable wood
Input	350 000 t/a
Product	FT-liquids;
Output Capacity	51 000 t/a; 17 mmgy
Facility Type	pilot
Partners	TRI, EfT, Earthtech AECOM, Miron Construction, Laurentian Engineering
Investment	200 000 000 USD
Status	planned
Start-up Year	2012
Contact Person	Bob Byrne bbyrne@flambeauriverpapers.com
Web	www.flambeauriverpapers.com

Table 32: Flambeau River Biofuels

Thermochemical conversion of biomass using advanced gasification technologies followed by FT catalytic conversion into renewable liquid fuels and waxes

Project Owner	Forschungszentrum Karlsruhe GmbH
Project Name	bioliq
Location	Karlsruhe, Germany
Technology	thermochemical
Raw Material	lignocellulosics;
Input	0,5 t/h
Product	diesel; gasoline type fuel;
Output Capacity	608 t/a; 100 l/h
Facility Type	pilot
Partners	LURGI GmbH
Status	under construction
Start-up Year	2016
Contact Person	Prof. Dinjus eckhardt.dinjus@itc-cpv.fzk.de
Web	http://www.fzk.de/bioliq

Table 33: Forschungszentrum Karlsruhe

Figure 40: Picture of Forschungszentrum Karlsruhe Plant in Karlsruhe, Germany

Project Owner	Frontier Renewable Resources
Project Name	Kinross Plant 1
Location	Kincheloe, Michigan, United States
Technology	biochemical
Raw Material	lignocellulosics; wood chip
Input	700 t/d
Product	ethanol; lignin;
Output Capacity	60 000 t/a; 20 mmgy
Facility Type	commercial
Partners	Mascoma Corporation J.M. Longyear
Status	planned
Contact Person	Frontier Renewable Resources
Web	info@frontier-renewable.com

Table 34: Frontier Renewable Resources

The unique technology developed by Mascoma Corporation uses yeast and bacteria that are engineered to produce large quantities of the enzymes necessary to break down the cellulose and ferment the resulting sugars into ethanol. Combining these two steps (enzymatic digestion and fermentation) significantly reduces costs by eliminating the need for enzyme produced in a separate refinery. This process, called Consolidated Bioprocessing or “CBP”, will ultimately enable the conversion of the solar energy contained in plants to ethanol in just a few days.

Project Owner	GTI Gas Technology Institute
Project Name	pilot
Location	Des Plaines, Illinois, United States
Technology	thermochemical
Raw Material	lignocellulosics; forest residues, stump material, and bark in both pellet and chip form that will be delivered in super sacks. Moisture content will be about 10 wt% or less and will not require additional drying.
Product	FT-liquids;
Output Capacity	26 t/a; 25 gal/d
Facility Type	pilot
Partners	Carbona (Finland and USA) biomass gasification process (based on cooperation with VTT of Finland), Velocys (USA) Fischer Tropsch Technology, UPM (funding)
Funding	2 000 000 USD
Status	under construction
Start-up Year	2010
Contact Person	Howard Meyer howard.meyer@gastechnology.org
Web	www.gastechnology.org

Table 35: Gas Technolgy Institute (GTI)

Carbona (Finland and USA) biomass gasification process is originally based on licenses from the Gas Technology Institute and has subsequently been developed further by Carbona. Its first commercial application is under the Skive BGGE Small Modular Biopower project.

Carbona tar reforming know-how is based on cooperation with VTT of Finland in conjunction also with the Skive Project and subsequent development by Carbona for application to synthesis gas at pressure.

Velocys (USA) Fischer Tropsch technology is based on parallel arrays of microchannels making a process-intensive reactor licensed from Battelle. Testing will consist of medium-pressure gasification of biomass with the raw synthesis gas cleaned to levels as required for a liquid fuels production reactor followed by subsequent compression for the FT system. After verifying the performance of the cleanup system, a FT reactor will be integrated into the system.

Project Owner	Inbicon (DONG Energy)
Project Name	pilot 1
Location	Fredericia, Denmark
Technology	biochemical
Raw Material	lignocellulosics; straw
Input	0,1 t/h
Product	ethanol; c5 molasses; solid biofuel;
Output Capacity	several t/h;
Facility Type	pilot
Investment	5 000 000 EUR
Funding	2 500 000 EUR
Status	operational
Start-up Year	2003
Contact Person	Michael Persson miper@dongenergy.dk
Web	www.inbicon.com

Table 36: Inbicon – pilot 1

Figure 41: Picture of Inbicon Pilot 1 Plant in Fredericia, Denmark

hydrothermal pre-treatment, high gravity hydrolysis, yeast fermentation

Project Owner	Inbicon (DONG Energy)
Project Name	pilot 2
Location	Fredericia, Denmark
Technology	biochemical
Raw Material	lignocellulosics;
Input	1 t/h
Product	ethanol; c5 molasses; solid biofuel;
Output Capacity	several t/h;
Facility Type	pilot
Investment	15 000 000 EUR
Funding	5 000 000 EUR
Status	operational
Start-up Year	2005
Contact Person	Michael Persson miper@dongenergy.dk
Web	www.inbicon.com

Table 37: Inbicon – pilot 2

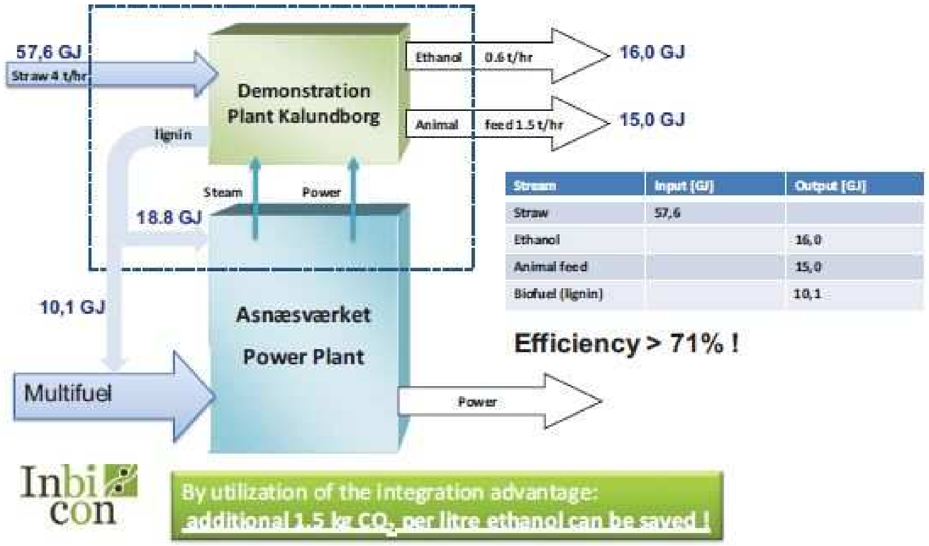
Figure 42: Picture of Inbicon Pilot 2 Plant in Fredericia, Denmark

hydrothermal pre-treatment, high gravity hydrolysis, yeast fermentation

Project Owner	Inbicon (DONG Energy)
Project Name	demo
Location	Kalundborg, Denmark
Technology	biochemical
Raw Material	lignocellulosics; wheat straw
Input	30 000 t/a
Product	ethanol; c5 molasses; solid biofuel;
Output Capacity	4 300 t/a; 1,5 mmgy
Facility Type	demo
Investment	50 000 000 EUR
Funding	10 000 000 EUR
Status	operational
Start-up Year	2009
Contact Person	Michael Persson miper@dongenergy.dk
Web	www.inbicon.com

Table 38: Inbicon - demo

Figure 43: Picture of Inbicon Demo Plant in Kalundborg, Denmark



Stream	Input [GJ]	Output [GJ]
Straw	57,6	
Ethanol		16,0
Animal feed		15,0
Biofuel (lignin)		10,1

Figure 44: Process Diagram Inbicon

Output: 4,300 tonnes ethanol per year 13,100 tonnes of lignin pellets per year 11,250 tonnes of C5-molasses (70% DM)

Project Owner	Iogen Corporation
Project Name	demo
Location	Ottawa, Ontario, Canada
Technology	biochemical
Raw Material	lignocellulosics; wheat, barley and oat straw
Input	30 t/d
Product	ethanol;
Output Capacity	1 600 t/a; 2 Ml/a
Facility Type	demo
Status	operational
Start-up Year	2004
Contact Person	Mandy Chepeka info@iogen.ca
Web	www.iogen.ca

Table 39: Iogen - demo

Figure 45: Picture of Iogen Plant in Ottawa, Canada

Iogen technology makes it economically feasible to convert biomass into cellulosic ethanol using a combination of thermal, chemical and biochemical techniques. The yield of cellulosic ethanol is more than 340 litres per tonne of fibre. The lignin in the plant fibre is used to drive the process by generating steam and electricity, thus eliminating the need for fossil CO2 sources such as coal or natural gas.

Pretreatment: Iogen developed an efficient pretreatment method to increase the surface area and "accessibility" of the plant fibre to enzymes. We achieve this through our modified steam explosion process. This improves ethanol yields, increases pretreatment efficiency, and reduces overall cost.

Enzyme Production: Iogen has new, highly potent and efficient cellulase enzyme systems tailored to the specific pretreated feedstock. Iogen already has a worldwide business making enzymes for the pulp and paper, textiles and animal feed industries.

Enzymatic Hydrolysis: Iogen developed reactor systems that feature high productivity and high conversion of cellulose to glucose. This is accomplished through separate hydrolysis and fermentation using a multi-stage hydrolysis process.

Ethanol Fermentation: Iogen uses advanced microorganisms and fermentation systems that convert both C6 and C5 sugars into ethanol. The "beer" produced by fermentation is then distilled using conventional technology to produce cellulosic ethanol for fuel grade applications.

Process Integration: Large-scale process designs include energy efficient heat integration, water recycling, and co-product production that make the overall process efficient and economical. Iogen has successfully validated these improvements within its demonstration scale cellulosic ethanol facility.

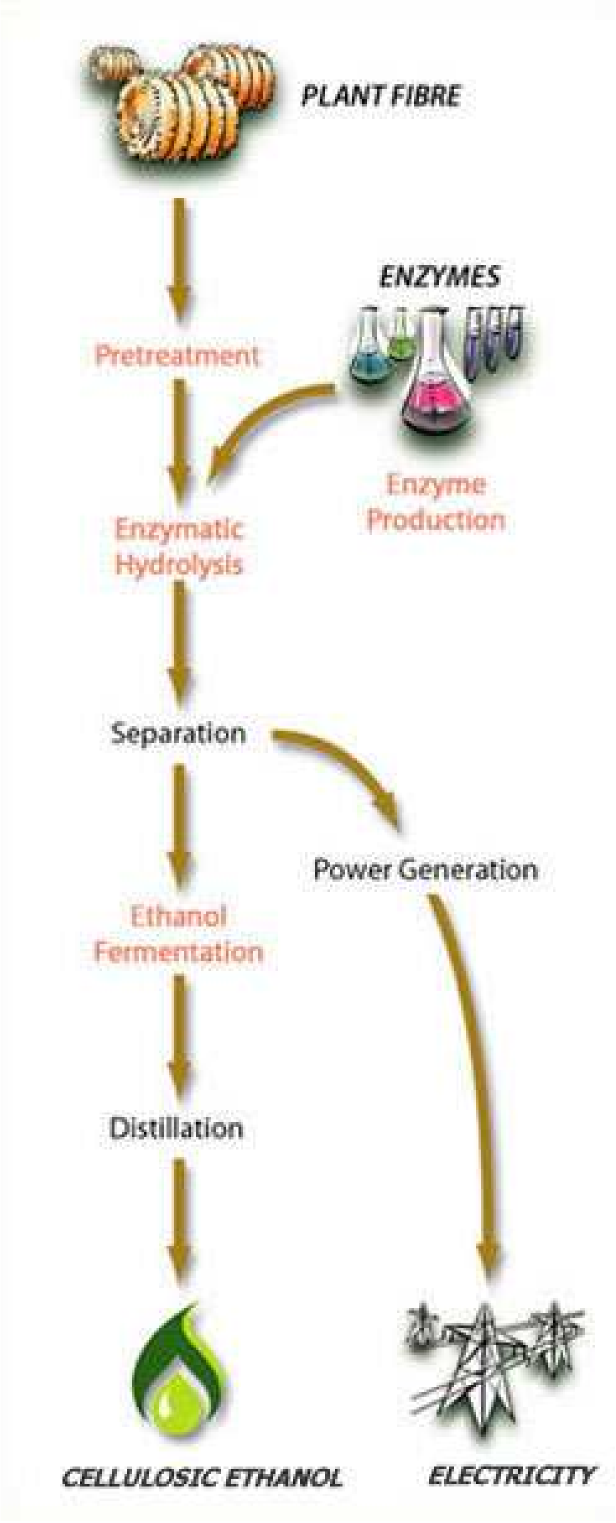


Figure 46: Process Diagram Iogen

Project Owner	Iogen Corporation
Project Name	commercial
Location	Birch Hills, Saskatchewan, Canada
Technology	biochemical
Raw Material	lignocellulosics; wheat straw, etc.
Product	ethanol;
Output Capacity	70 000 t/a; 90 Ml/a
Facility Type	commercial
Partners	Royal Dutch Shell Oil Company; investor: Goldmann Sachs
Status	planned
Start-up Year	2011
Contact Person	Mandy Chepeka info@iogen.ca
Web	www.iogen.ca

Table 40: Iogen - commercial

Project Owner	Iowa State University
Project Name	BioCentury Research Farm
Location	Boone, Iowa, United States
Technology	Three lines: biochemical, thermochemical and bioprocessing
Raw Material	lignocellulosics; grains, oilseeds, vegetable oils, glycerin
Input	5 t/d
Product	ethanol; FT-liquids; biodiesel; pyrolysis oils;
Output Capacity	200 t/a; 5 t/d
Facility Type	pilot
Investment	18 000 000 USD
Funding	2 500 000 USD
Status	operational
Start-up Year	2009
Contact Person	Lawrence Johnson; ljohnson@iastate.edu
Web	www.biocenturyresearchfarm.iastate.edu

Table 41: Iowa State University

Figure 47: Picture of Iowa State University Plant in Boone, USA

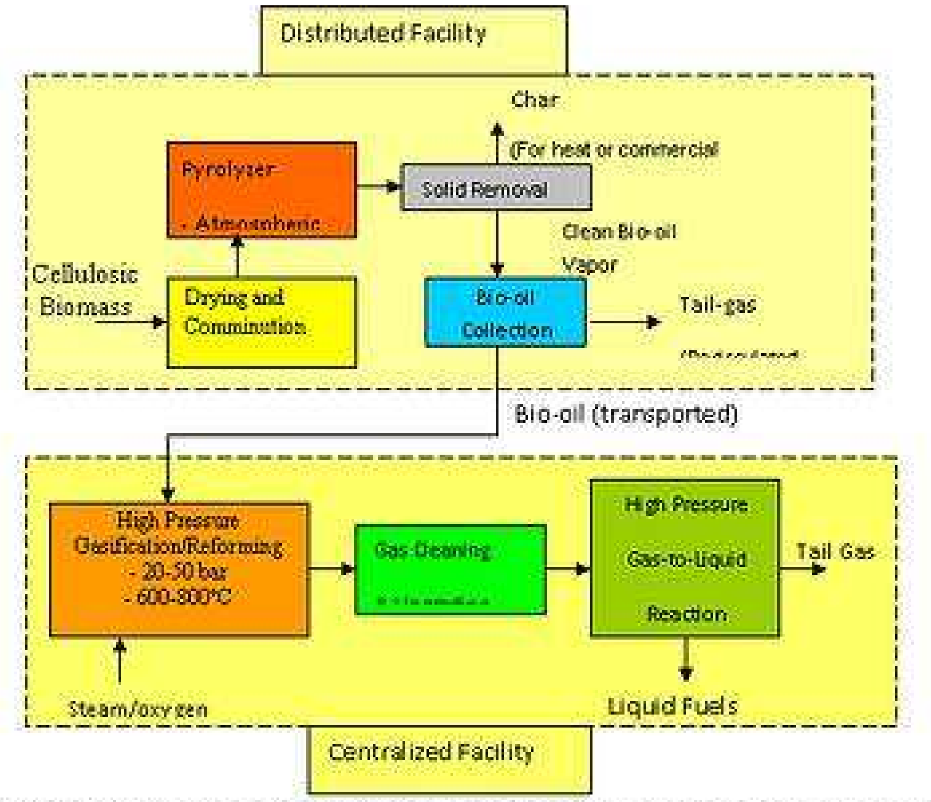


Figure 1. Simplified flow chart of a thermochemical process for converting biomass to liquid fuels via a combination of fast pyrolysis, gasification and gas-to-liquid reaction steps.

Figure 48: Process Diagram Iowa State University (thermochemical process)

The Iowa State University BioCentury Research Farm is an integrated research and demonstration facility dedicated to biomass production and processing. Activities at the Farm include cultivar development and testing; biomass harvest, storage, and transportation; biomass processing; and byproduct disposal.

The bioprocessing facility will offer three different lines for processing ground and pretreated biomass: a biochemical train, a thermochemical train, and a bioprocessing train (hybrid technologies). The products can be fuels and other biobased products. Byproduct recycling to the field shall be optimized.

Project Owner	KL Energy Corporation
Project Name	Western Biomass Energy
Location	Upton, Wyoming, United States
Technology	biochemical
Raw Material	lignocellulosics; wood waste, including cardboard and paper
Input	33 500 t/a
Product	ethanol;
Output Capacity	4 500 t/a; 1,5 mmgy
Facility Type	demo
Partners	South Dakota School of Mines and Technology
Investment	7 200 000 USD
Status	operational
Start-up Year	2007
Contact Person	Steve Corcoran hr@klenergycorp.com
Web	http://www.klenergycorp.com/

Table 42: KL Energy

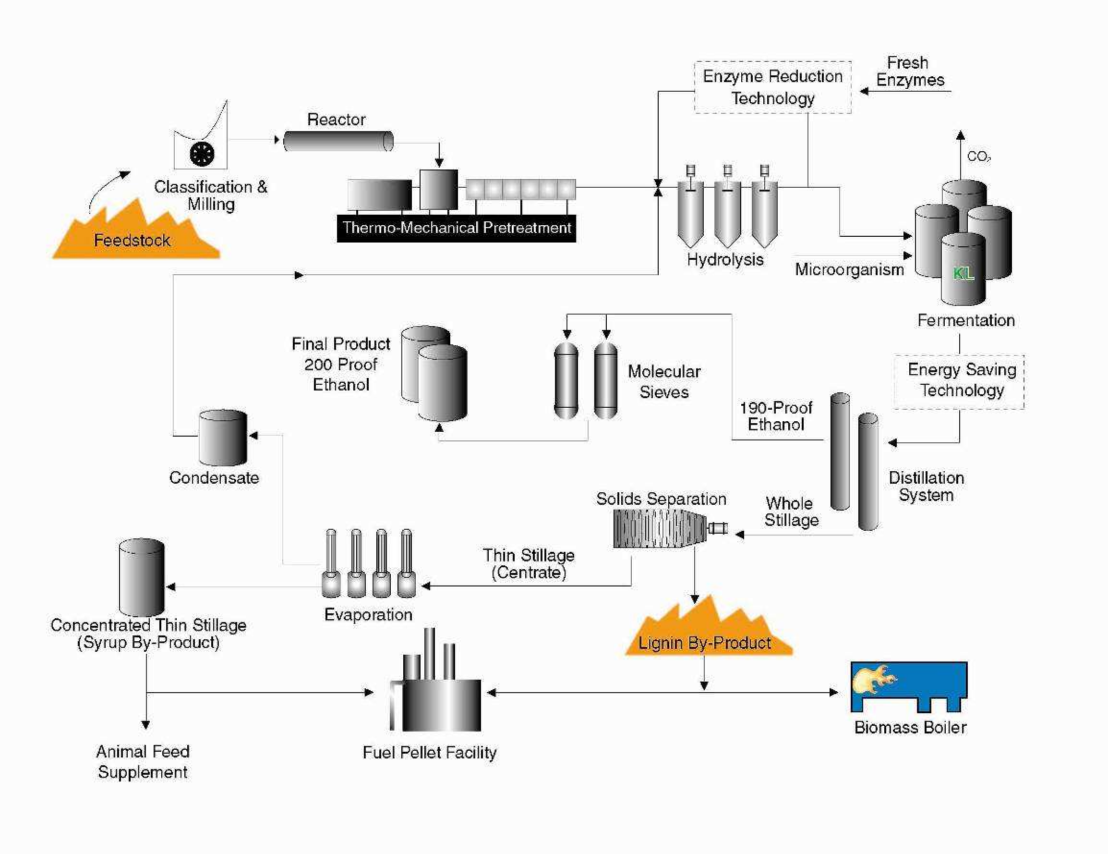


Figure 49: Process Diagram KL Energy

Our designs, processes and operations are environmentally safe and sound. CBE plants produce ethanol by processing wood waste from wood mill and lumber processing facilities. Feedstock is “standing dead” forests from insect infestation or “slash pile” accumulation from private and national forest thinning operations. The wood is converted to ethanol through a proprietary pretreatment enzyme technology developed by KL using virtually no acids.

This environmentally friendly process is the “greenest” of all of the technologies currently in development for production of CBE.

Figure 50: Picture of KL Energy Plant in Upton, USA

Project Owner	Lignol Energy Corporation
Project Name	pilot
Location	Burnaby, British Columbia, Canada
Technology	biochemical
Raw Material	lignocellulosics; hardwood & softwood residues
Input	1 t/d
Product	ethanol; lignin;
Output Capacity	80 t/a; 0,1 Ml/a
Facility Type	pilot
Investment	20 000 000 CAD
Status	operational
Start-up Year	2010
Contact Person	Paul Hughes phughes@lignol.ca
Web	www.lignol.ca

Table 43: Lignol

Lignol Innovations is commercializing its unique integrated cellulose to ethanol process technology for biorefining ethanol (fuel alcohol), pure lignin and other valuable co-products from renewable and readily available biomass. The technology is based on original ‘Alcell’ biorefining technology that was developed by General Electric and Repap Enterprises at a cost of over $100 million.

The Lignol delignification process was first developed by General Electric Corp. in the early 1970s to produce ethanol and organosolv lignin to be used as a clean burning gas turbine fuel. The process was subsequently applied to the pulp and paper industry, commercialized by Repap Enterprises between 1987 and 1997 to generate wood pulp. Repap refocused the Alcell delignification process as a pulping process in which lignin (the natural glue in wood) was removed, and following bleaching, produced a 100% cellulose/hemicellulose wood pulp.

Project Owner	Mascoma Corporation
Project Name	Demonstration Plant
Location	Rome, NY, United States
Technology	biochemical
Raw Material	lignocellulosics; Wood Chips, Switchgrass and other raw materials
Input	5 t/d
Product	ethanol; lignin;
Output Capacity	500 t/a; 0,125 mmgy
Facility Type	demo
Partners	Marathon Oil Chevron Technology Ventures General Motors State of New York
Status	operational
Start-up Year	2003
Contact Person	Nathan Margolis Mascoma Corporation 67 Etna Road Lebanon, NH. 03766
Web	www.mascoma.com

Table 44: Masocma

The unique technology developed by Mascoma Corporation uses yeast and bacteria that are engineered to produce large quantities of the enzymes necessary to break down the cellulose and ferment the resulting sugars into ethanol. Combining these two steps (enzymatic digestion and fermentation) significantly reduces costs by eliminating the need for enzyme produced in a separate refinery. This process, called Consolidated Bioprocessing or “CBP”, will ultimately enable the conversion of the solar energy contained in plants to ethanol in just a few days.

Project Owner	Mossi & Ghisolfi - Chemtex Italia
Project Name	pilot
Location	Tortona, Piedmont, Italy
Technology	biochemical
Raw Material	lignocellulosics; corn stover, straw, husk, woody biomass
Input	200 t/a
Product	ethanol;
Output Capacity	50 t/a;
Facility Type	pilot
Status	operational
Start-up Year	2009
Contact Person	Dario Giordano dario.giordano@gruppomg.com
Web	www.gruppomg.com

Table 45: Mossi & Ghisolfi - pilot

Project Owner	Mossi & Ghisolfi - Chemtex Italia
Project Name	demo
Location	Piedmont, Italy
Technology	biochemical
Raw Material	lignocellulosics;
Input	160 000 t/a
Product	ethanol;
Output Capacity	40 000 t/a;
Facility Type	demo
Status	planned
Start-up Year	2011
Contact Person	Dario Giordano dario.giordano@gruppomg.com
Web	www.gruppomg.com

Table 46: Mossi & Ghisolfi - demo

Enzymatic conversion of selected Biomasses. Pretreatment, handling of pre-treated material and hydrolysis done in equipment specifically designed.

Project Owner	M-real Hallein AG
Project Name	biorefinery
Location	Hallein, Austria
Technology	biochemical
Raw Material	lignocellulosics; sulfite spent liquor (SSL) from spruce wood pulping
Input	600 000 SSL (33% dry content) t/a
Product	ethanol;
Output Capacity	12 000 t/a; 15 Ml/a
Facility Type	demo
Status	planned
Start-up Year	2016
Contact Person	Dr. Fritz Struber fritz.struber@m-real.com
Web	www.m-real.com

Table 47: m-real Hallein

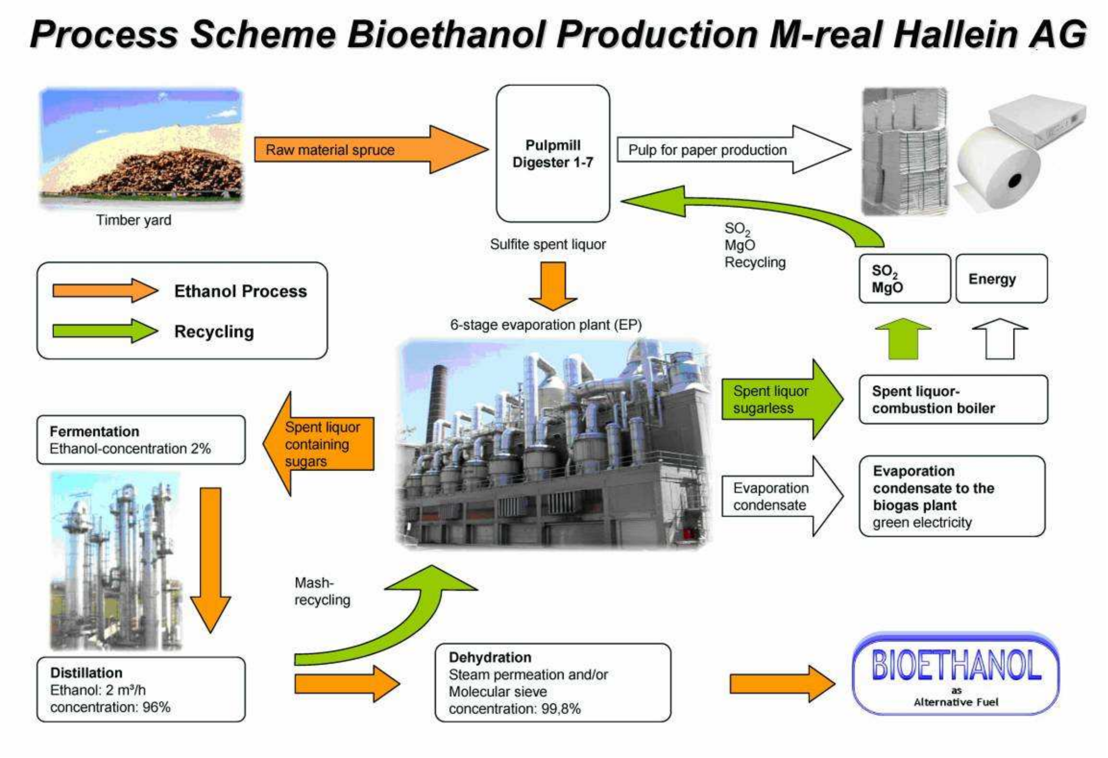


Figure 51: Process Diagram m-real Hallein

Pulp for the paper mill is produced by cooking spruce chips with acidic magnesium bisulfite cooking liquor. After concentration of the sulfite spent liquor (SSL) in the evaporation plant it is incinerated in the combustion boiler to produce steam and electricity, whereas magnesium oxide and sulfur dioxide are recycled to produce new cooking liquor.

The concept for the production of ethanol is to ferment the wood sugars from SSL and to distil off the ethanol in the distillation plant. Afterwards the 96% ethanol is dehydrated by molecular sieves to get water free absolute ethanol. The mash will be recycled as described above.

Project Owner	NSE Biofuels Oy, a Neste Oil and Stora Enso JV
Project Name	demo
Location	Varkaus, Finland
Technology	thermochemical
Raw Material	lignocellulosics; forest residues
Product	FT-liquids;
Output Capacity	656 t/a; slipstream from 12 MW thermal gasifier
Facility Type	demo
Partners	Neste Oil / Neste jacobs, Stora Enso, Foster Wheeler, VTT
Status	operational
Start-up Year	2009
Contact Person	Steven Gust steven.gust@nesteoil.com
Web	www.nesteoil.com; www.storaenso.com

Table 48: NSE Biofuels (Neste Oil and Stora Enso JV) - demo

Project Owner	NSE Biofuels Oy, a Neste Oil and Stora Enso JV
Project Name	commercial reference plant
Location	Varkaus, Finland
Technology	thermochemical
Raw Material	lignocellulosics; forest residues
Product	FT-liquids;
Output Capacity	100 000 t/a;
Facility Type	commercial
Partners	Neste Oil / Neste jacobs, Stora Enso, Foster Wheeler, VTT
Status	planned
Start-up Year	2016
Contact Person	Steven Gust steven.gust@nesteoil.com
Web	www.nesteoil.com

Table 49: NSE Biofuels (Neste Oil and Stora Enso JV) - commercial

Figure 52: Picture of NSE Biofuels Plant in Varkaus, Finland

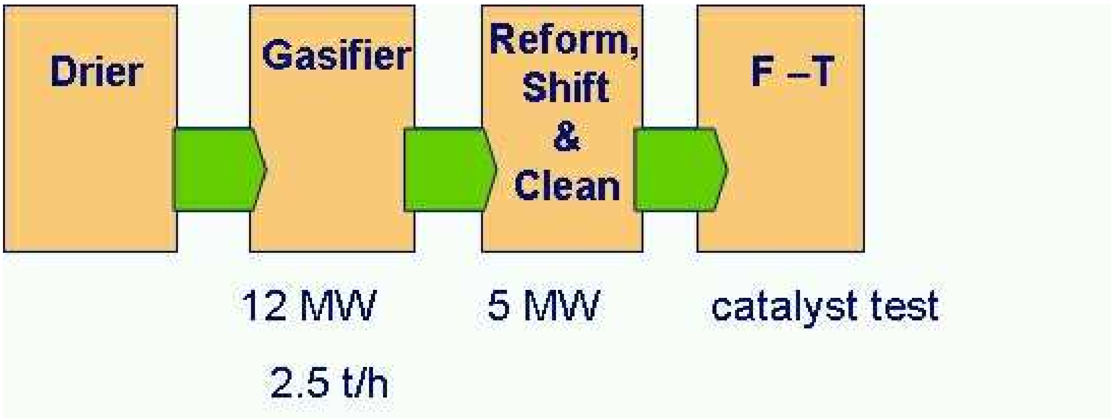


Figure 53: Process Diagram NSE Biofuels

Fischer-Tropsch production of paraffins from biomass; fluid bed gasifier with tar reformer

Project Owner	Pacific Ethanol
Project Name	West Coast Biorefinery (WCB)
Location	Boardman, Oregon, United States
Technology	biochemical
Raw Material	lignocellulosics; wheat straw, corn stover, poplar residuals
Input	5,8 t/h
Product	ethanol; biogas; lignin;
Output Capacity	8 000 t/a; 2,7 mmgy
Facility Type	demo
Partners	BioGasol, LLC; and U.S. Department of Energy's (DOE) Joint Bioenergy Institute (DOE's Lawrence Berkeley National Laboratory and Sandia National Laboratories)
Investment	48 600 000 USD
Funding	24 300 000 USD
Status	planned
Start-up Year	2010
Contact Person	Harrison Pettit hpettit@pacificethanol.net
Web	www.pacificethanol.net

Table 50: Pacific Ethanol

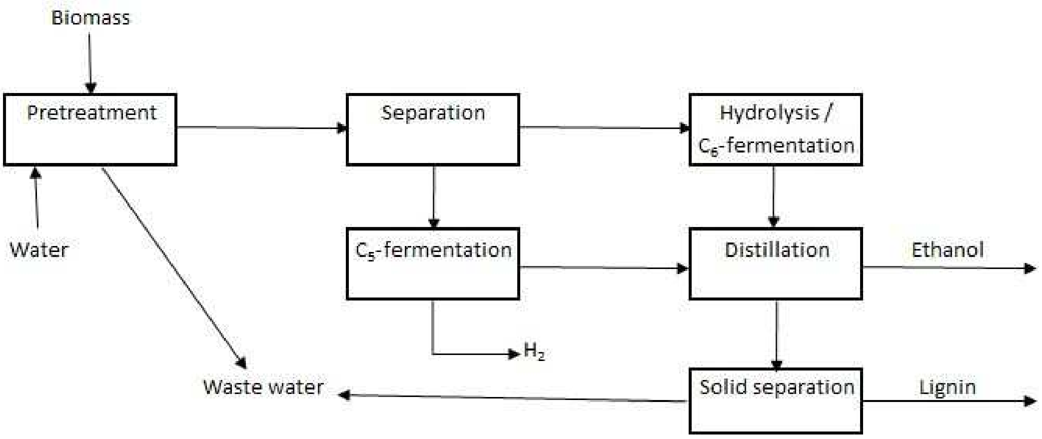


Figure 54: Process Diagram Pacific Ethanol

Project Owner	POET
Project Name	Scotland
Location	Scotland, South Dakota, United States
Technology	biochemical
Raw Material	lignocellulosics; corn fiber, corn cobs and corn stalks
Product	ethanol;
Output Capacity	60 t/a; 0,02 mmgy
Facility Type	pilot
Investment	9 000 000 USD
Status	Operational
Start-up Year	2008
Web	www.poet.com

Table 51: POET – pilot

Figure 55: Picture of POET Pilot Plant in Scotland, USA

Enzymatic Hydrolysis

Project Owner	POET
Project Name	Project Liberty
Location	Emmetsburg, Iowa, United States
Technology	biochemical
Raw Material	lignocellulosics; corn cobs, agricultural residues, biochemical processing; 100 mgy corn etoh + 25 mgy LC etoh
Product	ethanol;
Output Capacity	75 000 t/a; 25 mmgy
Facility Type	commercial
Partners	State of Iowa, Iowa Power Fund, U.S. Department of Energy
Investment	250 000 000 USD
Funding	120 000 000 USD
Status	planned
Start-up Year	2011
Web	www.projectliberty.com

Table 52: POET - commercial

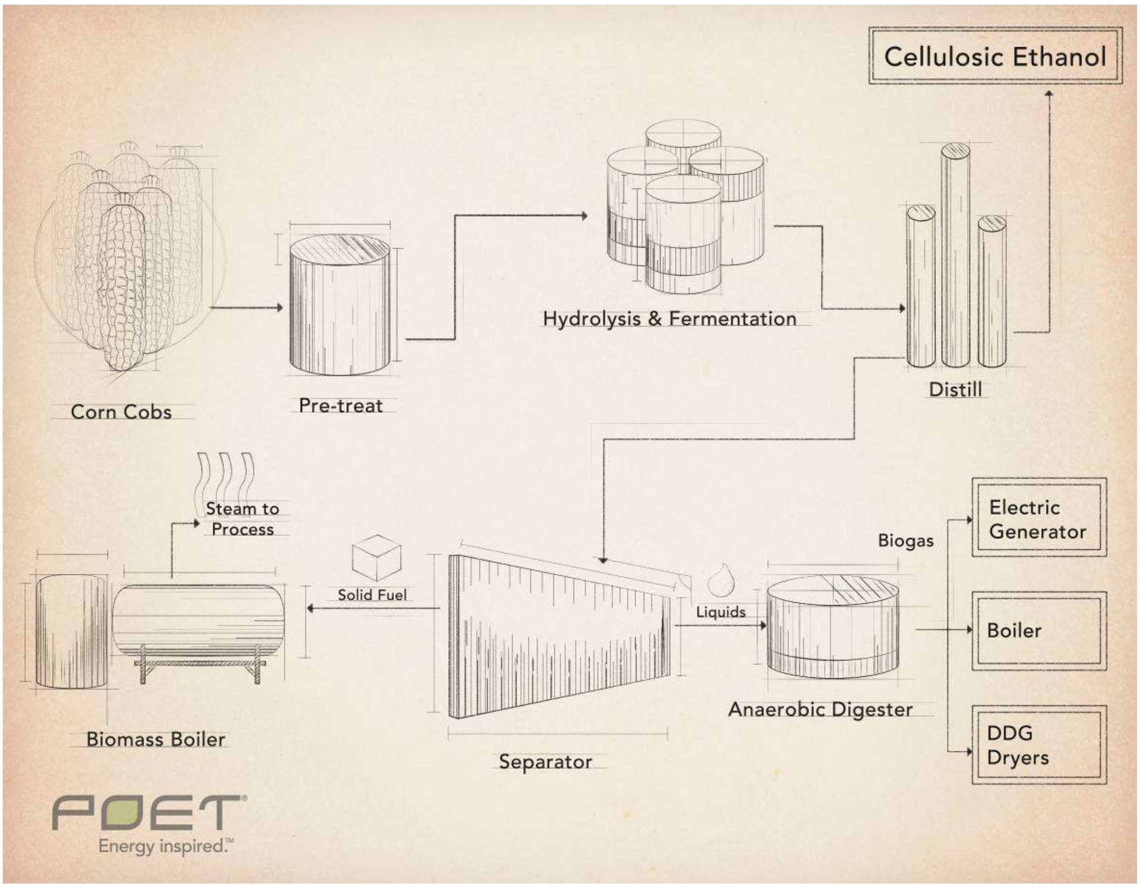


Figure 56: Process Diagram POET

Enzymatic Hydrolysis

Project Owner	PROCETHOL 2G
Project Name	Futurol Project
Location	POMACLE, France
Technology	biochemical
Raw Material	lignocellulosics;
Product	ethanol;
Output Capacity	2 700 t/a; 3,5 Ml/a
Facility Type	demo
Partners	ARD, IFP, INRA, LESAFFRE, CHAMPAGNE CEREALES, TEREOS, TOTAL, ONF, CREDIT AGRICOLE DU NORD EST, UNIGRAINS, CGB
Investment	76 000 000 EUR
Status	under construction
Start-up Year	2016
Contact Person	Benoit TREMEAU General Secretary +33 3 26 05 42 80

Table 53: PROCETHOL 2G

Queensland University of Technology
Brisbane Australia

Project Owner	Queensland University of Technology
Project Name	Smart State Sugarcane Biorefinery
Location	Mackay, Queensland, Australia
Technology	biochemical
Raw Material	lignocellulosics; Sugarcane bagasse & other lignocellulosics
Input	0,02 t/h
Product	ethanol;
Output Capacity	several t/h;
Facility Type	pilot
Partners	Mackay Sugar Limited, Sugar Research Limited, Viridian pty Ltd, Hexion
Investment	7 500 000 AUD
Status	under construction
Start-up Year	2010
Contact Person	Les Edye l.edye@qut.edu.au
Web	www.qut.edu.au

Table 54: Queensland University of Technology

Soda pulping and ionic liquid based pretreatments, lignin recovery, saccharification with commercial enzymes, conventional fermentation of hexoses

Project Owner	Range Fuels, Inc.
Project Name	K2A Optimization Plant
Location	Denver, Colorado, United States
Technology	thermochemical
Raw Material	lignocellulosics; Georgia pine and hardwoods and Colorado beetle kill pine
Product	mixed alcohols;
Output Capacity	several t/a;
Facility Type	pilot
Status	operational
Start-up Year	2008
Contact Person	Patrick Wright patrick@rangefuels.com
Web	http://www.rangefuels.com/

Table 55: Range Fuels -pilot

Figure 57: Picture of Range Fuels Plant in Denver, USA

Project Owner	Range Fuels, Inc.
Project Name	commercial
Location	Soperton, Georgia, United States
Technology	thermochemical
Raw Material	lignocellulosics; Wood and wood waste from nearby timber harvesting operations
Product	ethanol; methanol;
Output Capacity	300 000 t/a; 100 mmgy
Facility Type	commercial
Partners	Department of Energy, Merrick and Company, PRAJ Industries Ltd., Georgia Forestry Commission, The State of Georgia, Truetlen County Development Authority; BioConversion Technology; Khosla Ventures; CH2MHill
Funding	76 000 000 USD
Status	under construction
Start-up Year	2010
Contact Person	Patrick Wright patrick@rangefuels.com
Web	http://www.rangefuels.com/

Table 56: Range Fuels - commercial

Figure 58: Picture of Range Fuels Plant in Soperton, USA

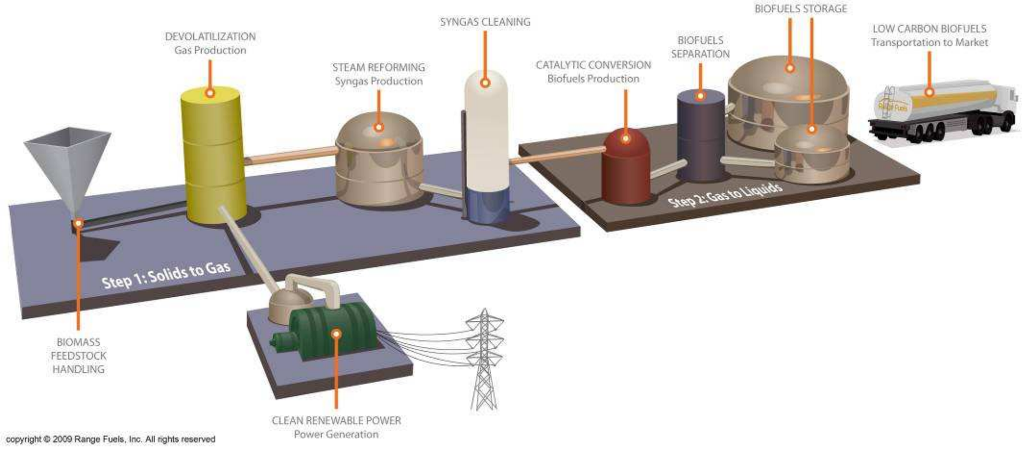


Figure 59: Process Diagram Range Fuels

Range Fuels is focused on commercially producing low-carbon biofuels, including cellulosic ethanol, and clean renewable power using renewable and sustainable supplies of biomass that cannot be used for food. The company uses an innovative, two-step thermo-chemical process to convert biomass, such as wood chips, switchgrass, corn stover, sugarcane bagasse and olive pits to clean renewable power and cellulosic biofuels.

In the first step of the process heat, pressure and steam are used to convert the non-food biomass to a synthesis gas or syngas. Excess energy in this step is recovered and used to generate clean renewable power.

In the second step the cleaned syngas is passed over a proprietary catalyst and transformed into cellulosic biofuels, which can then be separated and processed to yield a variety of low carbon biofuels, including cellulosic ethanol and methanol.

This suite of products can be used to displace gasoline or diesel transportation fuels, generate clean renewable energy or be used as low carbon chemical building blocks; all of which can reduce the country's dependence on foreign oil, create immediate jobs, and dramatically reduce GHG emissions.

Project Owner	Research Triangle Institute
Project Name	Synfuel production
Location	Research Triangle Park, North Carolina, United States
Technology	thermochemical
Raw Material	lignocellulosics;
Input	0,5 t/d
Product	FT-liquids; mixed alcohols;
Output Capacity	22 t/a; 0,01 mmgy
Facility Type	pilot
Partners	North Carolina State University, University of Utah
Investment	3 000 000 USD
Funding	2 000 000 USD
Status	planned
Start-up Year	2016
Contact Person	David Dayton ddayton@rti.org
Web	www.rti.org/process

Table 57: Research Triangle Institute

Figure 60: Picture of Research Triangle Institute Plant in Research Triangle Park, USA

Biomass-derived syngas will be generated in the University of Utah’s pilot-scale gasification system from woody biomass and a combination of wood and lignin-rich hydrolysis residues generated at NCSU. RTI will integrate their dual fluidized bed reactor system called the “therminator” into the gasification process.

The “therminator” which operates between 600–700ºC (1112–1292ºF) with a novel attrition-resistant triple function catalyst system, to simultaneously reform, crack, or remove tar, ammonia (NH3), and hydrogen sulfide (H2S) down to ppm levels. The catalyst is circulated between coupled fluidized-bed reactors to continuously regenerate the deactivated catalyst.

The gas leaving the therminator will be cooled and filtered before it enters the second (polishing) stage, consisting of a fixed-bed of a mixed-metal oxide-sorbent catalyst, to further reduce the tar, NH3, H2S, and heavy metals to less than 100 ppb each so that the syngas can be directly used in a downstream process for synthesis of liquid transportation fuels.

Once installed in the University of Utah gasification facility, therminator gas cleanup performance will be validated during for 300 hours of operation in Phase 1 of the project. The results from these Phase I trials will be used as input for gasification process models that will also be developed during Phase I. The results from the gasification trials, and the process and economic modeling will then be used to guide the Phase 2 work. In particular these results, in consultation from DOE and industry, will be used to direct the selection of the gas to liquids catalyst towards a Fischer-Tropsch catalyst system for hydrocarbon production or a molybdenum sulfide-based catalyst system for mixed alcohol synthesis.

Phase 2 will follow the successful demonstration of the gas cleanup technology to produce a clean syngas that is suitable for a fuel synthesis process. The targeted tar, sulfur, chloride, and nitrogen impurity concentrations will meet or exceed the levels required for the projected 5-year operation of a Fischer-Tropsch catalyst system for hydrocarbon production or a molybdenum sulfide-based catalyst system for mixed alcohol synthesis.

RTI will design and build a slurry bubble column reactor system to convert the clean syngas into a liquid transportation fuel. This unit operation will be installed in the University of Utah gasification facility downstream of the therminator and operated for 500 hours (at least 100 hours continuously) in an integrated biomass gasification/gas cleanup and conditioning/fuel synthesis process.

RTI will be the prime contractor and will be responsible for the overall project. The project will be managed within the Center for Energy Technology (CET) and Dr. David C. Dayton will serve as the overall project manager. The NCSU team will be led by Dr. Steven Kelley and include four faculty, two from Wood and Paper Science and two from Chemical Engineering. Dr. Kevin Whitty will lead the University of Utah team in the Institute for Clean and Secure Energy that will be responsible for the operation of the gasification facility.

Successful validation of these integrated gas cleanup and fuel synthesis operations will provide invaluable data and operating experience to reduce the risk of scale-up and commercialization of these technologies and contribute to the development of a robust biofuels industry.

Project Owner	SEKAB Industrial Development AB
Project Name	IDU
Location	Örnsköldsvik, Sweden
Technology	biochemical
Raw Material	lignocellulosics; flexible for wood chips and sugarcane bagasse
Product	ethanol;
Output Capacity	4 500 t/a; 6 Ml/a
Facility Type	demo
Status	planned
Start-up Year	2011
Contact Person	info@sekab.com +46 660 758 00
Web	www.sekab.com

Table 58: SEKAB – demo 1

Project Owner	SEKAB
Project Name	democombine
Location	Örnsköldsvik, Sweden
Technology	biochemical
Raw Material	lignocellulosics; wood chips or sugarcane bagasse, depending on location
Product	ethanol;
Output Capacity	50 000 t/a; 60 Ml/a
Facility Type	demo
Partners	SEKAB will be a technology provider and the plant would probably be owned by some other partner, maybe with minority ownership of SEKAB.
Investment	1 500 000 000 SEK
Status	planned
Start-up Year	2014
Contact Person	info@sekab.com +46 660 758 00
Web	www.sekab.com

Table 59: SEKAB – demo 2

Enzymes with pretreatment of diluted acid in one step

Project Owner	SEKAB
Project Name	commercial plants
Location	Örnsköldsvik, Sweden
Technology	biochemical
Raw Material	lignocellulosics;
Product	ethanol;
Output Capacity	120 000 t/a; 150 Ml/a
Facility Type	commercial
Partners	SEKAB will be a technology provider and the plant would probably be owned by some other partner, maybe with minority ownership of SEKAB.
Status	planned
Start-up Year	2016
Contact Person	info@sekab.com +46 660 758 00
Web	www.sekab.com

Table 60: SEKAB - commercial

reference plant on best method

SOUTHERN RESEARCH
Legendary Discoveries. Leading Innovation.

Project Owner	Southern Research Institute
Project Name	technology development laboratory
Location	Durham, North Carolina, United States
Technology	suitable for biochemical, thermochemical and hybrid technologies
Raw Material	lignocellulosics; Cellullulosics, Municipal wastes, coal/biomass, syngas
Input	20 t/d
Product	FT-liquids; mixed alcohols;
Output Capacity	3 500 t/a; 10 t/d
Facility Type	pilot
Partners	Commercial and US government clients
Investment	40 000 000 USD
Funding	14 000 000 USD
Status	operational
Start-up Year	2003
Contact Person	Stephen Piccot piccot@southernresearch.org
Web	http://www.carbontoliquids.com/

Table 61: Southern Research Institute

Figure 61: Picture of Southern Research Institute Plant (outside) in Durham, USA

Figure 62: Picture of Southern Research Institute Plant (inside) in Durham, USA

Project Owner	Technical University of Denmark (DTU)
Project Name	Maxifuel
Location	Lyngby, Copenhagen, Denmark
Technology	biochemical
Raw Material	lignocellulosics; wheat straw, corn fibre
Input	0,06 t/h
Product	ethanol; biogas; lignin;
Output Capacity	10 t/a; 40 l/d
Facility Type	pilot
Partners	BioSystems, Cambi A/S, Novozymes
Investment	20 000 000 DKK
Status	operational
Start-up Year	2006
Contact Person	Niels Langvad nl@biogasol.com
Web	www.biogasol.com

Table 62: Technical University of Denmark (DTU)

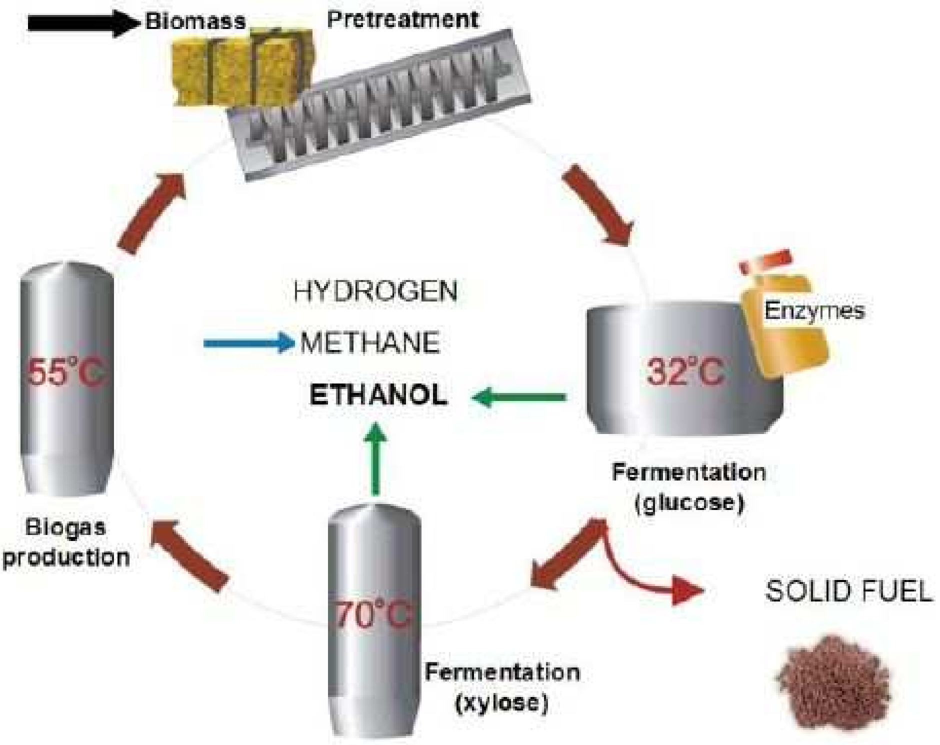


Figure 63: Process Diagram Technical University of Denmark (DTU)

Project Owner	Tembec Chemical Group
Project Name	demo
Location	Temiscaming, Quebec, Canada
Technology	thermochemical
Raw Material	lignocellulosics; spent sulphite liquor feedstock
Product	ethanol;
Output Capacity	13 000 t/a; 17 Ml/a
Facility Type	demo
Status	operational
Start-up Year	2003
Contact Person	Lyle Biglow lyle.biglow@tembec.com
Web	www.tembec.com

Table 63: Tembec Chemical Group

TERRABON

Project Owner	Terrabon
Project Name	Energy Independence I
Location	Bryan, Texas, United States
Technology	biochemical
Raw Material	lignocellulosics; municipal solid waste, sewage sludge, manure, agricultural residues and non-edible energy crops
Input	5 t/d
Product	ethanol; mixed alcohols; various chemicals;
Output Capacity	254 t/a; 0,09 mmgy
Facility Type	demo
Partners	Texas A&M University
Investment	3 000 000 USD
Status	operational
Start-up Year	2009
Contact Person	Malcolm McNeill mmcneill@terrabon.com
Web	http://www.terrabon.com/

Table 64: Terrabon

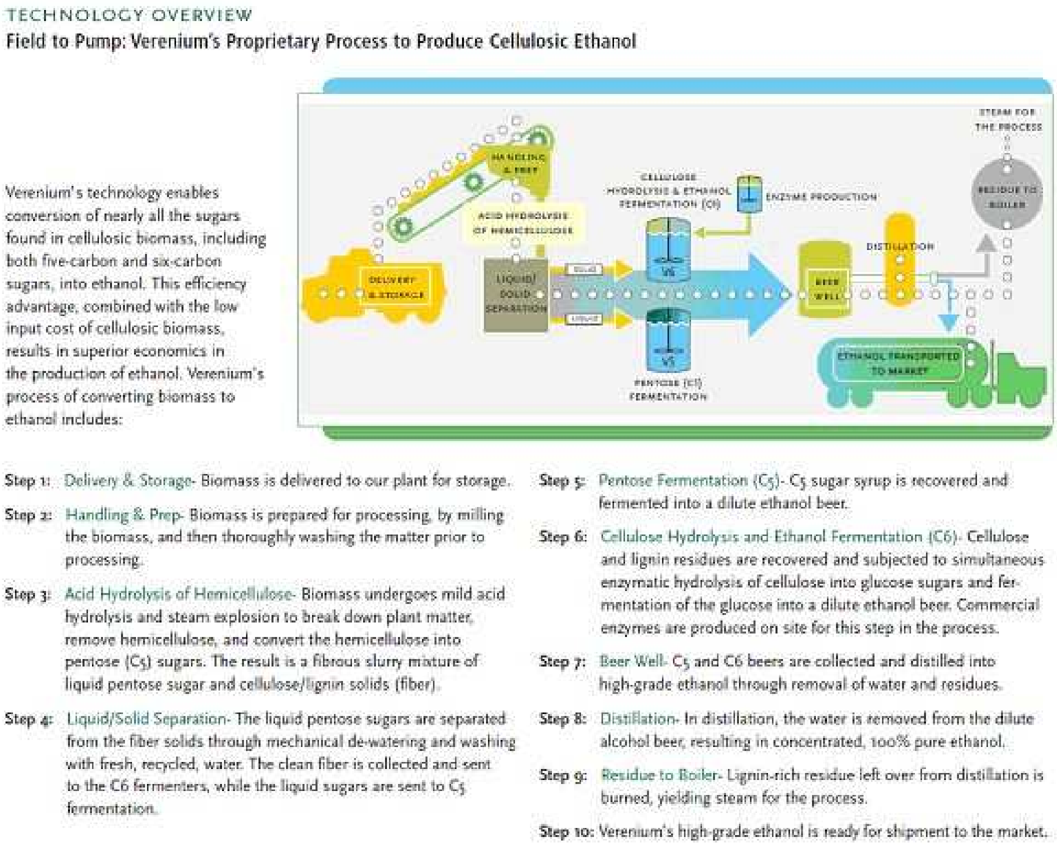
The biomass is pretreated with lime and oxygen to enhance digestibility before being fed to a mixed culture of acid-forming microorganisms derived from a saline environment. The acids are neutralized with either calcium carbonate or ammonium bicarbonate, thus forming carboxylate salts. The carboxylate salts are concentrated using vapor-compression evaporation before being chemically converted to an array of products.

The biomass is placed in a large, oxygen-free tank, similar to the rumen of cattle, where naturally occurring organisms convert the biomass to vinegar. No sterility is required and no enzymes must be added. A perfect example of a "biorefinery," a wide variety of chemicals and fuel products may be produced using the MixAlco technology, such as ketones, carboxylic acids, esters, ethers, aldehydes, primary and secondary alcohols, aromatics, cyclic, olefins and fuels such as gasoline, jet fuel and diesel.

The vinegar produced can be sold directly into the chemical market to make plastics or it can be converted into other chemicals such as acetone. By adding a small amount of hydrogen, alcohol fuels can be made that have higher energy content than conventional ethanol. The alcohols can be converted to gasoline that is virtually identical to conventional gasoline made from crude oil.

Project Owner	Verenium
Project Name	Jennings Pilot Plant Facility
Location	Jennings, LA, United States
Technology	biochemical
Raw Material	lignocellulosics; Sugar cane bagasse, energy cane
Product	cellulosic ethanol;
Output Capacity	150 t/a; 0,05 mmgy
Facility Type	pilot
Status	operational
Start-up Year	2007
Contact Person	Verenium Corporate Communications Corpcomm@verenium.com
Web	www.verenium.com

Table 65: Verenium - pilot



TECHNOLOGY OVERVIEW

Field to Pump: Verenium's Proprietary Process to Produce Cellulosic Ethanol

Verenium's technology enables conversion of nearly all the sugars found in cellulosic biomass, including both five-carbon and six-carbon sugars, into ethanol. This efficiency advantage, combined with the low input cost of cellulosic biomass, results in superior economics in the production of ethanol. Verenium's process of converting biomass to ethanol includes:

Step 1: Delivery & Storage- Biomass is delivered to our plant for storage.

Step 2: Handling & Prep- Biomass is prepared for processing, by milling the biomass, and then thoroughly washing the matter prior to processing.

Step 3: Acid Hydrolysis of Hemicellulose- Biomass undergoes mild acid hydrolysis and steam explosion to break down plant matter, remove hemicellulose, and convert the hemicellulose into pentose (C5) sugars. The result is a fibrous slurry mixture of liquid pentose sugar and cellulose/lignin solids (fiber).

Step 4: Liquid/Solid Separation- The liquid pentose sugars are separated from the fiber solids through mechanical de-watering and washing with fresh, recycled, water. The clean fiber is collected and sent to the C6 fermenters, while the liquid sugars are sent to C5 fermentation.

Step 5: Pentose Fermentation (C5)- C5 sugar syrup is recovered and fermented into a dilute ethanol beer.

Step 6: Cellulose Hydrolysis and Ethanol Fermentation (C6)- Cellulose and lignin residues are recovered and subjected to simultaneous enzymatic hydrolysis of cellulose into glucose sugars and fermentation of the glucose into a dilute ethanol beer. Commercial enzymes are produced on site for this step in the process.

Step 7: Beer Well- C5 and C6 beers are collected and distilled into high-grade ethanol through removal of water and residues.

Step 8: Distillation- In distillation, the water is removed from the dilute alcohol beer, resulting in concentrated, 100% pure ethanol.

Step 9: Residue to Boiler- Lignin-rich residue left over from distillation is burned, yielding steam for the process.

Step 10: Verenium's high-grade ethanol is ready for shipment to the market.

Figure 64: Process Diagram Verenium

Project Owner	Verenium
Project Name	Jennings Demonstration Facility
Location	Jennings, LA, United States
Technology	biochemical
Raw Material	lignocellulosics; Sugarcane bagasse, dedicated energy crops, wood products and switchgrass
Product	cellulosic ethanol;
Output Capacity	4 200 t/a; 1,4 mmgy
Facility Type	demo
Investment	79 000 000 USD
Status	operational
Start-up Year	2009
Contact Person	Verenium Corporate Communications Corpcomm@verenium.com
Web	www.verenium.com

Table 66: Verenium - demo

Verenium's technology enables conversion of nearly all the sugars found in cellulosic biomass, including both five-carbon and six-carbon sugars, into ethanol. This efficiency advantage, combined with the low input cost of cellulosic biomass, results in superior economics in the production of ethanol.

Verenium's process of converting biomass to ethanol includes:

Step 1, Biomass Handling and Preparation: Biomass is delivered to the facility, and is prepared for processing by milling and washing.

Step 2, Pentose Syrup Production and Cellulose Fiber Preparation: The biomass is hydrolyzed using steam and mildly acidic conditions. This portion of the process creates five carbon sugar (pentose) syrup from the hemicellulose found in the biomass, and prepares the remaining cellulose fiber for further enzymatic conversion into glucose. The cellulose fiber and pentose syrup slurry is then sent to a liquid/solid separation step where the pentose syrup is separated from the fiber solids.

Step 3, Fermentation: In one tank, the pentose syrup is fermented directly through the action of a proprietary industrial fermentation microorganism to make a pentose (C5) beer. In another tank, the cellulose fibers are mixed with specialized enzymes and additional proprietary industrial fermentation microorganism. The enzymes and the microorganism then work in concert with each other to simultaneously breakdown the cellulose into glucose, and ferment the glucose into a hexose (C6) beer.

Step 4, Distillation: The C5 and C6 beers are combined and sent to distillation for recovery of the ethanol from the beer. Distillation residues are collected, dewatered, and sent to the biomass boiler as fuel to create steam and power used for the entire facility.

Project Owner	Vienna University of Technology
Project Name	FT pilot
Location	Güssing, Austria
Technology	thermochemical
Raw Material	lignocellulosics; syngas from gasifier
Input	7 Nm3/h
Product	FT-liquids;
Output Capacity	several t/a; 0,5 kg/h
Facility Type	pilot
Partners	Repotec, Biomassekraftwerk Güssing
Status	operational
Start-up Year	2005
Contact Person	Reinhard Rauch reinhard.rauch@tuwien.ac.at
Web	http://www.ficfb.at

Table 67: Vienna University of Technology

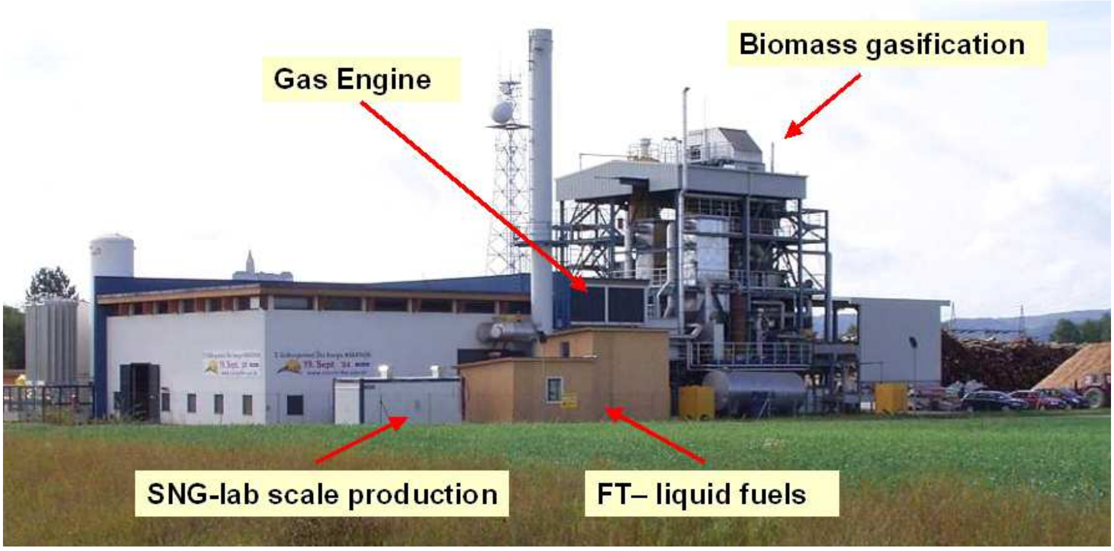


Figure 65: Picture of Vienna University of Technology Plant in Güssing, Austria

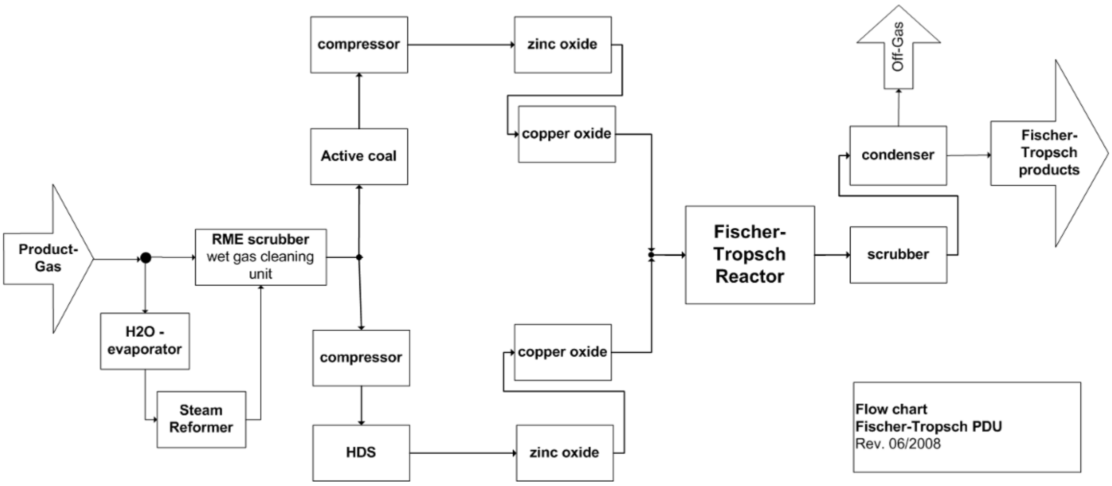


Figure 66: Process Diagram Vienna University of Technology

Aim of the work is to convert the product gas (PG) of the Biomass gasification plant with a Fischer-Tropsch (FT) process to liquid fuels, especially to diesel. A FT-PDU (process development unit) is operated, which converts about 7 Nm3/h PG at 25bar in a Slurry reactor to FT-products.

The gas cleaning of the raw PG consists of several steps. First a RME-scrubber is used to dry the gas. After the compression step, chlorine is separated with a sodium aluminate fixed bed. Organic sulphur components are hydrated with a HDS-catalyst and the H2S is chemically separated with Zinc oxide. Both is realised in fixed bed reactors. In alternative to the HDS also activated carbon filter can be used for gas cleaning. As catalyst in the slurry reactor, iron and cobalt based catalyst are used. The results from a Cobalt catalysts give mainly an n-alkan distribution from C1 to compounds higher than C60 n-alkanes. The iron based catalysts give more alkenes and oxygenated compounds. The analyses of the diesel fraction from the distillation of the FT-raw product show that the obtained diesel from the Cobalt catalyst has cetan-numbers of about 80 and is free of sulphur and aromatics.

Project Owner	Weyland AS
Project Name	Weyland
Location	Blomsterdalen, Norway
Technology	biochemical
Raw Material	lignocellulosics; concentrated acid; coniferous wood sawdust
Input	75 kg/h
Product	ethanol;
Output Capacity	158 t/a;
Facility Type	pilot
Partners	The Norwegian Research Council, Fana Stein & Gjenvinning AS, Sarsia Seed, Statoil
Funding	4 000 000 EUR
Status	under construction
Start-up Year	2010
Contact Person	Petter Bartz Johannessen pbj@weyland.no
Web	www.weyland.no

Table 68: Weyland

Research engineers at Bergen University College has developed new technology for efficient conversion of lignocellulosic feedstock into ethanol. The technology is based on the so called Strong Acid Process, where the disadvantage hitherto has been the high acid consumption. This disadvantage has been eliminated through the new technology and ethanol production by this method is competitive and virtually any type of cellulose containing feedstock can be processed. Coniferous wood, rice straw, corn cobs and bagasse have been successfully tested. Weyland AS was established 15th June, 2001 in order to further develop and commercialize the technology. The business idea is to offer complete plant or licenses for building of plants for the world market. A pilot plant using industrial components will be built for testing and demonstration purposes.

Project Owner	ZeaChem
Project Name	pilot
Location	Boardman, Oregon, United States
Technology	hybrid
Raw Material	lignocellulosics; poplar trees, sugar, wood, chips
Product	ethanol; mixed alcohols; various chemicals;
Output Capacity	4 500 t/a; 1,5 mmgy
Facility Type	pilot
Partners	GreenWood Resources
Status	under construction
Start-up Year	2010
Contact Person	Carrie Atiyeh catiyeh@zeachem.com
Web	www.zeachem.com

Table 69: ZeaChem

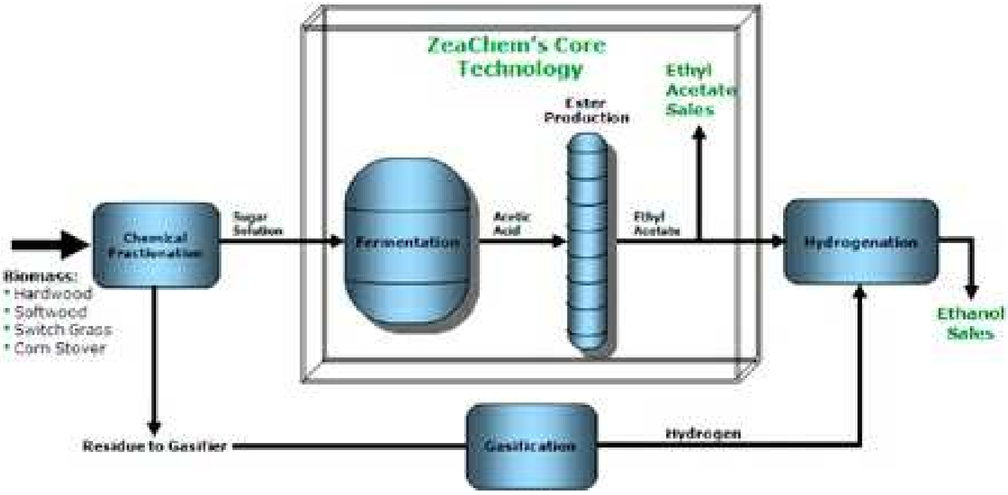


Figure 67: Process Diagram ZeaChem

ZeaChem utilizes a hybrid process of biochemical and thermochemical processing that preserves the best of both approaches from yield and efficiency perspectives. ZeaChem's process, although tightly protected by Intellectual Property (IP), utilizes no new organisms or process.

After fractionating the biomass, the sugar stream (both xylose [C5] and glucose [C6]) are sent to fermentation where an acetogenic process is utilized to ferment the sugars to acetic acid without CO2 as a by-product. In comparison, traditional yeast fermentation creates one molecule of CO2 for every molecule of ethanol. Thus the carbon efficiency of the ZeaChem fermentation process is nearly 100% vs. 67% for yeast. The acetic acid is converted to an ester which can then be reacted with hydrogen to make ethanol.

To get the hydrogen necessary to convert the ester to ethanol, ZeaChem takes the lignin residue from the fractionation process and gasifies it to create a hydrogen-rich syngas stream. The hydrogen is separated from the syngas and used for ester hydrogenation and the remainder of the syngas is burned to create steam and power for the process.

The net effect of combining the two processes is that about 2/3 of the energy in the ethanol comes from the sugar stream and 1/3 comes from the lignin steam in the form of hydrogen. At an expected Nth plant yield of 135 gallons per bone dry ton (gal/BDT), the process is nearly balanced with the necessary steam and power generated from the non-hydrogen portion of the syngas stream.

5 Data Summary

Overall, data from 66 projects for the production of biofuels from lignocellulosic raw materials has been gathered. More projects were identified, but not for all projects identified data was provided by the pursuing companies. Thus, those projects for which no data was provided are not included in the following graphs and tables. Another 15 projects using other innovative technologies but not from lignocellulosic raw materials have been identified but are not included in the following considerations.

5.1 Technology applied

Of the 66 projects for which data was provided, 37 were classified to use a biochemical pathway, 23 use a thermochemical pathway, and 6 use some kind of combination of these (hybrid technology). Output capacities are in the range of <50 t/a through <500.000 t/a, as can be seen in the following graph.

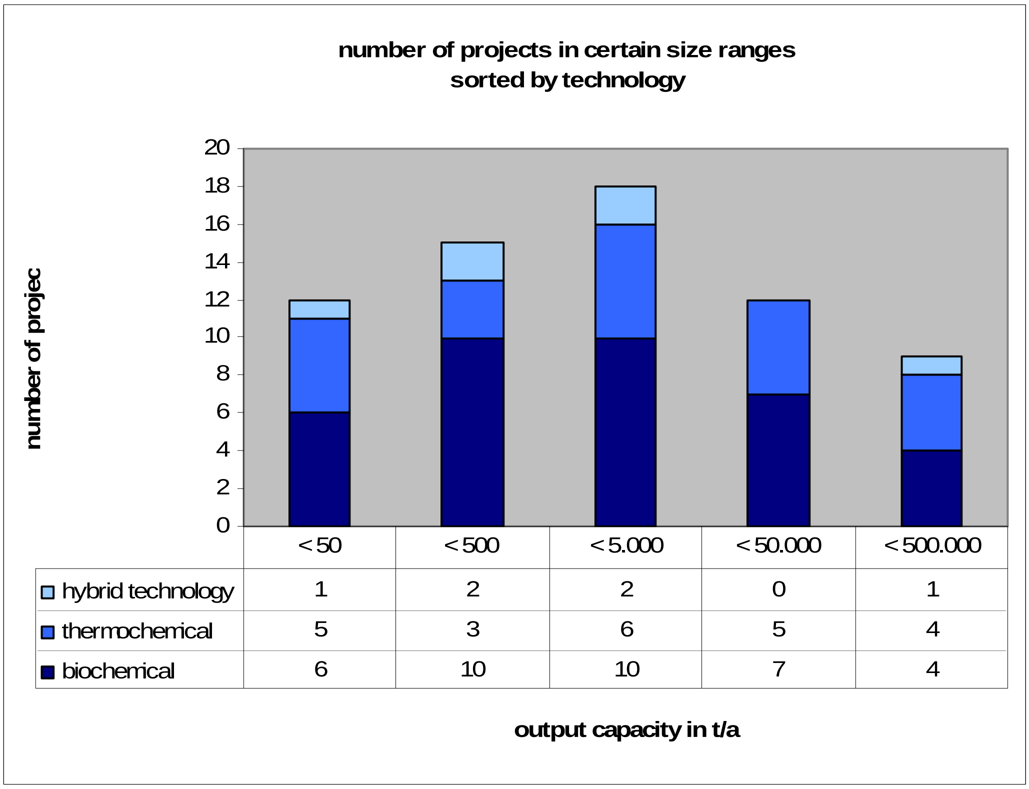


Figure 68: Diagram of Projects sorted by Technology

5.1.1 Biochemical pathway

Throughout the 37 projects for which data is available, a variety of lignocellulosic feedstocks is being used, including agricultural residues, wood and wood residues from forestry and forest products, dedicated energy crops, and municipal solid waste. The most frequently cited feedstocks are corn cobs, corn stover, wheat straw and wood waste. Woodchips, sugarcane bagasse and sulfite spent liquor are also applied in some cases. Individual companies pursue specific opportunities.

Most technologies include steam explosion or acids for pretreatment, followed by enzymatic hydrolysis and fermentation. Enzymes are often provided by Novozymes, but some companies like Iogen and Mascoma produce their own enzymes. Mascoma combines enzyme production, hydrolysis and fermentation in a single step (consolidated bioprocessing). Terrabon uses a completely different approach: a pretreatment with lime and oxygen is followed by microbial conversion into vinegar; a wide range of products can be derived from this.

Integrated production of power and steam is applied in various cases: Some companies separate lignin at the beginning of the process and use it for power and steam generation (Inbicon, Iogen, Lignol Energy Corporation). Verenium uses the distillation residues for steam generation, and KL Energy separates lignin after ethanol distillation and sells lignin pellets as a by-product. POET integrates ethanol production from corn cobs into an existing grain ethanol plant and uses part of the collected biomass for power production. Abengoa also couples ethanol production with a biomass CHP. The concept of m-real Hallein foresees integration of ethanol production into an existing pulp mill with production of ethanol and energy and recycling of chemicals from the sulfite spent liquor (SSL); and Borregaard Industries are successfully producing ethanol from SSL since 1930.

The technology briefs of the various companies are summarised in the table below.

Company	**Technology Brief**
Abengoa Bioenergy Biomass of Kansas	steam explosion, biomass fractionation, C5/C6 fermentation, biomass gasification CHP
AE Biofuels	ambient temperature cellulose starch hydrolysis
BBI BioVentures	-
BioGasol	products: ethanol and methane
Borregaard Industries	pulp for the paper mill is produced by cooking spruce chips with acidic calcium bisulfite cooking liquor; hemicellulose is hydrolyzed to various sugars during the cooking process; after concentration of the SSL, the sugars are fermented and ethanol is distilled off in several steps; part of the 96% ethanol is dehydrated to get absolute ethanol
DDCE	enzymatic hydrolysis
Frontier Renewable Resources	uses Mascoma technology, see below
Inbicon (DONG Energy)	coupled to multifuel biomass power plant, lignin is separated for fuelling power plant, hydrothermal pre-treatment, high gravity hydrolysis, yeast fermentation
Iogen Corporation	lignin separation for steam and electricity generation, modified steam explosion, own enzyme production, separate hydrolysis and fermentation, process integration: heat integration, water recycling, co-product production
Iowa State University	The Iowa State University BioCentury Research Farm is an integrated research and demonstration facility dedicated to biomass production and processing.. The bioprocessing facility will offer three different lines for processing ground and pretreated biomass: a biochemical train, a thermochemical train, and a bioprocessing train (hybrid technologies).
KL Energy Corporation	enzymatic fermentation, lignin separation after ethanol distillation, lignin pellets as co-product
Lignol Energy Corporation	pulping process, lignin removal, wood pulp conversion to ethanol

Company	Technology Brief
Mascoma	yeast and bacteria engineered to produce large quantities of the enzymes necessary to break down the cellulose and ferment the resulting sugars into ethanol (consolidated bioprocessing)
Mossi & Ghisolfi	enzymatic conversion of selected biomasses; pretreatment, handling of pre-treated material and hydrolysis done in equipment specifically designed
M-real Hallein AG	integrated into pulp mill: fermentation of sugars from SSL, distillation, sugarfree SSL back to combustion boiler for energy and chemicals recycling
Pacific Ethanol	separate C5 and C6 fermentation
POET	integrated into conventional ethanol facility, utilizes corn cobs for production of cellulosic ethanol and own power requirements
PROCETHOL 2G	-
SEKAB Industrial Development AB	enzymes with pretreatment of diluted acid in one step
Southern Research Institute	Carbon-to-Liquids (C2L) Development Center incorporates a broad range of infrastructure and support facilities to assist clients in building, validating and optimizing pilot-scale processes with capacities of up to 20 tons/day of feedstock material.
Terrabon	biomass pretreatment with lime and oxygen, microbial conversion into vinegar, wide range of products can be derived
Verenium	separate C5 and C6 fermentation, distillation residues sent to boiler for steam generation
Weyland	based on strong acid process, but with lower acid consumption; virtually any type of cellulose containing feedstock can be processed; coniferous wood, rice straw, corn cobs and bagasse have been successfully tested

Table 70: Technology Briefs of Companies applying Biochemical Technologies

5.1.2 Thermochemical pathway

While nearly all projects using the biochemical pathway aim for ethanol as a final product, the type of biofuel produced varies between the 23 projects using the thermochemical pathway. Products range from FT-liquids, SNG, and DME to ethanol, methanol and mixed alcohols. The type of biofuel produced does not depend on the feedstock in use but on the demand for replacement of either gasoline or diesel fuel in the respective region.

Feedstocks used include wood chips and pellets from forestry and forestry residues, municipal solid waste (MSW), and sulfite spent liquor (SSL).

Gasification technologies applied quite equally split between fluidised bed gasifiers and entrained flow gasifiers, and within each of these types a variety of different concepts is being pursued. For example, CHOREN applies a low temperature entrained flow gasifier in front of a high temperature entrained flow gasifier, while Forschungszentrum Karlsruhe uses fast pyrolysis in front of a high temperature entrained flow gasifier, and Chemrec uses the spent sulfite liquor from the pulping process in its entrained flow gasifier. Generally, fluidised bed gasifiers build smaller than entrained flow gasifiers.

The technology briefs of the various companies are summarised in the table below.

Company	**Technology Brief**
Chemrec	The recovery boilers in this dissolving cellulose mill are replaced by a gasification based fuel generating and pulp mill cooking chemicals recovery system.
CHOREN	low-temperature gasification followed by high-temperature gasification with air and/or oxygen; char, ground to a combustible dust, is blown into the hot gasification agent which leads to raw synthetic gas; purification and preparation of raw gas, followed by conversion into a liquid fuel using the Fischer-Tropsch (FT) technology; wax generated in the FT synthesis is further processed by hydrocracking; diesel and light hydrocarbon (naphtha) products are separated by distillation
CTU – Conzepte Technik Umwelt AG	fast internal circulating fluidised bed gasification + catalytic conversion – SNG
Cutec	fluidised bed – FT-liquids
ECN	production of Substitute Natural Gas from woody biomass using MILENA gasification, OLGA tar removal, gas cleaning, gas upgrading and methanation – SNG
Enerkem	fluidised bed + catalytic conversion – ethanol
Flambeau River Biofuels LLC	gasification followed by FT catalytic conversion into renewable liquid fuels and waxes
FZK Forschungszentrum Karlsruhe	Fast pyrolysis in decentral twin-screw reactors producing a liquid slurry (biosyncrude); gasification of slurry in a central high-pressure entrained flow gasifier; gas conditioning and synthesis to methanol or DME; further transformation into other biofuels or biochemicals possible
GTI Gas Technology Institute	Carbona biomass gasification; Velocys Fischer Tropsch technology based on parallel arrays of microchannels making a process-intensive reactor licensed from Battelle
Iowa State University	The Iowa State University BioCentury Research Farm is an integrated research and demonstration facility dedicated to biomass production and processing. The bioprocessing facility will offer three different lines for processing ground and pretreated biomass: a biochemical train, a thermochemical train, and a bioprocessing train (hybrid technologies).
NSE Biofuels Oy	Fischer-Tropsch production of paraffins from biomass; fluid bed gasifier with tar reformer
Range Fuels	using heat, pressure, and steam the feedstock is converted into synthesis gas (syngas), which is cleaned before entering the second step; excess energy in this step is recovered and used to generate clean renewable power; syngas is passed over a catalyst and transformed into mixed alcohols.
Research Triangle Institute	dual fluidized bed reactor system; gas cooling and filtering; polishing catalyst; synthesis of liquid transportation fuels (FT-liquids)

Company	Technology Brief
Southern Research Institute	C2L site for various pilot projects –- thermochemical conversion, catalytic liquids synthesis, hot and cold syngas cleaning – product: FT-liquids, mixed alcohols
Tembec Chemical Group	Black liquor gasification – product: ethanol
VUT Vienna University of Technology	fast internal circulating fluidised bed + catalytic conversion – product: FT-liquids

Table 71: Technology Briefs of Companies applying Thermochemical Technologies

5.1.3 Hybrid technologies

6 projects are classified as applying combinations of biochemical and thermochemical pathways. 3 of these projects are being pursued by Coskata (operational pilot facility, operational demoplant, and commercial facility planned). Coskata´s technology combines gasification of the biomass (wood chips) with a microbial conversion of the resulting syngas into ethanol and a combination of distillation and membrane pervaporation for ethanol recovery.

ZeaChem is currently building a pilot facility which applies chemical fractionation of the sugars from the lignin as a first step. The sugars are being fermented into acetic acid and then converted into ester, while the lignin is being gasified into a hydrogen-rich gas. The hydrogen from this gas is used to hydrogenate ethanol from the ester, while the remainder of the syngas is burned for steam and power generation.

Iowa State University operates the BioCentury Research Farm with three different processing lines (biochemical, thermochemical and hybrid), but provides no details on the processes applied. Finally, the Southern Research Institute offers infrastructure for clients to validate and optimise their processes applying biochemical, thermochemical or hybrid pathways; again, no technology details are provided due to confidentiality agreements.

Company	Technology Brief
Coskata	biomass gasification, syngas into bioreactor, microbial conversion into ethanol, distillation and pervaporation separation, no enzymes required, energy requirements reduced to 50%
Iowa State University	The Iowa State University BioCentury Research Farm is an integrated research and demonstration facility dedicated to biomass production and processing. The bioprocessing facility will offer three different lines for processing ground and pretreated biomass: a biochemical train, a thermochemical train, and a bioprocessing train (hybrid technologies).
Southern Research Institute	Carbon-to-Liquids (C2L) Development Center incorporates a broad range of infrastructure and support facilities to assist clients in building, validating and optimizing pilot-scale processes with capacities of up to 20 tons/day of feedstock material.

Company	**Technology Brief**
ZeaChem	chemical fractionation and separate treatment of the resulting two streams; (a) C5 and C6 fermentation to acetic acid and conversion of acetic acid to ester, (b) lignin gasification into hydrogen-rich syngas; then both streams are brought together again and the hydrogen is used for hydrogenation of ester to ethanol; the remainder of syngas is burned for steam and power

Table 72: Technology Briefs of Companies applying Hybrid Technologies

5.2 Project Status

By end of June 2010 the status of 33 projects is operational, 13 projects are under construction or under commissioning, and 20 projects are planned.

Operational facilities are comparatively small, the largest being those of Borregaard Industries and Tembec Chemical Group, both producing app. 15000 t/a of ethanol from spent sulfite liquor.

The owners of the operational facilities are:

Company	**Country**	**Technology**
Abengoa Bioenergy New Technologies	United States	biochemical
AE Biofuels	United States	biochemical
Borregaard Industries LTD	Norway	biochemical
Coskata	United States	hybrid
CTU – Conzepte Technik Umwelt AG	Austria	thermochemical
Coskata	United States	hybrid
Cutec	Germany	thermochemical
DDCE DuPont Danisco Cellulosic Ethanol	United States	biochemical
Enerkem	Canada	thermochemical
EtanolPiloten I Sverige AB	Sweden	biochemical
Inbicon (DONG Energy)	Denmark	biochemical
Inbicon (DONG Energy)	Denmark	biochemical
Inbicon (DONG Energy)	Denmark	biochemical
Iogen Corporation	Canada	biochemical
Iowa State University	United States	hybrid
Iowa State University	United States	biochemical
Iowa State University	United States	thermochemical
KL Energy Corporation	United States	biochemical
Lignol Energy Corporation	Canada	biochemical
Mascoma Corporation	United States	biochemical
Mossi & Ghisolfi – Chemtex Italia	Italy	biochemical
NSE Biofuels Oy, a Neste Oil and Stora Enso JV	Finland	thermochemical

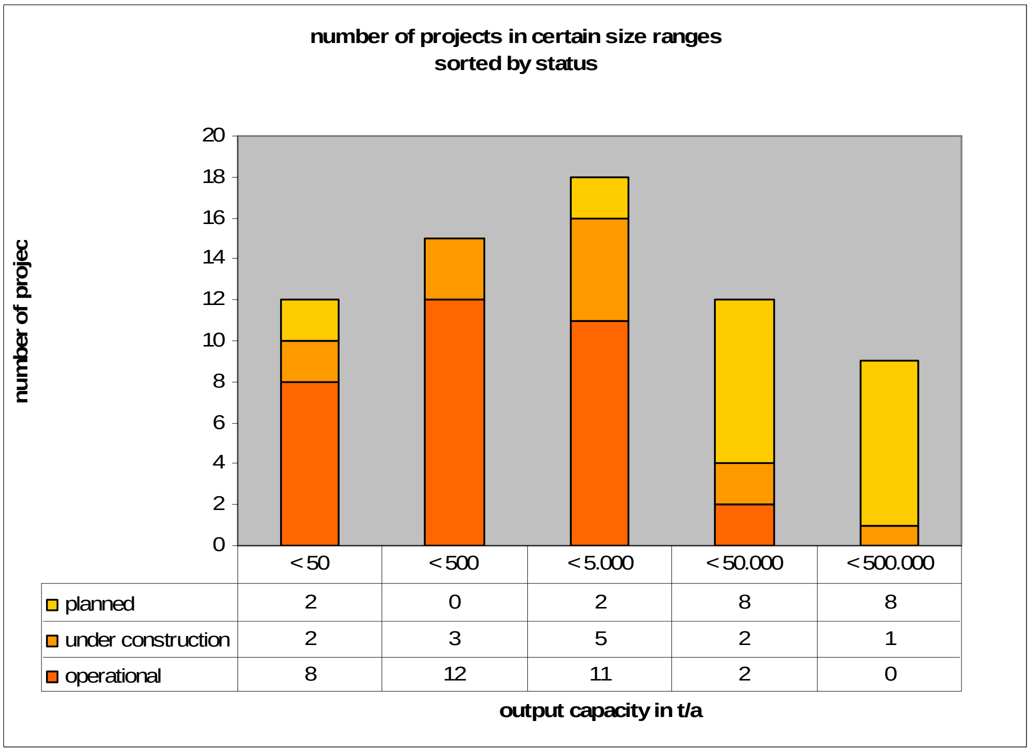
Company	**Country**	**Technology**
POET	United States	biochemical
Range Fuels, Inc.	United States	thermochemical
Southern Research Institute	United States	biochemical
Southern Research Institute	United States	thermochemical
Southern Research Institute	United States	hybrid
Technical University of Denmark (DTU)	Denmark	biochemical
Tembec Chemical Group	Canada	thermochemical
Terrabon	United States	biochemical
Verenium	United States	biochemical
Verenium	United States	biochemical
Vienna University of Technology	Austria	thermochemical

Table 73: List of Operational Facilities

Two projects with a capacity of up to 50000 t/a are currently under construction: CHORENs FT-liquids beta plant in Freiberg, Germany, which is under commissioning now and will be operational in 2010, and Abengoa´s ethanol plant in Hugoton, USA, which is due for start-up in 2011. The largest project under construction is Range Fuels´ plant in Soperton, USA, with a capacity of 300000 t/a of ethanol production, due for start-up in 2010. Range Fuels already operates the K2A Optimization Plant in Denver, USA.

Planned projects include commercial scale facilities (for those companies that are currently building demoplants), demonstration scale facilities and a few pilot plants. Many more projects may be planned but have not yet been announced, depending on company policies and the stability and favourability of the political framework.

An overview on the capacities sorted by status is given in the graph below.



	< 50	< 500	< 5.000	< 50.000	< 500.000
🟨 planned	2	0	2	8	8
🟧 under construction	2	3	5	2	1
🟥 operational	8	12	11	2	0

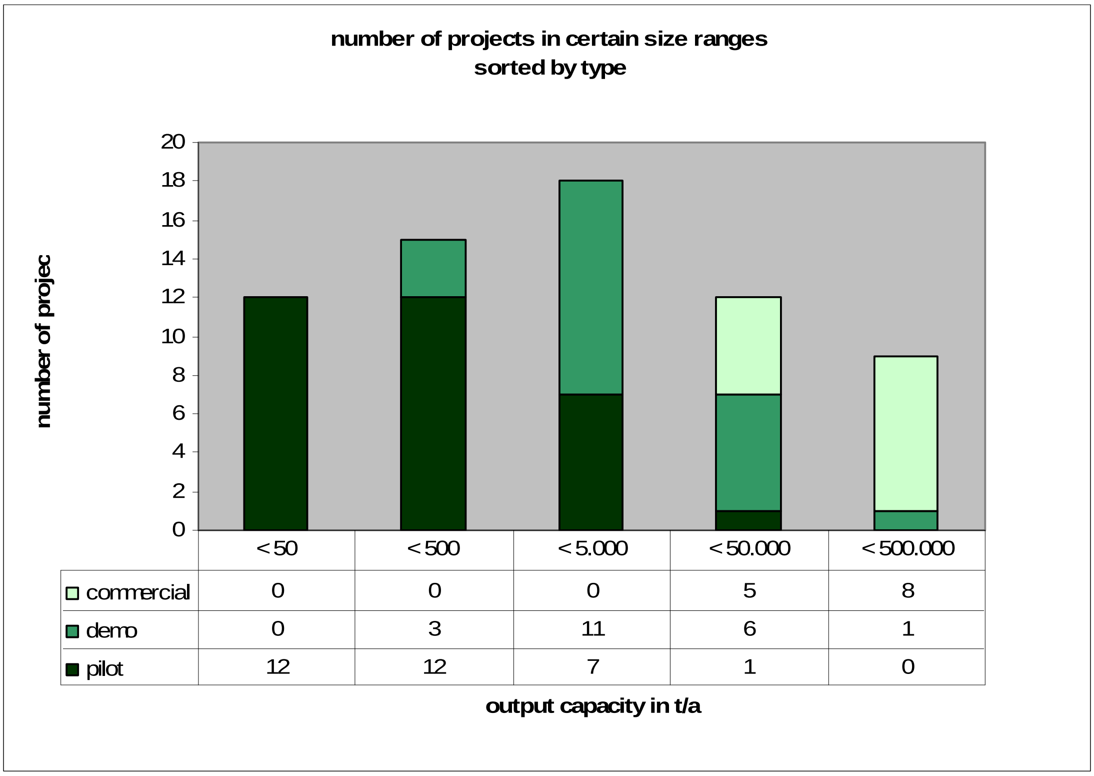
Figure 69: Diagram of Projects sorted by Status

5.3 Project Type

32 production facilities are classified by the project owner to be pilot facilities, 21 are demonstration facilities, and 13 are commercial facilities. Generally, pilot facilities have rather small capacities, while most demo facilities range from 500 to 50000 t/a, and commercial facilities have even larger capacities.

Several companies operate a pilot scale facility while building a demoplant and announcing plans for a commercial facility. Examples include Abengoa, CHOREN, Coskata, Enerkem and SEKAB. Some more companies are also listed at least twice with upscaling projects, like BioGasol, Chemrec, ECN, Inbicon, Iogen, Mossi & Ghisolfi, NSE Biofuels, POET, Range Fuels and Verenium. Mascoma plans to build its first commercial plant in cooperation with Frontier Renewable Resources, and the gasification technology of the Vienna University of Technology has recently been upscaled in a project of CTU.

The graph below illustrates the number of pilot, demo and commercial scale projects.



	< 50	< 500	< 5.000	< 50.000	< 500.000
□ commercial	0	0	0	5	8
🟩 demo	0	3	11	6	1
■ pilot	12	12	7	1	0

Figure 70: Diagram of Projects sorted by Type of Facility

5.4 Project Capacities

The capacities of the demonstration and commercial facilities sorted by technology are depicted over the timeline in the graph below. Thermochemical facilities tend to have high capacities up to 300.000 t/a; planned biochemical facilities may range up to 150.000 t/a by 2015.

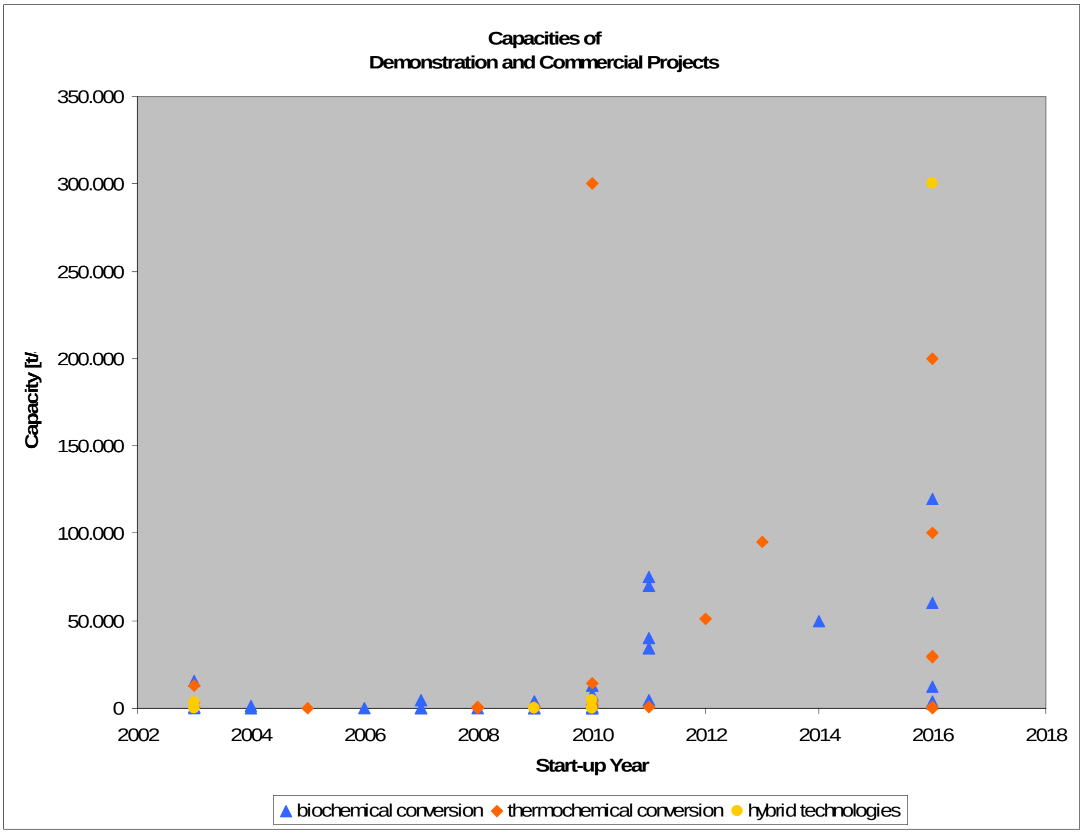


Figure 71: Diagram of Project Capacities (demo and commercial scale)

The ten largest projects in this overview are listed in the table below. Except for the Range Fuels´ project which is currently under construction, all of these are in the planning stage and due for start-up not before 2011.

Company	State	Technology	Product	Capacity [t/a]	Status
Range Fuels	USA	thermochemical	ethanol; methanol;	300.000	under construction
Coskata	USA	hybrid	ethanol;	300.000	planned
CHOREN Industries	Germany	thermochemical	FT-liquids;	200.000	planned
SEKAB	Sweden	biochemical	ethanol;	120.000	planned
NSE Biofuels	Finland	thermochemical	FT-liquids;	100.000	planned
Chemrec	Sweden	thermochemical	methanol; DME;	95.000	planned
POET	USA	biochemical	ethanol;	75.000	planned
Iogen	Canada	biochemical	ethanol;	70.000	planned
Frontier Renewable Resources	USA	biochemical	ethanol; lignin;	60.000	planned
Flambeau River Biofuels	USA	thermochemical	FT-liquids;	51.000	planned

Table 74: List of Ten Largest Projects

5.5 Cumulative Capacities

Summing up the production of all projects for which data was provided, the current production capacity for biofuels from lignocellulosic raw materials equals 57 500 t/a - which is about 0,1% of the current total production of biofuels worldwide (62 000 000 t/a in 2008). Taking into account all facilities that are currently under construction or planned, the cumulative capacity of all these projects could reach 680 000 t/a in 2012. Although this is a tenfold increase in production capacity it still represents only 1,1% of the worldwide biofuels production in 2008. Yet it is unclear how many production facilities will actually be operational by 2012.

The possible development of lignocellulosic biofuel production capacities is depicted below. Please note that the increase in capacities depicted below is based on data provided for 66 projects. Companies that have not yet provided data are not included.

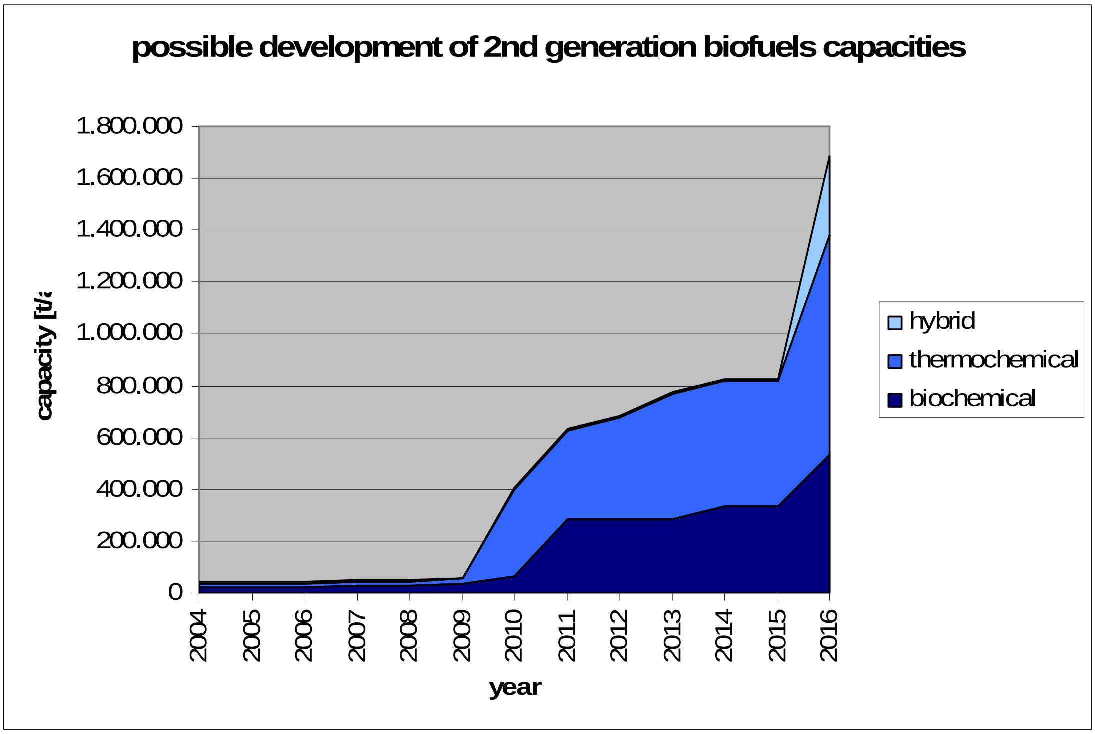


Figure 72: Diagram of Cumulative Capacities of Projects in this Overview

Authors note: If you wish to add your company´s project to the database or to have your data updated, please contact dina.bacovsky@bioenergy2020.eu.