European Commission

ART Fuels Forum

ARTFuels

Continuing the work of the Sub Group on Advanced Biofuels for the RED II market deployment for Advanced Biofuels

Technology status and reliability of the value chains: 2018 Update

28 December 2018

Edited by: Ingvar Landälv, Lars Waldheim

& Kyriakos Maniatis

Continuing the work of the Sub Group on Advanced Biofuels

"Technology status and reliability of the value chains: 2018 Update"

Compiled by:

Ingvar Landälv — **Fuels & Energy Consulting**
Lars Waldheim — **Waldheim Consulting**

Date: 28 December 2018

Disclaimer

This report has been prepared for DG ENER and ART Fuels Forum based on the information received from technology suppliers and plant operators as well as from public sources as background material to give the status of existing technologies but without the ambition of describing all developments in the area in detail. However, the view and opinions in this report are the author's and do not necessarily state or reflect those of the Commission, the ART Fuels Forum or the organization that are members of, or observers to the ART Fuels Forum. References to products, processes, or services by trade name, trademark, manufacturer or the like does not constitute or imply an endorsement or recommendation of these by the Commission or the Organizations represented by the ART Fuels Forum Members' and Observers. Neither the Commission nor any person acting on the Commission's, or, the Organizations represented by the ART Fuels Forum Members' and Observers' behalf make any warranty or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information contained herein.

EUROPEAN COMMISSION

Sub Group on Advanced Biofuels

"Technology status and reliability of the value chains"

Title page original report

Compiled by:

Ingvar Landälv
Division of Energy Sciences,
Luleå University of Technology

Assisted by:
Freya Burton of Lanzatech
Francisco Girio of LNEG
Susanna Pflüger of EBA
Ilmari Lastikka of NESTE
Eelco Dekker of Methanol institute

Co-edited by:
Kyriakos Maniatis of DG ENER
Lars Waldheim, Independent Consultant
Eric van den Heuvel, studio Gear Up
Stamatis Kalligeros, Assistant Professor,
Hellenic Naval Academy

Date: 14 February 2017

Disclaimer

Table of Contents

This page intentionally left blank

NOTE TO THE READER

Any changes or additions to the 2017 version, i.e. the essence of the update, is shown with characters in blue while the 2017 text is shown in black characters.

In 2018, in relation to the Alternative Renewable Transport Fuels Forum, (AFF) activities and also related to an on-going IEA Bioenergy study of the future cost of biofuels, it was concluded that it would be suitable to make an update of the SGAB report "Technology status and reliability of the value chains", and broaden it to also include what was seen as emerging technologies. The update of the report was sponsored by DG ENER as a side activity within AFF, and the support of DG ENER is gratefully acknowledged.

The authors, Ingvar Landälv and Lars Waldheim, have in principle used the same methodology as in the previous version, i.e. primarily approaching developers and project owners for information, and which have been complemented by publicly available information as required. Since information has not been obtained to the same extent as in the previous report, in particular from the emerging technologies, more information from public sources has been used in this update. The authors gratefully acknowledge the valuable assistance of Dr Stamatis Kalligeros in the final editing of the report.

Key Messages

A lack of long-term stable legislation hinders the development of promising routes to reach demonstration and commercial deployment stage. This is in particular the case for capital intensive technologies.

The level of innovation and belief in technology progress among industrial parties is high and has led into significant progress in technology development. A wide range of different value chains are being demonstrated at industrial scale. These value chains differ in conversion technology, the feedstocks used, the process employed and the resulting liquid and gaseous fuels.

- Hydrogenated Vegetable Oil (HVO) is already commercial today at a scale of millions of tonnes. The EU oil industry is retrofitting existing refineries to produce HVO. Future production capacity growth is limited by availability of sustainable oils but could double. However, when used oils and process residues from industrial operations are taken into consideration on a global scale the capacity can increase significantly. The expansion can be based on proprietary technologies from several licensors representing both own-operate entities but also at least two world-scale contractors that can provide technology to any third party. This is the technology that has increased the most in capacity since the previous version of this report, in particular if the projects which have been announced for construction are included.
- In the previous version of this report, it was concluded that lignocellulosic or second generation (E2G) ethanol was on the verge of being commercial with several industrial scale first-of-a-kind plants using a variety of integrated technologies in early operation. The technology developers were competing in licensing their technology to locations with strong support policies. All of them were based on agricultural residues while technologies based on forestry residues still have to reach the level of industrial scale demonstration. However, in recent years there has been some set-backs among the pioneers; Abengoa and Biochemtex were both forced into administration and the Hugoton and Crescentino facilities were closed. DuPont left the biofuel production area and sold its plant for other purposes. On the positive side, Raizen is expanding their plant in Piracicaba, Clariant has gone beyond the demonstration plant and has broken ground on a commercial plant in Romania while St1 has operated its forest residue demo plant and is pursuing a commercial project in Norway. Finally, the Crescentino plant has been taken over by Versalis Spa, a subsidiary to ENI, and operations are to be resumed. In addition to what was reported in the 2017 report, a strong policy for ethanol production in India has generated technology developments by Praj and DBT-ICT that has reached demonstration scale. Also, a few industrial scale projects are in construction and several more are in various stages of planning.
- Gasification technologies lag relative to 2G ethanol, with a small number of plants in early operation and in pilots. Technically it could provide quantities in 2030 if the move to scale can be accomplished by 2020. Due to high investment intensity for large demo

scale plants, larger scale installed plant capacities are needed for this value chain which makes it more complex to realize the first-of-a-kind industrial scale plant even though their total fuel production costs are comparably attractive. Several projects were approved for NER300 funding but so far none is in an active stage. The only European plant in operation, GoBiGas was closed and GoGreenGas is apparently struggling. In North America, Enerkem has started producing ethanol and the Fulcrum and Red Rock biofuels project have both come into construction phase, and addition there are some projects planned.

- Two relatively small trials of co-processing pyrolysis oil (PO) in refineries in Brazil and the USA were known to have taken place when the previous version has been published. If successful, a large number of relatively small pyrolysis plants will have to be built to come to sizable total volume within the decade to come. Upgrading capacity for pyrolysis oil will at first instance largely use existing refinery infrastructure. One new pyrolysis plant has come into operation while two others have been announced. Additional co-processing trial have been made or are in planning, but still at low blend fractions.

- Biological base methane is already commercially available for use as transport fuel in captive fleets or injecting in the natural gas grid. The further development with respect to the scale that bio-based methane is used in transport depends on the competitive demand for biomethane for use in Combined Heat and Power (CHP)-plants. Compared to the situation reported in 2017 there has been an increase in the number of installations and their output.

- Power to Gas or Liquids (PtG/L) is being developed at demonstration scale currently given the expected availability of excess renewable power. However, Carbon Capture and Utilization (CCU) is not a widely used technology at large scale yet and the technology at present can only access smaller carbon dioxide sources. Thus, it may have a limited impact by 2030 unless close coupled integration with large sources providing cheap renewable electricity will be demonstrated.

- Algae technology is at the early demonstration scale and still in the process of optimising energy efficiency as is required for the harvesting, drying and processing of algal products to fuels. Opportunities in fuel markets are still limited with the exception of biomethane, and the low energy prices drives the development towards targeting high-value specialities. This development may therefore make an indent in the biofuels market post-2025.

- Recycled carbon fuels, in the previous version referred to as Low Carbon Fossil Fuels, from waste industrial streams for the production of liquid or gaseous fuels have been acknowledged by the RED II[1] to contribute to the decarbonisation but it will be the meber states that decide on in which way. Certain technologies have moved forward

[1] DIRECTIVE (EU) 2018/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 on the promotion of the use of energy from renewable sources. (OJ L 328, 21.12.2018, p.128).

in one case reached and in other cases are close to reaching the first-of-a-kind plant status. They may possibly offer significant quantities by 2030.

- New and emerging technologies that were not included in the previous version of the report due to that the assessment of the technical maturity was not high enough to have an impact at an industrial scale in the short-term. Such technologiues have been considered more in detail in this updated version. In general, these technologies are now being developed in small pilot plants and have, with few exceptions, still some ground to cover before these technologies become commercial. One exception is lignin depolymerisation, where there is a plan to construct an industrial scale demonstration in Sweden in the next few years.

The technologies, described in this report, are all striving to increase their respective Technology Readiness Level (TRL) and to reach industrial deployment. However, the low energy prices and other uncertainties on the market situation and political risks is a common barrier that for the last years has been a common obstacle to overcome.

1. Introduction

1.1 Background

The SGAB decided that it was necessary to establish the actual state of the art of advanced and renewable fuels technologies addressing all value chains as well as their current status of development beyond any doubt. Furthermore, it was aimed to collect directly information from the various organisations developing the technologies in order to avoid ambiguity and establish the status based on their direct input. The following information was requested by all contacted organisations:

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation

Especially the "Type of Plant" (Pilot, Demonstration, and Commercial) and the "Hours in operation" provided for the reliability on the actual state of the various technologies sought by the SGAB. Only in few cases, where organisations did not respond, and their technology was considered of importance for the report, the information was collected from published data.

The SGAB Vice Chair, Ingvar Landälv from Luleå University of Technology, was asked to manage and coordinate this work since he has also been involved in the European Industrial Bioenergy Initiative (EIBI) and the European Biofuels Platform, EBTP (since June 2016 combined into ETIP Bioenergy[2]). Most of the figures delineating the general conversion pathways with its corresponding text were taken with permission from the EBTP. Text and figures have however been updated and improved under direct collaboration with the EBTP Secretariat.

Furthermore, and as already noted *the format of this report is such that the text of the version from 2017 has been kept when no additional information has been available or no editing has been deemed necessary except for minor editorials. Any changes or additions to the 2017 version, i.e. the essence of the update, is shown with different color of characters.*

1.2 Structure

As the title of this report expresses the following information is intended to give STATUS and RELIABILTY information for various conversion pathways of biomass feedstocks to advanced biofuels. These conversion pathways have been grouped under four sections.

1. Thermochemical conversion

[2] European Technology and Innovation Platform Bioenergy

2. Biological conversion
3. Power to Gas or Liquid conversion
4. Algae development

Three of these pathways (Section number 1, 2, and 4) coincide with six identified conversion chains from feedstock to products developed as part of the work carried out by European Industrial Bioenergy Initiative (EIBI) and European Biofuels Technology Platform (EBTP). Section 3 (Power to Gas or Liquid) is currently not within those conversion pathways identified by EIBI but for the purpose of this report it is elaborated in a corresponding way as the other pathways.

The thermochemical conversion pathway has a number of distinct different conversion routes depending on end product and therefore part 1 has four sub-sections. The biological conversion pathway is, based on the same reasoning, divided also into four sub-sections.

This report addresses the status and reliability of the advanced biofuels sector by referring to plants in operation, or in some cases close to being in operation in tables for each developer. When known, also projects in planning or announced have been noted in the text. A large number of plant owners, plant operators and technology developers have been asked to give their input and address at least the following:

A short description with name, location and background and list of key technologies utilized in the plant. The information provider was asked also to classify the plant as a Pilot plant (P), a Demonstration plant (D) or a Commercial plant (C). Finally, the following additional points were also addressed:

1. Start-up year – plus current status
2. Plant size expressed as feedstock consumption e.g. as ton dry biomass/day or MW Lower Heating Value (LHV) including other important feeds/utilities such as electric power.
3. Plant product capacity expressed as ton/day, m^3/day, Nm^3/h of product or similar – status including important by-products
4. Efficiency number, e.g. tonnes of product per tonne of dry biomass or MW_{out}/MW_{in}. should be able to be calculated from item 2 and 3 - status
5. Number of hours of operation since start-up (comment length of continuous operation or similar) – reliability description
6. Next step (e.g. first full sized plant planned for start-up in year 20xx) – status
7. Comment potential technology barriers or potential show-stoppers

As a consequence of the above approach what is described in this updated report (with some exceptions where information has been obtained from the internet) can be summarized as based on information provided by plant owners, plant operators and technology developers. As a general conclusion it can therefore be said that presented data is up to date and has a high level of certainty.

This report does not have the intention of being complete. This means that the report gives examples where information has been validated but does not imply that all and every developer is included, and there were technologies in a variety of development stages for which the information was not sufficient and which therefore was omitted.

1.3 Contributors to the original report from 2017

The work in this SGAB Report was directed and coordinated by Professor Ingvar Landälv of Lulea University of Technology (LTU), Co-Chair of the SGAB. The Chair and the Rapporteurs contributed to revising and commenting on the text. However, the majority of the information, data and photographs were received from the Members of the SGAB. Considering that these are leading experts in their individual fields, this is therefore a state-of-the-art report on the Technology Status and Reliability of the Value Chains for advanced biofuels.

The structure of the work was based on 4 topical groups and the following organisations volunteered to assist in gathering information for the report:

Proposed topical groups in the report	**Partners who have indicated interest to participate**
Thermochemical conversion	LTU
	Enerkem
	VTT
Biological conversion	Lanzatech
	Clariant
Power to G-or-L conversion	Methanol Institute
	GERG
	LTU
Algae development	LNEG

Companies, operators and developers within and outside the SGAB group have been approached and in this provided information to this report. Members of SGAB also provided information during SGAB meetings.

The SGAB and the Core Team (Chair, Vice-Chair and Rapporteurs) acknowledge the high-quality contributions of persons and organizations that have made this Report an updated overview of the status in the technology area of advanced fuels.

1.4 Abbreviations

Abbr.	Full name	Abbr.	Full name
2G	Second Generation	HFO	Heavy Fuel Oil
AD	Anaerobic Digestion	HMF	Hydroxy-methyl-furfural
APR	Aqueous Phase Reforming	HP	Hydropyrolysis
APP	Advanced Plasma Power	HTFT	High Temperature Fischer-Tropsch
ASTM	American Society for Testing and Materials	HTG	Hydrothermal Gasification
ATJ	Alcohol to Jet	HTL	Hydrothermal Liquefaction
bbl	barrels	HVO	Hydrotreated Vegetable Oils
BF	Blast Furnace	IMPCA	International Methanol Producers & Consumers Association
BL	Black Liquor	IRW	Improved Raceways
bpd	barel per day	ISCC	International Sustainability & Carbon Certification
BTG	Biomass Technology Group BV	KIT	Karlsruhe Institute of Technology
BtL	Biomass to Liquid	LBM	Liquefied Bio-Methane
BTX	Benzene Toluene and Xylenes	Nm^3	Volume of gas in m^3 at STP
C	Commercial Plant	LCA	Life Cycle Analysis
CAPEX	Capital Expenditures	LEAR	Low Energy Algae Reactor
Cat-HTR	Catalytic Hydrothermal Reactor	LHV	Lower Heating Value
CBM	Compressed Bio-Methane	LNG	Liquified Natural Gas
CCS	Carbon Capture and Sequestration	LNEG	Portugal National Laboratory of Energy and Geology
CCU	Carbon Capture and Utilisation	LoI	Letter of Intent
CEN	European Committee for Standardization	LPG	Liquified Petroleum Gas
CERTH	Center for Research & Technology Hellas	LTFT	Low Temperature Fischer-Tropsch
CFB	Circulating Fluidized Bed	LTU	Lulea University of Technology
CHP	Combined Heat & Power	M&G	Mossi Ghisolfi
CNG	Compressed Natural Gas	MCV	Medium Calorific Value
CP	Catalytic Pyrolysis	MFA	Mixed Fatty Acid
CRI	CRI Catalyst Company	MHF	Multiple Hearth Furnace
CRW	Cascade Raceways	MHPSE	Mitsubishi Hitachi Power Systems Europe
D	Demonstartion Plant	MI	Methanol Institute
DEMA	Direct Ethanol from MicroAlgae	MSW	Municipal Solid Waste
DG	Directorate General	Mt	Mega tons (metric?)
DME	Dimethyl Ether	NER	New Entrants' Reserve
DoD	Department of Defense (USA)	NGV	Natural Gas Vehicles
DOE	Department of Energy (USA)	OPEX	Operational Expenditures
DW	Dry Weight	P	Pilot Plant
E2G	2nd Generation Ethanol	PBR	Photo Bio Reactor
EBA	European Biogas Association	PCH	PyroCatalytic Hydrogenation
EBTP	European Biofuels Technology Platform	PDQ	Pressurized Direct Quench
EIB	European Investment Bank	PDU	Pressurized Development Unit
EIBI	European Industrial Bioenergy Initiative	PNNL	US Department of Energy - Pacific Northwest National Laboratory
ERA-NET	European Research Agency - Network	PO	Pyrolysis Oil
ETS	Emissions Trading System	PPA	Purchase Price Agreement
EU	European Union	ppm	parts per million
FAME	Fatty Acid Methyl Esters	PSA	Pressure Swing Absorption
FCC	Fluid Catalytic Cracking	PtG	Power to Gas
FEED	Front-End Engineering Design	PtL	Power to Liquid
FGS	Fordonsgas Sverige AB	R&D	Research & Development
FPO	Fast Pyrolysis Oil	RDF	Refuse Derived Fuel
FT	Fischer-Tropsch	REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
FQD	Fuel Quality Directive	RED	Renewable Energy Directive
GERG	European Gas Research Group	RFO	Renewable Fuel Oil
GET	Güssing Energy Technologies	RON	Research Octane Number
GFR	Green Fuels Research the innovation branch of the Green Fuels biodiesel company	RTP	Rapid Thermal Processing
GMO	Genetically modified	RW	Raceway
gpy	gallons per year	RWGS	Reverse Water Gas Shift Unit
GTI	Gas Technology Institute	SGAB	Sub Group on Advanced Biofuels
GWP	Greenwall Panels	SHF	Separate Hydrolysis and Fermentation
HDO	Hydrodeoxygenation	SIP	Synthesized Iso-Paraffinic

Abbr.	Full name	Abbr.	Full name
SNG	Synthetic Natural Gas		
SOEC	Solid Oxide Electrolysis Cell		
SPK	Synthetic Paraffinic Kerosene		
SPV	Special purpose vehicle		
SRC	Short Rotation Coppice		
SSF	Simultaneous Saccharification and Fermentation		
STP	Standard Temperature and Pressure		
TCR	Thermo-Catalytic Reforming		
toe	tonnes of oil equivalent		
tonnes	Metric tonnes		
tons	US short tonnes		
TOC	Total Organic Carbon		
TOFA	Tall Oil Fatty Acids		
TPBR	Tubular Photo Bio Reactor		
TRL	Technology Readiness Level		
UK	United Kingdom		
USA	United States of America		
USDA	United States Department of Agriculture		
VC	Value Chain		
VGO	Vacuum Gas Oil		
VSA	Vacuum Swing Adsorption		
VTT	VTT Technical Research Centre of Finland		
WFOG	Waste Fats, Oils, and Greases		
WWTP	Wastewater Treatment Plant		
WGS	Water Gas Shift		
XtL	Anything to LIquid		

2. Thermochemical conversion

This chapter explores the following four conversion routes:

- Production of syngas (hydrogen plus carbon monoxide) by means of gasification meant for further synthesis to liquid products. Methane can be either such a large component in the raw gas that it needs to be converted to syngas to avoid too big losses of gas energy or so little that it can be let though the system (later bled out) and be finally used as a fuel.
- Production of syngas and methane by means of gasification where the process is designed to convert all syngas to methane (bio-methane)
- Production and upgrading of energy intermediates, such as pyrolysis oil, torrified biomass and various lignin rich fraction from e.g. the wood pulping process or from cellulosic ethanol plants. Pyrolysis and lignin fractions may be further processed to produce fuels such as diesel or upgraded and further processed within a conventional refinery. Alternatively, these and other similar energy intermediates can be utilized as gasifier feedstocks.
- Conversion of a wide variety of triglyceride or fatty acid wastes and residues to Hydrotreated Vegetable Oil (HVO) via Hydrotreatment.

2.1 Feedstocks

For gasification, pyrolysis and torrefaction, any lignocellulosic material is suitable as feedstock. The term lignocellulosic covers a range of plant molecules/biomass containing cellulose, with varying amounts of lignin, chain length, and degrees of polymerization. This includes wood from forestry and associated residues, Short Rotation Coppice (SRC), and lignocellulosic energy crops, such as energy grasses and reeds. It also includes more specific feedstocks such as by-products from e.g. forest industry such as black liquor and lignin extracted from black liquor.

Sorted Municipal Solid Waste (MSW) is also a potentially suitable feedstock for thermochemical conversion processes. For further details regarding definitions and descriptions see SGAB working document Terminology and Glossary.

HVO is within its range of liquid feeds, after suitable pre-processing, flexible in its feedstock requirements allowing the use of a wide range of fatty-acid containing materials originating from waste and residue streams for example vegetable oils, tallow and other biogenic industrial waste and residue fats and oils.

2.2 Synthetic fuels via gasification

2.2.1 Gasification

Gasification is an endothermic, thermochemical process run at 800°C-1,500 C and at sub-stoichiometric conditions (typically λ = 0.2-0.5[3]). After feedstock preparation of the raw material, it is fed into the gasifier. Typical gasification agents are oxygen and water/steam. The raw gas mainly consists of hydrogen (H_2), carbon monoxide (CO), methane (CH_4) and tar and char components where the desired syngas components are H_2 and CO. The non-combustible components are inert gases and ash.

Entrained-flow gasifiers operate at high temperatures (1,000°C-1,500 C), normally above the melting point of the inorganic material of the feedstock. The feedstock is either in liquid form or, if dry, transformed into fine particles with typical size <1mm.

Bubbling and circulating bed gasifiers, in contrast, can use chip size feed material and are operated at lower temperatures (700 C-950 C) below the softening temperature of the inorganics in the feedstock. The lower temperature also results in more methane and hydrocarbons in the gas.

The energy needed to carry out the gasification reactions normally comes from partial combustion of the feedstock. The gasification pressure is typically 0.1MPa-3.0MPa.

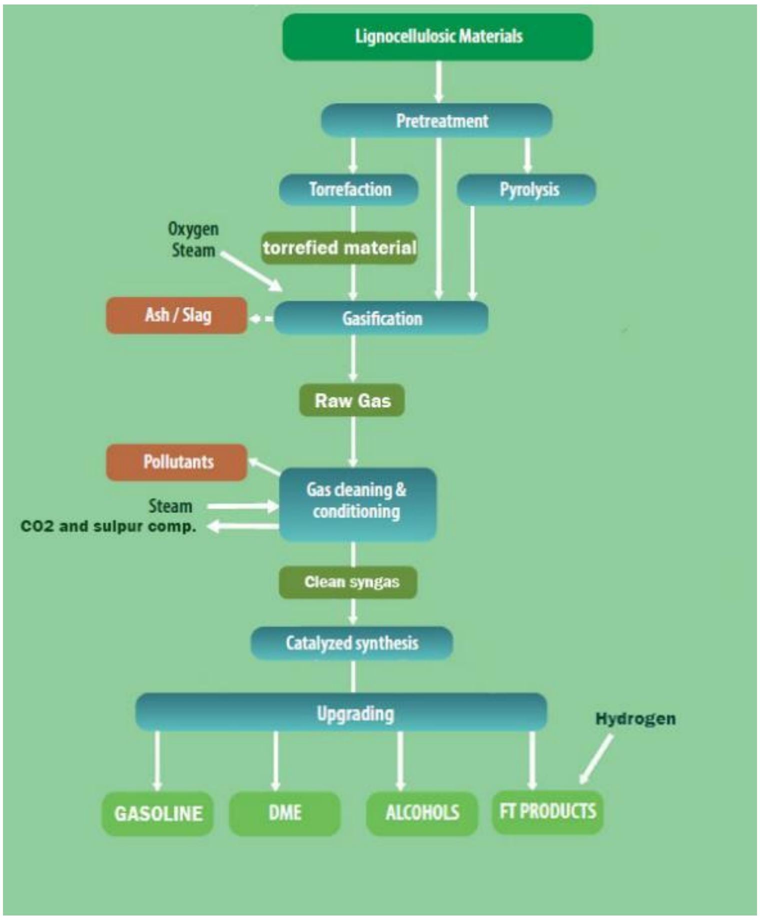


Figure 2.1 Synthetic Fuels via Gasification

2.2.2 Gas conditioning and clean up

Impurities of the raw gas depend on the gasification condition, biomass used and type of gasifier. They can cause corrosion, erosion, deposits and poisoning of catalysts. It is therefore necessary to clean the raw gas. Depending on technology, impurities such as dust,

[3] λ denotes the actual oxygen to fuel ratio relative to the oxygen to fuel ratio required for complete combustion of the fuel without excess oxygen.

ashes, bed material, tars, alkali, sulphur and chloride compounds are removed through various cleaning steps. Components having mainly poisonous effects for downstream catalysts are sulphur and chloride compounds and some other trace components. When a high H_2+CO yield is the goal with the gasification process, in the case of fluidized beds, CH_4 needs to be reformed to CO+H_2 in an additional process step to increase the syngas yield.

For entrained flow gasifiers, the higher operating temperatures in the gasifier causes this reaction to proceed to a satisfactory conversion already in the gasifier.

The partly cleaned raw gas will thereafter be conditioned to obtain the desired H_2/CO ratio for the desired products via the catalytic Water Gas Shift (WGS) reaction ($CO+H_2O \rightleftarrows H_2+CO_2$). For most synthesis products, a ratio of 2 (methanol, DME and LTFT) or 3 (methane) can be accomplished by a one-stage split-flow WGS reactor only treating a part of the whole gas stream and mixing the outlet gas with the remaining, untreated gas. For hydrogen production, of for synthesis of ammonia, the full gas stream is treated in 2 or 3 WGS reactors at gradually lower temperature to maximise the yield of hydrogen and the conversion of CO.

Finally, the acidic CO_2 and sulphur components in the gas are removed from the synthesis gas. This is normally done by a physical or chemical liquid absorption process. There are cases where the sulphur removal needs to take place before the water-gas shift, but CO_2 removal will always be needed downstream in order to remove the CO_2 formed by the shift reaction. In many cases the synthesis gas is also compressed from the gasification pressure to the required synthesis pressure which can be over 10MPa.

If external hydrogen is available the water gas shift reaction can be omitted and by also reversing the reaction, even CO_2 removal can be dispensed with. This scenario is feasible if renewable electricity becomes available in sufficient quantities at cost that are sufficiently low to allow its use for producing hydrogen by electrolysis. The addition of external hydrogen would result in a very significant increase in the carbon conversion from biomass feed to advanced biofuels, and a corresponding reduction in CO_2 emission as more biofuels would be produced to substitute fossil fuel from the same quantity of biomass feedstock. (See section 4).

2.2.3 Product formation

2.2.3.1 Fischer-Tropsch (FT)-Liquids

In the Fischer-Tropsch (FT) process, the clean syngas is converted into alkanes, alkenes and oxygenates using mostly iron and cobalt as catalysts. The conversion is very exothermic and not selective. A mix of hydrocarbons ranging from methane to C100+ components is obtained. The Low Temperature Fischer-Tropsch (LTFT) technology (200°C-220 C and less than 3MPa) provides outputs primarily for diesel production. In the high temperature case (HTFT 300°C-350 C), a product fraction more compatible with gasoline and chemicals is produced. The raw product cannot be directly used as fuel but needs to be upgraded via a number of product upgrading (hydro-treatment, hydrocracking) and separation processes commonly used in the oil refining industry.

2.2.3.2 *Methanol and Dimethyl Ether (DME)*

Methanol is industrially formed from syngas in the presence of a copper catalyst at 6.0MPa-10.0MPa pressure and about 260 C. The conversion is exothermic and very selective and about 80% of the syngas energy is transferred to energy in the methanol (+95% carbon conversion). The synthesis is followed by a distillation section where the water by-product is separated, and the pure methanol is obtained.

DME is formed by methanol dehydration in the presence of a different catalyst (e.g. silica-alumina). The reaction is slightly exothermic. DME is stored in the liquid state at 0.5MPa pressure and ambient temperature, like Liquefied Petroleum Gas (LPG).

Alternatively, DME can be produced through direct synthesis using a dual-catalyst system which permits both methanol synthesis and dehydration in the same process unit, with no intermediate methanol separation.

2.2.3.3 *Synthetic Gasoline*

Syngas can be converted to methanol and then further via DME to synthetic gasoline or directly via methanol to gasoline. The gasoline quality is such that it can be blended into today's commercial gasoline grades.

2.2.3.4 *Product formation through biological gas fermentation*

Gas fermentation is carried out by acetogenic microbes that are able to use a wide variety of carbon rich gases as a substrate. The biological fermentation process can be applied to a wide variety of gases, including gases obtained from the gasification of biomass as well as other societal or industrial residues, such as gasified MSW or the direct use of waste gases from industrial processes, e.g. in the steel and metallurgical industries. Description of technology and on-going activities are found in chapter 3.5.

2.2.3.5 *Hydrogen as a product*

As noted above, the synthesis gas upgrading, and in particular the WGS reactors, can be designed in such a way that a hydrogen-rich gas can be obtained. Such a gas, and much like other sources of hydrogen from chemical processes can be treated in a conventional PSA unit to obtain commercial grade hydrogen. Hydrogen produced in such process could be used in e.g. refineries as these installations already have a large consumption of (fossil) hydrogen or be used for integrated upgrading of other biofuels by hydrogenation e.g. in FT plants or provide a hydrogen commodity product.

2.2.4 Pilots, Demonstration and Commercial plants

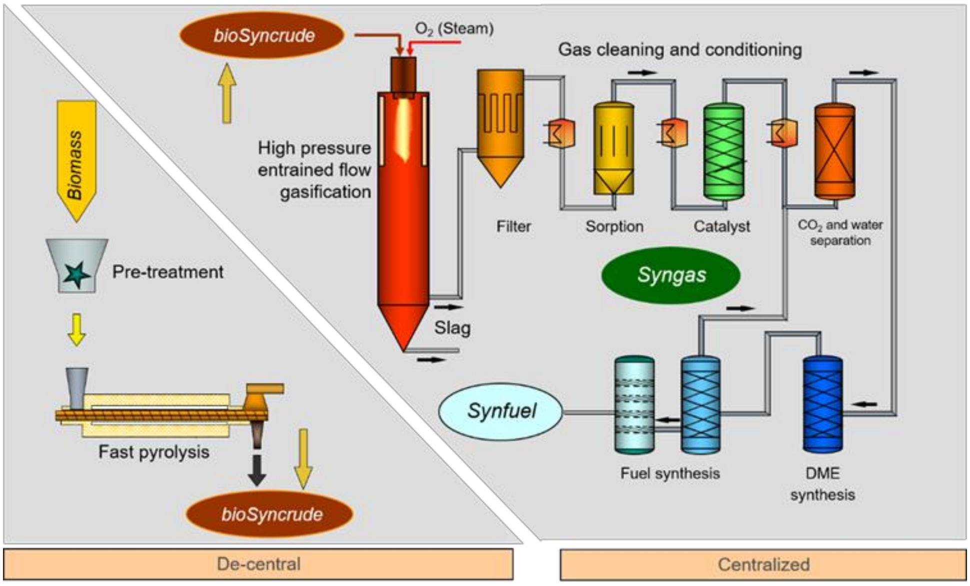
2.2.4.1 *The bioliq® pilot plant at Karlsruhe Institute of Technology (KIT), Germany*

The key technologies in the bioliq plant are:

- Twin-screw reactor with sand operated heat carrier loop at approx. 500°C (Lurgi/Ruhrgas process), two-stage condensation.
- Colloidal mixing and storage for biosyncrude preparation.

- High pressure Entrained Flow Gasifier with cooling screen, oxygen blown, operated at 1,200°C to 1,600°C to efficiently convert the suspension fuel (slurry) into high-quality synthesis gas.
- High temperature, high pressure syngas treatment, higher potential for heat recovery.
- DME / gasoline synthesis with new heat pipe technology for removal of heat of reaction.

The main characteristic of the bioliq concept in relation to other biomass gasification concepts is the de-centralized, dispersed collection and pre-processing of biomass resources in a number of smaller pyrolysis units to increase the energy density of the intermediate relative to the feed (e.g. straw or agricultural wastes) to reduce the logistic cost for the transports to a central, large gasification and synthesis plant, see figure below.



The bioliq process concept

The pilot plant, that has been constructed in steps starting in 2006, is owned and operated by KIT in Germany. The pyrolysis plant has been in operation since 2010, the entrained flow gasifier started operation in 2013. The complete process chain was operated in 2014 for the first time. Feedstock for the process chain is residual lignocellulosic biomass (i.e. straw). The pyrolysis char and bio-oil (see section 2.4.1) produced from biomass are mixed to produce a slurry “Biosyncrude”, a fuel which is fed to the entrained flow gasifier via intermediate storage. The high viscosity slurry is gasified with oxygen at 4.0MPa-8.0MPa. Hot syngas cleaning techniques are developed at KIT to operate at full system pressure to remove or decompose particulates, various catalyst poisons and other undesired gas components to meet the high-quality requirements of the synthesis gas. These are complemented by a conventional Selexol scrubber for CO_2 separation. The syngas is converted to gasoline via a direct DME synthesis route.

The plant is active and operated in campaigns of 2 to 5 weeks duration.

bioliq plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation, December 2017 (op. hours w. fuel)
Pyrolysis	P	2010	0.5 tonnes/h	0.45 tonnes/h	--	2,400 (630)
Gasification	P	2013	1 tonnes/h	1,700 Nm³/h	--	4,800 (900)
Hot gas cleaning	P	--	1,700 Nm³/h	1,700 Nm³/h	--	1,200 (200)
Synthesis	P	2014	700 Nm³/h	0.2 tonnes/h	--	2,600 (160)

The whole process chain has been developed and built by a consortium with KIT and industrial companies as partners (Air Liquide/Lurgi etc.). The individual process steps are, in principle, (with the exception of the hot gas cleaning section), commercially proven for fossil feedstocks. Meanwhile, the whole process chain has been verified for operation with lignocellulosic biomass feedstocks. The individual process steps and the process chain have been evaluated by an external technical and scientific review; no technology barriers towards a full-size plant have been identified. There are on-going studies in 2018 to develop a “bioliq Roadmap” for the future development and scale-up of the process to full commercial scale (magnitude 1,000MW thermal input gasifier) in two capacity steps, but the results and details are not yet ready for dissemination.

KIT’s bioliq plant, Germany

LTU Green Fuels’ BioDME plant, Sweden

On-going optimization includes e.g. optimized energy and feedstock efficiency for the production chain in terms of “Field-to-Wheel”; Proof of feedstock flexibility; Development of processes for new fuel compounds.

2.2.4.2 The BioDME plant in Piteå, Sweden

The key technologies in the BioDME plant are:

- Chemrec Black Liquor (BL) gasification technology operating at close to 3.0MPa.
- HaldorTopsoe syngas to methanol and DME technology.

Today the plant is owned and operation by LTU Green Fuels AB, associated with Luleå Technical University (LTU). The gasification plant was started in September 2005 and the Bio-

DME unit in November 2011. The main feedstock has been sulphate (Kraft) BL from the neighbouring sulphate mill but also sulphite liquor has also been successfully tested.

In the construction of a BL gasification to fuels plant the gasification technology was the only innovative part of the facility. The downstream parts to produce bio-DMEwere already commercially proven.

The plant has been operated in periods of 2 to 3 weeks with a yearly uptime in the order of 40%-60% of the calendar time.

When the bio-DME project was finished, and the plans for the Domsjö project (see below), had been put on hold, the plant was sold to LTU Green Fuels AB for use in a multi-client R&D project around gasification and biofuels that was operated in campaigns of one-week duration or more, between 2013 and 2016.

During this project, BL has been mixed and co-gasified with Pyrolysis Oil (PO) to augment syngas generation capacity for a certain BL, i.e. pulp output, capacity. Syngas generation can increase 100%-200% via pyrolysis oil addition. Pyrolysis oil is converted to syngas with about 85% marginal efficiency when gasified in combination with BL which makes this type of co-gasification a very efficient way to upgrade pyrolysis oil energy.

Furthermore, HaldorTopsoe decided to test their novel so-called CONRAD once-through methanol technology upstream of the existing commercial methanol to DME conversion unit.

However, after the end of this project in 2016, the plant has been idling despite several attempts to arrange funding for continued operation and development of the facility. The accumulated operating hours in the table below have not changed since this time. Nevertheless, the plant is maintained in an operative state and can be reactivated if the opportunity arises.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation 2016
Chemrec gasifier, Piteå	P	2005	3MW (20 tonnes dry BL per day)	1.8MW	--	>27,000
Gasifier +BioDME, Piteå	P	2011		4 tonnes DME/d	--	~11,000

In 2010-2012 the Domsjö Mill in Örnsköldsvik planned to change out their old sulphite recovery boilers to Chemrec gasification technology converting its liquor to methanol at a capacity of 180MW liquor to be gasified in two gasifiers plus one spare gasifier. The Swedish government awarded a 55 million EUR (€) grant for the investment and the project was approved from the Directorate General Competition in Brussels, but Sweden lacked the long-term biofuel market policy which was necessary to make financing possible. The project was therefore stopped, and the grant received from the Swedish Government as investment support was not used. The pulp mill is still in need of a new chemical recovery unit (have two more than 50-year-old recovery boilers) and the project may thus be reopened.

2.2.4.3 The GTI gasification-based pilot plant, Des Plaines, USA

The key technologies in the biomass to synthetic gasoline plant are:

- U-Gas based Carbona steam/oxygen gasification technology already in place at GTI.
- HaldorTopsoe catalytic syngas cleanup
- HaldorTopsoe Tigas process to produce gasoline from generated syngas

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation 2016
GTI/Carbona/HTAS/, Chicago	D	2012	19.2 tonnes/d	3 tonnes/d	--	3,000

The plant has been operated in several test campaigns at elevated pressure, and some 30 tons of gasoline was produced for car fleet testing. The totally automatic process operation was smooth and reliable. The product is 89-92 Research Octane Number (RON) gasoline. The quality of the product has been approved by USA officials to be directly blended with conventional gasoline in the USA. The process is claimed to be technically ready for scale-up to commercial plant size.

The GTI gasification plant, Des Plaines, USA

Enerkem Demonstration Plant, Westbury, Quebec, Canada

However, since the end of the TIGAS project gasification and synthesis test activities in late 2014, there has been no further biomass gasification R&D activities in the plant and the operating hours remains unchanged since. Nevertheless, the plant or parts thereof have been used for other activities such that the plant is still operative.

2.2.4.4 Enerkem's Demonstration Plant, Westbury, Quebec, Canada

Enerkem's demonstration facility in Westbury, Quebec, employ's Enerkem's in-house technology to convert waste wood (decommissioned telephone poles) and post-sorted municipal solid waste to methanol and ethanol. The technology was scaled-up from its pilot facility which had accumulated 4,500 hours of operation. Key technologies are:

- Gasification technology: Bubbling fluidized bed operating at low pressure (0.2MPa-0.4MPa)
- Gas cleaning technology: wet scrubbing and absorber/stripper system developed by Enerkem
- Synthesis technology: Syngas to methanol and ethanol catalytic synthesis process developed by Enerkem

Conditioned syngas production began in 2009, methanol production in 2011 and ethanol production in 2012.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Enerkem, Westbury	D	2009	48 tonnes (dry basis bone)/d	11 (ethanol) tonnes/day		12,800

The Westbury demonstration plant has been used by Enerkem to validate & further develop its commercial plant design. Technical issues that needed optimisation were feedstock feeding, feedstock gasification, syngas clean-up and catalytic synthesis and these have been overcome, tested and demonstrated in this facility before designing Enerkem's commercial plants.

Successful demonstration of MSW-to-methanol and ethanol in this plant since 2009 was followed by the deployment of Enerkem's technology at commercial scale at its Edmonton biorefinery.

2.2.4.5 Enerkem's first commercial Plant, Edmonton, Canada

The key technologies in the Enerkem Edmonton plant have been developed by Enerkem Inc. and have been tested at demonstration scale as described above. The Edmonton plant comprises the same process technology.

The plant converts post-sorted municipal solid waste (fraction remaining after separation for recycling and composting) to methanol and ethanol. The plant is located on the site of the City of Edmonton's integrated waste management center and will help the city increase its waste recycling rate to 90%.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Enerkem Edmonton	C	2015	300 tonnes/d	88 (ethanol) tonnes/day	---	Accumulated over 5,000 hours - Presently in EtOH production ramp-up phase

The plant was commissioned for methanol production and completed a performance test producing methanol in summer 2015 with an uptime of 60% over the last month of operation before a planned shut-down to expand the production capacity. The plant has resumed operations for methanol production since April 2016 and has produced over 4 million liters. The methanol being produced since April 2016 meets IMPCA (International Methanol Producers & Consumers Association) specifications. The facility has also received the ISCC (International Sustainability & Carbon Certification) one of the approved EU certification schemes for the production of its methanol to be also sold as a biofuel under the 2009/28/EC Renewable Energy Directive (RED). A methanol to ethanol conversion module was added in 2016 and started in 2017. Ethanol is Edmonton Alberta Biofuels the primary product. The plant has achieved its technical and commercial milestones to methanol and is presently ramping-up its production of ethanol.

The plant was complemented by a methanol-to-ethanol conversion module added in 2016 and which was commissioned in 2017. Regarding the status of the installation in 2018 it was said to be ramping up production with a target to reach the nameplate capacity by the end of the year. Ethanol is expected to be the primary product.

Enerkem Plant in Edmonton, Canada

Illustration of Enerkem's VANERCO project, Canada

Enerkem is planning a plant, the VANERCO plant, in Varennes, Canada utilizing the same technology as in previous plants. The plant will convert waste from the industrial, commercial and institutional sector, urban waste as well as construction and demolition debris to methanol and ethanol. Construction will start in 2019. The initial production will be on methanol with expansion to ethanol in the future.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Vanerco/ Enerkem	C	2021	350 tonnes/d (dry)	320 tonnes/d (methanol)	----	Project in development

A major Dutch partnership including Nouryon (former AkzoNobel), Enerkem, Air Liquide and the Port of Rotterdam is developing a plant in the Netherlands using Enerkem's conversion technology to manufacture methanol from domestic and other post-recycle waste.

2.2.4.6 The Sunshine Kaidi New Energy Group pilot (China) and demonstration

See comment in section 2.2.5.3.

The FT diesel and naphta demonstration plant project is planned to be constructed by Sunshine Kaidi (Finland) New Energy Co. Ltd, owned by Chinese company Sunshine Kaidi New Energy Group. The group has in-house technology for the key processes. A pilot plant has been operated since 2013 in Wuhan, China. The plant has an AlterNRG gasifier and a fixed bed cobalt based FT process (technologies owned by Kaidi). Pilot plant data and operations are confidential.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Pilot plant, Wuhan, China	P	2013	--	--	--	--
Reference plant, Ajos, Kemi, Finland	D/C	2019	~800 MW	500 tonnes/d FT diesel 167 tonnes/d bio-naphtha	--	Project in development

Kaidi's New Energy Group pilot, China

2.2.4.7 The BioTfueL pilot plant, France

The BioTfueL project objectives is to develop a BTL technology. The partners are Avril, Axens, CEA, IFP Energies nouvelles, Thyssenkrupp Industrial Solutions and Total.

The key technologies used in the BioTfueL plant are;

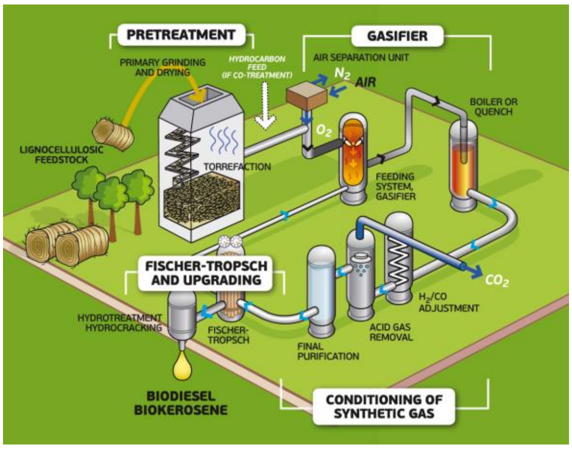
- ThyssenKrupp POLTORR double-zone-MHF (Multiple Hearth Furnace) torrefaction system
- ThyssenKrupp PRENFLO PDQ (Pressurized Direct Quench) Technology
- Axens GASEL® Technology

The biomass pre-treatment pilot plant based on the POLLTORR technology is located on an AVRIL site near Compiègne. France.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
BioTfueL, Dunkerque, France	D	2018	3 tonnes/hr (15 MW)	A small FT unit for validation tests	Steam / power production not installed	Commissioning + R&I cold tests only this far

The aim of the project is to develop, built and operate two demonstration plants in order to develop and market a complete BtL-XtL process for the conversion of biomass in high quality Jet Fuel and Diesel. The BioTfuel plant will be able to gasify and convert 100% of torrified biomass as well as biomass/petroleum coke and biomass/coal mixtures to be fully independent of potential seasonal feedstock restrictions and/or customer economical feedstock needs. The nameplate capacity of the PRENFLO PDQ Gasifier operating under 3.0MPa-3.5MPa bar is $15MW_{th}$.

However, since the GASEL FT technology has been extensively tested in a pilot plant in Italy, the GASEL unit is only taking a very limited amount of the syngas for validation purposes. The commissioning of the two demonstration plants (Torrefaction unit near Compiègne and grinding, gasification, gas treatment and a sub-pilot FT Test Unit in Dunkerque) is on-going. The test program will be executed until 2020.



BioTfueL process scheme

BioTfueL pilot plant (main unit), Dunkerque, France

2.2.5 Project under construction or in planning

2.2.5.1 The Fulcrum Sierra Biofuels Plant (USA)

Fulcrum Bioenergy was founded in 2007 and in 2008 Fulcrum Sierra Biofuels LLC was formed as an SPV for a biorefinery project in Storey County, Nevada. The Sierra Biofuels plant is located at the Tahoe-Reno Industrial Center (often referred to as TRI, but not to be confused with the gasifier developer TRI) in the City of McCarran, Storey County, east of Reno, Nevada. The project originally was designed to produce ethanol and power and involved InEnTec as a gasification technology partner and was supported by a USDA loan guarantee.

During the initial years long-term, zero-cost MSW feedstock agreements were secured with solid waste companies to provide a reliable stream of RDF for Sierra Biofuels.

In 2013, it was announced, that in addition to the MSW-to-ethanol project, the company had validated an MSW-to-jet fuel concept in the company's demonstration facilities in Durham, NC (incidentally the seat of the PDU facilities of the gasifier supplier TRI) and in 2014 it became apparent that the Sierra Biofuels project product had changed from ethanol to bio-jet.

Form 2014 up to 2017, several strategic relationships were announced, with Cathay Pacific, United Airlines and AirBP, respectively, where these combined equity stakes in the project with product off-take agreements. Also, a USDA loan guarantee and a DoD grant of 105 and 70 million $US, respectively for the bio-jet project. The plant cost was then estimated to 266 million $US for an output of 48,000m^3 of neat SPK bio-jet.

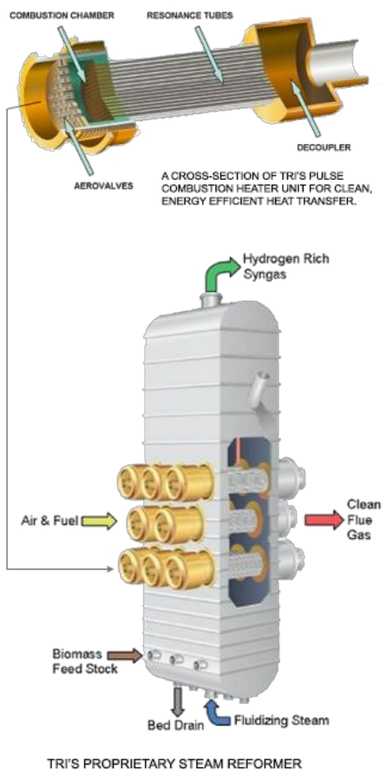
In 2015, the construction was initiated on the Phase 1 of the Sierra project, the feedstock processing facility, which became operative in 2016. In late 2017, the company had met financial closure on the Fulcrum Sierra Biofuels project, replacing the USDA loan guarantee with a loan financed via a Nevada state bond issue. Finally, in May 2018, the company could initiate Phase 2 of the Sierra project, the construction of the biorefinery.

The gasifier technology supplier ThermoChem Recovery Inc. (TRI), founded in 1996, has developed a gasification technology for various waste and biomass feedstocks, including Black Liquor (BL) and RDF and built a few industrial scale gasifiers for BL in the 1990's and early 2000's, most of which had limited operating hours.

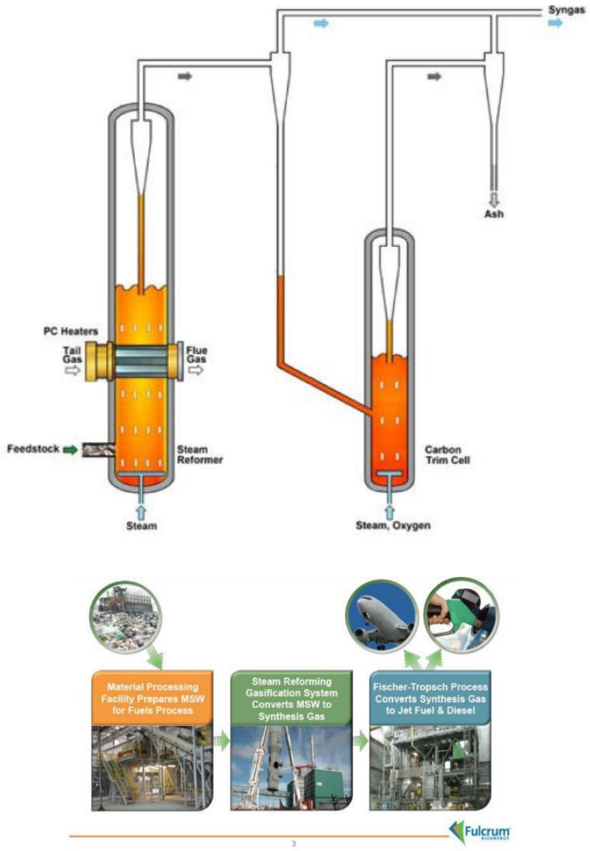
TRI also have had funding from the DOE Integrated Biorefinery Program for two FT projects, the Flambeau River the New Page project. To support these projects, TRI built an integrated 4 tonnes/day PDU plant with a 10% slip-stream EFT FT technology at the Southern Research Institute in Durham, North Carolina that was operative in 2009. The company claims that the PDU has been operated for various test purposes for more than 10,000 hours.

As shown above, TRI has been cooperating with Fulcrum as of at least 2013 on the MSW-Fischer Tropsch development, also involving EFT as the supplier of the synthesis technology, but in September 2018, however, Fulcrum Bioenergy selected the Johnson Matthey/BP as the licensor for the Sierra facility.

TRI has developed several proprietary technologies, see figure below, including a plug-type feed system. The TRI gasification system utilizes a "steam reformer" as the primary stage. This is an indirectly heated, steam blown, low-pressure and uncommonly deep fluidized bed (> 4m), that operates at medium temperature. A proprietary heat exchanger termed "pulsed heater", where the pulsations enhance the heat transfer, supplies the heat required for the steam reforming reactions using part of the product gas as fuel. As a second stage, there is a steam/oxygen blown low-pressure fluidized bed operating at higher temperature, the "Carbon trim cell". The indirect steam gasification and the use of oxygen results in a Medium Calorific Value (MCV) fuel gas or synthesis gas. For cleaning and upgrading of the gas downstream of these units TRI has developed a multi-step gas cleaning process named KASyn™. This can include secondary gas treatment to convert methane and tar and other processes in gradually lower temperatures to remove the common contaminants down to levels acceptable for synthesis gas applications



TRI gasifier schematic



TRI gasification process

The Fulcrum Sierra Biofuels plant receives baled RDF from the Feedstock Processing Facility operated by the company since 2016. The second phase biofuel plant is now under construction with and due to be operative in 2020. In this plant the RDF will be gasified and the gases processed in a partial oxidation unit together with naphtha and tail gas from the FT unit. The gas is then cleaned up to a synthesis gas quality and compressed to be subsequently used in a JM/BP fixed bed FT unit. The crude liquids, less the naphtha which is recycled in the process, will not be upgraded on site as previously planned. Instead they will be transported to the Andeavor (formally known as Tesoro) refinery to be further processed into transportation fuel.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Fulcrum Sierra Biofuels, Tahoe (ND)	C	2020	160,000 tonnes/y RDF	40,000 m^3-FT crude	--	---

Already in 2017 Fulcrum was announcing plants for several sister plants to be constructed the near future, the second one to be sited in Gary, Indiana, to serve the Chicago area. In addition, also MSW agreements for future projects in 19 states for up to 20 years had been negotiated, enough to produce 2.5 million m^3 per year.

2.2.5.2 The Red Rock Biofuels plant (USA)

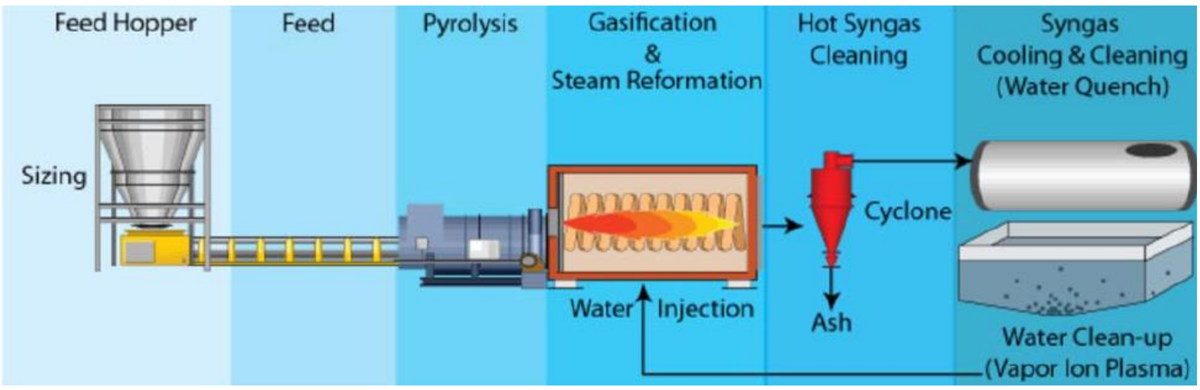
The Red Rock Biofuels project involves construction of a new biofuels plant at Lakeview, Oregon, USA, and associated infrastructure to produce jet fuel, diesel fuel, and naphtha from a woody, primarily of mill and forest residues. The plant is partially funded by a 70 million $US DoD grant and bond financing arranged by the state of Oregon.

Red Rock has partnered with TCG Global on the gasification process. The FT technology selected comes from Velocys based on its Fischer Tropsch microchannel reactor technology for small-scale distributed production of biofuels via, and this will be one of the first full-scale versions of this technology.

Red Rock Biofuels main process blocks

FedEx and Southwest Airlines have off-take agreements for the total available volume of jet fuel from the Red Rock plant.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Red Rock Biofuels Lakeview, OR	C	2020	127,000 tonnes dry wood/y	58,000 m^3 FT fuel Diesel 40%, Kerosene 40%, Naphtha 20%	--	---



TCG gasification process

The TCG Global gasification technology has been tested by others in a plant that was constructed in Denver, Colorado for Red Lion Bio-Energy in 2004 at a scale of 9-25 dry tonnes/day. The gasification plant was in 2008 moved to Toledo, OH, USA, for the purpose of a DOE Integrated Biorefinery (IBR) project started in 2010 the primary objective was to upgrade the 23 tonnes/day Red Lion thermochemical conversion (TCC) system and build a new liquid fuel production (LFP) system supplied by Greyrock Energy that directly converts biomass into diesel fuel.

Construction of the plant in Toledo, started in April 2012. Plant performance and validation tests were initiated in Q2 2012 and seventeen test campaigns were carried out until Q3 2013. The integrated IBR plant was operated on wood, rice hull and other materials for a total of 992 hours and the gasifier for some 200 hours in addition, excluding start-up and shut-down periods.

2.2.5.3 Other project in planning stage

Project not mentioned below that are still in planning stage include;

Aemetis Riverbank. The scope of the installation is to convert 117,000 tonnes/yr of biomass to 45,000m^3 of ethanol, at an own operating conventional ethanol plant at Riverbank, CA, USA. The technology used is InEnTec gasification and Lanzatech gas fermentation (see also Sections 3.5.2.1 to 3.5.2.3). An integrated test plant at a scale of 1 tonne/hr feed and with a transportable gas fermentation unit, provided by Lanzatech, was operated at InEntEc, Richland, WA, for 120 days continuously with 94% up-time to meet requirements of an USDA loan guarantee. The project engineering has started but the ground-breaking has not been announced.

Bayou Fuels project, a 900 tonnes/day dry wood input, 250m^3 FT fuel output plant developed by Velocys located in Natchez, Adams County, Mississippi using the TRI gasification technology and Velocys FT system.

Ajos. Kaidi plans to implement a full-scale demonstration plant, 800MW feedstock 670 tonnes/day FT liquids, in 2020 at the Ajos island, Kemi, Finland (previously also being the site for a different BTL project receiving NER300 support, but later cancelled). In April 2018, the environmental permit was received.

Värmlandsmetanol, a 100,000 tonnes/yr methanol plant at Hagfors Sweden developed by the company by the same name and using the HTW gasification process and other TKK technologies

UK waste to jet fuel, a study for RDF gasification FT plant in the UK involving FT developer Velocys, Shell, British Airways, with APP as the gasification partner and Velocys as the FT supplier.

2.3 Bio-methane via gasification

2.3.1 Gasification

Methane formation is favoured by low gasification temperature and therefore gasifiers operating at low temperatures are preferred, as these have a higher content of the product already in the gasifier off-gas, which decrease the need for reactor volume and also the heat load in the downstream synthesis section. For further description of the gasification step see section 2.2.

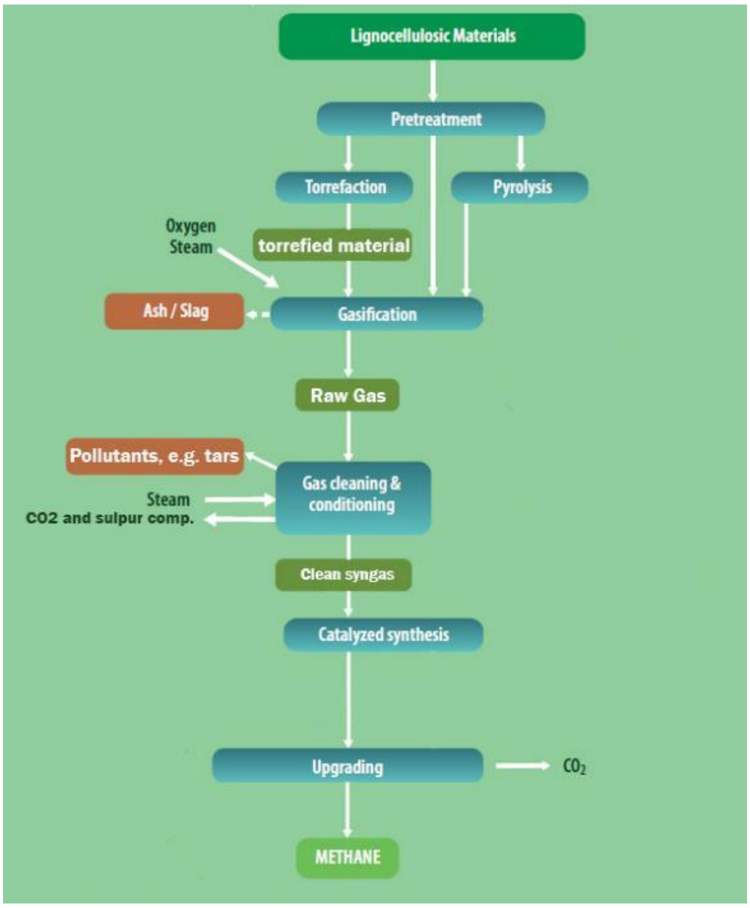


Figure 2.2 Bio-methane via Gasification

This favour bubbling and circulating bed gasifiers that are operated at lower temperatures (800°C-950°C) for this conversion route.

The raw gas mainly consists of H_2, CO, CH_4 and tar components. The gas is comparably rich in methane and contributes typically with about one third of the energy content of the raw gas from the gasifier. The non-combustible components are inert gases and particulate matters.

The energy needed to carry out the gasification reactions can either come from partial combustion of the processed material in the gasification stage as described above or allothermally, i.e. indirectly via heat exchangers or via a circulating, solid heat transferring medium (i.e., combustion and gasification are physically separated). In the latter case the heat may be generated by combustion of the non-gasified part of the feedstock material, char, internally produced wastes and product gas or from external fuel sources in air. These so-called indirect types of gasifiers therefore do not require oxygen to produce the syngas. They are on the other hand difficult to pressurize.

2.3.2 Gas conditioning and clean up

Impurities of the raw gas depend on the gasification condition and biomass used and can cause corrosion, erosion, deposits and poisoning of catalysts. It is therefore necessary to clean the raw gas. Depending on technology impurities such as dust, ashes, bed material, tars and alkali and chloride compounds are removed through various cleaning steps, either at temperature by catalytic reforming of tar or at low temperature by specific scrubbing media (e.g. biodiesel). Components having mainly poisonous effects on the catalysts are sulphur and chloride compounds.

The (partly) cleaned raw gas will be conditioned before further processing to methane can be carried out. The desired H_2/CO ratio of 3.0 is obtained by the water-gas shift reaction. This adjustment can be carried out upstream of the methanation, or, as a part of the methanation process, if suitable catalysts and higher temperature of operation is used.

The CO_2 and sulphur component in the gas needs to be removed. This is normally done by a physical or chemical absorption process. Sulphur components can either be removed before or after the water-gas shift reaction but before the methanation step which follows.

The removal of CO_2 can be performed by various types of commercially available technologies. Type of technology is mainly dependent on plant size. Some concepts have a CO_2 removal also upstream the shift unit but regardless if that is the case a final CO_2 removal step is required downstream of the methanation

2.3.3 Product formation

Biomethane production requires methanation of the cleaned syngas, followed by a (final) CO_2 removal. In the methanation step (catalysed by Nickel Oxide at 2.0MPa-3.0MPa pressure and order of 400°C temperature) carbon monoxide reacts with hydrogen forming methane and water.

The conversion is very exothermic and very selective. As both CO and H_2 are undesired components in natural gas, the process is driven to high CO conversion by extensive recirculation.

2.3.4 Pilots, Demonstration and Commercial plants

2.3.4.1 Biomass CHP Güssing, Austria

The plant is a CHP (Combined Heat & Power) facility (gasification at atmospheric pressure combined with two gas engines) but it has during periods been test site for gas conversion technologies where a slip stream from the plant has been used as feed stream for a Bio-SNG (Synthetic Natural Gas) pilot (1MW capacity), two FT diesel pilots (5kg/day and 1 barrel per day (bpd) respectively), a pilot for production of higher alcohols (1-2 liters/day) and a pilot for hydrogen production (3 Nm^3/day).

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation 2017
Güssing	C	2002	8-10MW	$2.0MW_{el}$ $4.5MW_{th}$	---	>80,000

The Güssing concept has been duplicated in several places for CHP applications by Repotec, Ortner Anlagenbau and also lately by GREG. After construction and start up of a couple of plants in the same approximate size as the Güssing plant the technology was scaled up about 4 times and implemented in Gothenburg, Sweden.

Biomass CHP Güssing, Austria

GoBiGas plant in Gothenburg, Sweden

The operation of the plant has had its main revenue from a 13-year preferential Feed-in-Tariff Power Purchase Agreement (PPA) contract, the duration of which terminated in late 2016. Since the revenues from a market-based PPA was significantly lower the operation was no longer economically viable and the plant and also the associated R&D activities were closed.

2.3.4.2 *The GoBiGas plant in Gothenburg, Sweden*

Göteborg Energi (Gothenburg Energy), which is owned by the city of Gothenburg, has the mission to actively contribute to the sustainable development of the city. Gothenburg Energy has in the past invested heavily in biogas from AD plants including upgrading to bio-methane and in 2005 set a target to produce 1TWh of renewable gas by 2020. Gothenburg Biomass Gasification Project, GoBiGas, was aiming to supplement conventional AD biogas production via the biomass gasification route. It has been Göteborg Energi's first investment outside of conventional biogas production and also the largest investment in the biogas area.

After a review of the technology status, the project was split into two phases to reduce the technical risks, a first demonstration phase of 20MW product gas to be followed by a second phase of 80-100MW output of bio-methane, but the entire project viability was based on scaling-up the capacity.

The Phase 1 project was decided in 2010 but the bulk of the design and construction work could only be started in 2011, when the EU state-aid scrutiny had approved the grant support from the Swedish government. Planning work for Phase 2 was on-going in parallel to the work on Phase 1. This resulted in a successful application to the EU NER300 program in 2011, and in 2012 a grant of 58.8 million EUR (€) was made available for Phase 2.

The gasification technology implemented in the GoBiGas plant is a four-times scale up from the original reference plant in Güssing, Austria (see above) done by Valmet as a licensee of Repotec. The GoBiGas plant is similar to the Güssing plant up to and including tar removal via RME scrubbing. Then follows the synthesis gas upgrading and conversion sections, the technology of which have been provided by Haldor Topsöe A/S. Active carbon filters are used for the removal of vapor phase tar species, the gas is compressed to 1.6MPa before the main treatment and synthesis section. Initially, there are additional contaminant removal steps by sorbents and catalysts. Following this treatment, sulphur is removed in an amine wash and the H_2/CO ratio is adjusted in a water gas shift reactor. Following the Water Gas Shift (WGS) reactor, CO_2 is removed in a second amine wash and the gas passes several methanation reactors using combinations of gas recirculation and gas cooling with heat recovery to control the temperature. Finally, the gas is dried to the grid dew point level by mol sieves before being to the grid interface, where it is compressed to the grid pressure.

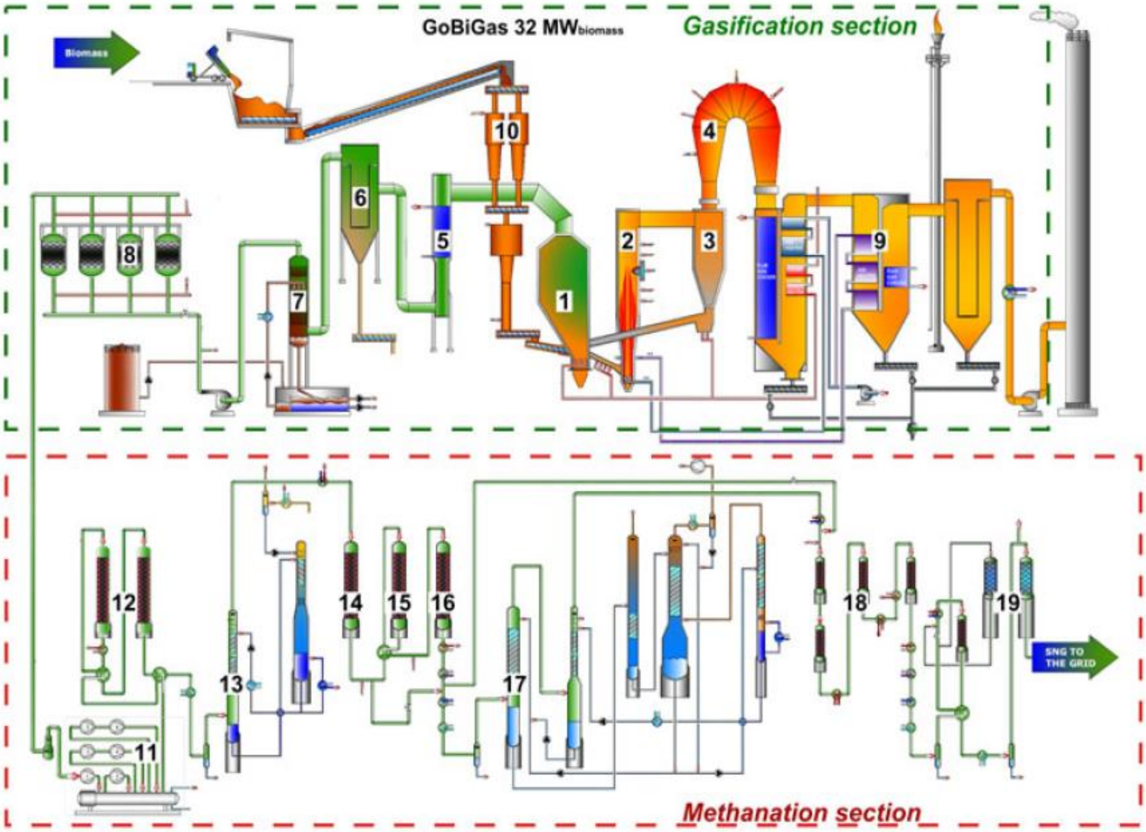


Figure 1. Process schematic of the Gothenburg Biomass Gasification (GoBiGas) biomass to biomethane plant: 1, gasifier; 2, combustion chamber; 3, cyclone; 4, post-combustion chamber; 5, raw gas cooler; 6, raw gas filter; 7, rapeseed methyl ester scrubber; 8, carbon beds; 9, flue gas train; 10, fuel feeding system; 11, product gas compressor; 12, hydration of olefins and COS; 13, H_2S removal; 14, guard bed; 15, water–gas shift reactor; 16, pre-methanation; 17, CO_2 removal, 18, methanation; and 19, drying. [Colour figure can be viewed at wileyonlinelibrary.com]

The GoBiGas process flowsheet[4]

[4] Alamia A. Larsson An., Breitholtz C., Thunman H.: "Performance of large-scale biomass gasifiers in a biorefinery, a state-of-the-art reference". Int. J. Energy Res. Vol. 41, pp. 2001–2019, 2017. DOI: 10.1002/er.3758.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation by February 2018
GoBiGas	D	2013	6.8 tonnes/h (pellets, 5.5% moisture) 8.9 tonnes/h (Forest residue, 20% moisture)	20MW SNG	6 MW Distr. heat	Gasifier 12,000 h Methanation 70 GWh produced

The plant commissioning started in late 2013. Approximately a year later, the first Bio-SNG (Synthetic Natural Gas) was delivered to the grid. In the autumn of 2015 and beginning of 2016 the first continuous operation of advanced biofuel production for over 1,000 hours, achieving over 90% of the design capacity. At start up the plant encountered problems with too a high formation of tars. This was resolved via adding small quantities of alkali salts to the feedstock. The active carbon filter beds were a bottleneck for reaching full capacity, but changes were implemented to this system.

After this period, where operation had been based on wood pellets, trials with other fuels began, but fuel quality issues, in particular the high and varying moisture content of the fuels used, made the operation unstable, and the net gas production fell such that the synthesis section could not be operated. In the autumn of 2017, it was decided to go back to pellet operation to reach the nameplate capacity and accumulate operational hours. In February 2018, the operation was stopped for economic reasons. At this point, the plant output was at the nameplate capacity and it had operated without interruption for over 1,800 hours.

Until February 2018 supplied 70GWh, mainly during the latter part of 2015-2016 and 2017-2018. The plant has also delivered district heat to the Gothenburg district heating network. Gothenburg Energy and Chalmers Technical University have published reports on the project where the project history, the technology and the experiences are presented. The table below shows a summary of the fuel used and main issues encountered.

Fuel	Pellets	Wood Chips	Bark	Recovered Wood Class A1
Hours of operation (h)	≈10,000	≈1,150	≈750	≈100
Fuel moisture (%)	8-9	24-30	20-23	19-21
Load	80-100%	55-70%	40-70%	55-85%
Load-limiting factor	-	Moisture, fuel feed-mechanical	Fuel feed-mechanical	Fuel feed-mechanical
η_{CH_4}	50-63%	40-55%	45-55%*	45-55%*
$CO_{2,eq}$	80-85%**	-	-	-

*Estimation base on gasification performance.
**During steady state operation.

However, the market development for bio-methane did not meet the expectations, and the bio-methane prices went down following the decline in the general energy prices in, but also because of imports of subsidized bio-methane from notably Denmark. This led to a write-off of the phase 1 book value and that the city council cancelled the plan for investment in GoBiGas Phase 2. Since the plant even after the write-off was making an operating loss the company first tried to divest the plant in 2017, and then in early 2018 decided to stop the operation and mothball the plant.

2.3.4.3 The "Gogreengas" Pilot Plant, Swindon, UK

The Gogreengas pilot plant is a development facility for proving and optimizing the process for manufacturing Bio-SNG from Refuse Derived Fuel (RDF) and biomass feedstocks. The project is a partnership between Cadent (*aka* National Grid Gas Distribution), Advanced Plasma Power (APP), Progressive Energy and Carbotech (a subsidiary of Viessmann).

The funding and strategic backing for the project comes from the UK energy regulator Ofgem's Network Innovation Competition, the European BioEnergy Securing the Future ERANET programme and the project partners.

Dried RDF and other feedstocks are converted to syngas in a two-stage gasification process using APP's Gasplasma® technology (fluidized bed gasifier at atmospheric pressure designed by Outokompou Energy, close-coupled with a plasma converter). The plasma stage removes tars leaving a syngas which is predominantly CO and H_2 and is also used to vitrify the ash. After further conventional gas processing, the syngas undergoes a water gas shift to adjust the proportions of the CO and H_2, followed by catalytic methanation. The arising CO_2 is removed from the methane using a pressure swing absorption unit to produce pipeline / vehicle quality Bio-SNG.

The design incorporates provisions to evaluate a number of reactor configurations and a variety of catalyst bed geometries during the testing period.

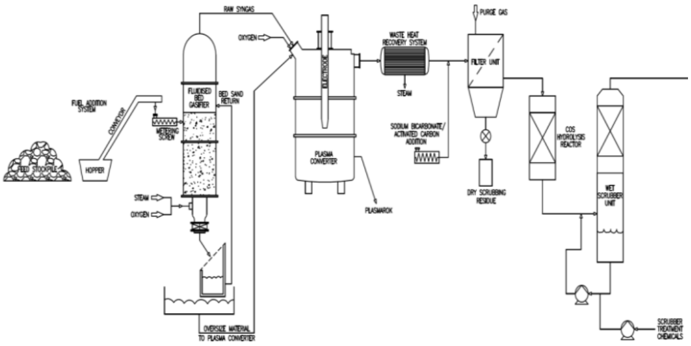
Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Gogreengas Swindon	P	2016	0.4 tonnes/d	0.050MW	-	n/a
Gogreengas Swindon	D	2019-202**?**	10,000 tonnes/year	4MW 22GWh		In construction

The plant has been commissioned and initial experimental work undertaken using test gases. End-to-end operation is about to commence, initially at low dilutions, and the plant will be progressively brought on stream and optimized during the remainder of 2016.

The process challenges include the removal of heat in the highly exothermic methanation reactions given the smaller scale than conventional fossil plants, and the production of a substitute natural gas that meets the stringent regulations for gas grid injection.

The project partners have commenced construction of a commercial Bio-SNG facility on the same site that will process 900kg/h of dry RDF to produce $3MW_{th}$ of pipeline / vehicle quality Bio-SNG under commercial contracts. The process is similar to the process described above, i.e. fluid bed gasifier, plasma reactor, gas cleaning by filtration and scrubbing compression to 1.3MPa, sulphur removal, and water gas shift. The synthesis system to be used is the AMEC Foster Wheeler VESTA process, a multi-reactor once through process with CO_2 removal after the methanation via an activated carbonate scrubber.

The “Gogreengas” Pilot Plant, Swindon, UK



The “Gogreengas” Block flow diagram

The information from one of the partners is that there have been major cost overruns and that SPV GoGreenGas was forced into administration in mid-2018 while the plant has not yet been completed. If the administrator can find a new principal willing to carry on with the construction, the plant could be operational by the end of 2019, but there is also a risk that the project is liquidated.

2.3.4.4 SGW Systems

SCW Systems in Alkmaar, the Netherlands is developing a Hydrothermal Gasification (HTG) system to convert wet biomass to bio-methane. A demo unit of several modules totalling 2MW output was constructed in 2017. There are plans for scaling this up to 2.

2.3.4.5 Other project in planning

In addition to the projects that have or are being implemented, which are described below, projects in various stages of planning include;

Ambigo, a 3MW bio-methane developed by a consortium including Investa and Synova Power based on the ECN suite of technologies (MILENA gasification, OLGA tar removal, ESME methane synthesis) to be constructed in Alkmaar, the Netherlands

Bio2G, a 200MW bio-methane developed by E.ON Sweden based on the GTI gasification technology and Topsöe methanation process for a location in southern Sweden.

2.4 Production and upgrading of pyrolysis products and lignin rich fractions

2.4.1 Pyrolysis

Pyrolysis is the chemical decomposition of organic matter by heating in the absence of oxygen. The biomass decomposes into vapour including steam, aerosols, and char; the proportions of these three states depend on temperature and duration of the pyrolysis. Two alternatives are thermal and catalytic pyrolysis.

The decomposition which mostly results in a liquid fraction is of particular interest as the liquid is transportable and storable. The highest yield of liquid fraction is obtained by thermal fast pyrolysis. This type of technology opens up for a concept where the intermediate product, the pyrolysis oil, is produced locally and upgrading of the oil is done in large plants fed by products from a large number of pyrolysis oil plants.

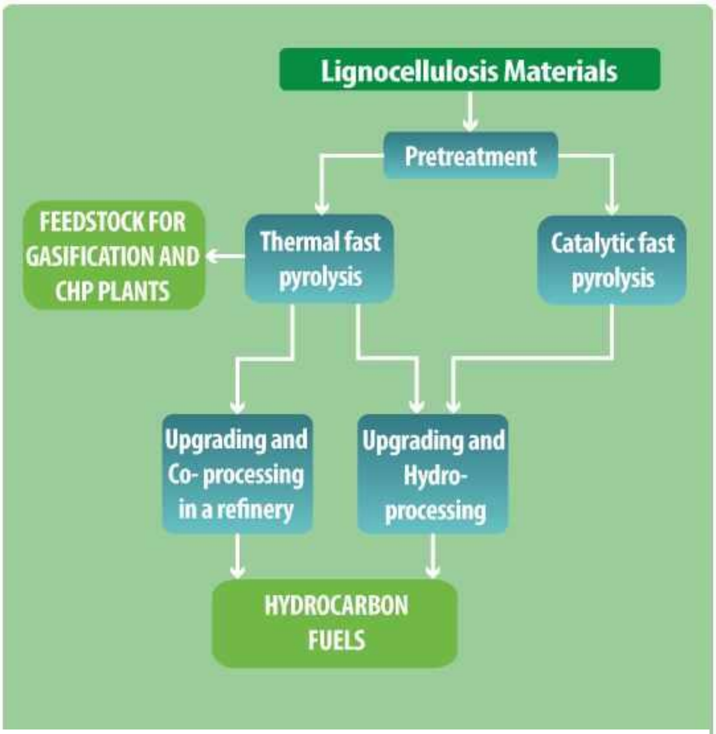


Figure 2.3 Production and upgrading of pyrolysis products and lignin-rich fraction

Fast pyrolysis takes place in order of seconds at around 500 C. In preparation, the biomass needs to be dried to typically less than 10% water and crushed/milled to particles of less than 5mm. The heating medium is typically sand, but also catalysts have been used. The biomass decomposes into organic vapours, non-condensable gases, pyrolysis water, and char. When the gaseous components cool down and condense, a dark brown viscous liquid is formed from the organics and the water, which is called fast pyrolysis oil or sometimes bio-oil. The use of the word “oil” implies that its characteristics are similar to conventional crude oil-based products. However, this is not the case, the oxygen content is as high as for biomass, it is acidic, and the bio-oil cannot under normal circumstances be mixed with or dissolved in either conventional oil or with water.

Pyrolysis Oil is obtained in yields of up to 65%wt on dry feed basis. The by-products char and gas are used within the process to provide the process heat requirements plus possibly also extra energy for export. Pyrolysis oil has a heating value about half that of conventional fuel oil and typically also has some ash. It is currently commercially used in CHP stand-alone applications or replacing fossil fuels. For this purpose, the product has been certified for EU

Regulation for Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH[5]) and has an American Society for Testing and Materials (ASTM) specification for use as renewable fuel oil while the European Committee for Standardization (CEN) develops standards for wider applications.

A different quality pyrolysis oil is generated in catalytic pyrolysis, where catalyst is used as heating media instead of sand. The oil has typically a lower oxygen content at the expense of a lower mass and energy yield.

2.4.2 New technology developments – Upgrading/Co-processing of pyrolysis oil and other lignin rich fractions

2.4.2.1 Via pyrolysis oil and torrefaction

There are on-going developments for pyrolysis oil to be upgraded and co-fed in existing refineries. The mixed bio-fossil products will have the same combustion properties as conventional fossil transport fuels.

The following summarizes various routes possible to upgrade virgin biomass to different types of fuels. Technology developers have been working in all of these areas for the past 10 - 20 years. Technology developers have built several plants at pilot (P)/ demo (D) stage. The commercialization of these processes will depend on how effective they are for finding solutions to catalyst lifetime in the different parts of the process and how compatible the intermediates are with fossil fractions and processing. These are listed below:

- Fast pyrolysis → gasification or co-gasification with e.g. black liquor → synthesis to biofuel product (KIT, LTU).
- Fast pyrolysis → (stabilization) → co-feed to refinery Fluid Catalytic Cracking (FCC) (Ensyn, UOP, PetroBras; Repsol, Grace) – see below.
- Fast pyrolysis → stabilization → Hydrodeoxygenation (HDO) and Hydrocracking (Biomass Technology Group BV (BTG), US Department of Energy - Pacific Northwest National Laboratory (PNNL)).
- Catalytic pyrolysis → Hydrodeoxygenation and Hydrocracking (Anellotech, Center for Research & Technology Hellas (CERTH)).
- Thermocatalytic reforming → Pyrolysis → Post-treatment of vapors in contact with char → upgrading in a refinery (Susteen Technologies GmbH)
- Hydropyrolysis (hydrogen + catalysts) → Hydrodesulphurization + Dearomatization (Gas Technology Institute (GTI)/ CRI Catalyst Company (CRI)).

---

[5] Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH).

- Hydrothermal treatment (HTL) → oil intermediate → upgrading by FCC or HDO (Steeper Energy, Licella, Suncarbon and others).
- Esterification → oil intermediate → upgrading by HDO (Sunpine & Preem).
- Lignin depolymerization → oil intermediate → upgrading by HDO (Renfuel, Biorefly).

Product qualities vary considerably: Fast pyrolysis liquids have low quality due to their high content of water (~25%wt) an acid (3.0-4.0%wt) as well as inherent instability; Catalytic pyrolysis liquids have a water content of 5.0-6.0%wt and are stable; hydropyrolysis liquids contain no water.

In FCC co-processing, the pyrolysis oil is transported to a refinery where it is co-processed in its FCC unit. Typically, a few percent of pyrolysis oil will be added to current petroleum-based feed to the FCC unit. In the FCC process the larger molecules will be broken down to fuel-type carbon lengths using elevated temperature and presence of a cracking catalyst. Also, deoxygenation of the pyrolysis oil will take place to produce mainly CO_2, CO, soot/coke and water. The product streams from the FCC process will, as a result, contain a percentage of renewable, cellulosic feedstock derived fuel. As the level of modifications required to the FCC unit are limited, the capital requirement to implement FCC co-processing is relatively low. The described concept has been developed by UOP in their laboratories. The concept was thereafter initially verified during 2013 in an oil refinery in the Chicago area. Further larger-scale tests have been made by Petrobras and Ensyn.

Pyrolysis oil has also been gasified and co-gasified with black liquor from the pulping process with very good results, see section 2.2.4.

The other methods referred to above are being developed in laboratory and pilot scale.

2.4.2.2 Via fraction of lignin

Lignin from pulping processes or from fermentation of lignocellulosic materials can be used as an intermediate for the production of biofuels.

Lignin is a polymeric substance composed of phenolic monomers and is one of the main components of wood and grasses after cellulose and hemi-cellulose. After pulping it is found dissolved in the pulping liquor. In the case of ethanol production by other means than by chemical pulping, it is found as a solid after the pre-treatment or after fermentation depending on the process configuration.

The processing of the lignin is by first, de-polymerization to mono- and oligomers. This can be done on the dissolved material in a liquor or by extracting lignin and as a solid or re-dissolve it. The oligomeric and monomeric substances are then separated and hydro-treated to produce aromatic and cyclical hydrocarbons.

There are activities for recovering lignin from cellulosic ethanol plants, but the main focus is on bio-based materials rather than on biofuels, even if there are some activities.

In Sweden, lignin separated from black liquor is processed in a similar type of process, and pilot scale units are being implemented.

2.4.3 Pilots (P), Demonstration (D) and Commercial (C) plants

2.4.3.1 The Bioliq plant at KIT, Germany

The Bioliq plant at KIT has a pyrolysis step as pre-treatment of the feedstock (straw) upstream the gasification plant. See chapter 2.2.4

2.4.3.2 The Fortum plant in Joensuu, Finland

The pyrolysis technology used in the Fortum, Joensuu plant extracts a part stream from bed material circulation loop from a biomass fuelled Circulating Fluidized Bed (CFB) boiler and feeds it to the pyrolysis reactor. Downstream of the pyrolysis unit, the vapours are separated and condensed while the sand, the char and the remaining gases are returned to the boiler. The by-products (char and uncondensed gases) are fully utilized by re-feeding them as fuel to the CFB boiler.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Valmet, Tampere, FI	P	2008	7 tons/day (1.5 MW)			Not available
VTT, Otaniemi, FI	P	2015	0.5 ton/day			3,600 (2015)
Fortum, Joensuu FI	C	2013	50MW	30MW		Not reported

The plant has been operated as a demonstration unit, using different kind of raw materials and production parameters in order to develop and optimize the process. Final product has been used for replacing Heavy Fuel Oil (HFO) and tested with several sizes of boilers, from 1MW to 300MW. During 2017 the Joensuu plant produced 12,000 tonnes of pyrolysis oil.

The technology used has been developed by the VTT R&D institute in Finland, and the plant was constructed by the boiler and machinery company Valmet that holds the rights to commercially exploit the technology.

Fortum has two similar projects in NER 300[6] (New Entrants' Reserve) in two different Baltic states. These plans are to expand the production and end-user concepts to new customers and markets, including further development of the oil quality and processes in order to generate higher valued products such as transportation fuels. This far, neither of these projects has come to construction phase.

[6] NER 300 is so called because it is funded from the sale of 300 million emission allowances from the New Entrants' Reserve (NER) set up for the third phase of the EU Emissions Trading System (EU ETS).

VTT, Fortum and Valmet are also engaged in developing the technology further by R&D on the integrated upgrading of the pyrolysis vapours within the process.

Fortum, Valmet and the Swedish refiner Preem has recently entered into a cooperation to extend the value chain from bio-oils to biofuels. Valmet and Fortum's role are to develop and commercialize production technology for upgraded pyrolysis oil suitable e.g. as refinery co-feed, based on a thermal pyrolysis technology platform similar to Fortum's Joensuu bio-oil plant. Preem will focus on processing the upgraded pyrolysis oil into transportation fuels under refinery conditions with feasible technology. Based on the good results of the previous project phase, the companies are moving to larger-scale testing.

Fortum's plant in Joensuu, Finland

Empyro's plan, Hengelo, Holland

2.4.3.3 The Empyro plant, Hengelo, Holland

The Empyro plant utilizes the BTG-BtL pyrolysis process in which the rotating cone reactor is integrated in a circulating sand system composed of a riser, a fluidized bed char combustor, the pyrolysis reactor, and a down-comer. In this concept, char is burned with air to provide the heat required for the pyrolysis process. Oil is the main product; non-condensable pyrolysis gases are combusted and are used to generate additional steam and power. Excess heat is used for drying the feedstock.

The technology has been developed in a 5 tonnes/day pilot plant at the BTG facilities since 1998.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
BTG, Enschede, NL	P	1998	5 tonnes/d	3 tonnes/d (crude pyrolysis oil)	-	> 2,000*

* Intermittent operation only (was not designed for continuous operation)

In 2015 the technology was scaled-up to a 5 tonnes/hr plant, Empyro, at Hengelo, also in the Netherlands.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product	Hours in operation
Empyro, Hengelo, NL	D/C	2015	120 tonnes/d (clean wood residues, 5% moisture) 25 MW	77 tonnes/d (crude pyrolysis oil)	8MW steam 0.7MW_{el}	> 14,000 in late 2018

Empyro runs at design capacity. The Empyro plant design is based on experiences from the BTG pilot plant. This plant has the following overall data.

In 2016, a cooperation was initiated with the French engineering company Technip for the implementation of the fast pyrolysis technology.

BTG-BtL is involved in up-grading of the co-processing of crude pyrolysis oil in existing refineries (primarily co-FCC) and/or upgrading processes from crude pyrolysis oil to advanced biofuels. Development of the right catalysts for upgrading of crude pyrolysis oil to advanced biofuel is a key task. The company is also developing its technology to enable commercial production of crude pyrolysis oil from agricultural non-food residues.

In the area of upgrading of the bio-oil, BTG has validated the feasibility of the co-processing of bio-oil and Vacuum Gas Oil (VGO) in an FCC unit. BTG is also working on a 2-step approach, stabilization using Picula™ catalyst and hydrotreatment using commercial catalysts (NiMo/CoMo). The company has four continuous hydrotreaters at lab-scale (~ 1 kg/day) and is commissioning a new a pilot unit (~ 50kg Fast Pyrolysis Oil (FPO)/day) for further process and catalyst development on hydrotreatment of pyrolysis oil (HORIZON2020 projects Fastcard, 4REFINERY, Waste2Road).

In addition, in 2018 BTG will also commission a new 3 tonnes/d demo plant for pyrolysis oil fractionation (ref. Bio4Products) for the development of bio-based products.

2.4.3.4 ENSYN plants in Canada

The key technology used in the Renfrew plant is ENSYN Rapid Thermal Processing (RTP) technology. RTP™, converts non-food biomass from the forest and agricultural sectors to liquids through fast pyrolysis. The residence time in this unit operating at 520°C is 1-2sec (typical for fast pyrolysis), where after the product vapours are condensed using quenching by cold pyrolysis liquid.

The Ensyn plants produces a Renewable Fuel Oil (RFO), a petroleum-replacement to be used for heating purposes. There are several plants utilizing the RTP technology in operation.

ENSYN has formed a joint venture with Honeywell UOP called Envergent. One task for the new company is to develop a process which makes it possible to combine fast pyrolysis of biomass feedstocks with upgrading of the product to a degree which makes it possible to combine pyrolysis technology with crude oil refining in existing oil refineries. See chapter 2.4.2.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Rhinlander, Wiconsin (Op. by Kerry)	C 5 units	1989 1995 2002 2014	30-40 tonnes/d	Food ingredients, Heating fuel		
Renfrew, Ontario	D	2006, improved 2015	70 tonnes/d	400 kg/hr>20,000 tonnes/yr (depending on feedstock) 3 million gpy 10,000m^3	---	Not given
Cote Nord, Quebec	C	2018	180 tonnes/d	10.5 million gallons per year (gpy) 40,000 m^3		

The latest addition is Cote Nord, Quebec. The plant is co-located at Arbec's sawmill in Port Cartier and is forest slash as feedstock. The product oil, 38,000m^3/yr, is primarily dedicated to heating customers in the U.S. Northeast. The investment was approx. 105 million $CDN.

ENSYN's plant in Renfrew, Canada

Additional projects are planned for Vienna, Georgia, USA, 20 million gallons per year (gpy) (76,000m^3), for which a 70 million $US loan guarantee has been granted, and for Aracruz, Espiritu Santo, Brazil, 22,000gpy (84,000m^3).

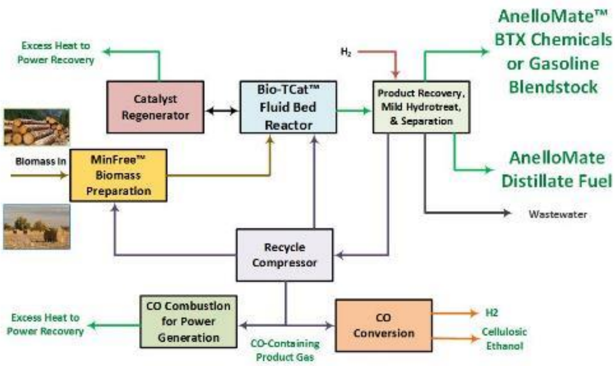
In the area of upgrading of the Fast Pyrolysis Oil (FPO), recently tests involving the coprocessing of 100,000 gallons, 380m^3, were conducted in a California refinery at a rate of <5%. The tests were successful and has resulted in an off-take agreement.

2.4.3.5 Anellotech

Anellotech, Pearl River, NY, USA, is developing, Thermo Catalytic Biomass Conversion (Bio-TCat™) for production of chemicals from renewable, non-food biomass

Biomass (wood, sawdust, corn stover, sugar cane bagasse (byproduct), and other non-food materials) is dried and ground, in addition to a proprietary MinFree pretreatment process to ensure low mineral content in the TCat-8 feedstock which is critical for catalyst performance.

The biomass is rapidly heated, and the resulting gases are immediately converted into hydrocarbons by a proprietary, reusable, sand-like zeolite catalyst. Bio-TCat™ performs all process reactions in one fluid bed reactor, where biomass is thermally broken down and then catalytically converted into Benzene, Toluene and Xylenes (BTX). This single step process uses a cost-effective catalyst being jointly developed with Johnson Matthey, to produce bio-BTX in commercially-attractive yields.



Anellotech, Pearl River, NY Block flow diagram


Anellotech pilot plant at Pearl River, NY

The resulting mixture of bio-BTX can be further purified and separated by using well-known commercial technologies at either grass-roots or existing petrochemical infrastructures.

The company has operated a PDU unit in Pearl River since 2013. The TCat8 Pilot Plant at Silsbee, Texas, was designed in cooperation with IFPEN, and has a capacity not disclosed. Operations started in February 2018 and has operated for over 2,000 hours with continuous catalyst circulation including a fluid bed reactor, catalyst stripper, catalyst regenerator, quench tower, and recycle compressor by October 2018 and regularly completes uninterrupted 24/7 runs.

Commercial Bio-TCat plant design and process licensing will be completed by Axens. Along with its development partners IFPEN and Johnson Matthey, Anellotech will also develop next-generation catalysts.

2.4.3.6 Susteen technologies GmbH, Germany

The Thermo-Catalytic Reforming technology (TCR) has been developed by Fraunhofer UMSICHT and Susteen Technologies GmbH, is a spin-off company of the Fraunhofer UMSICHT. The process utilizes both the intermediate pyrolysis (heating of organic matter to 350°C-500°C, at moderate heating rates 50°C/min-200°C/min, with solid residence times in minutes) combined with post catalytic reforming of the pyrolysis products (heating to 500°C-750°C) in contact with the char formed acting as a catalyst. Various feedstocks can be applied and over 50 types of residual biomass feedstock types, sludges and other wastes have been tested. It is claimed that the process can process mixed feedstock fractions with moisture contents ranging from dry to over 30%, particle sizes 3mm–30mm and feedstock containing up to 10%wt in plastics.

The process converts nearly any type of biomass and organic waste residue into a gas (20%-40%wt), high quality low oxygenated bio-oil (TCR-oil) (5%-14%wt), and char (22%-50%wt), and an aqueous phase (15%-25%wt) that is immiscible with the TCR-oil.

The gas has a high energy value, 14-18MJ/kg, and is hydrogen-rich and basically free of tars. The oil is largely decarboxylated, and an energy contents of 32-38MJ/kg, oxygen content below 10% and water content ranging 1%-5% depending on feedstock and process conditions.

The TCR reactor system

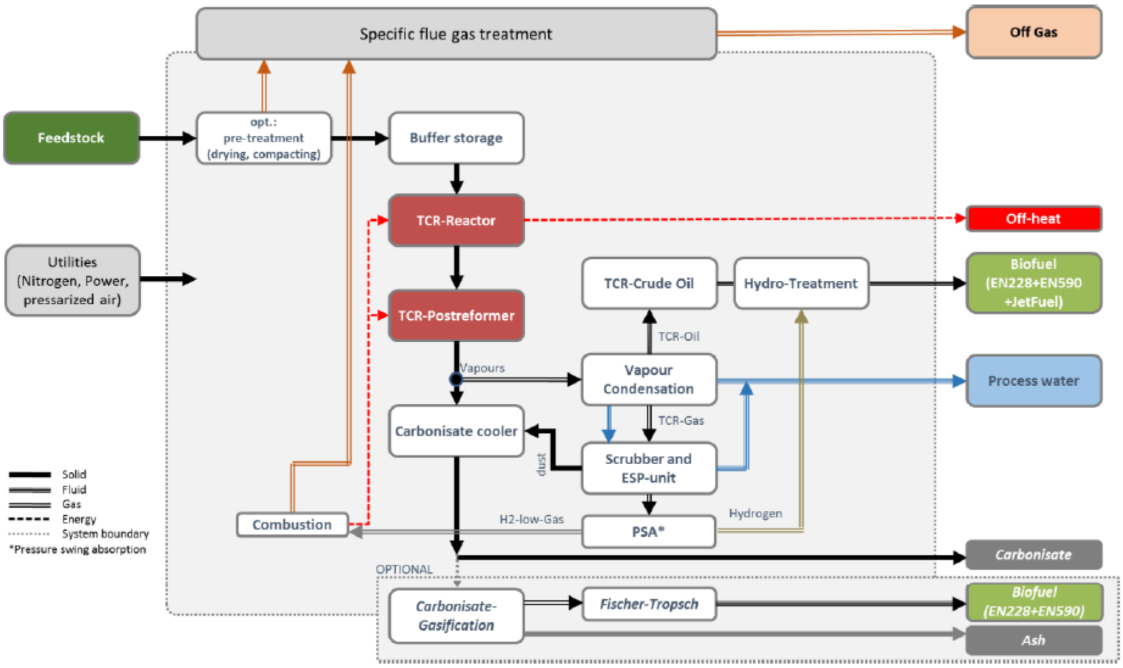
TCR300 plant, Sulzbach-Rosenberg, Bavaria, Germany

The char is undergoing an extended duration pyrolysis achieving very high carbonization levels above 90%. The char can be a product in itself or is suitable for gasification to generate additional gas, and the low content of volatiles in the char gives a low-tar gas. For smaller scale applications a simple updraft gasifier has been integrated with the TCR® reactor system and successfully demonstrated at pilot scale. Due to a low gasification temperatures ash vitrification can largely be avoided resulting in good nutrient availability in ash for relevant types of feedstock such as sewage sludge.

The TCR® has originally been tested on a 2kg/hour bench-scale semi-continuous reactor system since 2013. Over 50 different types of feedstock have been tested and assessed by Fraunhofer UMSICHT on this reactor since 2013. Altogether 4 lab-scale reactors have been deployed in the meantime to provide experimental platforms to R&D partners in the UK, Italy and Chile.

Two TCR 30 pilot plants with a feedstock capacity of 30kg/h have been built and tested since 2014 and 2015, respectively. The units have successfully demonstrated that the TCR® process can be scaled into small-industrial scale at continuous operation achieving over 2,500 hours of operation.

The first TCR® industrial prototype plant with a capacity of approx. 300kg/h of sewage sludge dry matter has been commissioned for test operation in May 2018 in Bavaria, Germany. The reactor system is installed in 3 module frames and serves to test and optimize scale-up engineering designs with a particular focus on an efficient thermal heating system utilizing syngas from TCR or char gasification and further optimizations of the product gas train. The project also tests the integration of a 180kW$_{el}$ dual-fuel CHP plant and an upstream gasification unit for char gasification.



The complete TCR concept for biofuels production

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	Co-product	Hours in operation
TCR30 Germany UK, Canada	P	2015	30 kg/h	Crude oil,	Gas, Carbonisate	>2,500
TCR300 Germany	D	2018	300 kg/h	Crude Oil	Char/Ash, Power, Heat	400
TCR500	C	In constr. 2019/2020	500 kg/hr			

The TCR500 (500kg/h capacity; feedstock: mainly sewage sludge) demonstrator is part of an ongoing Horizon2020 project, 2SYNFUELS. The equipment is in the planning phase, purchasing has started. Operation will start by the end of 2019-beginning 2020.

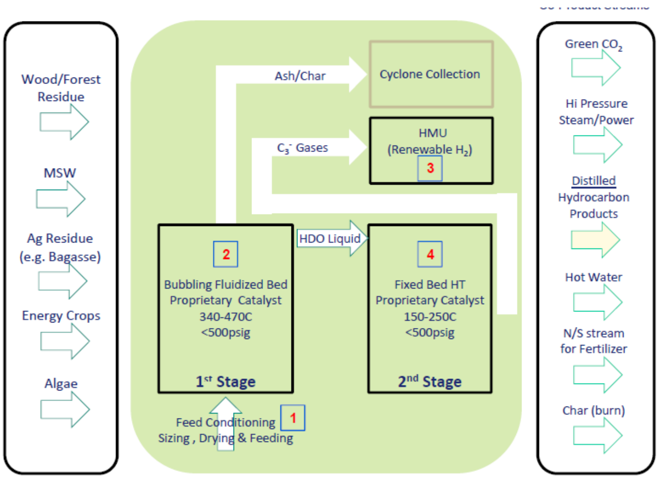
Susteen is also engaged with Green Fuels Research in developing a biodiesel and bio-jet process, SABR-TCR®, see Section 2.4.4.7

Currently three commercial small industrial scale demonstrators are in planning stage targeting feedstocks ranging from food and market waste, forestry residue to industrial organic residue at 500kg/h scale. These initial commercial projects will focus on decentralized waste-to-energy applications to facilitate technology maturity and growth. Deployment of at least 1-2 of these planned units is targeted for 2020.

2.4.3.7 IH2

The process was developed at GTI, Chicago, IL, USA and where CRI has assisted in developing the catalyst. CRI, a catalyst company within the Shell group, and GTI have joint development and commercial agreements in place whereby the process is marketed by CRI.

The IH2 technology is a catalytic thermochemical process that converts biomass directly to high purity hydrocarbon fuels and/or blend stocks with an energy content recovery (~70%) in all configurations. The process uses catalytic hydropyrolysis, i.e. pyrolysis in the presence of a high concentration of hydrogen, in a pressurized fluidized bed.



The IH2 process schematic


The IH2 pilot plant, Bangalore, India

The liquids formed are processed by an integrated hydrodeoxygenation/hydrotreatment unit while the gases that have a high hydrogen and hydrocarbon content are converted to a hydrogen-rich gas by steam reforming. The hydrogen is recovered and used in the hydropyrolysis and the upgrading steps. In addition, thermal energy can be recovered for production o stem and/or power.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
GTI Chicago	P	2011	50 kg/day	fuels		n.a.
CRI, Banaglore, IN	P D	2017	5 tons/day	fuels		n.a.

In late 2017 CRI announced that a licensing agreement was entered with the Norwegian saw mill company Bergene Holm AS. The Swedish oil company Preem AB have also entered into a cooperation, with the intention to realize full scale biofuel production sites in Norway through Biozin Holding AS, a daughter of Bergene Holm AS. The first production facility is intended to be located adjacent to the Bergene Holm AS saw mill in Åmli in southern Norway using mill residues from Åmli and forestry residues from the region. The product will be refined by one of Preem's refineries in Sweden. In late 2018, the companies announced that a second step would be taken, a Front-End Engineering Design (FEED) study, and that Preem takes an equity position in Biozin Holding AS

2.4.3.8 G4 Insight

The Canadian company G4 Insight develops a process called PyroCatalytic Hydrogenation (PCH). Dried and comminuted biomass is vaporized in a pressurized (< 2MPa) hydrogen atmosphere by using a recirculating heating media to create a fast pyrolysis process. The generated vapours and aerosols are separated from the solid phase mixture of char and media. The char is further separated from the heating media for use in the reformer.

The pyrolysis vapours are catalytically converted into methane and steam in the presence of hydrogen gas. This is performed at catalyst temperatures below 650°C, which minimizes the formation of poly-aromatic hydrocarbons. The hot gases are cooled in a controlled process and the methane gas is separated and purified from the liquids and remaining hydrogen. Separation and purification of a high-grade methane mixture is performed by a proprietary PSA process and ant it is claimed that the energy conversion is above 70% on an HHV basis while the methane purity levels is over 98% and meet all other grid specifications.

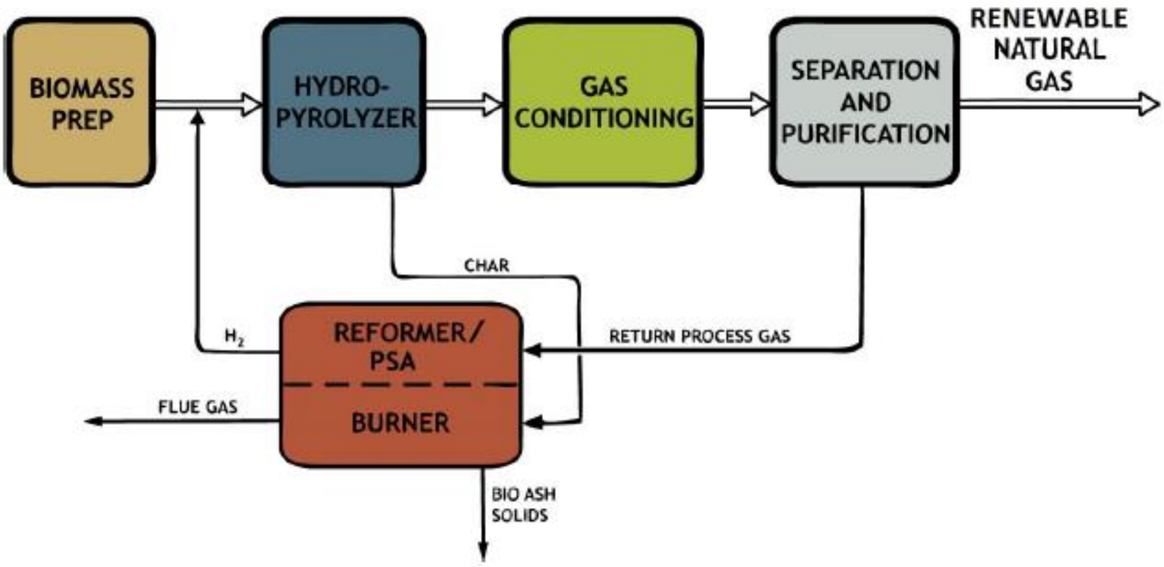
A portion of the methane, water, and excess hydrogen is recirculated into a steam methane reformer to generate the hydrogen required for the hydropyrolyzer. The heat source for the endothermic reforming process is the combustion of the char generated in the pyrolysis process.

The PCH technology is in the process demonstration phase and the Process Demonstration Unit, Placer County, CA has achieved 88% to 100% of commercial target performance for core processes, and the product gas is also used in a CNG vehicle.

A “demonstration” unit of 100kg/day biomass started commissioning in Edmonton, Alberta, Canada, in 2018

Plants in two capacities, 4MW and 115MW output, are foreseen as commercial units.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Placer County, CA, USA	P	2015	n.a	SNG		n.a
Edmonton, Alberta, Canada	D	2018	0.1 tons/day	SNG		n.a



The PCH process

2.4.3.9 Setra

The Swedish forest product company Setra has announced plans for a plant co-located at the Kastet saw mill, Gävleborg, Sweden to produce pyrolysis oil, 25,000-30,000 tonnes from 80,000-90,000 tonnes/year saw dust to be operational by 2020. The indicated use of the PO is for biofuel production. The technology and supplier selection are on-going.

2.5 Upgrading of a wide variety of wastes and residues to Hydrotreated Vegetable Oils (HVO)

HVO can be produced from a wide variety of materials containing triglycerides and fatty acids.

Within this range of materials, HVO is flexible in its feedstock requirements allowing the use of a wide range of low-quality waste and residue materials still leading to production of hydrocarbon drop-in products.

The block diagram illustrates the key process steps leading form the fatty acid containing feedstocks to renewable hydrocarbon products suitable for blending into the refinery product slate. The key additional feedstock needed is hydrogen which today comes from a fossil source.

HVO type of biofuels can be produced by either investing in stand-alone facilities or by converting the existing oil refineries into HVO technology production or co-production facilities.

In 2017, 5 million tonnes/yr of HVO was produced globally expected to increase to 6-7 million tonnes/yr by 2020 and continue to increase thereafter.

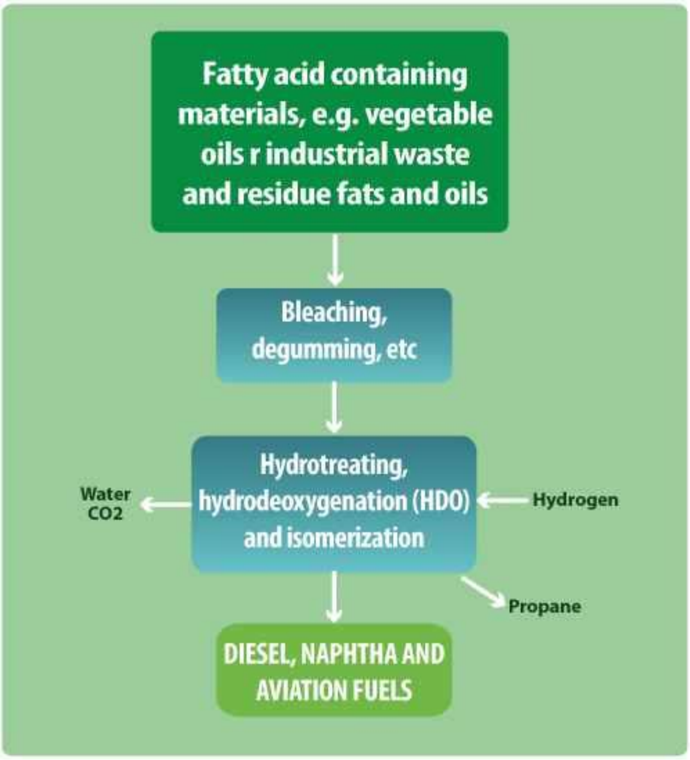


Figure 2.4 Upgrading of waste and residues to Hydrotreated Vegetable Oils (HVO)

The main limitation for the HVO capacity is to source raw materials (vegetable oils, grease, tallow and UCO etc.) from sources that are acceptable from a sustainability perspective on the market where they are sold. Vegetable oils, and in particular palm oil and other edible oils, have been debated from a sustainability perspective, both from a food vs. fuel and an iLUC perspective. The RED II also has caps on biofuels from such feedstocks as well as on biofuels from some waste lipid fractions in the EU.

2.5.1 HVO Stand-alone production facilities

Neste was the first to invest in an HVO refinery (Porvoo 2007). Currently, Neste has a production capacity of 2.7 million tonnes/yr, with stand-alone refineries in Porvoo (Finland), Singapore and Rotterdam (the Netherlands). The Porvoo plant benefits from synergies with the parallel fossil refinery operations with regard to utilities, and the Rotterdam and Singapore facilities are stand-alone facilities for renewable diesel production. Neste have announced a final investment decision for a new production line in Singapore in December 2018, which will extend Neste's renewable overall product capacity to close to 4.5 million tons annually in 2022.

In the US, Diamond Green operates an HVO stand-alone facility of 430 thousand tonnes/yr, and in Finland, UPM operates since 2015 their HVO refinery of the capacity of 100 thousand tonnes/yr. In addition, in the US, Renewable Energy Group has an HVO facility of 225 thousand tonnes/yr, and. All companies have recently announced either expansions or new facilities.

There are also three dedicated HVO plants in China, Yangzhou Jianyuan Biotechnology (120kt) Nanjing, Jiangsu province, Huan Yu (Hainan 1,000 or even 150kt) and Eco Investments (120kt) Zhangiagang, Jiangsu province. All of these uses mainly UCO as feedstock.

UrbanX Renewables Group is planning to build a 5,000 barrel-per-day plant (230,000 tonnes/yr) in the Los Angeles area in California at an former biodiesel plant site. The plant will produce renewable diesel, jet, and naphtha from waste oil feedstocks based on a license for ARA and Chevron Lummus Global ISOCONVERSION process,

Ryze Renewables in cooperation with Phillips 66 is repurposing existing biodiesel facilities by installing PDI hydrogenation technology in its facilities in Nevada. In Reno, 150,000 tonnes/yr is due for start-up in 2019. In Las Vegas 300,000 tonnes/yr is due on stream in 2020.

Emerald Biofuels plans to invest in a facility of 250,000 tonnes/yr, to be followed by other facilities in the USA.

Petrixo Oil and Gas announced in 2014 its intention plans to establish Fujairah Bio Fuel Refinery in the United Arab Emirates that would ultimately have a production capacity of 1 million tonnes per year of biofuel products. The first phase was the construction of a production of 400,000 tonnes/yr using the UOP/ENI Ecofining process and locally grown oil crops to also produce vegetable oil. The project will use waste from the oilseeds to generate electricity for internal use. However, as of 2018, the project does not seem to have come into construction.

In the USA, SG Preston announced its intention to build a 120 million gpy (350,000 tonnes/yr) plant in Lawrence County, Ohio, using the UOP Ecofining process and plans for yet another four similar-capacity installations have been announced. However, the first installation has not yet come to construction. NEXT Renewable Fuels has also announced plans for a plant in Port Westward, Oregon, with a capacity of 2.3 million m^3 (600 million gpy) to be on stream in 2021 and have signed off-take agreements with Shell and others.

2.5.2 HVO production through refinery conversion

There is a large number of traditional oil refineries in the EU with refinery technology suitable for HVO conversion, as they have two hydrotreaters which were originally designed for removal of sulphur and nitrogen from fossil feeds by hydrogen treatment. Already ENI S.P.A (ENI) has converted their Venice refinery to 0.3 million tonnes/yr of HVO, and a refinery in California has been converted by Altair to 0.2 million tonnes/yr output. A second ENI refinery, Gela in Sicily is being converted to 0.7 million tonnes/yr product, as is the Total refinery at La Mede, France.

Additional refinery conversions may take place in the future as soon as the market conditions look more favourable for renewable fuels than fossils.

ENI and Petronas have announced studying revamp projects for two Indonesian refineries.

2.5.3 Co-processing

In addition to the 100% HVO production, biofuels can be produced through co-processing. In co-processing, biomaterial is fed into refinery units together with fossil feeds typically in low (<5%wt-10%wt) blends, but higher blends are in use by e.g. Preem in Sweden. As the refinery processes are complex and units interlinked, co-processing bio-feeds in integrated refinery lines results in fractionation of bio-components in multiple products streams.

Co-processing already takes place in the EU, but detailed information about co-processed bio-volumes are not publicly available. A rough estimation of the volume *potential* of co-processed biofuels could be that if 30% of EU refining capacity (230 million tonnes/yr) would use 5% bio-feed, the resulting biofuel volume would be in the range of 3.5 million tonnes/yr.

Preem in Gothenburg Sweden has production of 150,000 tonnes/yr through co-processing. Preem is expanding the hydrogen capacity to expand the capacity further based on a variety of feedstock to 500,000 tonnes per year.

ConocoPhillips is also co-processing to 40,000 tons of products in Cork, Eire.

CEPSA's three refineries (Huelva-La Rabida, Algeciras–San Roque and Tenerife), the REPSOL refineries in La Coruña, Tarragona, Bilbao and Cartagena as well as the BP refinery in Castellon are all capable of co-producing HVO. The feedstock is mostly palm oil, along with fossil fuel but also UCO. The overall HVO co-production capacity is of the order of 700,000 tonnes/yr, but the capacity of all individual refineries have not been found (Huelva-La Rabida 278kt, Bilbao 60kt, Cartagena 60kt, Castellon 60-120kt). The official statistics indicate an actual production in 2017 of 350,000 tonnes/yr.

Petrobras already in 2008 had refurbished five refineries to produce HVO by the H-Bio process based a total of 425 million liter/year of soy bean oil, but it appears that this capacity is not used due to the cost of the vegetable oil.

Sinopec of China test plant of 20,000 tonnes/yr co-processing capacity and have plans for increasing its co-processing capacity.

GALP in Portugal has a co-processing capacity of 47,000 tonnes/yr at its Sines refinery since 2017, this being a smaller capacity than previously anticipated for a joint project with Petrobras.

Also, the St1 refinery in Gothenburg Sweden is expanding its hydrogen capacity, to allow co-production of 200,000 tonnes/yr of biodiesel as from 2021.

Andeavor has announced a plan to convert the Dickinson Refinery, North Dakota, USA, to process 12,000 barrels of renewable feedstocks, including soybean oil and distillers corn oil, into renewable diesel fuel (i.e. approx. 400,000 tonnes/yr output). The project is expected to be completed in late 2020 and is subject to permitting approval.

Kern Oil, Bakersfield, California, is meant to be able to process up to 20% tallow alongside it's crude in a co-processing capability amounting to an estimated 12,000 tonnes/yr.

2.5.4 Pilots, Demonstrations and Commercial Plants

2.5.4.1 Neste

Neste has developed its own technology for HVO processing in cooperation with a catalyst partner and commercialized this under the name of Neste Renewable Diesel (produced with Neste's NEXBTL technology). Neste is by far the largest producer on the market at present and controls around two third of the world production capacity.

At present the capacity in the existing plants in Porvoo, Rotterdam and Singapore plants are 2.7 million tonnes per year. By additional debottlenecking the capacity is expected to increase to 3 million tonnes/yr by 2020 in these installations.

Neste has also announced that a final decision on an expansion of the Singapore operations by adding a new line operative producing approximately 1.3 million tonnes/yr of product, thereby bringing the Neste total global renewable product capacity close to 4.5 million tons annually in 2022. The current plant capacities, after various capacity increases since start-up from debottlenecking etc., and planned future production capacity expansions are shown in the table below.

<table>
<tr><th>Plant</th><th>Type P/D/C</th><th>Start-up year</th><th>Feedstock</th><th>Product</th><th>By-product MW</th><th>Hours in operation</th></tr>
<tr><td rowspan="2">Porvoo, Finland</td><td>C</td><td>2007</td><td rowspan="4">Various Vegetable Oils and waste streams</td><td>200,000 tonnes/yr</td><td>-</td><td>commercial operation since start-up</td></tr>
<tr><td>C</td><td>2009</td><td>200,000 tonnes/yr</td><td>-</td><td>commercial operation since start-up</td></tr>
<tr><td>Singapore</td><td>C</td><td>2010</td><td>1,100,000 tonnes/yr

New line decided 1,300,000 tonnes/yr</td><td>-</td><td>commercial operation since start-up

Operative in 2022</td></tr>
<tr><td>Rotterdam, The Netherlands</td><td>C</td><td>2011</td><td>1,200,000 tonnes/yr</td><td>-</td><td>commercial operation since start-up

Expanded capacity operative in 2020</td></tr>
</table>

Neste's HVO plant, Rotterdam, The Netherlands

2.5.4.2 UPM's Lappeenranta Biorefinery plant, in Lappeenranta, Finland

The UPM Lappeenranta biorefinery, producing wood-based renewable diesel from forestry residue (crude tall oil), started commercial production in January 2015. The biorefinery, located on the same site as the UPM Kaukas pulp and paper mill, has proven its technological and commercial capability. UPM has publicly announced that the biorefinery reached profitable results already at the end of 2015. Total investment: 175 million EUR.

The key technology used in the Lappeenranta biorefinery is hydro-treatment provided by Haldor Topsoe.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Lappeenranta biorefinery	C	2015	Crude tall oil (capacity confidential)	100,000 tonnes/yr (120 million litre/yr)	--	~10,000

The plant has run very reliable with the longest run being over several months. There are no technical barriers encountered so far.

Crude tall oil is a natural extract of wood, mainly from conifers. Crude tall oil is gained as a result of the separation process of fibrous material from wood. It is a residue of pulp manufacturing. Crude Tall Oil is part of Annex IX, part A and therefore classified by the European institutions as residue and eligible for double-counting and is part of the sub-target for advanced biofuels. In Lappeenranta, a significant part of this renewable raw material comes from UPM's own pulp mills in Finland – like the Kaukas mill site next door.

In addition to the Lappeenranta plant, UPM is studying a biorefinery project in Kotka with a capacity of 500,000 tonnes/year. The plans have not publicly detailed, but feedstocks such as Brassica carinata oil from plantations in Uruguay could be part of the feedstock basis, together with wood residues and other wastes.

UPM's Lappeenranta Biorefinery plant, Lappeenranta, Finland

Diamond Green Diesel, Louisiana (USA)

2.5.4.3 Diamond Green Diesel, Louisiana (USA)

The plant is a joint venture between Darling Ingredients Inc. and Andeavor. Darling is specializing in production of specialty ingredients from animal origin for applications in the food, feed and fuel industries. Valero is the largest independent petroleum refiner and marketer in North America. The plant utilizes the Ecofining™ process from UOP to convert feedstocks like vegetable oils, animal fats and greases to "drop in" hydrocarbon fuels via deoxygenation, isomerization and product separation.

The plant is co-located next to a petroleum refinery to leverage existing assets and to minimize capital cost. Capacity is planned to be increased to 18,000 barrel/day.

The company also announced that it will add another 400 MMgy (1,200,000 tonnes/yr) of production capacity expected to come online in late 2021. The project, estimated to cost 1.1 billion $US, will also include construction of a new, 50-60 MMgy (150,000-200,000 tonnes/yr) renewable naphtha—or green gasoline—plant and improved logistics capabilities.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Diamond Green Diesel	C	2013	10,000 barrel/day (470,000 tonnes/yr)	Confidential	Confidential	Continuous Since 2013
	C	Expansion in 2016	Total 830,000 tonnes/yr	Confidential	Confidential	Since 2018

2.5.4.4 Eni's Green Refinery Projects, Venice and Gela, Sicily, Italy

The plant utilizes the Ecofining™ process from UOP to convert feedstocks like vegetable oils, animal fats and greases to "drop in" hydrocarbon fuels via deoxygenation, isomerization and product separation. The project involves the conversion of an existing oil refinery into a biorefinery by a revamp of two existing hydrotreating units. Hydrogen is provided by the existing catalytic reforming unit.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Eni Venice	C	2014	375,000 tonnes/yr Expansion plans to 11,575 barrel/day 500,000 tonnes/yr	Confidential	Confidential	Continuous Since 2014
Eni Gela	C	Expected 2018	550,000 tonnes/yr	Confidential	Confidential	2018

Integration with existing facilities provides utilities, ancillaries and all off-site support. The project schedule was significantly shorter in comparison to grassroots unit construction (<24 months) and entailed significantly reduced project capital investment relative to grassroots option.

Eni's Green Refinery Project, Venice, Italy

AltAir Renewable Jet Fuel Project, Los Angeles, USA

There were plans to expand the Venice capacity further, up to 500,000 tonne/yr of products, but this decision is still pending.

Also, the Gela refinery on Sicily has been converted to process 700,000 tonne/yr feedstock and is due to come into operation in 2019.

2.5.4.5 *The World Energy (fka AltAir) Renewable Jet Fuel Project, Paramount, CA, USA*

The Paramount, Los Angeles plant utilizes UOP Renewable Jet Fuel Process to convert feedstocks like vegetable oils, animal fats and greases to "drop in" hydrocarbon fuels via deoxygenation, isomerization, hydrocracking and product separation. The plant was initially installed to produce 114,000m^3 (30 million gpy) but the production has been expanded to 170,000m^3 (45 million gpy). Yet another expansion is in planning to a total output of 1.1 million m^3 (306 million gpy)

The product slate is directed towards jet fuel and green diesel. The Altair plant is a retrofit part of an existing petroleum refinery.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
AltAir	C	2016 Expansion program Planned expansion	2,500 barrel/day 130,000 tonnes/yr	Confidential	Confidential	Operating 2016 2018 n.a.

2.5.4.6 Total

Total has rebuilt the refinery at La Mede to process vegetable oil, initially palm oil and local rape seed oil to diesel. This plant uses the Vegan technology from Axens. The plant is in commissioning in late 2018 and expected to come to nameplate capacity in 2019.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
La Mede	C	2018	500,000 tonnes/year	Confidential	Confidential	Commissioning on-going

2.5.4.7 REG

The company uses its own proprietary Synfining technology. It has recently announced plans for an expansion at the Geismar site in two steps, the first adding 37,000 gpy (11,000 tonnes/yr), the second expansion adding 10,000 gpy (30,000 tonnes/yr).

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
REG Geismar	C	2018	220,000 tonnes/year	Confidential	Confidential	Commissioning on-going

The company have also together with Phillips 66 in November 2018 announced plans for a new large-scale HVO plant (capacity not made public) constructed adjacent to the Phillips 66 Ferndale Refinery in Washington state. Planned feedstocks include a mix of Waste Fats, Oils, and Greases (WFOG), including regionally-sourced vegetable oils, animal fats and used cooking oil (UCO).

2.5.4.8 SCA-St1

The Swedish pulp and paper company SCA and Finish fuel company St1 are cooperating on a commercial biorefinery project with a capacity of 100,000 tonnes/yr based on tall oil. The biorefinery will be co-located with the Östrand mill outside Sundsvall and permitting procedures have been initiated. The Östrand mill will also be expanded to increase the tall oil output, but also tall oil from the Obbola and Munksund mills will be used in the biorefinery.

2.5.4.9 UCO based biodiesel UCO-ME

In total, the EU consumed 2.7 million tonnes of UCO and 0.8 million tonnes of animal fats for biofuels in 2017. This is a strong increase since 2001 when only 0.7 million tonnes of UCO and 0.3 million tonnes of animal fats were used. The share of UCO in the biodiesel feedstock mix is expected to increase to 22%. In 2017, the largest EU producers of UCO-ME were the Netherlands, Germany, and the United Kingdom. The Netherlands was by far the largest user of animal fat followed by Finland and France, but this also includes the HVO facilities in the two first countries, so how much is UCO-ME cannot be concluded. Germany, the United Kingdom, Denmark, Spain, Austria, Ireland, Italy, and Hungary also used animal fats but to a much lower extent. It has not been possible to find the share of all bio-diesel plant that produces UCO-ME, but in Spain 16 of 53 plants were pre-dominantly producing UCO-ME, but then not at an annual production corresponding to the nameplate capacity.

2.5.4.10 SABR-TCR®

The SABR-TCR® technology ("Sustainable Aviation Through Biofuel Refining") is developed by bio-diesel company Green Fuels Research Ltd. (UK) and Susteen Technologies GmbH, see Section 2.4.3.6.

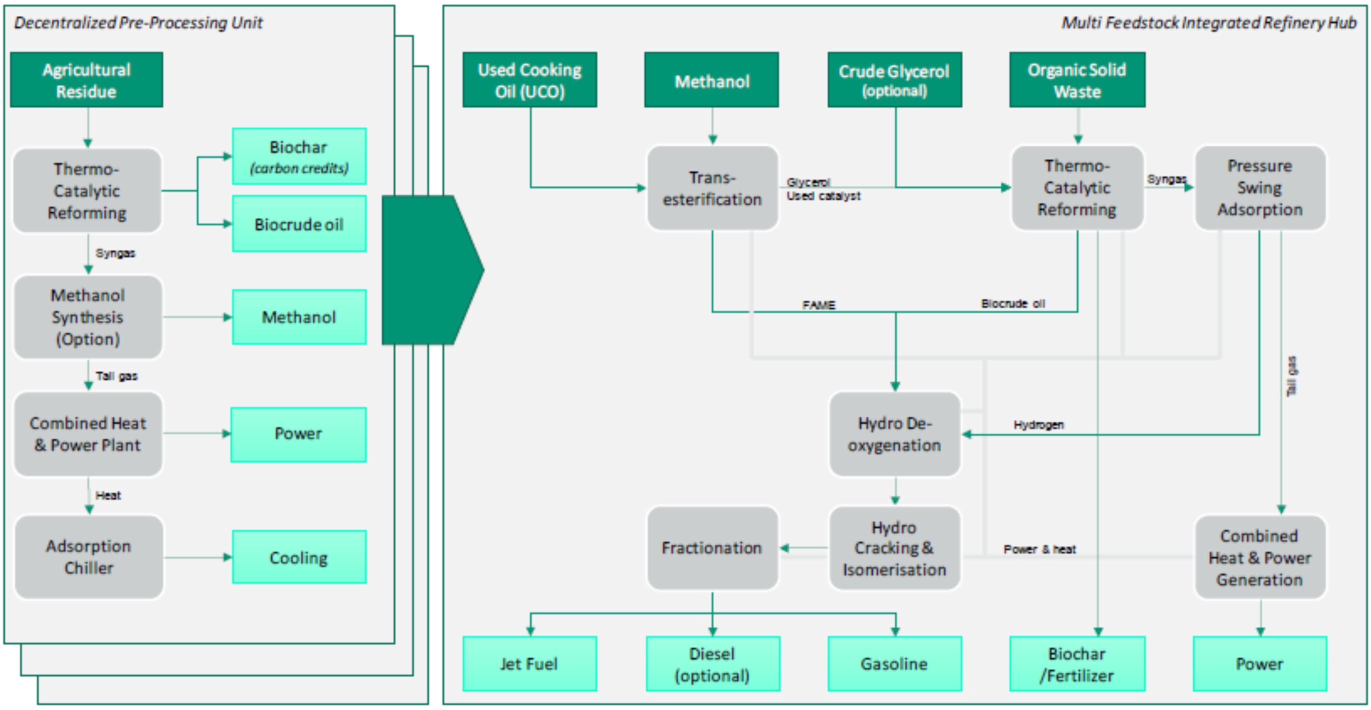
Green Fuels Research (GFR), the innovation branch of the Green Fuels biodiesel company, has developed and patented SABR, a new process for obtaining renewable aviation fuel from waste cooking oil, animal fat residues or other waste bio-oils. The SABR technology can both be used in greenfield plants, but considering the overcapacity of FAME plants, also be retrofitted to existing biodiesel production facilities.

The SABR technology uses a combination of hydrodeoxygenation, hydro cracking & isomerization and fractionated distillation to produce sustainable aviation fuel from FAME which is compliant to ASTM D7566 -11. SABR technology for SAF has been successfully tested at pilot scale since 2015 and is currently being scaled up to approx. 1,000 tonnes/year of fuel output.

In parallel a TCR® reactor processes organic waste fractions or other biomass residue to produce biocrude oil, hydrogen-rich synthesis gas and biochar. The system can also process glycerol from the transesterification as a co-feedstock thereby closing the loop on that side-product while increasing fuel yields.

While biocrude is co-refined with FAME in the SABR reactor, the hydrogen for oil refining is supplied from the TCR® syngas through industry standard PSA technology. The fuel components produced from TCR® biocrude are chemically comparable with fossil aviation and road fuels. Road fuel components comply with relevant norms, while the aviation fuel component is expected to meet the chemical parameters of fossil aviation fuel as well.

Nevertheless, TCR® aviation fuel components will still require adequate certification. During the certification process the alternative sale of TCR® fuel fractions into road fuel markets is viable.



The SABR-TCR® technology ("Sustainable Aviation Through Biofuel Refining")[7]

Additional biocrude oil could be supplied from satellite TCR® units processing locally available biomass residue without major transportation overhead, while supplying renewable power and biochar for agricultural use at such satellite locations. Using tail gases from the main processes the SABR-TCR® platform will produce sufficient renewable power and heat to cover its entire process energy demand from renewable sources, and any excess sold to third parties.

A demonstration project titled "FlexJET"[8] funded by the Horizon 2020 program is developing and demonstrating the concept, also including the construction and operation of a TCR500 commercial module.

A strategic partnership formed by Curcas Diesel Brasil Ltda., Green Fuels Research Ltd. (UK), Susteen Technologies GmbH (Germany), and RenewCo Ltda. (Brazil) has established an international consortium also including UMSICHT research institute (Germany), Embrapa Agroenergia (Brazil) and University of Birmingham (UK). The technology consortium proposes

[7] SABR-TCR: A Stand Alone Biorefinery Solution for ICAO´S "NO COUNTRY LEFT BEHIND". CAAF/2-IP/8 21/9/17. Conference on Aviation and Alternative Fuels, Mexico City, Mexico, 11 to 13 October 2017. Available at https://www.icao.int/Meetings/CAAF2/Documents/CAAF.2.IP.008.1.en.pdf
[8] http://www.flexjetproject.eu/

to demonstrate the integrated SABR-TCR® platform at pilot scale in Juiz de Fora, MG (Brazil) in the 2017-2021 timeframe. A pilot plant with a capacity of producing 1,000 tons per year of fuels (at least 50% SAF) is anticipated.

The above plans are linked to the Plataforma de Bioquerosene e Renováveis da Zona da Mata launched in June 2018, in an initiative led by the Municipality of Juiz de Fora together with 45 municipalities of the Zona da Mata region in Minas Gerais, Brazil. The objective is to implement a highly integrated value chain, “from research to fly”, to produce biofuels for the aviation sector. This initiative is based on a reforestation effort of native species across 130,000 hectares of the Brazilian Mata Atlantica Biome, incorporating processes to promote sustainable development in the region and produce biofuels for the heavy transport and aviation sectors. The Zona da Mata initiative will address both the off-setting requirements of ICAO’s CORSIA scheme and the need for biofuel to ensure the long-term sustainability of the aviation industry.

2.5.4.11 HVO developments in India

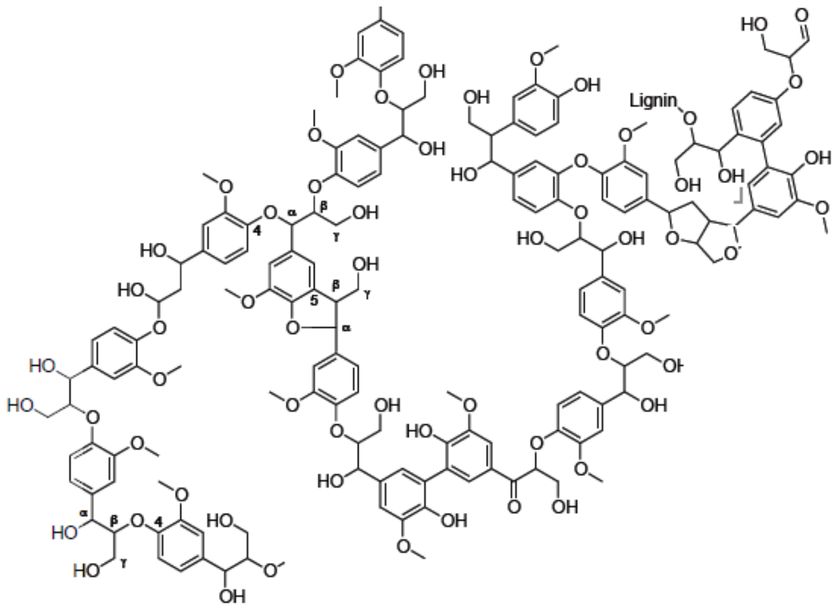
Indian Oil Corporation Ltd (R&D Centre) has developed a technology for co-processing of non-edible oils in the diesel hydrodesulfurization/ hydrotreating units of the refinery. A trial run of the technology was successfully carried out on at commercial scale in April 2013 at the Manali Refinery of Chennai Petroleum Corporation Ltd219 with 6.5% of Jatropha oil with diesel feed.

2.5.5 New Technology Developments

Hydrothermal liquefaction (HTL) of biomass is a thermochemical conversion process of wet biomass (lignocellulosic or other biomasses) into liquid fuels and chemicals by processing in a hot, pressurized water environment for sufficient time to break down the solid biopolymeric structure to liquid and gaseous components. This technology proposes an interesting method for bio-fuel production from various wet biomasses without additional drying of the feedstock that would be necessary for other thermal processes. HTL process usually produces four different product fractions which are: gas phase, solid residue, liquid aqueous phase and liquid oily phase, i.e., bio-crude. These four phases may not form directly as the bio-crude may be attached to the solid phase, from which it needs to be separated for example by means of extraction. The produced bio-crude has several utilization routes starting from simple blending into bunker fuel, but it can also be upgraded by co-feeding it to refinery units.

Typically, reaction temperatures of HTL vary from 250 C to 380 C (but can be higher) and pressure range is 4MPa-30MPa, so that water is in liquid form. The operating conditions are quite challenging in terms of having a slurry that can be pumped, which in many cases may require biomass pre-processing similar to second generation ethanol processes. Furthermore, the slurry and the product have an impact on pump, valves and reactor materials. The residence time needed to break down biopolymeric structures depends on temperature conditions in the process. Residence times of the biomasses inside the reactor are usually between 10 minutes and 1 hour and depend on the temperature and if the HTL processes are either batch operated or continuous. Most of the research has been done in batch processes, but several technology developers (PNNL/Genifuel, KIT, Aalborg University and Steeper Energy, Licella) are coming up with continuous systems. HTL has been studied for various biomass types from lignocellulose to manure, algae and wastewater sludge. VTT has studied the HTL process using black liquor as the raw material and found a special challenge in the recovery of the cooking chemicals.

However, this process has still to reach the demonstration phase and its contribution by 2030 is considered limited unless significant progress can be achieved within the next 5 years, i.e. by realising the prototype and commercial plants that are being planned in e.g. Canada and Norway.Another technology that has attracted attention is the conversion of lignin. Lignin is a bio-polymer which is together with cellulose and hemicellulose the main components of plant material. Lignin constitutes in the range of 10%wt to 30%wt of plants, depending on species, etc. It is also one of the few bio-aromatic substances that are abundantly available. The use of lignin as a raw material for producing various chemicals has therefore attracted attention for a long time, e.g. Borregaard, see Section 3.2.4.10, is making vanilla flavour from lignin and lignosulphonates used e.g. in concrete is a bulk product from sulphite mills. The interest in lignin chemistry has risen due to the interest for bio-based materials and green chemistry as well as that in when second generation, cellulosic ethanol takes of as an industry, lignin will be produced as a by-product in large quantities, and maybe valorised better than for its fuel value.



A representation of the structure of lignin[9]

Also, the conversion of lignin in Kraft black liquor to bio-materials and biofuels have been studied. In the paper and pulp mill, the Kraft recovery boiler is the single most costly component in the mill and when pulp production increases, it will eventually also be the bottleneck. By removing some of the lignin from the liquor going to the recovery boiler, pulp production can

[9] https://www.nrel.gov/research/gregg-beckham.html

increase without investing in a new recovery boiler, and hence there are strong drivers for the lignin extraction and valorisation of this concept. This can be done by processing the black liquor as-is, or by separation of the lignin by e.g. precipitation (e.g. Lignoboost process, a demo plant at Bäckhammar and 2 commercial units, Domtar, Canada, Sunnila, Finland) or by filtration (e.g. Suncarbon, demonstration at Smurfit Kappa Kraftliner, Piteå). The lignin can thereafter be process into different products.

Apart from the more commercial scale developments presented below there are also other activities e.g. using base-catalyzed HTL depolymerization of LignoBoost lignin at being developed at Chalmers Technical University and by Suncarbon, HTL of filter-seprated ligning with CO_2 acidification., and hydrogenolysis at RISE Innventia.

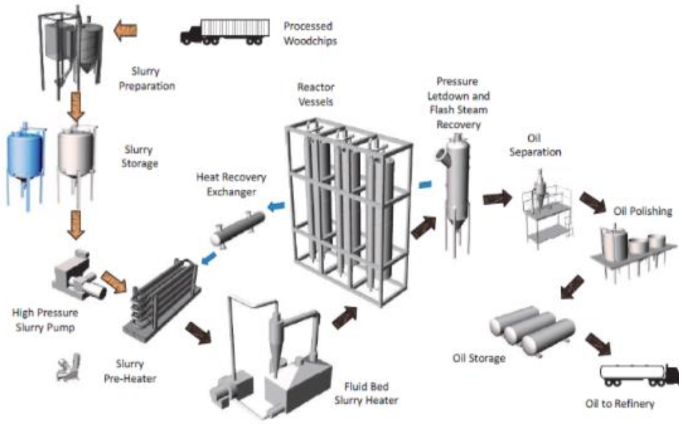
2.5.5.1 Licella

Licella was formed in Australia in 2008. Licella's technology currently uses non-food, sustainable plant material such as radiata pine sawdust. It is mixed with water to form a slurry, and injected into a continuous flow, Catalytic Hydrothermal Reactor (Cat-HTR). The heat and pressure in the reactor rapidly transform the feedstock into refinery ready, 'drop-in' biocrude oil.

In 2009-2012, Licella's proprietary technology was trialled for verification and validation of the Cat-HTR process at a pilot plant in Somersby, north of Sydney, New South Wales, where radiata pine sawdust has successfully been converted into biocrude oil. A second, larger pilot plant was used after 2011 and a demonstration plant started operation in 2013.

While the pilot plants required very fine wood particles, <0.3mm in diameter, the demonstration plant accepts woody waste feedstock from 3mm to 6 mm diameter.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Licella Pilot 1, Somersby, AU	P	2009	(1 kg/hr)	(0.5 l/hr)		Operated to 2012
Licella, Pilot 2, Somersby, AU	P	2011	15 kg/hr	4 l/hr		
Licella, Demo, Somersby, AU	D	2013	125-1,250 kg/hr	500-4,000 l/yr		



TLicella demo plant, Somersby, AU The Licella process flowsheet

Licella™ has formed a joint venture with Canfor Pulp, a Canadian supplier of pulp and paper products. The joint venture was formed to integrate Licella's Cat-HTR™ platform into kraft and mechanical pulp mills, utilising waste streams to create renewable fuels and chemicals. Canfor and Licella have started a project to perform engineering work to integrate the Cat-HTR into Canfor Pulp's Prince George (British Columbia) mill. The plant is said to process wood wastes and other by-products and the output of this first project is 70,000-90,000m^3/yr. The refiner Husky Energy in Prince George is working, through a Low Carbon Fuel Standard agreement, to develop the capacity for co-processing with the Canfor Pulp/ Licella joint venture.

2.5.5.2 Steeper Energy/Silva Green fuels

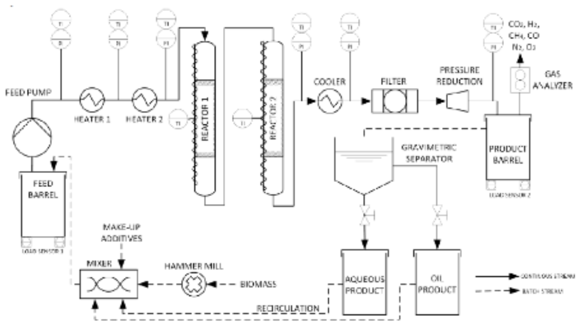
Steeper Energy Aps in Denmark was formed in 2011, and also has a Canadian subsidiary. Hydrofaction™ is Steeper Energy's proprietary implementation of hydrothermal liquefaction which applies supercritical water as a reaction medium for the conversion of biomass directly into a high-energy density renewable crude oil, referred to as Hydrofaction™ Oil. The process is claimed to utilize a wide-range of biomass feedstocks (Forestry and agriculture residues, energy plants/crops, industrial food processing, sugar refining, oil seed milling, production wastes from alcohols or ethanol, urban source separated wastes, animal manures or bio-solids (sewage sludge) and, aquatic biomass, etc.) and to process feedstocks as-harvested without the requirement of pre-drying. Steeper Energy has tested over fifty different feedstocks and mixtures including:

The biomass, pre-treated to allow slurrying the solids in recycled water and HTL oil to 15%-20%wt solids, is injected as a slurry into a 400°C pre-heated reactor at supercritical pressure (35MPa). The reactor allows rapid heat up to the reaction conditions and has a slurry residence time of ~15 minutes and then quickly cooled down to 70°C.The process conditions, with the operating temperature and pressure well above the critical point of water, and the use of homogeneous catalysts, (K_2CO_3), a few %wt in the slurry, leads to the formation of low-oxygen renewable crude oil. The catalyst together with control of the pH to alkaline conditions, gives the desired catalytic effects. The catalyst is recovered and recycled to improve the process economics. Additionally, recycling of oil to the and process water effluent to the slurrying step is a unique feature of Hydrofaction™ which brings synergistic benefits in various parts of the process. The process is claimed to achieve biomass-to-oil conversions of 45% on a mass basis and 85% on an energy basis, with water and a gas being the by-products. The excess water is purged, the catalyst is recovered, and the Total Organic Carbon (TOC) reduced to allow disposal. The HTL process only consumes approximately 10%-15% of the energy in the feedstock biomass. The heat energy is also recycled between the heating and cooling of the process medium.

The oil has a high heating value, 38 MJ/kg or more and a low oxygen content, typically around 10%.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Steeper, Aarhus, DK	P	2013	30kg/hr slurry	(0.5l/hr)		4,750 Nov. 2017

The HTL oil produced can be upgraded by refinery processes. Steeper Energy cooperates with the University of Aalborg, Denmark and with the Universities of Calgary and Alberta on the upgrading of the oil.



The Steeper pilot plant flowsheet

The Steeper pilot plant, Aarhus, Denmark

A continuous pilot facility, located at the campus of Aalborg University, Denmark is in operation since 2013. The pilot plant has demonstrated the Hydrofaction™ technology and has surpassed 4,750 hours of hot operation with over 1,750 hours of oil production hours up to November 2017.

Since 2015, Steeper Energy has a collaboration with Silva Green Fuels AS, a Norwegian JV company between Statkraft, a Norwegian energy company ad Södra Skogsägarna, a Swedish pulp mill company. A demonstration plant at the former Södra mill at Tofte, Norway, is planned to start-up spring 2019, with a capacity of about 4,000 litres per day. The raw material will consist of residual products from the forest industry. However, as far as known the construction on site has not yet been started.

2.5.5.3 RENFUEL

RenFuel is a Swedish biofuel company that is a spin-off from a research group at Uppsala University in 2012, that developed a renewable, lignin-based bio-oil under the product named

Lignol. The subsidiary company Renfuel Production AB company has a minority shareholder and financial guarantor in the form of Preem, the largest fuel company in Sweden.

Lignol is manufactured using the feedstocks lignin and a Mixed Fatty Acid (MFA) as blend oil. In particular Tall Oil Fatty Acids (TOFA), seem to be of interest. Lignin and an MFA are processed into Lignol using process chemicals and utilities at mild pressure and mild temperature. A pilot plant with a capacity of 0.4 tonnes/hr has been in operation at the Bäckhammar mill since 2016.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Renfuel, Bäckhammar, SE	P	2016		0,4 tonnes/hr		

In September 2017, RenFuel concluded a cooperation and development agreement with the forestry industry company Rottneros regarding collaboration on the development of lignin extraction from Vallvik Mill in Söderhamn and a LOI for coming guarantee volumes of raw material, lignin, to Lignol plant. In May 2018, RenFuel also signed a cooperation agreement with Preem to secure downstream capability and guarantee revenue from Lignol: This forms the basis for being able to produce 77,000 tonnes/yr of Lignol for commercial use from 2021, using 25,000 tonnes/yr lignin and 50,000 tonnnes/yr MFA.

2.5.5.4 Swedish Cellulose Company (SCA)

The pulp and paper company SCA is, in addition to the planned biorefinery project with St1, see Section 2.5.4.8, developing a black-liquor-to-biofuel process. The details of the process are not publicly available.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
SCA, Obbola, SE	P	2016		1 litre/hr		Operated to 2012

A 24 litre/day crude bioliquids pilot unit was constructed in 2016 at the Obbola mill in mid-Sweden.

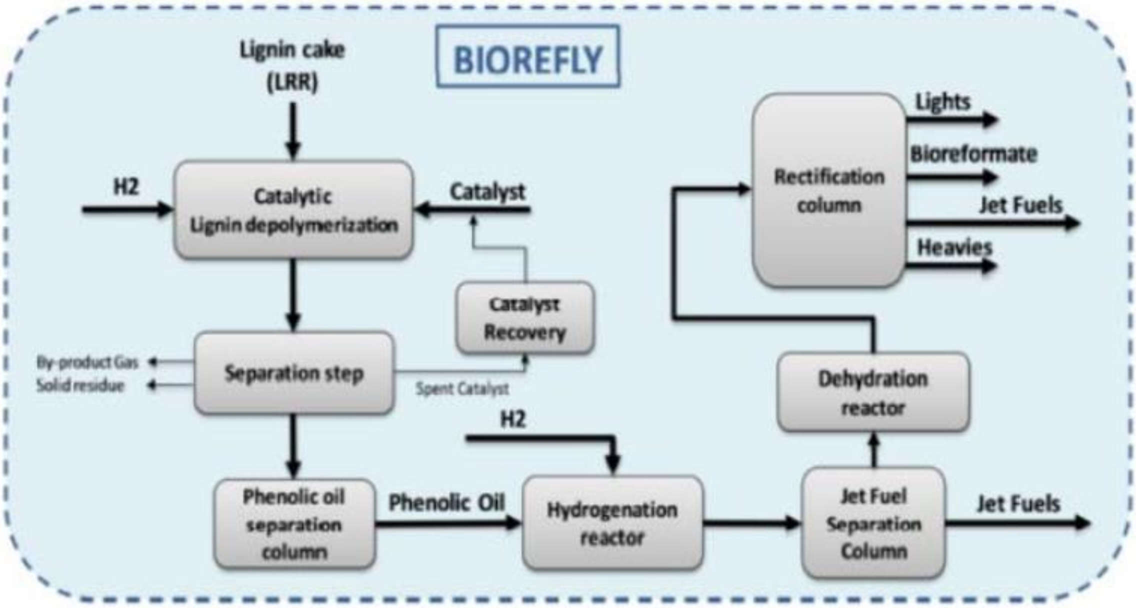
2.5.5.5 BioREfly, (Mossi & Ghisolfi)

Mossi & Ghisolfi (M&G) of Italy is investigating if the lignin fraction being a by-product from their second-generation ethanol plant can be upgraded using fermentation pathways. The project is called BIOREFLY. The research goals of the FP7 project are linked to the construction and operation of a pilot plant based on second generation technology. The goal of the BIOREFLY project is the construction of a 2,000 tonnes/y bio jet fuel plant.

It will use lignin cake obtained from the conversion of both dedicated energy crops and agricultural residues in the second-generation bioethanol production biorefinery in Italy.

The feedstock is lignin derived from the Biochemtex PROESA® technology is characterized by having ~60% moisture content. The first phase of the process focuses on the continuous conversion of the lignin-rich feedstock by means of a hydro-cracking reaction in presence of hydrogen gas and heterogeneous metal catalyst between 250°C to 370°C and in a pressure range of 12MPa to 200MPa. This process phase aims at liquefying and depolymerizing the feedstock into a dense and quite viscous oil composed of monomer and oligomers of lignin and depolymerized heavy hydrocarbons, “phenolic oil”. In the second step, a second catalytic hydrogenation/hydrodeoxygenation reaction, the phenolic oil is converted to a less viscous and dense oil, rich in long chain alkanes, cyclic aliphatics (naphthenics) and small amount of cycloalcohols with a negligible amount of oxygen (~1%). This product is separated by fractionation into kerosene, naphtha etc.

Due the business difficulties of the M&G group in 2017 and its impact on the ethanol business, the project was suspended; however in 2018 the assets of Biochemtex (which owns the PROSEA technology) were taken over by VERSALIS SpA, a daughter company of ENI, and it is expected that the project will restart by mid-2019.



BioREfly process[10]

[10] Chiaramonti D., Buffia M., Palmisano P., Redaelli S.: “Lignin-Based Advanced Biofuels: a Novel Route Towards Aviation Fuels”. Chemical Engineering Transactions, Vol. 50, pp. 109-114, AIDIC Servizi S.r.l., 2016. DOI: 10.3303/CET1650019.

3. Biochemical conversion

This chapter separates the following four conversion routes:

- Sugars to alcohols
- Sugars to hydrocarbons
- Hemi- and Cellulosic material to bio-methane via anaerobic digestion
- Gas to alcohols and hydrocarbons

With respect to initial treatment of the feedstock the first two (sugar) conversion routes are carried out in basically the same way. The diversification follows thereafter.

3.1 Feedstock and its pre-treatment (for alcohols and hydrocarbons)

Lignocellulose is the structural material of biomass. It consists of cellulose (mainly C6 sugar polymers like the sugar extracted from sugar and starch crops), hemicellulose (mainly C5 sugar polymers) and lignin (aromatic alcohol-polymers). The term "lignocellulosics" includes agricultural and wood residues, wood from forestry, Short Rotation Coppices (SRCs), and lignocellulosic energy crops, such as some of the energy grasses and reeds. It also applies to waste fractions such as cellulosic fibres from cardboard and recycled paper.

3.1.1 State of the art pre-treatment processes

A pre-treatment is generally first applied on the raw material before saccharification to separate the different components referred to above. The most common one is the steam explosion with or without an acid catalyst. The nature of the pre-treatment has large impact on the accessibility of the cellulose and hemicellulos for saccharification and also for the formation of inhibitors for the enzyme and yeast, respectively.

Once the cellulose and the hemi-cellulose are separated from the lignin solids in the pre-treatment it is mixed with some water and saccharification of the cellulose polysaccharides and hemicelluloses oligomers can take place, generally speaking through enzymatic hydrolysis (use of specifically developed cellulases and hemi-cellulases enzymes cocktails), but also acid hydrolysis has been used. After this pre-treatment the substrate, a viscous two-phase fluid, is ready for further processing into various types of products. Lignin is separated before or after fermentation and usually dried to be used as a fuel for the process and/or for power generation.

The saccharification step and the fermentation step can be performed separately, Separate Hydrolysis and Fermentation (SHF) or combined into one step, Simultaneous Saccharification and Fermentation (SSF).

3.1.2 Organosolve processes

As an alternative to the thermochemical treatment of biomass via, typically, steam explosion, and treatment with chemicals such as acids, bases and enzymes in various combinations, organosolve processes, originally developed as alternative pulping processes, have also been developed to produce ethanol. The organosolve process is said to yield a purer cellulose fraction with less inhibitors than the conventional processes, and also better lignin product as the cellulose is more delignified, and the lignin having less traces of cellulose and also being less depolymerized. However, the use of solvent requires a costly make-up and also recovery process consuming energy. There is therefore an economy-related ambiguity between the aims of producing cellulose and lignin as starting point for bio-based chemistry or for ethanol production among most developers.

Chempolis in Oulu, Finland, established in 1995, is developing a fractionation process where wood- and non-wood fibre are treated with formic acid in a single-stage process for a few hours at 110°C–125°C. The liquor containing the lignin and the hemicellulose hydrolysate is separated from the solid cellulose. The liquor is further processed to a lignin fraction and a pentose syrup, while the formic acid is recovered by evaporation/distillation. The cellulose product can either be used as fibres, the formicofib™ process or for ethanol production formicobio™ process. The fibre production line has been demonstrated as of 2008, papermaking from the fiber as of 2010 and ethanol production since 2011 in a pilot plant capable of processing 25,000 tonnes per year of non-wood and non-food raw material. Since 2017, Fortum is the largest share-holder and attempts have been made to establish plants in China and India. In India a JV was established with Numaligarh Refinery Ltd. for a biorefinery in Assam, India, to convert 300,000 tonnes/yr of bamboo annually into ethanol and other products, but the construction has not been initiated.

The French company Compagnie Industrielle de la Matière Végétale, CIMV, was founded in 1998, in order to implement a proprietary biorefinery technology. It took the company ten years of laboratory work to reach the construction of a 50 kg/hr pilot plant in 2006 at Loisy-sur-Marne, Marne, France, to develop and validate the process. In 2017, a 1 tonne/day pilot was taken into operation at SAS Pivert, Venette, Oise, France.

In the CIMV process, wheat straw, or other biomass, is treated with water solution of acetic acid and formic acid in two stages for a number of hours at 105°C and atmospheric pressure. The lignin is dissolved, and the hemicellulose is hydrolysed to oligo and monosaccharides into the liquor, which is separated from the solid cellulose. The solvent is recovered by evaporation/distillation and the lignin is precipitated by adding water and separated from the pentose syrup by filtration. The process can use the pentose syrup to produce ethanol. In addition, the cellulose, which is of high purity, can be hydrolysed enzymatically with less inhibitors than convention cellulosic ethanol processes, and also used for ethanol production.

3.2 Ethanol and higher alcohols from lignocellulosic sugar via fermentation

3.2.1 Yeast fermentation to ethanol

C6 sugars are fermented by bioengineered, including genetically modified, microorganisms. Most commonly these are of strains derived from traditional yeasts that are also used for the production of wine, beer or bread.

For the fermentation of C5 sugars genetically modified yeasts have been developed in the recent years.

As ethanol can be toxic for microbial strains at high doses, there is a limit to the maximum concentration in the brew produced by the yeasts, but there is also a strong interaction on the amount of water added in the process upstream to have a suitably low viscosity feed in the enzymatic step and the energy use in the final separation of the ethanol.

Also, the water addition in the upstream pre-processing reduces the ethanol content. The upgrading of ethanol from lower concentrations to the required minimum 98.7%wt for the application as biofuel is performed employing the following known and widely applied technological steps in beverage production:

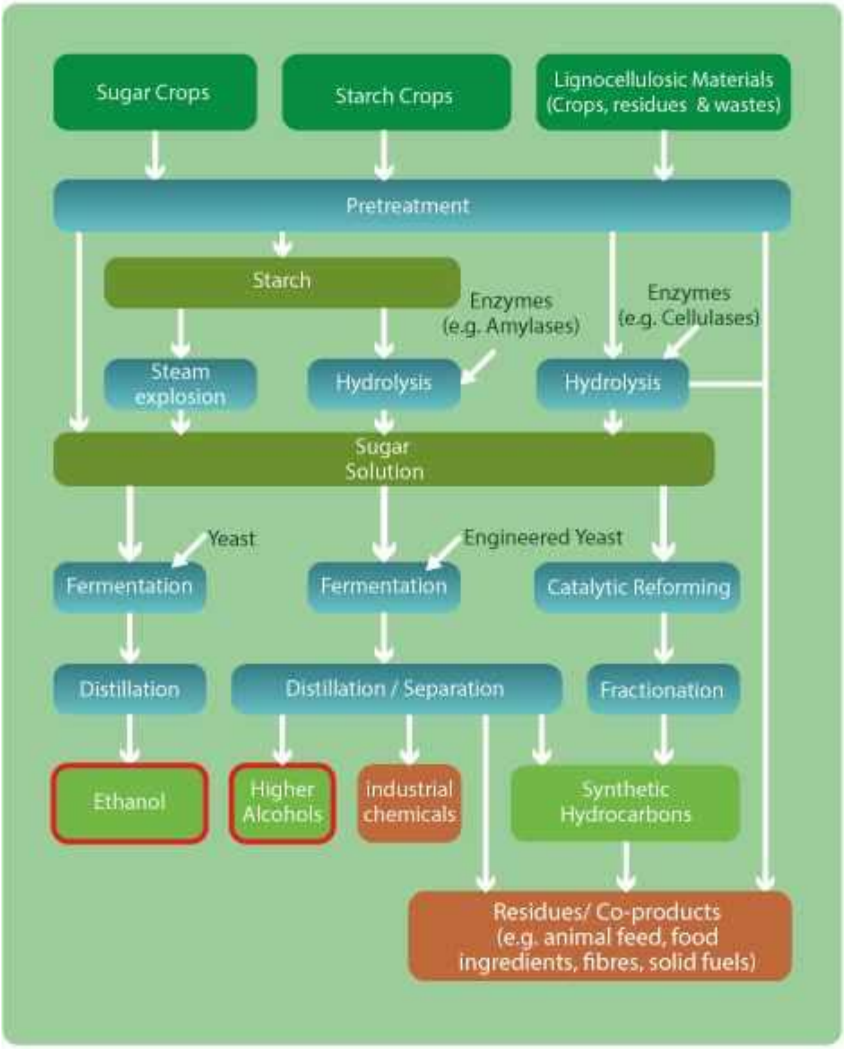


Figure 3.1 Ethanol and higher alcohols via fermentation

- Evaporation of ethanol: in this step the first evaporation of ethanol is performed in order to obtain 'crude' ethanol with concentration ~45%vol.
- Rectification: in rectification the ethanol concentration is increased to ~96%vol. for hydrous alcohol.

Dehydration is additionally required to arrive at 99.5%vol. for blending in gasoline. The remaining azeotropic water in the hydrous alcohol is removed in order to obtain the fuel bioethanol with concentration 98.7%wt and water content below 0.3%wt using zeolite absorbents in a Vacuum Swing Adsorption (VSA) process.

3.2.2 Yeast fermentation to butanol

There is significant interest in the production of butanol as a biofuel because its properties are more adequate to a gasoline blend (e.g. vapor pressure, water entrainment) but the production cost is still more expensive than for ethanol. Some bacteria naturally produce butanol and yeast can be engineered to produce butanol instead of ethanol. Butanol may serve as an alternative fuel, as e.g. 85% Butanol/gasoline blends can be used in unmodified gasoline engines. This pathway can be used for producing both n-butanol and iso-butanol. However, the latter also has a high value as a chemical building block (Gevo, Butamax). At present there are no quality standards for using butanol as a blend with gasoline.

3.2.3 Microbial Fermentation via Acetic Acid

Microbial fermentation of sugars can also use an acetogenic pathway to produce acetic acid without CO_2 as a by-product. This increases the carbon utilization of the process. The acetic acid is converted to an ester which can then be reacted with hydrogen to make ethanol.

The hydrogen required to convert the ester to ethanol could be produced through gasification of the lignin residue. This requires fractionation of the feedstock into a sugar stream and a lignin residue at the beginning of the process (Zeachem).

3.2.4 Pilots, Demonstration and Commercial plants

3.2.4.1 The Hugoton Plant, Kansas, USA

The Hugoton plant was in late 2016 sold to Synata Bio. The plant entity was in bankruptcy following the default of the mother company and was sold for 48.5 million $US through the bankruptcy court. The purchase excluded the intellectual property contained in the process and license agreements with Abengoa Bioenergy New Technologies LLC. Synata Bio has taken over technology earlier belonging to the company Coscata, a company which have been active in fermentation of syngas. Current status of the Hugoton plant is not known.

Abengoa, which also has been producing first generation ethanol in several installations in the EU and USA, developed its lignocellulosic ethanol technology based on data received from its pilot plant (capacity 100 m^3/year) which was started up 2007 in the US and its Salamanca demonstration plant started up 2009 in Spain (capacity 5,000 m^3/year). The pilot plant was operated with a variety of feedstock materials and the demonstration plant was initially fed with wheat straw which later was replaced by the biomass fraction separated out from municipal solid waste material. The operational experiences have led to development of own patented technology and development of its own enzymes for the pre-treatment of the feedstocks. Experiences from the two afore mentioned plants led to construction of the first commercial plant in the USA. The key technologies are based on a sulfuric acid-catalysed steam explosion pre-treatment, in situ enzyme production, enzymatic hydrolysis and co-production of C5 and C6 sugars to ethanol.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product	Hours in operation
Hugoton	C	2014	997.7 tonnes/d (dry)[11]	~95 million litre/yr	18 MW_{el}	n/a

The plant has (in 2016) started to export ethanol (several rail cars). Currently the plant is going through various plant optimization issues such as feedstock handling optimization. Data provided in the quoted article indicates an energy conversion efficiency from biomass to ethanol of about 33%.

Abengoa's Hugoton Plant, Kansas, USA

3.2.4.2 *Crescentino plant, Italy*

Versalis SpA, the chemicals arm of Italian energy company Eni, has acquired Mossi Ghisolfi (M&G) Group's "green" businesses, in September 2018. M&G has experienced financial difficulties in its PET plastic division spilling over to the biofuels part. The acquired operation includes the four companies of Biochemtex S.p.A., Beta Renewables S.p.A., IBP Energia S.r.l. and the Italian Bio Products S.r.l. Many of the operations are based on biofuels, but they also include products used in bio-based plastics. The new owner of the Crescentino plant was in the autumn of 2018 not in a position to share further data and experiences about the plant or future plans for the technologies.

The Biochemtex plant of BetaRenewables (a company in the Italian M&G Group) uses its own technology (PROESA technology) to produce ethanol from various types of feedstocks. The PROESA technology utilizes heat treatment followed by enzymatic hydrolysis for

[11] Data from http://www.abengoabioenergy.com/web/en/2g_hugoton_project/ Waste from ethanol production plus extra biomass.

pretreatment of the feedstocks. The plant is a combination of a large demonstration plant and a commercially operated plant. The Crescentino plant was the first plant in the EU but also on a global scale to produce cellulosic ethanol.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Beta Renewables	C	2013	n/a	25,000 -40,000 tonnes/yr	n/a	--

The plant has been in operation for two years (2016) with support from NER 300 and also from the FP7 framework program.

Production capacity varies depending on type of feedstock. Straw as feed yields less ethanol (25,000 tonnes/year) than if the feed is e.g. Arundo (40,000 tonnes/year). Conversion rates also vary accordingly, and typical yield of ethanol can be expressed as 4.5-6.5 tonnes dry biomass per tonne of ethanol. On an energy efficiency basis (biomass to ethanol) this corresponds to 32% to 22%.

Feedstock quality/consistency is listed as the most challenging variable effecting production and plant availability.

Biochemtex' Crescentino plant, Italy

DuPont's Nevada Plant, Iowa, USA

3.2.4.3 DuPont's Nevada Plant, Iowa, USA

Following the merger with DOW and the decision to leave the biofuels business, DuPont put the 30 MMgy (90,000 tonnes/yr) cellulosic ethanol plant in Nevada, Iowa, up for sale in the autumn of 2017. In November 2018 it was sold to Verbio North America Corp., the U.S. subsidiary of German bioenergy producer Verbio Vereinigte BioEnergie AG. Verbio is planning to convert the facility to produce renewable natural gas (RNG) from straw.

DuPont constructed and commissioned its commercial sized cellulosic ethanol facility in Nevada, Iowa (US). Commission took place in 2016. The technologies used in the plant are developed and owned by DuPont. The process used to convert these feedstocks involves mild alkaline pretreatment, Bio-catalytic saccharification (enzymes) and fermentation (both C5 and C6 sugars), ethanol recovery, filtration, evaporation, and anaerobic digestion.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Nevada	C	Target 2016	~960 tonnes/d	~247 tonnes/d	--	----

On a yearly basis the plant will use 350,000 dry tonnes of corn stover to produce 90,000 tonnes of ethanol. Key areas of concern which may affect ability to attract many licensees of the DuPont Cellulosic Ethanol Technology are clarity and stability of biofuel regulation, biomass collection and supply, capital requirement and cost of operation. Starting up of a first of its kind plant and technology licensing business during a period of very low oil prices is also challenging.

3.2.4.4 GranBio's Bioflex 1 Plant, Alagoas, Brazil.

The Bioflex 1 plant is owned by GranBio and is utilizing the PROESA two-stage pretreatment steam explosion technology from BetaRenewables, enzymes from Novozymes, and yeast from DSM in Holland. The Bioflex plant is co-located with an existing first-generation ethanol plant from sugarcane, the Caeté suger mill. Both facilities only share a common CHP unit integrated in the same site that uses both sugarcane bagasse (1G plant) and lignin (from 2G plant). The integrated power unit coproduce 70MW_{el}, having a surplus of 50MW_{el} sold to the grid. The PROESA technology is the first to have been licensed and used in two commercial facilities.

The plant is designed to produce 195 tonnes/d of ethanol from 1,000 tonnes/d of bone-dry bagasse. This gives an energy conversion efficiency of about 28% for bagasse to ethanol. The plant is designed to operate for 8,000 hours per year.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Bioflex 1, São Miguel dos Campos,Alagoas, Brazil	C	Q4 2014	400,000 tonnes/yr	65,000 tonnes/yr	Steam and power	see text

The year of 2016 was dedicated for adjustments in equipment and production processes in order to achieve operational stability. During the fourth quarter of 2016 and the first quarter of 2017, the company performed production tests. In the end of the first semester of 2017, GranBio exported the amount of ethanol produced during such tests, 5 million litres, to the USA. From that point onwards, the company started the reengineering projects which aim at achieving operational stability in commercial scale. The facility is now under recommissioning and is expected to reach partial operation in January 2019.

GranBio's Bioflex 1 Plant, Alagoas, Brazil

3.2.4.5 Raizen (Shell, Cosan), IOGEN, Costa Pinto, SP, Brazil

Raízen advanced ethanol plant has been co-located into an integrated site with an existing first-generation sugarcane ethanol plant (Usina Costa Pinto). Key technologies use the Iogen´s pretreatment technology based on acid-catalysed steam explosion followed by enzymatic hydrolysis (enzymes supplied by Novozymes) and fermentation.

The plant is designed to produce 40 million litres (32,000 tonnes) per year. During the 2017/2018 sugarcane season, the facility produced 12 million litres of 2nd Generation Ethanol (E2G), which corresponds to a yield of 211 litre of E2G per tonne of dry sugarcane biomass. The target is to reach 290 litres of E2G per tonne of dry sugarcane biomass. It is expected that the plant will reach its maximum production capacity of 40 million L in the 2018/2019 sugarcane season.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Piracicaba	C	2015	N/A	32,000 tonnes/yr	Steam and power	Not provided

Raizen has 24 conventional plants in operation and claim that a number of these can be equipped with a cellulosic plant in parallel as the Costa Pinto facility. The company states that seven more cellulosic ethanol plants will be taken into operation up to 2024.

3.2.4.6 POET-DSM Liberty Plant, USA

POET-DSM Advanced Biofuels company is a 50/50 joint venture between POET LLC and Royal DSM. This second-generation cellulosic ethanol plant is co-located with a grain-based 1G ethanol plant and uses a proprietary biomass pre-treatment technology contracted to ANDRITZ (through the US ANDRITZ subsidiary) based on a two-stage acid-catalysed steam explosion, followed by enzymatic hydrolysis with DSM-tailored enzymes. The fermentation of C5 and C6 sugars occurs in a single pot using DSM engineered yeast. The lignin streams as well the waste organic streams from the plant are mixed and undergoes anaerobic digestion to produce biogas for power supply.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product *	By-product	Hours in operation
Project LIBERTY	D/C	2015	770 tonnes/d (bone dry) corn stover[12]	60,000 tonnes/yr (or 20 million gallon/yr)	Energy (steam and biogas)	See text

The plant is currently (2016) ramping up production to full capacity. Information regarding performance is not provided. Provided information on product (at full capacity) and feedstock gives a conversion efficiency of biomass to ethanol of 33%. This is under the assumption that the plant is planned to be operated 8,000 full load hours per year.

The plant has started to ship product periodically by rail and the plan is to be at full capacity by year end 2016. Ramp-up efforts are primarily focused on improving biomass flow in pre-treatment.

Initial operations revealed problems with the pre-treatment part of the process. Toxicity in the fermentation has been resolved. The company has decided to invest in on-site production of enzymes and the plant is planned to be operational in the summer of 2019. The process has met close to its goal with respect to conversion efficiency reaching 70 gal/ton. This corresponds to 33% energy conversion efficiency.

To meet 770 tonnes / day of feedstock the plant needs to import about 260,000 tonnes per year. So far, the yearly import has been between 40,000 and 150,000 tonnes per year.

When the plant is in full operation the intension is to license the technology/process package for replication.

POET-DSM Liberty Plant, USA

The SEKAB Plant, Sweden

[12] at full capacity

3.2.4.7 The SEKAB Plant, Sweden

The SEKAB plant utilizes the following technologies:

- The plant is utilizing SEKAB's CelluAPP™ technology.
- Pre-treatment of the feedstock with heat and catalyst (alkali or acid if needed) followed by steam explosion.
- Enzyme hydrolysis (in batch or continues operation) with detoxing technology. Separation of hydrolyzed sugars before enzymatic hydrolysis
- Separation of sugars (if that is the end product, alternatively a lignin free sugar solution is desirable) Evaporation of the liquid to get a higher sugar concentration is possible.
- Fermentation with yeast or bacteria for production of ethanol or other chemicals
- Separation of solid and liquid before or after fermentation (SHF, SSF).
- Distillation of the final product. Separation of solids possible after distillation

Plant	Type P/D/C	Start-up year	Feedstock capacity[13]	Product	By-product	Hours in operation
SEKAB	P	2005	2 tonnes/d (dry) (=10.6 MWh/d)	3.5 MWh/d (ethanol)	4 MWh/d (lignin) 1MWh/d (biogas)	>60,000

The longest continuous run with the same process parameters has been 4 weeks but typically runs in three weeks campaigns. The plant is a development plant. For ethanol production the targets have been met but for other applications work is ongoing. It has been operated on a variety of feedstocks such as soft and hard wood, straw and bagasse.

A potential technology barrier is obtaining a long-term stable process with biocatalysts like enzymes and yeast.

The next step is to build the first reference plant in a production scale that can produce ethanol or other chemicals based on the SEKAB CelluAPP™ technology. One project with this goal is the CEG Plant Goswinowice in Poland, where NER300 support was received, but where activities have not yet started.

3.2.4.8 The Butamax plant, United Kingdom

Butamax™ Advanced Biofuels, LLC was formed to develop and commercialize biobutanol as a next generation renewable biofuel and chemical. The company benefits from the synergy of DuPont's proven industrial biotechnology experience and BP's global fuels market knowledge. The two companies own Butamax™ in a 50/50 venture. The Butamax™ plant demonstrates the microbial production of isobutanol as a single fermentative product, the process engineering for recovering biobutanol produced during fermentation, engineering

[13] soft wood as feedstock (about 1 tonne/d on straw)

design for optimized energy integrations, and various renewable fuel and chemical compositions.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Hull	P	2011	0.2-0.3 tonnes/d	0.057-0.068 tonnes/d of Isobutanol	n/a	n/a Batch unit runs continuously since 2011

The process is a batch process, which has been operated batch-after-batch for most of the last 4 years with planned shutdown for equipment changes and safety inspections. The pilot plant has now been mothballed because piloting testing is complete. No technical barriers have been reported so far.

The two owners of the Butamax™ technology announced in April 2017 that they have bought the first-generation ethanol facility in Scandia, Kansas (30,000 tonnes/y of ethanol) and have started detailed engineering of a Butamax™ plant for production of iso-butanol to become part of the facility, but the ethanol production will continue in parallel.

3.2.4.9 The Inbicon plant, Denmark

The plant has been used to demonstrate different process configurations. The most relevant configurations to mention are:

- Version 1: 2G Bioethanol based on C6 fermentation
- Version 2: 2G Bioethanol based on C5 and C6 fermentation.

The capacity of different unit operations was fitted to obtain a plant capacity of 4 t/h of straw input. Change of process configuration reduced the capacity of some unit operation and therefore also the overall capacity of the plant.

The key technologies used in the Inbicon demonstration plant (Kalundborg, DK) are a three-stage continuous process:

(1) biomass mechanical conditioning;

(2) hydrothermal pre-treatment followed by

(3) a pre-enzymatic hydrolysis at high dry matter consistency (up to 30% d.m.) which provides a continuous liquefaction.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product	Hours in operation
Inbicon Version 1	D	2010	96 tonnes/d (86% dry)	13 tonnes/d ethanol	30 tonnes/d lignin (90% dry) 45 tonnes/d C5 molasses (65% dry)	15,000

The plant was operated in a continuous mode during 2010 and 2011. The plant produced 98MWh/day of ethanol, 167MWh/day of lignin and 104MWh/day of C5-molasses from 386MWh/d of straw. The yield of ethanol was according to expectations.

In the first period of operation there were issues with impurities in the feedstock influencing the performance as well as excessive wear of certain equipment. These hurdles were overcome during the first year of operations.

Next step in development included conversion of both C6 and C5 sugars. The plant was then operated as follows.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product	Hours in operation
Inbicon Version 2	D	2013	24 tonnes/d (86% dry)	4.5 tonnes/d ethanol	9 tonnes/d lignin (90% dry) 7 tonnes/d C5 molasses (65% dry)	5,000

During 2013 and 2014 the plant was operated in campaigns of typically 4-6 weeks. The longest run lasted 9 weeks. In this version 2 technology using C5/C6 mixed sugar fermentation to ethanol the ethanol yield did improve 40%, from 200 litres/dry tonne feedstock (v1) to 280-300 litres/dry tonne feedstock (version 2). In version 2 the only co-product is lignin pellets used for power generation in a CHP plant nearby that belongs to the group DONG Energy.

The plant produced 34MWh/day of ethanol, 50MWh/day of lignin and 10MWh/day of C5-molasses from 97MWh/d of straw. The yield of ethanol was according to expectations.

DONG Energy's Inbicon plant, Kalunborg, Denmark

The Borregaard plant, Sarpsborg, Norway

The Inbicon, Kalundborg facility is no longer in operation and development activities with respect to cellulosic ethanol have been suspended. In 2017, the London-based investment firm Pioneer Point Partners signed a Letter of Intent (LoI) to the effect that they are ready to investment up to 160 million euro in the plant.

In 2018, New Energy Spirit Biomass Refinery LLC, announced plans for a biorefinery that will produce 16 MMgy of cellulosic ethanol (60,000 m3) and 110,000 tonnes of lignin pellets, due to break ground in Spiritwood, North Dakota, in the spring of 2019. The project is said to use Inbicon technology, and also be supported by Danish export credit facilities.

3.2.4.10 The Borregaard plant, Sarpsborg, Norway

The key technologies used in the Borregaard plant called BALI technology are a sulfite-based cooking pretreatment followed by enzymatic hydrolysis of the pretreated biomass, fermentation of the sugars to ethanol and processing of the lignin to value added performance chemicals.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product	Hours in operation
Sarpsborg	D	2018	1,200 tonnes/d (spruce)	0.28 tonnes/d ethanol 0.46 tonnes/d lignin chemicals	0.27 tonne/d CO_2	>40,000

The longest continuous run in the plant has been about 6 weeks. The plant has basically met all targets and no technology barriers have been identified. The next step is therefore to construct a commercial plant and Borregaard is actively pursuing that. Full scale plant data are based on input of 300,000 dry tonnes/yr of spruce which is expected to be converted to 138,000 tonnes/yr of lignin chemicals, 82,000 tonnes/yr ethanol (as 100%) with additional 80,000 tonnes/yr of CO_2.

Borregaard has together with a US company announced plans for a commercial sized plant to be located at the Fernandina Beach pulp mill in Florida. The US partner is the owner of the pulp mill. No investment decision has been taken.

3.2.4.11 IFP's Futurol pilot, Pomacle, France

IFP's Futurol process includes hydrothermal pretreatment technology followed by SSF (hexoses and pentoses) to produce bioethanol for biofuels and sustainable chemistry.

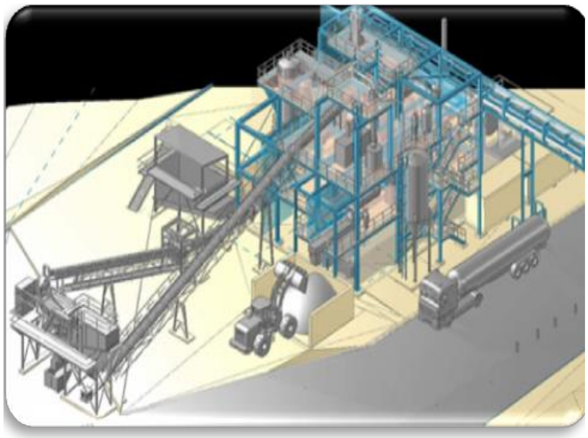
The plant comprises the following process steps: grinding, pretreatment, hydrolysis & fermentation, enzyme production, yeast propagation, distillation, lignin separation, stillage recycling, soluble sugars recovery.

The plant has been operated mainly to solve interface and transfer issues and was able to prove pre-treatment and biological operation at pilot scale. Effect of scale-up for pre-treatment needs to be developed and proven.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product *	By-product	Hours in operation
Pilot, Reims, F	P	2011	16GJ/d	0,25 tonnes/d (=7GJ/d)	7 GJ/d[14]	2,000 h/y

[14] can be burnt in industrial plants

IFP's Futurol pilot, Pomacle, France



IFP's Futurol Demonstration, Bucy-le-Long, France

3.2.4.12 IFP's Futurol Demonstration, Bucy-le-Long, France

The demonstration plant uses hydrothermal pre-treatment technology at industrial scale to produce pre-treated raw material suitable for down post processing in pilot plant, to produce bioethanol for biofuels and sustainable chemistry.

The plant specifically focuses feedstock handling, stone and metal removing, pre-treatment and energy recovery of steam used during hydrothermal process, and recycling of soaking liquor.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product	Hours in operation
Bucy-le-Long, F	D	2016	1,600 GJ/d	700 GJ/d	700 GJ/d	May 2016, the plant is on start-up

From summer 2016 the plant has delivered positive results for a safe scale-up to a commercially sized plant. All in all, the plant has processed 30+ operating conditions and been fed with an excess of 4,000 tonnes of biomass fractions. All the products from the pretreatment have been further processed in the downstream pilot plant having a capacity of 1 t/d.

The purpose of the plant is to study the effect of scale-up for pre-treatment and other process parts in view of a future commercialization.

The pilot and demonstration periods are complete and the Futurol process is in the commercialization phase, an activity handled by Axens.

3.2.4.13 Clariant development plant, Straubing, Germany

The key technologies used in the Clariant development plant are process steps for the fully-integrated production of cellulosic ethanol from agricultural residues. These consist of chemical-free steam pre-treatment, integrated on-site enzyme production, hydrolysis, solid-liquid separation, fermentation of C5/C6 sugars to ethanol, and ethanol purification.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product	Hours in operation
Clariant	D/C	2012	~15 tonnes/d	~3 tonnes/d	~4,5 tonnes/d (lignin)	46,000

Operation ramped up during 2012 and from 2013 until today the plant has been in continuous operation including test and optimization runs. Overall energy efficiency is that 0.95MW of ethanol is produced from 3MW of feedstock (straw). 1.2MW of lignin is generated as a by-product. The plant has met yield targets for the most prominent feedstock. Additional improvement potentials or process optimizations have been identified and either implemented at the plant already or included in the R&D pipeline.

No technical barriers remain according to the developers but feedstock supply at economically attractive prices are still challenging.

The next step is to extend the feedstock basis proven in performance runs and continue to further optimize the process for next generation plants. Support was made available by a FP7 demonstration project for a scale-up.

Clariant's development, Straubing, Germany

Cellunolix® plant under construction, Kajaani, Finland

Clariant has started construction of a commercial sized cellulosic ethanol plant in Romania. The announcement was made September 2018. Production capacity is 50,000 tonnes per year and the investment is estimated to over 100 million EUR (€).

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product	Hours in operation
Podari/ Romania	C	2020/2021	250,000 tonnes/y	50,00 0tonnes/y	(lignin)	In construction

The by-products from the process will be used for the generation of renewable energy with the goal of making the plant independent from fossil energy sources. The resulting cellulosic ethanol is therefore an advanced biofuel that is practically carbon-neutral.

3.2.4.14 Cellunolix® demonstration plant, Kajaani, Finland

St1's bioethanol plant on the Renfors in Ranta industrial estate in Kajaani, Finland was taken into use in 2017. Technology enhancement activities are expected to continue through

2019, to reach the full capacity. The GHG reduction is expected to be up to 90% vs. fossil comparator (RED calculation methodology). The raw material for the plant is sawdust from local sources.

The plant design is based on the St1 proprietary technology. Unit operations are typically based on commercially available technology packages. The project was organised on a Build-Own-Operate model, where St1 is responsible for design, permits and coordination and operations of the plant. Earlier St1 has built eight small scale waste or residue to bioethanol plant in Finland and in Sweden.

The process contains: acid-catalyst-based pre-treatment, hydrolysis, fermentation, lignin separation, evaporation, distillation, turpentine and furfural recovery units and utility stations. Lignin and evaporation residues are converted, fed in to the boiler plant in the vicinity. Fermentation organism utilize mainly C6 sugars while majority of C5 sugars remain as future potential. Some furfural is produced as a by-product but currently there are no recovery and utilization for this amount. It will be rectified and burned at boiler.

Target for the Cellunolix® Kajaani is to prove that softwood is technically and economically feasible raw material for bioethanol process. Compared to hardwood that is more common feedstock for bioethanol, softwood contains wood extractives (tar components) such as turpentine and resin acid that have to be removed. Saw dust is very homogeneous raw material and contains less foreign particles than other forest or agricultural residues.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product	Hours in operation
Cellunolix® Kajaani	D/C	2017	~270 tonnes/d (55% water)	~ 24 tonnes/d	~ 430 MW/d	
Cellunolix® (EIA in process)	C	2022		~120 tonnes/d		

Alternative use for saw-dust raw material is the incineration in the nearby boiler plant. But, since the moisture content of the solid residue after the bioethanol plant is lower than the moisture content of the fresh saw dust, the residue has higher caloric value.

Next larger capacity similar plant is already in design phase. Environmental Impact Assessment is on-going for three different locations. Production process and commercial feasibility of the first Cellunolix® unit is a key prerequisite for the investment decision, envisaged to take place in 2020.

In 2016, ST1 announced a planned Cellunolix plant at Follum in Hönefoss, Norway with a capacity to produce 50 million litres of advanced cellulosic bioethanol for transport fuel per year. The plant was expected to become operational by 2021.

3.2.4.15 GEVO

GEVO has developed technology to convert carbohydrates to isobutanol. In 2010, GEVO acquired a conventional ethanol plant at Luverne, Minnesota, and continuous to operate this plant, and lately is planning to install 1.5 G technology in the plant. It currently produces about 45,000 tonnes of animal feed, about 75 million liters per year of ethanol and 1,500 tonnes per year of vegetable oil. Since 2012, a parallel isobutanol plant has been installed with a capacity of IBA production capacity of 6 million liters per year. The IBA production line is a full-scale line that is operated in campaigns.

The company also operates a 0.5 million litre/yr facility pilot plant in Silsbee, Texas since 2010, where isobutanol produced at Luverne is converted to hydrocarbons for use as e.g. ATJ jet fuel.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product	Hours in operation
GEVO, Luverne, MN.	D/C	2012		6,000 m^3/yr IBA		

3.2.4.16 Developments in India

The government of India emphasise the energy security of the country and targets to reduce the import dependence by 10% by the year 2022 including a national policy on biofuels and an approval of the production of ethanol from lignocellulosic biomass in India. In 2009, a blending target for 2017 of 20% of both ethanol and biodiesel was set. However, supply side shortages have forced this plan to be reconsidered.

The oil marketing companies issued tenders for procurement of 3.75 billion liters of ethanol, also including lignocellulosic ethanol, to meet a revised target of ~10% blending in 2018, but only 1.40 billion where tendered due to limited molasses availability, the only feedstock approved for 1G ethanol, and due to the demand from other sectors. To cover the gap, also other feedstocks, e.g. sugar, may be approved for ethanol production.

Praj Industries and DBT-ICT Centre for Energy Biosciences are the leading entities in the ethanol field in India (See separate headlines below). Besides these two companies DBT-Indian Oil R&D (DBT-IOC) centre has operated a pilot batch-wise, at 4 tonne/day feed at IGL, Kashipur. A 10 tonnes/day demonstration plant is expected to be built in 2019 at Mathura. Also, Nagarjuna group in Hyderabad has been engaged in development activities.

In addition, the Ministry of Petroleum & Natural Gas has instructed oil marketing companies to invest in twelve lignocellulosic ethanol projects in India and is working on an advanced biofuel scheme for supporting investment in lignocellulosic ethanol projects through Viability Gap Funding. Praj technology is being considered for three projects.

In Punjab, SAB Industries Ltd. Is developing a 25,000 tonnes/yr product using rice paddy straw.

At Panipat, Haryan Indian Oil (IOLC) is constructing a 100 m^3/day using Praj's technology and a further similar project is in development at Dahej Gujarat. In the mid-term IOLC is also planning a 100 m^3/day plant Gorakhpur, Utttar Pradesh using its own technology and also a second plant in the same state.

Hindustan Petroleum Corporation Ltd is planning a 100 m^3/day plant in Bathinda, Punjab based on the DBT-ICT technology. There other projects are in planning in the states of Bihar, Andhra Pradesh and Uttar Pradesh.

Also using the DBT-ICT technology, Bharat Petroleum Corporation Ltd (BPCL) is setting-up ethanol biorefinery in Bina, Madhya Pradesh, with a capacity of 32,000 m^3/yr. BPCL plans to build another ethanol bio-refinery with an output of 30,000 m^3/yr at Bargarh, Odisha, by 2020, using the Praj technology, and is developing yet another project in Maharashtra. A further projecy is in planning at Aurangabad, Maharashtra.

In 2018, Numaligarh Refinery Ltd. formed a joint venture with Finish Fortum and Chempolis to develop a biorefinery in Assam, India that is planned to convert 300,000 tonnes of bamboo annually into ethanol, furfural, acetic acid and bio-coal, the latter to be used in a CHP plant. However, it is unclear if the project has come beyond the planning stage.

CVC Ltd is planning two projects in Guarajat and two in Punjab, respectively based on the Chemtex technology.

Additional projects, all at 200 m^3/day capacity, are in planning by JAP Innogy at Fatehgarh Saheb, Patiala and Sangrur, in Punjab state, while Mangalore Refinery & Petrochemical Ltd is planning a 100 m^3/day capacity installation at Harihar, Karnataka.

Praj Industries

Praj Industries is a large company in ethanol technology player with over 750 references in five continents with plant capacities up to 400,000 m^3/yr capacity for conventional ethanol.

The company has developed the “efinity” cellulosic ethanol technology. A pilot plant has been operated between 2009 and 2016 demonstrating operation for a number of agricultural wastes. A demonstration plant was taken into operation in 2017. The plant has a feedstock capacity of 12 tonnes/day and 1,000 m^3 ethanol per year.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product	Hours in operation
Praj, Pune, India	P	2009		1 tonne/d ethanol		
Praj, Maharashtra, Pune, India	D	2017	12 tonnes/d	1,000 m^3/yr ethanol	fertilizer	

Praj have been contracted for technology license and basic engineering for Bharat Petroleum (BPCL), Indian Oil (IOLC) and Hindustan Petroleum Corporation (HPC) for on 25,000 tonnes/yr plant each, where groundbreaking for the BPLC plant took place in 2018 while the other two plants are still in the engineering phase.

Praj demo plant, Maharashtra, Pune, India

DBT-ICT

The DBT-ICT Centre for Energy Biosciences, at the Institute of Chemical Technology, Mumbai has developed a technology in a 1 tonne/day pilot since 2009. The DBT-ICT cellulosic ethanol demonstration plant, located at Indian Glycols at Kashipur in Uttarakhand, was taken into operation in 2016 by. The plant has a capacity of 10 tonnes/d of feedstocks, typically agricultural residues.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product	Hours in operation
DBT-ICT, Mumbai	P	2009	1 tonnes/d			
DBT-ICT, Indian Glycols Kashipur, Uttarakhand	D	2016	10 tonnes/d			

3.2.4.17 Developments in China

Longlive Group established China's first cellulosic ethanol plant in Shandong province in 2012. It has a nameplate capacity of 50,000 tonnes/yr per annum Longlive Group plant in Shandong province, went into operation in 2012. It uses corncobs as feedstock to, besides ethanol, produce xylitol and other high value products using proprietary technology. Reportedly, the production level reached 25,000 tonnes in 2013. COFCO has also been developing a 50,000 tonnes per annum cellulosic ethanol demonstration project in cooperation with Sinopec and Novozymes since 2010, but as far as known construction has not yet started.

3.3 Hydrocarbons from sugar-containing material via biological and/or chemical processes

3.3.1 Via microbial fermentation Farnesene

Engineered yeasts can be used to ferment sugar into a class of compounds called isoprenoids which includes pharmaceuticals, nutraceuticals, flavours and fragrances, industrial chemicals and chemical intermediates, as well as fuels. One of these isoprenoids is a 15-carbon hydrocarbon, beta-farnesene. Beta-farnesenes can be chemically derivatized into a variety of products, including diesel, a surfactant used in soaps and shampoos, a cream used in lotions, a number of lubricants, or a variety of other useful chemicals. It has also been accepted for 10 % blending in jet fuel as Synthesized Iso-Paraffinic fuel, (SIP) in the ASTM D7566 standard. This process is applied by Amyris.

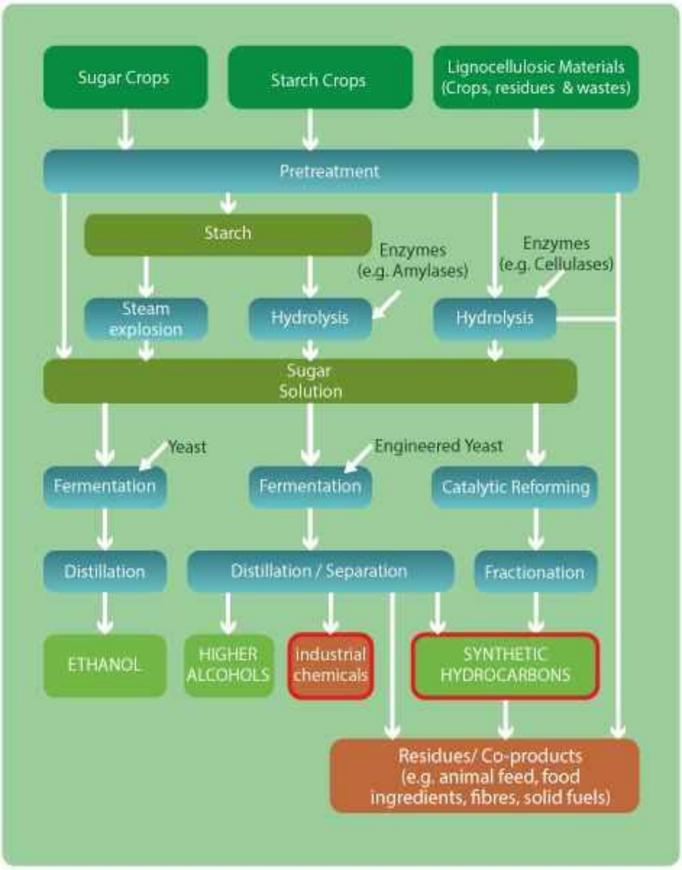


Figure 3.2 Hydrocarbons from sugar-containing material

3.3.2 Routes involving catalytic upgrading of sugars or platform chemicals that can be produced from sugars

Several different hydrolysis technologies can be used to solubilize lignocellulose to sugars, see section 0. These sugars can be further upgraded to fuels or fuel components at least through three routes:

- using the sugars as a feedstock for fermentation of chemicals that can be used as fuel components like ethanol, which can then be further catalytically oligomerized to produce hydrocarbons (as described in the previous section),
- converting the sugars into hydrocarbons catalytically in so called aqueous phase processing, and,
- converting the sugars into platform chemicals, such as Hydroxy-Methyl-Furfural (HMF), furfural or levulinic acid that can be further upgraded catalytically to fuel components or hydrocarbons.

3.3.3 Catalytic Reforming

Soluble carbohydrate streams can consist of a wide range of molecules such as C5/C6 sugars, polysaccharides, organic acids, furfurals and other degradation products generated from the deconstruction of biomass. These can be processed through Aqueous Phase Reforming (APR). The aqueous phase reforming step utilizes heterogeneous catalysts including zeolites, metals and noble metals at temperature and pressure (200°C-250°C, 3MPa-5MPa) to reduce the oxygen content of the carbohydrate feedstock. Some of the reactions in the APR step include:

- reforming to generate hydrogen;
- dehydrogenation of alcohols/hydrogenation of carbonyls;
- deoxygenation reactions;
- hydrogenolysis and
- cyclization.

Hydrogen is produced in-situ from the carbohydrate feedstock. The product from the APR step is a mixture of chemical intermediates including alcohols, ketones, acids, furans, paraffins and other oxygenated hydrocarbons. Once these intermediate compounds are formed, they can undergo further catalytic processing to generate a mixture of non-oxygenated hydrocarbons.

The chemical intermediates from the APR step can be react over a zeolite catalyst (ZSM-5) to produce a high-octane gasoline blend stock that has a high aromatic content similar to a petroleum-derived reformate stream. APR is being commercialized by Virent.

3.3.4 Pilots, Demonstration and Commercial plants

3.3.4.1 The Virent plant, USA

Virent has piloted two different technologies that convert sugars to "direct replacement" hydrocarbons: (1) sugar to reformate process and (2) sugar to distillate process. Both processes utilize Virent Aqueous Phase Reforming (APR) technology to first stabilize and deoxygenate the sugar feedstocks. The sugar to reformate process utilizes a second catalytic step that converts oxygenates derived from the APR technology to a highly aromatic reformate that can be fractionated and blended into the gasoline pool, the jet fuel pool, and the diesel fuel pool. The sugar to distillate process utilizes a different second catalytic step that converts the oxygenated derived from the APR to longer carbon chain paraffins and cyclic paraffins that are primarily in the jet fuel and diesel fuel boiling range.

Both larger scale pilot plants operated as designed and proved that the two technologies could be scaled utilizing bench top pilot plant data.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
"Eagle" Pilot	P	2009	0.35 tonnes/d	0.10 tonnes/d	n/a	6,200
"Falcon" Pilot	P	2013	0.12 tonnes/d	0.05 tonnes/d	n/a	1,200

The Eagle plant converts sugar to gasoline reformate while the Falcon plant produces distillates instead. The former product was blended into either the gasoline pool, into jet fuel, or into diesel fuel as well as used as a feedstock to generate paraxylene while the latter was fractionated and blended into either the gasoline pool, jet fuel pool or diesel fuel.

The Eagle plant has operated in seven (7) different campaigns for a total of 6,200 hours where the longest lasted 3,500 hours while the Falcon plant has operated one campaign for 1,200 hours.

Virent's Demonstration Unit for Sugar to Gasoline

Swedish Biofuels Pilot, Stockholm, Sweden

3.3.4.2 *The Swedish Biofuels Pilot, KTH, Sweden*

The pilot is demonstrating the Swedish Biofuel production method in which the feed are alcohols (C2-C5), obtained from biochemically converted wood waste or agricultural waste etc. by technologies described elsewhere in this report, are converted into hydrocarbons. The alcohols are produced by other cellulosic processes.

In the process developed, the alcohol mixture is then dehydrated into a mixture of the corresponding olefins. In the second stage, the olefins, together with carbon monoxide and hydrogen obtained e.g. by gasification or dry reforming of biogas using CO_2 from alcohol fermentation, are synthesized into higher alcohols. In subsequent stages, the higher alcohols are again dehydrated to olefins, which are then condensed into higher unsaturated compounds, including aromatics. At the final stage, the higher unsaturated compounds are hydrogenated to yield the corresponding paraffins. The mixed hydrocarbon product stream is separated into gasoline, kerosene and diesel by rectification.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product Jet SB-JP-8	By product, Biogas, Gasoline and Diesel	Time in operation h/year
ATJ	P	2009	0.040 MW (C2-C5 alcohols)	0.015 MW	0.020 MW	7,200 for a total of >40,000 hours

The plant has been in operation since 2009. The plant capacity has been increased over the years from an initial 5 tonnes/y to the current 20 tonnes/yr. The final products are fully synthetic motor fuels of kerosene, gasoline and diesel, which comply with the standard fossil fuel specifications for use in standard engines. Typical yield of aviation fuel is about 40%vol. and the rest being diesel (larger) and gasoline (smaller) fractions. Alcohols in the range C2 - C5 have been used as feedstocks for the pilot plant, either as a single alcohol or as a multi-component mixture, confirming the reproducibility of the process.

There are no expected technology barriers. The potential show stopper is the continuing low price of fossil oil.

The next step in the development of the technology is the construction of a pre-commercial industrial scale plant during the period of 2015-2019. The project is supported by an FP7 grant from the European Commission. The main goal of the project is the production of synthetic biofuels for use in aviation. The project will use the Alcohol to Jet (ATJ) pathway, as an alternative to the technologies available today, for the production of drop-in aviation fuels. The capacity of the plant will be 10,000 tonnes/yr, of which half will be aviation fuel with the rest being ground transportation fuels. Basic design is completed. Location of plant site is currently investigated.

3.3.4.3 The Amyris plant in Brazil

The Amyris industrial production plant in Brotas, Brazil converts sugarcane syrup into farnesene and other tailored molecules for a range of renewable products including a biocomponent for the diesel and jet-fuel (SIP).

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Amyris	C	2012	n/a	40 tonnes/d	none	20,500

Plant operations have been smooth with no potential show-stoppers or technology barriers. The longest run has been 11 months.

Amyris' plant, Brotas, Brazil

In 2017, Amyris sold the plant to DSM and DSM will mainly produce farnesene-based chemicals in the plant. Amyris is also focusing on the chemicals market and has other smaller volume production facilities to service this market, and also use toll manufacturers.

3.3.4.4 Global Bioenergies

The French company Global Bioenergies was founded in 2008 to develop a process converting renewable resources (sugar, crops, agricultural and forestry waste) into isobutene. The company has scaled-up the process to a demo plant in Dresden Germany.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Global Bioenergies, Dresden Germany	C	2017	n/a	100 tonnes/yr		

The results have been promising, and one batch of iso-butene has been process into gasoline and tested by Audi.

In 2016, Global Bioenergies and the Swedish companies Preem, Sekab and Sveaskog announced a collaboration to develop a high-performance fuel entirely based on forest resources. The consortium has signed a collaboration agreement to carry out a conceptual scope study for a first plant in Sweden.

Global Bioenergies is since 2017 coordinating a H2020 project, OPTISOCHEM, also including Clariant, INEOS, IPSB, TechnipFMC and Linz University for the purpose of converting agricultural residues (wheat straw) into isobutene derivatives for use in numerous applications

REWOFUEL is a H2020 project started in 2018 and coordinated by Global Bioenergies. The consortium includes Sekab, Graanul Invest, Neste Engineering Solutions, Repsol, Peab Asfalt, SkyNRG, Ajinomoto Eurolysine, IPSB, TechnipFMC and Linz University. The aim is to convert softwood residues into isobutene derivatives for use in gasoline and jet fuel.

In 2018 the company announce that it had received off-take LoI's for sufficient quantities of iso-butene, 49,000-64,000 tonnes/yr, to allow starting planning a first plant in France in cooperation with the sugar company Cristal Union.

3.3.4.5 REG (LS9)

LS9 was founded in 2005 and has received more than $75 million in funding from Chevron Technology Ventures, Flagship Ventures, Khosla Ventures, and Lightspeed Venture Partners. LS9 has developed genetically modified E.coli to produce a variety of green chemical alternates to petroleum-derived chemicals, the initial chemical products targeted are a group of fatty alcohol and specialty esters. In 2012, LS9 opened a 135,000 litre/yr demonstration in Lake Okeechobee, Florida.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product	Hours in operation
REG, Lake Okeechobee, FL.	P	2012		135 m³/yr.		

In 2014, LS9 was bought by REG Life Sciences, a daughter to REG, see Section 2.5.4.7. In 2016, REG and Exxon Mobil started a cooperation to develop biodiesel feedstock from sugars.

3.4 Biomethane via anaerobic digestion

3.4.1 Feedstocks

Typical feedstocks for biogas production are agricultural substrates, wet waste fractions from the agriculture and food industry sector and sludges from e.g. water treatment works in both cities and industries. Due to increased requirements for GHG reduction and also because it is a revenue-generating by-product from a waste stream, AD technologies are being more and more integrated into ethanol production. One other special case is recovery of landfill gas from waste landfills to prevent release of the methane formed over decades into the atmosphere.

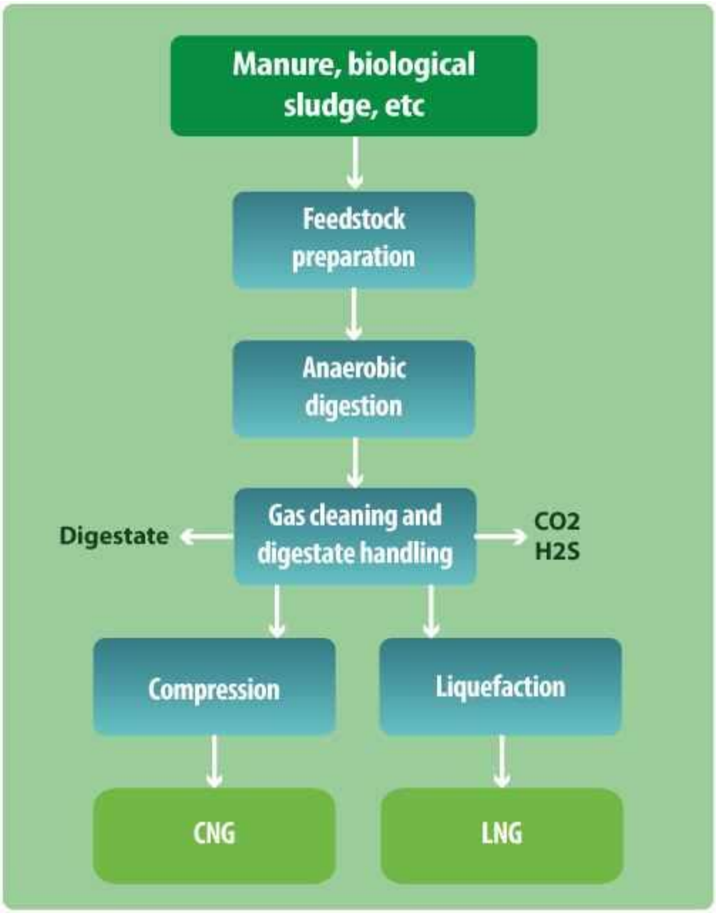


Figure 3.3 Biomethane via anaerobic digestion

Anaerobic digestion of organic material to biogas, a mixture of almost equal parts of methane and CO_2 with some trace gases (mainly nitrogen and sulphide), has a long history. In agricultural digestion it has recently reached a certain standard while the design of industrial plants is still under a strong development. All biomass fractions with the exception of lignin can be degraded by anaerobic microbes, however a pre-treatment of lignocellulosic compounds is strongly recommended to make the cellulose and hemi-cellulose better available for the bacterial degradation. This pre-treatment might be enzymatic, chemical or physical. It is fairly comparable to the pre-treatment for alcohol production from lignocellulosic material.

The residues and waters after digestion contain dissolved organics and inorganics as well as non-digested solids. Depending of the feed, these residues can have a value as e.g. fertilizers or require other treatments prior to their disposal.

3.4.2 Compressed Bio-Methane (CBM)

Organisations like European Biogas Association (EBA) and IEA Bioenergy Task 37 follows the development in the biogas and bio-methane area. Out of the total of some 18,000 biogas plants in Europe, of which over 95% are decentralized combined heat and power plants (CHP) at small scale (average 0.5MW_{el}), but with an aggregated installed generating capacity of 10GW. The number of plants have limited growth in recent year, 1%/year, after a period of double-digit growth rate in the last decade. The reason for this is the termination of schemes with, and the reductions in the value of, feed-in tariffs for electricity and also more and more restrictions on using agricultural substrates for the production of biogas. However, this also means that the application of upgraded biogas in transport becomes increasingly important, in particular in larger installations.

There were just above 500 plants where the bio-gas was upgraded to bio-methane in 2017. 200 of these were in Germany, almost 100 in the UK and 65 plants in Sweden. The total production of bio-methane is estimated to be 17TWh or 1.5 million tonnes of oil equivalent (toe), however the installed nominal capacity is three times larger. In order to reach the fuel quality standards for transportation and injection into the gas grid (EN 16723-2:2017 on natural gas and biomethane for use in transport, EN 16723-1:2016 for the injection of biomethane in the natural gas grid) the raw biogas must be upgraded to gas with equivalent quality characteristics to natural gas. The CH_4 content of the biogas must be increased ($\geq$ 97% CH_4) by removing most of the CO_2 from the biogas. Furthermore, the gas has to be dried and different trace gases (H_2S, siloxanes) have to be removed. Commercially available upgrading technologies which are used for the treatment of biogas include pressure swing absorption, pressurized water scrubbing, physical absorption, amine washing and membrane separation. The technologies are equally present across Europe, with water scrubbers taking the lead.

Bio-methane is perfectly suited to be used as a ‘drop in’ fuel in the existing natural gas systems. Europe has an extended gas grid allowing transporting also bio-methane which can be blended at any ratio with natural gas.

3.4.3 Liquefied Bio-Methane (LBM)

Where gas grids are not available, bio-methane can be turned into a liquefied state, a product known as liquefied bio-methane (LBM). Apart from logistic benefits, the major opportunity of LBM is the use in modified heavy-duty vehicles allowing them to operate in a same range as with diesel of 800 km to 1,000 km. LBM can be transported with via insulated tanker trucks designed for transportation of cryogenic liquids to filling stations for either Liquefied Natural Gas (LNG) vehicles or Compressed Natural Gas (CNG) vehicles.

Liquefaction of biogas can be combined with the upgrading process allowing the production of two products, LBM and liquid CO_2 which brings an additional financial income. Currently two different systems are on the market, a fully integrated upgrading and liquefaction process developed by GIS in The Netherlands and a sequential upgrading and liquefaction process where the off-gas can be recycled for a close to 100% recovery of both CH_4 and CO_2.Pentair Haffmanns was the first introducing this technology.

The number of LBM plants is increasing fast. Sweden was the forerunner with a first large plant in Lidköping[15], 60GWh, followed by the United Kingdom (UK) and the Netherlands and there is also a plant in Norway producing 125GWh, and where there are plans to expand the plant to double the capacity to 250GWh. But also, in the USA biogas is upgraded and liquefied on a landfill in Livermore.

3.4.4 Pilots, Demonstration and Commercial plants

The plants highlighted below are some examples as it is not meaningful to present all 500 installations in operation, and when new development have occurred since the first issue of this report, this has been noted.

3.4.4.1 Bio-methane plant of Malmberg/Västblekinge Miljö AB in Mörrum, Sweden

Malmberg's upgrading plant in Mörrum, Sweden, upgrades biogas to 99% pure bio-methane. The gas is stored in gas bottles and sold to the international power company EON, which provides it to their vehicle gas stations. Three municipalities are filling up their local busses with the resulting bio-methane. The feedstock is organic waste collected from around 250,000 people resulting in 18,000 tonnes of pure organic waste which is then dry digested producing 3,000 tonnes of biogas. The waste also generates 7,500 tonnes for composting and 7,500 tonnes recycles to fertilization.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product Nm^3/h	By-product	Hours in operation
Biomethane plant of Malmberg/Västblekinge Miljö AB	C	2004; New upgrading unit in 2015	~ 55 tonnes/d	400	20.5 tonnes/d compost and digestate	>50,000

The digestion method used is dry fermentation, meaning that food waste is digested in from the way it is generated, i.e. with no additional water mixed in. This provides a stable and energy efficient operation where the food waste is digested. Technology barriers are that the produced bio-methane cannot be injected into the grid as the Swedish gas network does not reach up to Mörrum. However, the bottling technique works well. Furthermore, a gas station is

[15] http://www.iea-biogas.net/case-studies.html

under construction at the Mörrum site that will provide all waste collecting vehicles with bio-methane at the same time they are unloading waste to the station.

Biomethane plant of Malmberg/Västblekinge Miljö AB in Mörrum, Sweden

Biomethane plant of Biogest Biogas/Greener for Life Ltd in Somerset, the UK

3.4.4.2 Bi-methane plant of Biogest Biogas/Greener for Life Ltd in Somerset, the UK

The plant produces at least 4,000 MWh electricity and 7.2 million m^3 of biogas/4.3 million m^3 of biomethane (40GWh) yearly using optimized feedstock mix of cattle slurry and manure, sugar beet, grass silage and maize silage.

Feedstock deliveries to the Anaerobic Digestion (AD) plant with upgrade system enables the farmer to sustainably utilize the farm wastes while allowing the farmer to manage the manure and crop rotations more efficiently.

The plant is a 2-stage AD plant which is suitable for operation with almost all types of feedstock. Power output ranges from 250kW-2,000kW and a bio-methane production of 80Nm³/h-500Nm³/h. The design is based on an external main digester and an internal post-digester. The main digester is a ring canal, thereby allowing a controlled plug flow.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product	Hours of operation
Biogas/biomethane plant of Biogest Biogas/Greener for Life Ltd	C	2014-2015	n/a	380 Nm³/h	11MWh$_{el}$/d (from Biogas for CHP) + digestate	<25,000

Next step: increased biogas production

3.4.4.3 Lidköping Biogas - Air Liquide and Swedish Biogas International in Lidköping, Sweden

The biogas production process is based on local vegetable waste products from grain trade and food production. The substrates are macerated, mixed and heated to 38°C before being pumped into the digestion chamber. New substrate material is continually pumped into the process that produces biogas and bio fertilizer. The bio-fertilizer is pumped to a covered storage pool.

Plant production is designed at 7.5MW_{th} with an annual target of 60GWh_{th}. Swedish Biogas International AB designed the production plant. The biogas is upgraded in accordance with the Swedish standard for biogas as a vehicle fuel in a water scrubber. A majority of the biogas is liquefied in the condensation plant. In order to liquefy the biogas, the majority of remaining CO_2 (down to <10ppm) is purged by Pressure Swing Absorption (PSA) system before the gas temperature is lowered using the Brayton cycle. The technology allows for liquefaction in the span of 140 C (at 0.5MPa) to 161 C (at atmospheric pressure), depending on the developing requirements of the vehicle market. The liquefied biogas is stored in a 115m^3, 20m tall insulated canister. The distributer, Fordonsgas Sverige AB (FGS), fills insulated 50m^3 trailers every second day and transports the gas to filling stations in Gothenburg. A smaller portion (around 30%) of the biogas produced and upgraded to biomethane is delivered directly to FGS's two compressors, which fills mobile storage containers in one of six filling places.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product	Hours of operation
Lidköping Biogas - Air Liquide and Swedish Biogas International	C	2011	220 tonnes/d	12 tonnes/d (liquified bio-methane)	1MW (com-pressed bio-methane)	25,000

As the demand for liquefied biomethane increases in Sweden, production of compressed biomethane at Lidköping plant will decrease.

Lidköping Biogas - Air Liquide and Swedish Biogas International in Lidköping, Sweden

NGF Nature Energy in Holsted, Denmark
Picture by NGF Nature Energy

3.4.4.4 NGF Nature Energy in Holsted, Denmark

NGF Nature Energy opened the Holsted Biogas plant in August 2015. The plant processes around 400 thousand tonnes of waste per year, split roughly between 75% agricultural waste, mainly manure and deep litter, and 25% industrial waste. The biogas produced is cleaned, upgraded to natural gas quality equivalent and injected into the grid. Production of bio-methane at the plant is 1,800Nm^3/h of pure methane, which equates to 130GWh, or the annual consumption of circa 8,000 households in Denmark, or fuel for 17,500 gas vehicles per annum.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours of operation
NGF Nature Energy	C	2015	1,096 tonnes/d	1,800 Nm^3/h (bio-methane)	n/a	<10,000

The next step foreseen is to use of the produced bio-methane as a transport fuel.

3.4.4.5 The VERBIOgas plants in Schwedt and Pinnow, Germany

VERBIO's bio-methane plant in Schwedt/Germany is operated on a very efficient mono-fermentation process based on 100% straw as raw material. The biogas is purified and conditioned to natural gas quality and fed into the natural gas grid. This so-called bio-methane is sold as bio-component into the CNG fuel market.

All main types of straw are tested in use and theses ones have already been approved to be suitable for the plant: wheat straw, barley straw, rye straw, corn straw, rape straw and triticale straw. Straw logistics is also operated and optimized by VERBIO. In accordance with the German standards for the natural gas grid the biogas produced is upgraded in an amine scrubber. Subsequently, the bio-methane is compressed and fed into the gas grid.

In the sense of maximum sustainability and maintenance of humus balance fermentation residues are brought back to the fields as a high-quality bio-fertilizer. The straw-bio-methane plant has been designed as an extension to the already existing bioethanol-bio-methane plant of VERBIO Ethanol Schwedt GmbH.

Verbiogas is made from 100% straw was fed into the natural gas grid for the first time in October 2014. At this time initial capacity of the plant was 8MW$_{th}$.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product	Hours of operation
Verbiogas (VERBIO AG) Schwedt, Germany	C	2014	120 tonnes/d (83% dry)	12 tonnes/d (compressed bio-methane)	Bio-fertilizer	15,000
Verbiogas, Pinnow, Germany	C	2019		10MW Output	Bio-fertilizer	

The capacity of the plant is going to be increased to 40,000 tonnes per year to provide 16.5MW$_{th}$ bio-methane in 2019 with an annual target of 140GWh$_{th}$ bio-methane to be fed into the grid.

VERBIOgas plant in Schwedt, Germany

A second plant of 10MW is under construction at Pinnow, Germany and due for start-up in 2019.

It was recently announced that Verbio have bought the Dupont cellulosic ethanol plant at Nevada. In the first phase planned expansion, VERBIO will supplement the existing facility by constructing a straw bio-methane plant with a thermal output of approximately 20MW. There are also plans for a similar capacity straw-based plant in India.

3.5 Hydrocarbons and alcohols from waste gaseous material via gas fermentation

3.5.1 Process principles

The conversion of CO rich gases through synthetic chemical pathways, for example FT or methanol synthesis, requires that H_2 be available in the synthesis gas. Industrial waste gases (e.g. from steel industry) often do not contain sufficient H_2 and therefore cannot be converted using conventional synthetic pathways without adding processing steps.

Gas fermentation utilizes gas streams with a range of CO and H_2 compositions to produce fuels and chemicals such as e.g ethanol and 2,3-butanediol at high selectivity and yields. While both CO/CO_2 and H_2 are utilized in the process, acetogenic microbes are also able to consume H_2-free CO-only gas streams, due to the operation of a highly efficient biological water gas shift reaction occurring within the microbe. This reaction allows the bacteria to compensate for any deficit of H_2 in the input gas stream by catalyzing the release of H_2 from water using the energy in CO. In the presence of H_2, synthesis of ethanol, higher alcohols or hydrocarbons from CO or CO_2 via hydrogenation or conventional chemical catalysts can be costly and require very large scale to be able to make the economics work. In addition, these processes require high substrate purity.

This pathway offers a highly differentiated technology with feedstock and end product flexibility. Gas fermenting microbes are claimed to be more tolerant to high levels of toxicity than synthesis catalyst, thereby avoiding expensive conditioning. Large-scale applications require the provision of insoluble gases into the growth medium; this challenge has been overcome through developments in gas delivery technology.

3.5.2 Pilots, demonstrations and commercial plants

3.5.2.1 The LanzaTech Plants in Caofoedian, China

LanzaTech, and its joint venture partner, Shougang Group have announced the successful start-up of a commercial facility converting industrial emissions to sustainable ethanol. The facility, located at the Jingtang Steel Mill in Caofeidian in Hebei Province, and began operations in May, 2018.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Ethanol	By-product MW	Hours of operation
LanzaTech	D	2013	450 Nm^3/hr H_2+CO	1.4 tonnes/d	n/a	6,500
Beijing Shougang LanzaTech New Energy Technology Co	C	2018	59,000 kg/h	135 tonnes/d		>7,000 (Feb. 2019)

Start-up of the Jingtang plant was successful with all trains operating normally with fermentation campaigns of 60 days. By February 2019 the plant had operated for more than 7000 hours and produced over 15 million liters of ethanol. The plant has reached 100% of design production rate in a single train.

3.5.2.2 LanzaTech MSW facility, Japan.

This project uses gasified MSW to produce ethanol through gas fermentation. Lanzatech's partner in Japan is the chemical company Sekisui.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Ethanol	By-product MW	Hours of operation
LanzaTech	D	2015	15 Nm^3/hr H_2+CO	0.05 tonnes/d	n/a	20,000 (Aug 2018)

LanzaTech's Shougong plant, China

LanzaTech's Plant in Ghent, Belgium

3.5.2.3 The LanzaTech Plant in Ghent Belgium

In Ghent, Belgium, a consortium of ArcelorMittal and LanzaTech, had in June 2018 official ground-breaking of its commercial demonstration facility at ArcelorMittal's integrated steel plant to create bioethanol from waste gases produced during the steelmaking process.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours of operation
ArcelorMittal	C	2020	---	63,000 tonnes/a	n/a	--

Project progress has been delayed due to obtaining regulatory approval for the ethanol under EU incentive regimes (RED, FQD) and for securing financing from the European Investment Bank (EIB). Optimization of the technology operated in China, will be implemented at this site. This will be the first project globally to demonstrate utilization of Blast Furnace (BF) gas in a live fermentation. This is particularly important as more than 80% of the carbon rich gases available at steel mills is BF gas, highlighting the first commercial application of using this gas stream globally.

3.5.2.4 Projects in Development

LanzaTech is planning three other plants in with those expanding their range of feedstocks used at commercial scale. These plants include a facility converting ferroalloy off gases into ethanol in South Africa (156 tonnes/day), a facility converting refinery off gases into ethanol in India (102 tonnes/day), and a facility to convert gasified agricultural waste into cellulosic ethanol in California (105 tonnes/day). These plants are all expected to be operational in 2020.

4. Power to Gas and Power to Liquid conversion

Power-to-Gas (PtG) and Power-to-Liquid (PtL) refers to technologies, which convert electric energy to another energy carrier, like for example methane or methanol.

In short electricity is converted to hydrogen through electrolysis. When combined with CO_2 this mixture can be converted through catalytic synthesis into a gaseous or liquid fuel, also called e-fuels. Because CO_2 is one of the relevant building blocks, Power-to-X (PtX) is also often referred to as an example of Carbon Capture and Utilization (CCU).

Depending whether the electricity comes from biomass (e.g. co-firing or CHP) or from renewable source like wind or solar, these fuels either are biofuels or 'renewable fuels of non-biological origin' as described in the RED II article 2 'definitions' (36).

As far as the CO_2 is concerned there are many different sources, either from biologic or fossil origin as illustrated by some examples in the table below.

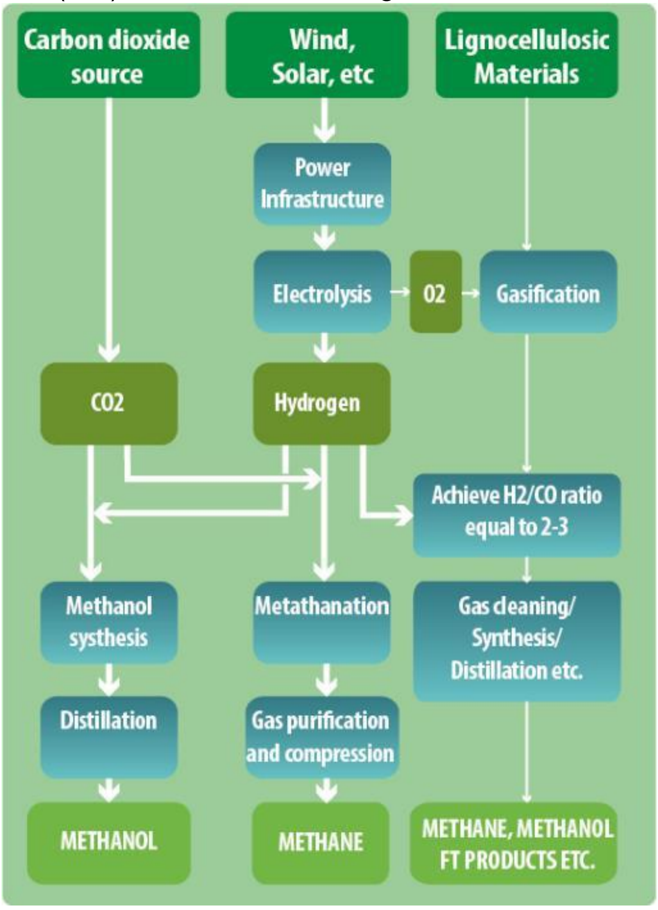
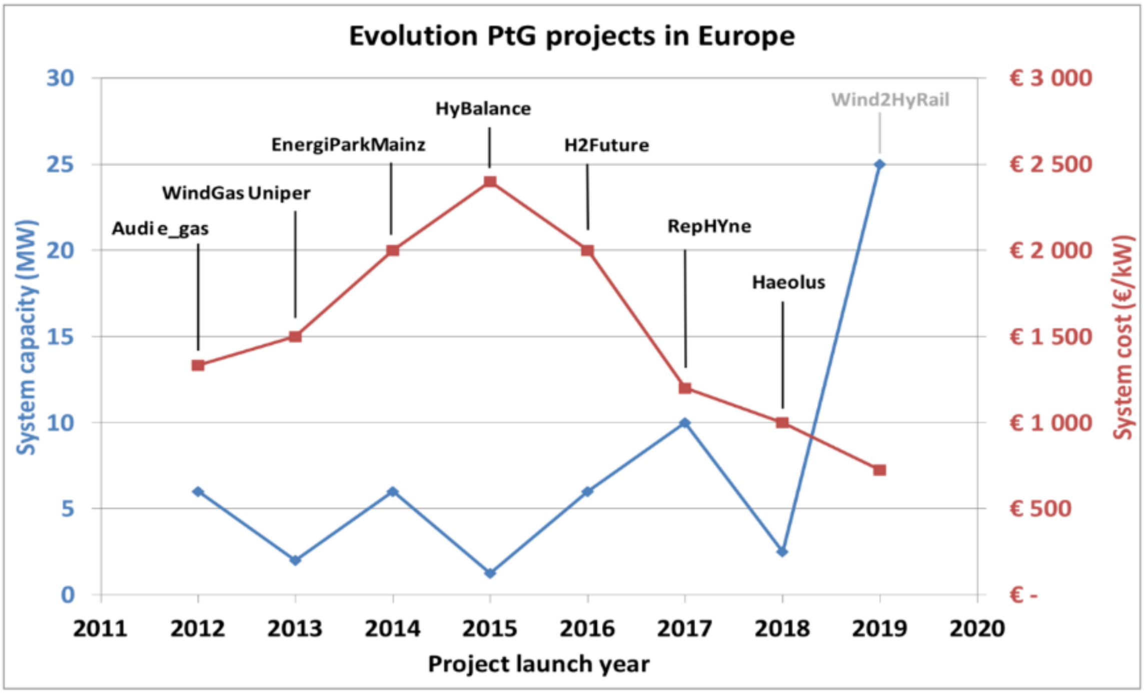


Figure 4.1 Power to G-or-L conversion pathways

Source	Output	Concentration
Industrial flue gases	Up to 700 tonnes/hr	~ 10-15%
Ethanol fermentation, distilleries and breweries	Up to 50 tonnes/hr	~95%
Biogas purification	Up to 0.7 tonnes/hr	~90%

Besides conversion pathways illustrated in Figure 4.1 (and described briefly below) hydrogen is one of the important building blocks for a large number of other potential production routes. The cost and efficiency of the hydrogen production facility from electricity is thus a key element in the calculation of the production cost of a fuel or chemical where hydrogen is an important part. The figure below put together by Hydogenetics Corporation illustrates examples of hydrogen plants in operation or in advanced stage of planning.



Examples of Power to hydrogen facilities. Source: Hydrogenics[16]

System capacity (MW) is power consumption and system cost covers the electrolyser unit to produce hydrogen in EUR per kW of hydrogen. The first four from the left are in operation while the others are in different development stages. E.g. H_2Future is planned to be on stream in spring of 2019.

4.1 Methane production

Converting CO_2 and H_2 into methane was first discovered by French chemist Paul Sabatier in 1897. By methanation, CO_2, captured from a point emission and the H_2 produced by electrolysis are catalyzed into CH_4. Either chemical catalysis or bio-catalysis can be used for methanation.

4.2 Methanol production

Conventional methanol is primarily produced through steam reforming of natural gas into syngas (CO, CO_2 and H_2) which is than reacted into methanol (CH_3OH) through catalytic conversion.

Power-to-Methanol technologies also rely on catalytic conversion technologies to convert CO_2 and H_2 into methanol.

[16] https://www.hydrogenics.com/

4.3 Adding H_2 to Syngas

A gasification process typically generates a raw synthesis gas which has a H_2 to CO molar (volumetric) ratio of around 1 (0.8 to 1.3). For most synthesis processes a higher ratio is needed, typically around 2 (methanol, FT) to 3 (methane). In order to accomplish the desired ratio in today's commercial plants, the raw syngas is passed through a so-called water gas shift reaction with which CO is reacted with H_2O to form H_2 and CO_2. The reaction is exothermic, and the syngas loses about 4%-7% of its heating value and results in substantial increased CO_2 emissions to the atmosphere.

One method to avoid the shift is by adding hydrogen to the process in order to reach the desired ratios. The hydrogen can be produced in the same way as hydrogen needed for the PtG/L concepts. See Figure above. Also, the oxygen from the electrolysis plant can be used in the gasification plant substantially reducing or even eliminating the need for an air separation plant.

If hydrogen addition is fully substituting the shift concept (at ratio requirement of 2) the syngas generation and thus the production capacity increases in the order of 50% from a given amount of biomass feedstock.

This concept is described in detail in e.g. so called GreenSynFuels Report[17] as well is the report Co-production of synthetic fuels and district heat from biomass residues, carbon dioxide and electricity: Performance and cost analysis[18].

4.4 Pilots, Demonstrations and Commercial Plants

4.4.1 Power to Hydrogen: Falkenhagen Hydrogen production and grid injection, Germany

E.ON's power-to-gas pilot unit in Falkenhagen, Germany has injected more than 2GWh of hydrogen into the gas transmission system in its first year. The Falkenhagen unit uses renewable-sourced electricity to power electrolysis equipment that transforms water into hydrogen, which is then injected into the natural gas transmission system. With an electrolyzer capacity of 2MW, it can produce 360Nm^3/h of H_2. E.ON delivers some of Falkenhagen's hydrogen output to its project partner, Swissgas AG, and makes some available to its residential customers through a product called "E.ON WindGas."

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours of operation
Falkenhagen	D/C	2013	(max) 2.0 MW_{el}	1.1 (H_2) MW	n/a	10,000

[17] http://serenergy.com/wp-content/uploads/2015/11/GreenSynFuels_report_final.pdf
[18] http://www.sciencedirect.com/science/article/pii/S0961953415000070

E.ON is currently building a second PtG pilot unit in Reitbrook, a suburb of Hamburg. The purpose of this unit is to optimize the transformation process by means of more compact and efficient electrolysis equipment.

Falkenhagen Hydrogen production and grid injection, Germany

Power to Gas: Audi/ Solar Fuels e-gas, Germany

4.4.2 Power to Gas: Audi/ Solar Fuels e-gas, Germany

The largest PtG demonstration plant has been developed by Solar Fuel GmbH, for Audi AG and built in Werlte in Germany. This plant has an electrical capacity of 6.3MW_{el}, producing 360Nm^3/h methane, which will be injected in the local gas distribution grid, and ultimately can be certified for use in Audi's Natural Gas Vehicles (NGV) range. The CO_2 source for the methanation process is the stripped CO_2 from a waste treatment biogas plant nearby.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product MW	By-product MW	Hours of operation
Audi	D/C	2014	6.3 MW_{el}	3.5	n/a	12,000

ETOGAS the plant constructor is expecting to be able to increase the scale to over 20MW_{el} input for the next generation of plant, and at the same time reduce the cost per MW significantly.

4.4.3 Power to Gas: BioCAT Plant, Copenhagen, Denmark

The system was tested at laboratory scale using a 10 m^3 reactor vessel and raw biogas as a carbon dioxide source, and was operated for more than 3,200 hours between January and November 2013 at Aarhus University, Foulum, Denmark. In February 2014, Electrochaea announced the development of BioCat, its commercial scale technology demonstration project, located at the wastewater treatment plant in Copenhagen. The main objective of the resulting project was to design, engineer, construct, and test a 1MW PtG plant based on Electrochaea's biological methanation technology. The project was commissioned in February 2016 and in April 2016 it produced its first methane. When fully operational, data will be collected over a 3,000 hours period of injection into a local distribution grid. Oxygen and heat, which are generated as by-products in the PtG process, is captured and utilized in the on-site wastewater operations. The facility will also provide frequency regulation services to the Danish power grid. Electrochaea acts as the project leader and is supported by Hydrogenics, Audi, NEAS Energy, HMN Gashandel, BIOFOS, and Insero Business Services.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours of operation
BioCat, Electrochaea	D	2016	1 MW_{el} and 50 m^3/hr of CO_2	50 (CH_4) m^3/h	0.1 MW_{th}	First methane produced April 2016

As a next technology step Electrochaea are looking to move to grid scale with over 10MW_{el} input, and are currently raising investment.

Electrochaea Biocatalytic Technology, Denmark

CRI's Power to Methanol plant, Iceland

4.4.4 CRI's Power to Methanol: The George Olah plant, Iceland

The largest Power-to-Methanol facility has been operating in Iceland for the last 6 years. CRI's 'George Olah' Renewable Methanol Plant in Svartsengi, near Grindavik, Iceland began production in late 2011 and was completed in 2012.

In 2015 CRI expanded the plant from a capacity of 1,300 tonnes per year to 4,000 tonnes per year. The plant now recycles 5,600 tonnes of carbon dioxide a year which would otherwise be released into the atmosphere.

All energy used in the plant comes from the Icelandic grid mix, which is generated from hydro and geothermal energy. The plant uses electricity to generate hydrogen which is converted into methanol in a catalytic reaction with carbon dioxide. The CO_2 is captured from flue gas released by a geothermal power plant located next to the CRI facility. The origin of the flue gas are geothermal steam emissions.

The only by-products are oxygen which is created as the plant uses electricity to split water into its constituent chemicals, and water from the methanol distillation step.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product	Hours of operation
G Olah	D	2011	6 MW	10 tonnes/day*	O_2	In commercial operation

* Correspond to catalytic end of run condition. It is 12 t/d at start of run.

The plant is in commercial operation. The renewable methanol is sold to fuel customers in Iceland, the Netherlands, UK, Denmark and Sweden.

Next step in development is a plant with a capacity of 50,000 to 100,000 tonnes per year for start-up in the 2020-2021 timeframe.

4.4.5 Sunfire's Power and CO_2 to FT products, Germany

Sunfire in Dresden, Germany has operated a pilot plant converting CO_2, power and water to crude FT product stream. The plant consists of three major process steps. First a Solid Oxide Electrolysis Cell (SOEC) fed with power and steam producing hydrogen (and Oxygen) thus operating in a high temperature steam mode. Thereafter a Reverse Water Gas Shift Unit (RWGS) fed by CO_2 and hydrogen driving the endo thermal reaction with electric power. Steam is chemically generated in the reversed water gas shift reaction but condensed out. The generated syngas is thereafter fed into a FT synthesis plant. The heat generated in this unit is fed as steam to the SOEC unit.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product	Hours of operation
Sunfire Dresden	P	2014	90 kW 11.2 kg CO_2/h	3.5 kg/h		2,900 h 2015-16

Energy efficiency from power to FT liquid is about 45%. Increased conversion efficiency could be accomplished through combination of the first two steps to a Co-SOEC unit including the reversed shift step. Overall efficiency could then get closer to 60%. Sunfire is planning for a first commercial plant in the size of 10 million litre of FT liquids. It would utilize 20 MW electric.

Sunfire's pilot in Dresden, Germany

4.5 Projects under plans and in construction

4.5.1 Power to Methanol: The MefCO2 project, Germany

Carbon Recycling International (CRI), Mitsubishi Hitachi Power Systems Europe (MHPSE), Hydrogenics, University of Duisburg and several other universities have launched a joint demonstration of load-following operation of power-to-methanol technology with a power plant. This will be demonstrated in the ongoing EU research project MefCO2 at the Steag owned and operated power plant in Lünen, Germany. Full commissioning and operation at Lünen are scheduled in 2017.

4.5.2 Power to Methanol: Liquid Wind approach, Sweden

Liquid Wind AB (LWAB) located in Gothenburg Sweden, together with a Scandinavian/UK consortium plan to develop and build 1 + 5 standardized elektro-methanol plants in Sweden. The facilities will be "regional production scale" operating 50MW of electrolyser capacity and producing 40-45,000 tonnes of methanol yearly.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product	Hours of operation
MefCO2	D	2017	1 MW	1 tonne/d	O_2	n/a

The first plant FlagshipONE will be located in Stenungsund in the heart of the chemical industry cluster in Sweden. FlagshipONE will use a mix of biogenic CO_2 and industrial fluegas CO_2. FlagshipONE will "trade" products such as heat, O_2 and H_2 with other chemical producers in the area. The power will be from renewable resources, primarily wind energy.

Basic engineering and permitting will be performed during 2019 and final investment decision is planned for Q1 2020. FlagshipONE will be operational in 2022.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product	Hours of operation
LW FlagshipONE	C	2022	50 MW	140 tonne/d	O_2	7,500

5. Algae development

5.1 Aquatic vs. terrestrial biomass

Photosynthetic algae (including macro- and micro-algae) and photosynthetic cyanobacteria have the potential to produce considerably greater amounts of biomass per hectare than terrestrial crops; some species could even directly produce fuel (H_2, ethanol or alkanes). Such aquatic biomass can be cultivated on non- arable land or even off-shore, using sea or brackish water, industrial carbon dioxide as carbon source and wastewater as nutrient input (nitrogen and phosphorus). Aquatic biomass are energy crops that do not compete with food crops for land or other resources.

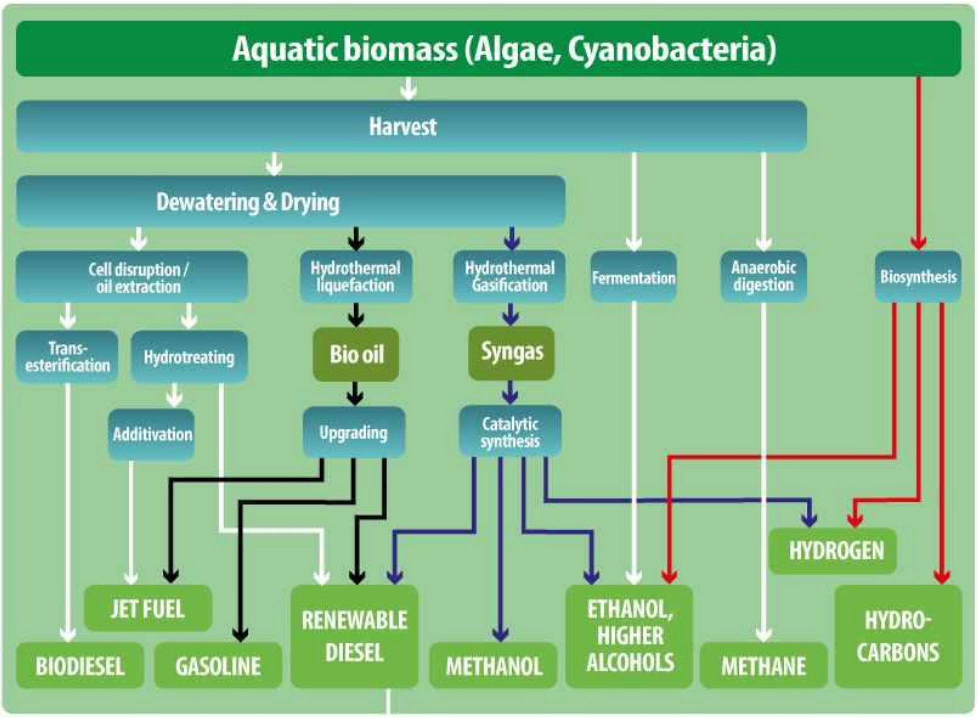


Figure 5.1 Algae development pathways

There are many parameters that influence aquatic biomass productivity and composition like irradiance levels, dark/light cycles, CO_2 and O_2 concentration, temperature, pH, salinity and nutrients. The maximum theoretical (dry) biomass productivity of algae can reach 100g/m^2/d but real productivities in good locations are around 15-20g/m^2/d at present (i.e. 70tonnes/ha/year). There are intensive R&D activities at lab and pilot scale to improve these results.

Algae biomass composition consists of carbohydrates, proteins, lipids and other products such as pigments, vitamins, etc., for use in food, cosmetics and other niche markets. The lipids have been the most interesting fraction for conversion into biofuels. Oleaginous strains (at least 20% lipid content on Dry Weight (DW) basis) can overproduce lipids (up to 70% lipids on DW basis) under selected severe stress conditions such as N and/or Si starvation.

5.2 Cultivation

Major distinctions of cultivation methods are between on-shore/off-shore and open/closed systems.

Large scale cultivation of microalgae in on-shore outdoor open pond systems and raceways is well established. Cultivation in open systems is only suitable for a few algal species which can tolerate extreme environmental conditions such high salinity (Dunaliella), high pH (Spirulina (Arthrospira)) or undergo extremely high specific growth rates (Chlorella).

Closed cultivation systems for microalgae, usually on-shore, utilize photobioreactors made of transparent tubes, plates, bags or domes, which permit culture of single species. Either biomass or lipid productivities in photobioreactors can nearly be twice as high as for open ponds. The scale of photobioreactors is yet limited by the build-up of oxygen which would rapidly reach inhibitor levels. Besides, the larger a photobioreactor the more difficult it is to keep the monoculture free of parasites or other unwanted species.

Heterotrophic and mixotrophic algae cultivation is done in stirred tank bioreactors or in fermenters.

Macroalgae (seaweed) are usually cultivated in off-shore farms but their productivity is much lower than that of microalgae and may also have a seasonality growth pattern. Their composition is mainly carbohydrates, not lipids.

5.3 Harvesting and drying

The typical microalgae concentration in cultivation broths is 0.02%-0.07% of total suspended solids (open ponds), in photobioreactors it ranges from 0.14%-0.7% dry matter. The recovery of the microalgae from the algae suspension is done in two steps. A pre-concentration step or bulk harvesting leads to a concentration of 2%-7%. Main methods are flocculation via thickeners, dissolved air flotation (for small microalgae) and sedimentation (for large microalgae). The second stage or concentration step is the thickening or dewatering and brings the concentration of solid matter up to 15%-25%. Main methods are centrifugation, filtration and ultrasonic aggregation. Finally, the harvested algal paste needs to be dried. To prevent microalgae degradation, the moisture level should be kept below 7%. Methods are solar-drying, drum-drying, freeze-drying and spray-drying. Apart from solar-drying, dewatering and drying is quite energy demanding and accounts for a large part of total energy consumption. Furthermore, due to the large volumes of water involved, nutrient balance and contaminant balancing is essential.

5.4 Conversion technologies

The most studied and developed bioenergy value chain is the extraction of algal lipids that are either esterified into biodiesel (FAME) or hydrotreated into renewable diesel (HVO or jet fuel). Left unrefined, the algal oil from freshwater species can act as straight vegetable oil. One of the most important R&D challenges in this value chain is to find an effective and non-costly lipid extraction process. This process involves applying shear forces or other methods at the level where the break up individual cell membranes are achieved to make the lipids accessible to other physical extraction processes. After extraction more than half of the biomass is present as a residue.

HTL of aquatic biomass as a whole allows for the production of a bio-oil and a syngas that can be further processed into hydrogen, methanol, ethanol, gasoline, renewable diesel, and jet fuel.

Three other options are fermentation for ethanol production, dark fermentation for hydrogen production and anaerobic digestion to produce bio-methane. All these four ways eliminate the need of drying the algal culture. Fermentation, dark fermentation, hydrothermal liquefaction treatment and anaerobic digestion are also a practical way to process the algal biomass leftover from other conversion routes.

In an emerging fuel production route, algae or cyanobacteria are not used as feedstock, but they are the actual producers of the fuel (hydrogen, ethanol or alkanes), which means that they are not consumed in this process. This pathway is also at pilot scale and huge efforts are being made to improve productivities and recovery technologies.

5.5 Synergies between biofuels and other industrial sectors

Microalgae provide dissolved oxygen that can be used by bacteria to break down and oxidize organic matter in wastewaters. This leads to the liberation of CO_2, phosphate, ammonia and other nutrients used by algae. Biofuel production in combination with wastewater treatment and nutrient recycling is thus predicted to be a near-term application.

In any case, the combination of biofuel production with the valorization of other fractions of the algal biomass (proteins, omega-3, vitamins, pigments, nutraceuticals) is necessary for the economic sustainability of the technological process.

5.6 Pilots, Demonstration and Commercial plants in Europe

Despite the intense effort in R&D in microalgae in recent years, the development and the transition to demonstration scale have not been accelerated as much as expected in Europe and worldwide. Most of the current pilot and demonstration plants, focusing on bioproducts (food, cosmetics and pharmaceuticals) are being developed through the biorefinery concept – in particular in the USA. Biofuels (biodiesel, ethanol) and other more advanced, pre-commercial products (long-chain alcohols, hydrogen, hydrocarbons, biojet fuel) are often interesting value adding co-products from these algae biorefineries. Exception were the FP7-funded microalgae plants (Algae Cluster) and the US Algenol company. These pilot and demo plants represented a dedicated effort to become algae-based plants focused on bioenergetic products. However, it is worthwhile to say that at the current high cost of production, microalgae-based oils are still not competing with biofuels obtained from food and oil crops. On the other hand, the concept of algae-based biorefinery which would lower production costs of biofuels through the integrated co-production of high value-added products is facing difficulties to reach a commercial level, and efforts have in many cases been redirected to only focus on one or more low-volume, high value products. As a result, to date, the number of demonstration facilities for the production of bioenergy vectors from algae, solar radiation and

CO_2, and downstream upgrading to biofuels is limited worldwide and the available data are scarce. The next examples represent the current status in EU of the main Algae facilities.

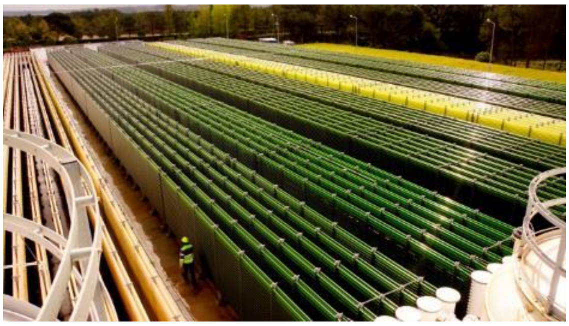
5.6.1 The Allmicroalgae (former AlgaFarm) plant, Pataias-Leiria, Portugal

The commercial microalgae plant was started under the name of AlgaFarm, a joint venture between the Portuguese cement and biotech companies Secil and A4F, respectively, to develop a process that initially used the combustion gases (CO_2) from the co-located Secil´s cement plant for the production of microalgae. This industrial-scale production unit started to operate in 2013 and resulted from the expansion of a pilot plant that has been in operation for three years. Until end of 2015, this plant was in commercial operation producing *Chlorella vulgaris* biomass directed for the food segment.

The AlgaFarm is a microalgae plant equipped with data acquisition system and fully automated control that constitute one of the largest production facilities of microalgae worldwide with closed photobioreactors, reaching 1,300m^3 of total volume of production. The downstream processing of biomass includes harvesting through microfiltration to a biomass concentration between 5% and 10% on DW basis. The treatment includes pasteurization, spray drying and final packaging under protective atmosphere free from O_2.

At the end of 2015, the company was renamed to Allmicroalgae, which is now 100%-owned by the cement company Secil. It became the new worldwide supplier of Allma Chlorella and has unveiled plans for a significant new phase of investment in its production facilities, mainly for supplying high quality algae ingredients for food, beverage and dietary supplement applications. Apparently, they have no plans to enter into the energy market at short-medium term.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours of operation
AlgaFarm	C	2013	CO_2 and fertilizer	ca. 100 tonnes/yr (dry matter) microalgae biomass[19]	n/a	Since 2013 until present



The Allmicroalgae (former AlgaFarm) plant, Pataias-Leiria, Portugal

The Buggypower S.L. plant, Porto Santo, Portugal

[19] Total Installed capacity on 2013/2014.

5.6.2 The Buggypower S.L. plant, Porto Santo, Portugal

This Demo plant is located at Porto Santo Island, Madeira, where solar radiation is optimal for microalgae cultivation and it is owned by a partnership between EEM-Empresa de Electricidade da Madeira and BFS-BioFuel Systems (Alicante, Spain). The demo plant utilizes 1,100m^3 of closed photobioreactors with air-lift 8m high and arranged in sequence to optimize solar capture and bacteriological control for a maximum quality of microalgae biomass.

This project has the main objective to replace the fuel from fossil resources, currently used in EEM thermal power station. The microalgae cultivation uses CO_2, seawater, sunlight and nutrients and consumes 1.87kg CO_2 per kg of dry biomass produced.

After oil extraction, the microalgae biomass is subjected to HTL for producing bio-oil. This bio-crude oil can be used both for the production of biofuels or as starting point for a biorefinery composed of "building blocks”. The project initial driver was to contribute to a fully sustainable and "eco-friendly" island, in terms of energy supply and use but this is not conceivable in the medium-term. The current status is a demonstration plant for optimizing the microalgae cultivation and harvesting operation units to profit the microalgae biomass as “premium quality” for supplement of animal feed and human food. The next step (medium-term) is to treat the residual leftover by HTL for producing bio-crude oil that can be used for biofuels or as a starting point for building blocks under a biorefinery concept.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours of operation
Buggy-power	D	2011	CO_2 and fertilizer	60 tonnes/yr (dry matter)	n/a	n/a

Buggypower has recently inaugurated a pilot production plant in Spain (at IMIDA – Instituto Murciano de Investigación y Desarrollo Agrario y Alimentario, San Pedro de Pinatar, Murcia). and was constructed to support the Algafeed Project, which has the aim to develop new fish feed based on marine microalgae.

5.6.3 BIOFAT FP7 project

(One of the FP7-funded ALGAE CLUSTER plants comprising BIOFAT, InTeSusAl, and All-gas, consortia)

The BIOFAT project demonstrated the performance level of state-of-the-art technologies to grow autotrophic microalgae in large-scale. There are two pilot plants in Portugal and Italy and a prototype in Israel that will make it possible to perform a LCA for a 10 ha or more unit in any location, using the best available technologies for inoculation (closed systems: GWP (Greenwall Panels) and TPBR (Tubular Photobioreactors) and for production IRW (Improved Raceways) and CRW (Cascade Raceways). The possibility to operate the two pilots and the prototype made it possible to obtain consistent data to develop a proxy that enables to estimate the performance in other locations. Both technologies were tested for *Nannochloropsis* (aiming the production of lipids - potentially for biodiesel) and *Tetraselmis* (aiming the production of carbohydrates - potentially for bioethanol). The technologies developed in the BIOFAT represent the state-of-the art technologies for large-scale production worldwide. The procedures for operation provide the best options in culture media development, harvesting, recirculation and biorefinery. The performance of any microalgae-based technology is strongly dependent on available resources, mostly the solar radiation. BIOFAT was able to show that the local productivities obtained in the Pilot Plants in two specific geographic locations (Pataias, Portugal and Camporosso, Italy) are relevant but they are not a decisive performance factor. More important is the model or proxy for such given technology that enables calculation of the general performance for any geographical location of an industrial algae-based plant.

It was also possible to prove that the technologies developed in BIOFAT can be used for the production of valuable compounds in a small scale with a positive economic balance, and if in a much higher-scale of several hundreds of ha, in a biorefinery framework where it will be possible to use the residues for biofuel applications. The feasibility of the larger-scale production strongly depends on location and available resources. The LCA (Life Cycle Analysis) developed with real information from the Pilot Plants in Portugal and Italy is therefore a unique tool for the necessary scale-up steps.

5.6.3.1 BPPP – BIOFAT Pataias Pilot Plant, Portugal

The Pilot Plant process scheme includes inoculum production in GWPs, production in TPBRs and production/starvation in CRWs. The harvesting technologies include pretreatment with filtration and culture medium recirculation, and centrifugation. The experience gained enabled to design the changes that are necessary in very large scale.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours of operation
BIOFAT	D (Pataias Pilot Plant, PT)	2013	CO_2 from industrial beer fermentation and fertilizer[20]	34 kg/d (dry matter) (microalgae biomass)[21]	n/a	Since Nov/2013 to Nov 2015 (about 17,280h of operation)

[20] the objective was to demonstrate the perfomance of the technology through improvement - the maximum results were obtained in the last months - and are completely correlated with solar radiation.
[21] the Biorefinery process demonstrated the transformation of oil from *Nannochloropsis* into biodiesel (according with the norms for use as biodiesel in Europe).

BIOFAT Pataias Pilot Plant Cascade Raceway – 2 x 1,500m^2– Designed and built by A4F. (BIOFAT FP7 project)

Camporosso Pilot Plant (BIOFAT FP7 project)
Source: with permission from A4F,
Coordinator of BIOFAT

5.6.3.2 BCPP – BIOFAT Camporosso Pilot Plant, Italy

The Pilot Plant process scheme includes inoculum production in GWPs model II (GWP-II), and production/starvation in IRWs. The harvesting technologies include pretreatment with filtration and culture medium recirculation, and centrifugation.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours of operation
BIOFAT	D (BCPP-Biofat Camporosso Pilot Plant, IT)	2015	the operation has not made in constant production mode	29 kg/d (dry matter) (microalgae biomass)	n/a	Since Aug/2015 to April 2016 (about 5,760h of operation)

The technology is developed and was optimized along the duration of the project and does not represent a barrier to the further development of the project. The next step is the implementation of a commercial plant with 10 ha, based on an optimized version of the two pilots installed.

5.6.4 InteSusAl FP7 Project, Portugal

(One of the FP7-funded ALGAE CLUSTER plants comprising BIOFAT, InTeSusAl, and All-gas, consortia)

The InterSusAl 1ha pilot demonstration plant was constructed at Necton's site in Olhão, in the Algarve region of Southern Portugal.

The overall objective of InteSusAl (Demonstration of integrated and sustainable microalgae cultivation with biodiesel validation) is to demonstrate an integrated approach to produce microalgae in a sustainable manner on an industrial scale.

More precisely, the project optimises the production of algae by both heterotrophic and phototrophic routes and demonstrates the integration of these production technologies (Raceway, PBR and Fermentation) to achieve the algae cultivation targets of 90-120 dry tonnes per hectare by annum.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours of operation
InteSusAl	D (1 ha site at Necton, PT)	2015	TBC	micro-algae biomass (wet/dry) main product – biodiesel Other products to be identified Product: ~110 kg/day dry weight (TBC)	TBC	Since Sept 2015 (about 5,856h of operation)

Construction of the pilot plant was completed during 2015 and operation began in 3rd quarter 2015.The 1 ha site is made up of 4 x 15m^3 TPBR, 1 x 200m^3 open pond raceway and 3 x 1m^3 heterotrophic fermentation systems.

One further 1m^3 heterotrophic fermentation systems (Heterotrophic pilot line #1) was retained at CPI, Middleborough, United Kingdom, to be operated in parallel with the 3 x 1m^3 heterotrophic fermentation systems.

InteSusAl utilizes both phototrophic and heterotrophic technologies for the growth of micro-algae.

The sustainability of this demonstration, in terms of both economic and environmental (closed carbon loop) implications is considered across the whole process, including optimum use of algal biomass resources to enable commercialization.

InteSusAl was heavily focused on the production of micro-algae biomass and the technologies required to process micro-algae following harvesting have not been evaluated or investigated during the project life cycle.

However, one conclusion which has been drawn that a site designed exclusively for the production of bio-diesel will not be a viable business option in the current climate. A number of co-products/by-products would first need to be identified as these products, their characteristics and end use dictate the reprocessing route, the equipment and quality systems required.

The technology and equipment required for converting extracted lipids into biodiesel is well known, however the downstream process of harvested algae biomass is less developed. The heterotrophic growth is performed using glycerol as the carbon source, a commercial supply of waste glycerol from an existing bio-diesel production is of suitable quality is required.

InteSusAl project is due to be completed on 31st July 2016. An output of the project is to design a larger scale integrated micro-algae demonstration site together with the preparation of a commercial business case for future exploitation. InteSusAl is seeking suitable follow-on projects to utilize the capacity of the 1-hectare site.

InteSusAl project, phototrophic growth, Portugal

InteSusAl project, heterotrophic growth, Portugal

5.6.5 ALL-GAS project, Spain

(Belongs to the FP7-funded ALGAE CLUSTER plants comprising BIOFAT, InTeSusAl, and All-gas, consortia)

All-gas plants are located in Southern Spain (Chiclana de la Frontera, Andalucia). All-gas project is composed by three scales technical plants: Pilot, Prototype and Demonstration. Pilot plant which comprises almost 200m^2 cultivation area is operated continuously since May 2012. Prototype plant which comprises 1,000m^2 cultivation area plus around 200m^2 downstream processes such as harvesting, anaerobic digesters, biogas upgrading, dewatering and biomass boiler is in continuous operation since September 2014. The final Demo plant which will comprise around 3 ha of cultivation is under construction and will be started up in early 2017.

The main objective of the All-gas project is the demonstration at large scale of sustainable biofuel (methane) production from microalgae biomass, therefore the key technologies used in order to reach the main goal are based on:

A. Low cost high rate algal ponds for growing the algae or also called raceway ponds. One of the achievements within the project is the patent of a new innovative Low Energy Algae Reactor (LEAR®), reducing the energy demand for growing algae at least 4 times compared to conventional paddle wheels.
B. Low energy demand harvesting with a two-step harvesting system combining:
   a. dissolved air flotation to produce feed for the digester (and reuse water),

b. centrifugal decanter for final dewatering of the digestate as fertilizer.

C. Some optimized anaerobic digesters for producing biogas (70% CH_4, 30% CO_2%).

D. A low-cost Capital expenditures (CAPEX) and Operational Expenditures (OPEX) biogas pre-treatment to reach 85% to 95% CH_4.

E. Overall energy balance for each m^3 of wastewater treated:

a. Internal use for mixing and harvesting can reach 0.15kWh/m^3 (electricity),

b. Bio-methane production can reach up to 0.05kgCH_4/m^3 (or 0.75kWh_{th}/d),

c. This is compared to conventional approaches, consuming around 0.5kWh/m^3 of electricity (for aeration, dewatering, pumping).

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
All-gas, Chiclana de la Frontera, ES	P	2014	Up to 40 kg/d (dry biomass)	Microalgae biomass converted to biomethane for vehicles: 5 kg/d (as CH_4)	Fertilizers, treated water for reuse	(operation since Sept 2014) (about 13,680h of operation)
All-gas, Chiclana de la Frontera, ES	D	2016/2017	Up to 1,000 kg/d (dry mass)	Microalgae biomass converted to biomethane for vehicles: 150 kg/d (as CH_4)	Fertilizers, treated water for reuse	Operational 2017

The harvesting system developed for the **All-gas project** is low energy demand (harvesting in two steps by combining a dissolved air flotation and a centrifugal decanter) but could be further optimized, as can the productivity of the digestion.

The **All-gas project** is addressing the circular economy, since a `waste´ (wastewater) is transformed into a valuable raw material to produce: energy, biofertilizers, water suitable for reuse, while the energy demand to treat the wastewater is drastically reduced (from 0.5kWh/m^3 in conventional aeration to around 0.15kWh/m^3 with algae and flotation).

All-gas process reduces drastically the GHG emissions; indeed, the All-gas process is a CO_2 bio-fixation system: Low carbon footprint.

No fresh water is used, N and P contained in the wastewater is recycled, and the water meets reuse quality: Low water footprint.

No arable land is needed so there is no competition with human needs. With the algae biogas, areal productivity is twice the conventional biofuels (sugarcane ethanol and palm oil diesel): around 10 cars per ha.

The main obstacle to widespread use is logistics: under favourable climate, for each 1,000m^3 of wastewater or a population of 5,000 people, an area of 1ha is needed – which can fuel 10 vehicles. This restricts the use for smaller towns up to 50,000 people (10ha). Furthermore, the vehicles have to travel to the Wastewater Treatment Plant (WWTP)and all the treatment chain (flotation, digestion, gas upgrading, fuel station) is only build/operated for this scale.

The next step is to be confirmed in 2017 at demonstration scale the results obtained at pilot and prototype plant, to confirm hydrodynamics at large scale (>5,000m^2 cultivation area).

The goal is to implement the project in other locations in order to study the effect of the climatic conditions on the global performance of the process, such as Mediterranean Basin (Northern Spain, Southern France, Italy, Greece), North Africa and Middle East.

All-Gas project, Spain

Overview of A4F Lisbon Experimental Unit and tubular photobioreactor of 1,000 L – Designed and built by A4F. (DEMA FP7 project)

5.6.6 The FP7 DEMA plant

The main goal of the DEMA project is to develop, demonstrate and license a complete economically competitive technology for the direct production of bio-ethanol from microalgae with low-cost scalable PBRs by 2016.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours of operation
DEMA	P (Lisbon, PT)	2015	80 kg/d (CO_2) 24 kg/d (nutrients)	35 kg/d (dry matter) (microalgae biomass)	n/a	7,680h/yr

Based on the initial proof-of-concept, the first results show, via LCA and economic balance, that it is feasible to use microalgae to directly produce bio-ethanol. The catalytic conversion of solar energy, H_2O and CO_2 into ethanol is being carried out by a metabolically engineered strain of the cyanobacterium, Synechocystis sp. PCC 6803. Produced bio-ethanol is continuously extracted from the culture media via a membrane technology process exploiting existing EU expertise and technology. This process design enables the economic and energy efficient production of biofuel at feasible capital and operational expenditure. A pilot plant was built in Lisbon (Portugal) by the biotech Portuguese company A4F.

The Pilot Plant process scheme includes inoculum production in GWPs with a total volume of 80lt and in TPBRs with a total volume of 1.1m^3. Up to 20% of the PBR's content is renewed daily and the harvesting technologies include ultrafiltration to separate the microalgae from the broth and subsequent centrifugation and spray drying to obtain dry biomass. The produced bioethanol is dehydrated by the use of a pervaporation module.

The technology itself is not a barrier, but the main show-stopper is the low production of ethanol by the Genetically modified (GMO) developed strain, which needs to be high enough to allow the process to be energetically sustainable. Ethanol separation is still the main energy-consumption step of Direct Ethanol from MicroAlgae (DEMA) process, however in future higher levels of produced ethanol shall decrease the energetic needs for the whole process. Thus, current ethanol production by GMO strain is DEMA's bottleneck.

Improvement of the ethanol separation procedure has to be performed in order to reduce energy costs. Furthermore, it is intended to undertake the scale-up of the process to a demonstration scale with 3.6ha by 2017, in Reunion Island, using Le Gol power plant's CO_2 produced during bagasse and coal burn as source for DEMA PBRs.

5.6.7 The FP7 Fuel4me plant

Fuel4me`s main goal was to demonstrate a sustainable, scalable process for biofuels from microalgae and to valorize the by-products by 2017. A pilot facility was planned to be built up in Spain with the aim to proof-the-concept of a continuous one-step process in which the lipid productivity in microalgae cultures is maximized and the lipid profile is optimized for the biofuel production. There is no enough public data to evaluate the current status of this plant.

5.6.8 The H2020 SABANA Project[22]

SABANA-Sustainable Algae Biorefinery for Agriculture and Aquaculture- is an Innovation Action project aiming at developing a large-scale integrated microalgae-based biorefinery for the production of biostimulants, biopesticides and feed additives, in addition to biofertilizers and aquafeed, using only marine water and nutrients from wastewaters (sewage, centrate and pig manure). The objective is to achieve a zero-waste process at a demonstration scales up to 5 ha sustainable both environmentally and economically. A Demonstration Centre of this biorefinery is expected to operate in order to demonstrate the technology, assess the operating characteristics of the system, evaluate environment impacts and collaborate with potential customers for use. It is expected to provide a solution for three current key issues in the EU (1- Improvement of the safety and sustainability of food production in agriculture and aquaculture; 2-Contamination problems resulting from nutrients dissemination and scarcity (phosphorous); and, 3-Minimization of greenhouse gas emissions from wastes (wastewater and flue gases)).

[22] Source: http://www.eu-sabana.eu/

5.7 Pilots, Demonstration and Commercial plants in Australia and the USA

The major algae-based pilot/demo and commercial plants outside of Europe are included in this section in a descriptive way, since the quantitative data is too scarce to evaluate the current status of those plants. The short presentations (below) are valuable in terms of main algae-based technologies being demonstrated worldwide but have little value in terms of identification of technological barriers and any potential show-stoppers that might have been identified but not publically reported.

5.7.1 Algae.Tec Ltd., AUSTRALIA

Algae.Tec[23] is an Australian advanced algae products company founded in 2007, focused on developing technology that captures waste carbon dioxide to produce commercial quantities of algae for use in the food (nutraceuticals) and fuel sectors (production of algal oil, production of renewable distillates via gasification and FT synthesis for substitution of diesel fuels and algal biomass for sale as feedstock to producers of biodiesel, jet fuel and ethanol). Algae.Tec Ltd. has carried out in excess of six years of laboratory, bench-scale and pilot tests and product trials to-date; assessed competitive algae technologies; and has applied the development phase results to detailed engineering evaluations of commercial plant operations. A joint venture with Reliance Industrial Investments and Holdings Limited (RIHL) India was recently established in order to validate the technology and further developments and improvements. A pilot algae plant is planned to be built in Jamnagar, India.

5.7.2 Sapphire Energy, Inc., USA

Sapphire is a venture capital backed San Diego-based company founded in 2007 for the purpose of growing and processing micro-algae into products towards very large and diverse markets where the unique attributes of algae provide valuable solutions. Sapphire's technology uses sunlight, CO_2, non-potable water, non-arable land, nutrients, and novel strains of algae in outdoor ponds to produce algae which they then convert into high-value oils, aquaculture and animal feeds, fuels and other valuable products.

Sapphire has three plants across California and New Mexico. In 2010, the company began construction of a still un-finished world's first commercial demonstration algae-to-energy farm in Columbus, New Mexico, a project backed by a grant from the United States Department of Energy and a loan guarantee from the United States Department of Agriculture (USDA). Construction of Phase 1 was completed on-time and on-budget in 2012, and the company paid back the USDA loan guarantee in 2013.

---

[23] http://algaetec.com.au/

Recently, Sapphire moved from a focus on algae biofuels only to a portfolio approach including algal oils for nutraceutical applications, protein and fuel. In energy area, Sapphire and Linde did agree to commercialize a new industrial scale conversion technology needed to upgrade algae biomass into crude oil. Together, the companies will refine the HTL developed and operated today by Sapphire Energy at pilot-scale. In addition, they intend to jointly license and market the technology into an expanded list of industries, including algae, municipal solid waste, and farm waste, in order to upgrade other biomass sources into energy. The agreement spans a minimum of five years through the development of Sapphire Energy's first commercial scale, algae-to-energy production facility.

5.7.3 Algenol, USA

Founded in 2006, Algenol[24], the top USA microalgae company, converts CO_2 from industrial emitters into transportation fuels through its direct to ethanol process. Algenol claims to have a proprietary technology employing cyanobacteria or blue green algae to convert CO_2 and seawater into pyruvate and then to ethanol and biomass by overexpressing fermentation pathway enzymes channelling the majority of photosynthetically fixed carbon into ethanol production rather than for cell maintenance. Algenol claims that its patented algae technology platform allows the production of the four most important fuels (ethanol, gasoline, diesel, and jet fuel) for around 1.30 $US per gallon each using proprietary algae, sunlight, carbon dioxide and saltwater at production levels of 8 thousand total gallons of liquid fuel per acre per year.

Sapphire Energy Inc., USA[25]

closed PBRs using patented VIPER technology, USA[26]

Algenol´s commercial development campus, in Florida, includes a Process Development Unit (PDU) which itself consists of a large aquaculture laboratory, two large inoculation greenhouses and 1,5ha of outdoor controlled testing area for initial deployment and

[24] www.algenol.com/
[25] Source: http://allaboutalgae.com/all-algae-photos/
[26] Source: Vitor Verdelho´s presentation at ESB 2013, Dec 5th, 2013 (with permission)

optimization activities. In 2013, upon completion of their Demo/Commercial 1ha Integrated Biorefinery plant of PBRs, Algenol claimed to establish the most sophisticated algae facility in the world where an algae strain can go from lab-scale development to commercial-scale production on one site. In 2014 and 2015, Algenol continued to operate the 1ha Integrated Biorefinery to demonstrate commercial viability of the technology by showcasing all of the upstream and downstream systems necessary to produce ethanol from microalgae. Algenol has continued to adapt and engineer PBRs that best complement its proprietary enhanced algae and optimize fuel production, resulting in 44 issued patents. From 2013, they moved to low-cost VIPER PBRs.

In 2015 it was announced their first commercial facility, to be located in the United States supported by a new 25 million $US investment from BioFields, a Mexican business group devoted to the development of renewable and clean energy projects. This new investment follows a previous investment of 40 million $US from BioFields in 2014 - in all, BioFields has invested 65 million $US in Algenol. This facility is not operating yet.

5.7.4 Heliae Development LLC, USA

Heliae is an Arizona-based algae platform technology company founded in 2008 carrying out mainly R&D on biofuels from microalgae. On 2012, it established a new focus leaving biofuels area and announced ground breaking at an expansion project at its 10ha production plant in Gilbert, Arizona. Heliae had invested nearly 3 million $US in the design and construction of a Demo plant of closed PBRs. The construction began in May 2015 and is expected to be operational soon.

In July 2014, Heliae announced a joint venture with top Japanese waste management and recycling company, Sincere Corporation, to develop a commercial algae production facility in Saga City, Japan. The joint venture has been named Alvita Corporation, and will combine Sincere Corporation’s operational skill, distribution networks and knowledge of the Japanese market with Heliae’s proprietary algae production technology to supply natural astaxanthin, a powerful antioxidant with broad health benefits, to the growing health and wellness market in the region. Nowadays, this company offer Volaris, a production platform that uses sunlight and low-cost carbon feedstocks to produce products from algae.

5.7.5 Joule Unlimited, USA

Joule Unlimited[27] was founded within Flagship VentureLabs™, and operates out of Bedford, Massachusetts and The Hague, The Netherlands, with production operations in Hobbs, New Mexico. Joule develops technology platforms for the production of sustainable, drop in, low carbon transportation fuels. The company pioneered a direct CO_2-to-fuel production platform, by reversing combustion through the use of solar energy.

[27] Source: http://www.jouleunlimited.com/

This platform applies engineered catalysts to continuously convert waste CO_2 directly into renewable fuels such as ethanol or hydrocarbons for diesel, jet fuel, and gasoline. Joule claimed to have successfully pilot-tested its platform for over two years, initiated demonstration-scale operations, and assembled a specialized team to lay the groundwork for commercial deployment. The company is moving to commercialize Joule *Sunflow®-E,* with Joule *Sunflow®-D* and additional hydrocarbon fuels to follow. They are expecting to deliver Joule Sunflow®-E and Joule Sunflow®-D for approximately 1.20 $US per gallon (50 $US per barrel). Joule's process requires only sunlight, waste CO_2 and non-potable water. At full-scale commercialization, a 10,000ha Joule plant will expect to produce a reserve value of 50 million barrels. Joule Unlimited and the German Heidelberg Cement, a multinational building material company, announced recently a partnership designed to explore application of Joule's technology to mitigate carbon emissions in cement manufacturing.

Heliae Development LLC, USA[28]

Joule Unlimited[29]

[28] Source: http://heliae.com/technology/
[29] Source: Vitor Verdelho´s presentation at ESB 2013, dec 5th, 2013 (with permission)