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Sub Group on Advanced Biofuels

Sustainable Transport Forum

Building up the future

Technology status and reliability of the value chains

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14 February 2017

Sub Group on Advanced Biofuels

“Technology status and reliability of the value chains”

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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.
- Lignocellulosic or second generation (2G) ethanol is 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 are competing in licensing their technology to locations with strong support policies. All of them are based on agricultural residues while technologies based on forestry residues still have to reach the level of industrial scale demonstration.
- 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.
- Two relatively small trials of co-processing pyrolysis oil (PO) in refineries in Brazil and the USA are known to have taken place. 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.
- 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.

- 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. This development may therefore make an indent in the biofuels market post 2025.
- Low Carbon Fossil Fuels from waste industrial streams for the production of liquid or gaseous fuels are close to reaching the first-of-a-kind plant status. They may possibly offer significant quantities by 2030.

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 SCAB 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 SCAB. Only in few cases, where organisations didn't 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[1]). 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.

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. 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

[1] European Technology and Innovation Platform Bioenergy

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. 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. tons of product per ton 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 report (with a few exceptions mentioned in the text where information has been obtained from the internet) can be summarized as based on information provided by plant owners, plant operators and technology developers who are members of the Sub-Group Advanced Biofuels (SGAB) or from companies who have provided information to members of SGAB. 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

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	LCA	Life Cycle Analysis
AD	Anaerobic Digestion	LEAR	Low Energy Algae Reactor
APR	Aqueous Phase Reforming	LHV	Lower Heating Value
APP	Advanced Plasma Power	LNG	Liquified Natural Gas
ASTM	American Society for Testing and Materials	LNEG	Portugal National Laboratory of Energy and Geology
ATJ	Alcohol to Jet	LPG	Liquified Petroleum Gas
bbl	barrels	LTFT	Low Temperature Fischer-Tropsch
BL	Black Liquor	LTU	Lulea University of Technology
bpd	barel per day	M&G	Mossi Ghisolfi
BTG	Biomass Technology Group BV	MHF	Multiple Hearth Furnace
BtL	Biomass to Liquid	MHPSE	Mitsubishi Hitachi Power Systems Europe
C	Commercial Plant	MI	Methanol Institute
CAPEX	Capital Expenditures	MSW	Municipal Solid Waste
CBM	Compressed Bio-Methane	Mt	Mega tons
CCS	Carbon Capture and Sequestration	NER	New Entrants' Reserve
CCU	Carbon Capture and Utilisation	NGV	Natural Gas Vehicles
CEN	European Committee for Standardization	OPEX	Operational Expenditures
CERTH	Center for Research & Technology Hellas	P	Pilot Plant
CFB	Circulating Fluidized Bed	PBR	Photo Bio Reactor
CHP	Combined Heat & Power	PDQ	Pressurized Direct Quench
CNG	Compressed Natural Gas	PDU	Pressurized Development Unit
CP	Catalytic Pyrolysis	PNNL	US Department of Energy - Pacific Northwest National Laboratory
CRI	CRI Catalyst Company	PO	Pyrolysis Oil
CRW	Cascade Raceways	ppm	parts per million
D	Demonstartion Plant	PSA	Pressure Swing Absorption
DEMA	Direct Ethanol from MicroAlgae	PtG	Power to Gas
DG	Directorate General	PtL	Power to Liquid
DME	Dimethyl Ether	R&D	Research & Development
DW	Dry Weight	RDF	Refuse Derived Fuel
EBTP	European Biofuels Technology Platform	REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
EIBI	European Industrial Bioenergy Initiative	RED	Renewable Energy Directive
ERA-NET	European Research Agency - Network	RFO	Renewable Fuel Oil
ETS	Emissions Trading System	RON	Research Octane Number
EU	European Union	RTP	Rapid Thermal Processing
FAME	Fatty Acid Methyl Esters	RW	Raceway
FCC	Fluid Catalytic Cracking	SGAB	Sub Group on Advanced Biofuels
FGS	Fordonsgas Sverige AB	SHF	Separate Hydrolysis and Fermentation
FT	Fischer-Tropsch	SIP	Synthesized Iso-Paraffinic
GERG	European Gas Research Group	SNG	Synthetic Natural Gas
GET	Güssing Energy Technologies	SRC	Short Rotation Coppice
GMO	Genetically modified	SSF	Simultaneous Saccharification and Fermentation
GTI	Gas Technology Institute	STP	Standard Temprature and Pressure
GWP	Greenwall Panels	tons	metric tons
HFO	Heavy Fuel Oil	TPBR	Tubular Photo Bio Reactor
HMF	Hydroxy-methyl-furfural	TRL	Technology Readiness Level
HP	Hydropyrolysis	UK	United Kingdom
HTFT	High Temperature Fischer-Tropsch	USA	United States of America
HTL	Hydrothermal liquefaction	USDA	United States Department of Agriculture
HVO	Hydrotreated Vegetable Oils	VC	Value Chain
IMPCA	International Methanol Producers & Consumers Association	VSA	Vacuum Swing Adsorption
IRW	Improved Raceways	VTT	VTT Technical Research Centre of Finland
ISCC	International Sustainability & Carbon Certification	WWTP	Wastewater Treatment Plant
KIT	Karlsruhe Institute of Technology	XtL	Anything to LIquid
LBM	Liquefied Bio-Methane		

2. Thermochemical conversion

This chapter explores the following three 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-1500 C and at sub-stoichiometric conditions (typically λ = 0.2-0.5[2]). 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 (1000°C-1500 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.

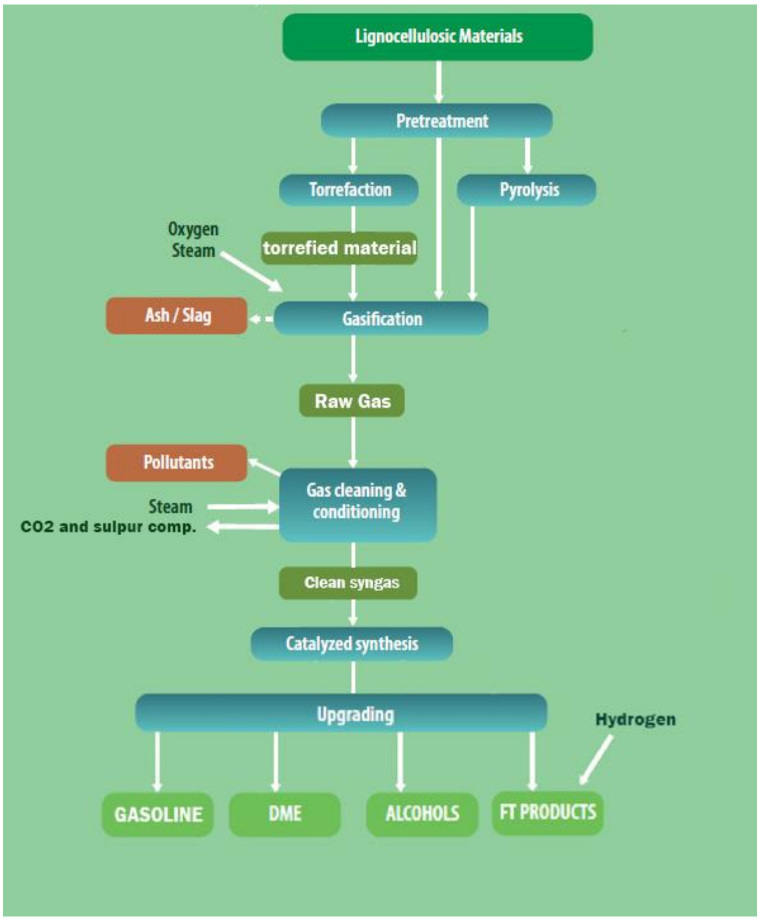

Figure 2.1 Synthetic Fuels via Gasification

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, ashes, bed material, tars, alkali, sulphur and chloride compounds are removed through various cleaning steps. Components having mainly poisonous effects for downstream catalysts are

[2] 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.

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.

Finally, the acidic CO_2 and sulphur components in the gas are removed. 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 would be possible if renewable electricity becomes available at sufficient prices and quantities to allow their use, and 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 (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. Description of technology and on-going activities are found in chapter 3.5.

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:

- Lurgi/Ruhrgas, fast pyrolysis reactor for production of slurry from lignocellulosic biomass
- Entrained Flow Gasifier with cooling screen
- DME / gasoline synthesis

The major issue of the Bioliq process is the de-centralized collection and pre-processing of biomass resources in a number of smaller units to increase the energy density for economical transport to a central, large gasification and synthesis plant.

The pilot plant 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 4.0 MPa-8.0 MPa. The syngas is converted to gasoline via a direct DME synthesis route. The plant is operated in 2 to 3 week periods.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Pyrolysis	P	2010	0.5 tonnes/h	0.45 tonnes/h	--	2,000
Gasification	P	2013	1 tonnes/h	1,700 Nm^3/h	--	3,000
Synthesis	P	2014	700 m^3/h (STP)	0.2 tonnes/h	--	2,000

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 commercially proven for fossil feedstock and the whole process chain has been adapted for operation with lignocellulosic biomass feedstock and intermediates. The commercialization is difficult due to low energy prizes. The planned next step is to carry out a commercial and technical feasibility study for fuel production from residual biomass including the development of a commercial feedstock supply concept together with potential suppliers for residues from agriculture and forestry. This will be followed by engineering of a demo facility for Biomass to Liquid (BtL) in Germany or Europe.

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.

KIT’s BioLiq plant, Germany

LTU Green Fuels’ BioDME plant, Sweden

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 3.0 MPa.
- HaldorTopsoe syngas to methanol and DME technology.

Today the plant is owned and operation by LTU. The gasification plant was started in September 2005 and the Bio-DME unit in November 2011. The feedstock is sulphate (Kraft) BL from the neighbouring sulphate mill but also sulphite liquor has also been successfully tested.

The synthesis plant downstream the gasifier has also been used for testing an innovative, once-through syngas to methanol conversion technology.

Recently 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.

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

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.

In construction of a BL gasification to fuels plant the gasification technology is the only innovative part of the facility. The downstream parts are already commercially proven. In the BioDME plant however HaldorTopsoe decided to test their novel so called CONRAD methanol technology upstream of the commercial methanol to DME conversion unit.

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 180 MW 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
Carbona/HTAS/GTI	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

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 scale-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	D	2009	48 tonnes (dry basis bone)/d	11 (ethanol) tonnes/day		12,800

The Westbury demonstration plant has been used by Enerkem to 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 plant.

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	C	2015	300 tonnes/d	88 (ethanol) tonnes/day	---	Accumulated 2,594 hours during production ramp-up (as of fall 2016)

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 in April 2016 and has produced about 240 tonnes as of the first week of May. 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 is being added in 2016 and will be ready for start-up in 2017. Ethanol is expected to be the primary product. The plant is currently producing and selling increasing volumes of bio-methanol and no technology barriers have been identified.

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 is expected to start in 2017.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Enerkem	C	2019	300 tonnes/d (dry)	99 tonnes/day (ethanol) or 142 tonnes/day (methanol)	----	Project in development

A major Dutch partnership including AkzoNobel, Enerkem and other partners aim to develop a plant in the Netherlands using Enerkem's conversion technology to manufacture synthesis gas from domestic and other waste and use it as a feedstock for making products such as methanol and ammonia.

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

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

The next step is to implement a full-scale demonstration plant. The raw material will be forest residues. The plant in Finland will include the following units:

- Biomass receiving and drying to about 85% dryness
- Plasma gasification technology (in-house technology and catalysts) at atmospheric pressure to produce tar-free syngas
- Cleaning and conditioning of syngas
- Gas-to-liquid conversion by Fischer-Tropsch synthesis
- Refining the FT- intermediate products to the final products

- Utilities

The separate process units represent either proven technology in commercial scale or demonstrated in pilot plant scale. Combination of the units using wood as raw material is new in commercial scale. In the reference plant further optimizing and improvements will be made. The main target is to still improve the greenhouse gas savings, although the basic requirements of the RED will be met.

Kaidi's New Energy Group pilot, China

2.2.5 Project under construction

2.2.5.1 The BioTfueL pilot plant, France

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

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
BioTfueL	P	2016	15 MW	--	--	---

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 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}. The commissioning of the two demonstration plants (Torrefaction unit in Venette and grinding, gasification, gas treatment and a sub-pilot FT Test Unit in Dunkirk) will start end of 2016. The test program will start in 2017 and will be executed for three years.

BioTfueL pilot plant (torrefaction unit), France

BioTfueL pilot plant (main unit), France

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. For further description of the gasification step see section 2.2.

This favours 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.

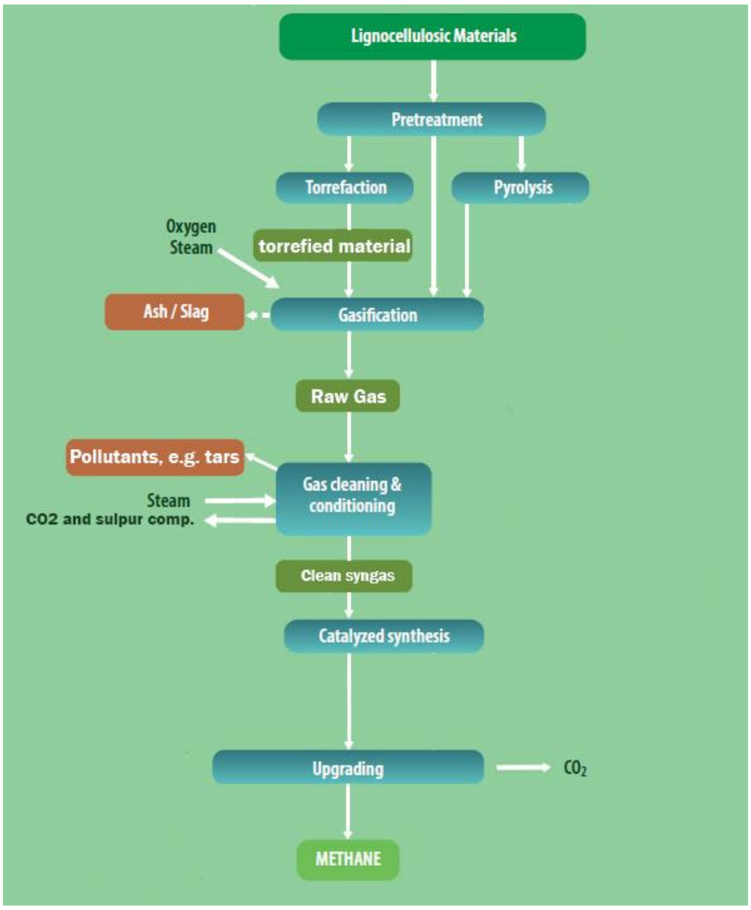

Figure 2.2 Bio-methane via Gasification

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 type 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

(owned by Güssing Energy Technologies (GET) with Technikum Güssing, operated by Bioenergy2020+ and the Technical University Vienna)

The plant is a CHP (Combined Heat & Power) facility (gasification at atmospheric pressure combined with a gas engine) 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
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

2.3.4.2 The GoBiGas plant in Gothenburg, Sweden

The gasification technology implemented in the GoBiGas plant is a four times scale up from the original plant in Güssing, Austria (see above) done by Valmet under a license from Repotec. The GoBiGas plant furthermore includes tar removal via scrubbing and active carbon filters. Water gas shift and methanation units have been provided by Haldor Topsöe A/S. The plant also includes acid gas removal technology.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation by Dec 2015
GoBiGas	D	2013	6.8 tonnes/h (pellets, 5.5% moisture) 8.9 tonnes/h (Forest residue, 20% moisture)	20 MW	Distr. heat	Gasifier 6,400h Methanation 2,100h

The plant first delivered Bio-SNG (Synthetic Natural Gas) to the grid in December 2014 and has until December 2015 supplied 30GWh, mainly during the latter part of 2015. The plant has also delivered 25GWh district heat to the Gothenburg district heating network.

The plant is currently shifting feedstock from wood pellets to forest residues.

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 have been limiting when reaching full production and a smaller revamp of the unit is under way.

However, and in spite of that the GoBiGas phase1 plant is now in its initial operation, the plan for investment in GoBiGas 2 at a scale of 100MW biomethane product has been stopped by the city council.

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 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	P	2016	0.4 tonnes/d	0.050MW	-	n/a

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 plant will be operational by the end of 2017, enabling wider commercial deployment.

The “Gogreengas” Pilot Plant, Swindon, UK

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.

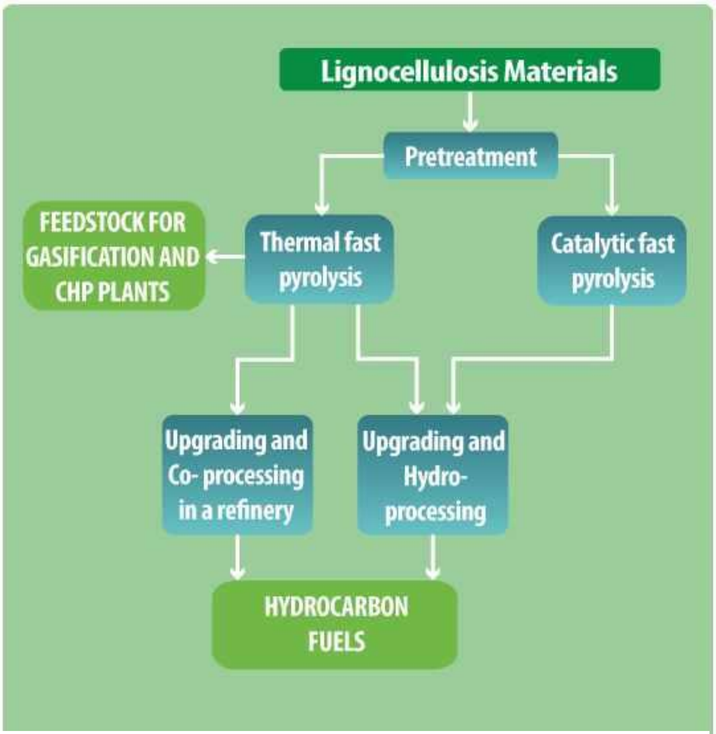

Figure 2.3 Production and upgrading of pyrolysis products and lignin-rich fraction

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[3]) 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.

- 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) (UOP, PetroBras; Repsol, Grace) – see below.
- Fast pyrolysis → stabilization → Hydrodexygenation and Hydrocracking (BTG Biomass Technology Group BV (BTG), US Department of Energy - Pacific Northwest National Laboratory (PNNL)).
- Catalytic pyrolysis → Hydrodexygenation and Hydrocracking (Anellotech, Center for Research & Technology Hellas (CERTH)).
- Hydropyrolysis (hydrogen + catalysts) → Hydrodesulphurization + Dearomatization (Gas Technology Institute (GTI)/ CRI Catalyst Company (CRI)).

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 -6%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

[3] 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).

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 CO_2, CO, soot 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 verified during 2013 in an oil refinery in the Chicago area.

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.

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 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.

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 pretreatment 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 plant extracts a part stream from bed material circulation loop from a biomass fuelled Circulated 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
Fortum	C	2013	50 MW	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.

Fortum has two similar projects in NER 300[4] (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.

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

[4] 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).

gases are combusted and are used to generate additional steam and power. Excess heat is used for drying the feedstock.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product	Hours in operation
Empyro	D/C	2015	120 tonnes/d (clean wood residues)	77 tonnes/d (crude pyrolysis oil)	8MW	>3,500 by 31/8/2016

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

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

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

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.

2.4.3.4 ENSYN plant in Renfrew, 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.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Renfrew	D	2006, improved 2015	70 tonnes/d	>20,000 tonnes/yr (depending on feedstock)	---	Not given

The plant produces a Renewable Fuel Oil (RFO), a petroleum-replacement to be used for heating purposes.

There are more than 10 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.

ENSYN's plant in Renfrew, Canada

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.

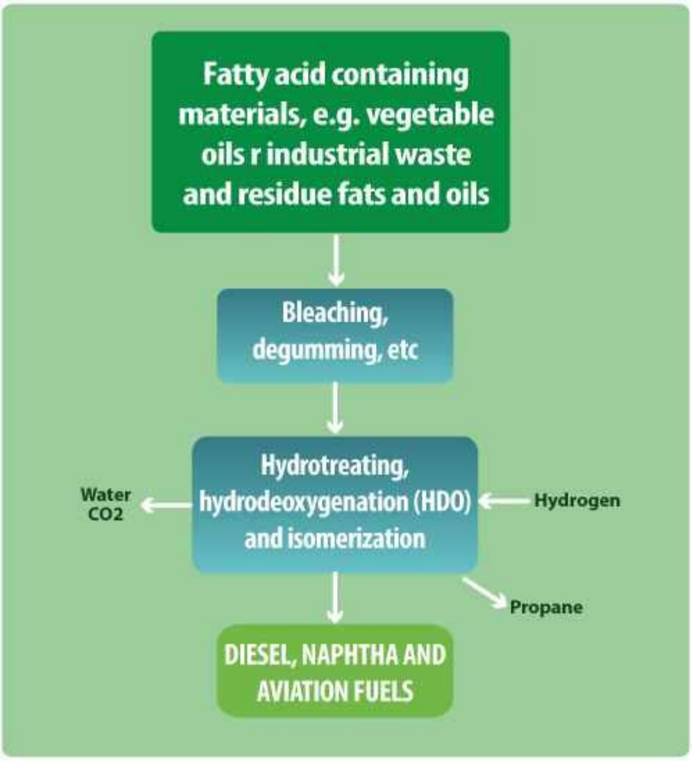

Figure 2.4 Upgrading of waste and residues to Hydrotreated Vegetable Oils (HVO)

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.

2.5.1 HVO Stand-alone production facilities

Currently, 3.5 million tonnes/yr of HVO production takes place globally expected to increase to 6-7 million tonnes/yr by 2020. In the EU, further refinery conversions and co-processing have the potential to provide additional biofuel volumes in the range of 12 million tonnes/yr on top of that.

Neste was the first to invest in an HVO refinery (Porvoo 2007). Currently, Neste has a production capacity of 2.4 million tonnes/yr, with stand-alone refineries in Porvoo (Finland), Singapore and Rotterdam (the Netherlands).

In the US, Diamond Green operates a 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 a (currently idle) HVO facility of 225 thousand tonnes/yr, and Emerald Biofuels plans to invest in a facility of 250 thousand tonnes/yr in 2018.

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 0.2million tonnes/yr output. A second ENI refinery, Gela in Sicily is being converted to 0.5million 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.

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.

At least Preem in Sweden has production of 200,000 tonnes/yr through co-processing, and Repsol and Cepsa in Spain are estimated to produce co-processed biofuels in the scale of approx. 60,000 tonnes/yr each while ConocoPhillips is also co-processing in Cork, Eire.

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.

Plant	Type P/D/C	Start-up year	Feedstock	Product	By-product MW	Hours in operation
Porvoo, Finland	C	2007	Various Vegetable Oils and waste streams	200,000 tonnes/yr	-	commercial operation since start-up
	C	2009		200,000 tonnes/yr	-	commercial operation since start-up
Singapore	C	2010		1,000,000 tonnes/yr	-	commercial operation since start-up
Rotterdam, The Netherlands	C	2011		1,000,000 tonnes/yr	-	commercial operation since start-up

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.

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 Valero. 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.

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

2.5.4.4 *Eni's Green Refinery Project, Venice, 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	11,575 barrel/day	Confidential	Confidential	Continuous Since 2014

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

2.5.4.5 The AltAir Renewable Jet Fuel Project, Los Angeles, USA

The 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 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	2,500 barrel/day	Confidential	Confidential	Operating-2016 Start-up Completed

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.

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 (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.

A pretreatment 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. There are also examples of cooking and organosolv processes. The nature of the pretreatment 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 pretreatment 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 pretreatment 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).

3.2 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:

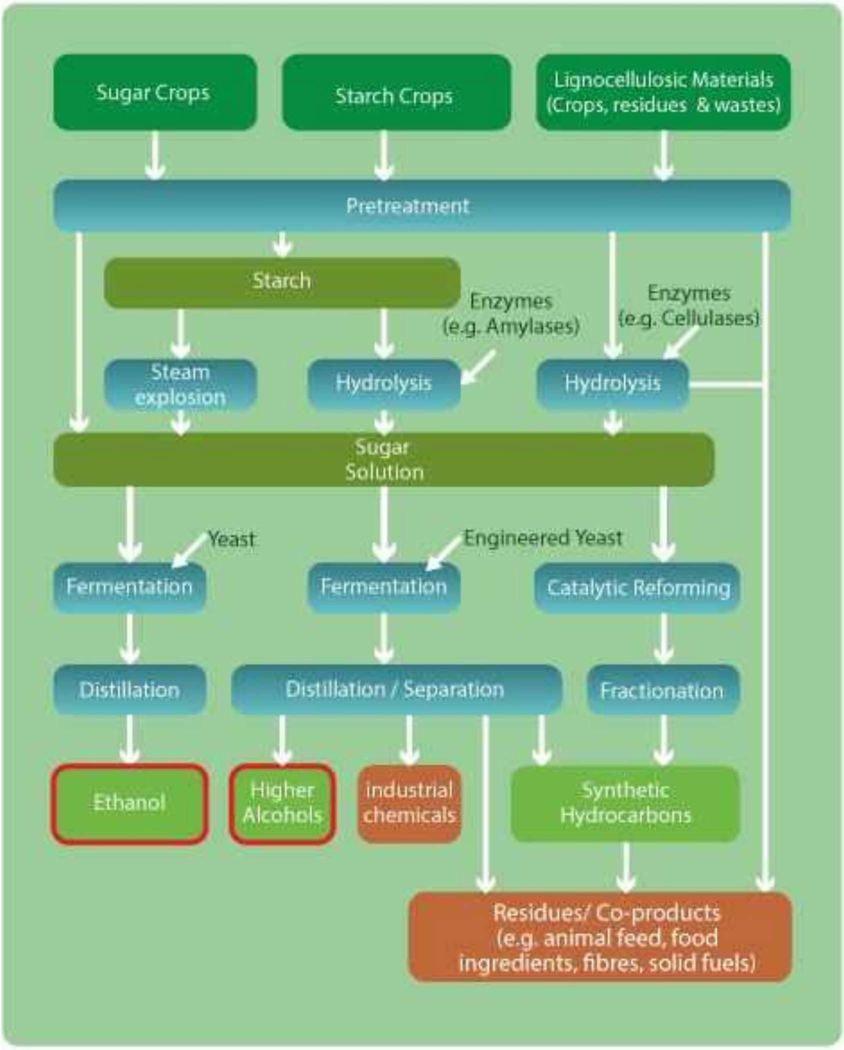

Figure 3.1 Ethanol and higher alcohols via fermentation

- 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 to arrive at 99.5%vol. for blending in gasoline. The remaining azeotropic water 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

Abengoa, which also was producing first generation ethanol in several installations in the EU and USA, has 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 pretreatment 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 pretreatment, 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)[5]	~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%.

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

Abengoa's Hugoton Plant, Kansas, USA

3.2.4.2 Crescentino plant, Italy

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 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 ton 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

DuPont has constructed and is currently commissioning a commercial sized cellulosic ethanol facility in Nevada, Iowa (US). 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 in Denmark, and yeast from DSM in Holland. The Bioflex plant is co-located with an existing first-generation ethanol plant from sugarcane. 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 70 MW_{el}, having a surplus of 50 MW_{el} sold to the grid. The PROESA technology is the first to have been licensed and used in two commercial facilities.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Bioflex 1, São Miguel dos Campos-Alagoas	C	Q4 2014	400,000 tonnes/yr[6]	65,000 tonnes/yr	Steam and power	N/A

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 but stable long term operation has so far not been reached. The plant has been operational for 18 months. The pre-treatment area of the plant is going through optimization in order make in fully operational.

GranBio's Bioflex 1 Plant, Alagoas, Brazil

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

Raísen 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 Logen´s pretreatment technology based on acid-catalysed steam explosion followed by enzymatic hydrolysis (enzymes supplied by Novozymes) and fermentation.

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	N/A

[6] from http://www.biofuelsdigest.com/bdigest/2014/09/24/granbio-starts-cellulosic-ethanol-production-at-21-mgy-plant-in-brazil/

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 pretreatment 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[7]	60,000 tonnes/yr (or 20 million gallon/yr)	Energy (steam and biogas)	Currently in ramp-up; proprietary

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 pretreatment.

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

[7] 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.
- Pretreatment 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[8]	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)	>50,000

The longest continuous run with the same process parameters has been 4 weeks. The plant is a development plant. For ethanol production the targets have been met but for other applications work is ongoing.

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 Butamax™ plant demonstrates the microbial production of isobutanol as a single fermentative product, the process engineering for recovering biobutanol produced during fermentation, engineering design for optimized energy integrations, and various renewable fuel and chemical compositions.

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

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.

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 ton feedstock (v1) to 280-300 litres/dry ton 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

3.2.4.10 The Borregaard plant, 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	2013	1,200 tonnes/d (spruce)	0.28 tonnes/d ethanol 0.46 tonnes/d lignin chemicals	0,27 ton/d CO_2	>23,000

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.

3.2.4.11 *IFP's Futurol pilot, Pomacle, France*

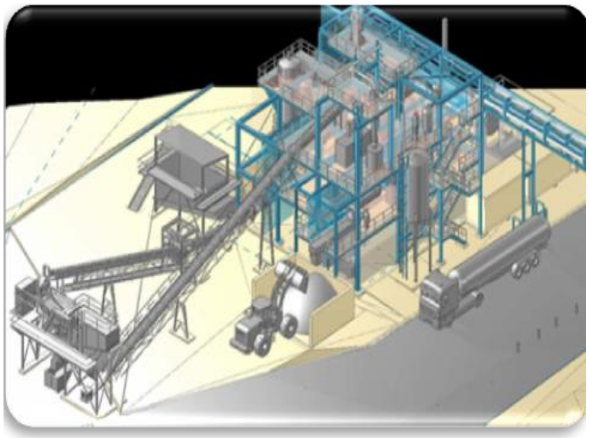
IFP's Futurol process includes hydrothermal pretreatment technology followed by SSF (hexoses and pentoses) to produce bioethanol for biofuels and sustainable chemistry.

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

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[9]	2,000 h/y

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

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.

[9] can be burnt in industrial plants

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

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

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)	~30,000

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

3.2.4.14 Cellunolix® demonstration plant, Kajaani, Finland

The Finnish investor, North European Bio Tech Oy (NEB), an associated company of SOK Corporation and energy company St1, is finalising a construction of bioethanol plant on the Renforsin Ranta industrial estate in Kajaani, Finland. Commissioning of the unit will take place during 4th quarter of 2016. The GHG reduction will 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 plant is being delivered by St1 Biofuels Oy who is also responsible for design, permits and coordination and will be operating the plant once it is completed. 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	2016	~270 tonnes/d (55% water)	~ 24 tonnes/d	~ 430 MW/d	
Cellunolix® (EIA in process)	C	2019		~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 2018.

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.

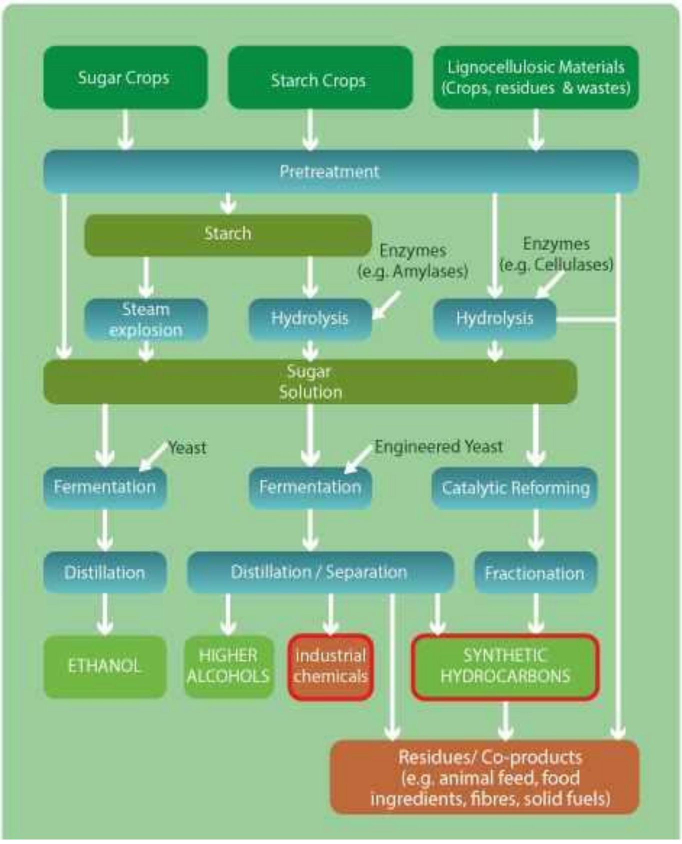


Figure 3.2 Hydrocarbons from sugar-containing material

3.3.2 Routes involving catalytic upg 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 - 250°C, 3 - 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. 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.

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

3.4 Biomethane via anaerobic digestion

3.4.1 Feedstocks

Typical feedstocks for biomethane production are wet waste fractions from the agriculture and food industry sector and sludges from e.g. water treatment works in both cities and industries. One special case is recovery of landfill gas from waste landfills to prevent release of the methane formed over decades into the atmosphere.

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 pretreatment of lignocellulosic compounds is strongly recommended to make the cellulose and hemi-cellulose better available for the bacterial degradation. This pretreatment might be enzymatic, chemical or physical. It is fairly comparable to the pretreatment for alcohol production from lignocellulosic material.

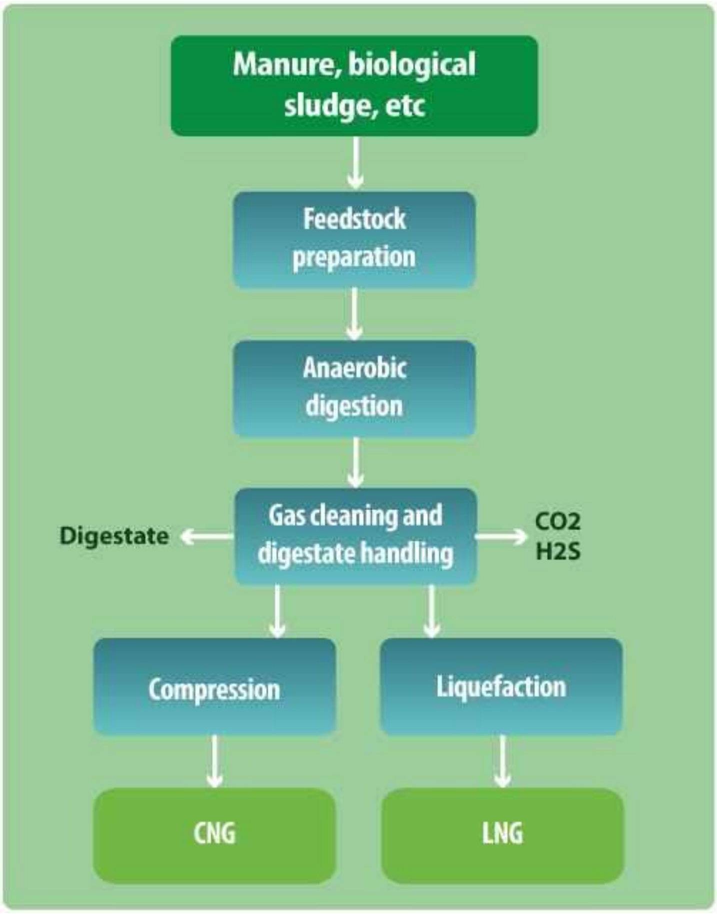


Figure 3.3 Biomethane via anaerobic digestion

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)

Out of the total of some 17,000 biogas plants in Europe over 95% are decentralized combined heat and power plants (CHP) at small scale (average 0.5 MW_{el}). However, with the reductions in feed-in tariffs for electricity the application of biogas in transport becomes increasingly important.

There are only close to 400 plants where the bio-gas was upgraded to bio-methane. Half of these were in Germany, some 60 plants in Sweden and some 40 plants in the UK. The total production of bio-methane is estimated to be 14 TWh or 1.2 million tonnes of oil equivalent (toe). In order to reach the fuel quality standards for transportation and injection into the 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[10], 60 GWh followed by the United Kingdom (UK) and the Netherlands. But also in the USA biogas is upgraded and liquefied on a landfill in Livermore.

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

3.4.4 Pilots, Demonstration and Commercial plan

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/Västble kin-ge 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 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 250 - 2,000kW and a bio-methane production of 80 - 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 Nm^3/h	11 MWh$_{el}$/d (fr. 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)	1 MW (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

3.4.4.5 NGF Nature Energy in Holsted, Denmark

NGF Nature Energy opened the Holsted Biogas plant in August 2015. The plant processes around 400 thousand tons 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.

3.4.4.6 The VERBIOgas plant in Schwedt, 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.

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

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}. Within the next 3 years the capacity of the plant is going to be increased to 16.5MW_{th} with an annual target of 140GWh_{th} bio-methane to be fed into the grid.

VERBIOgas plant in Schwedt, Germany

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 Plant in Caofoedian, China

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

3.5.2.2 LanzaTech MSW facility, Japan.

This project uses gasified MSW to produce ethanol through gas fermentation. The total number of hours the plant has been run over time is around 4,000h, run in series of campaigns.

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	4,000

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, LanzaTech, Primetals Technologies and E4tech agreed to start the construction of Europe's first-ever commercial demonstration facility at ArcelorMittal's integrated steel plant to create bioethanol from waste gases produced during the steelmaking process. It is estimated that this plant will be online for around 8,000 hours run through a series of campaigns rather than in one entire year.

Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours of operation
LanzaTech	C	2017	50,000 Nm^3 H_2+CO	143 tonnes/d	n/a	8,000 hr/yr

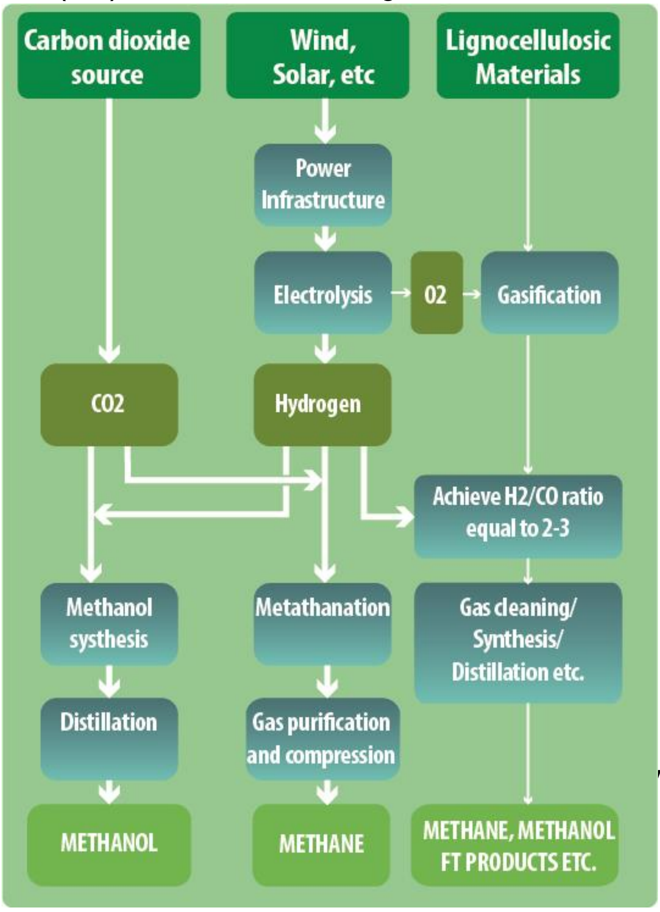
The construction of the €87 million flagship pilot project commenced in 2016, with bioethanol production expected to start mid-2017. Construction will be in two phases, with phase one providing an initial capacity of 16,000 tonnes of ethanol per annum by mid-2017 and phase two, which will be completed in 2018, bringing the total capacity to 47,000 tonnes of ethanol per annum.

Many of the technical difficulties with the gas fermentation system have largely been overcome by LanzaTech during the course of the development. The process operates close to ambient temperature and atmospheric pressure, resulting in reduced CO_2 emissions and minimizing heating and cooling costs. LanzaTech has also demonstrated the ability to manipulate the organism for high yields of highly specific products.

After full commercial operation of the first phase unit in Ghent, the plan is that a second facility will be constructed and operated at the same facility. Further roll out has been mapped out by ArcelorMIttal across the EU over the next 10 years. The anticipated potential of the full deployment at identified ArcelorMittal sites is around 300,000 tonnes of ethanol per year, or 380 million liters.

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 amended RED.

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.

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%

4.1 Methane production

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.

4.3 Adding H2 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 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[11] as well is the report Co-production of synthetic fuels and district heat from biomass residues, carbon dioxide and electricity: Performance and cost analysis[12].

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

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.

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

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 5 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 [i] oxygen which is created as the plant uses electricity to split water into its constituent chemicals, and [ii] 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	10,000

The plant has been in operation for 10,000 hours. The renewable methanol is sold to fuel customers in Iceland, the Netherlands, UK, Denmark and Sweden.

4.5 Projects under 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 is scheduled in 2017.

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

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.

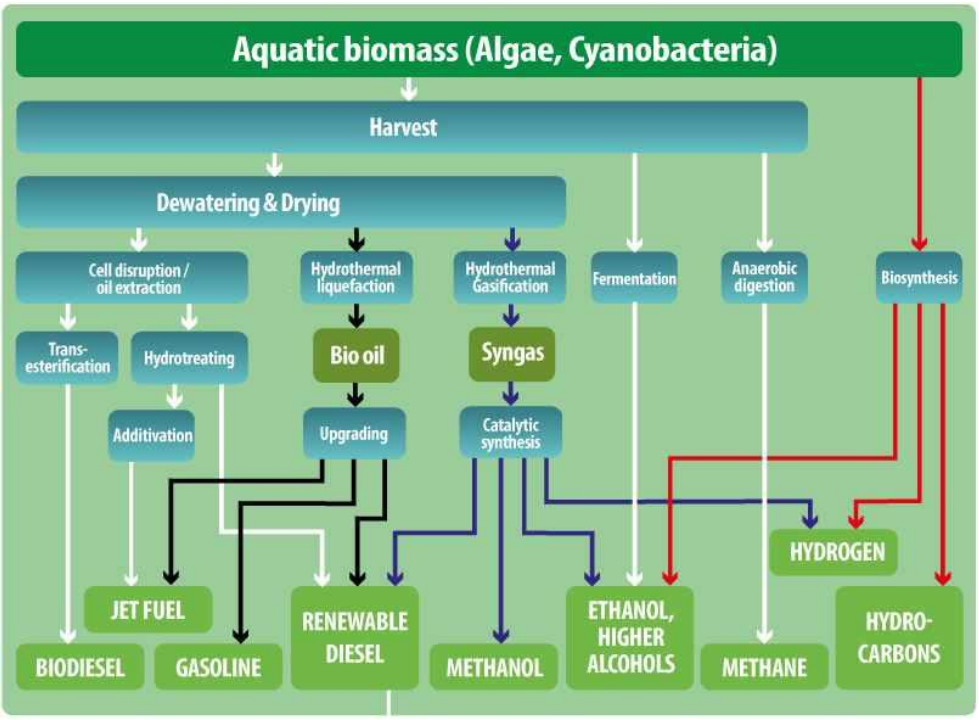


Figure 5.1 Algae development pathways

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 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.

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

Two other options are fermentation for ethanol production and anaerobic digestion to produce bio-methane. All these three ways eliminate the need of drying the algal culture.

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. An exception is the current FP7 funded microalgae plants (Algae Cluster) and the US Algenol company. These pilot and demo plants represent a dedicated effort to become algae-based plants focused on bioenergetic products. However, it is worthwhile to say that the current high cost of producing 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. 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.

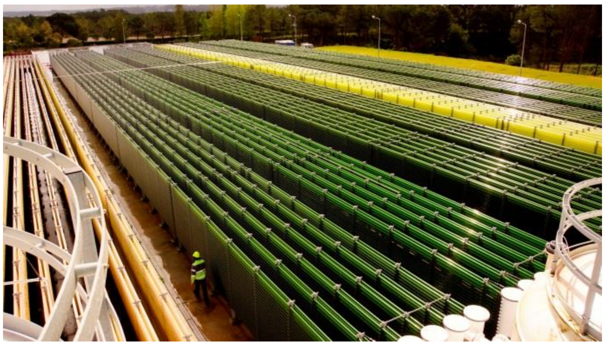
5.6.1 The Allmicroalgae (former AlgaFarm) plant, Pataias-Leiria, Portugal

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 1,300 m^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[13]	n/a	Since 2013 until present



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

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

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 subject 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

[13] Total Installed capacity on 2013/2014.

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

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.

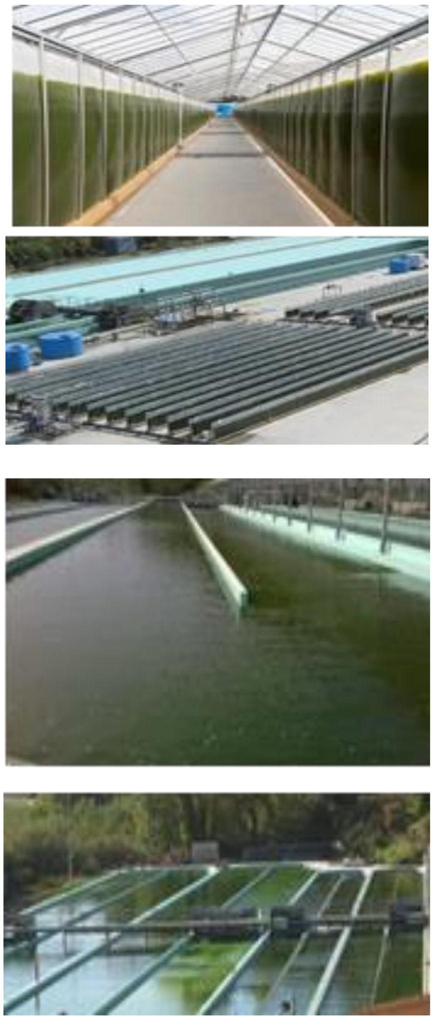
It was also possible to prove that the technologies developed in BIOFAT can be used for the production of valuable compounds in a small scale with a positive economic balance, and if in a much higher-scale of several hundreds of ha, in a biorefinery framework where it will be possible to use the residues 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[14]	34 kg/d (dry matter) (microalgae biomass)[15]	n/a	Since Nov/2013 to Nov 2015 (about 17,280h of operation)

BIOFAT Pataias Pilot Plant Cascade Raceway – 2 x 1500 m^2 – Designed and built by A4F. (BIOFAT FP7 project)



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

[14] 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.
[15] the Biorefinery process demonstrated the transformation of oil from *Nannochloropsis* into biodiesel (according with the norms for use as biodiesel in Europe).

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 tons 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.

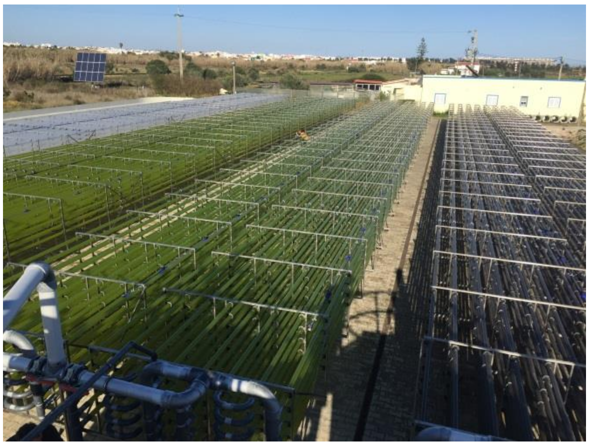
The sustainability of this demonstration, in terms of both economic and environmental (closed carbon loop) implications is considered across the whole process, including optimum use of algal biomass resources to enable commercialization.

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 200m² cultivation area is operated continuously since May 2012. Prototype plant which comprises 1,000m² cultivation area plus around 200m² 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 pretreatment 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	P (Chiclana de la Frontera, ES)	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	D (Chiclana de la Frontera, ES)	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	(not operational yet)

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.

5.7 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[16] 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.

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.

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

5.7.3 Algenol, USA

Founded in 2006, Algenol[17], 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 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[18]

closed PBRs using patented VIPER technology, USA[19]

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 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.

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

In 2015 it was announced their first commercial facility, to be located in the United States supported by a new $25 million 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 from BioFields in 2014 — in all, BioFields has invested $65 million 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 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[20] 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.

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 per gallon ($50 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.

[20] http://www.jouleunlimited.com/

Heliae Development LLC, USA[21]

Joule Unlimited[22]

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