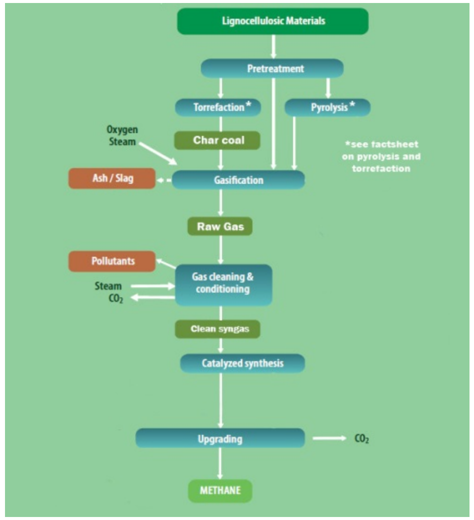
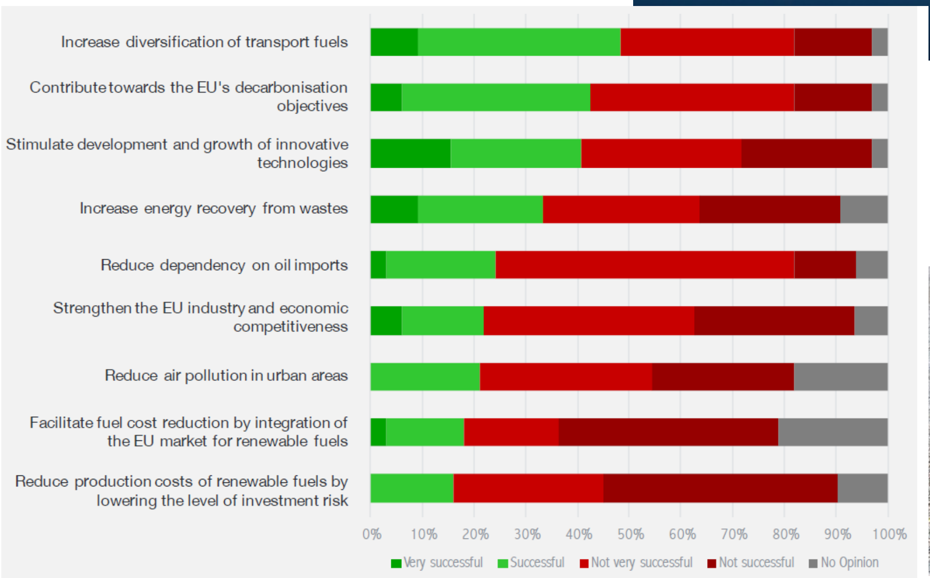
Subgroup Advanced Biofuels
initiated by
Sustainable Transport Forum (STF)



Summary on technology status and Cost of Biofuels

June 22, 2017
Ingvar Landälv,
Luleå University of Technology



Members of SGAB

1	Aho	Mika	ST1
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6	Gameson	Tom	ABENGOA
7	Gaupmann	Gloria	Clariant
8	Girio	Francisco	LNEG
9	Greening	Paul	ACEA
10	Hamje	Heather	Concawe
11	Harrison	Pete	EU Climate Foundation
12	Holmgren	Jennifer	Lanzatech
13	Hudson	Leigh	British Airways
14	Hull	Angelica	Swedish Biofuels
15	Janhunen	Marko	UPM
16	Judd	Robert	GERG
17	Klintbom	Patrik	VOLVO
18	Labrie	Marie-Helene	ENERKEM

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20	Lastikka	Ilmari	NESTE oil
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22	Marchand	Philippe	Total
23	Mirabella	Walter	European Fuel Oxygenates Association
24	Murfin	Andrew	Shell
25	Schapers	Eline	SkyNRG
26	Sipila	Kai	VTT
27	Stefenson	Per	Stena Lines
28	Stępień	Adam	Copa-Cogeca
29	Strömberg	Jonas	SCANIA
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31	Venendaal	René	BTG
32	Vink	Tim	Honeywell/UOP
33	Wellinger	Arthur	EBA
34	Zschocke	Alexander	Lufthansa

SGAB Core Team

Chair: Kyriakos Maniatis, DG ENER

Co-Chair: Ingvar Landälv, Luleå Univ.

Rapporteurs:
Lars Waldheim
Eric van den Heuvel
Stamatis Kalligeros

Members of SGAB representing …

Interest Group	Numbers
Technology providers	12
Oil companies	3
Airlines	2
Industry associates	7
Heavy duty transports	2
Maritime transport	1
Consultants	4
IEA	1
Think tanks	2
TOTAL	34

Observers of SGAB

1	Bach	Heinz		Austria
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4	Cluyts	Ivo	Ministry of Environment	Belgium
5	Desplechin	Emmanuel	ePure	European Association
6	Florea	Leonard	Regulatory Authority for Energy	Romania
7	Garofalo	Raffaello	EBB	European Association
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10	Leahy	Patrick	Department of Transport	UK
11	Neeft	John	Netherlands Enetrprise Agency	The Netherlands
12	Nicolau	Alexandra	General Directorate for Energy & Geology	Portugal
13	Pezzaglia	Marco	Consultant, Italian Ministry of Economic Development	Italy
14	Pinheiro	Sérgio Manso	General Directorate for Energy & Geology	Portugal
15	Stausbøll	Yvonne	UPEI	Association
16	Weber	Thomas	Federal Ministry for the Environment	Germany

European Commission

Sub Group on Advanced Biofuels

Sustainable Transport Forum

Building up the future

Technology status and reliability of the value chains

Compiled by: Ingvar Landälv
Edited by: Kyriakos Maniatis, Lars Waldheim, Eric van den Heuvel & Stamatis Kalligeros

14 February 2017

Disclaimer

This report has been prepared for the Sub Group Advanced Biofuels (SGAB) based on the information received from its members as background material and as such has been accepted and used as working material by the Editorial Team to give the status of existing technologies without the ambition of describing all developments in the area in detail. However, the view and opinions in this report are of the SGAB and do not necessarily state or reflect those of the Commission or the organization that are members of, or observers to the SGAB group. References to products, processes, or services by trade name, trademark, manufacturer or the like does not constitute or imply an endorsement or recommendation of these by the Commission or the Organizations represented by the SGAB Members' and Observers Neither the Commission nor any person acting on the Commission's, or, the Organizations represented by the SGAB Members' and Observers' behalf make any warranty, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information contained herein.

Information asked for:

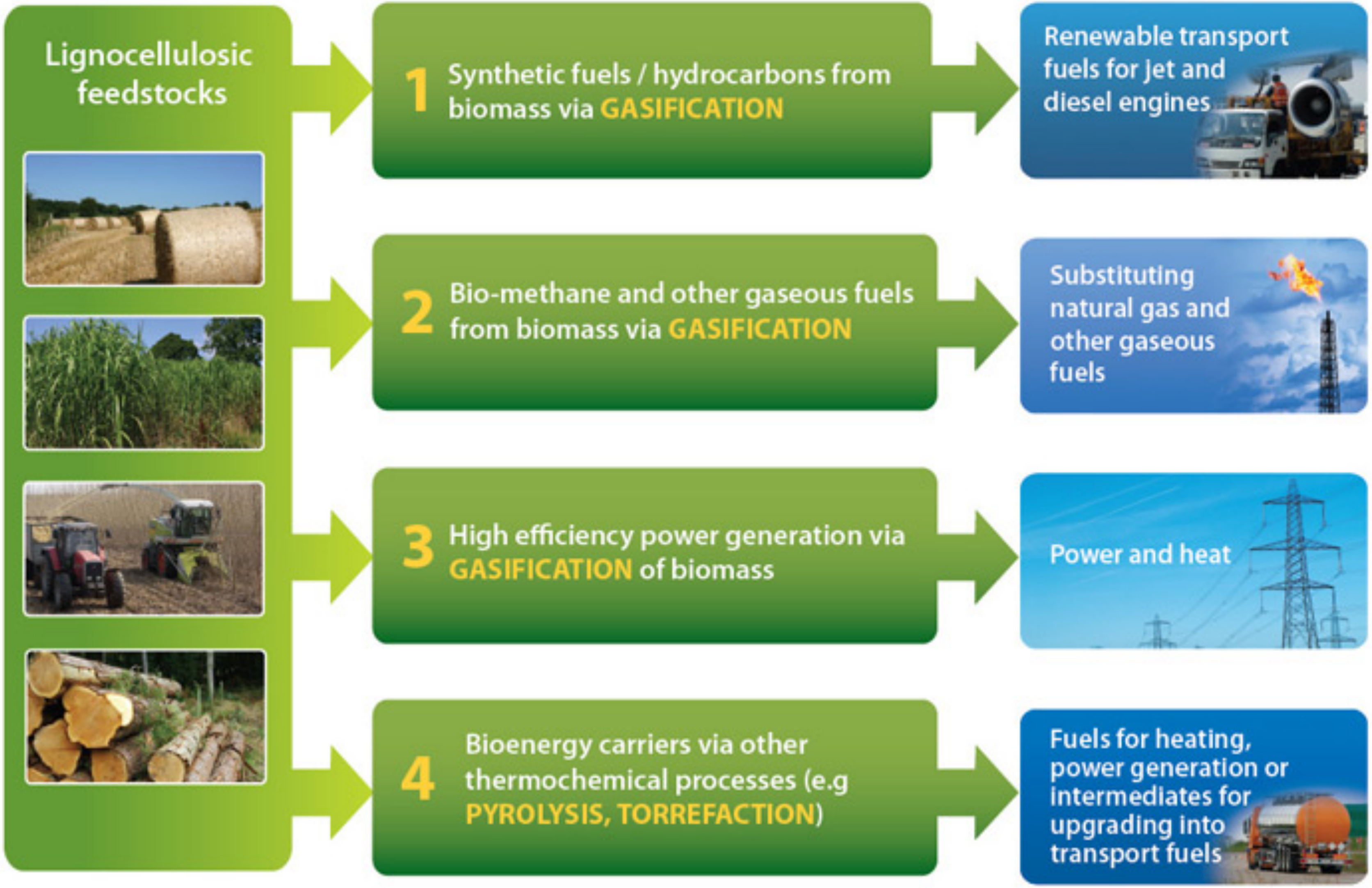
A short description with name, location and background and list of key technologies utilized in the plant. The information provider was asked also to classify the plant as a Pilot plant (P), a Demonstration plant (D) or a Commercial plant (C). Finally, the following additional points were also addressed:

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

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

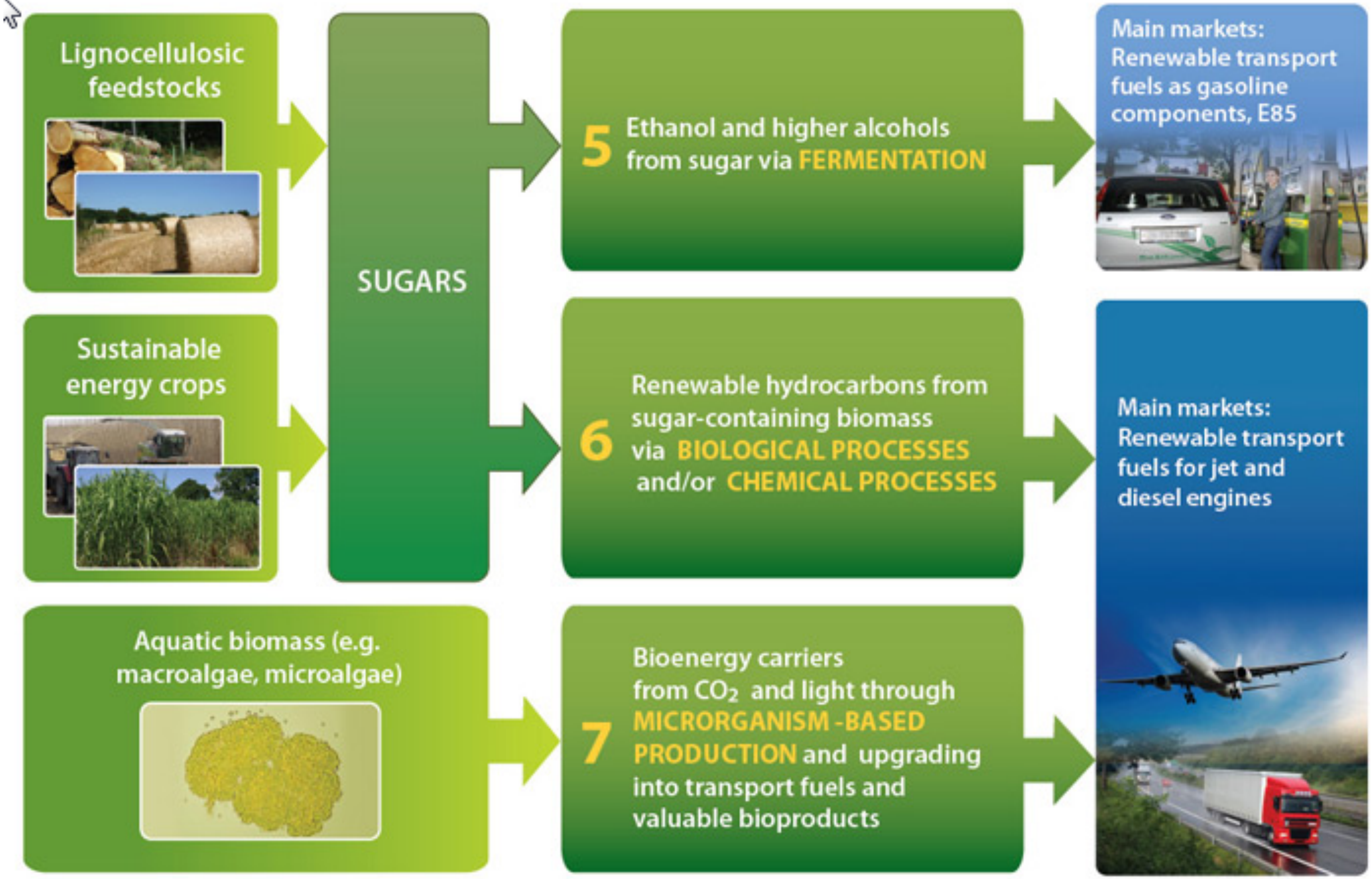
Proposed topical groups in the report	Partners who have indicated interest to participate
Thermochemical conversion	LTU
	Enerkem
	VTT
Biological conversion	Lanzatech
	Clariant
Power to G-or-L conversion	Methanol Institute
	GERG
	LTU
Algae development	LNEG

ETIP Bioenergy Value Chain 1-4: Thermochemical



Source: European Biofuels Technology Platform

ETIP Bioenergy Value Chain 5-7: Biochemical



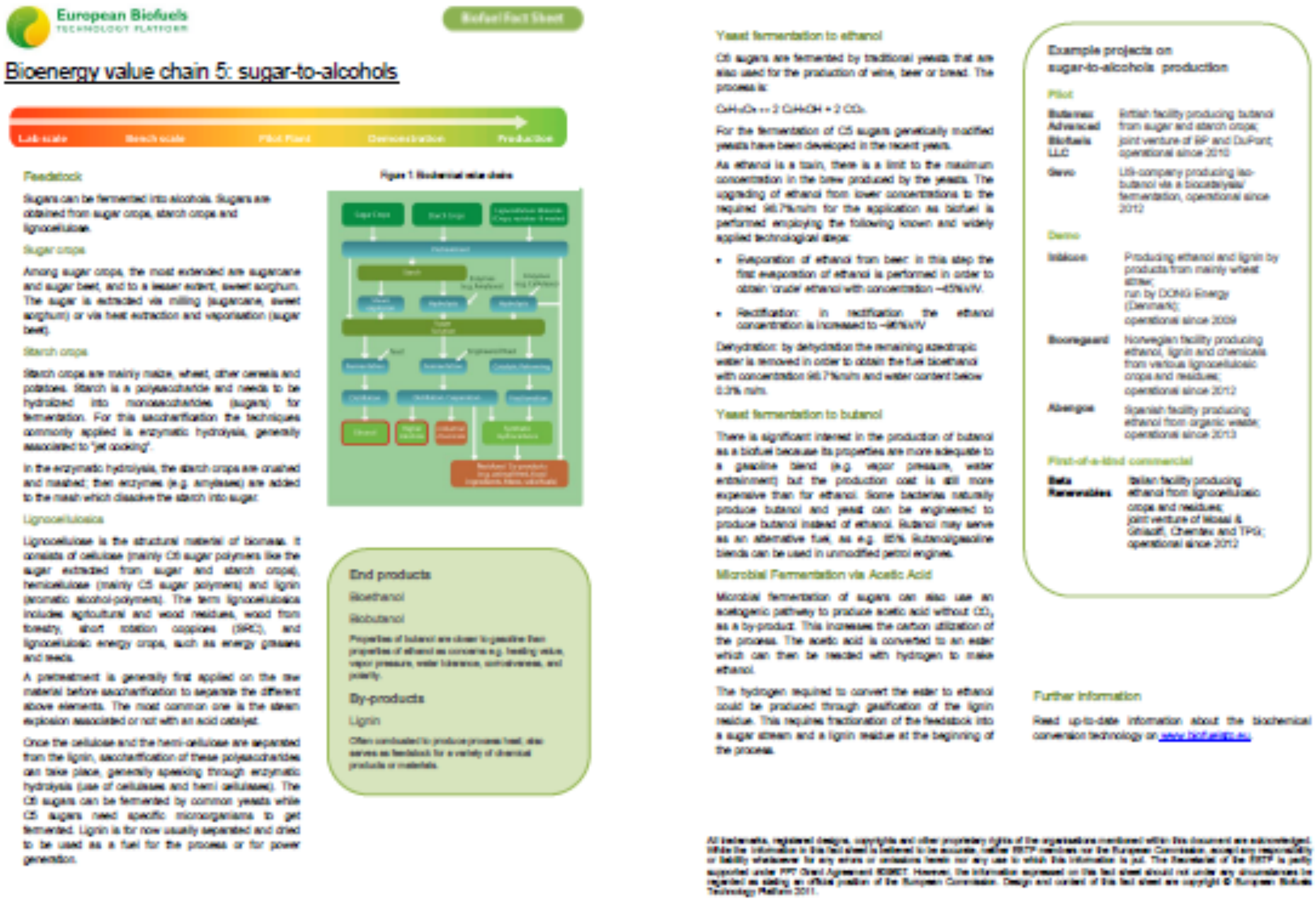
Source: European Biofuels Technology Platform

Main Chapters in the Report *"Technology status and reliability of the value chains"*

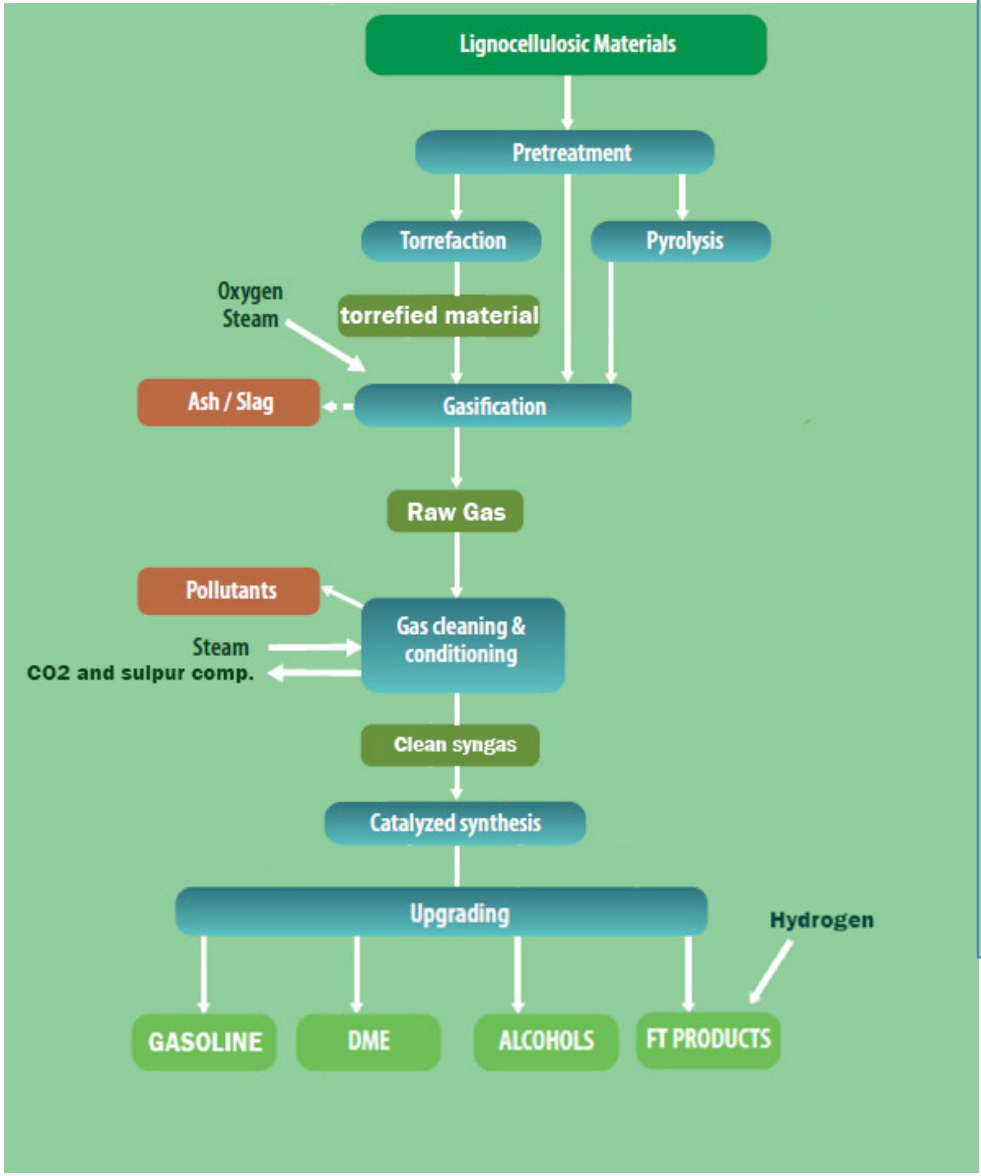
Chapters are correlated to the seven value chains defined by EIBI

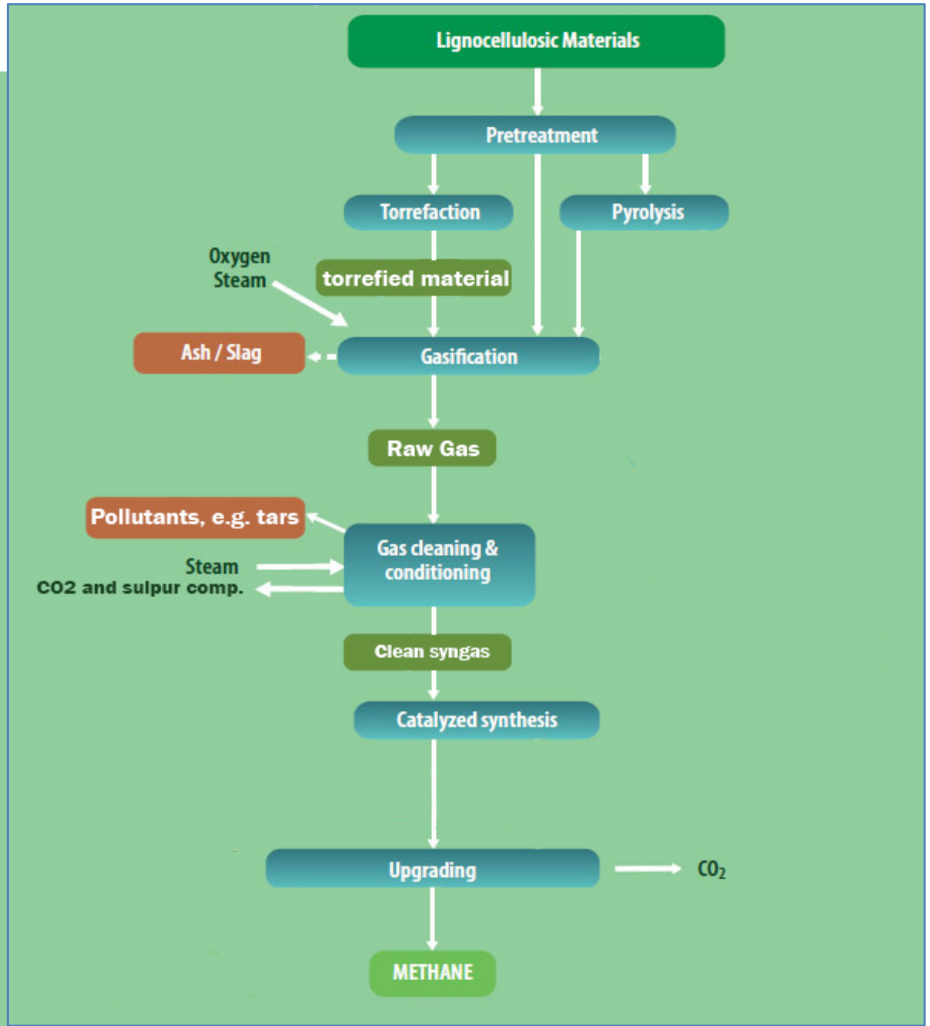
#	Proposed topical groups in the report	EIBI Value chains
1	Thermochemical conversion	1,2 and 4
2	Biological conversion	5-6
3	Power to G-or-L conversion	---
4	Algae development	7

Example: Value Chain 5



Synthetic Fuels and Biomethane via Gasification





Example: Enerkem, Edmonton, CA

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.

(Text not complete)

Example: GoBiGas, Gothenburg, SE

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.

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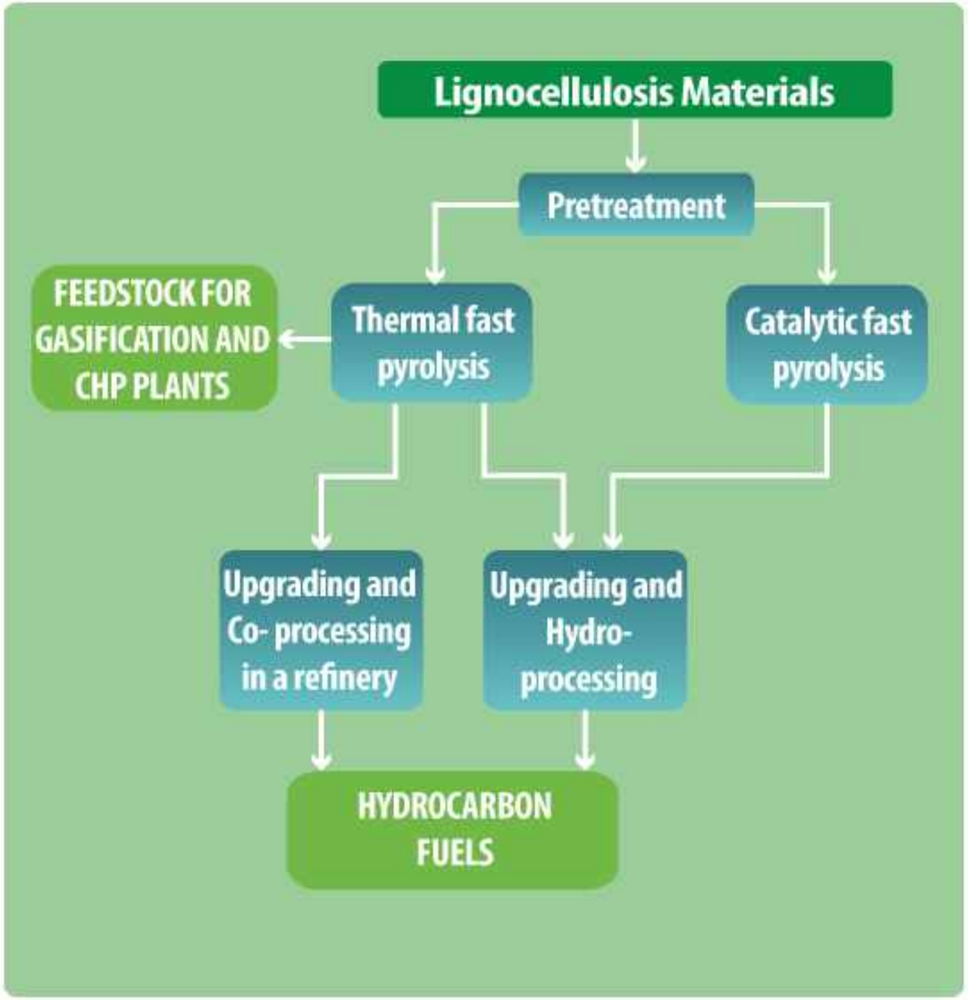
Production and upgrading of pyrolysis products and lignin rich fractions



Example: Empyro's plan, Hengelo, Holland

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

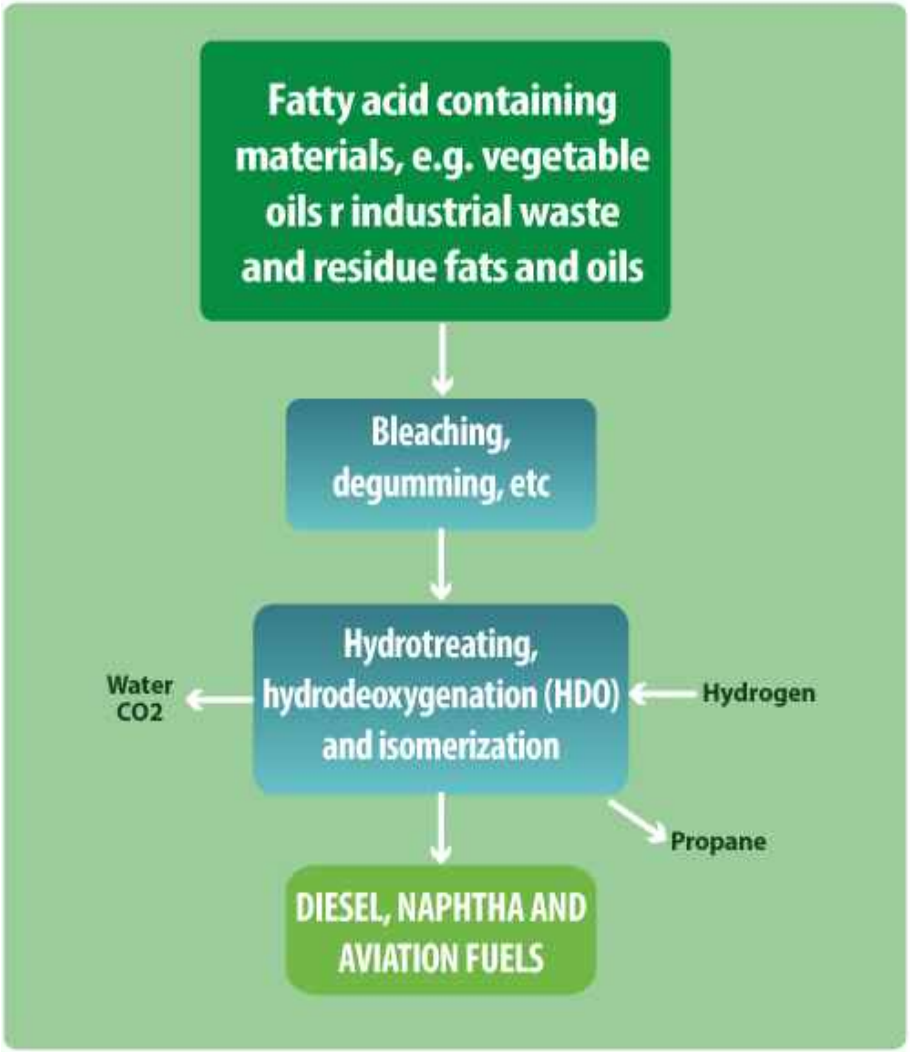
Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product	Hours in operation
Empyro	D/C	2015	120 tonnes/d (clean wood residues)	77 tonnes/d (crude pyrolysis oil)	8MW	>3,500 by 31/8/2016

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.

(Text not complete)

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

1. **HVO Stand-alone production facilities**
2. **HVO production through refinery conversion**
3. **Co-processing**



Example:
UPM's Lappeenranta Biorefinery plant, 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.

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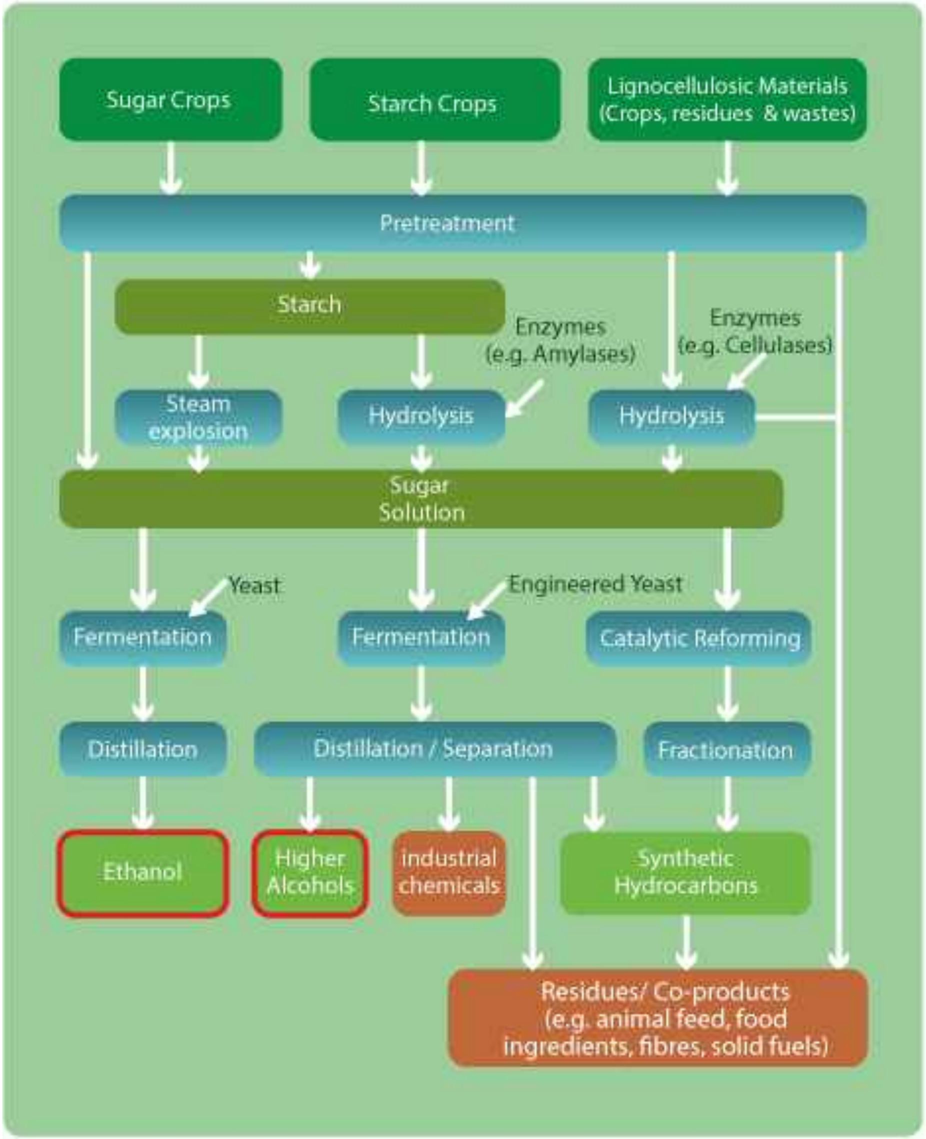
Ethanol and higher alcohols from lignocellulosic sugar via fermentation



Example:
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.

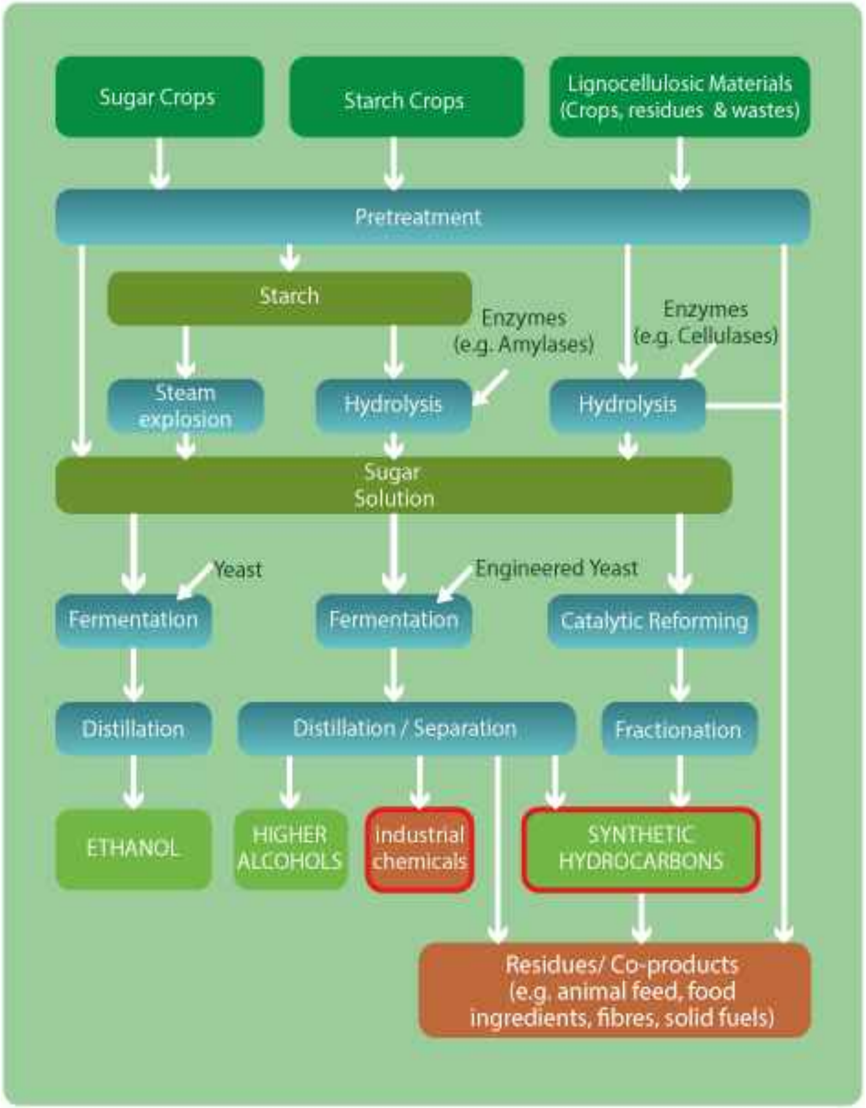
Plant	Type P/D/C	Start-up year	Feedstock capacity	Product	By-product MW	Hours in operation
Beta Renewables	C	2013	n/a	25,000 -40,000 tonnes/yr	n/a	--

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.

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



Example: 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.

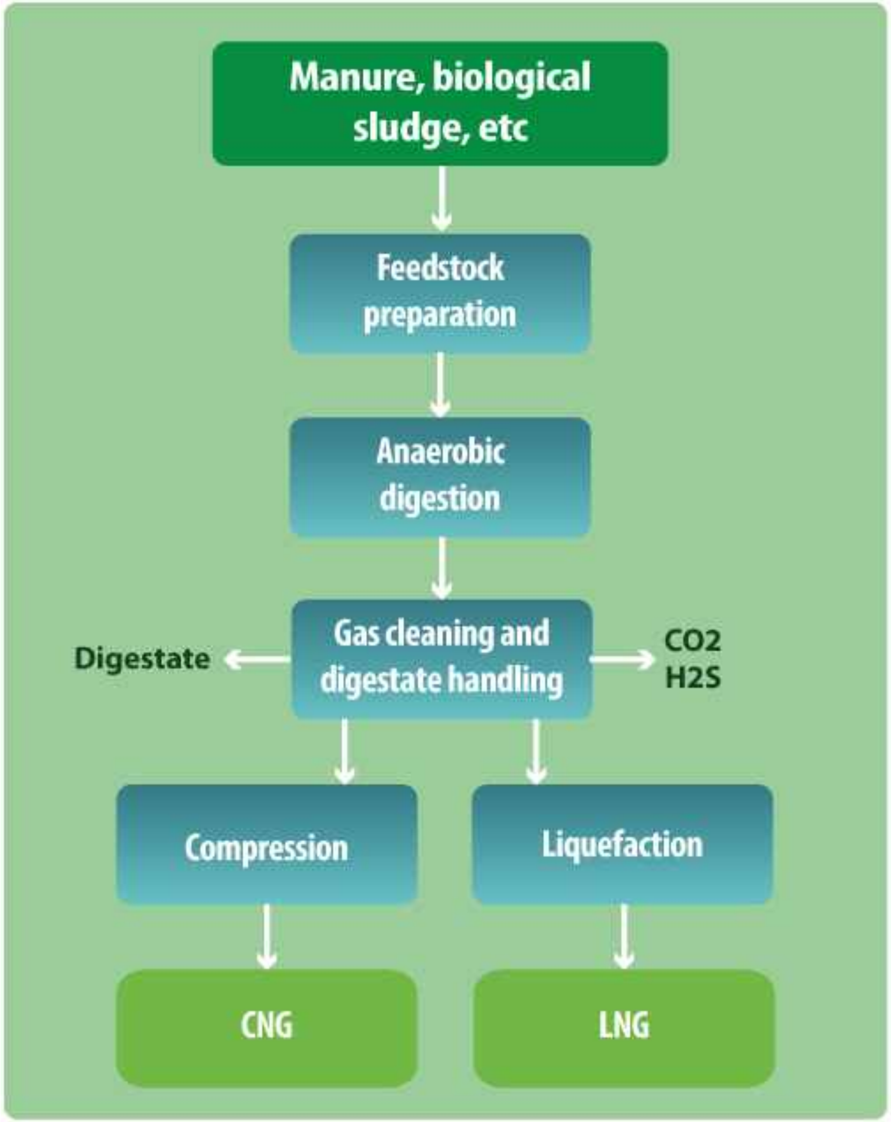
Both larger scale pilot plants operated as designed and proved that the two technologies could be scaled utilizing bench top pilot plant data.

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.

Biomethane via anaerobic digestion



Example: The VERBIOgas plant, 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.

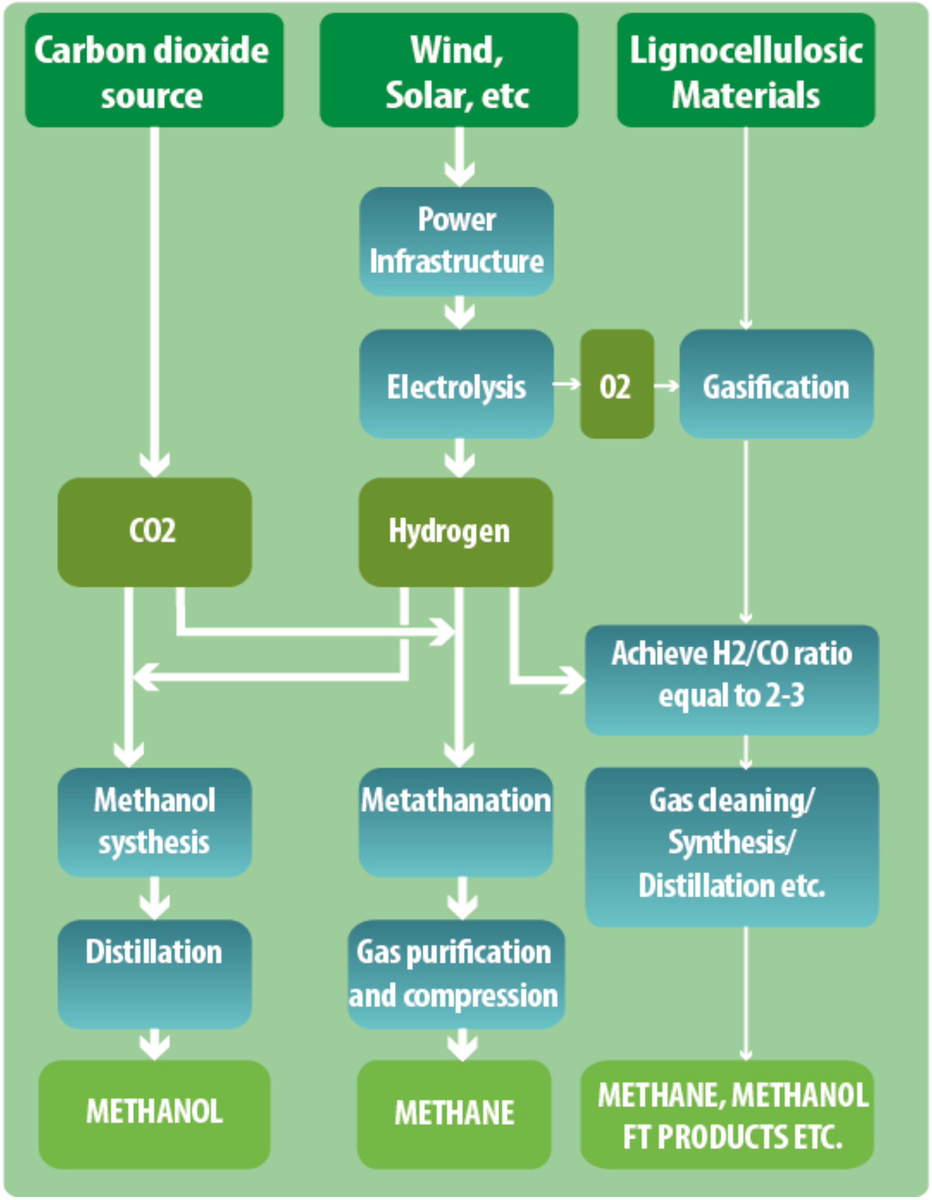
Hydrocarbons and alcohols from waste gaseous material via gas fermentation

Example:
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

Power to Gas and Power to Liquid conversion



Example:
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.

Example:
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.

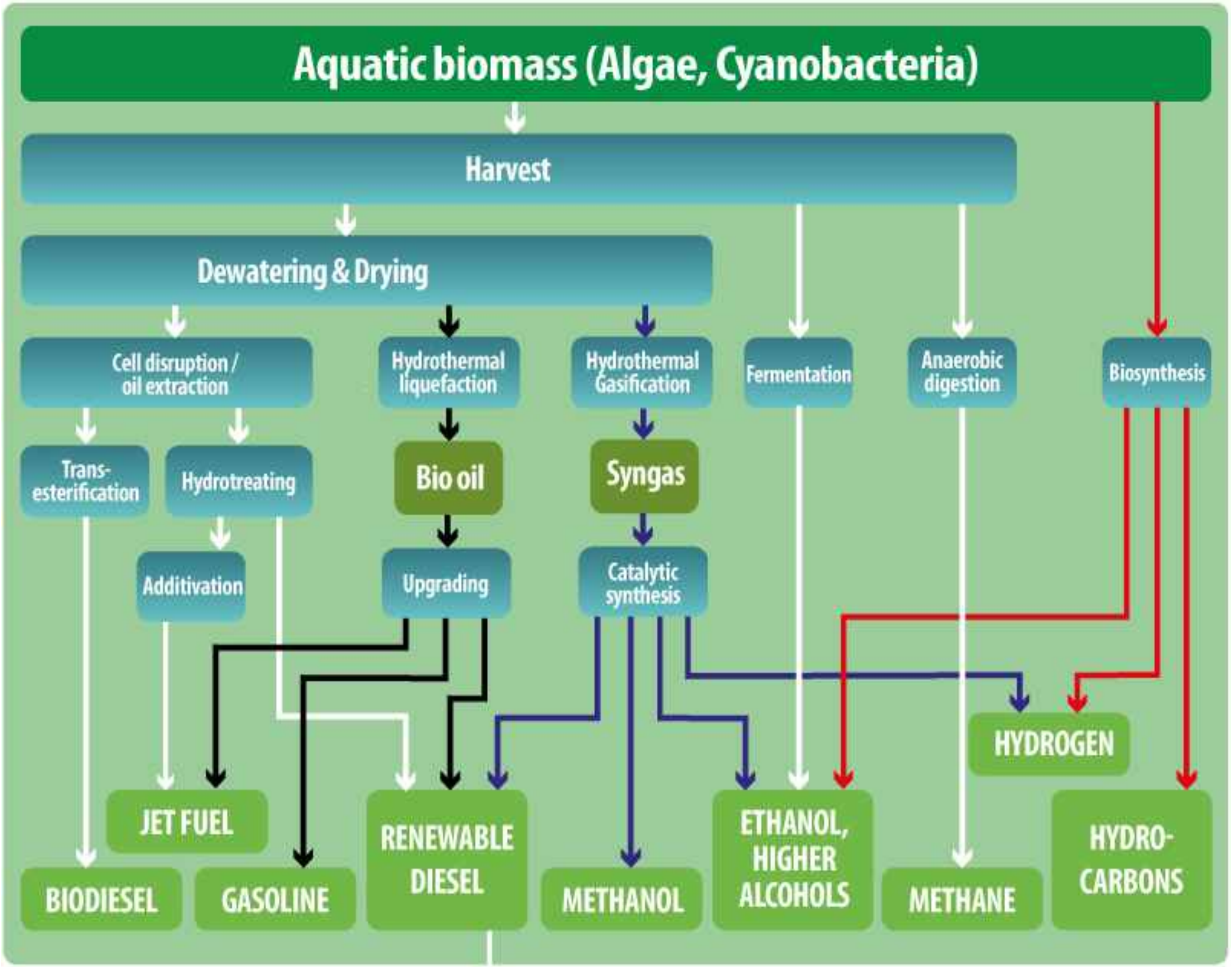
All energy used in the plant comes from the Icelandic grid mix, which is generated from hydro and geothermal energy. The plant uses electricity to generate hydrogen which is converted into methanol in a catalytic reaction with carbon dioxide. The CO_2 is captured from flue gas released by a geothermal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

Algae development



Example:
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	34 kg/d (dry matter) (microalgae biomass)	n/a	Since Nov/2013 to Nov 2015 (about 17,280h of operation)

Technology Status - 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.

European Commission

Sub Group on Advanced Biofuels

Sustainable Transport Forum

Building up the future

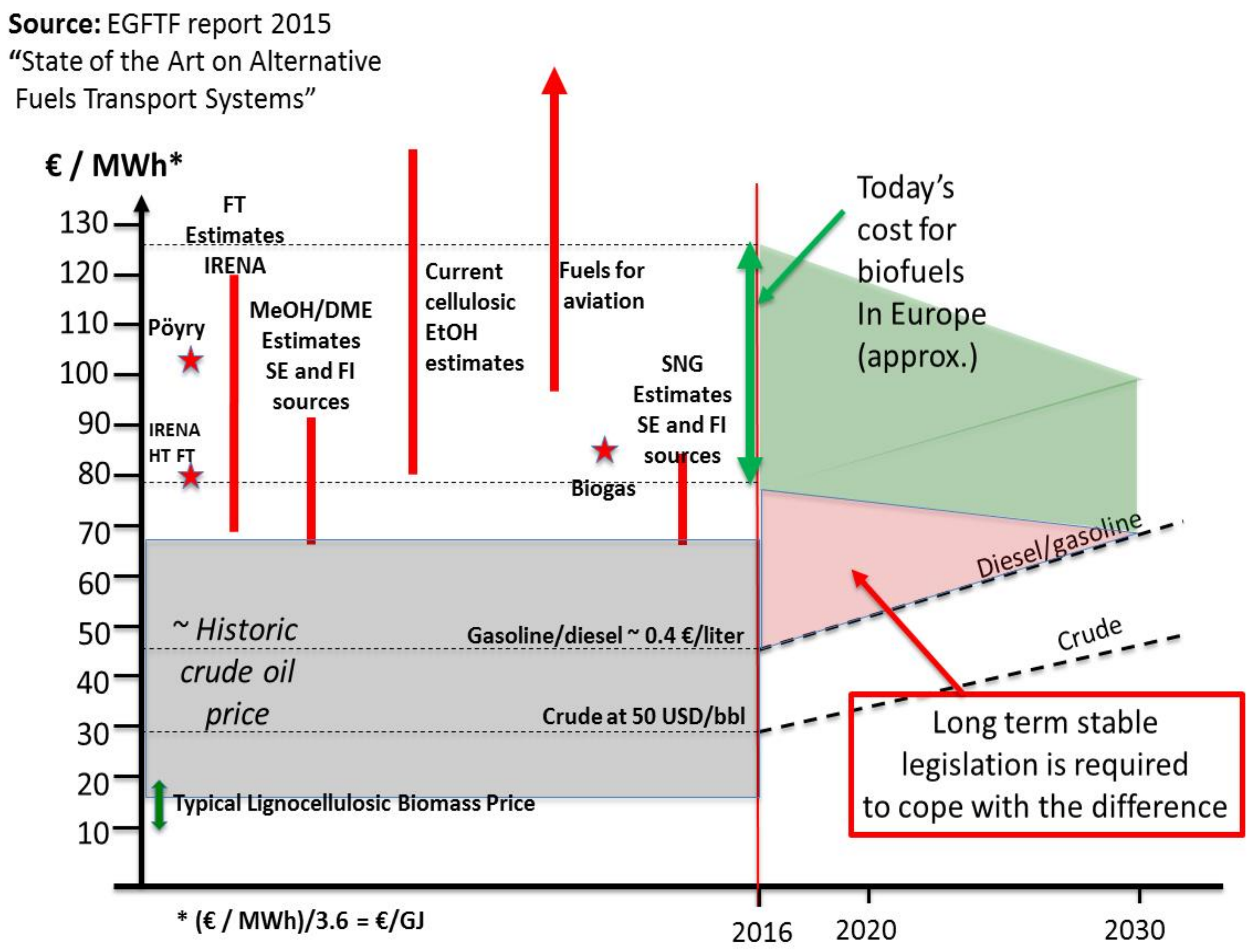
Cost of Biofuel

12 February 2017

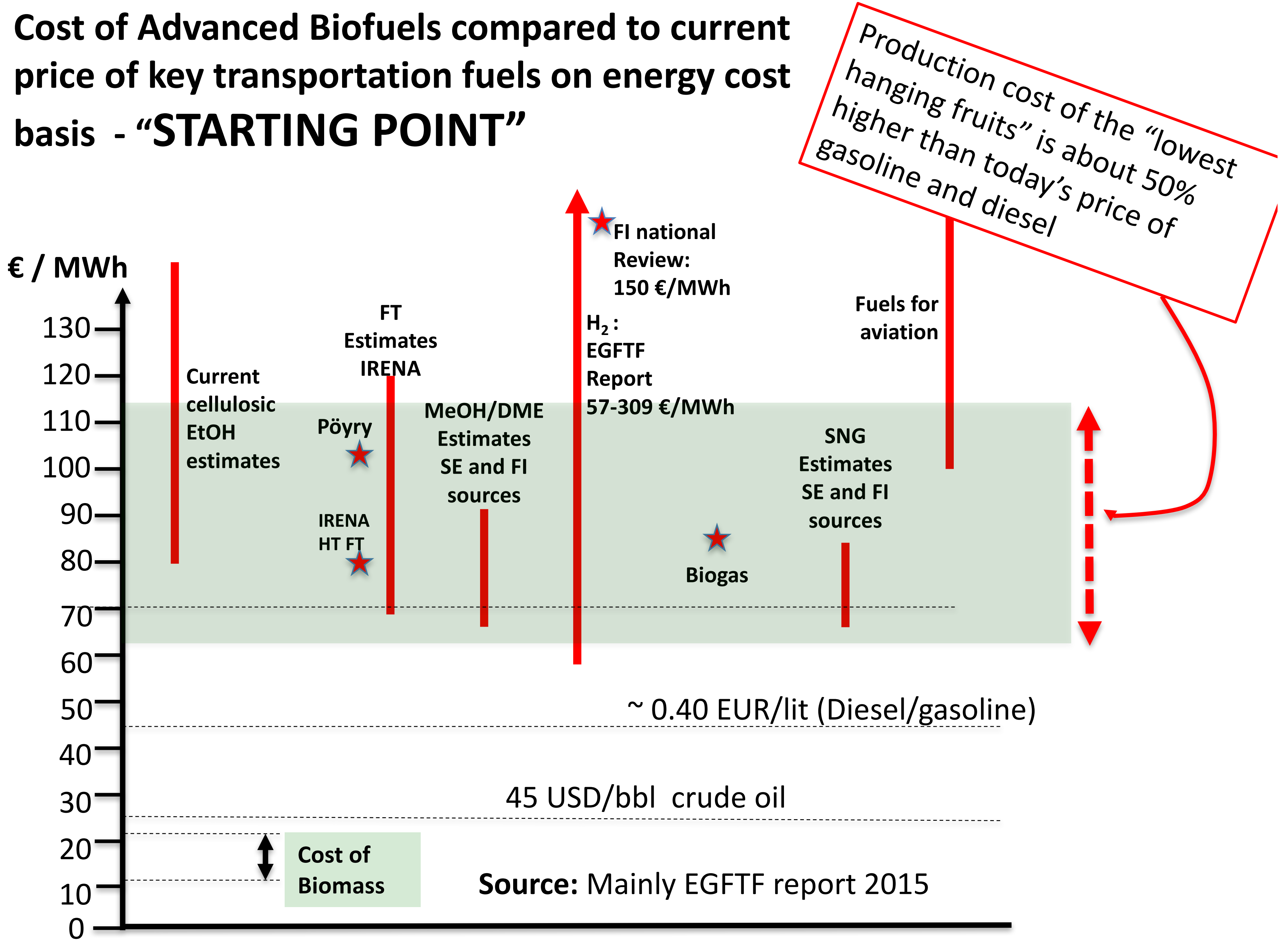
Compiled by: Ingvar Landälv & Lars Waldheim

Edited by: Kyriakos Maniatis,
Eric van den Heuvel & Stamatis Kalligeros

Figure 3. Cost of some selected biofuels compared to the historic crude oil price (in Cost of Biofuels)



Cost of Advanced Biofuels compared to current price of key transportation fuels on energy cost basis - "STARTING POINT"



Actions for SGAB members

- Review and comment
- Insert other sources of information with respect to production cost of advanced biofuels
- Source to include cost of fuel e.g. as EUR/MWh or €/GJ (lower heating value)
- Source should also reveal at least

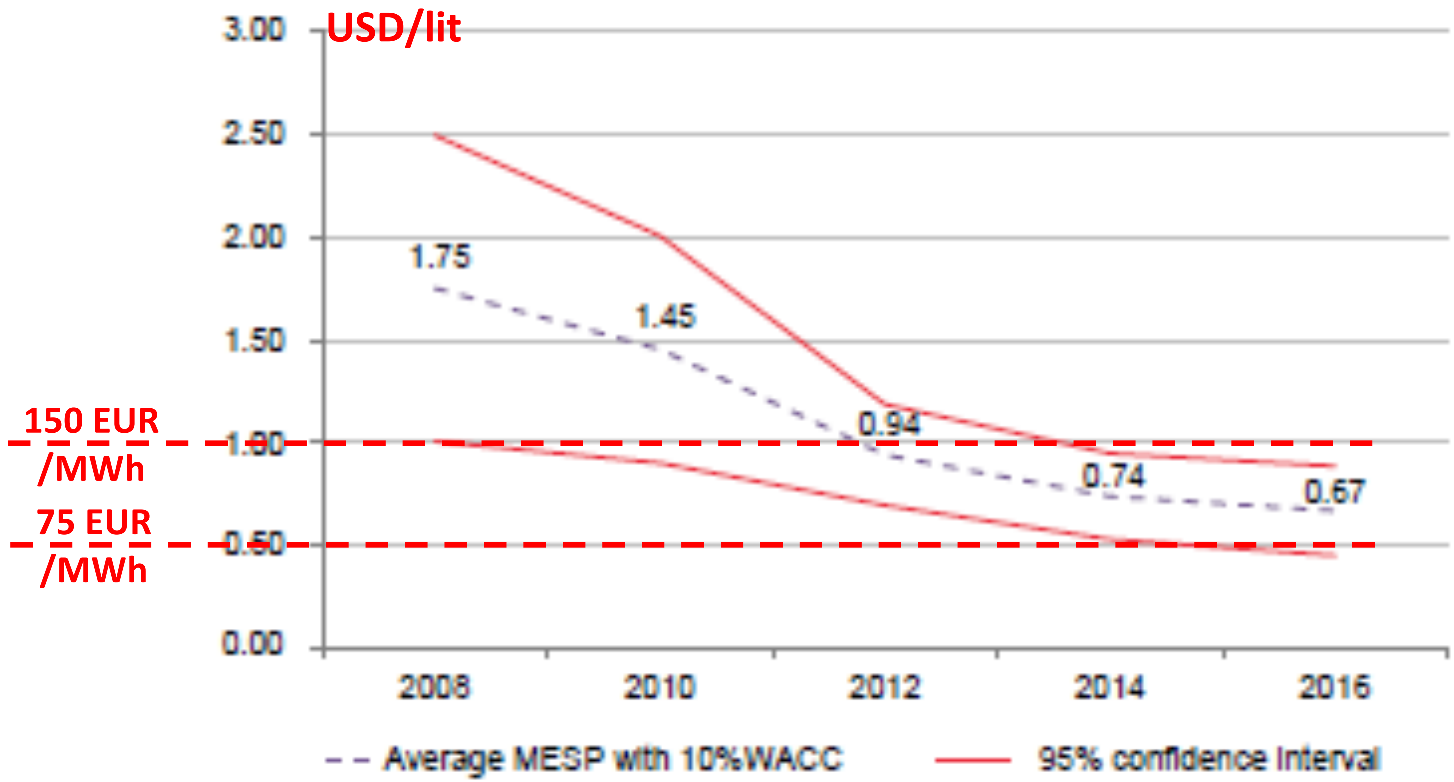
  - cost of capital

  - cost of feedstock

Minimum 2nd generation ethanol selling price

(Source: Blomberg's *Cellulosic ethanol costs: Surveying an industry,* March 2013)

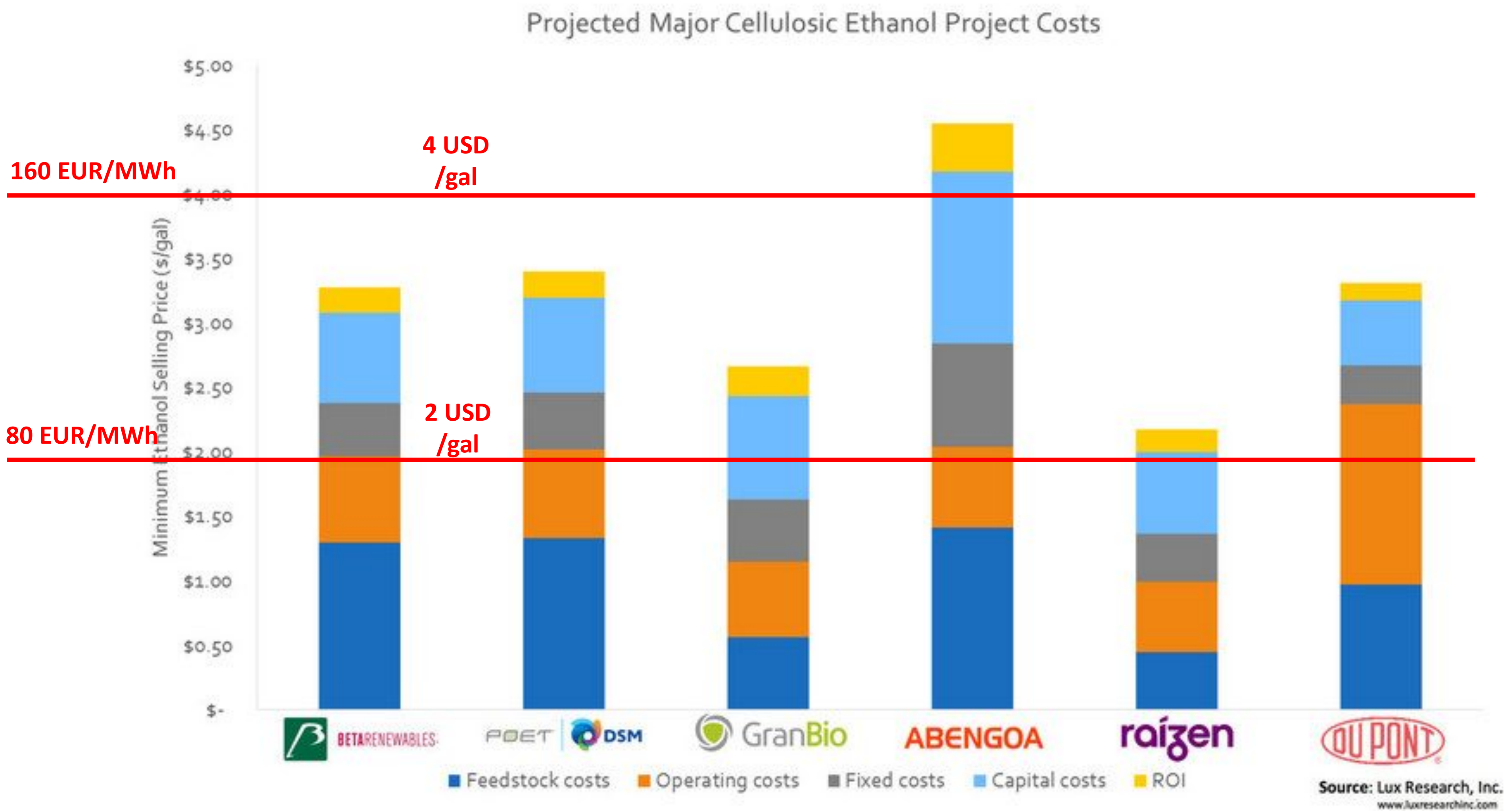
Capital: 10% WACC
Feedstock: 75 USD/mt (dry)



Source: Bloomberg New Energy Finance Notes: the 95% confidence interval represents the area in which 95% of the survey participants' MESPs fell into – or two standard deviations from the mean; the MESP includes capex costs at 10% WACC; and feedstock costs are fixed at $75 per dry tonne.

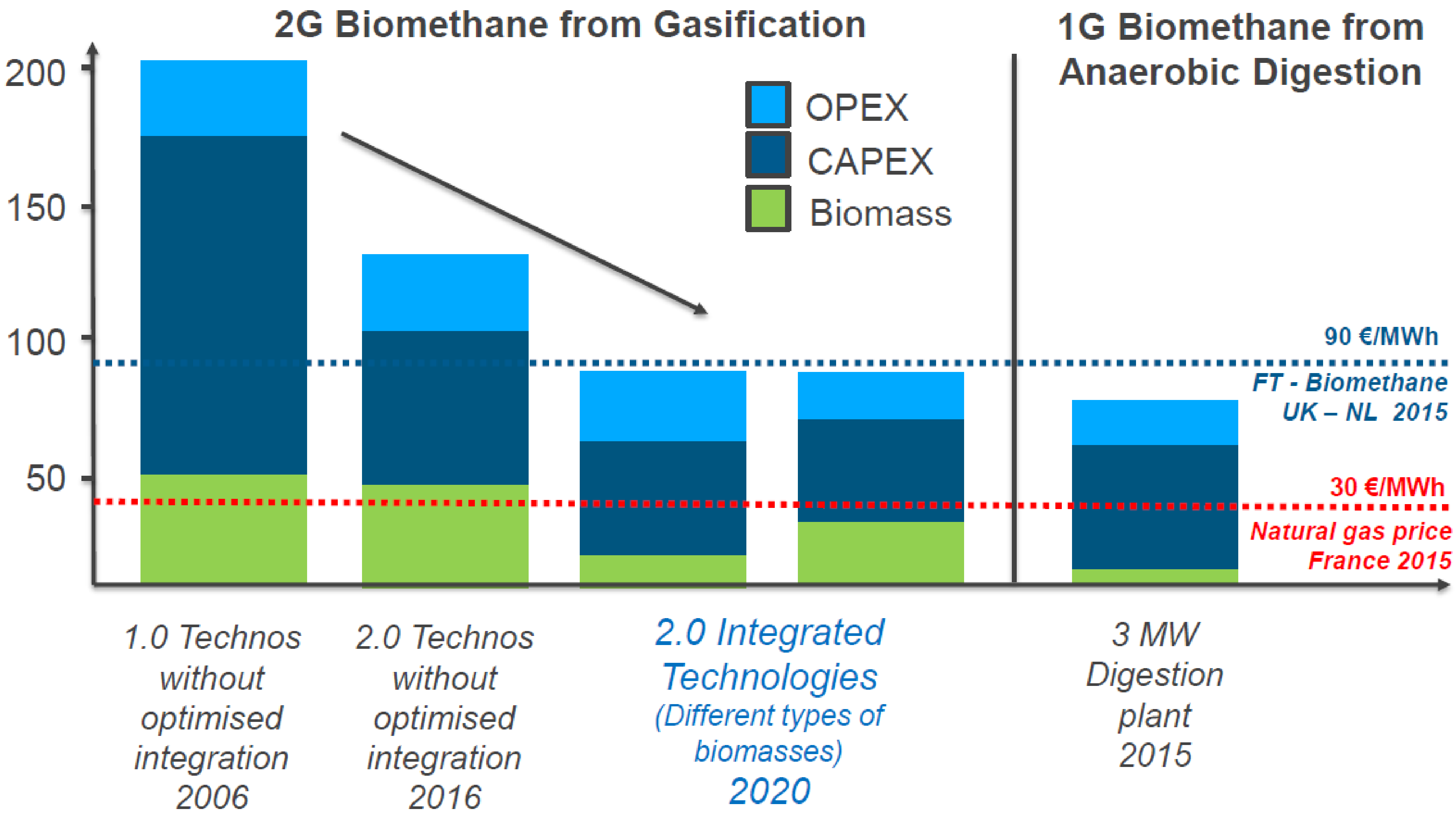
Production cost for 2nd generation Ethanol

(From PennEnergy Feb 24, 2016)



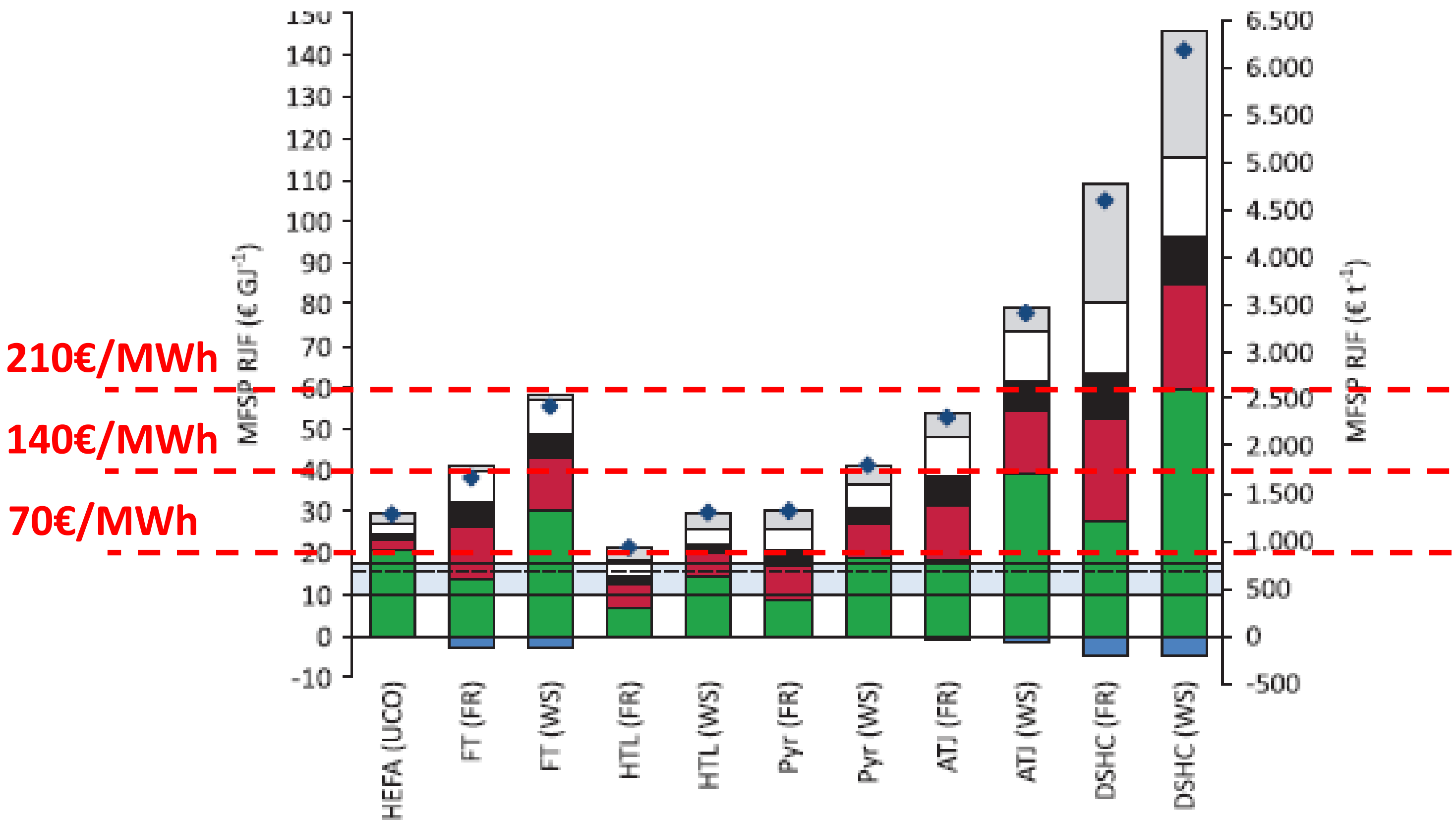
Source: http://www.pennenergy.com/marketwired-power/2016/02/24/
raizen-has-lowest-price-as-cellulosic-ethanol-hinges-on-feedstock-cost.html

Biomethane selling price



Source: http://www.engie.com/ and EBA

"The feasibility of short-term production strategies for renewable jet fuels – a comprehensive techno-economic comparison"



Full article: Wiley on line Library Oct 19, 2015

Source: Utrecht Univ. & SkyNRG

Legend

- MFSP = **Minimum Fuel Selling Price**
- Utilities & other raw materials
- Other OPEX (incl. corporate taxes)
- Maintenance and repairs
- CAPEX
- Feedstock
- Non-hydrocarbon co-products

Top ten percentile of the fossil jet fuel in the period 2005-2014 (17.6 € GJ^{-1})

Average fossil jet fuel price 2014 (15.1 € GJ^{-1})

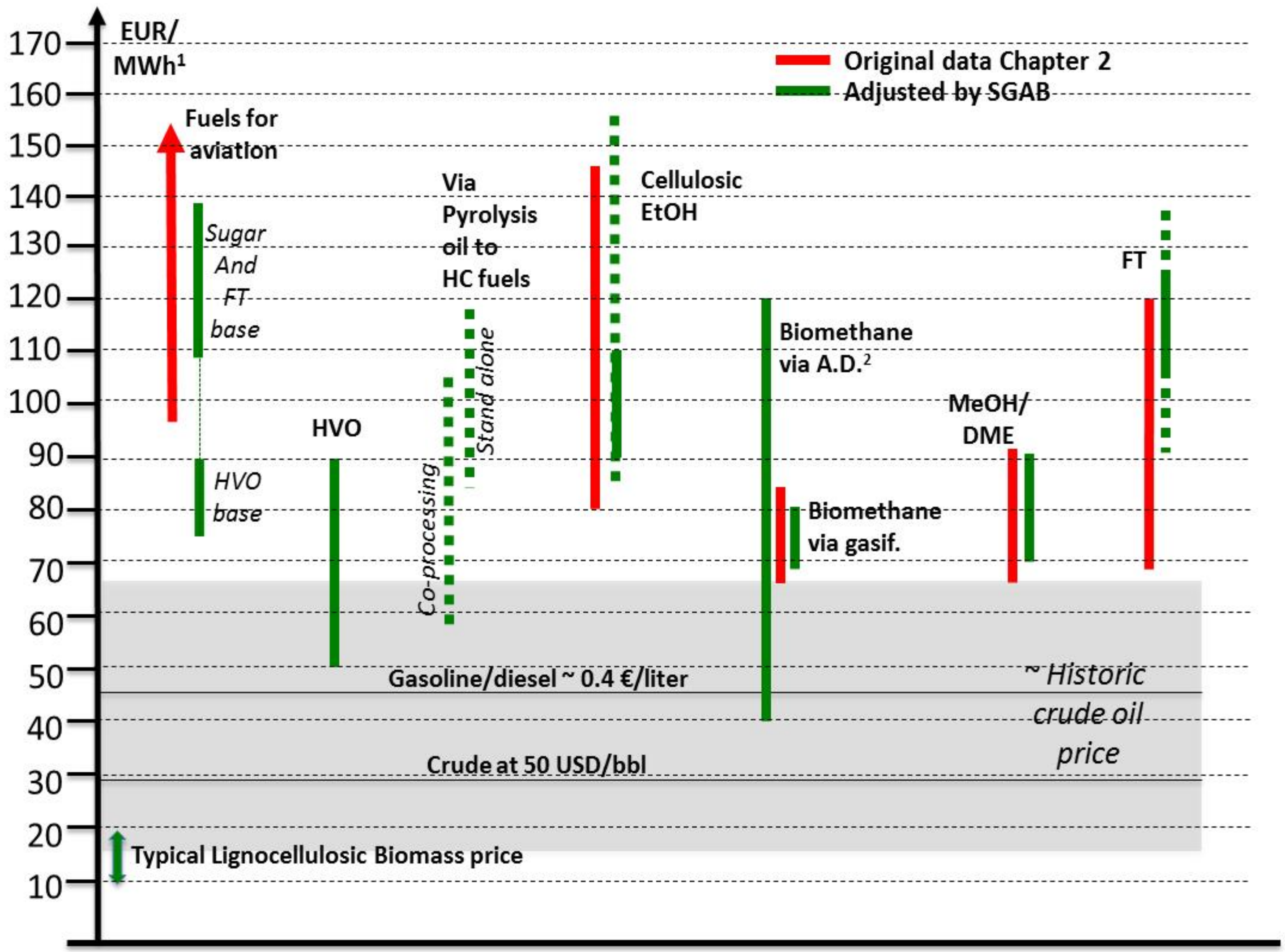
Bottom ten percentile of the fossil jet fuel in the period 2005-2014 (9.4 € GJ^{-1})

Abbreviations

HEFA = Hydroprocessed Esters and Fatty Acids
FT = Fischer-Tropsch
HTL = Hydrothermal Liquefaction
Pyr = Pyrolysis
ATJ = Alcohol-to-Jet
DSHC = Direct Sugars to Hydrocarbons

UCO = Used cooking oil
FR = Forestry residues
WS = Wheat straw

Figure 1: Summary of Production Costs



[1](EUR / MWh)/3.6 = €/GJ

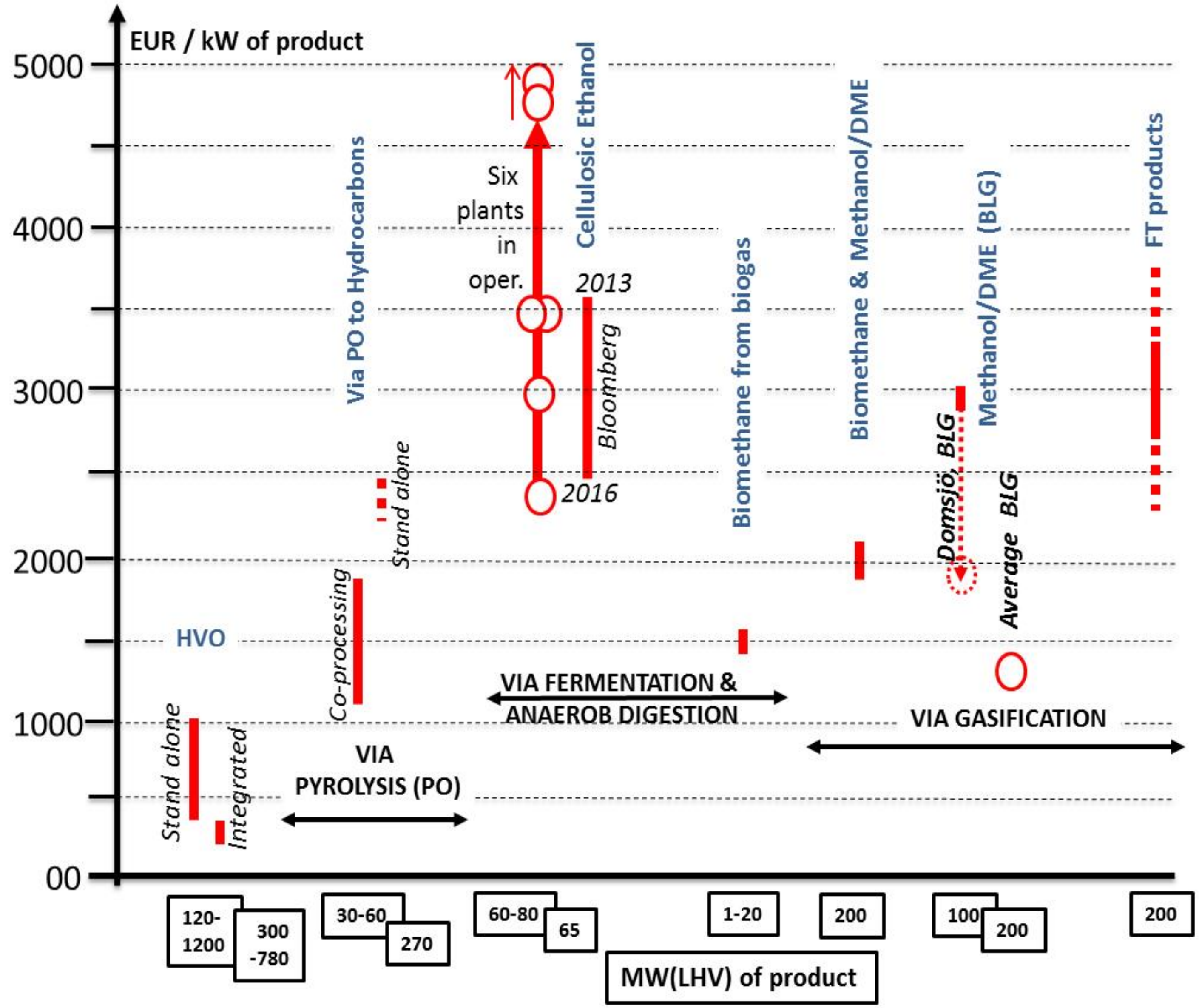
[2]Anaerobe Digestion
(large span due to very different feedstock costs)

Table 1. Summary of Biofuels Production Costs (from Cost of Biofuels)

Biofuel type production costs	Feedstock price EUR/MWh	Production cost range EUR/MWh	Production cost range EUR/GJ
Aviation HEFA	40-60	80-90	22-25
Aviation sugar fermentation or FT synthesis	Sugar: 65-85 FT: 10-20	110-140	31-39
HVO liquids	40	50-70	14-19
	60	70-90	19-25
Biomethane from biogas	0-80	40-120	11-34
Cellulosic ethanol	13	103	29
	10	85	24
Biomethane & ethanol from waste	(1)	67-87	19-24
FT liquids from wood	20	105-139	29-35
	10-15	90-105	25-29
Biomethane, methanol or (DME (Dimethyl Ether) from wood	20	71-91	20-25
	10-15	56-75	16-21
Pyrolysis bio-oil co-processing	10-20	58-104	14-27
Pyrolysis bio-oil stand alone	10-20	83-118	23-33

([1]) Base: Net tipping fee of 55 EUR/ton, energy content of 4.4 MWh/ton, Conversion efficiency of 50%

Figure 17. Investment intensity for different conversion routes (EUR per kW of product)



Cost of Biofuels - Key Messages

Biofuels will remain more expensive than fossil fuels (with rare exceptions) unless the costs of mitigating climate change are going to be factored in the cost of fossil fuels.

- The cost of biofuels is mainly governed by the cost of the resource (feedstock) and cost of capital (the investment) and only value chains based on waste streams with zero or negative cost offer possibilities for competitive cost production at present.

<u>Commercially available biofuels</u>

- Biomethane produced from waste streams and via biogas (anaerobic digestion) has at present the lowest cost at about 40-50 €/MWh. In certain niche markets it can be competitive to fossil fuels.
- Hydrotreated Vegetable Oils (HVO) have a production cost in the range of 50-90 €/MWh subject to the cost of the feedstock.
- Aviation HEFA can be produced at a cost of 80-90 €/MWh

<u>Cellulosic ethanol at the stage of early commercialisation</u>

- The production cost of cellulosic ethanol is estimated in the range of 90-110 €/MWh subject to the feedstock cost.

<u>Biofuels in the stage of first of a kind (FOAK)</u>

- Biomethane, methanol and ethanol from waste and biomass via gasification have a production cost of 60-80 €MWh.

From Presentation December 2007

Do something !

Finally, we do not want to hear …

Why did you not make it Real ?

Thank you !