ECN

Energy research Centre of the Netherlands

Lignocellulosic feedstock biorefinery for co-production of chemicals, transportation fuels, electricity and heat

Presented at International Workshop on Biorefinery, 22 June 2009, Madrid

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Lignocellulosic feedstock biorefinery for co-production of chemicals, transportation fuels, electricity and heat – Overview of the IP BIOSYNERGY (FP6)

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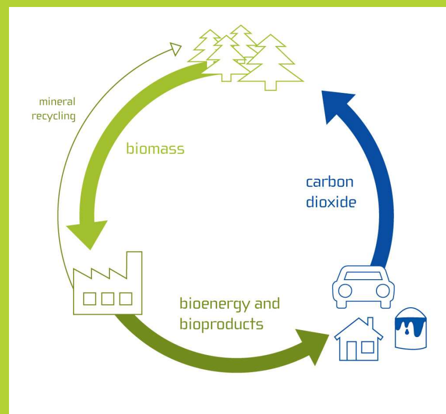

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  - Production of biobased chemicals via (bio)chemical conversion
  - Integral biomass-to-products chain design & optimisation
- Preliminary conclusions & perspectives

Lignocellulose as feedstock

- Low-cost feedstock (~50-60 € / ton d.w.; 3-4 € /GJ) e.g straw, wood residues, energy crops,..
- Alternative source of sugars (to replace starch and sugar agrofeedstock)
- High availability / Limited competition with food production
- High CO_2 reduction when used for 2-G biofuels and biobased products

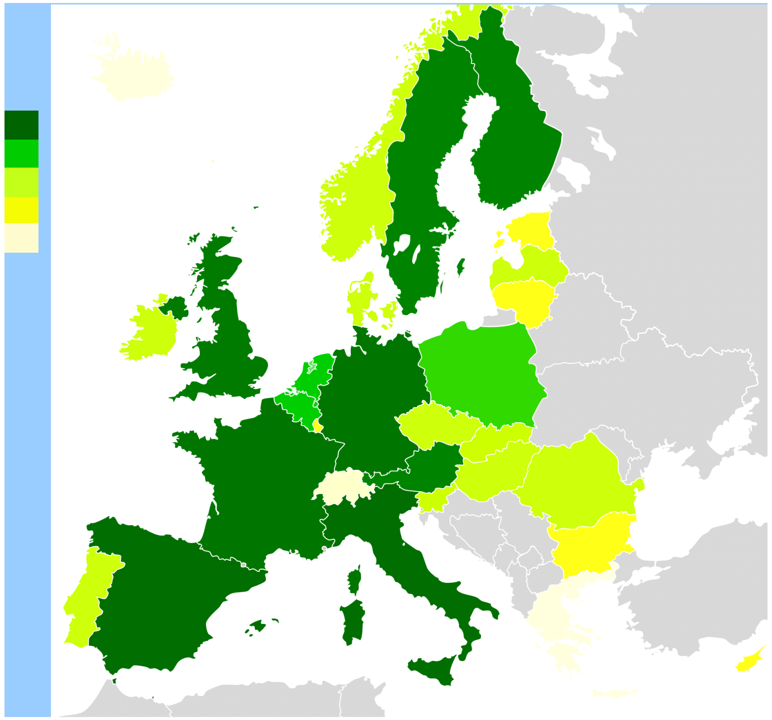




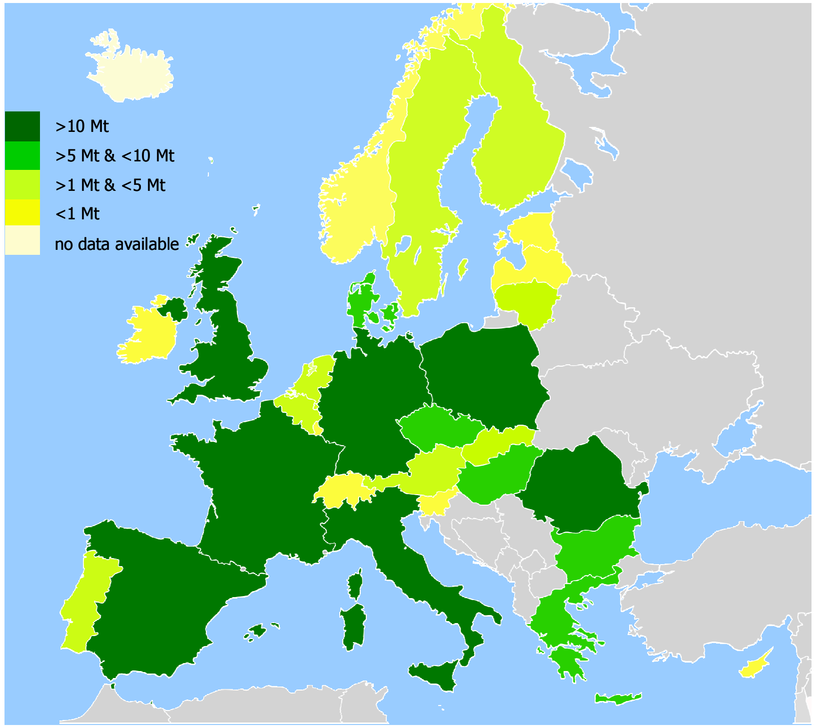


Availability of lignocellulose in the EU-27

1) Residues from wood & wood products, pulp and paper production
2) Agricultural residues of food and feed crops (straw, stover,..)



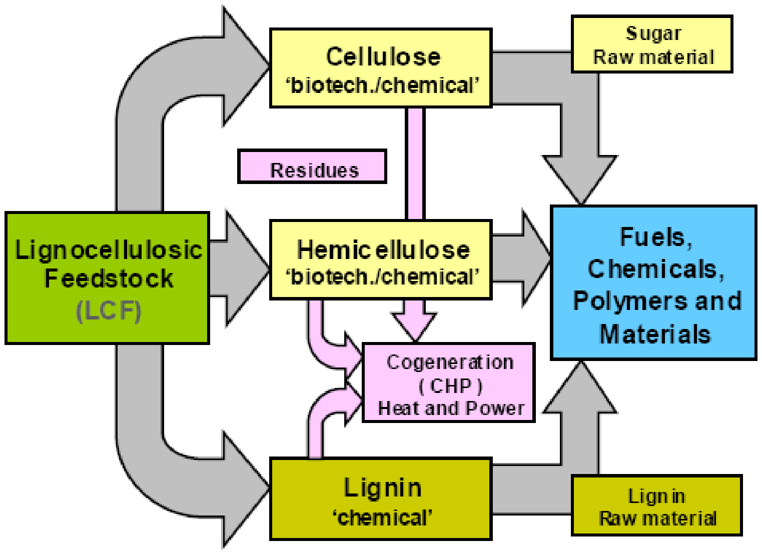
Production of wood and wood products, pulp, paper and paper products in EU27; Data 2004, Eurostat)



Agricultural residues of food and feed crops (data for 2000) in EU27+, Source: Refuel,2007

Environmentally compatible bio-energy potential EU-25: 7,950 PJ / 530 Mton d.b.(2010) to 12,350 PJ / 820 Mton d.b. (2030). Source: EEA, 2007.

Lignocellulosic Feedstock Biorefinery



Source: Kamm et al., Wiley-VCH, 2006

- Abundant low-cost feedstock: wood, straw, corn stover, cellulose containing residues and waste

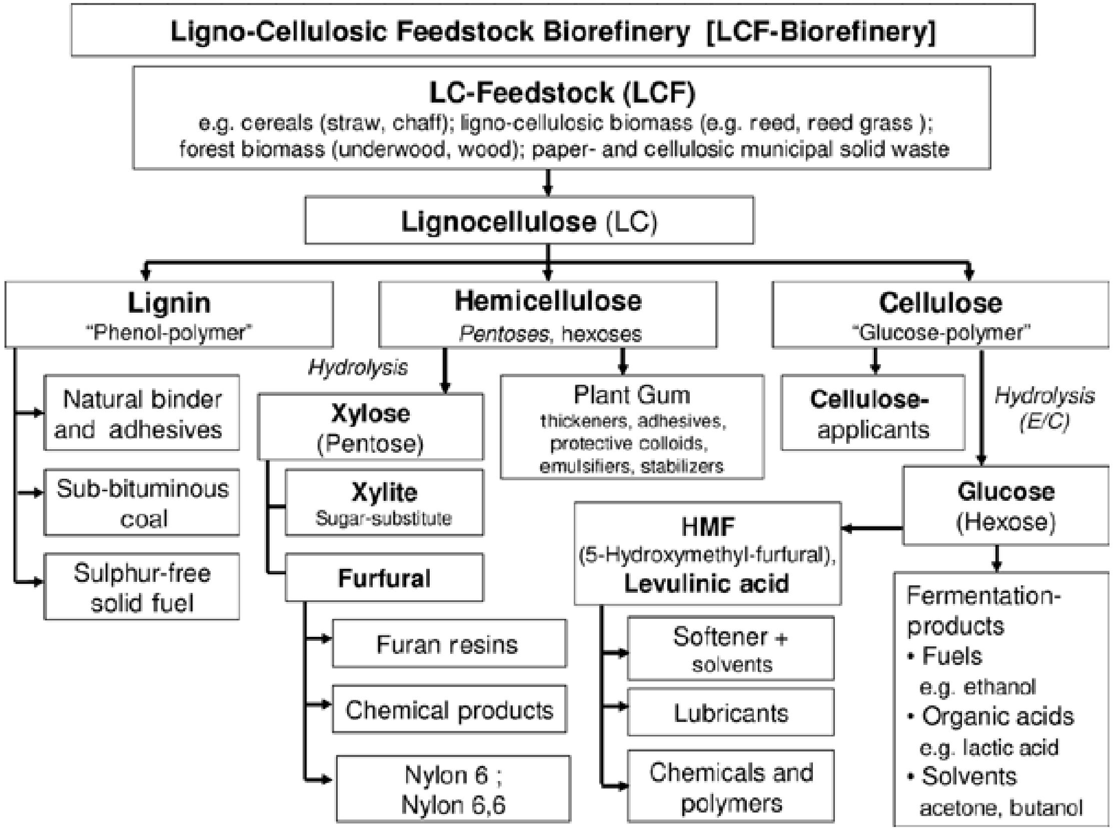
- Multiple products : transportation fuels, chemicals, polymers, materials electricity and heat
- Aim is to optimize revenues and minimize environmental impact

- Physical-chemical pre-treatment & fractionation of lignocellulose
- Enzymatic hydrolysis of (hemi)cellulose
- Fermentation / chemical conversion of intermediates
- System integration
  - CHP from process residues
  - Heat integration, water recycle

BIOSYNERGY

Potential products Lignocellulose Biorefinery

Biorefinery is the sustainable processing of biomass into a spectrum of marketable products and energy (IEA Definition)



Kamm, B.; Gruber, P.R.; Kamm, M.; Biorefineries, Industrial Processes and Products, Wiley-VCH, 2006

Products generated via

- **Fractionation**
- (Thermo)chemical conversion and bioprocessing

Natural monomer structure largely preserved

Products have a good position in the market as "building blocks" e.g.:

- Furfural
- HMF/Levulinic acid
- Fermentation products

Integrated Project BIOSYNERGY

BIOmass for the market competitive and environmentally friendly **SYN**thesis of bio-products – chemicals and/or materials – together with the production of secondary en**ERGY** carriers – transportation fuels, power and/or CHP – through the biorefinery approach.

- Development of integral cellulose-ethanol based LC Biorefinery
- Focus on valorisation of residues from cellulose ethanol production to make the production of this biofuel more cost competitive
- Bioprocessing and thermochemical pathways combined
- Process development from lab-scale to demonstration at pilot-scale.

17 partners from industry, R&D institutes and Universities from10 EU countries

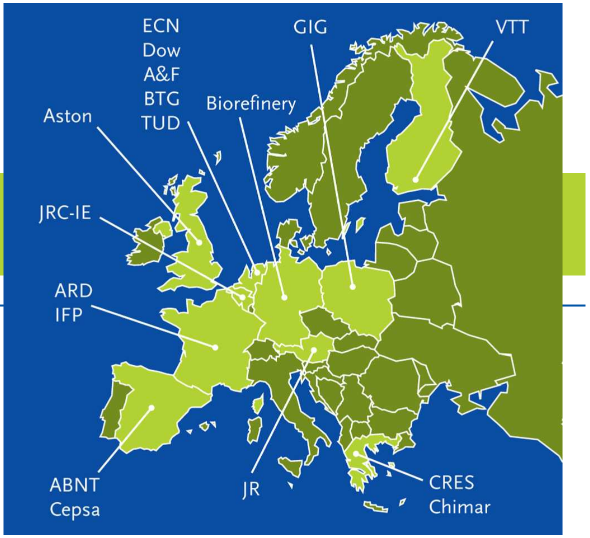
EU FP6 Program: Contract No. 038994 – SES 6. EC Officer: Silvia Ferratini.

Duration: 1-1-2007 – 31-12-2010 (48 months). Budget: 13.4 M€, EC grant 7M€

BIOSYNERGY

Consortium

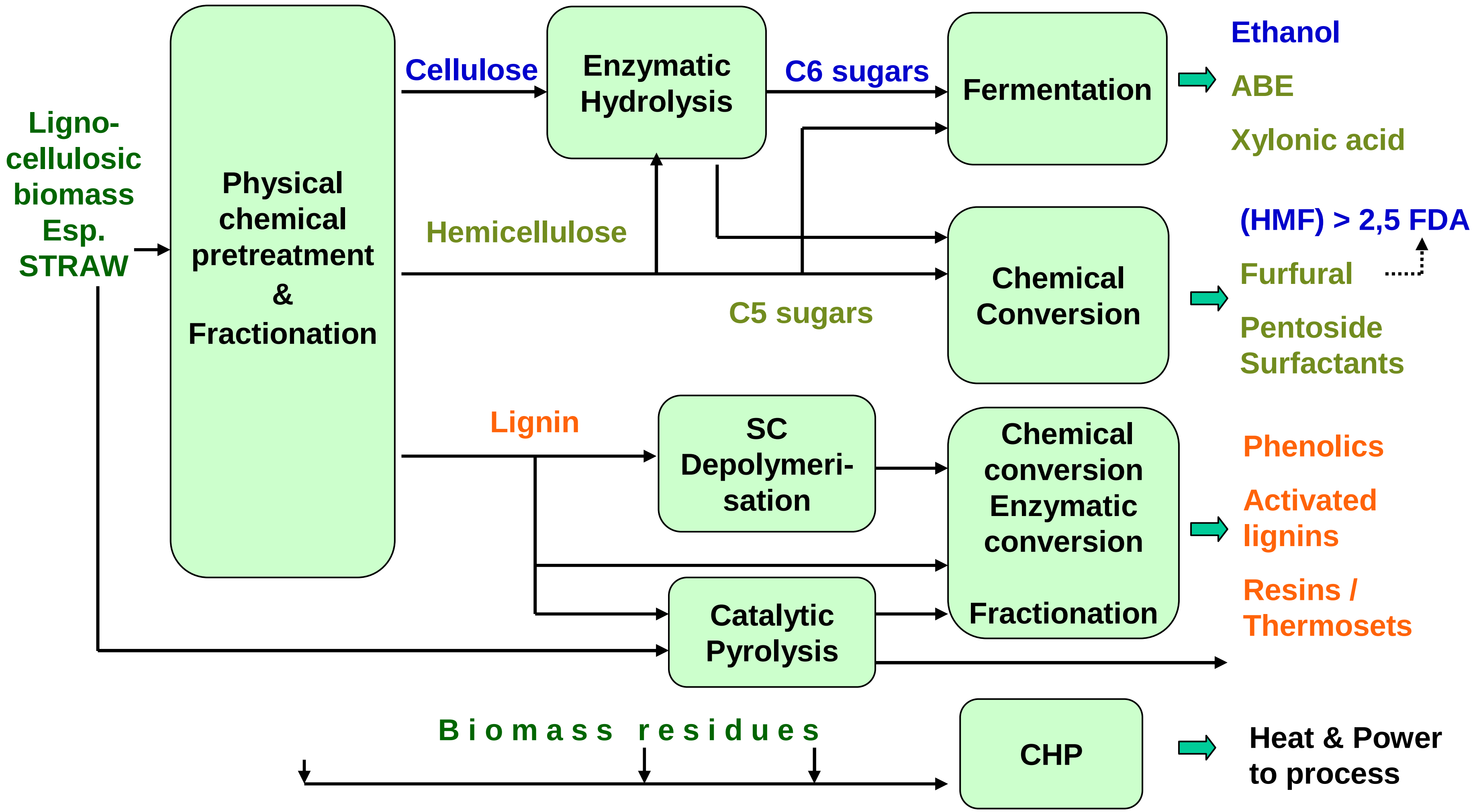
17 partners from industry, R&D institutes
and Universities from10 EU countries



1	Energy research Centre of the Netherlands (ECN)	The Netherlands	NL
2	Abengoa Bioenergía Nuevas Tecnologías S.A. (ABNT)	Spain	ES
3	Compania Espanola de Petroles S.A. (Cepsa)	Spain	ES
4	DOW Benelux B.V. (Dow)	The Netherlands	NL
5	VTT Technical Research Centre of Finland (VTT)	Finland	FI
6	Aston University (Aston)	United Kingdom	UK
7	WUR Agrotechnology and Food Innovations B.V. (A&F)	The Netherlands	NL
8	Agro Industrie Recherches et Développements (ARD)	France	FR
9	Institut Francais du Pétrole (IFP)	France	FR
10	Centre for Renewable Energy Sources (CRES)	Greece	EL
11	Biomass Technology Group (BTG)	The Netherlands	NL
12	Joanneum Research Forschungsgesellschaft m.b.H. (JR)	Austria	AT
13	Biorefinery.de (Biorefinery)	Germany	DE
14	Glowny Instytut Gornictwa (GIG)	Poland	PL
15	Joint Research Centre – Institute for Energy (JRC-IE)	The Netherlands	NL
16	Chimar Hellas S.A. (Chimar)	Greece	EL
17	Delft University of Technology (TUD)	The Netherlands	NL

Product lines in the IP BIOSYNERGY

Multi-product biorefinery, Focus on residues cellulose ethanol i.e. C5 and lignin valorisation

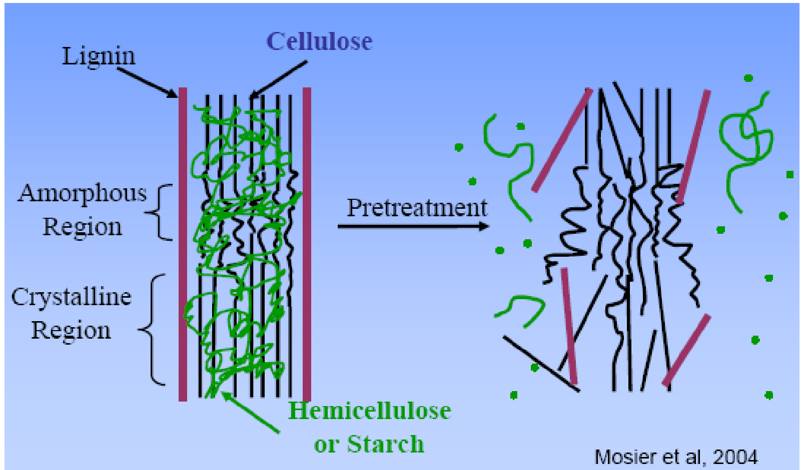


BIOSYNERGY

Physical-chemical pretreatment & fractionation

Goals:

- Controlled fractionation of lignocellulose into fractions with sufficient quality for production of (bio)chemicals: cellulose, hemicellulose, lignin
- Enhance access cellulose for enzymatic hydrolysis to sugars in high yield /low enzyme use
- Minimize by-product formation and the use of chemicals, water and energy
- Preferably lignin as high purity byproduct available
- Reduce costs: Fractionation is a major cost driver.
- Vital for DSP and quality of end -products

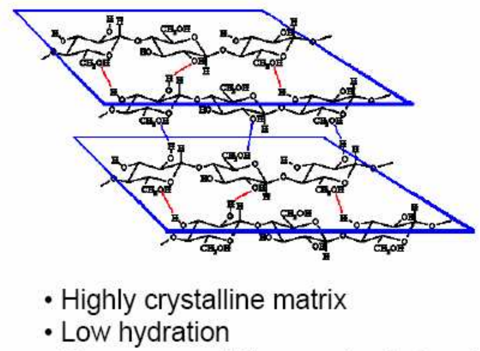


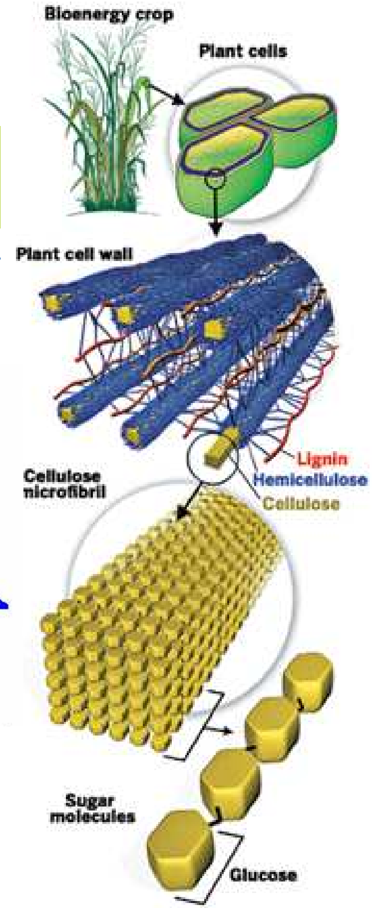
Mosier N, Wyman C, Dale B, Elander R, Lee YY, Holtzapple M, Ladisch MR, 2004. Features of promising technologies for pretreatment of lignocellulosic biomass. Bioresource Technology, Volume 96, Issue 6, April 2005, Pages 673-686

Physical-chemical pretreatment & fractionation

- Challenge: Biomass recalcitrance caused by
  - Complex structure of the plant cell wall
  - high crystallinity of cellulose

- Several routes under development:
  - Steam pre-treatment
  - Mild-acid/thermal pre-treatment
  - Mild alkaline pretreatment
  - Organosolv
  - Ammonia Fiber Explosion (AFEX)
  - ……



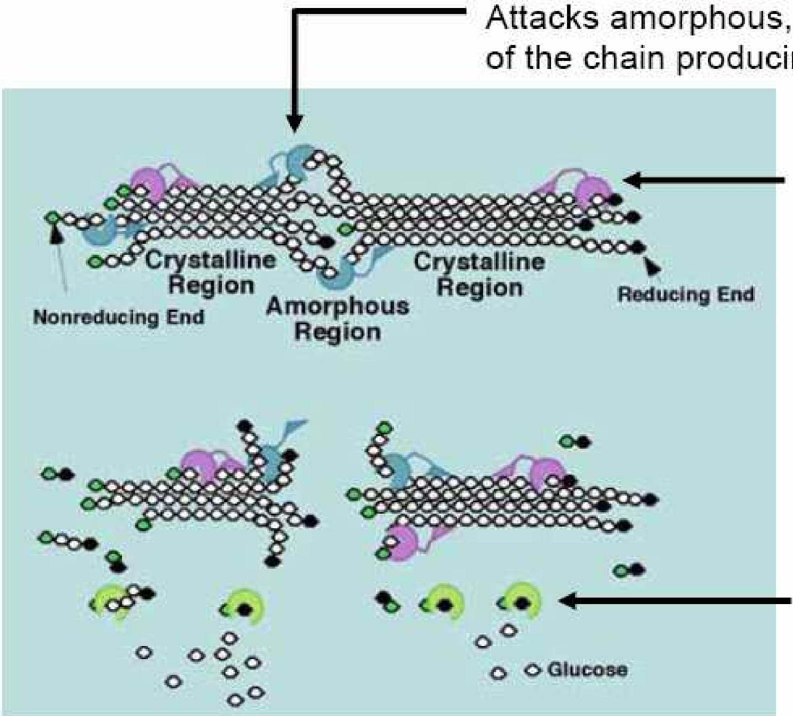


- Most processes suffer from drawbacks: formation of inhibitors, high use energy or chemicals, waste production, high cost etc.
- Most routes produce relatively low quality lignin residue

Enzymatic cellulose hydrolysis

3 types of enzyme activity required for cellulose hydrolysis to glucose

Endo-cellulase (endoglucanase)
Attacks amorphous, non-crystalline regions of the chain producing oligosaccharides

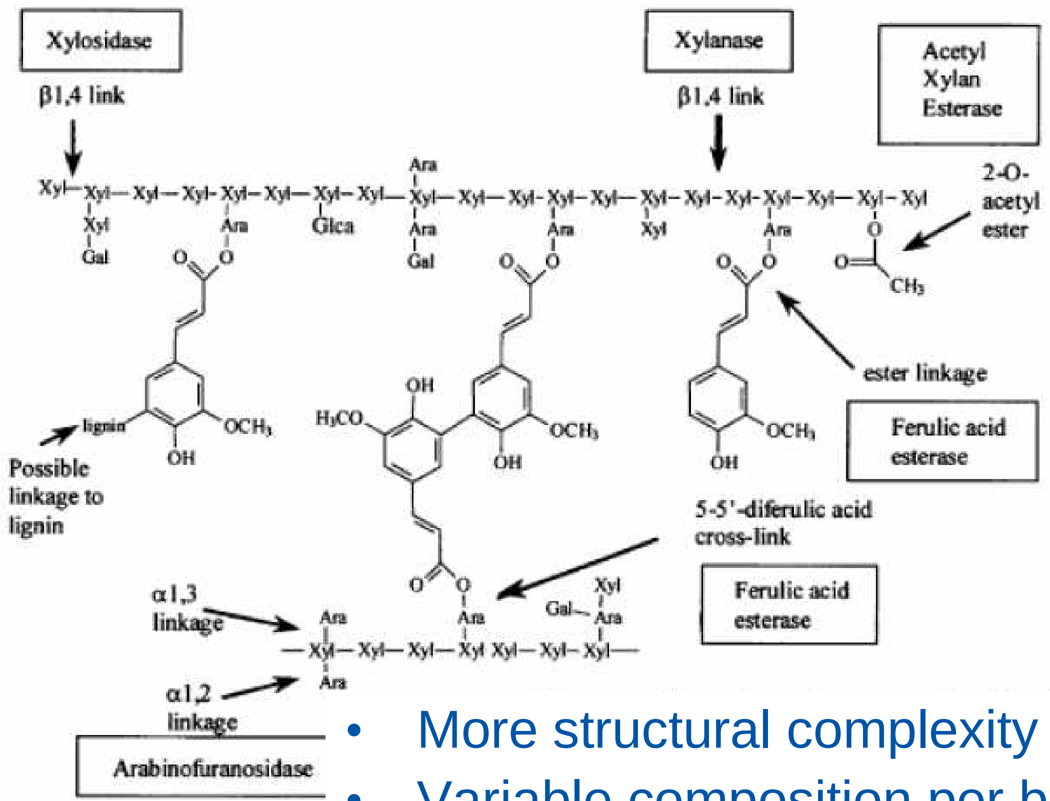


Exo-cellulase (cellobiohydrolase)
Attacks chain ends producing cellobiose

β-glucosidase
Attacks oligosaccharides and cellobiose producing glucose

Source: Kevin A. Gray Ph. D. , 2007. Conversion of lignocellulosic biomass into liquid transportation fuels Diversa Corporation/Celunol, San Diego, CA , USA. http://www.epobio.net/workshop0705/presentations/KevinGray.pdf

Enzymatic hemicellulose hydrolysis



Source: Kevin A. Gray Ph. D. , 2007. Conversion of lignocellulosic biomass into liquid transportation fuels Diversa Corporation/Celunol, San Diego, CA , USA. http://www.epobio.net/workshop0705/presentations/KevinGray.pdf

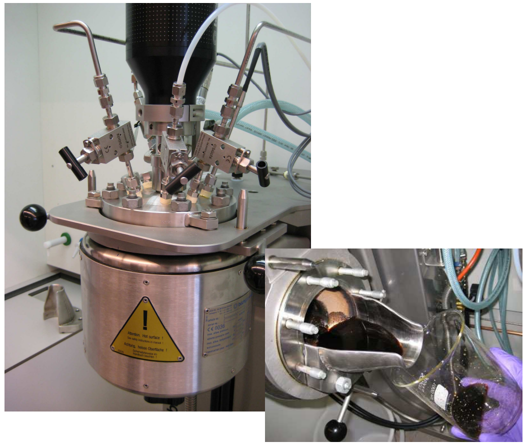
- More structural complexity than cellulose
- Variable composition per biomass source
- Specific, tailor made combination of enzyme activities required per feedstock

Advanced physical/chemical fractionation (WP1)

- Model feedstocks: straw, woods

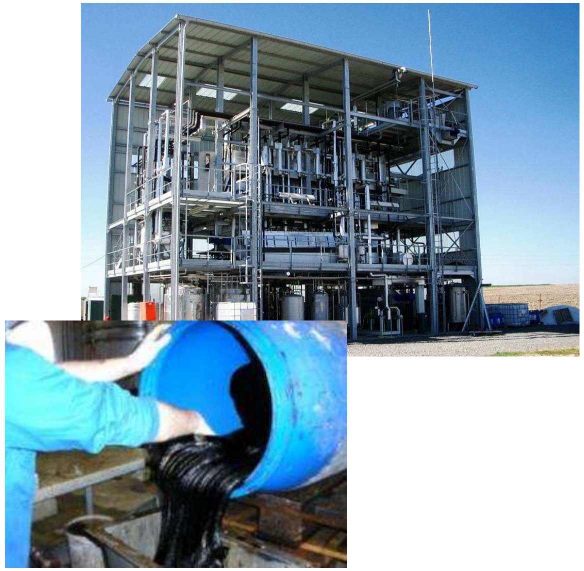
Processes studied

- Mechanical/Alkaline fractionation (A&F)*
- Ethanol/water Organosolv (ECN)*
- Organic acid organosolv (Avidell process; ARD)
- Acid hydrolysis (Biorefinery.de)
- Reference technology: steam explosion (ABNT)



Ethanol/H2O Organosolv, ECN

Mech./alk pretreatment A&



Acid organosolv Pilot plant ARD

Partners: A&F, ABNT, ARD, Bioref, ECN, TUD

BIOSYNERGY

Enzymatic Hydrolysis (WP1)

- Tests with commercially available enzymes on BIOSYNERGY cellulose fractions by A&F, Bioref, ARD

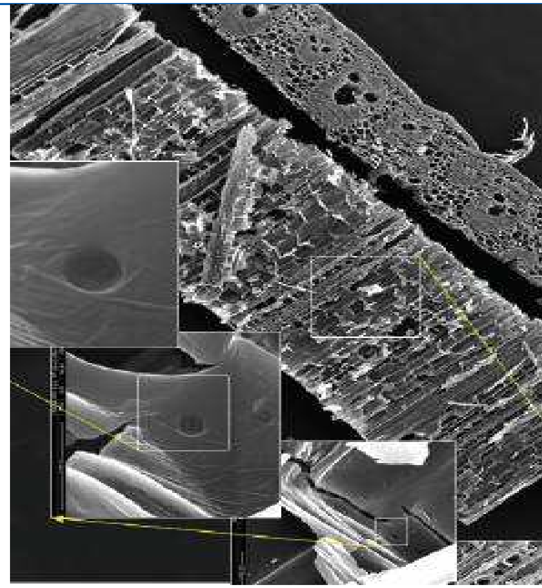
- Target ABNT: Developing tailor-made enzyme mixture able to hydrolyse substrates at costs < 0,02 €/l ethanol
  - High productivity strains (>100 g protein per liter broth)
  - Increased effective activity (dosages< 5mg protein/g glucan entering hydrolysis)
  - Developing a host able to produce the required enzyme mixture for the ethanol production process at industrial scale
  - Developing the enzyme mixture processing and manufacturing technology using the selected host

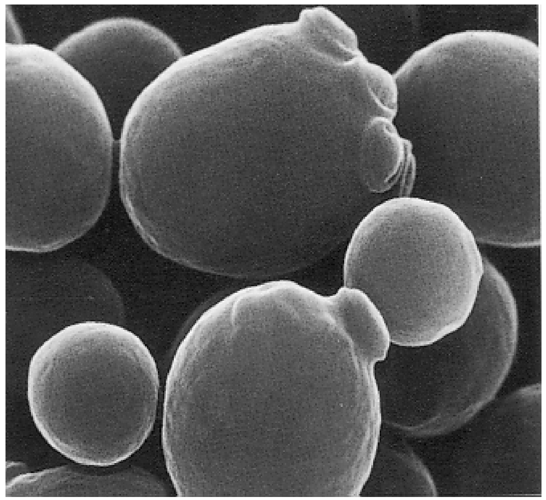
BIOSYNERGY

Enzymatic Hydrolysis (WP1)

Progress ABNT to date

- Selection of base enzyme cocktail for setting up process conditions.
- Expression and purification of selected enzymes from the cocktail.
- Enzyme supplementation studies.
- Cost reduction fermentation media.
- Conceptual design on-site enzyme production plant.

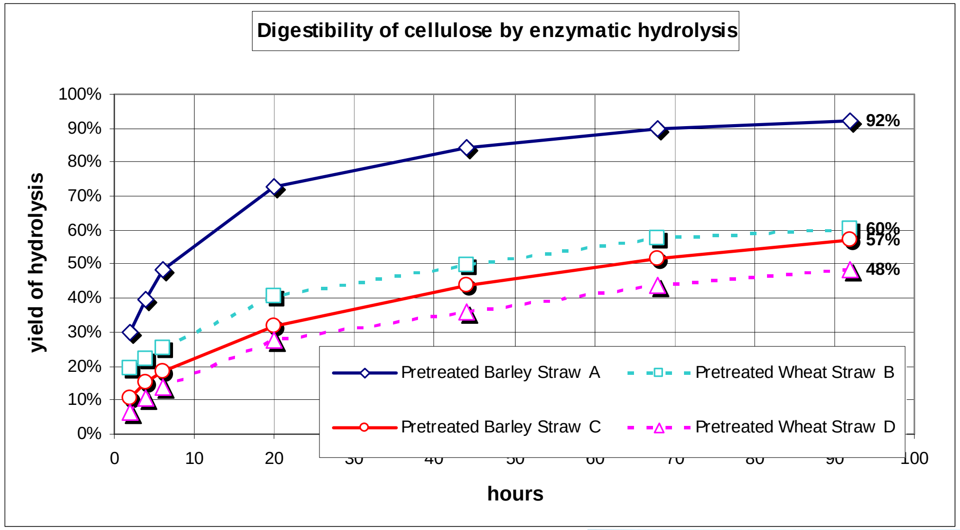




![BIOSYNERGY]

Preliminary conclusions pretreatment/fractionation

- No clear "winner": All studied routes lead to significant fractionation of C5, C6 sugars and lignin from lignocellulose
- Differences in cellulose hydrolysis yields

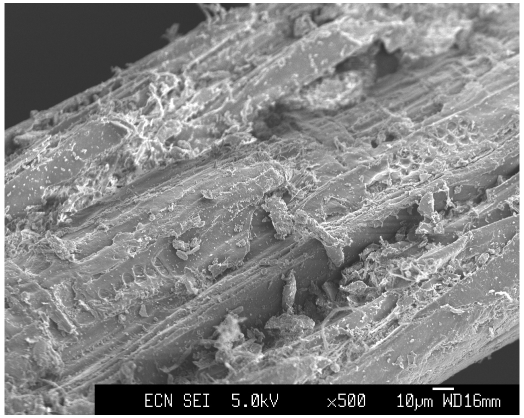


- Processes need to be optimised toward a particular goal, for example:
  - Hemicellulose hydrolysis for further processing of C5
  - High enzymatic degradability of the cellulose fraction
  - Recovery of a high quality lignin stream
- Benchmarking/Economic evaluation in progress

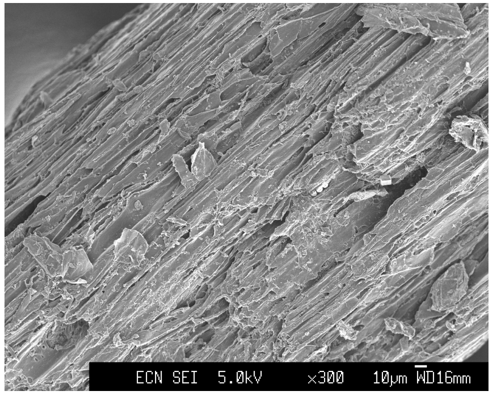
Lignin products from Modified Organosolv Fractionation (ECN)

Ethanol/water organosolv offers efficient pretreatment and good lignin quality

Fresh willow



Pre-treated willow (190℃,60 min,60wt% EtOH)



Feedstock / sample	Mw	PD
Poplar	2419	3.5
Barley straw	3006	4.1
Willow	3452	4.1
Alcell®	2985	3.6

- Cellulose fibrous structure remains intact
- Effective extraction of hemicellulose and lignin (up to 60%)
- Good access to enzymes. Cellulose hydrolysis yield up to 90%
- Purity and MW distribution of lignin indicate suitability for chemicals production > tests underway

- Acid organosolv (Avidell) also produces good quality lignin
- Solvent recycle crucial for organosolv methods

Innovative thermo-chemical conversion (WP2)

Topics

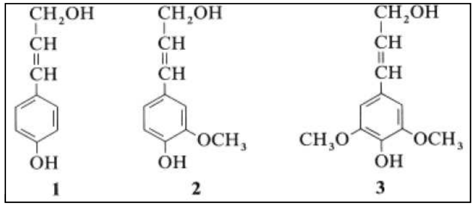
- Staged (catalytic) thermochemical processing of biomass and lignin
- Catalytic fast pyrolysis
- Integrated development of separation/ upgrading technology

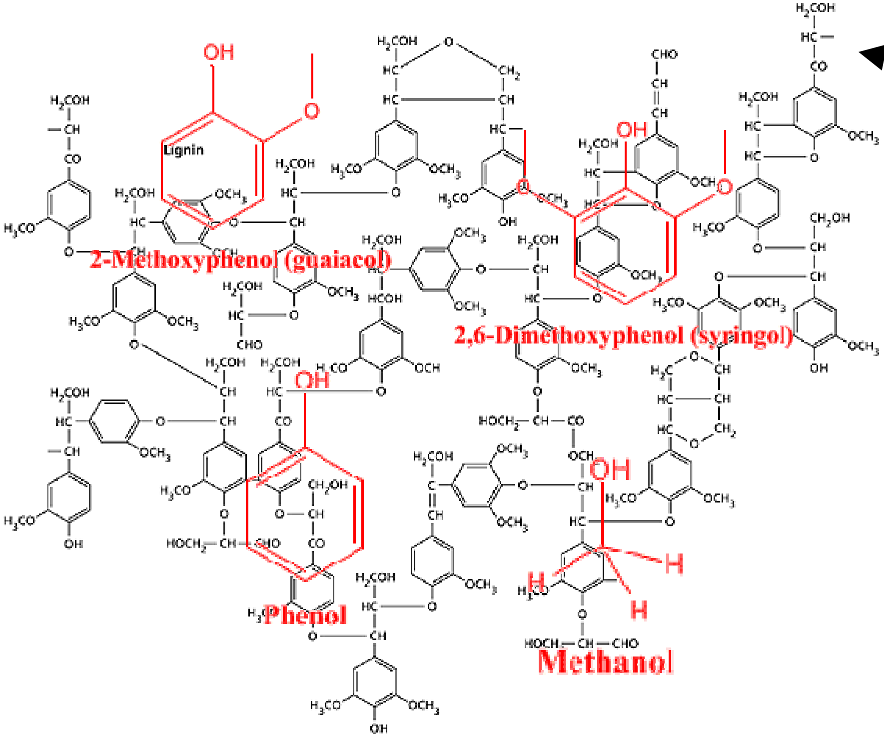
Partners: ECN, Aston, BTG

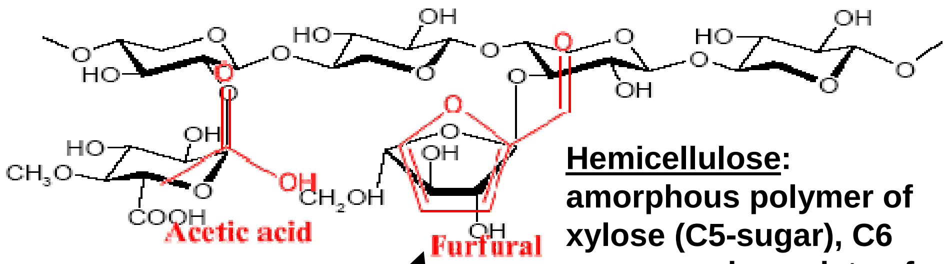
BFB reactor ECN

Thermochemical production of chemicals from wood

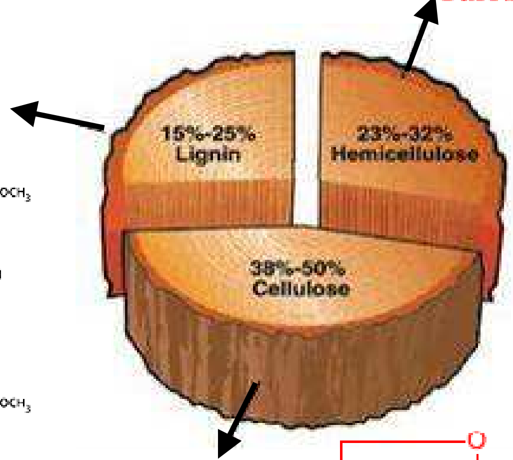
<u>Lignin</u>: amorphous copolymer of phenyl-propene units; formed via a random radical copolymerisation of: (1) coumaryl alcohol, (2) coniferyl alcohol, (3) sinapyl alcohol



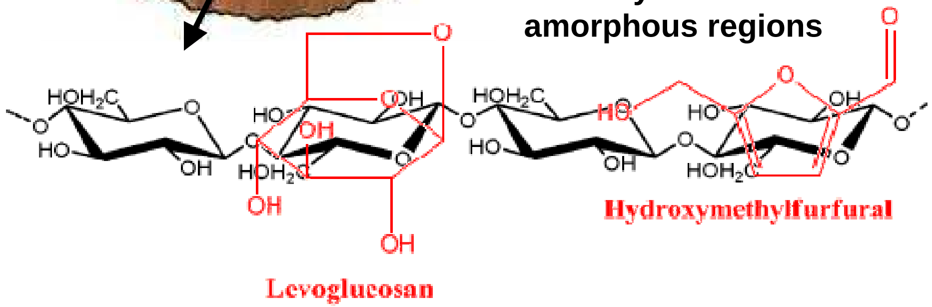




<u>Hemicellulose</u>: amorphous polymer of xylose (C5-sugar), C6 sugars and a variety of side-chains



<u>Cellulose</u>: polymer of glucose (C6-sugar) with both crystalline and amorphous regions



Products arise in mixtures

BIOSYNERGY

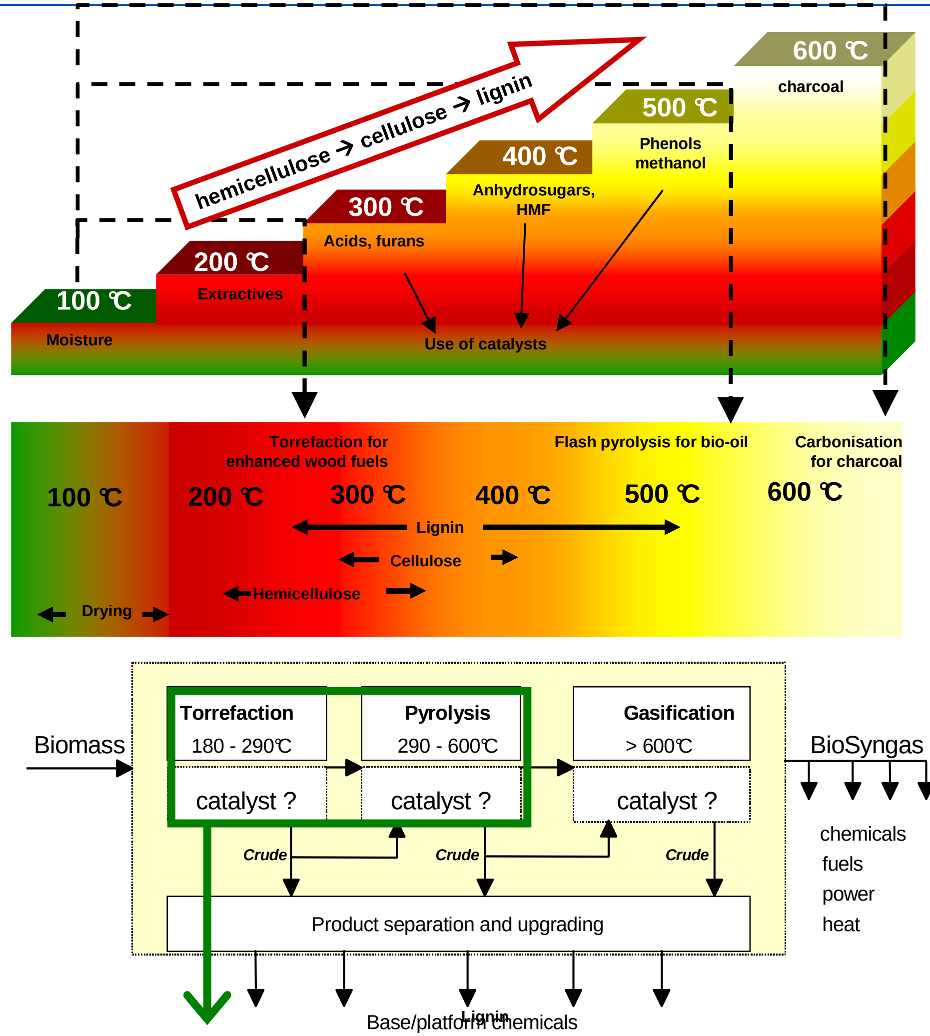
Staged thermochemical processing

Opportunities

- Sequential thermal decomposition hemicellulose > cellulose > lignin
- Condensable products: C2-C4, acids, furans, anhydrosugars, phenolics (+ char and syngas)

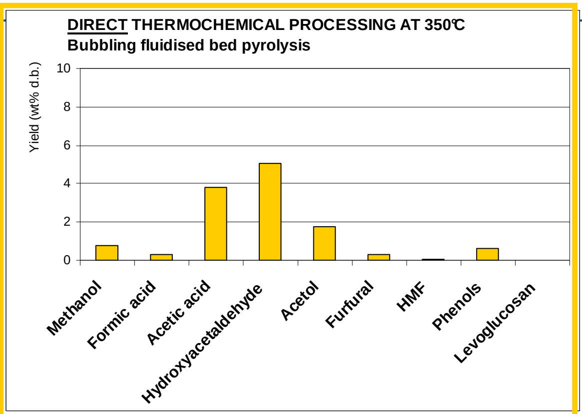
Challenges

- Optimisation of individual product or product group yields via catalysis, process conditions: temperature, heating rate, vapour and solid residence times
- Product separation and upgrading

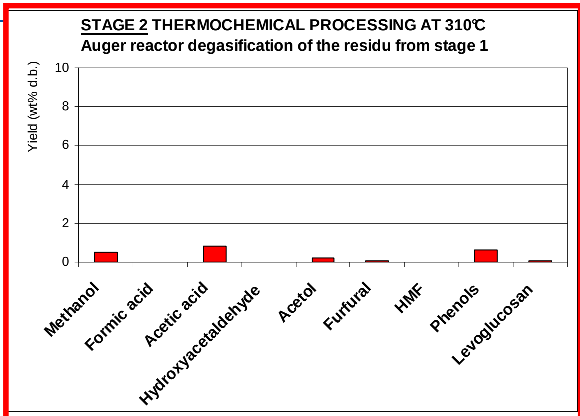


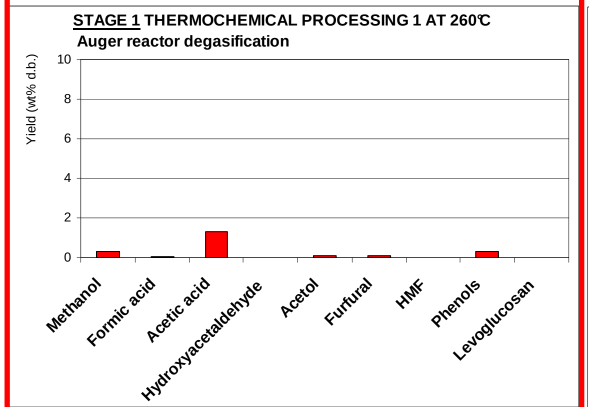
Bio-cascade for drying, torrefaction and pyrolysis

Comparison thermochemical processing straw

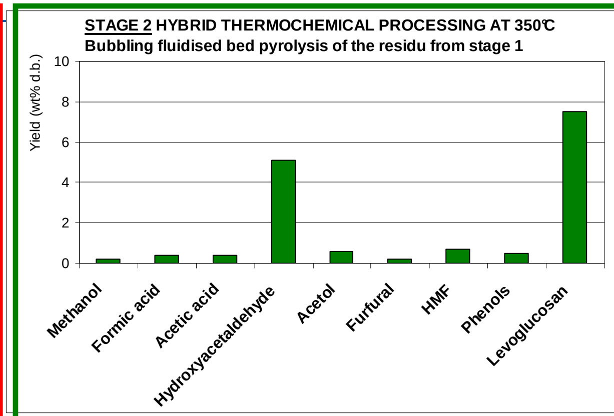


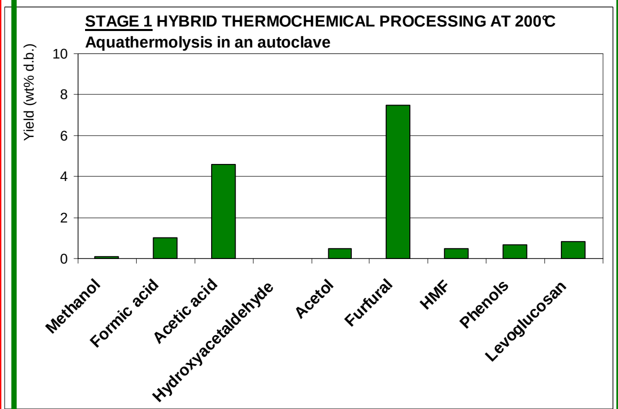
One-step BFB pyrolysis





Staged (de)gasification





Hybrid thermochemical processing

Selected chemicals from wheat straw via 1-step BFB pyrolysis**, via** staged degasification in an auger reactor **and via** hybrid thermochemical processing involving aquathermolysis and BFB pyrolysis **showing the superior performance of the hybrid concept**

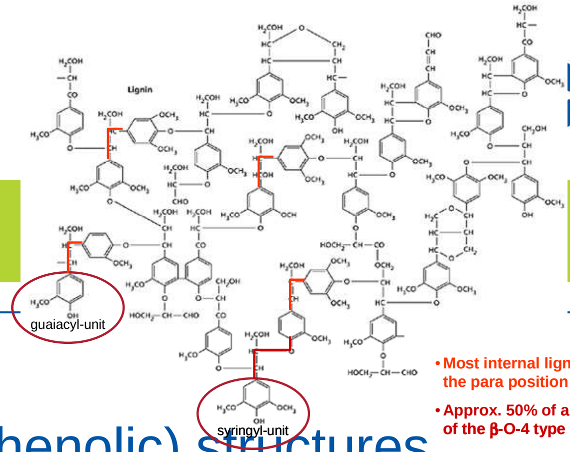
P.J. de Wild et al, " Biomass valorisation by a hybrid thermochemical fractionation approach"; submitted to International Journal of Chemical reactor Engineering, 2009

Upgrading thermochemical product mixtures & bio-oils

- Staged condensation for separation of (groups of) chemicals from pyrolysis vapours
- Procedures to improve quality of pyrolysis oil (filtration, dewatering)

80-250 kg/hr rotating cone fast pyrolysis pilot plant at BTG

Lignin valorization



- Most internal lignin bonds via the para position
- Approx. 50% of all bonds are of the β-O-4 type

- Lignin contains numerous valuable aromatic (phenolic) structures
- Valorisation to products (even partial) improves carbon footprint and revenues of the biorefinery

<u>Technologies</u>

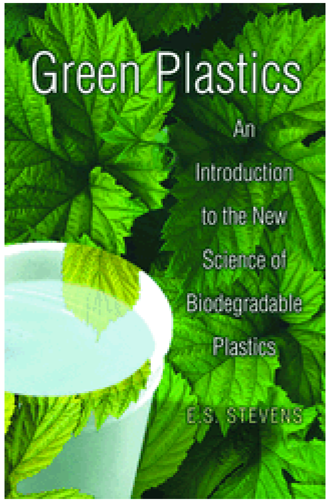
- Combustion for heat and/or power
- Gasification for syngas
- Hydroliquefaction for transportation fuels (reformulated gasoline)
- Direct application ‘organosolv’ lignins
- Pyrolysis for production of chemicals (monomeric phenols) and/or performance products

Successful valorisation of lignin is a key-issue for an economically viable lignocellulosic biorefinery.

BIOSYNERGY

Potential applications of lignin-derived phenolics

'Green' plastics



- **epoxies**
- **Poly-Urethanes**
- **polyolefins**

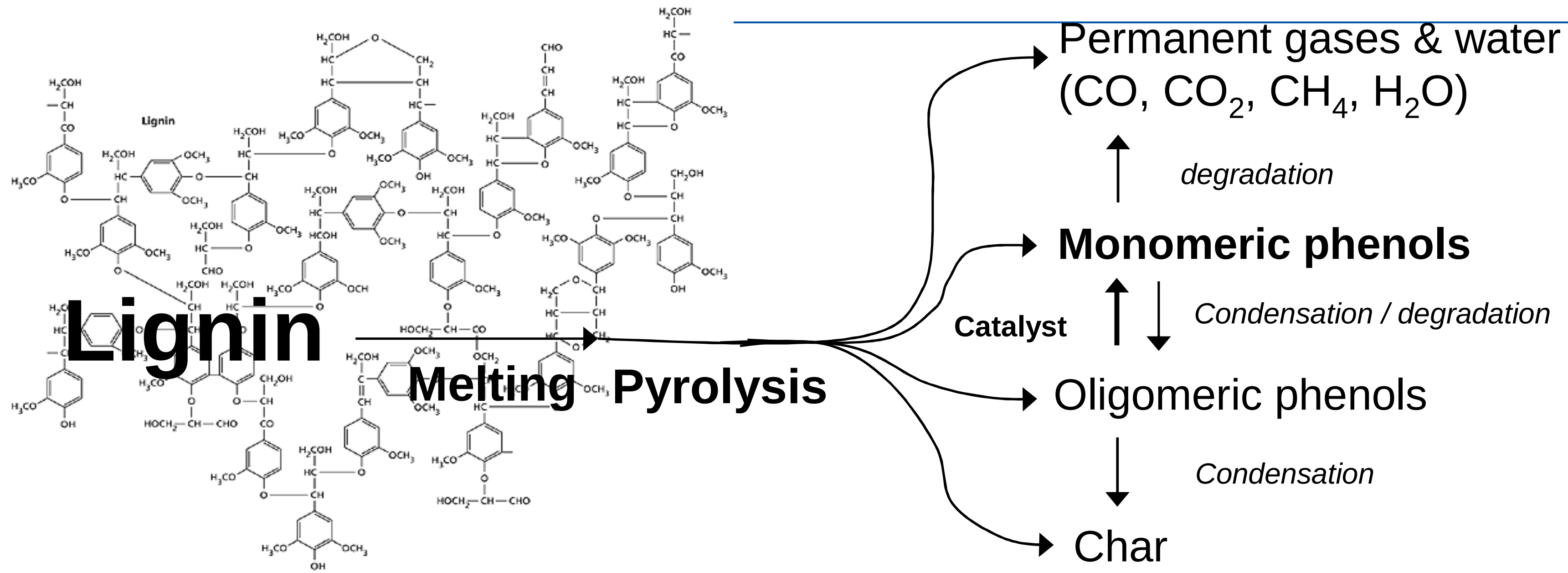
Wood-adhesives and resins

- **Fuel additives** (aromatic ethers)
- **BTX**
- **Binders**

- **Carbon Fiber (for CF composites)**

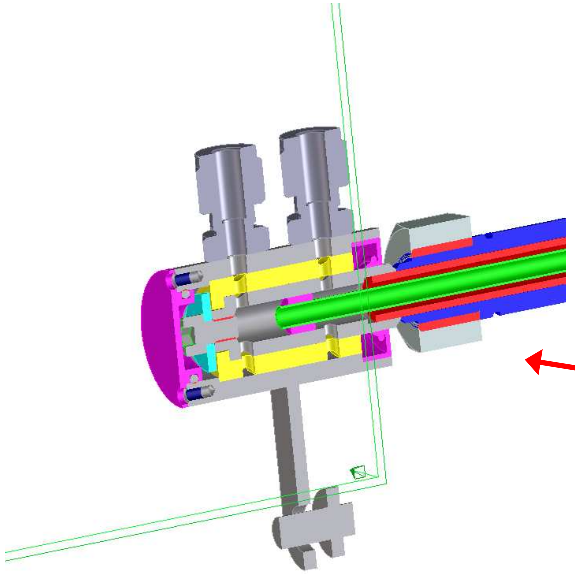
Specialty phenolics for high-value applications such as fragrances and pharmaceuticals

Lignin thermal conversion via pyrolysis: challenges

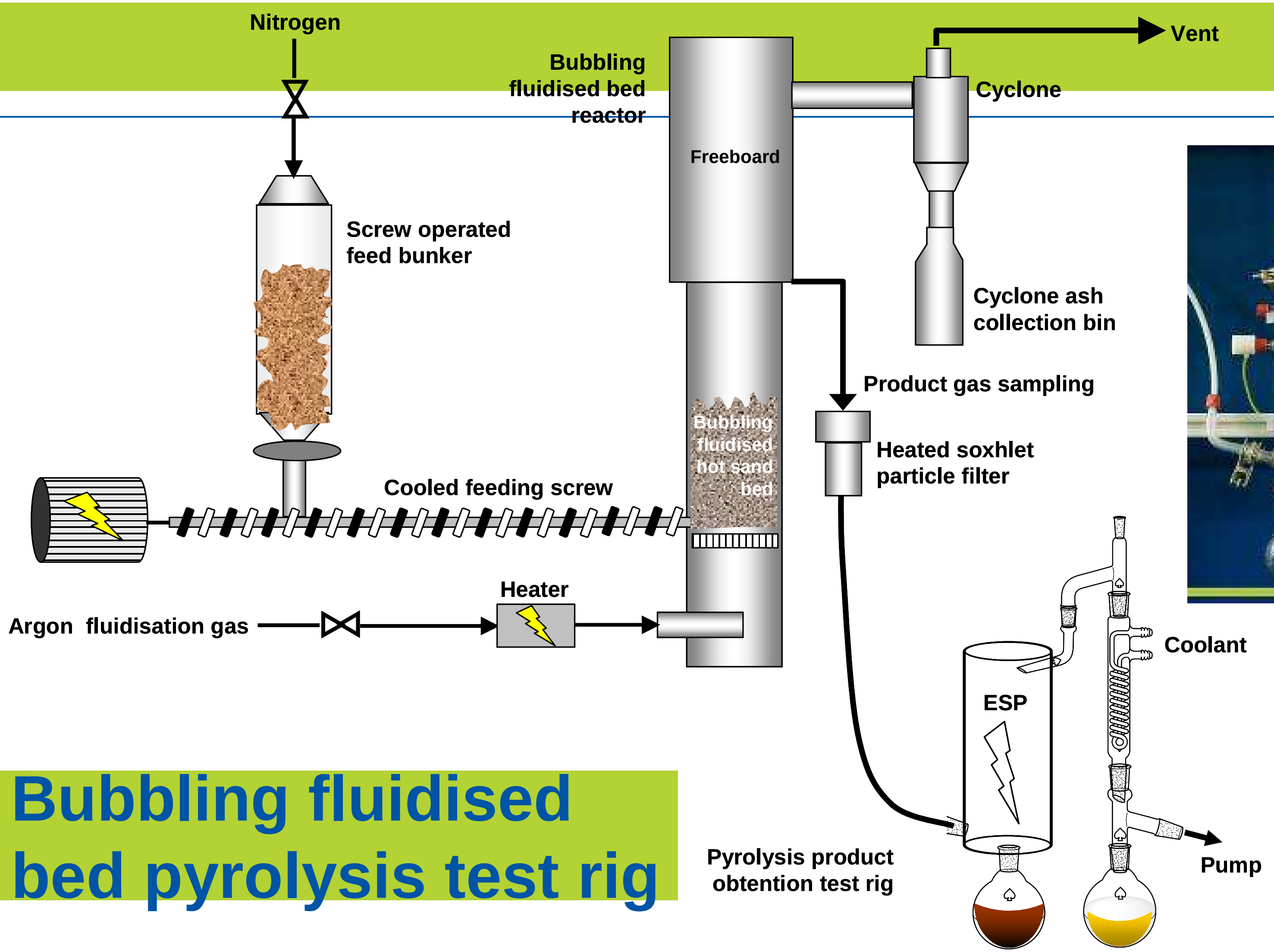


- First of all a <u>proper feeding procedure</u> is required to overcome lignin's thermoplastic behaviour that causes severe operational problems such as screw feeder clogging by molten lignin, agglomeration and subsequent defluidisation of the reactor bed.
- For a maximal conversion of lignin into (monomeric) phenols there is a <u>narrow window of pyrolysis conditions</u> such as temperature, heating rate, vapour and solid residence time.
- Use of catalyst to improve product selectivity and yield

Improving feeding behaviour: construction of a water-cooled screw feeder

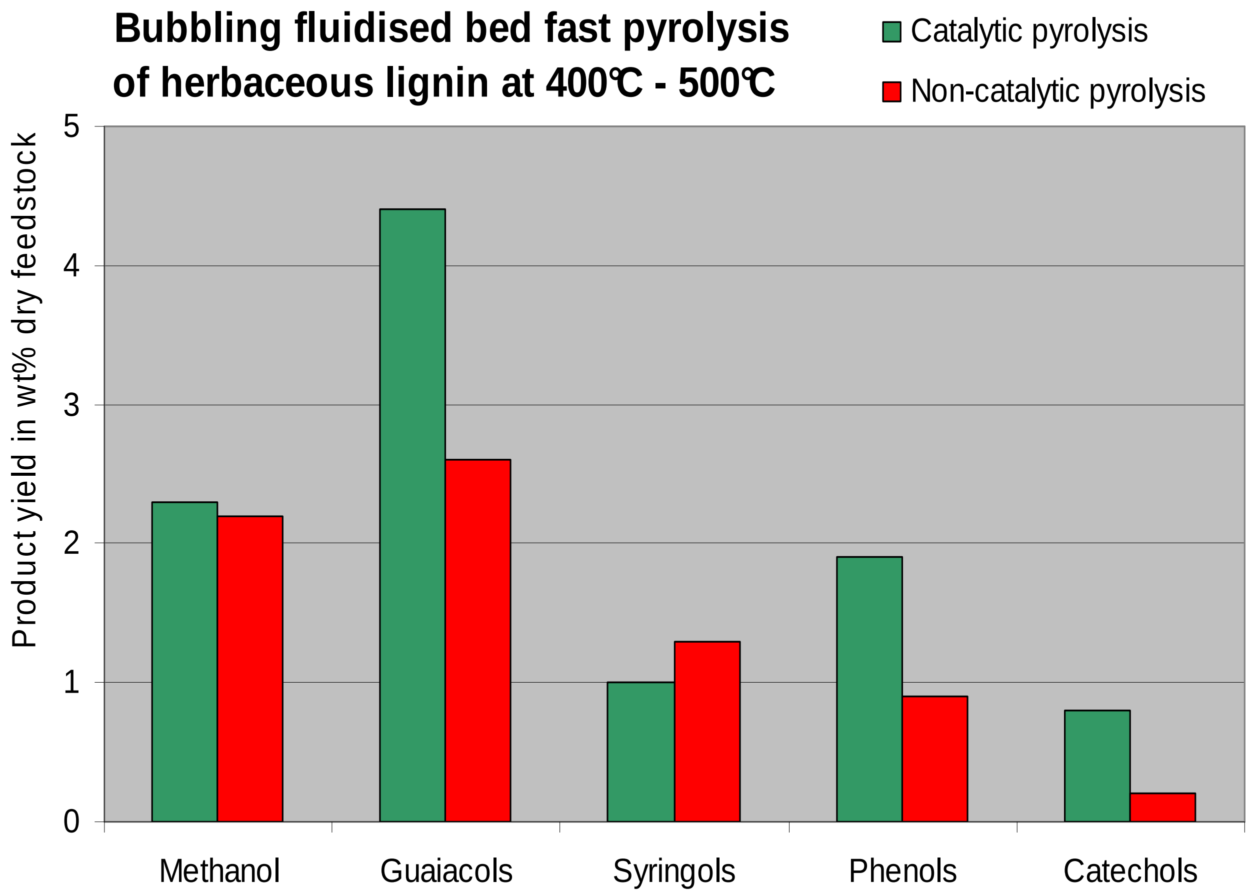


- Hollow screw design



Bubbling fluidised bed pyrolysis test rig

Improving thermal processing by application of a catalyst



Up to 10 wt% monomeric phenols (20 wt% incl. oligomers) from straw lignin produced

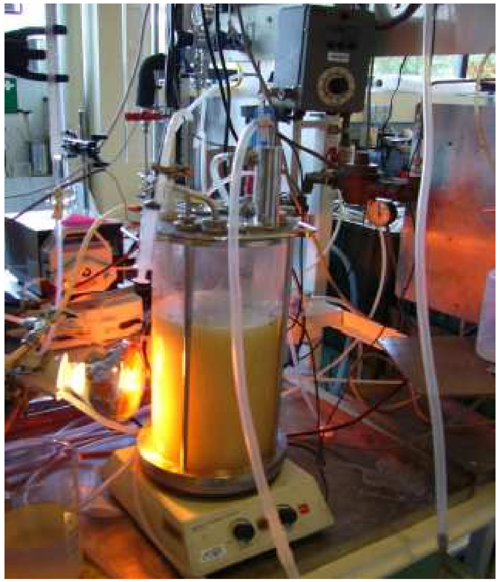
BIOSYNERGY

Advanced biochemical conversion (WP3)

Objectives

Development of advanced biochemical processes for conversion of sugars and lignin into value-added products

- Acetone-butanol-ethanol (ABE) fermentation: IFP-A&F
- Xylose conversion to xylonic acid VTT
- Production and analysis of functional lignin derivates: VTT
- Separation of product mixtures by Multiphase Rotating disk Contactors: GIG



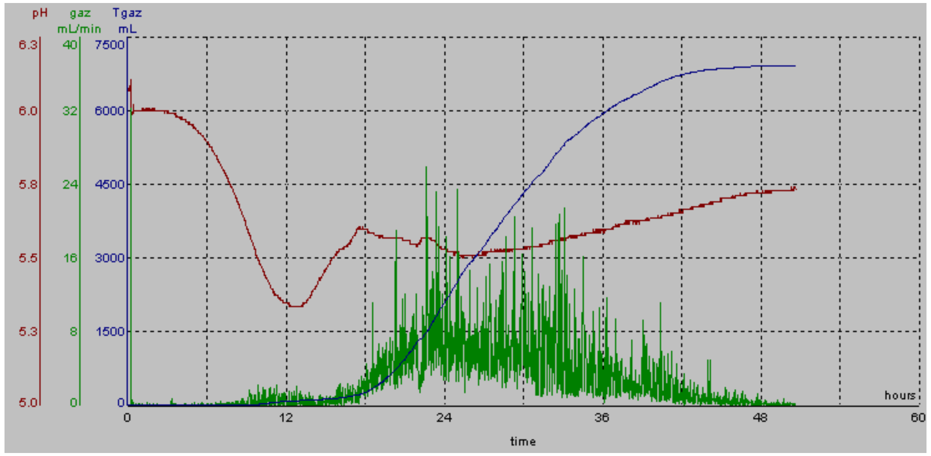
ABE fermentation at IFP

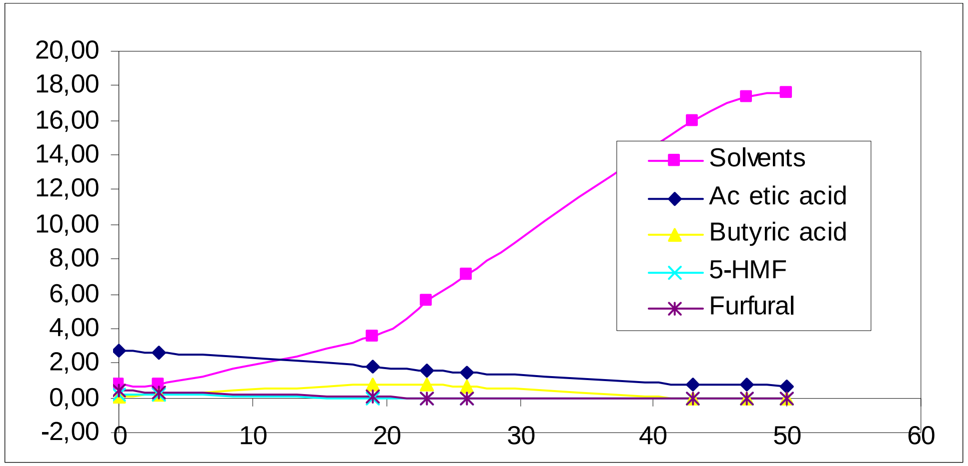
BIOSYNERGY

ABE – Production on wheat straw hemicellulose hydrolyzate

- Successful screening and selection of strains on pure substrates
- ABE Production on wheat straw hemicellulose hydrolyzates prepared by steam explosion in mild acidic conditions
- 50% Hydrolysate in synthetic medium (60 g/L total sugars (Glu 9; Xyl 51 g/L)
- Strain *Clostridium beijerinckii* NCIB 8052 / pH controlled at 5.3

- Results :
  - •Gas release : 8.9 L / L
  - •Final solvents (ABE) : 17,6 g/L





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Planned scale-up ABE fermentation (ARD/IFP/A&F)

Lab-scale (150L)

Intermediate scale (10 m^3)

Fermentor 80 m^3

Membranes purification

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Functional lignin derivatives: lignin ‘activation’

- Enzymatic lignin modification by *Trametes hirsuta* laccases
- Aim: improvement of reactivity (cross linking behaviour)

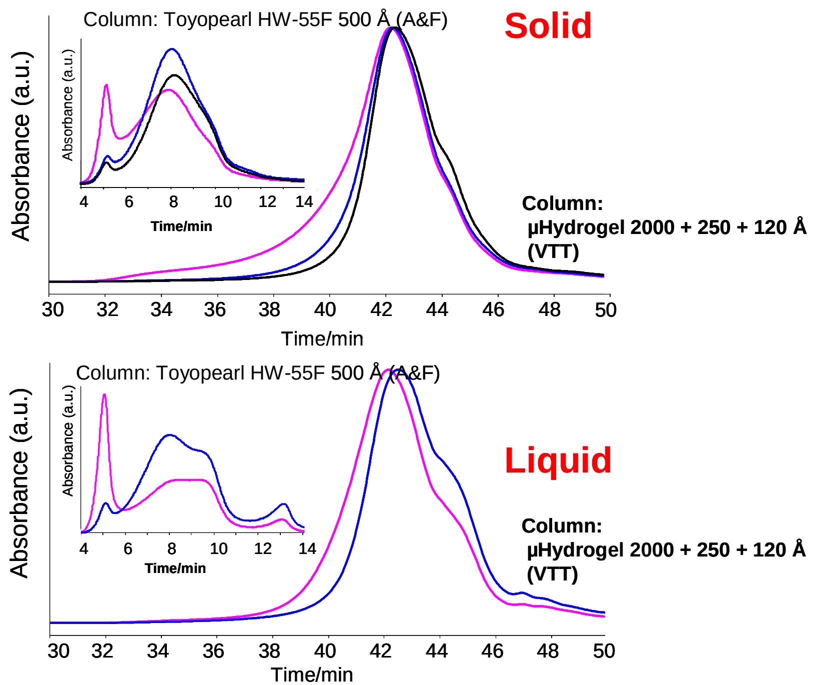
Characterization of modified lignin polymers by chemical and spectroscopic methods.

SEC of a model lignin

ThL treated lignin

Solubilized / Control lignin

Raw lignin / unsolubilised / untreated lignin



Mattinen et al. (2008). "Polymerization of different lignins by laccase," *BioRes.* 3(2), 549-565.

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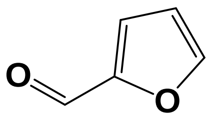
Production & characterisation platform chemicals (WP4)

Partners: DOW, A&F, ARD, Bioref, GIG, Chimar, TUD

- Products from Lignin, Cellulose and Hemicellulose fractions
- Lignin depolymerisation in supercritical CO_2: A&F
- Hydroxymethylfurfural production from glucose dehydration>> high conversion rates and selectivity Biorefinery.de
- Analysis kinetics furfural synthesis from xylose and modelling furfural production process: TUDelft

C5, C6 sugars based materials from WP1,2 →



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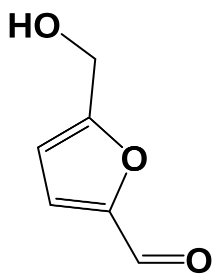
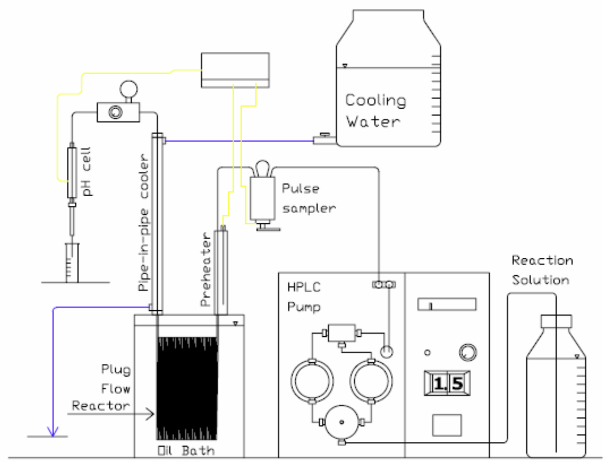


HMFu

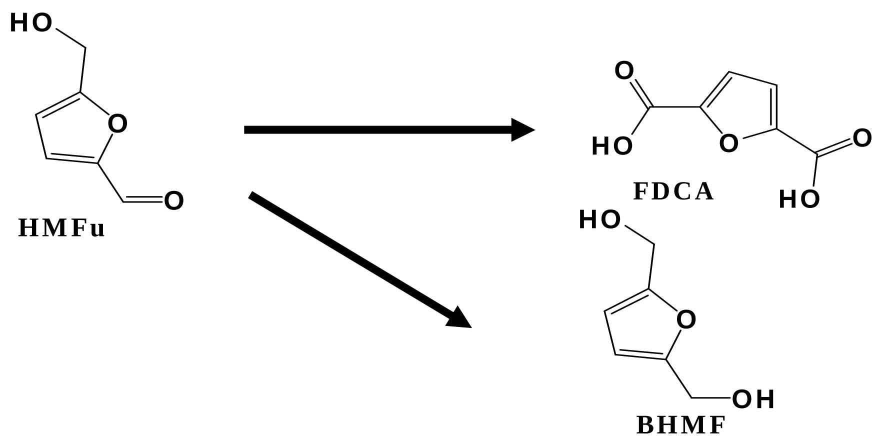


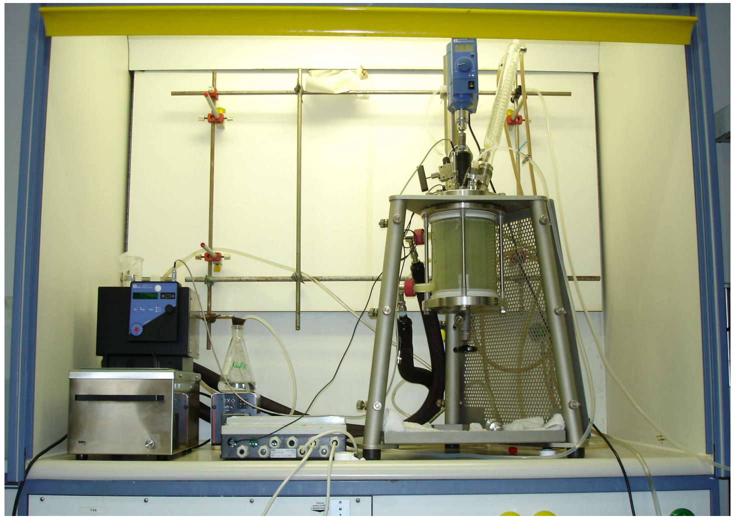
Marcotullio G., Heidweiller H.J., De Jong W. Reaction kinetic assessment for selective production of furfural from C-5 sugars contained in biomass. Paper presented at the 16th European biomass conference and Exhibition in Valencia, Spain, 2-6 June 2007

•Scheme of lab scale reactor TUDelft

Value added chemicals from platform chemicals

- Synthesis of 2,5-furandicarboxylic acid from HMF: Biorefinery.de / A&F
- Development of technologies for production of Diol-Components





- Polymerisation trials and application testing in progress

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Application testing and market validation

- Succesfull tests performed by Chimar thermosetting phenol-formaldehyde resin with phenol substitution up to 50 wt% by (organosolv) lignin for particle board application (lab scale)

- Use of pentoses based surfactants for paper impregnation in the wood-based industry

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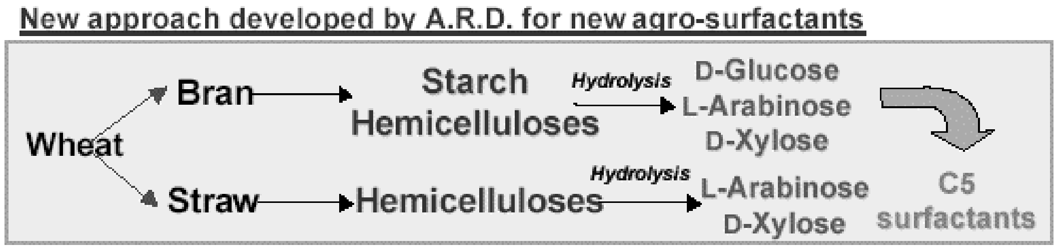
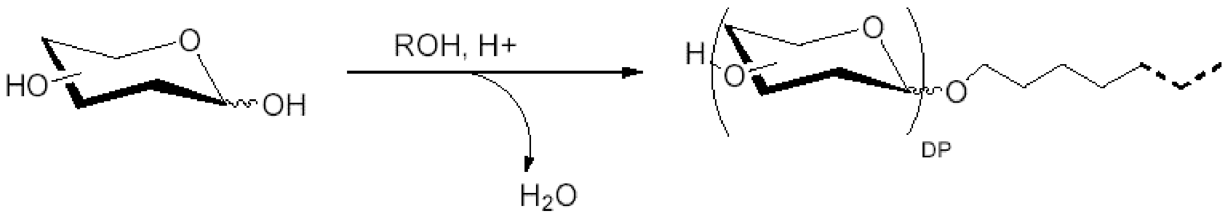
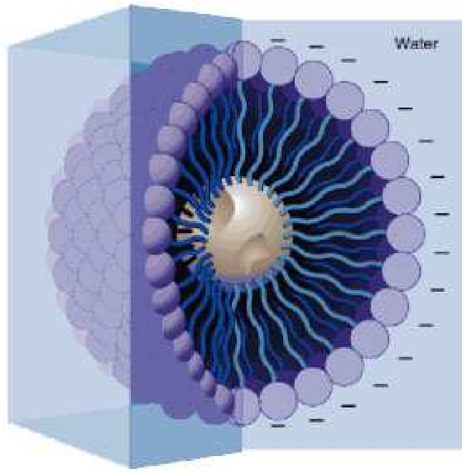
Pentose valorisation as raw material for surfactants; ARD







- Reaction of: Pentoses + Fatty alcohols (ROH) C:4 - C:18
- Production of pentoside surfactants by a green technology in order to access the price level of fossil based competitors (1.5 €/kg)
- Development of technology to directly convert pentose containing hydrolyzates to surfactants in high yields: <u>good progress obtained</u>

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Some market applications of pentose based surfactants

Planned scale up pentoses valorisation in surfactants ARD

- Production pentoside surfactants from C5 hydrolyzates at 100-1000 kg scale (ARD)

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Conceptual design biorefinery plant (WP5)

Basic design for integral lignocellulose biorefinery plant at an existing cellulose ethanol site: AB BCyL demonstration plant, Salamanca.

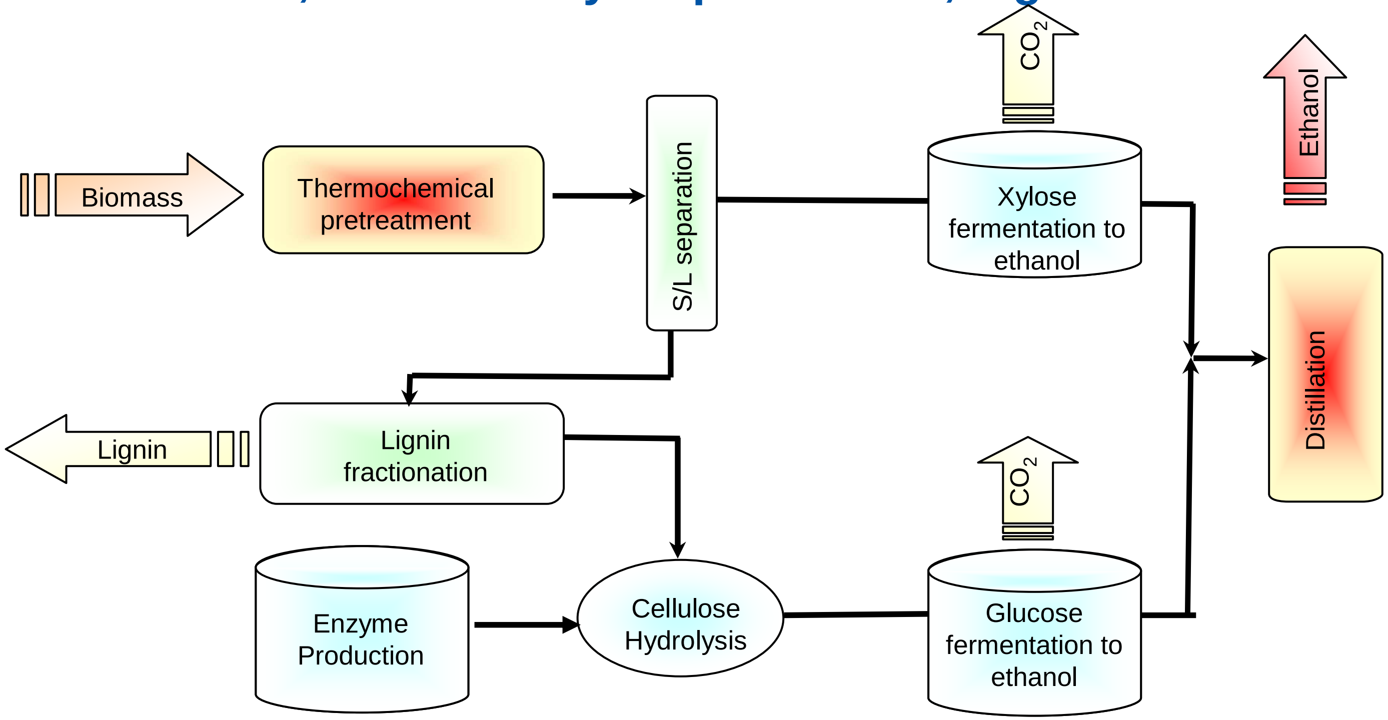
- Targeted outputs:
  - bio-ethanol,
  - chemicals & materials
  - CHP
- maximized revenue and minimized environmental impact

Partners: ABNT, Aston, ECN

BCyL cellulose ethanol pilot plant AB, Salamanca, 5 Million L EtOH / year

Conceptual design biorefinery plant (WP5)

- **Integral model for the BCyL lignocellulose to bio-ethanol process scaled-up to 400 ton/day of wheat straw incl. biomass fractionation, C5 fermentation, On-site enzyme production, Lignin valorisation**

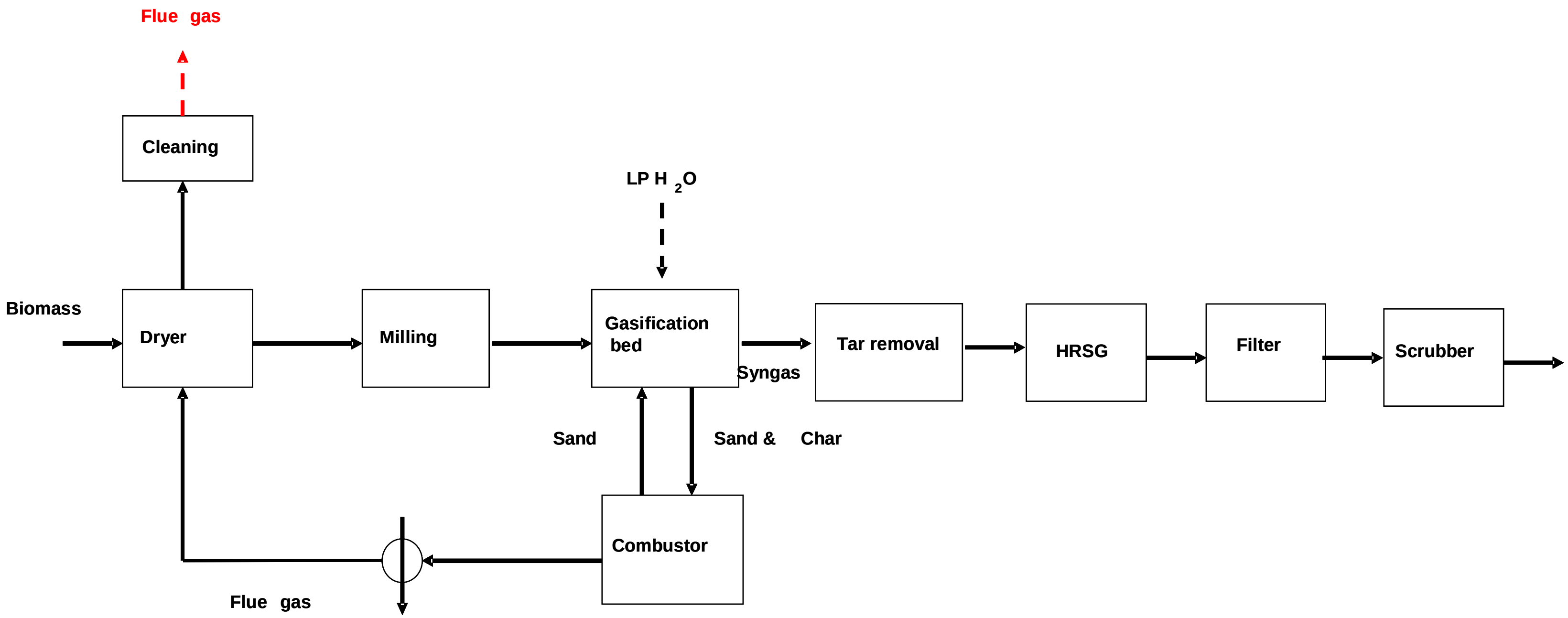


- **Economic model to evaluate design concepts and scenarios**
- **First economic results when integrated it in the developed concept**

Conceptual design biorefinery plant (WP5)

- Additional concept: BCyL biomass to bioethanol up-graded model + biomass gasification + synthesis of ethanol = **100% Ethanol Biorefinery**

  - **Gasification and catalysis model**

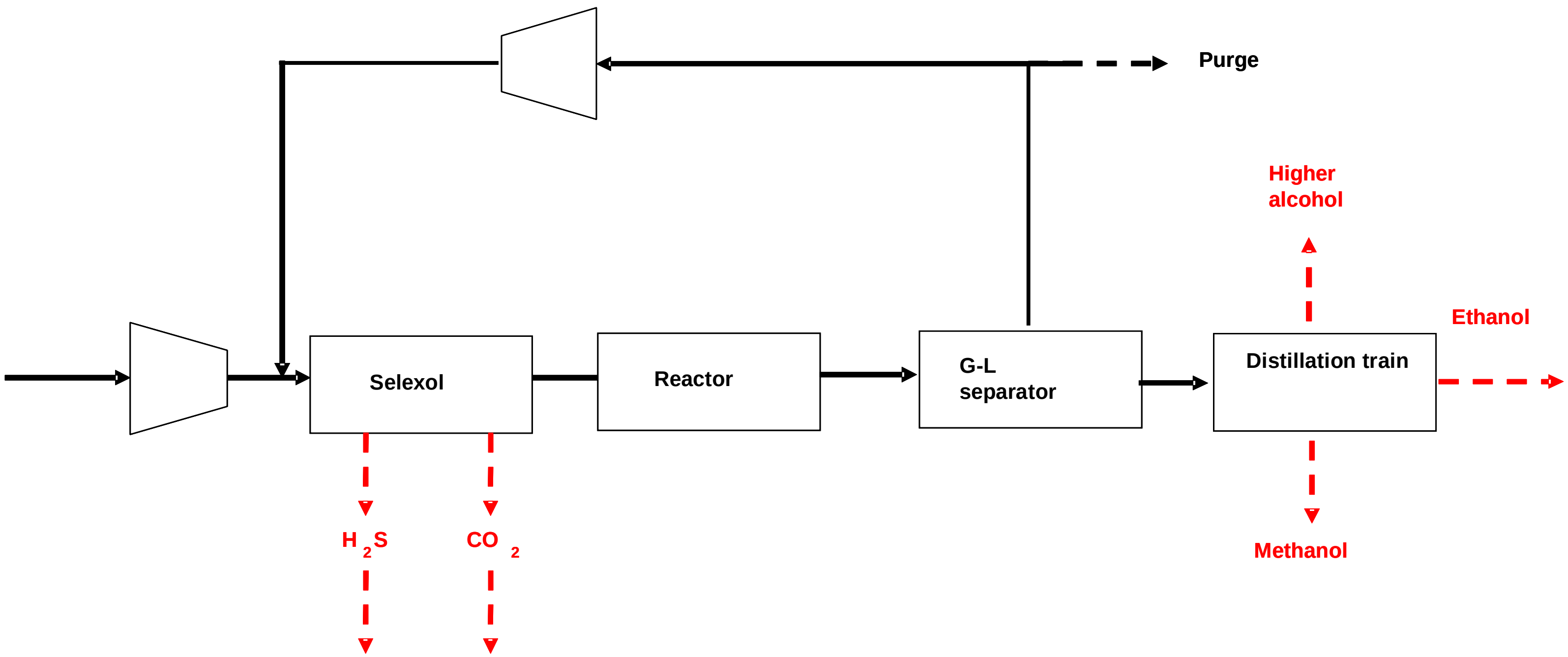


  - **Gasification and gas cleaning section**

BIOSYNERGY

Conceptual design biorefinery plant (WP5)

- BCyL biomass to bioethanol up-graded model + biomass gasification + synthesis of ethanol = **100% Ethanol Biorefinery**
    - **Gasification and catalysis model**



- **Synthesis section**

Biomass-to-products chain design (WP6)

Partners: **Aston,** ECN, IFP, CRES, JR, JRC, Cepsa, ABNT.

Objectives

Identification of the most promising biorefinery chains for the European Union, in terms of:

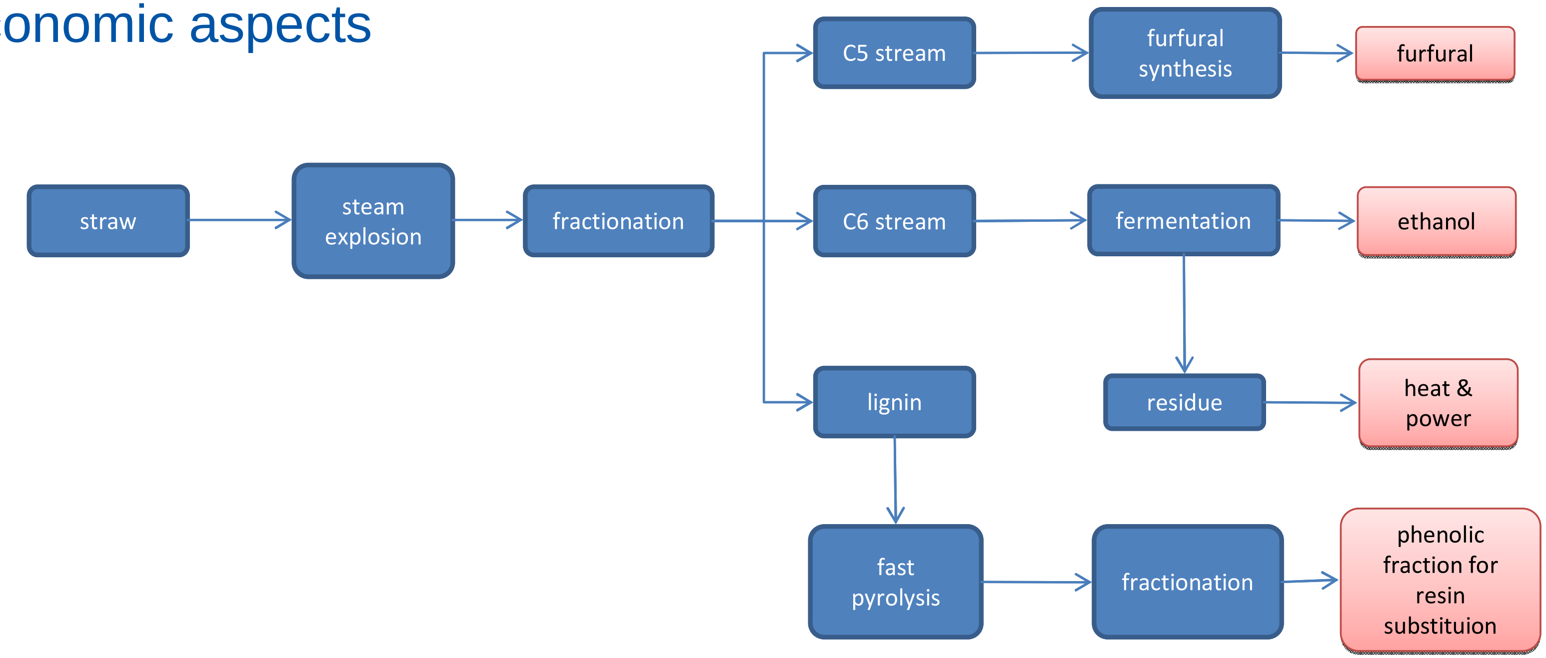
- Performance as yield and efficiency,
- Energy efficiency,
- Environmental performance as LCA,
- Cost as capital, operating and product costs
- Socio-economic aspects

Focus on ethanol based biorefineries

Biomass-to-products chain design (WP6)

Development modelling tool with modular structure

- Process synthesis
- Process simulation
- Process comparison using MCDA incl. LCA, economics, socio-economic aspects

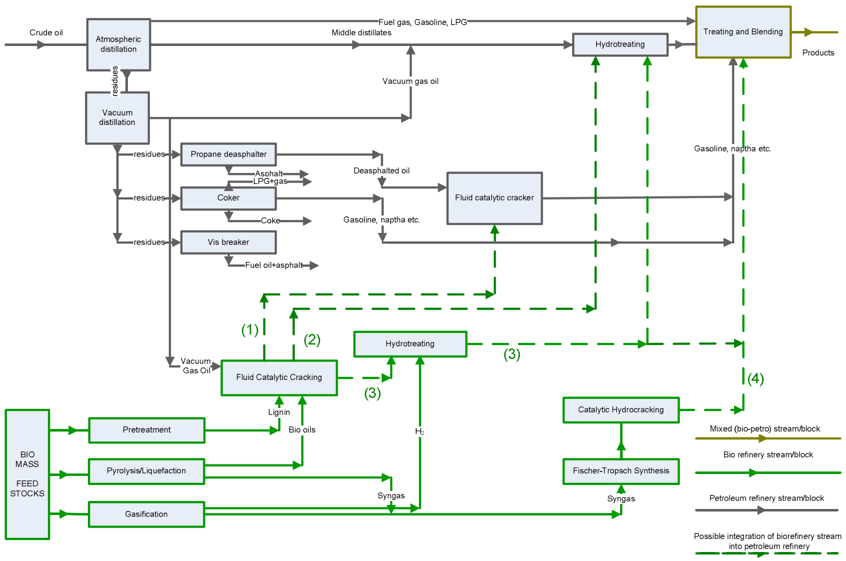


Biorefinery co-producing ethanol, furfural, phenolic resins and CHP

Integration in conventional petrochemical refinery

Substitution of fossil fuels by biomass or biomass-derived intermediates in an existing petrochemical refinery

Partners: Aston, Cepsa, IFP, ECN, JRC



Petrochemical complex of Cepsa is taken as base-case to:

1. identify potential substitution places for bio-based intermediates
2. select matching upstream technologies
3. to perform integral techno-economic and environmental chain assessments
4. to calculate overall costs and environmental data

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Integration in conventional petrochemical refinery

Approach

- Desk study and modelling
- Conversion tests fast pyrolysis oil by Cepsa underway

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Preliminary conclusions & perspectives

- Development LC Biorefinery –combining bioprocesses, chemical processes + CHP – offers good perspectives to fully exploit the potential of lignocellulose.
- Biosynergy RTD shows good progress and provides a basis for large-scale valorization of C5 sugars and lignin. Scale-up is planned for two C5 conversion routes.
- Pretreatment and enzymatic hydrolysis are critical for fractionation and therefore for the quality of the end products and techno-economic feasibility:
  - Pretreatment technologies need to be optimised toward a particular goal.
  - Organosolv is a good candidate when the aim is to valorize all fractions AND produce a high quality lignin.
  - Enzymes are a major processing tool in the LC Biorefinery. Further development and cost reduction are needed.
  - Integrated development Feedstock-pretreatment-hydrolysis-fermentation is required.

Preliminary conclusions & perspectives

- Lignin valorization (at least in part) to chemicals is an important tool for economic profitability and for reduction of the carbon footprint.
- Direct application of (organosolv) lignin, catalytic thermochemical processing (pyrolysis) and enzymatic lignin conversion show promising results for lignin valorization

- Separation technology development is vital for both biochemical and thermochemical processing technologies

- Development of integrated processes / chain optimisation is a major success factor and is also one of the major challenges. This includes process integration but also the integration of environmental and socio-economic aspects.

Acknowledgements

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SenterNovem EOS-LT

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