ZAMBEZI pretreatment process

Macrofuels

CONFIDENTIAL

10-11 January 2017

Ed de Jong
VP Development

First and second generation biomass

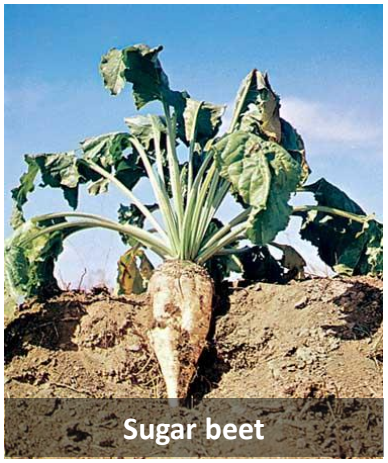
For bio-based chemical & fuel production

Now

First generation (1G) – Sugar cane, corn, sugar beet, wheat


Corn

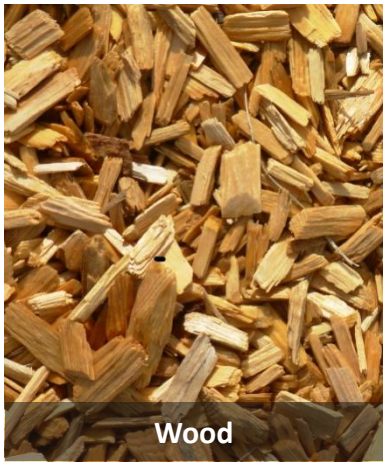

Sugar cane

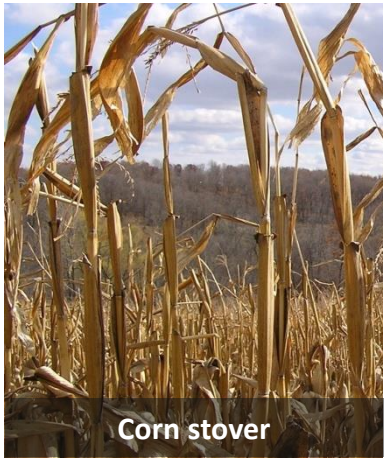

Sugar beet

Future

Second generation (2G)

Wood, agricultural residue, recycled paper, energy crops, seaweeds


Wood


Corn stover


Recycled paper


Sea Weed

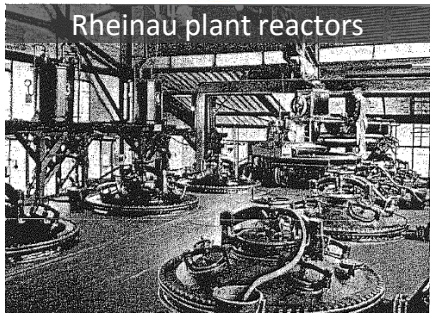
2G Sugar Technologies Evaluated by Avantium

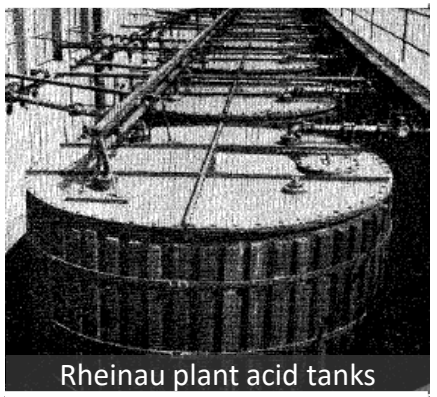
Technology	Example Companies	Advantages	Disadvantages	Application Area
Pre-treatment + enzymatic hydrolysis	M&G Chemtex /Beta Renewables Sweetwater Comet …	+ High yield + Mild conditions	- Mixed products - Enzyme cost	- Biofuels
Dilute acid / high temperature		+ Cheap process	- Low yield - Poor selectivity (Inhibitors)	- Biofuels
Organosolv + enzymatic hydrolysis	ECN Lignol CIMV	+ High grade lignin + High grade cellulose fibre	- High solvent recycle costs - Enzyme cost	- Biofuels - Biochemical
Hot Compressed Water	Renmatix	+ Low cost reagents	- Low yield - High pressure/temp	- Biofuels - Biochemical
Concentrated acid / low temperature hydrolysis ('Bergius process')	Avantium Stora Enso (Virdia)	+ High yield + High purity	- Acid / sugar separation - Corrosion	- Biofuels - Biochemicals

Avantium selected technology

Bergius Concentrated HCl hydrolysis technology

1916	Bergius began development of industrial process of saccharification
1933	Mannheim-Rheinau plant completed (single step hydrolysis) 6-8 kt/a mixed sugars
1939	Regensburg plant completed (destroyed 1945) 20 kt/a sugars
1948-59	Modified- Rheinau process (with sugar fractionation) 12 kt/a glucose
1953-55	Japan pilot plant
1957–87	Russia pilot plants (10 m3 scale hydrolysis reactors)
1980's	Dow USA: Pilot Plant - HCl recovery by solvent extraction
2007	HCl CleanTech (Israel) → → Stora Enso (2014) (HCl recovery via amine complexation)


Rheinau plant reactors


Rheinau plant acid tanks


Regensburg plant

2013-2015 Avantium studied all available know-how on Bergius process and developed proprietary improvements leading to glucose production competitive to 1G glucose

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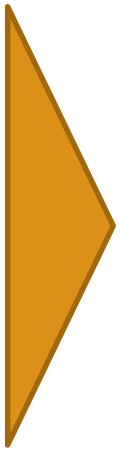
ZAMBEZI Process

- Features
  - Concentrated acid, low temperature, two-stage, high selectivity
  - Near quantitative conversion of cellulose to glucose
  - Fractionation: glucose, C5/C6 sugars, extractives and lignin
  - Feedstock flexibility: forestry residues (wood), wastepaper, corn stover and bagasse

- Technical Breakthroughs
  - Acid sugar separation
  - Materials of construction
  - Lignin deacidification

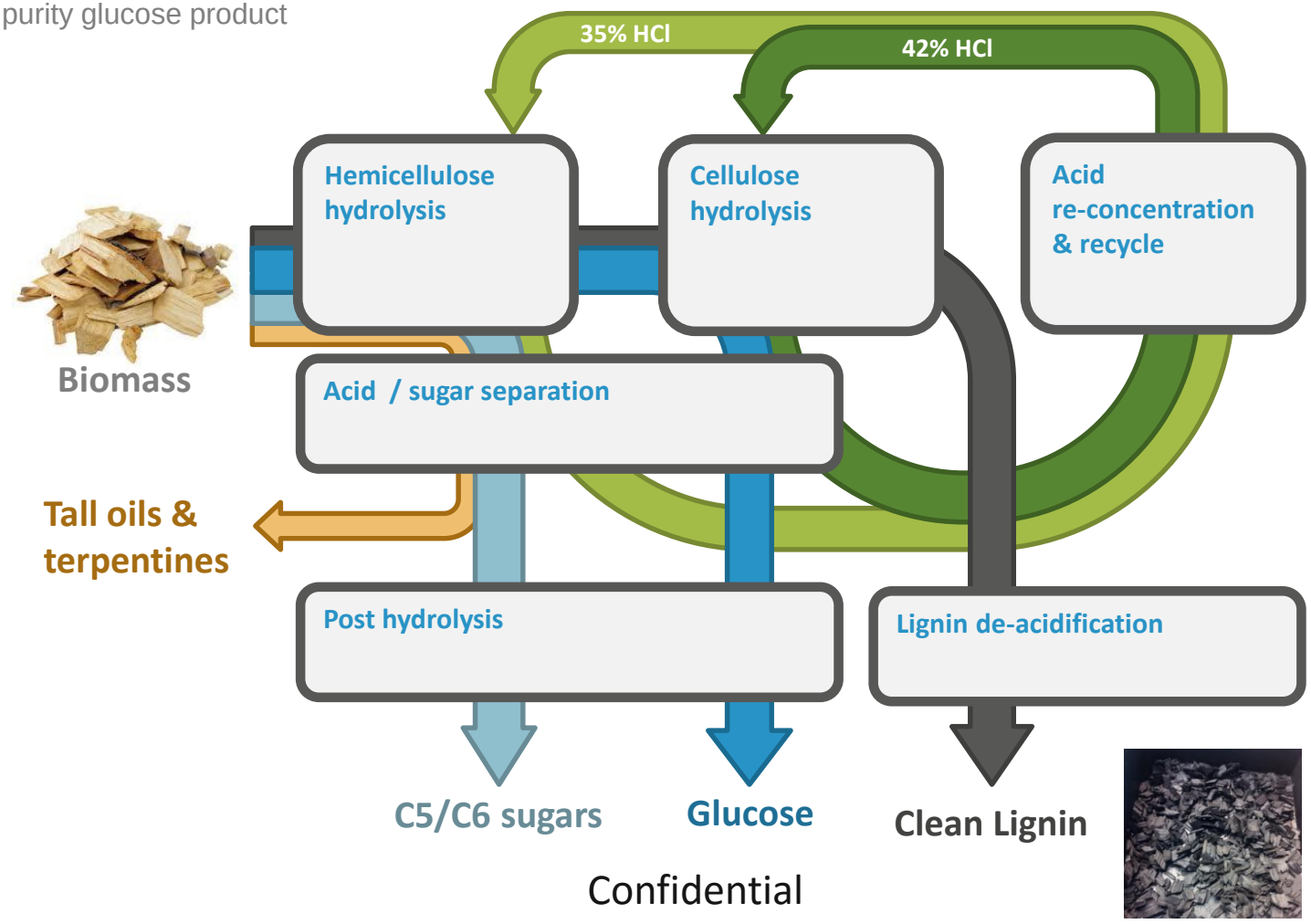


IP filed

ZAMBEZI Process

Process outline

Improved Bergius-Rheinau process
Two stage, concentrated HCl hydrolysis
Acid / sugar separation by proprietary technology
High purity glucose product



Zambezi process for seaweeds / attention points

Positive

- Presence of Cl^- is not an issue => works with 42% HCl
- High content of carbohydrates
-

Negative

- Low amounts of lignin / risk of plugging of the reactor
  - Addition of a co-feed
- Low density
  - Pelletizer / combine with addition of co-feed
- High water content

Unknown

- Behavior of the carbohydrates in the hydrolysis
- Effect of seasonal variability

ZAMBEZI Hydrolysis Equipment

HYDRO\2

- After exploratory experiments in simple glass columns, we decided we needed a dedicated set-up …

- Requirements:
  - Safe operation of reactor system, generation of 42% HCl and storage of acid & hydrolyates
  - Generation of 42% HCl without the need for an HCl gas cylinder
  - Continuous controlled flow of 37 - 42% HCl and acid+sugar containing hydrolysates over a packed bed of wood
  - Continuous removal of hydrolysate “product”
  - Easy removal of solid residual lignin
  - HCl resistant columns, tubing, values, pumps & containers
  - Multiple reactors in series (at least 2)
  - Transparent reactors
  - Optional cooling

ZAMBEZI Hydrolysis Equipment

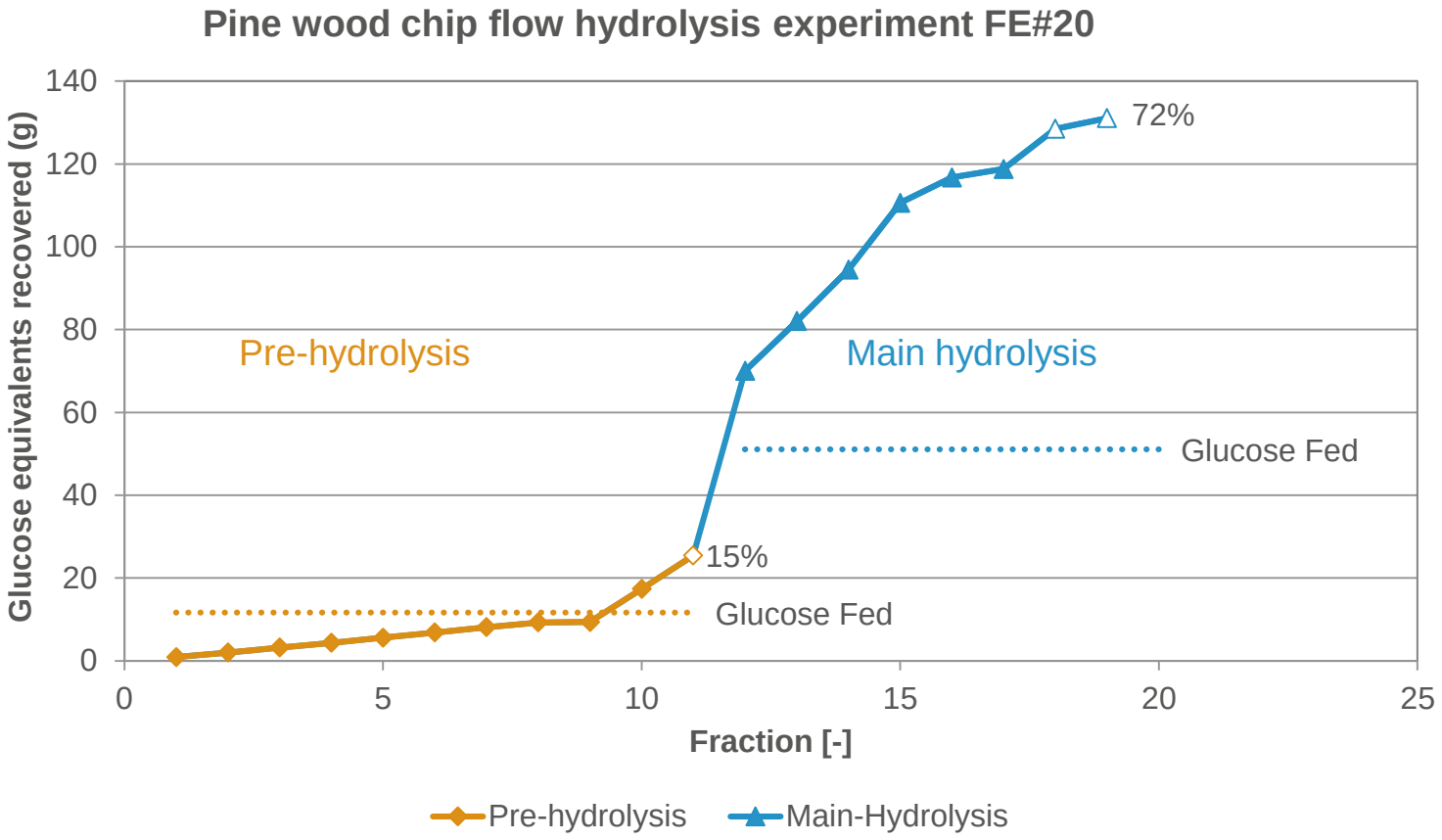
HYDRO\2

- Solution:
  - Reactors: 2 reactors that can be connected in series
  - Pump: Regular HPLC pump + “displacement column”
  - MoC: Transparent UPVC columns, PVC tubing, glass valves & bottles
  - Cooling: Jacketed columns + chiller
  - 42% HCl: Generation on demand
  - Storage: Pressure capable epoxy coated glass bottles (4 bar) + storage in dedicated freezer
- Technology development and safety approval process was quite time consuming

HYDRO\2 Hydrolysis reactor system

ZAMBEZI Experimental Results

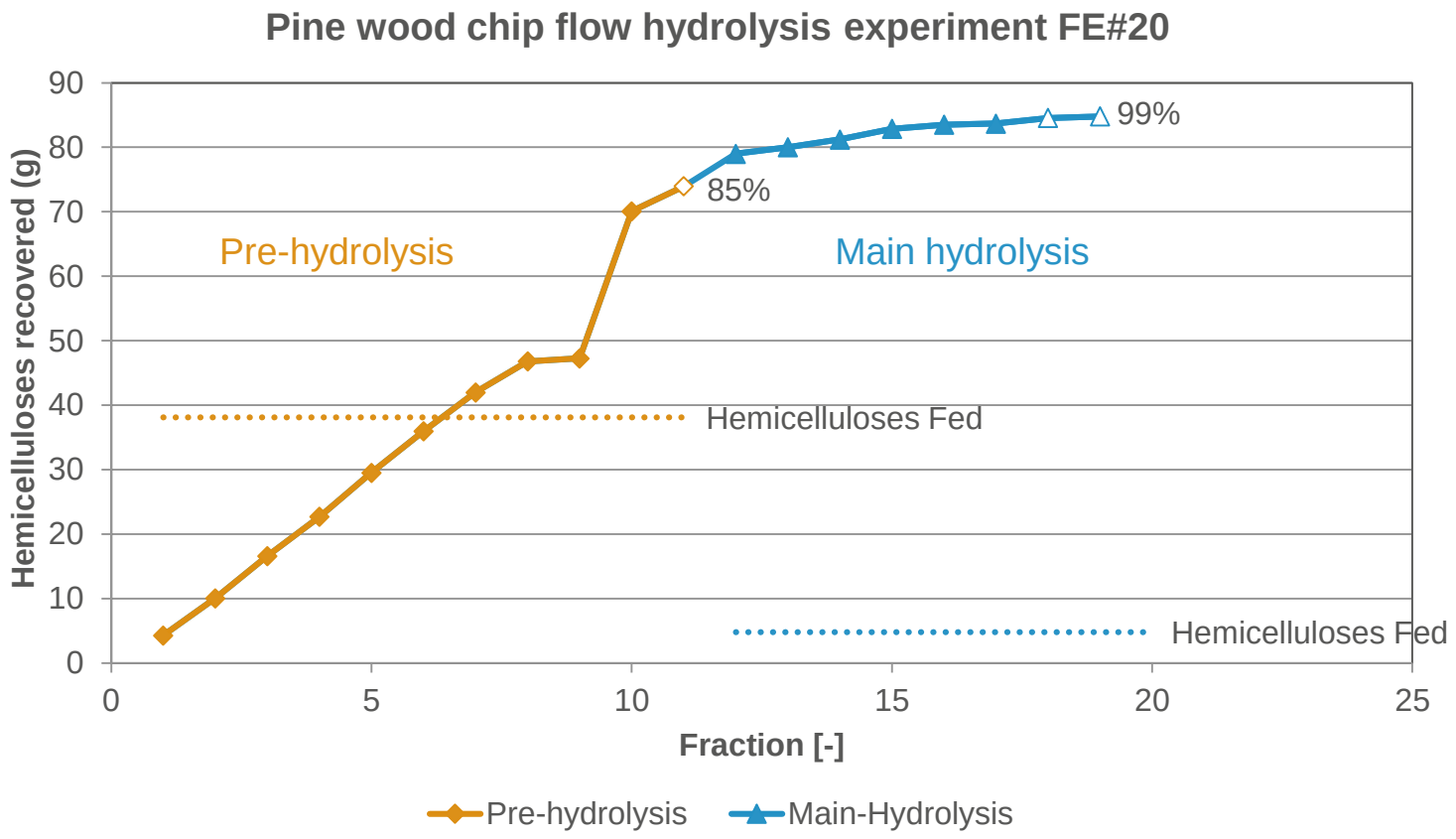
Glucose



Not optimised. Not under commercial process conditions.

ZAMBEZI Experimental Results

Hemicelluloses (=Mannose + Xylose + Arabinose)



Not optimised. Not under commercial process conditions.

Why non-food Biomass?

- Reasons:
  - Economic:
    - Available at good price (needs to be proven for seaweeds)
    - Good and proven logistics
  - Technological:
    - Tests at lab scale have been done on the basis of wood chips
    - Does not require other pre-processing step
    - Retains structural integrity after process (does not crumble or slump)
  - Sustainable:
    - Good ecological footprint
    - Undisputed

- We continue to evaluate alternative feedstock options
  - (Seaweeds (inside macrofuels), algae, waste streams)

IP – Freedom To Operate (FTO)

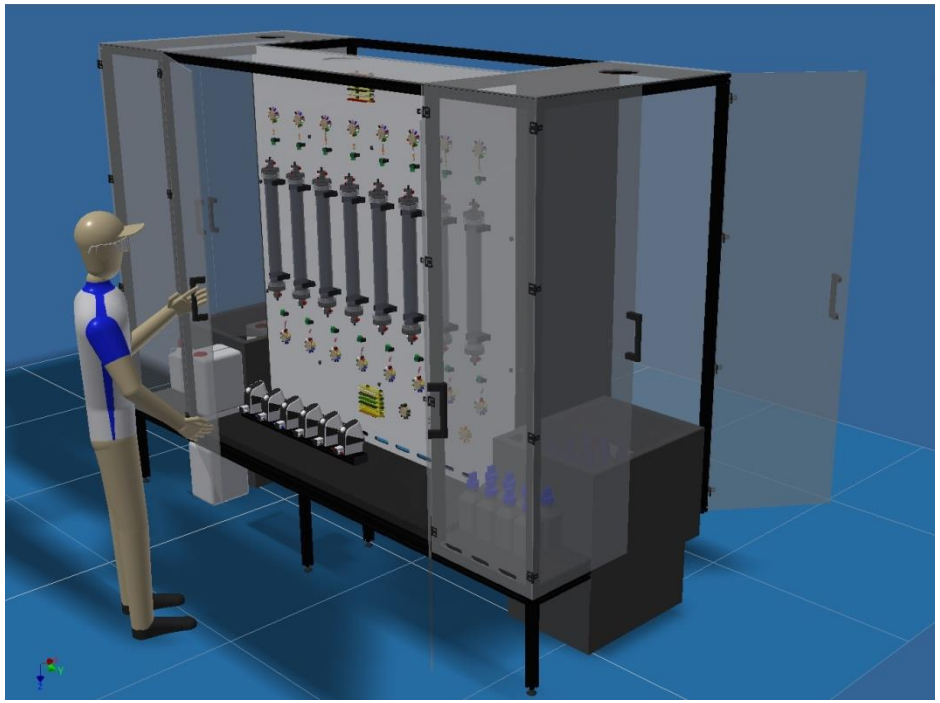
- More than 150 patents and patent applications evaluated

- NO FTO conflicts were found on / around the Avantium innovations (sugar-acid separation, lignin-acid separation, materials of construction).

HYDRO\3

Lab scale automated hydrolysis unit

- Currently building new lab scale automated hydrolysis unit (HYDRO\3)
  - 8 x 1 litre PVC reactors in series
  - Automated operation, 24 x 5
- Improved safety, data quality & productivity of lab scale hydrolysis process R&D
- Utilize Avantium's technology development expertise
- Allow smooth pilot plant start-up (reduce start-up time, lower cost, lower risk)



HYDRO\3 3D Layout

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Status Hydro 3 building

Market assessment

- Megatrends that drive the need for sustainable and innovative technologies for using 2nd generation biomass
  - Population Growth
  - Climate Change
  - Resource Scarcity

- World population is expected to grow from 7 to 9-10 billion by 2050, which together with increased average living standards will double resource demands

- Growing tension developing for land use in bio-fuel vs traditional agriculture for Feed & Food (cascading principle)

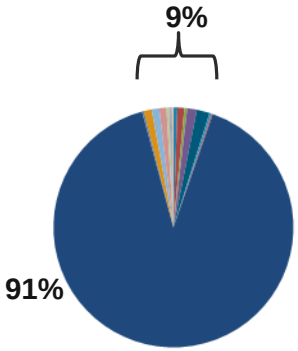
- 311 million tonnes of plastics produced in 2014 expected quadruple to 1.2Bn tonnes in 2050 which will create huge opportunity for sustainable biobased plastics (World Economic Forum 2016)

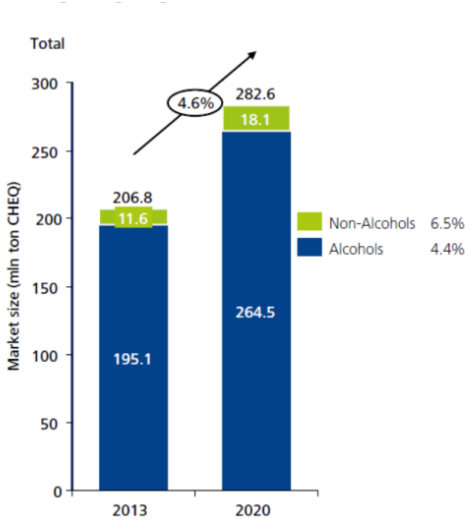
Market Potential for Glucose

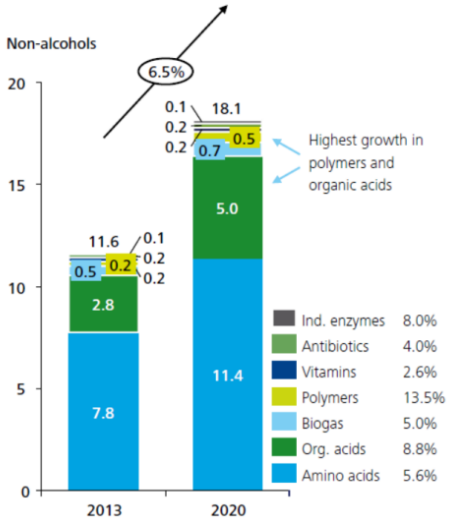
Bio vs fossil market size 2015 – Growth potential

Bio-Market Sales

$ 65 bn

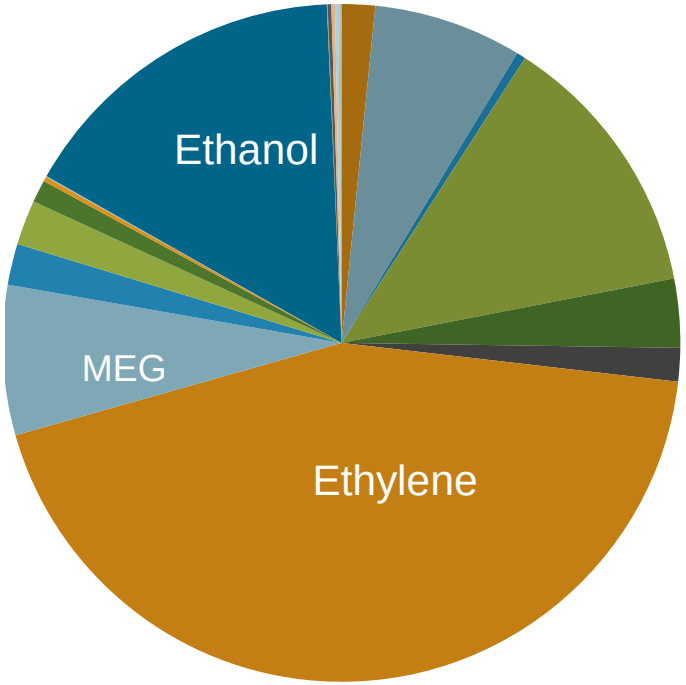






Related Fossil & Bio Sales

$400 bn

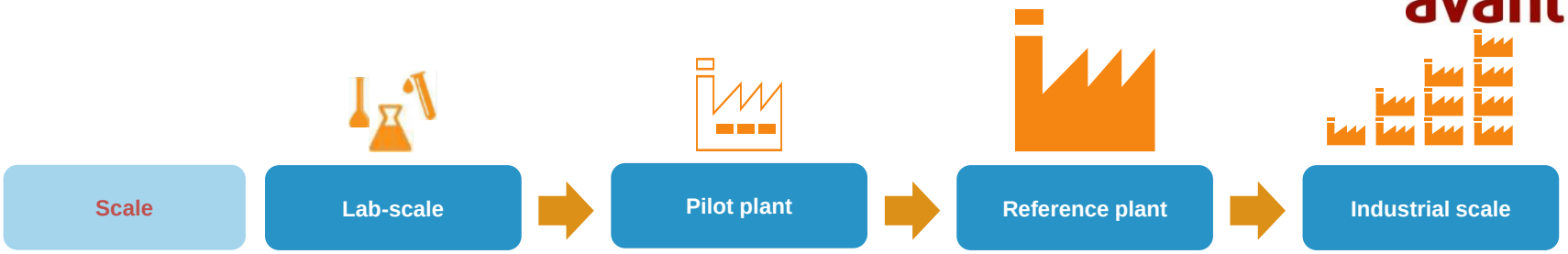


- Adipic acid
- Iso-butene
- Isoprene
- p-xylene
- Acrylic acid
- BDO
- Ethylene
- MEG (Ethylene glycol)
- Acetone
- Acetic acid
- n-butanol
- 5-HMF
- Isobutanol
- Succinic acid
- Ethanol
- Farnesene
- Itaconic acid
- Lactic acid
- Furfural
- Xylitol
- PDO
- Algal lipids
- PHAs
- Sorbitol
- Levulinic acid
- FDCA
- 3-HPA

From Opportunities for the Fermentation Based Chemical Industry; Analysis of Market Potential and Competitiveness in North West Europe – Deloitte 2014

From the Sugar Platform to Biofuels and Biochemicals
Final report for the European Commission Directorate-General Energy
N° ENER/C2/423-2012/SI2.673791
April 2015

Partnering Strategy



Envisioned strategy

Phase I — Stand-alone

Phase II — Partnering

Phase III — Licensing

Strategic choices

- Stand-alone
- Partnering
  1) Strategy for Flagship
  2) Strategy for multiplicity of licenses
- Sell technology

Partnering Universe

Feedstock

- Pulp & paper
- Forestry
- Agricultural
- Marine

Conversion

- Chemical
- Engineering
- Site / Services

Off-takers

- 2G Glucose
- Mixed Sugars
- Lignin (specialty or energy)
- Specialties depending on feedstock (extractives, tall oils, ...)

ZAMBEZI Pilot Plant

- Additional reactors & greater automation required to operate in continuous counter current mode
- Have decided to take the process to pilot scale

- Pilot plant objectives
  - Scale-up and prove Avantium innovations at scale
  - Optimise process operation
  - Gain operational experience
  - Collect data for engineering a commercial scale plant
  - Produce sugars, lignin and extractives for application development

- Scale: 10 tonnes / year dry wood feed

Aknoledgements

- Co workers: Ben McKay, Martijn Kersbulck, Erik Hagebols, Robert-Jan van Putten, Gerard van Klink, Jan Kees van der Waal, Alan Smith, Gert-Jan Gruter

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QUESTIONS ?