Imperial College London

Biorefineries – the future of biomass conversion?

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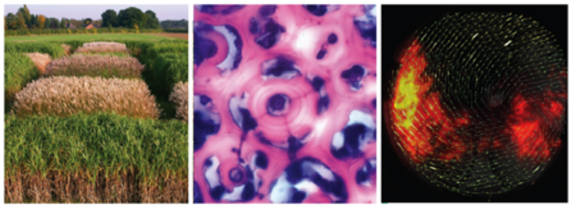
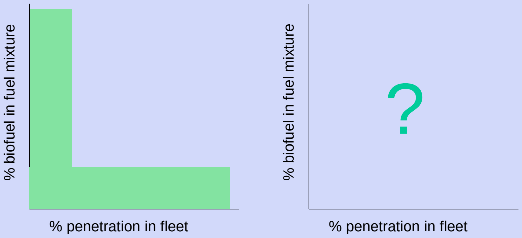


Biofuels



Today

Future

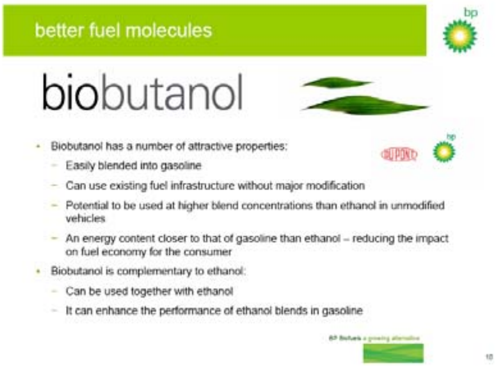
1st generation EtOH
Fossil Energy Fraction: 50-70%

2nd generation fuel
Fossil Energy Fraction: 20%

Biofuels: classification

Oxygenates	**Generation**	**Process**
Methanol	2nd	Thermal
Ethanol	1st and 2nd	Biological or Thermal
Butanol	1st and 2nd	Biological or Thermal
Mixed alcohols	2nd	Thermal
DME	2nd	Thermal
Hydrocarbons		
Biodiesel	1st	Phys/chemical
Synthetic diesel	2nd	Thermal (long term bio)
Synthetic gasoline	2nd	Thermal
Hydrogen	1st and 2nd	Thermal or Biological

(Bridgewater, 2006)



better fuel molecules

biobutanol

- Biobutanol has a number of attractive properties:
  - Easily blended into gasoline
  - Can use existing fuel infrastructure without major modification
  - Potential to be used at higher blend concentrations than ethanol in unmodified vehicles
  - An energy content closer to that of gasoline than ethanol – reducing the impact on fuel economy for the consumer
- Biobutanol is complementary to ethanol:
  - Can be used together with ethanol
  - It can enhance the performance of ethanol blends in gasoline

BP Biofuels a growing alternative

10

Biofuels and bioenergy

- A significant proportion of world primary energy demand (~ 430 EJ) can be met from bio-sources
- Present motor fuel demand could be met from biofuels using 8 – 20% of world arable land resource
- Plant productivity for food has been raised dramatically over the past 7,000 yrs of agriculture
- Biofuels from energy crops are needed *now* to meet the challenge of global climate change and energy security

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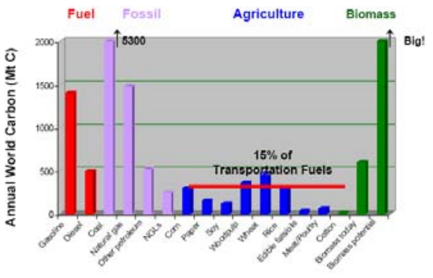
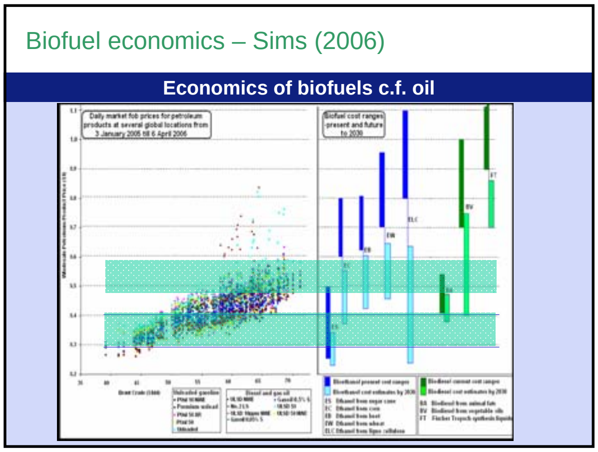
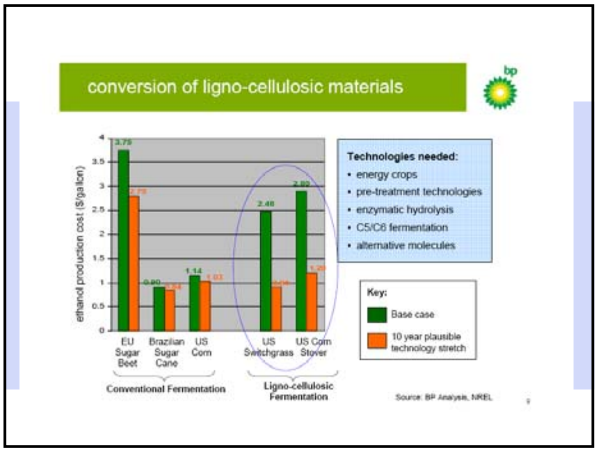
what carbon “beyond petroleum”?





Biofuel economics – Sims (2006)

Economics of biofuels c.f. oil

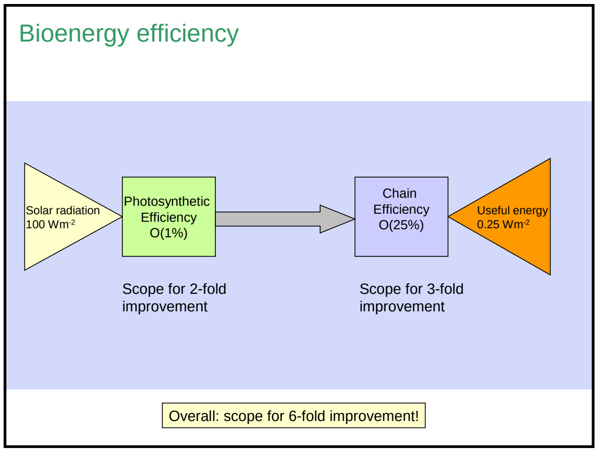


conversion of ligno-cellulosic materials

Technologies needed:

- energy crops
- pre-treatment technologies
- enzymatic hydrolysis
- C5/C6 fermentation
- alternative molecules

Source: BP Analysis, NREL

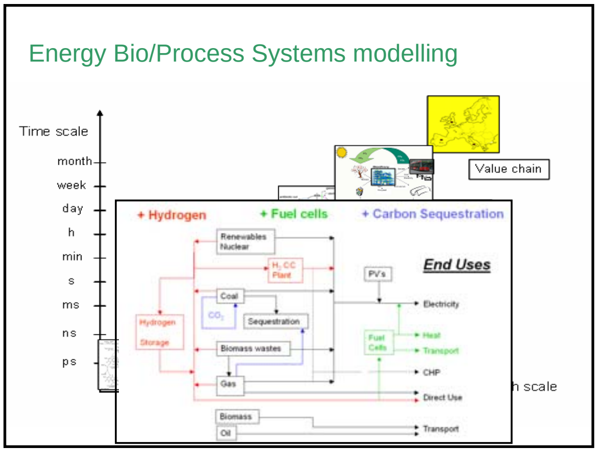


Bioenergy efficiency

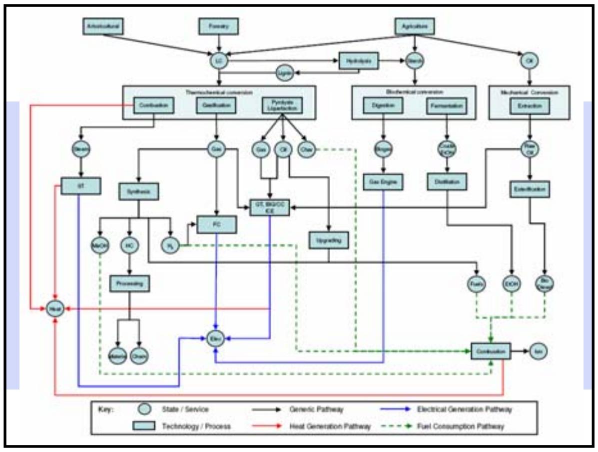
Scope for 2-fold improvement

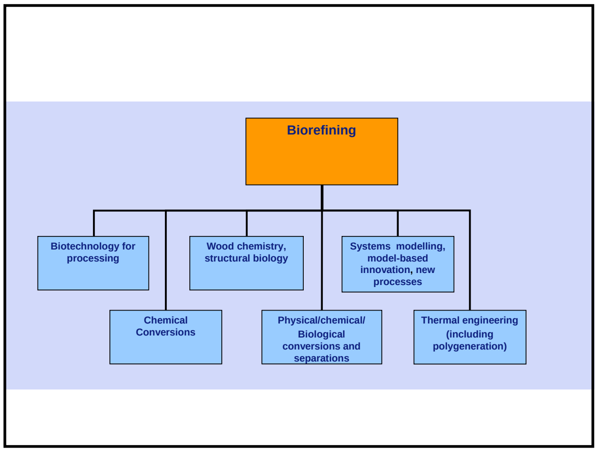
Scope for 3-fold improvement

Overall: scope for 6-fold improvement!



Energy Bio/Process Systems modelling





Biorefining

Biotechnology for processing

Wood chemistry, structural biology

Systems modelling, model-based innovation, new processes

Chemical Conversions

Physical/chemical/ Biological conversions and separations

Thermal engineering (including polygeneration)

Biorefinery - aspirations and objectives

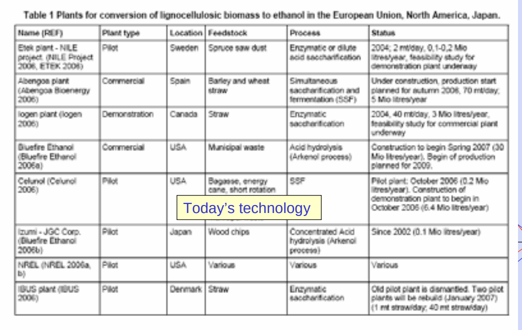


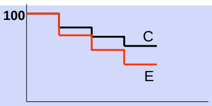
Table 1 Plants for conversion of lignocellulosic biomass to ethanol in the European Union, North America, Japan.

Name (REF)	Plant type	Location	Feedstock	Process	Status
Etek plant - NILE project. (NILE Project 2006, ETEK 2006)	Pilot	Sweden	Spruce saw dust	Enzymatic or dilute acid saccharification	2004; 2 mt/day, 0,1-0,2 Mio litres/year, feasibility study for demonstration plant underway
Abengoa plant (Abengoa Bioenergy 2006)	Commercial	Spain	Barley and wheat straw	Simultaneous saccharification and fermentation (SSF)	Under construction, production start planned for autumn 2006, 70 mt/day; 5 Mio litres/year
Iogen plant (Iogen 2006)	Demonstration	Canada	Straw	Enzymatic saccharification	2004, 40 mt/day, 3 Mio litres/year, feasibility study for commercial plant underway
Bluefire Ethanol (Bluefire Ethanol 2006a)	Commercial	USA	Municipal waste	Acid hydrolysis (Arkenol process)	Construction to begin Spring 2007 (30 Mio litres/year). Begin of production planned for 2009.
Celunol (Celunol 2006)	Pilot	USA	Bagasse, energy cane, short rotation	SSF	Pilot plant: October 2006 (0.2 Mio litres/year). Construction of demonstration plant to begin in October 2006 (6.4 Mio litres/year)
Izumi - JGC Corp. (Bluefire Ethanol 2006b)	Pilot	Japan	Wood chips	Concentrated Acid hydrolysis (Arkenol process)	Since 2002 (0.1 Mio litres/year)
NREL (NREL 2006a, b)	Pilot	USA	Various	Various	Various
IBUS plant (IBUS 2006)	Pilot	Denmark	Straw	Enzymatic saccharification	Old pilot plant is dismantled. Two pilot plants will be rebuild (January 2007) (1 mt straw/day; 40 mt straw/day)

Today's technology

C eff

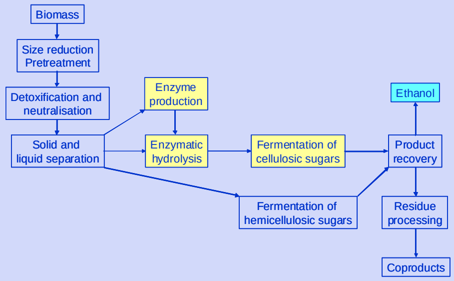
Insights from thermodynamics and chemistry



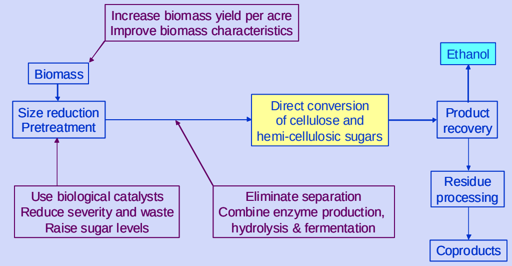
- Drivers: energy and carbon parsimony
- Avoid shaftwork
  - Favour heat over work
- Avoid extreme conditions
  - Favour ambient processing
- Avoid auxiliary reagents and "useless" waste streams (acid, lime, gypsum,…) → supplemented hot water + CBP?
- Optimise breaking and making of bonds
  - Preserve biomass fractions; search for high selectivity (enzymes, synthetic biology agents, hybrid processes …)
  - High specificity of targets, e.g. break lignin-hemicelluose linkages through chemo-enzymatic techniques
- Mass intensity: use as much of the material as possible
- Energy integration: optimise heat and work cascades

Insights support rational RD&D and drive technology development

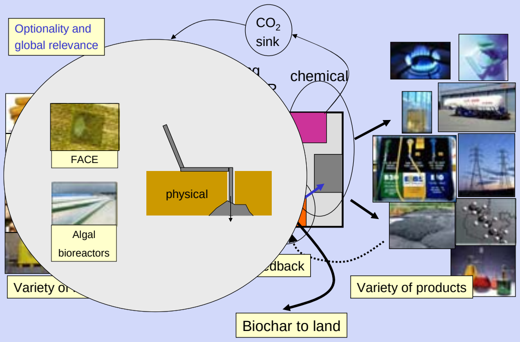
Separate LC saccharification and fermentation



"Ideal" LC SSF or Combined Bioprocess



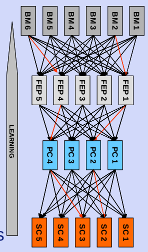
The flexible, modular biorefinery



The challenges: achieving the aspirations

Integrate biotechnology, chemistry and engineering

- Physico-chemo-biotechnological:
  - Optimised pre-treatment: harvest to fermenter
- Mission-oriented biotechnology
  - Next generation products: higher alcohols and alkanes
  - Next generation process specific organisms
- Robust, intensified biorefineries
  - Integrated refinery design
  - Hybrid (thermal/chemical/bio) processing
  - Extracting maximum value from biomass
- Optimise the products against market requirements



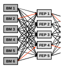
Timing and viability of second generation

- Separate saccharification and fermentation – plants being constructed now (pentose utilising yeasts, thermophiles, “*E coli*”)
- Depending on pretreatment methods, Combined Bioprocessing requires cellulolytic and “xylanolytic” strains (3-5 years) – options to add catabolic capability or engineer fermentation pathways.
- SSF is an interim solution

Critical factors for second generation

- Need feedstock optimised methods
  - Particle size reduction is expensive
- Acid treatment is expensive (acid + neutralisation) and corrosive.
- Steam explosion can be effective but requires high specification equipment
- Ammonia based methods look interesting but require good recovery
- Enzymes difficult to recover (for SSF)

Pre-treatment of biomass



Preserve value in fractions; enable access to process agents

- The ideal pre-treatment process should:
  - Remove structural and compositional impediments to cellulose/hemicellulose hydrolysis
  - Be flexible and adaptible
  - Preserve high value fractions
- Technical objectives to screen for
  - Increase accessible surface area
  - Improve digestibility/fermentation
  - Decrystalise cellulose
  - Remove (some) hemicellulose +lignin
  - Break linkages + alter lignin structure
  - Support carbon and energy parsimony (avoid shaftwork and over-reaction)
  - Minimise production of fermentation inhibitors

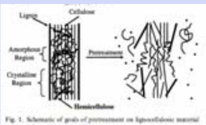
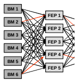
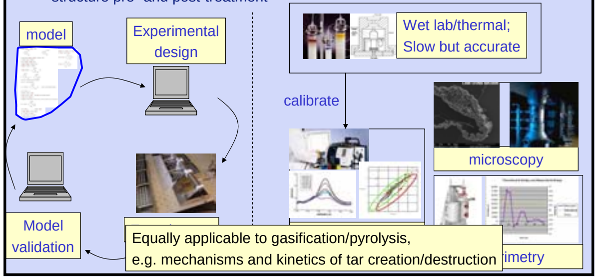


Fig. 1. Schematic of goals of pretreatment on lignocellulosic material (adapted from Hsu et al., 1980).

Rational approach to pre-treatment optimisation



- Devise conceptual and mathematical models
- Devise experiments for optimised information
- Adapt HTT methods to support understanding – composition and structure pre- and post-treatment



model

Experimental design

Wet lab/thermal;
Slow but accurate

calibrate

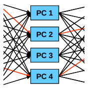
microscopy

Model validation

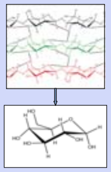
imetry

Equally applicable to gasification/pyrolysis,
e.g. mechanisms and kinetics of tar creation/destruction

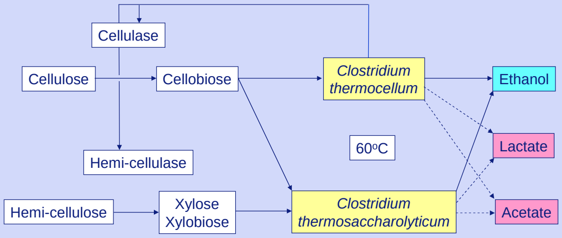
Biotech vision: an efficient consolidated bioprocess



- Improve lignocellulose degradation
  - Better understanding of cellulose/hemicellulose degradation
    - Structure and function of cellulases/cellulosome
    - Engineer for improved performance
  - Discover novel and evolve better cellulases/hemicellulases
- Integrated and consolidated bioprocess
  - Combine enzyme production and fermentation
    - Engineer cellulolytic microbe for fuel formation
    - Engineer fuel producer for cellulase production
- Link effectively with pre-treatment



Metabolic engineering for improved C5 and C6 sugar utilisation – an example



Cellulase

Cellulose

Cellobiose

Clostridium thermocellum

Ethanol

Hemi-cellulase

60^oC

Lactate

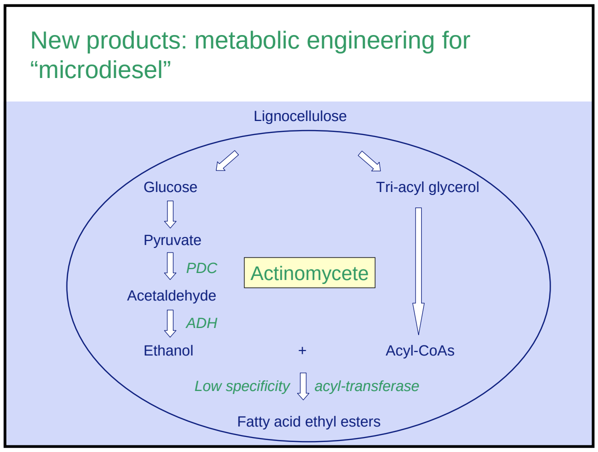
Hemi-cellulose

Xylose
Xylobiose

Clostridium thermosaccharolyticum

Acetate

Engineer a single organism that utilises both C5 and C6 sugars
Efficiently degrades lignocellulose
Produces no unwanted side-products (e.g. lactate and acetate)



New products: metabolic engineering for “microdiesel”

Lignocellulose

Glucose

Pyruvate

PDC

Acetaldehyde

ADH

Ethanol

Actinomycete

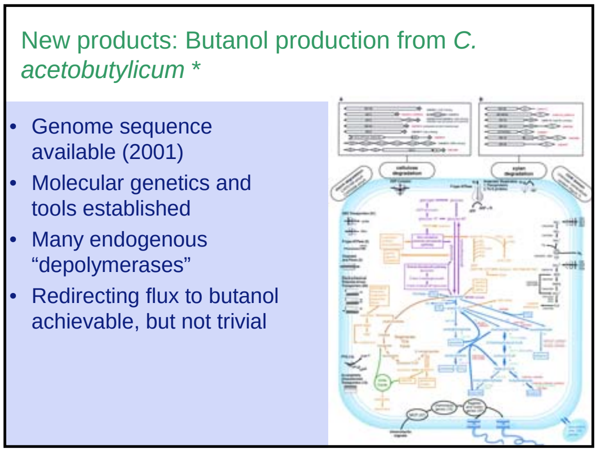
Tri-acyl glycerol

Acyl-CoAs

\+

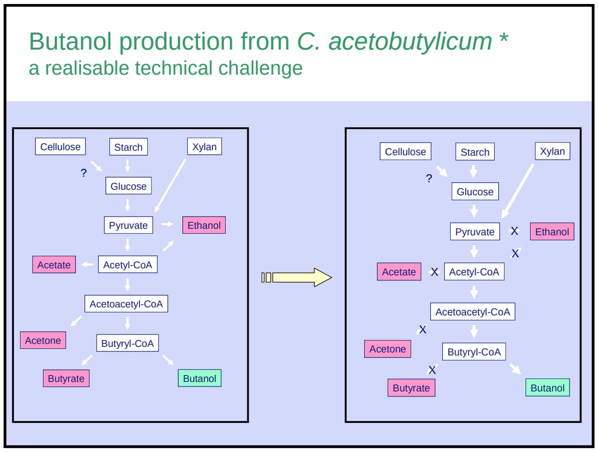
Low specificity *acyl-transferase*

Fatty acid ethyl esters



New products: Butanol production from *C. acetobutylicum* *

- Genome sequence available (2001)
- Molecular genetics and tools established
- Many endogenous “depolymerases”
- Redirecting flux to butanol achievable, but not trivial

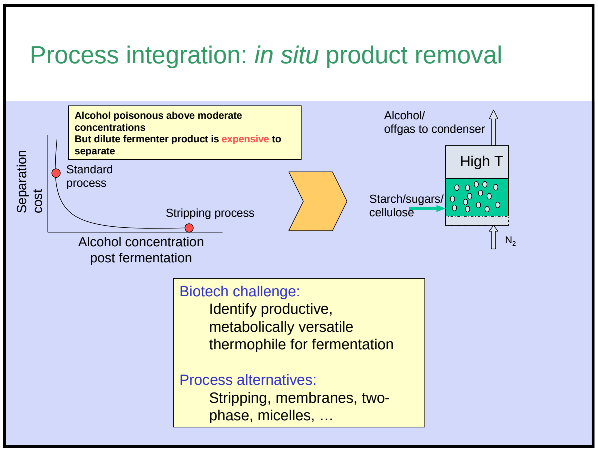


Butanol production from *C. acetobutylicum* *

a realisable technical challenge

Cellulose
Starch
Xylan
?
Glucose
Pyruvate
Ethanol
Acetate
Acetyl-CoA
Acetoacetyl-CoA
Acetone
Butyryl-CoA
Butyrate
Butanol

Cellulose
Starch
Xylan
?
Glucose
Pyruvate
X
Ethanol
X
Acetate
X
Acetyl-CoA
Acetoacetyl-CoA
X
Acetone
Butyryl-CoA
X
Butyrate
Butanol



Process integration: *in situ* product removal

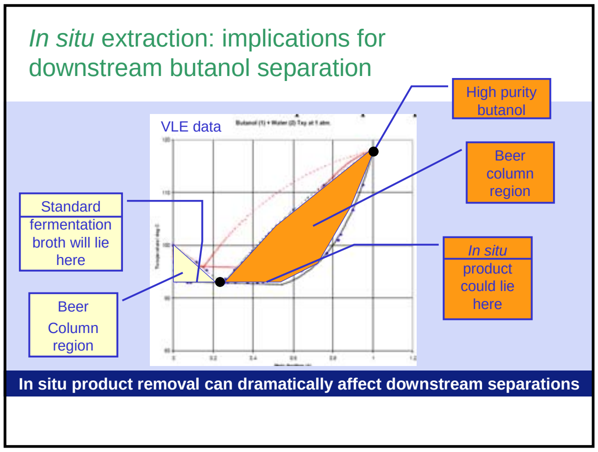
Alcohol poisonous above moderate concentrations
But dilute fermenter product is expensive to separate

Separation cost
Standard process
Stripping process
Alcohol concentration post fermentation

Alcohol/
offgas to condenser
High T
Starch/sugars/
cellulose
N_2

Biotech challenge:
Identify productive, metabolically versatile thermophile for fermentation

Process alternatives:
Stripping, membranes, two-phase, micelles, …



In situ extraction: implications for downstream butanol separation

VLE data

High purity butanol

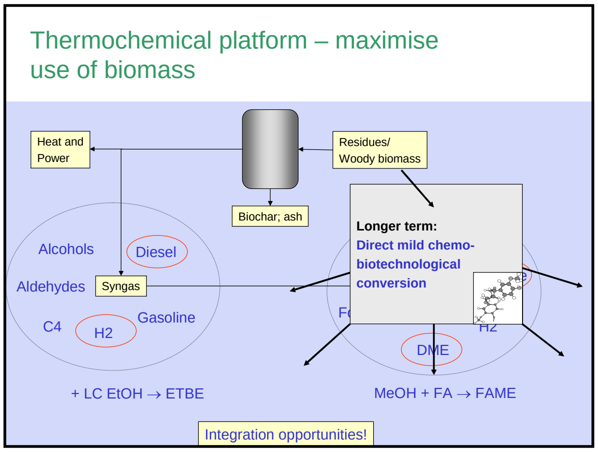
Beer column region

Standard fermentation broth will lie here

In situ product could lie here

Beer Column region

In situ product removal can dramatically affect downstream separations



Thermochemical platform – maximise use of biomass

Heat and Power

Residues/ Woody biomass

Biochar; ash

Alcohols
Diesel
Aldehydes
Syngas
Gasoline
C4
H2

Longer term:
Direct mild chemo-biotechnological conversion

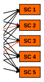
Fe
H2
DME

\+ LC EtOH → ETBE

MeOH + FA → FAME

Integration opportunities!

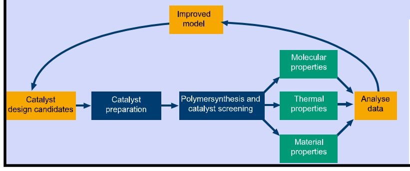
Co-product synthesis: capabilities and high throughput techniques



- Key principle is developing **competences**:
  - Small molecule chemistry
  - Carbohydrate chemistry
  - Lignin chemistry

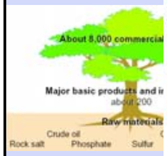
Flexible response to changing markets

- High throughput methodologies will be essential for a a flexible approach to co-products synthesis, e.g. catalysts screening:



Biocompatible catalysts

New Verbund concept



(BASF)

All Products - #7 of 21: Previous Next

View: All Products (21) | Pill Blends (3) | Pills (14) | Powders (1) | Creams, Salves and Gels (2)

BioBran - MGN-3 Arabinoxylan Compound (Natural GMO-Free) - 250 mg

Helps the Body Maintain a Strong Immune System!

50 tablets

- Naturally derived from rice bran.
- Rich in polysaccharides, proteoglycans such as arabinoxylan, and other hemicelluloses, this natural compound boosts the body's immune system.
- BioBran is suitable for vegetarians and contains no genetically modified Ingredients.

Enlarge Photo

Miraculous

"My mother was Diagnosed on April 13, 2001 with Large cell cancer on the right upper lung, close to the mediastinum, involving the posterior chest wall, 3cm in size. The prognosis was not good due to the fact that she was unable to have a lobectomy b..." -- Lynne

More Info below.

Our Price: $85.58 US

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Biomass

extract

↓

convert

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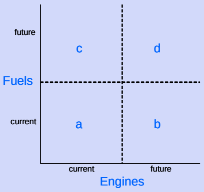
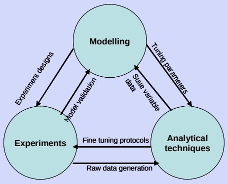
synthesise

Biofuels evaluation



What



How

- Performance: mixing, ignition delay, combustion
- Emissions: characterisation (composition, particle size), toxicology

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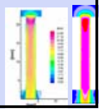
New opportunities for biofuels

- Practically important
  - processes (atomisation, evaporation, ignition, autoignition…)
  - problems (soot burn-out, NOx & noxious gas generation & emission…)
  - challenges (lean burn, stratified charge, drive-by-wire, closed-loop control strategies, high pressure versatile injectors)

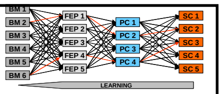
posed by fuels in ICEs becoming amenable to fundamental experimental and computational analysis.

- *Much* less guesswork about the science of fuels
- New engine designs:
  - GDI engines
  - hybrid and downsized powertrains
  - the “more premixed diesel”
  - HCCI : Can we ‘design’ a fuel/fuel additive/blend for HCCI engines?

Can we optimise an aviation biofuel?



Summary



- Challenges: preserve energy and carbon in biomass
  - Robust, inexpensive processes
  - Producing tightly specified, forward-looking products
  - Hybrid processes combining best of breed “process agents” (heat, organisms, enzymes, catalysts, solvents, ….)
  - Integrated approach to physical, chemical, biological and engineering challenges
- New type of interdisciplinary research programme
  - Science (chemical/bio/phys), Engineering (chemical/thermal/mech), Systems (techno-economic, supply chains, sustainability)

Desired outcomes: robust and repeatable processes and thriving biorefining industry