Workshop on Sustainable Biorefineries

Theme 1: Biorefinery innovations and integrated configurations
Biorefinery ideas and concepts
Advanced biorefinery configurations (multiple feedstocks, products, and platforms)

Theme 2: Hands-on problem solving: Sustainable biorefinery value chain creation
Unlocking the value of urban waste by the recovery of functional products for circular economy
Economic value and life cycle assessments for optimal and sustainable biorefinery systems

Theme 3: Resource and energy efficient multi-platform biorefinery systems

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Workshop on Sustainable Biorefineries

Lecture 1: Biorefinery ideas and concepts

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Objectives

- Reduce fossil fuel consumption
- Meet energy and fuel demands using locally available biomass
- Create a dynamic and competitive chemical sector globally
- Explore process integration tools for biorefinery design
- Carry out techno-economic analysis and Life Cycle Assessment (LCA) for feasible design

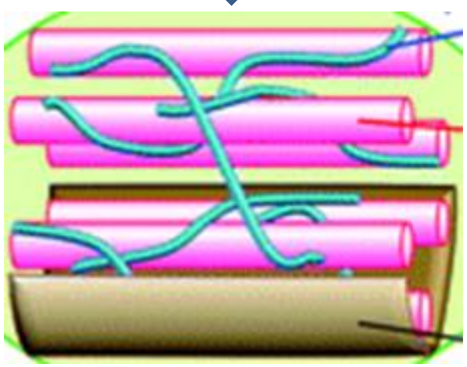
Biomass

- Wood waste, saw mill dust, sago bark and sago fibre (Malaysia) and sugarcane and blue agave bagasse (Mexico)
- Grass silage, empty fruit bunch
- Oily wastes and residues
- Aquatic: algae and seaweed
- Organic residues: municipal waste, manure and sewage
- Wastewaters
- Energy crops: switchgrass and miscanthus

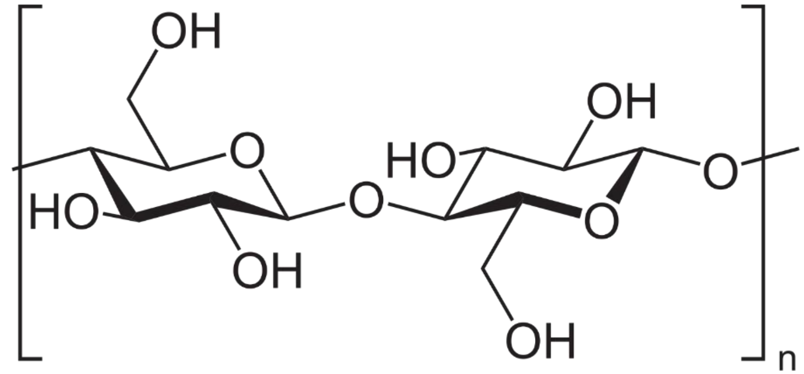
Biorefineries and Chemical Processes: Design, Integration and Sustainability Analysis, First Edition.
Jhuma Sadhukhan, Kok Siew Ng and Elias Martinez Hernandez.

Companion Website: http://www.wiley.com/go/sadhukhan/biorefineries

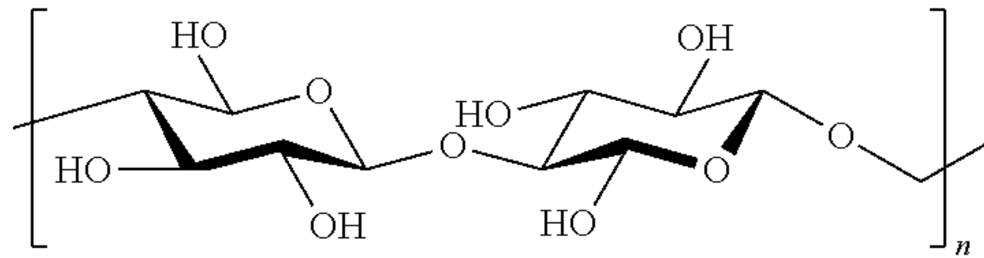
Lignocellulose Structure



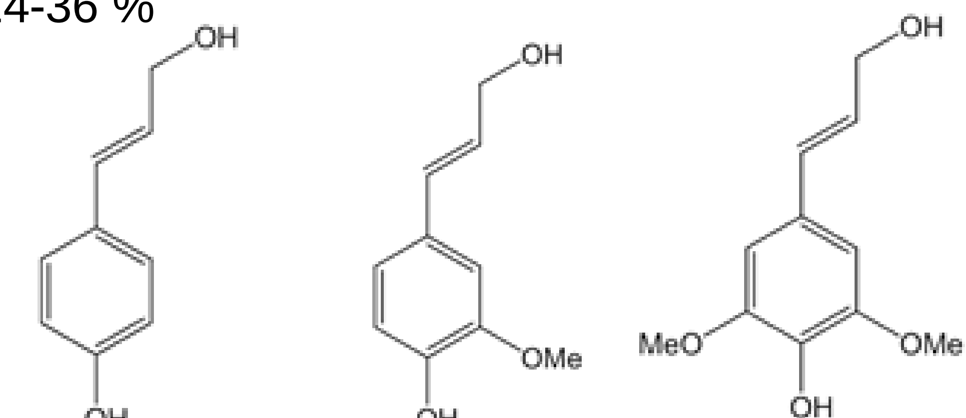
Cellulose 38-54 %



Hemicellulose 24-36 %



Lignin 15-25 %



P-coumaryl alcohol   Coniferyl alcohol   Sinapyl alcohol

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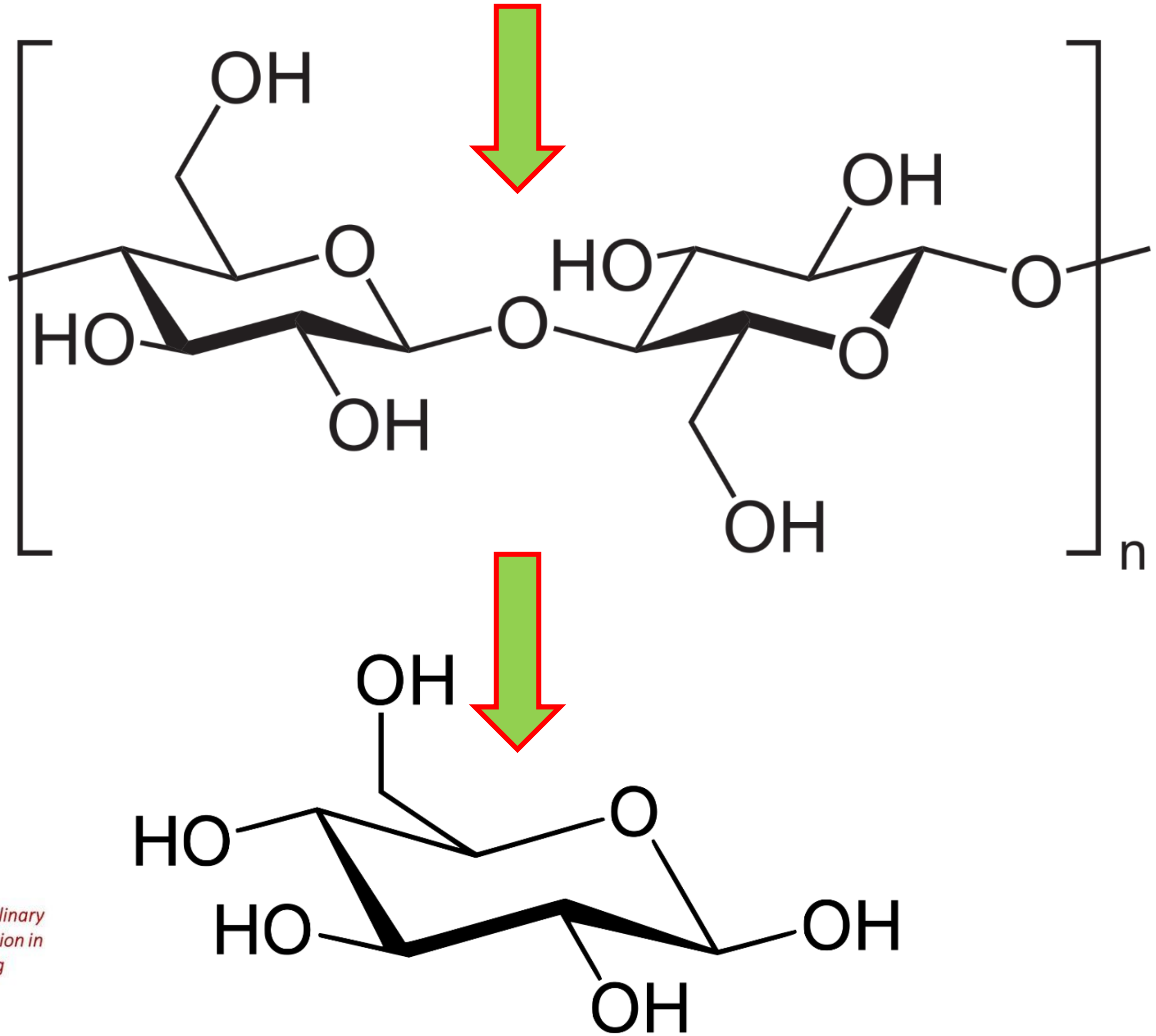
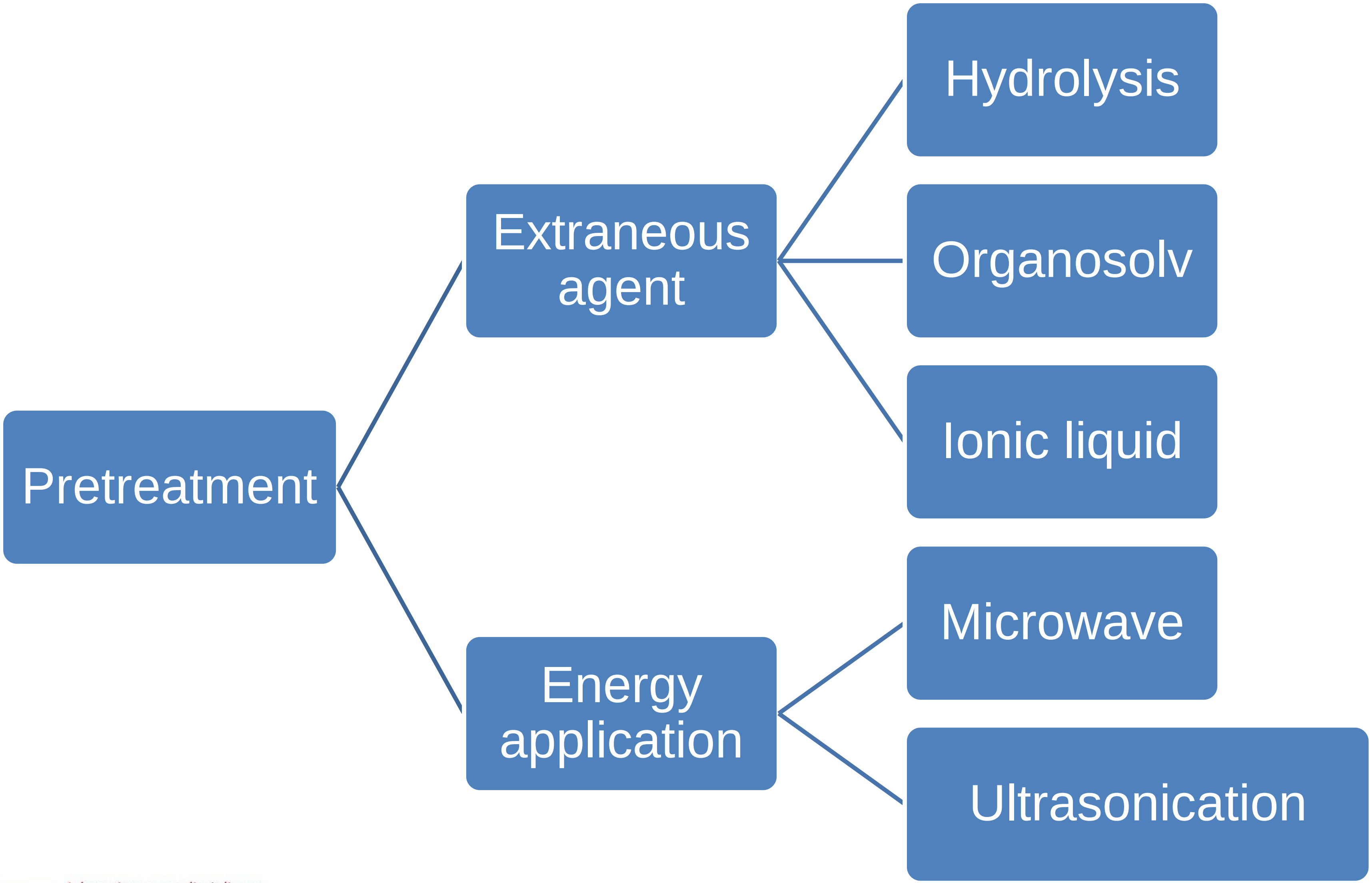
Cellulose Decomposition into Glucose

β-(1–4)-glycosidic bond



Lignocellulose Pretreatment



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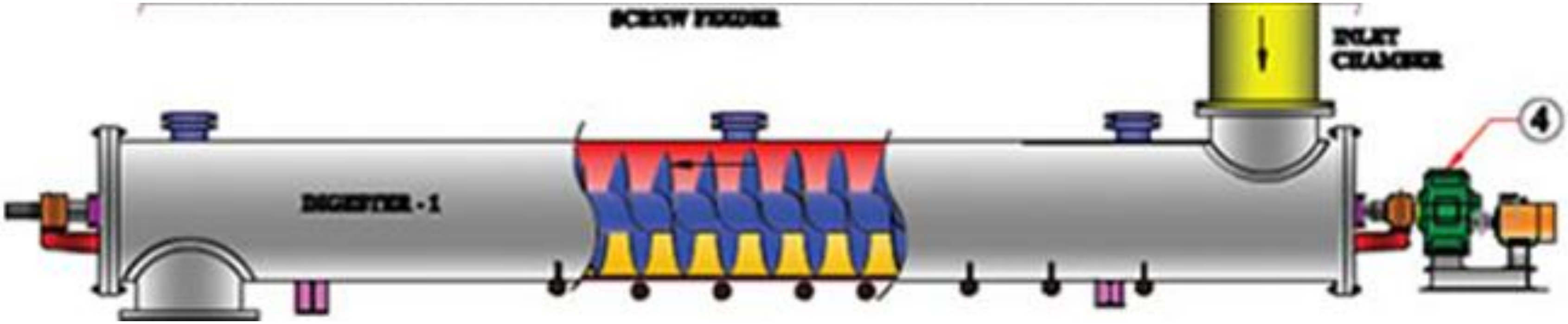
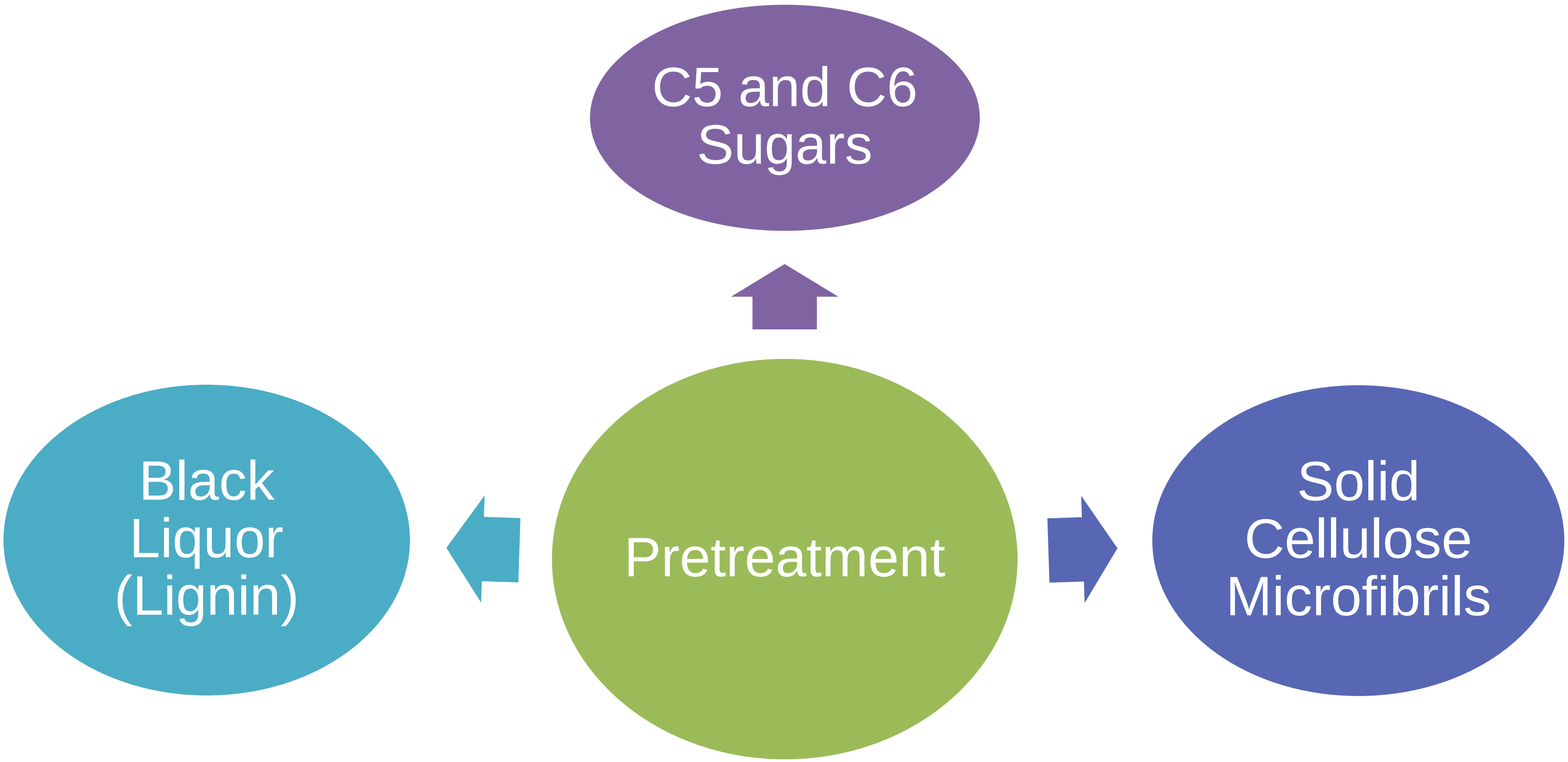
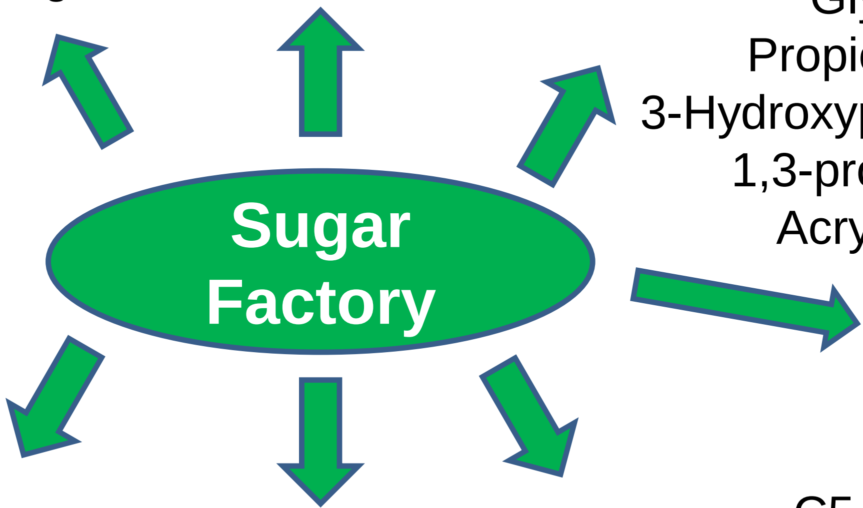
Mechanical, Steam and Chemical Pulping



Biorefinery Platforms



Biorefinery Products: Sugar Factory



C1
Syngas
Biogas

C2
Ethanol

C3
Acetic acid
Lactic acid
Glycerol
Propionic acid
3-Hydroxypropionic acid
1,3-propanediol
Acrylic acid

C4
3-Hydroxybutryolactone
Malic acid
Theonine
Succinic acid
Aspartic acid
Fumaric acid

C5
Arabinoxylan
Furfural
Levulinic acid
5-Hydroxymethylfurfural
Xylitol
Xylonic acid

C6
Glucaric
Gluconic acid
Butanol
1,4-butanediol
Sorbitol
Adipic acid
Citric acid
Caproate

>C6
Caprylate
Polyhydroxyalkanoates (PHA)

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Biorefinery Products: Lignin Factory

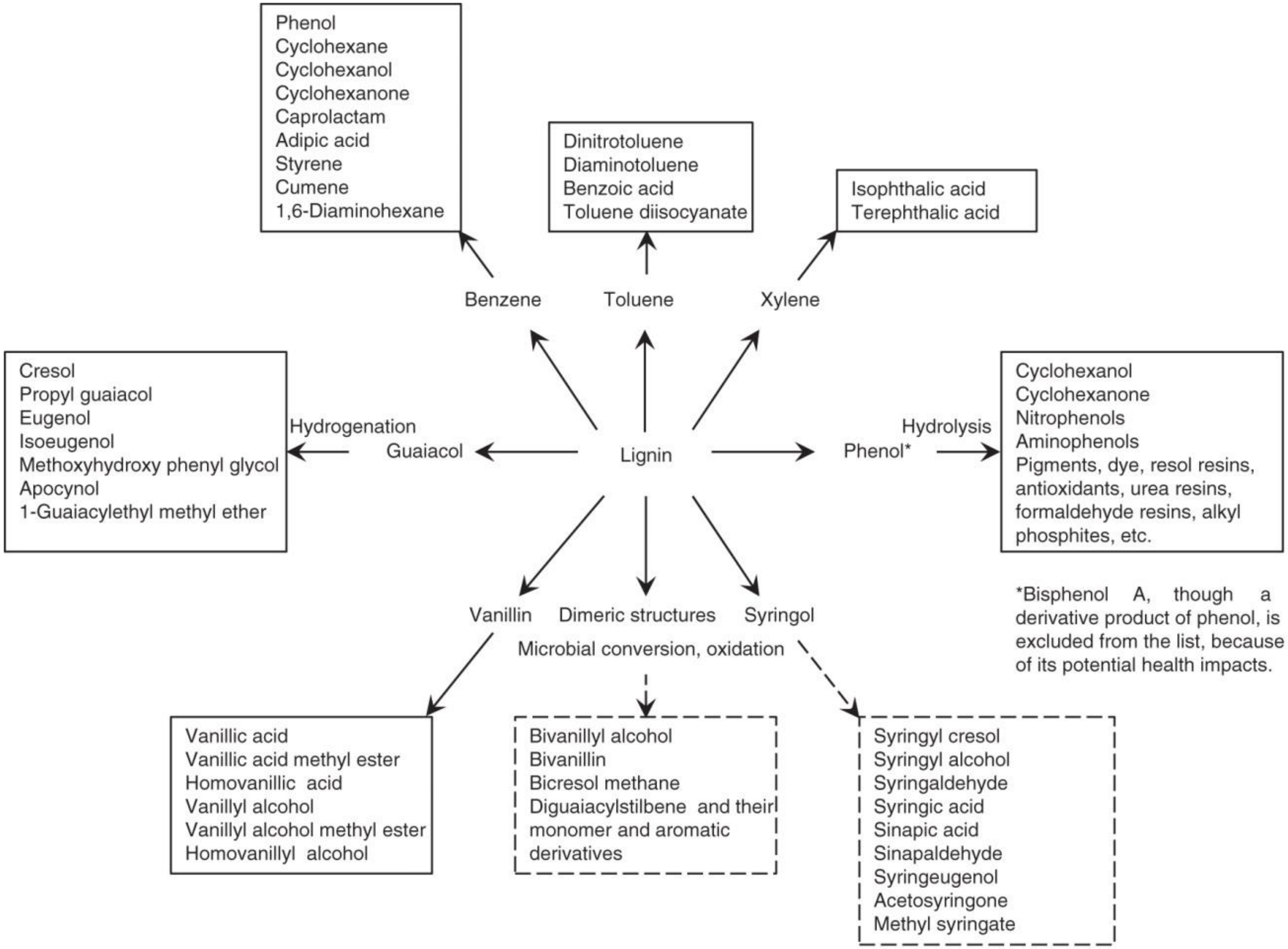

Figure 1.8 *Chemicals from lignin. The chemistries and markets are yet to be fully known for the blocks and arrows shown in dotted lines.*

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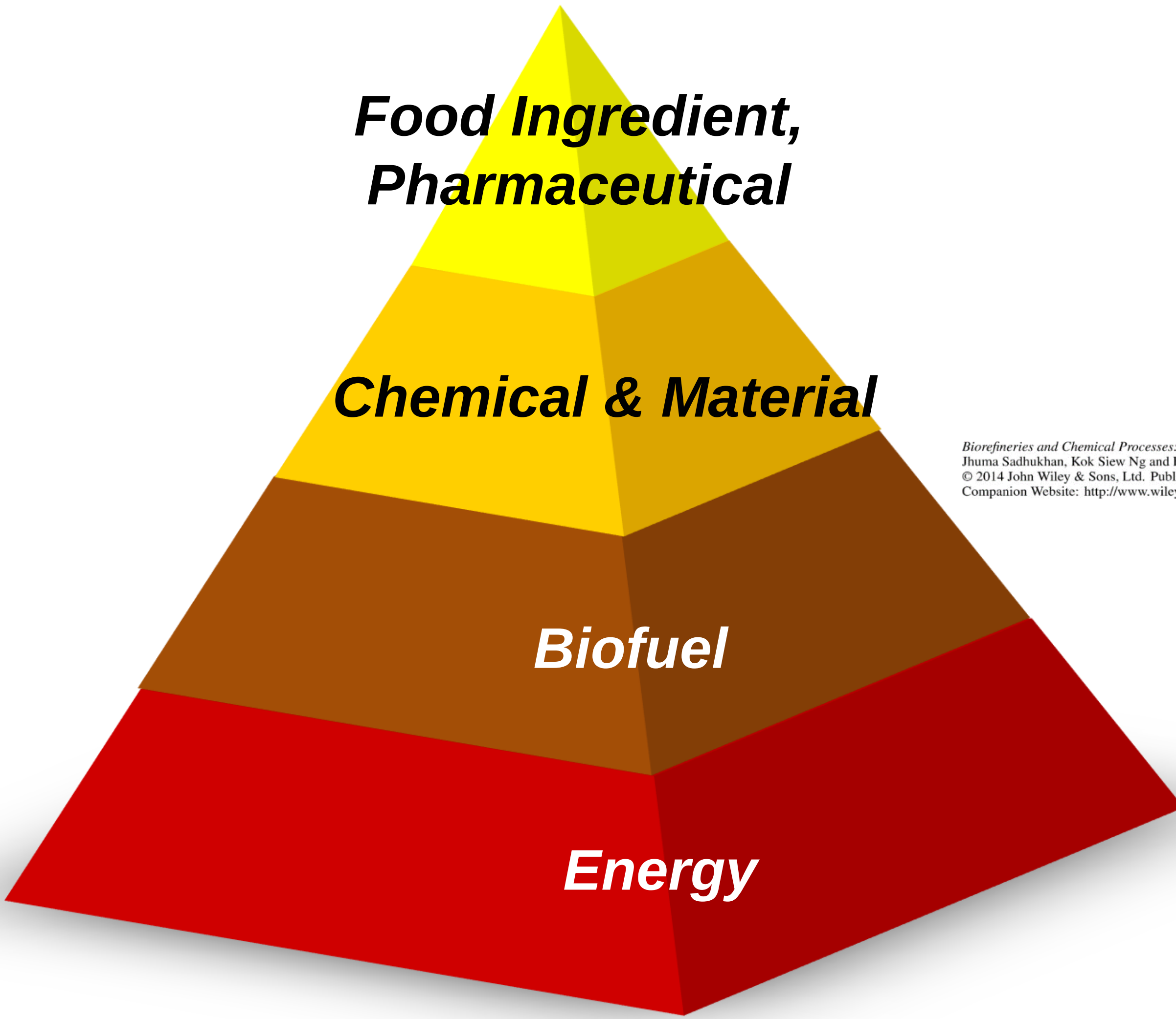
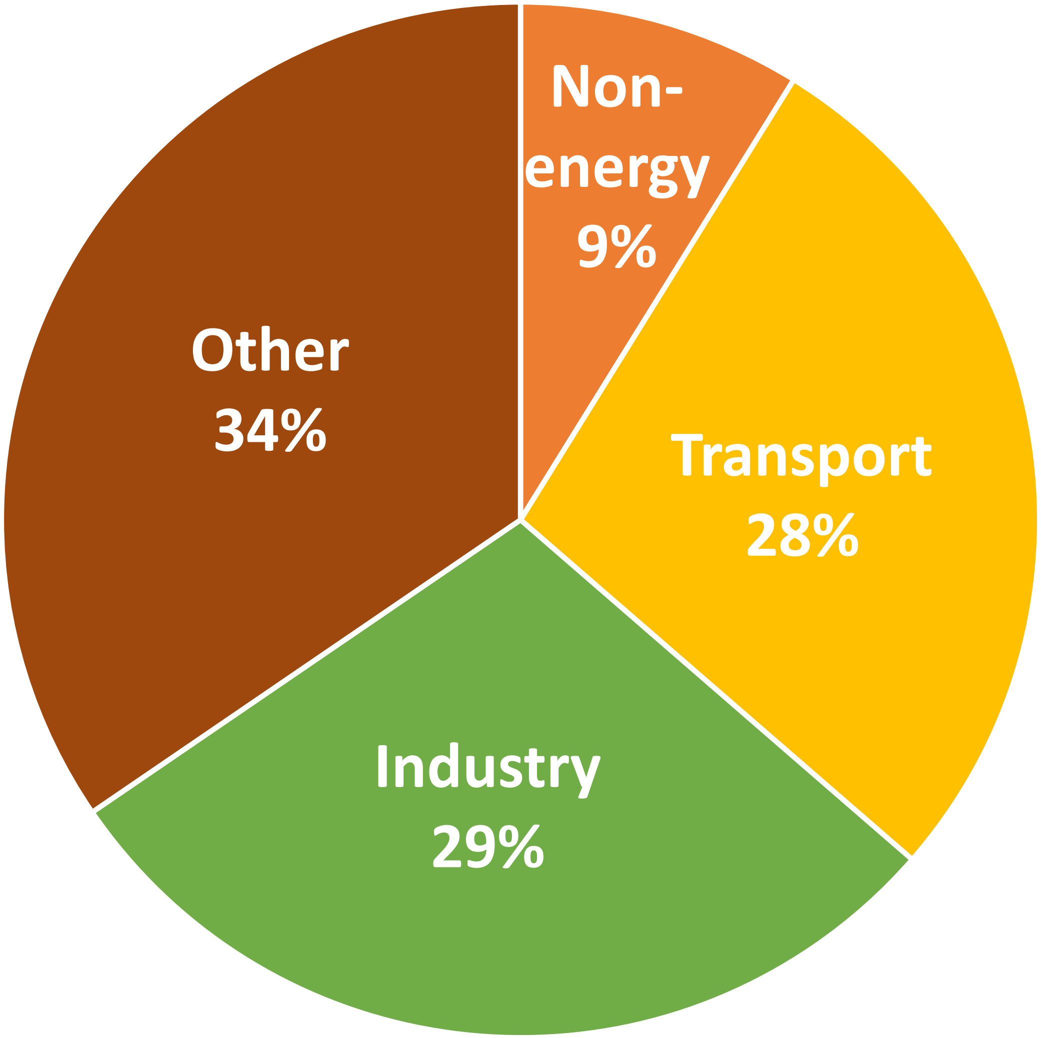
Biorefinery End Product Value & Volume

High Value Low Volume Product: Hard to find market



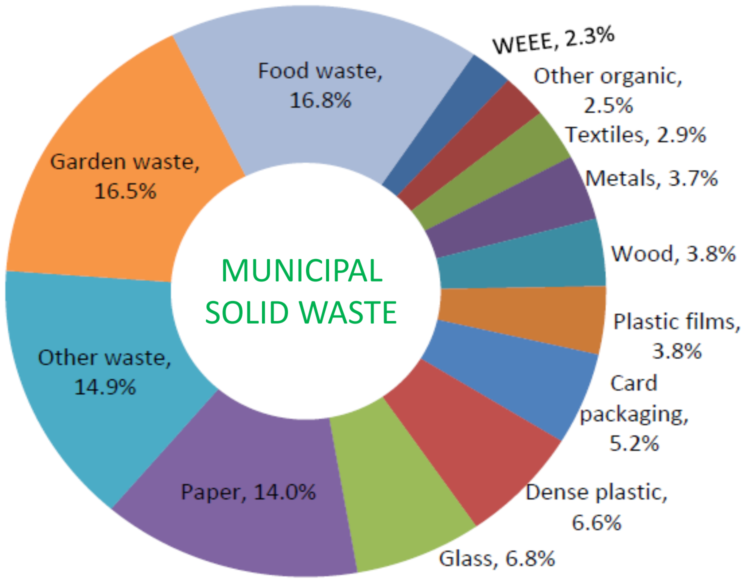
High Volume Low Value Product: Easy to find market

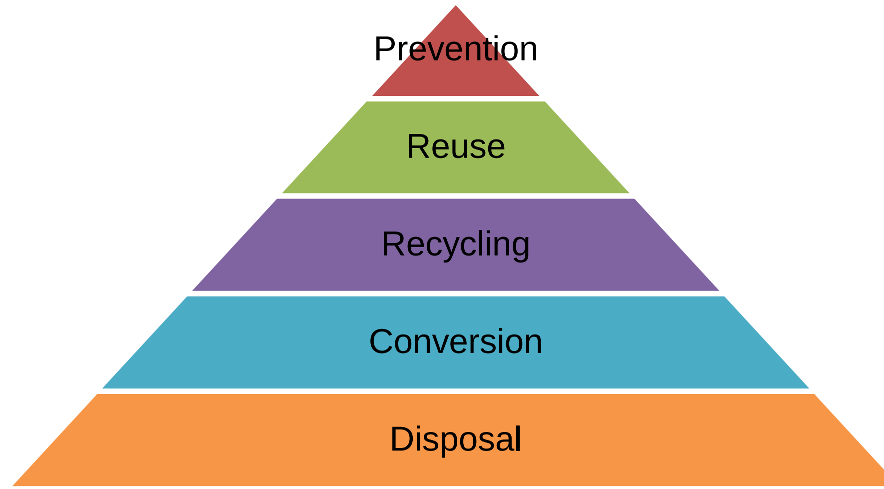
Total Mtoe Consumption

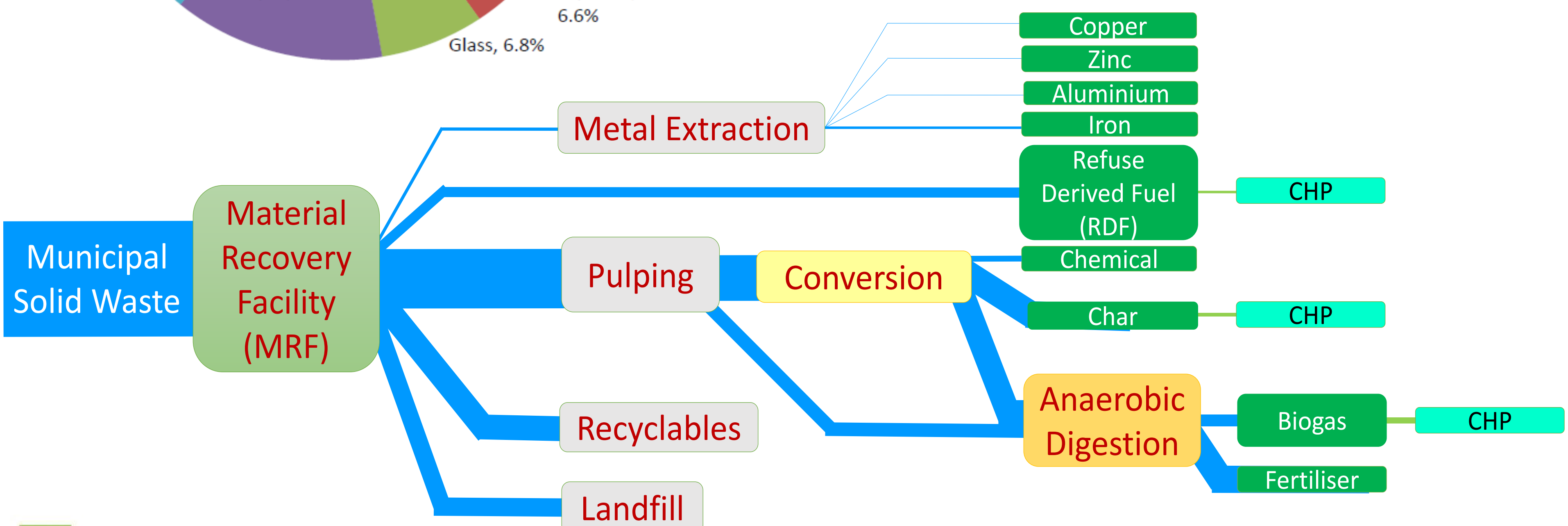


http://www.iea.org/sankey/ (9302 Mtoe in 2013)

Mass Transfer From Waste To Products







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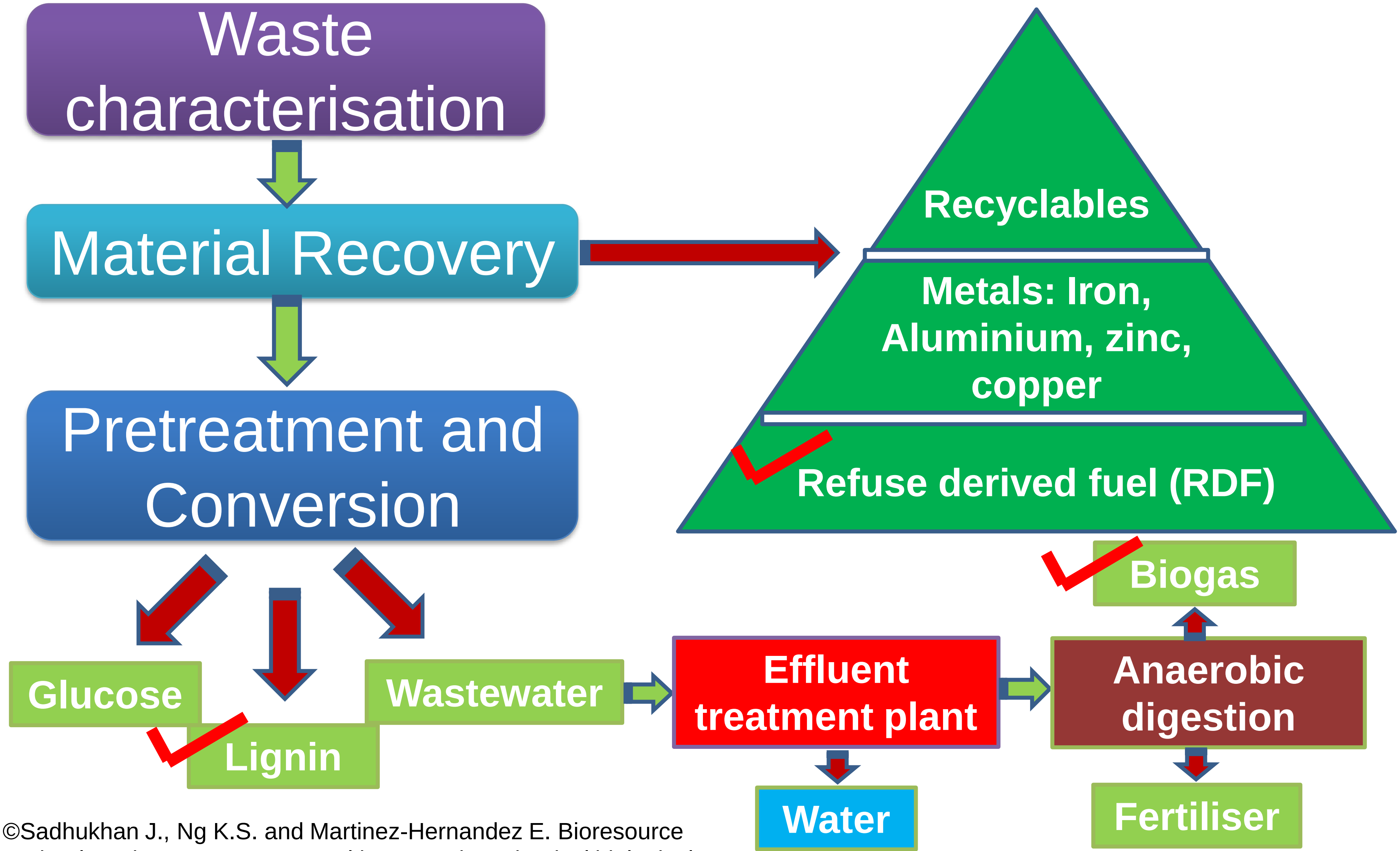
Sequence of Waste Valorisation



©Sadhukhan J., Ng K.S. and Martinez-Hernandez E. Bioresource Technology, in press. 2016. Novel integrated mechanical biological chemical treatment (MBCT) systems for the production of levulinic acid from fraction of municipal solid waste: A comprehensive techno-economic analysis. http://dx.doi.org/10.1016/j.biortech.2016.04.030

Technology Readiness Level

Mature	Developed	Developing
• Bioenergy • Fermentation- Bioethanol • Transesterification- Biodiesel • Anaerobic digestion- Biogas	• Pyrolysis- Bio-oil • Gasification- Syngas • Hydrothermal liquefaction- Fuel • Algae- Biofuel	• Catalytic (hydro)processing- Chemical and Fuel • CO_2 reduction or reuse- Fuel and Chemical • Resource recovery from waste- Functional products

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Biomass Chemical Nature

We are able to evaluate a whole biorefinery value chain from biomass characteristics

Characteristic	Physical	Thermochemical	Biochemical	Chemical
Chemical composition		×	×	×
Proximate and ultimate analyses		×		
Moisture content	×	×	×	×
Ash content	×	×	×	
Energy content	×	×		×
Density	×			
Particle size/size distribution	×	×	×	×
Digestibility/biodegradability			×	
Nutrient type and content			×	

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Summary

- Types and characteristics of biomass
- Biomass constituents and pretreatment
- Biorefinery platforms and products
- Waste valorisation and mass transfer into products
- Technology readiness levels
- Process design philosophy

Workshop on Sustainable Biorefineries

Lecture 2: Advanced biorefinery configurations (multiple feedstocks, products, and platforms)

Dr Elias Martinez Hernandez
Dr Jhuma Sadhukhan
Dr Kok Siew Ng

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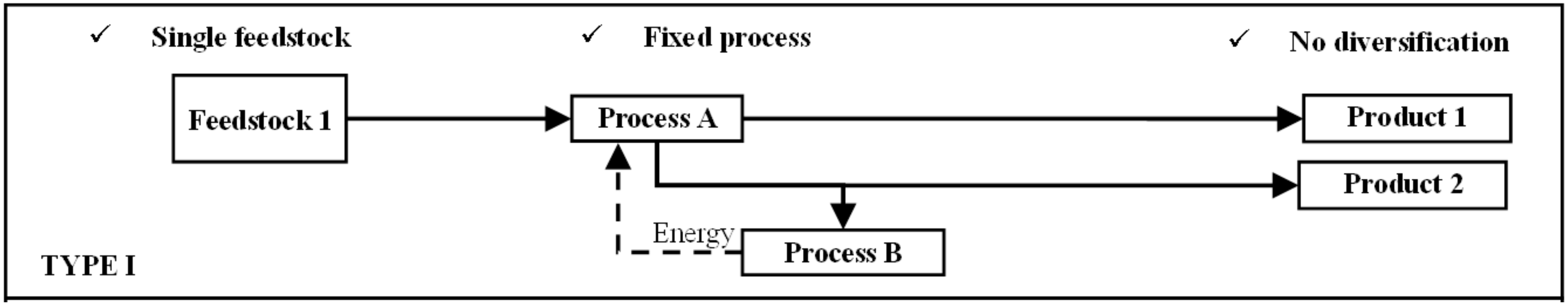
Objectives

- To comprehend how advanced and highly integrated biorefinery configurations can be generated by combining processes in a synergistic manner

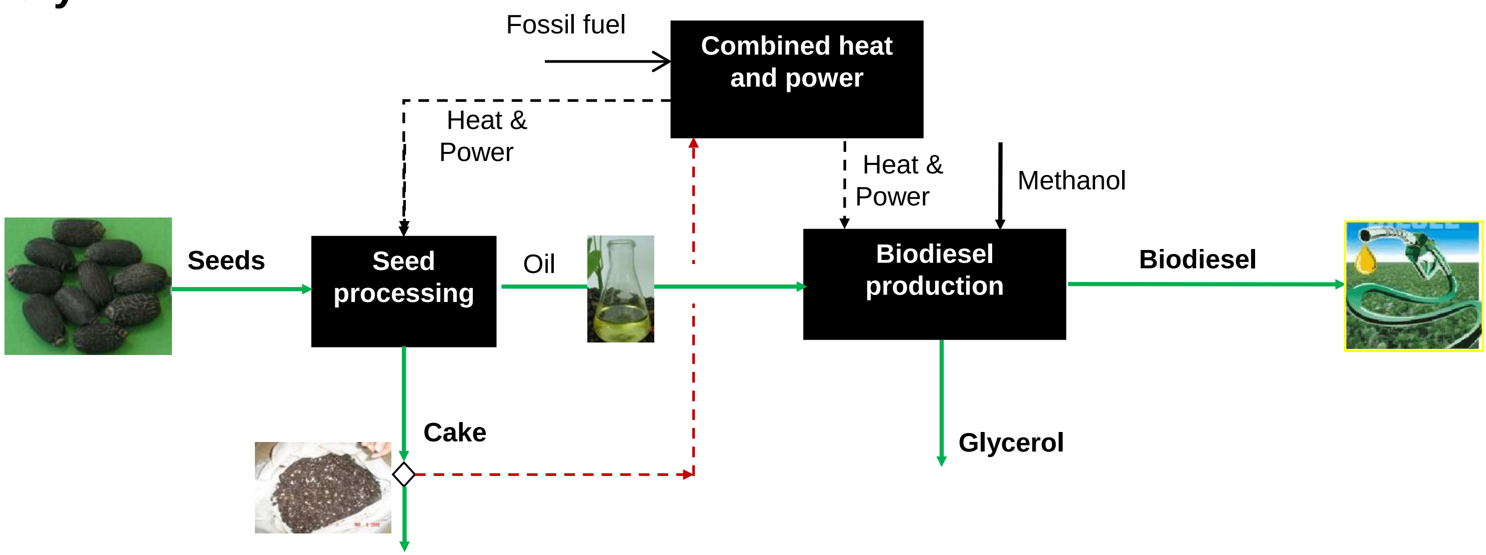
- To study advanced biorefinery configurations to unlock the value of urban waste by the recovery of functional products

- To encourage integrative thinking when developing innovative biorefinery schematics

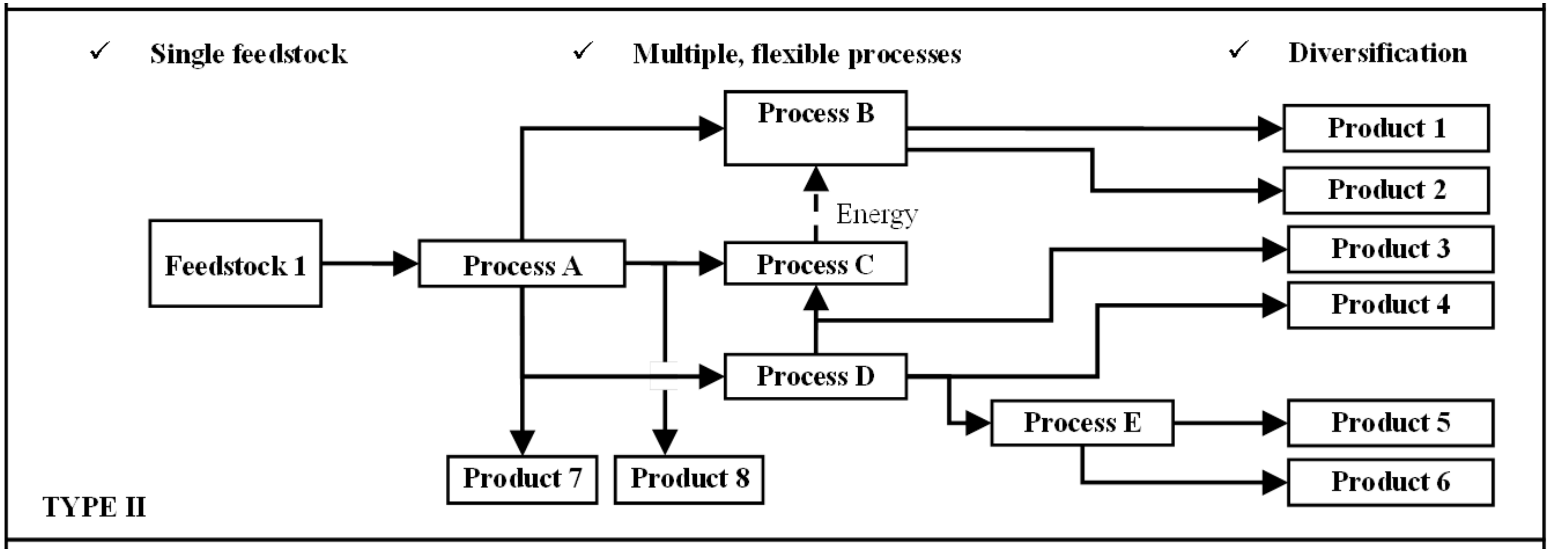
Biorefinery Configurations (1)



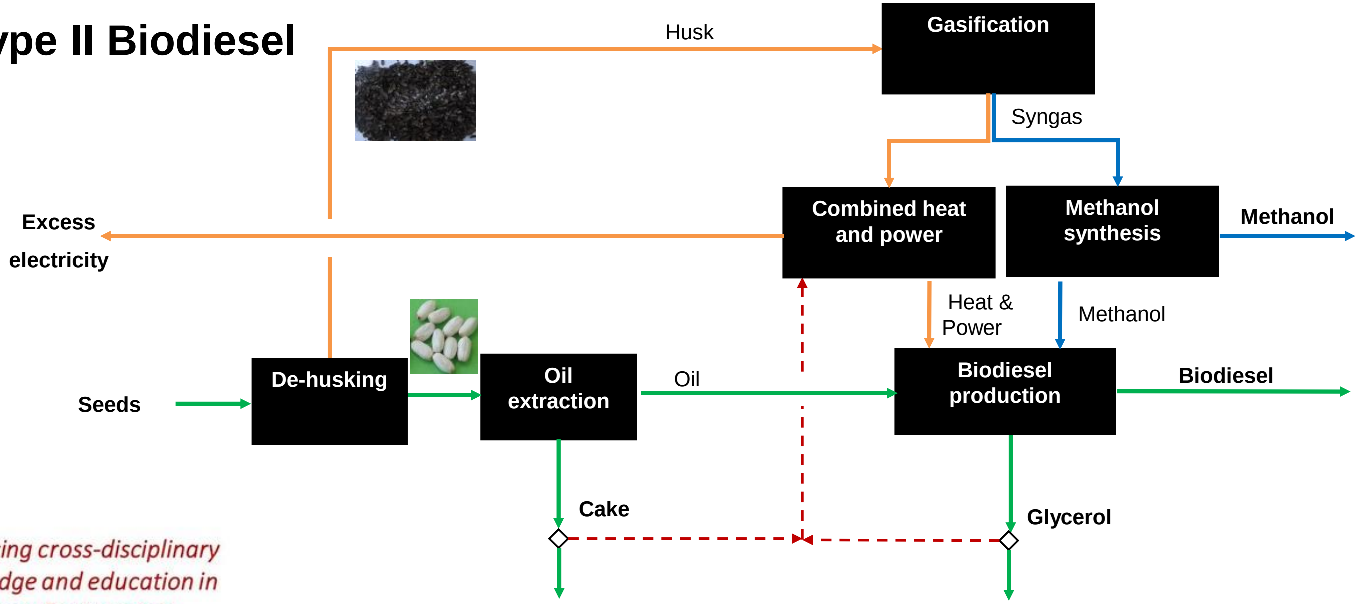
Example Type I biodiesel biorefinery



Biorefinery Configurations (2)



Example: Type II Biodiesel biorefinery



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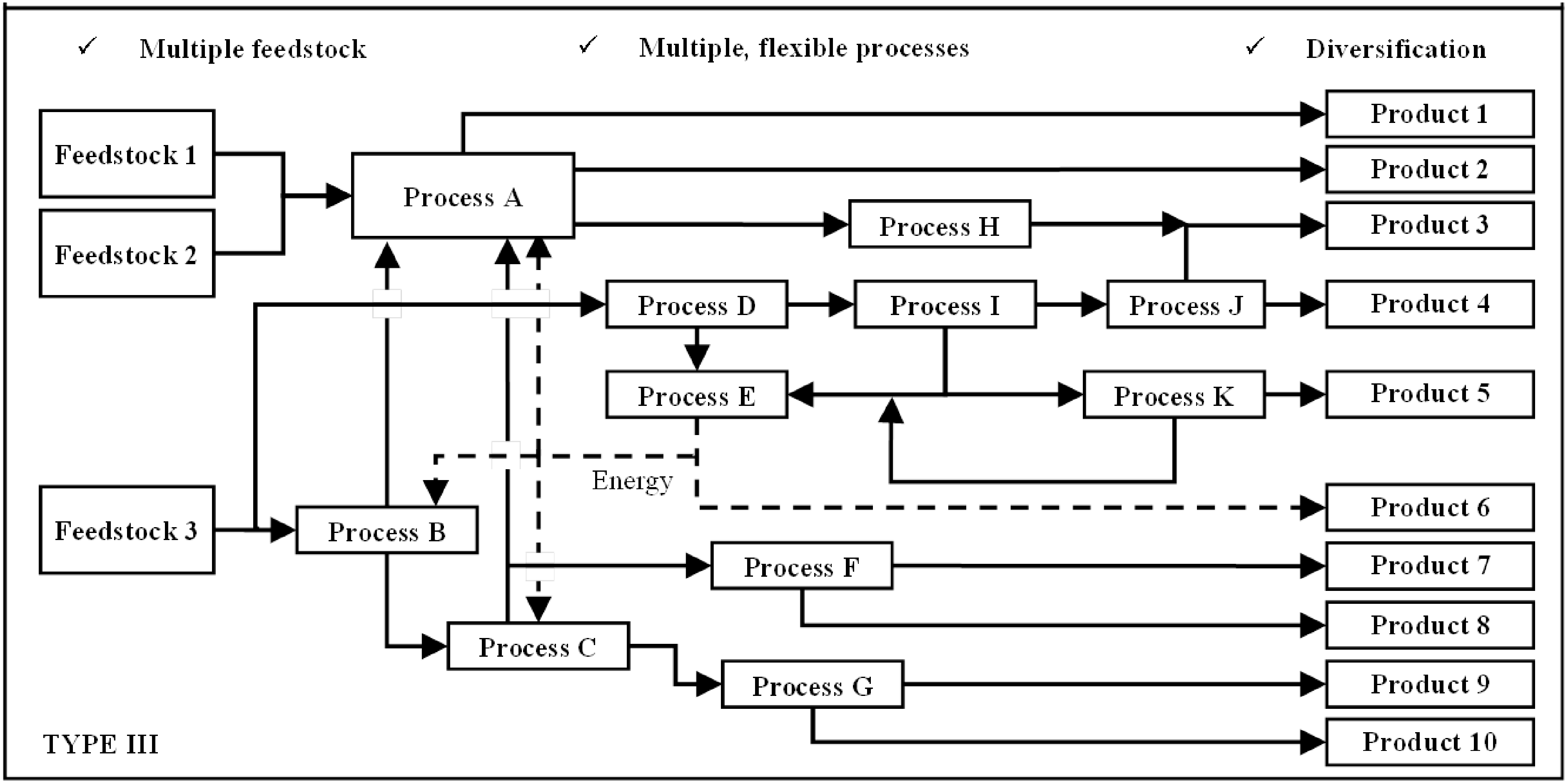
Biorefinery Configurations (3)



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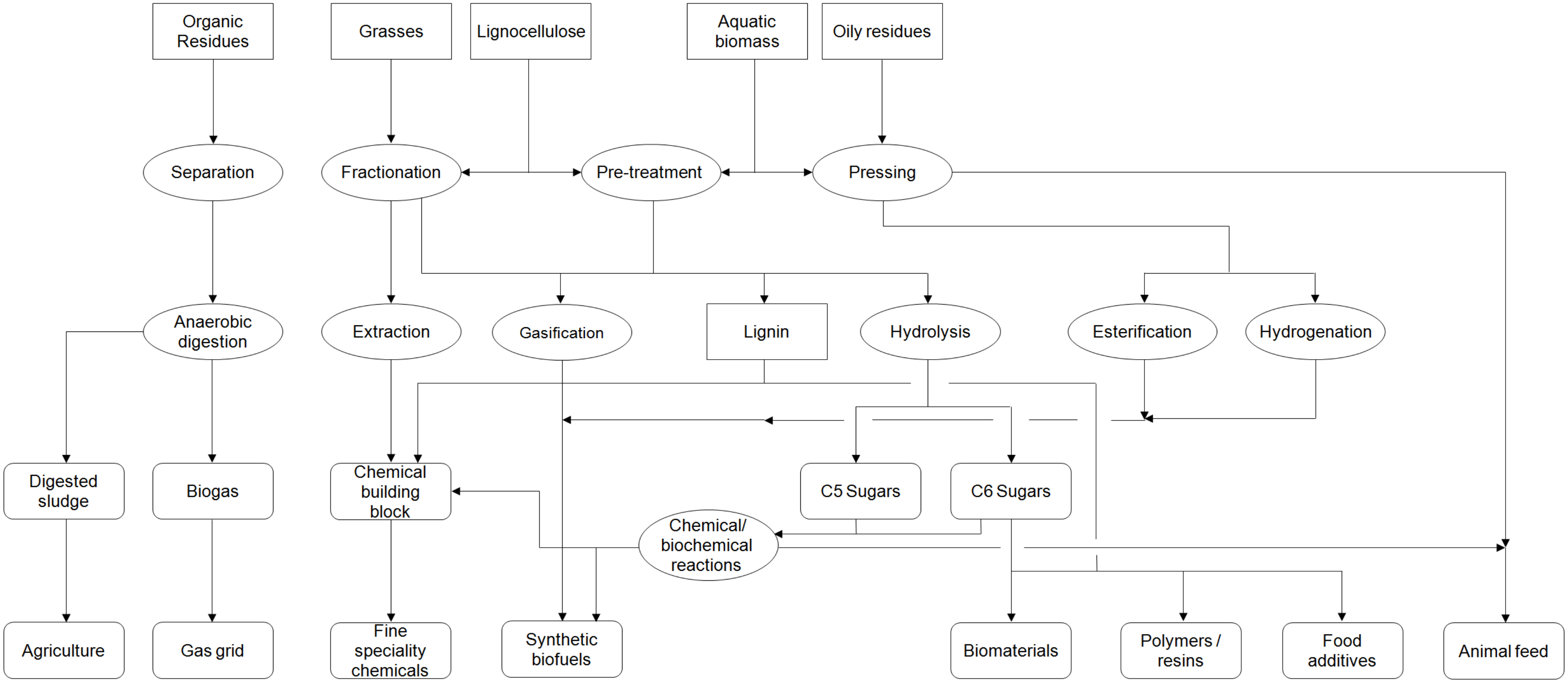
Advanced Biorefinery Configurations

Network of interlinked biorefinery configurations



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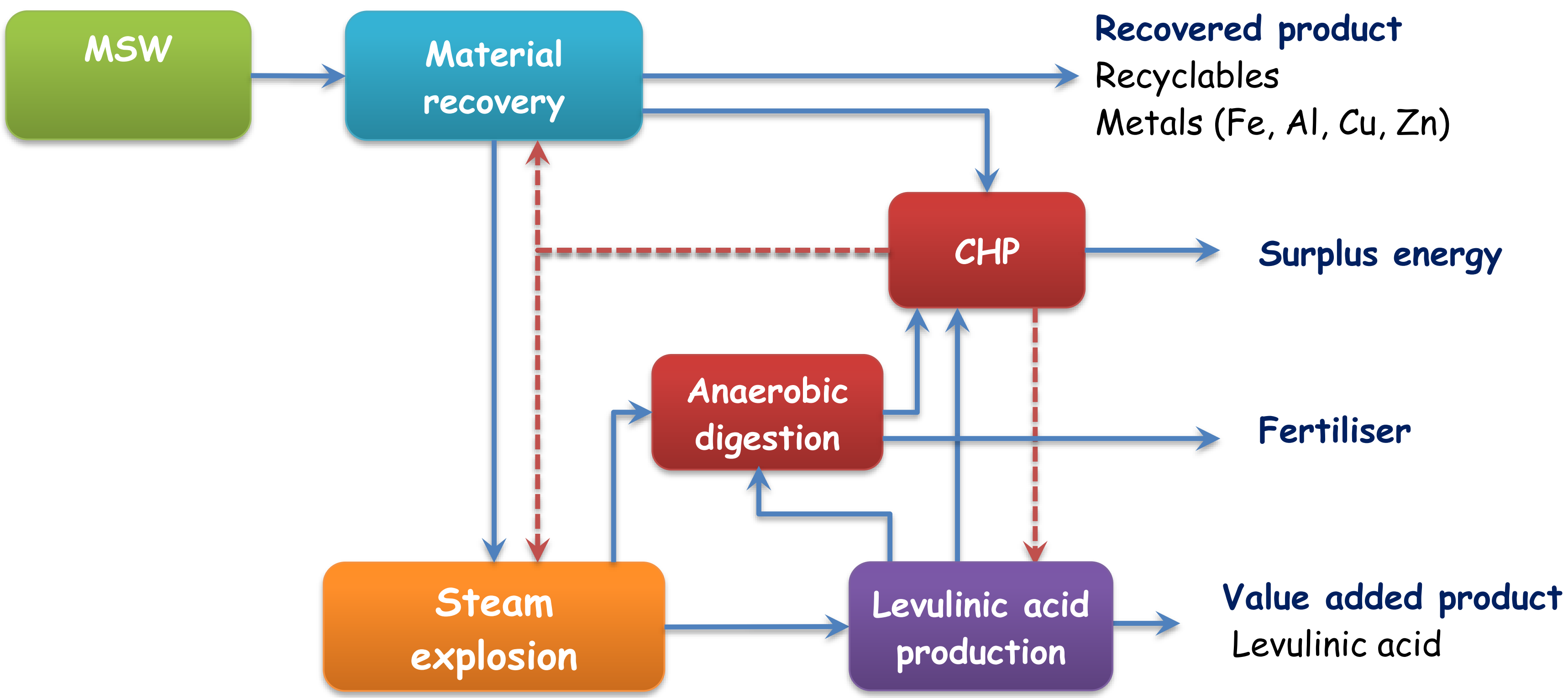
Unlocking the Value of Urban Waste by the Recovery of Functional Products for Circular Economy



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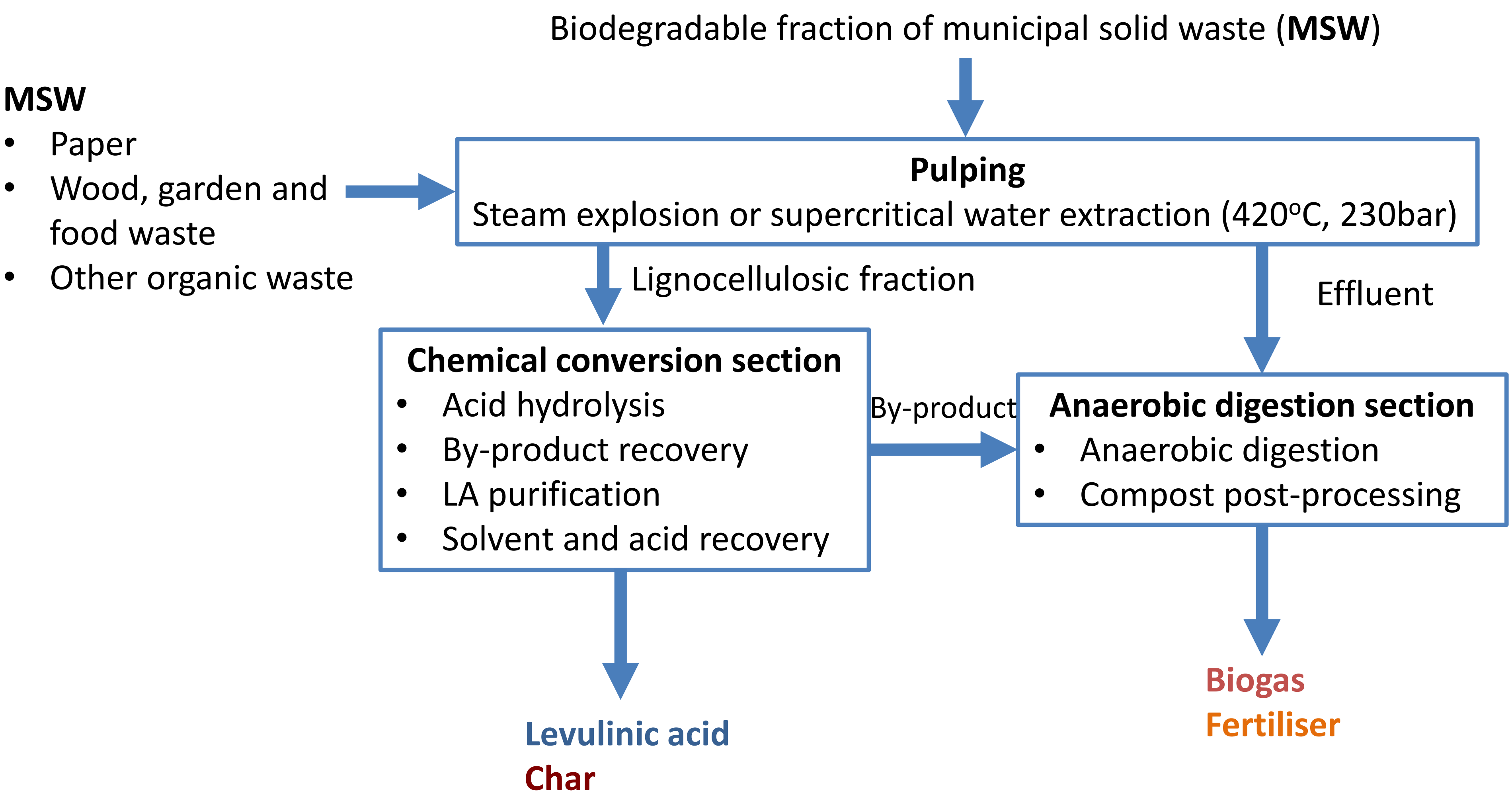
Unlocking the Value of Organic Waste by the Recovery of Functional Products for Circular Economy



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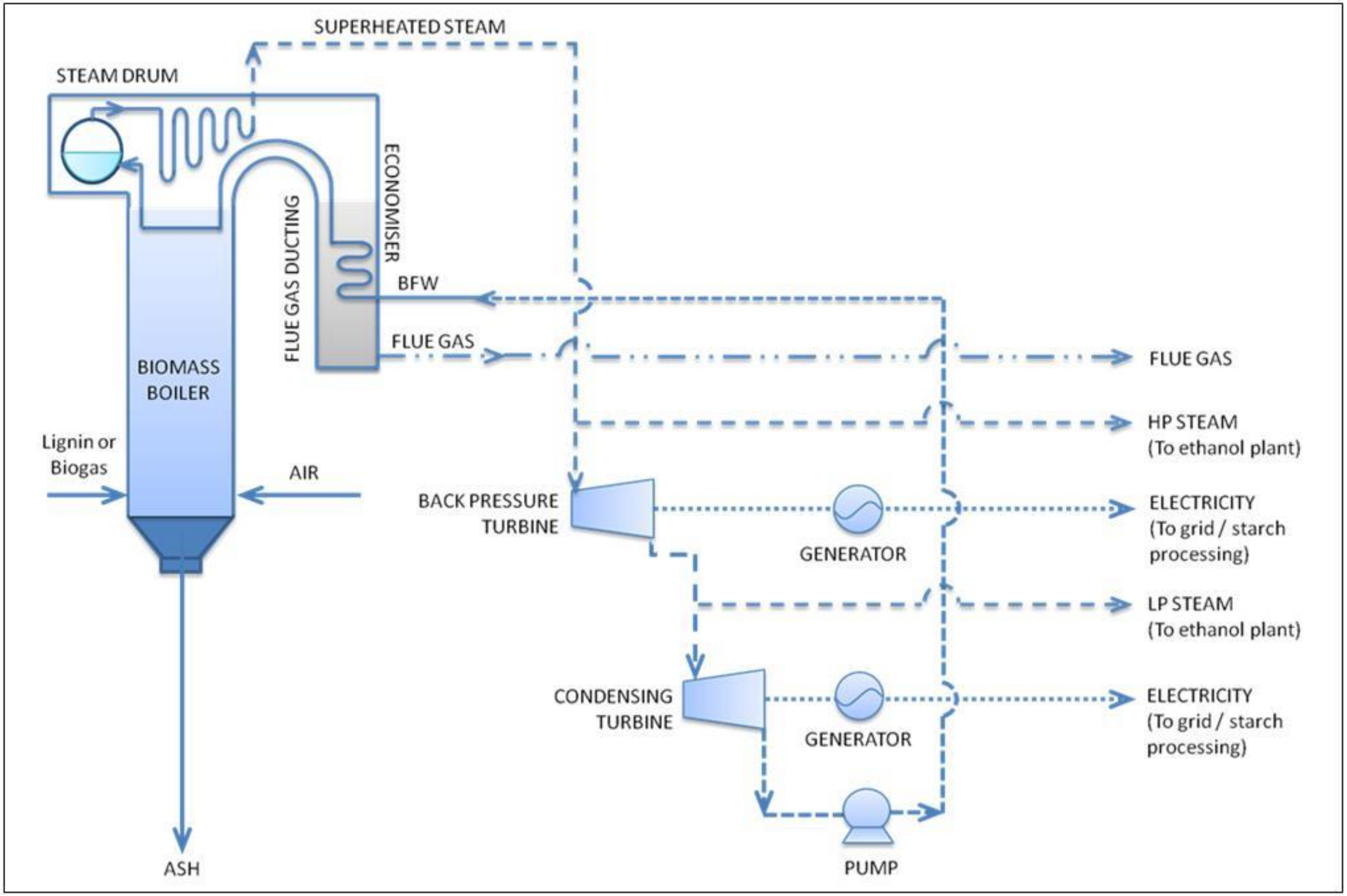
Combined Heat and Power (CHP) System



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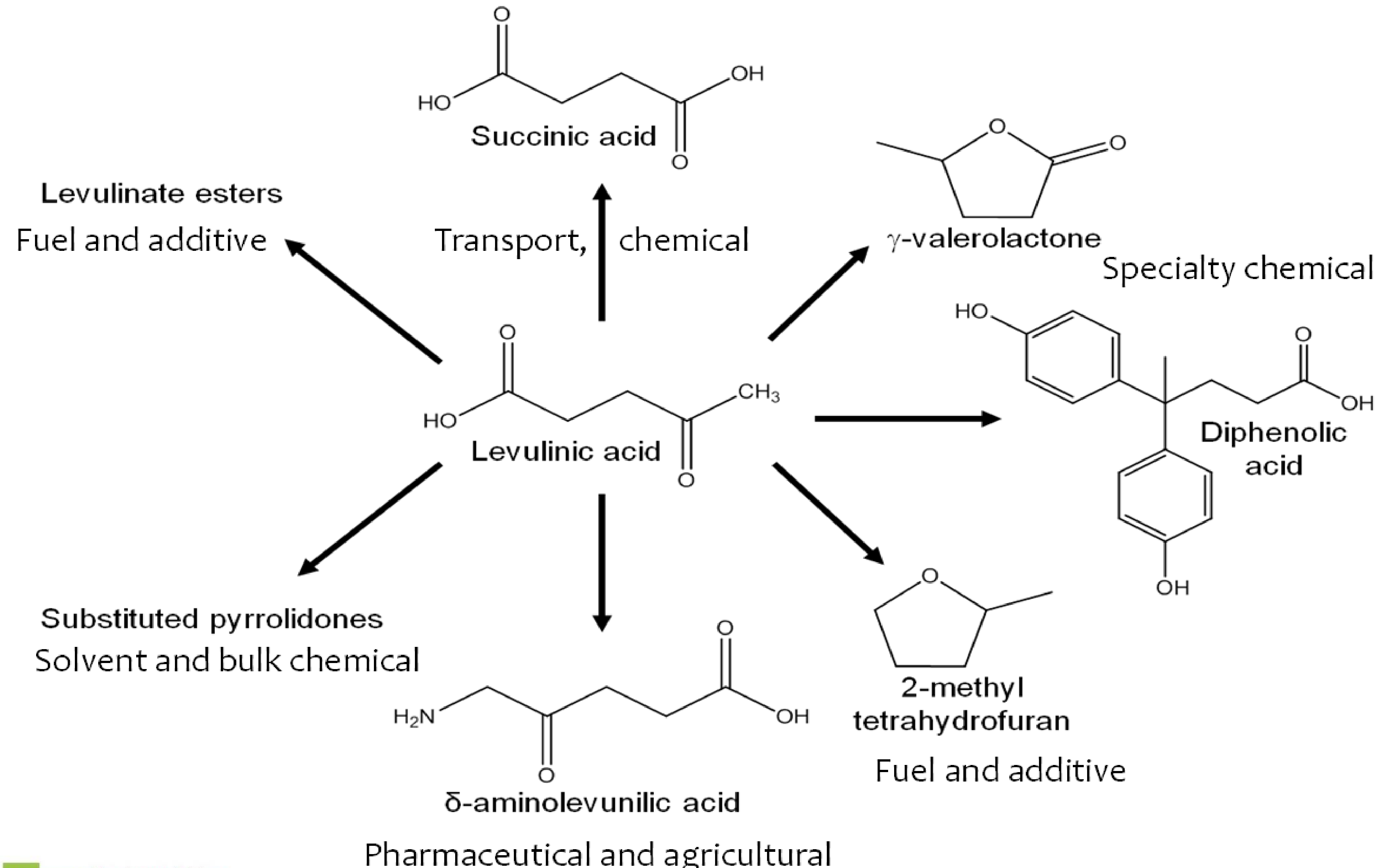
©Wan, Y.K., Sadhukhan, J., and Ng, D.K.S. (2016) **Techno-economic evaluations for feasibility of sago biorefineries, Part 2: Integrated bioethanol production and energy systems**. *Chemical Engineering Research & Design*, Special Issue on Biorefinery Value Chain Creation, 107, 102-116.

Levulinic Acid: An Important Building Block Chemical



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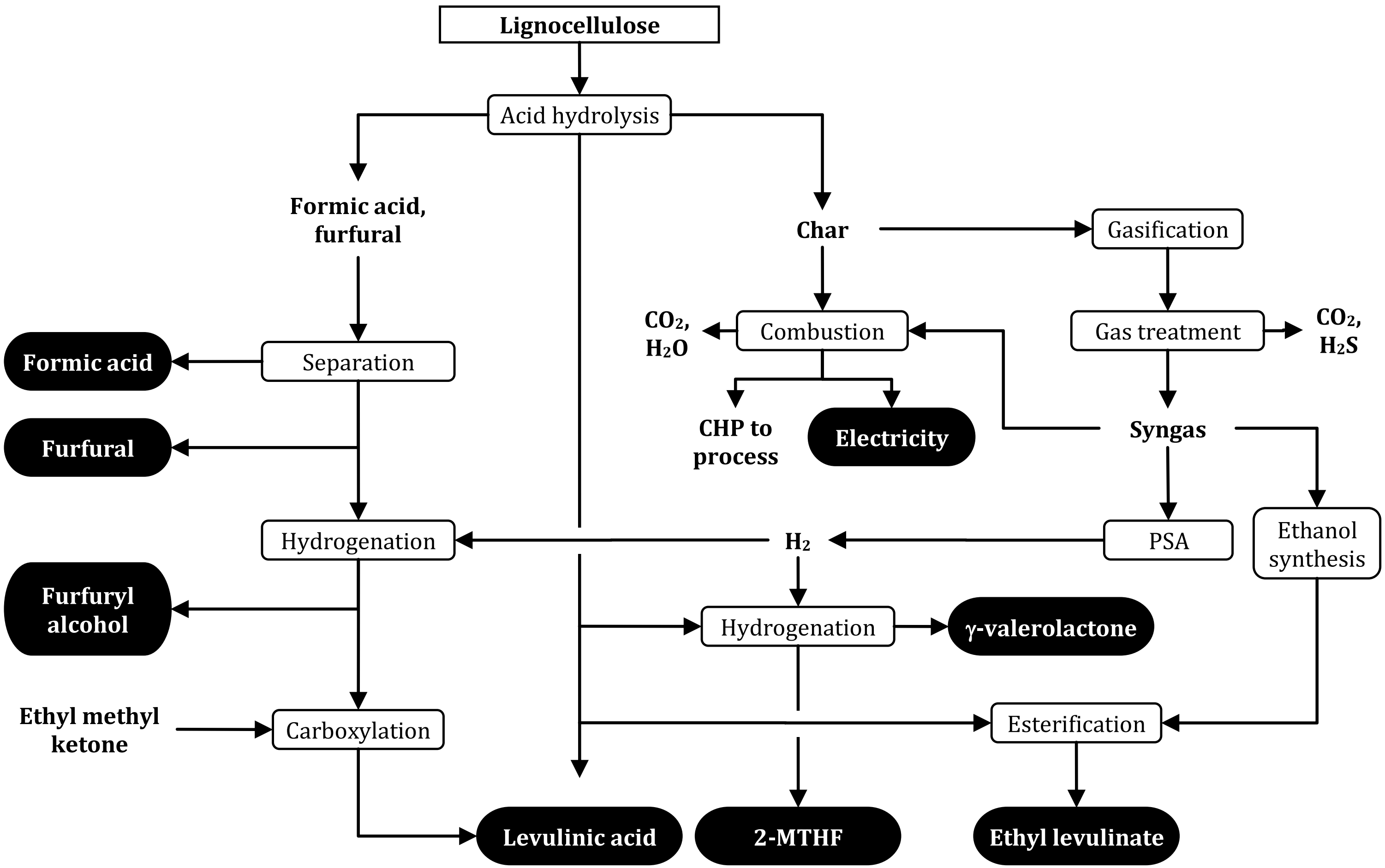
Advanced Levulinic Acid Biorefinery



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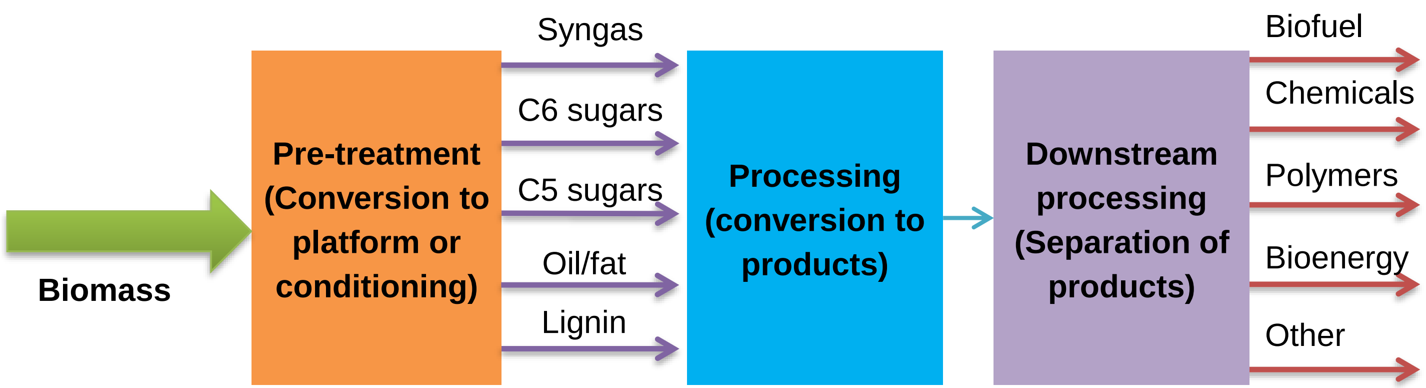
General Biorefinery Scheme



Working Session 2.1

Pick a biomass feedstock, for example from where you live or your working place. With at least one product in mind, draw a biorefinery configuration by choosing and connecting appropriate processes and platforms.

Congratulations you now have your first conceptual biorefinery!

Biorefinery Process Features

Biomass feedstock	Pretreatment	Platform	Conversion	Separation
Dedicated crops Lignocellulosic crops (wood, short rotation coppice (SRC) and poplar) Non-food oil crops (Jatropha, palm oil) Grasses (green plant material, switchgrass and miscanthus) Marine/aquatic biomass (algae, seaweed) **Residues** Lignocellulosic residues (crop residues, wood residues, bagasse) Oily residues (animal fat, used cooking oil) Organic residues & others (Organic fraction of Municipal Solid Waste, manure, green plant material)	**Thermochemical** Gasification Pyrolysis Hydrothermal liquefaction **Biochemical** Enzymatic hydrolysis **Chemical** Hydrolysis/pulping **Physical** Extraction Milling Pressing	C5 sugars C6 sugars Oils Biogas Syngas Hydrogen Organic juice Bio-oil Lignin Electricity and power	**Thermochemical** Combustion Water gas shift Fischer-Tropsch Hydrogenation **Biochemical** Fermentation Anaerobic Digestion Ezymatic processes Photofermentation Bioelectrochemical **Chemical** Esterification Transesterification Dehydration Steam reforming Electrochemical Chemical synthesis Other catalytic processes	Extraction Filtration Distillation / flashing Absorption Adsorption Crystallisation Ion Exchange Membrane based separation Electro-dialysis Centrifugation Sedimentation Flocculation-coagulation

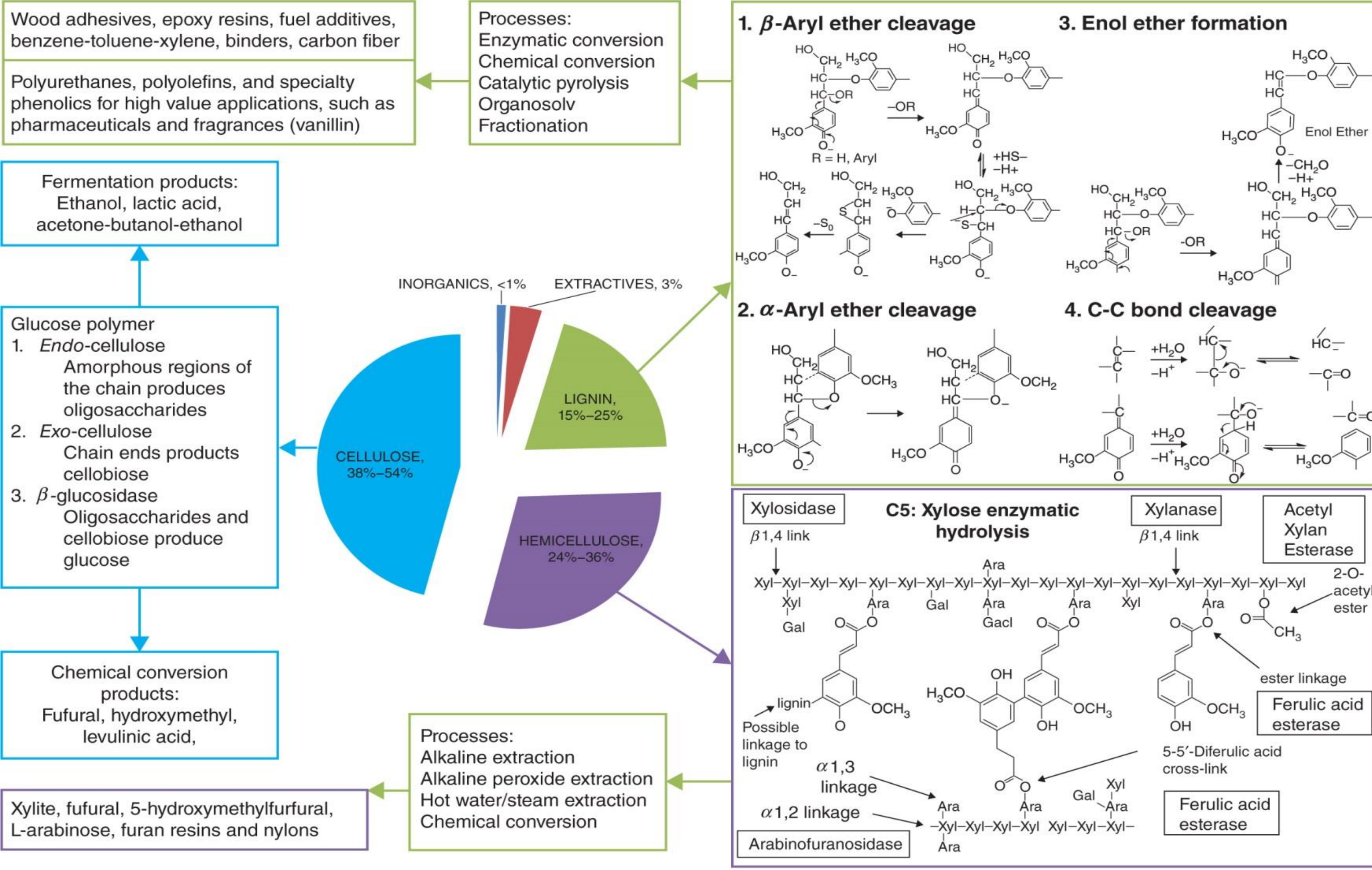


Figure 1.10 *Preprocessing technologies, mechanisms and products.*

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Summary

- Existing biorefineries can be evolved into more complex but flexible processes
- Advanced and highly integrated biorefinery configurations can be generated by combining process features in a synergistic manner for enhanced sustainability
- Resource efficiency can be enhanced by multi-platform biorefinery systems
- The value of urban waste can be unlocked by the recovery of functional products for circular economy
- The whole process design should involve an integrated design framework supported by tools and methods as shown in this workshop

Workshop on Sustainable Biorefineries

Lecture 3: Hands-on problem solving (Unlocking the value of urban waste by the recovery of functional products for circular economy: Levulinic acid production example)

Dr Elias Martinez Hernandez
Dr Jhuma Sadhukhan
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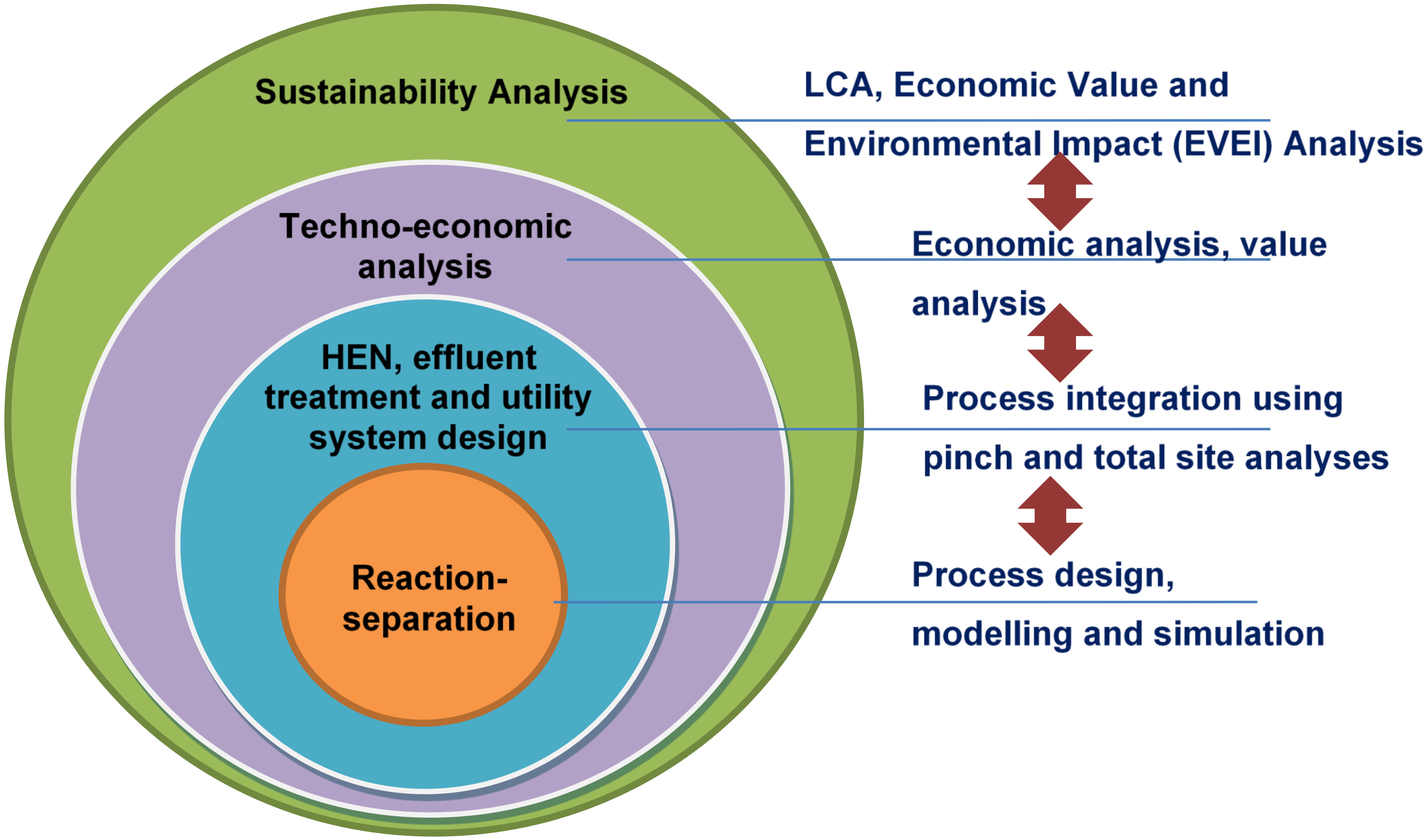
Objectives

- To analyse and understand the impact of biomass chemical nature on biorefinery performance (yield)
- To have an understanding of process simulation for mass and energy balances
- To apply integrated framework for designing a sustainable biorefinery

Process Engineering: Onion diagram



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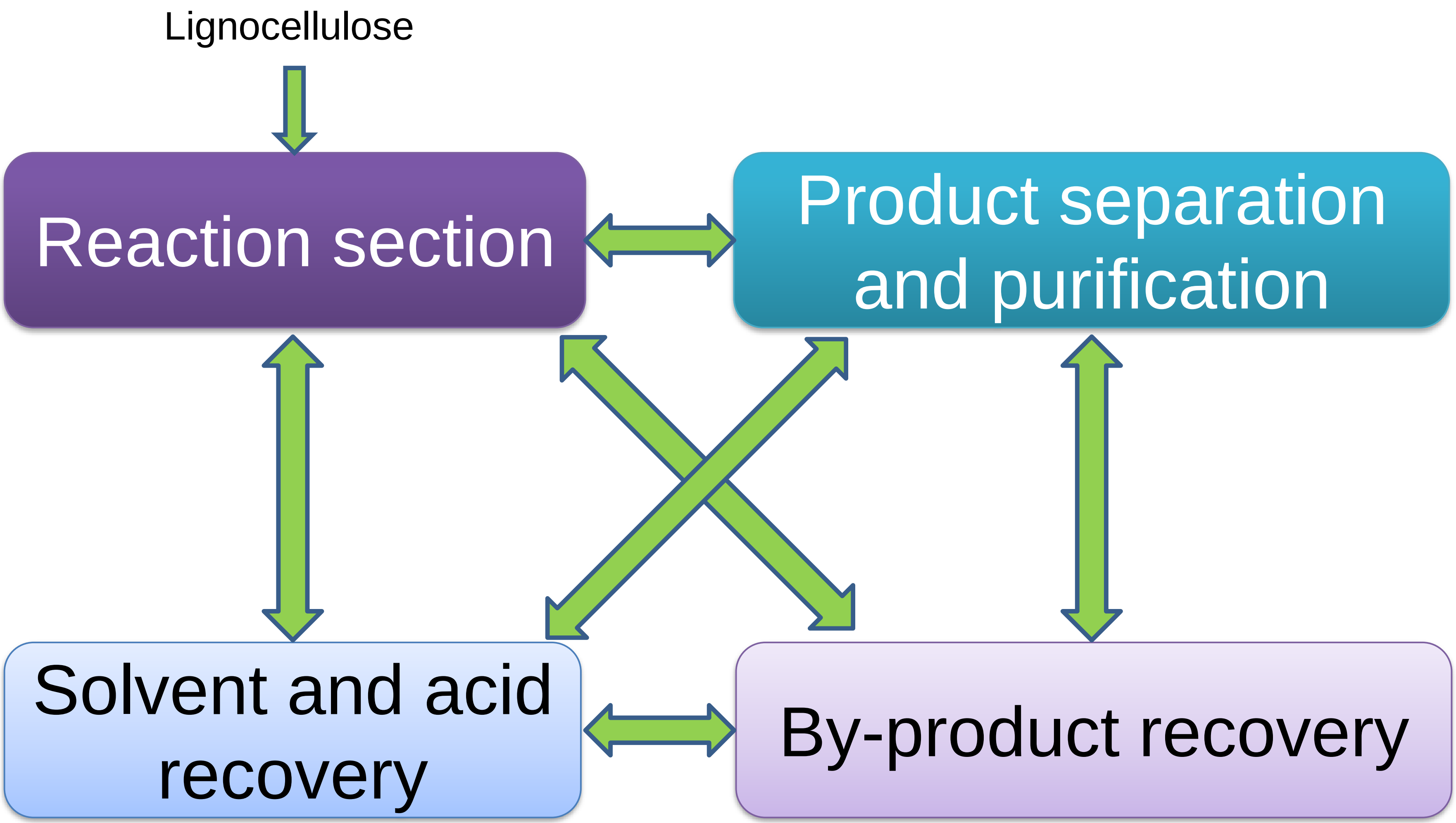
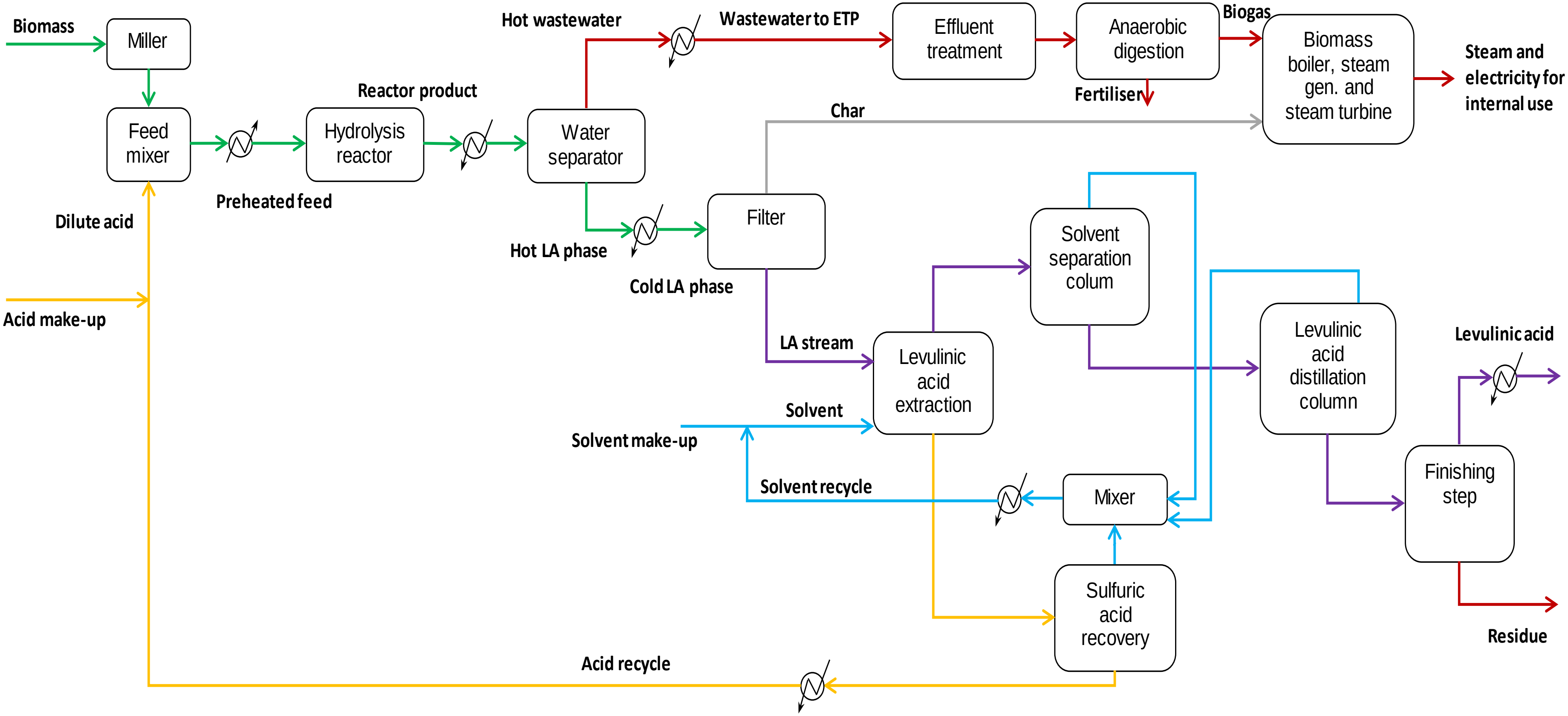
Process Integration



Process Design, Modelling and Simulation



Software

- Input: biomass wet analysis
- Comprehensive flowsheet
- Output:
  - Mass and energy balances
  - Energy recovery
  - CHP system
  - Inventories
  - Techno-economic performance
  - Value Analysis
  - LCA
  - EVEI Analysis

Biomass

Flowsheet

Economic analysis

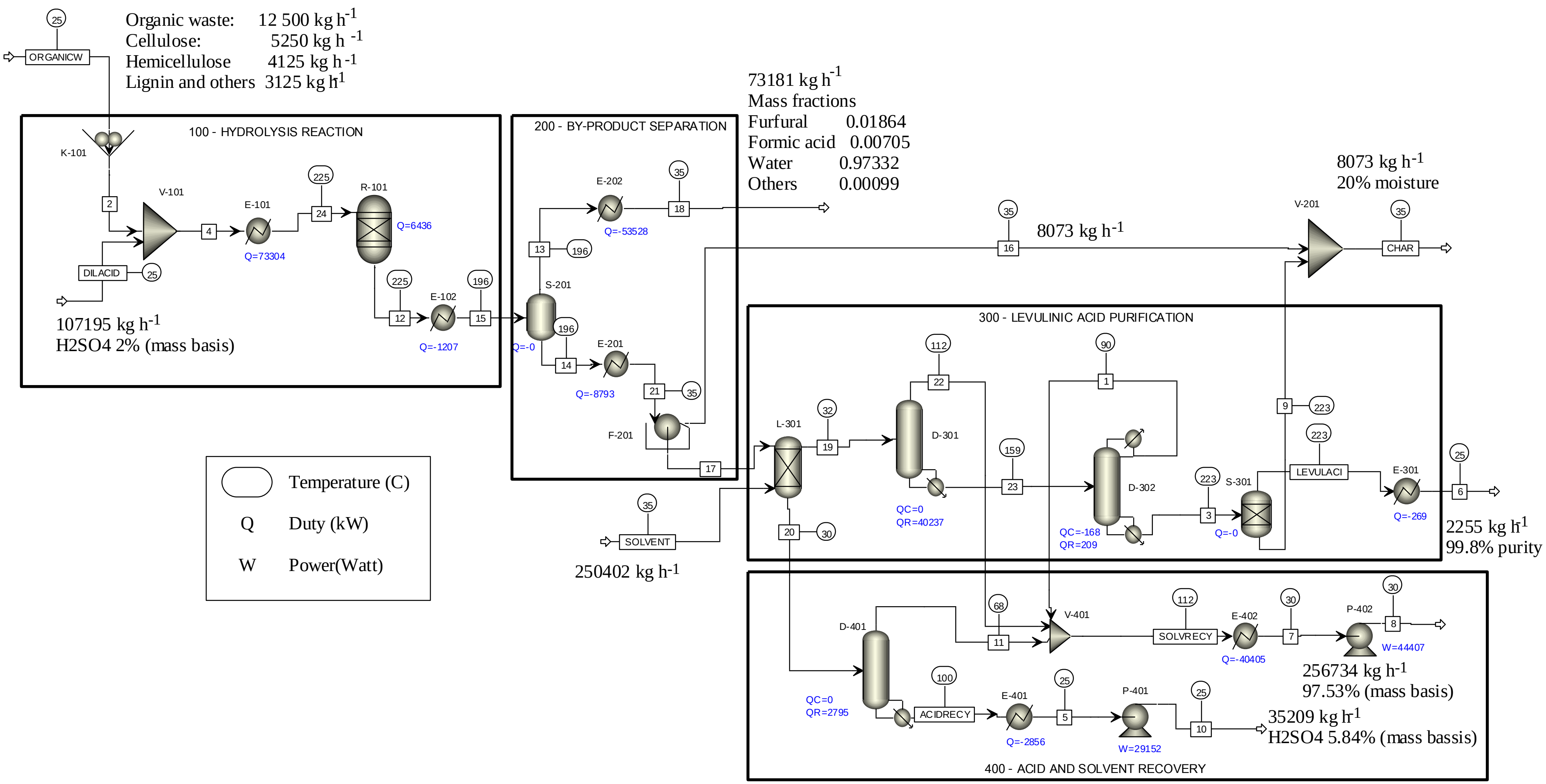
Value analysis

Life cycle assessment

EVEI analysis

LA Biorefinery Simulation

Simulation flowsheet in Aspen Plus® process simulator



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LA Biorefinery Simulation

Specify biomass chemical composition

Problem: Components are not in database

Solution: approximate with a model compound

- Cellulose modelled as $C_6H_{10}O_5$
- Hemicellulose modelled as $C_5H_8O_4$
- Lignin modelled as $C_{7.3}H_{13.9}O_{1.3}$
- Char modelled as C

Select model for estimation of components' physical properties: NRTL-RK (non-random two liquids – Redlich Kwong) used due to the presence of polar components.

Reactor Models

Data available	**Aspen Plus® Model**	**When it is useful?**
Product yields	RYield model	Chemical reactions unknown or not well defined but expected yields are known (e.g. pre-treatment of lignocellulosic biomass)
Reaction stoichiometry and conversion	RStoich model	Chemical reactions and expected conversions are known (e.g. hydroprocessing)
Only possible reaction products are known and approximation to equilibrium	RGibbs model	Thermochemical process (e.g. gasification), especially involving gas phase
Reaction stoichiometry	REquil model	Thermochemical processes, neutralisation reactions, reversible reactions
Reaction kinetics in Aspen plus® format	RPlug or CSTR	Well defined chemical reactions and kinetics Tubular (RPlug) or tank reactor (CSTR) (e.g. pyrolysis)
Reaction kinetics and batch size	RBatch	Batch processes such as fermentation if kinetics is known

LA Biorefinery Simulation

RYield model is used for LA simulation shown here. Product yields can be obtained based on individual biomass components, for example:

Biomass component

Product

	LA	Formic acid (FA)	Furfural	Char	Water
Cellulose	46%	18%	-	36%	-
Hemicellulose	-	-	40%	35%	25%
Lignin	-	-	-	100%	-

This captures variation in yield with biomass composition.

However, RYield model in Aspen Plus® needs the overall reactor yield.

LA Biorefinery Simulation

RYield model in Aspen Plus® needs the overall reactor yield factors for mass balance.

The various reactions of cellulose, hemicellulose, lignin, char can be lumped into an overall reaction such as:

Lignocellulosic Biomass + water + H_2SO_4

$\longrightarrow$ LA + FA + Furfural + Char + water + H_2SO_4

Yield factors can then be calculated as the ratio of mass of component *i* in reactor outlet to reactor inlet mass.

$$Yield\ of\ i = \frac{mass\ of\ i\ in\ reactor\ outlet}{reactor\ mass\ inlet}$$

Therefore, mass of each component in reactor outlet is

Mass of *i* = reactor mass inlet × Yield of *i*

Practice Calculation

Calculate the reactor outlet composition as mass percentage by using the following yield data if total slurry input to reactor is 125,052 kg/h and contains 2143 kg/h of H_2SO_4.

Product	Yield (fraction)	Outlet mass (kg/h)	Composition (% mass)
Levulinic acid	0.0196		
Formic acid	0.0077		
Furfural	0.0134		
Water	0.9067		
Char	0.0525		

What about H_2SO_4?

Is this the final attainable LA yield?

Solution

H_2SO_4 is just a catalyst and its mass does not change through the reactor. Therefore, the basis for calculating the yield in this case is: 125,052 - 2143 = 122,909 kg/h

Product	Yield	Outlet mass (kg/h)	Composition (% mass)
Levulinic acid	0.0196	2415	2
Formic acid	0.0077	945	1
Furfural	0.0134	1650	1
Water	0.9067	111440	89
Char	0.0525	6459	5
H_2SO_4	-	2143	2
Total		125,052	100

Final attainable yield depends on the overall process, including downstream separations

Separation Processes

Separation process	Driving force	Application example
Distillation, flash columns	Relative volatilities	Ethanol, biodiesel separation
Extraction, Absorption	Solubility in liquid solvent	Levulinic acid extraction, CO_2 absorption
Adsorption	Solubility in solid sorbent	CO_2 adsorption
Membrane-based separations:		
Microfiltration	Pressure gradient	Yeast cell separation
Ultrafiltration	Pressure gradient	Bacteria cell separation
Nanofiltration	Pressure gradient	Proteins, enzymes, sugars, amino acids, colorants
Reverse Osmosis	Pressure gradient	Organic acid concentration
Dialysis	Concentration gradient	Non-charged particles
Electrodialysis (ED)	Electrical field	Organic acid separation
ED with bipolar membrane	Electrical field	Organic acid separation
Pervaporation	Pressure gradient	Ethanol dehydration

Biorefineries and Chemical Processes: Design, Integration and Sustainability Analysis, First Edition.
Jhuma Sadhukhan, Kok Siew Ng and Elias Martinez Hernandez.

Companion Website: http://www.wiley.com/go/sadhukhan/biorefineries

Separation Processes

Separation process	Driving force	Application example
Crystallisation	Difference in solubility and supersaturation	Succinic acid production
Ion exchange	Electrostatic attraction	Organic acids separation
Centrifugation	Centrifugal force	Algae harvesting, solids separation
Sedimentation	Difference in density between solids and liquid	Algae harvesting
Coagulation-flocculation	Electrostatic attraction	Algae harvesting
Precipitation	Solubility	Organic acids separation

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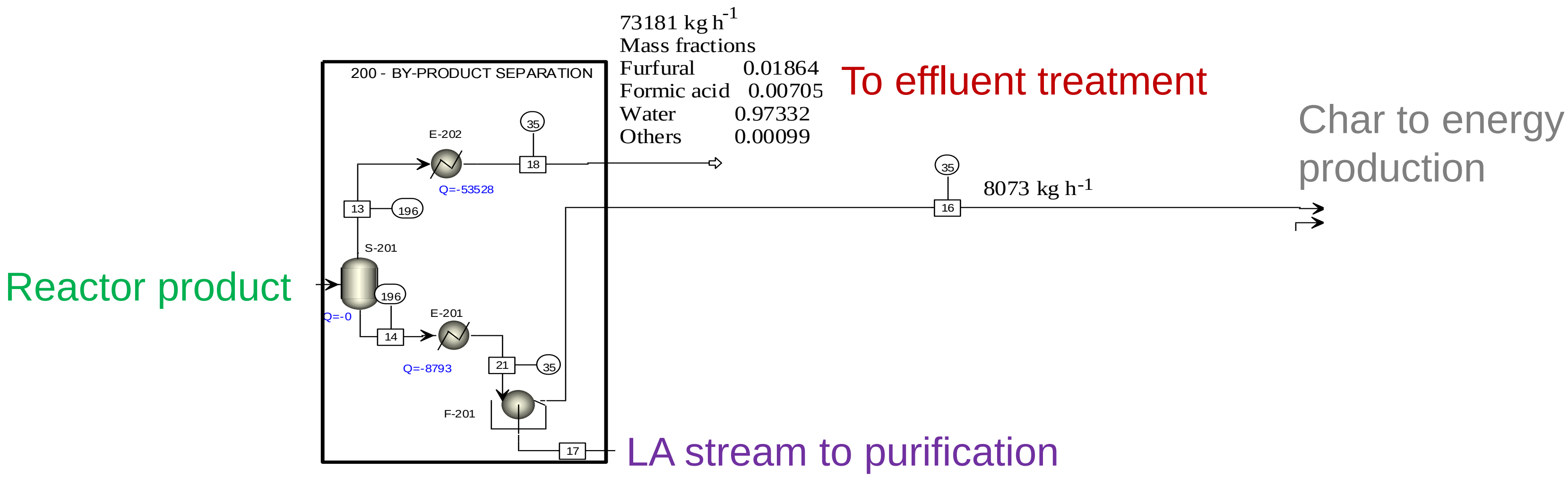
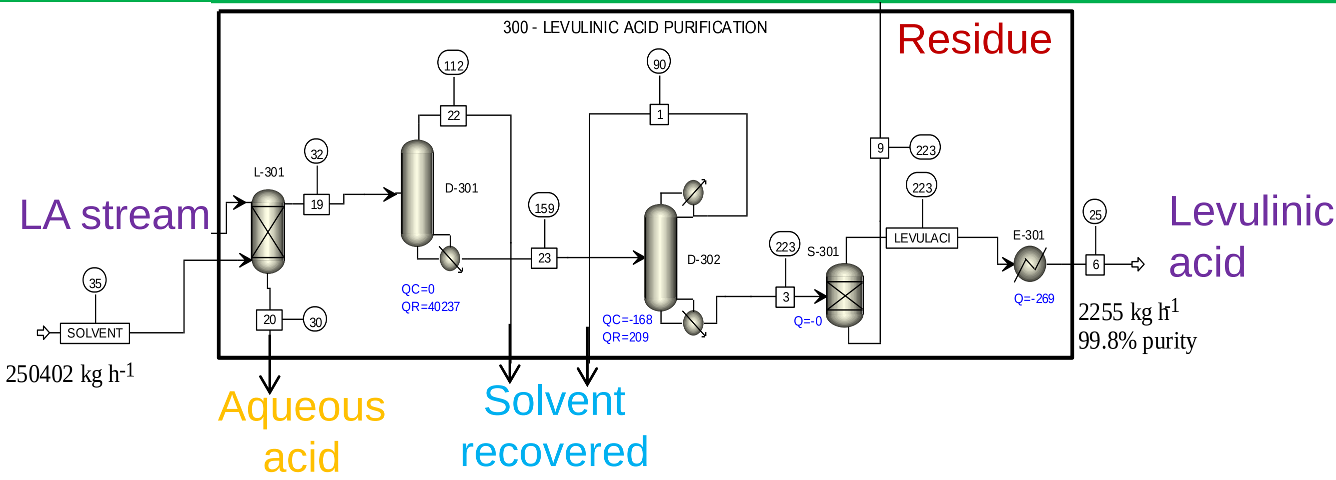
LA Biorefinery Simulation



By-product separation section. Simulate processes as follows:

- Water and volatile by-products separation from LA rich phase in two-phase separator ***Flash2*** model. Conditions correspond to the second reactor (196°C and 14 bar). At these conditions, furfural, formic acid and water are flashed into the vapour phase. LA remains in liquid phase.
- Char (solid) is then separated from the liquid phase rich in LA using a ***Filter*** model. The cake obtained contains the char, tar and remaining solids.

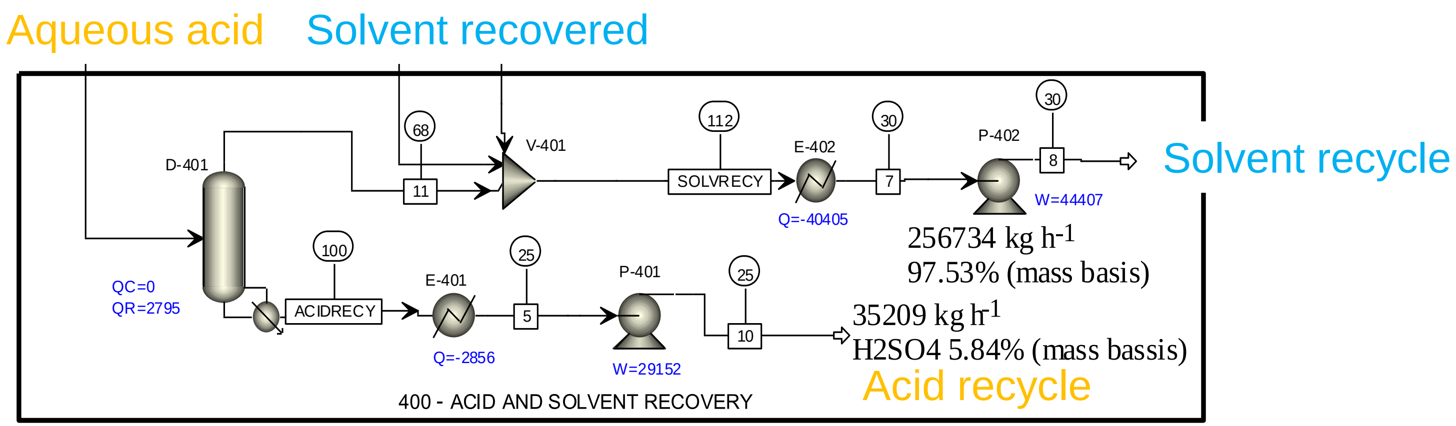
LA biorefinery simulation



LA purification section. Simulate processes as follows:

- Solvent extraction of LA using ***Extract*** model. LA is extracted from the filtrate liquid using MIBK (Methyl isobutyl ketone) in an extraction column. Due to solubility difference, LA is transferred to the solvent forming a mixture easier to separate by distillation.
- Solvent separation from LA using Distillation ***RadFrac*** model. Due to volatility difference, MIBK easily separates from LA.
- Levulinic acid purification by distillation using ***Radfrac*** model. Then, finishing separator ***Sep*** model, to remove remaining impurities, if any.

LA biorefinery simulation



Acid and solvent recovery section. Simulate processes as follows:

- Sulfuric acid recovery using Distillation <u>*RadFrac*</u> model
- Acid is cooled down and pumped back to slurry mixer
- Solvent streams are recovered from distillation columns using <u>*Mixer*</u> model, then cooled down and pumped back to extraction column

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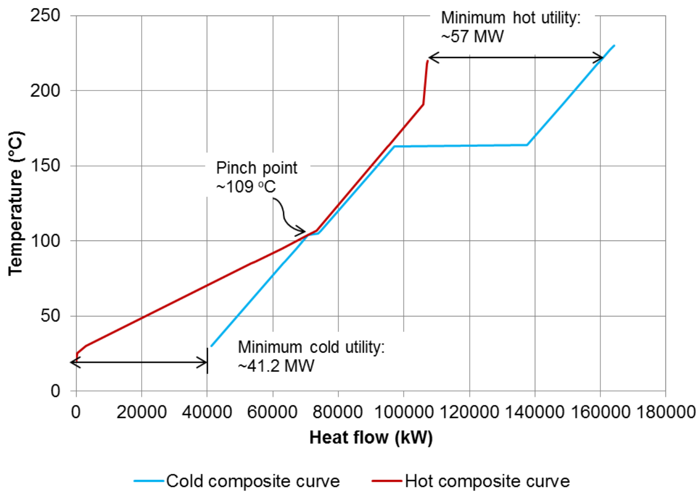
LA biorefinery – Utility targeting

Data extraction

Cold streams	Duty (kW)	T_{supply} (°C)	T_{target} (°C)	CP (kJ °C⁻¹)
Acid recovery column reboiler	2795	99	100	2795
Solvent recovery column reboiler	40237	158	159	40233
Levulinic acid recovery column reboiler	209	222	223	209.0
Reactor feed	73304	25	225	366.5
Total hot utility	116545			

Hot streams	Duty (kW)	T_{supply} (°C)	T_{target} (°C)	CP (kJ °C⁻¹)
Reactor effluent	1207	225	196	41.6
Hot LA phase	8793	196	35	54.6
Levulinic acid	269	223	25	1.4
Hot wastewater	53528	196	35	332.5
Recycled solvent	40405	112	30	492.7
Recycled acid	2856	100	25	38.1
Levulinic acid recovery condenser	168	91	90	168.0
Total cold utility	107226			

Pinch analysis



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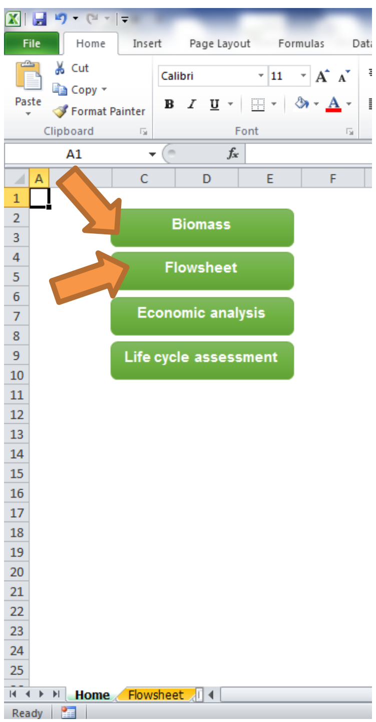
Working Session 3.1
Questions

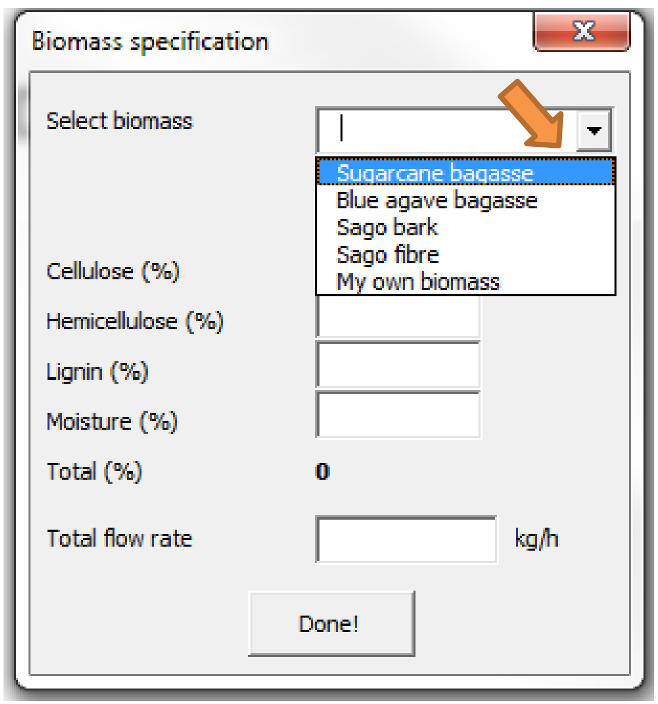
Calculate the following using sugarcane bagasse as the feedstock in the spreadsheet based simulator.

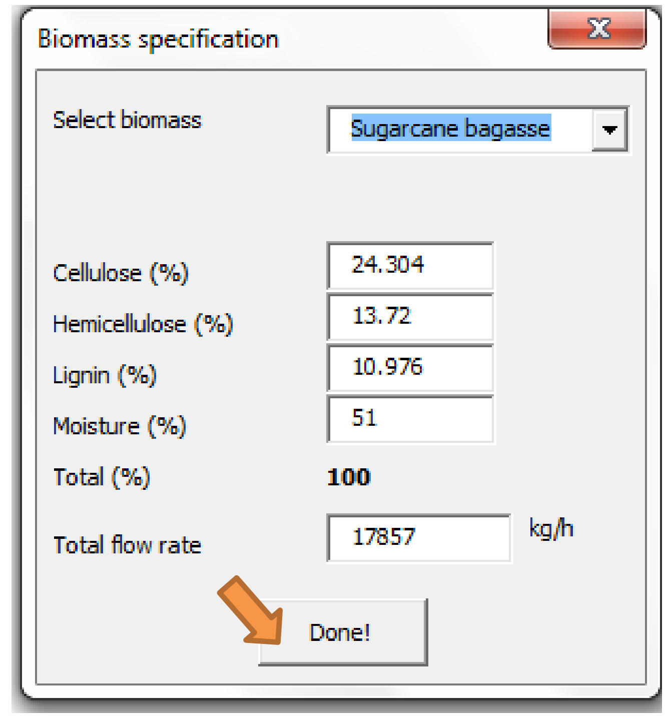
1. Levulinic acid (LA) yield in wt% of biomass input.
2. Utility demands (heating, cooling, electricity).

Working Session 3.1
- Solutions

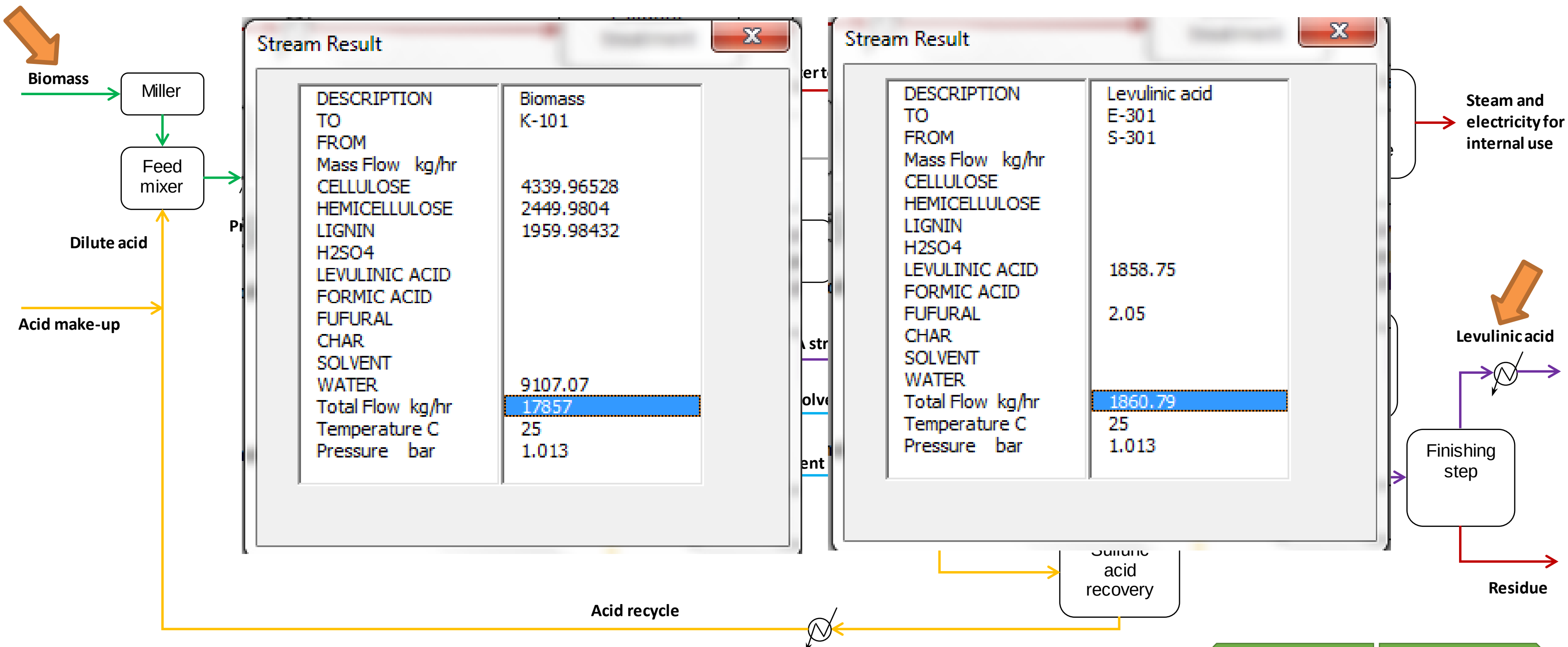
- Open the simulation spreadsheet “*LA simulation.xlsm*”. In the ***Home*** tab, click the **Biomass** button.
- Select sugarcane bagasse from the options in the drop list button.
- Change flow rate if needed and click **Done!**
- Click **Flowsheet**







- To calculate overall yield we need the flow of biomass input and flow of purified LA. For dry mass basis, we need water flow as well.
- Click on the ***Biomass*** stream label and note the Total Flow.
- Click on the ***Levulinic acid*** stream label and get the Total Flow.



Back to Home | To Economic Analysis

1. The overall LA yield from sugarcane bagasse is

$$Overall\ LA\ yield = \frac{1861}{17857} = 10.4\%$$

On dry biomass basis:

$$Overall\ LA\ yield = \frac{1861}{17857 - 9107} = 21.3\%$$

We have a higher value product:

Ethanol 0.3 – 0.5 $/kg

vs

LA: 5 – 8 $/kg

2. The utility demands can be found on the Flowsheet tab.

Hot Utility	**42.1**	MW
Cooling water	**32.2**	MW
Electricity	**51.5**	kW

Working Session 3.2
(Effect of biomass composition on LA yield)
Questions

Compare LA yield results between sugarcane bagasse, blue agave bagasse and sago bark. Discuss the effects of moisture and lignin contents in biomass, on LA yield.

It may be useful to set up a table like this

Biomass	Sugarcane bagasse	Blue agave bagasse	Sago bark
Cellulose			
Hemicellulose			
Lignin			
Moisture			
Total flow			
Dry biomass flow			
LA flow			

Working Session 3.2
- Solutions

Results' table looks like this

Biomass	Sugarcane bagasse	Blue agave bagasse	Sago bark
Cellullose	24.304	32.34	23.1
Hemicellulose	13.72	9.31	17.31
Lignin	10.976	7.35	56.83
Moisture	51	51	2.76
Total flow	17857	17857	17857
Dry flow	8750	8750	17364
LA flow	1861	2476.06	1774
Yield	**10.4%**	**13.9%**	**9.9%**
Yield (dry biomass basis)	**21.3%**	**28.3%**	**10.2%**

Summary

- Process simulation
- Unit operation specifications
- Process modelling and stream analysis
- Mass and energy balance
- Biomass wet analysis to technical performance evaluations

Workshop on Sustainable Biorefineries

Lecture 4: Economic value and life cycle assessment (LCA) for optimal and sustainable biorefinery systems

Dr Jhuma Sadhukhan
Dr Kok Siew Ng
Dr Elias Martinez Hernandez

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Objectives

- Concepts and methods including graphical visualisation tools.
- Cost components, especially in the context of waste management and treatment sector, such as gate fees.
- Utility system design.
- Discounted cash flow analysis.
- Life cycle assessment.

Revenues (e.g. million $ / year)

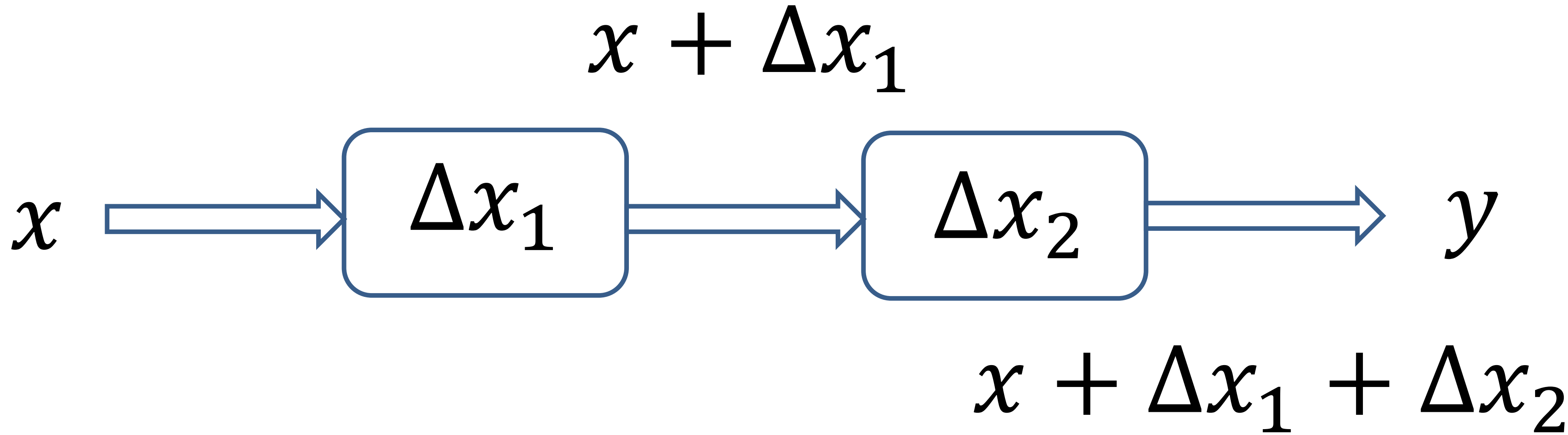
+ Product values
– Feedstock costs

+ (Credits)
– (Taxations)
– (Landfill costs)
– (Emission costs)
Etc.

The Three Most Important Economic Terms for Economic Comparisons Between Systems

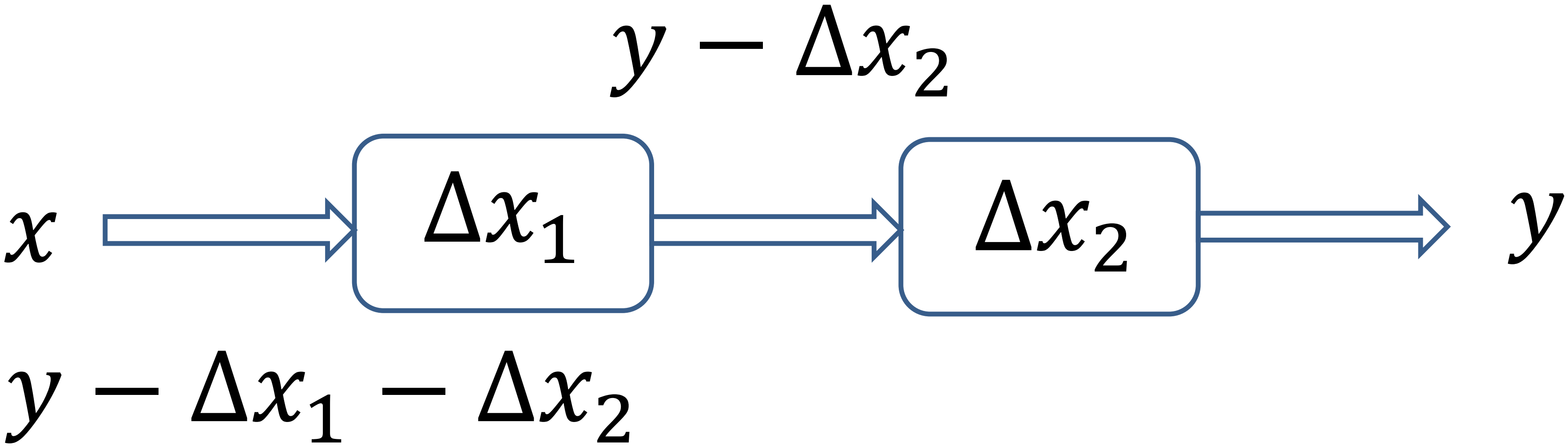
- **Economic Margin** = Revenues – Total OPEX – Annual capital cost
- **Value on processing** (VOP) = Revenues w/o feedstock costs – Total OPEX – Annual capital cost
- **Cost of production** (COP) = Revenues w/o product values + Total OPEX + Annual capital cost
- Apply the above terms to all the life cycle stages for life cycle costing of systems

Concept of Value Analysis



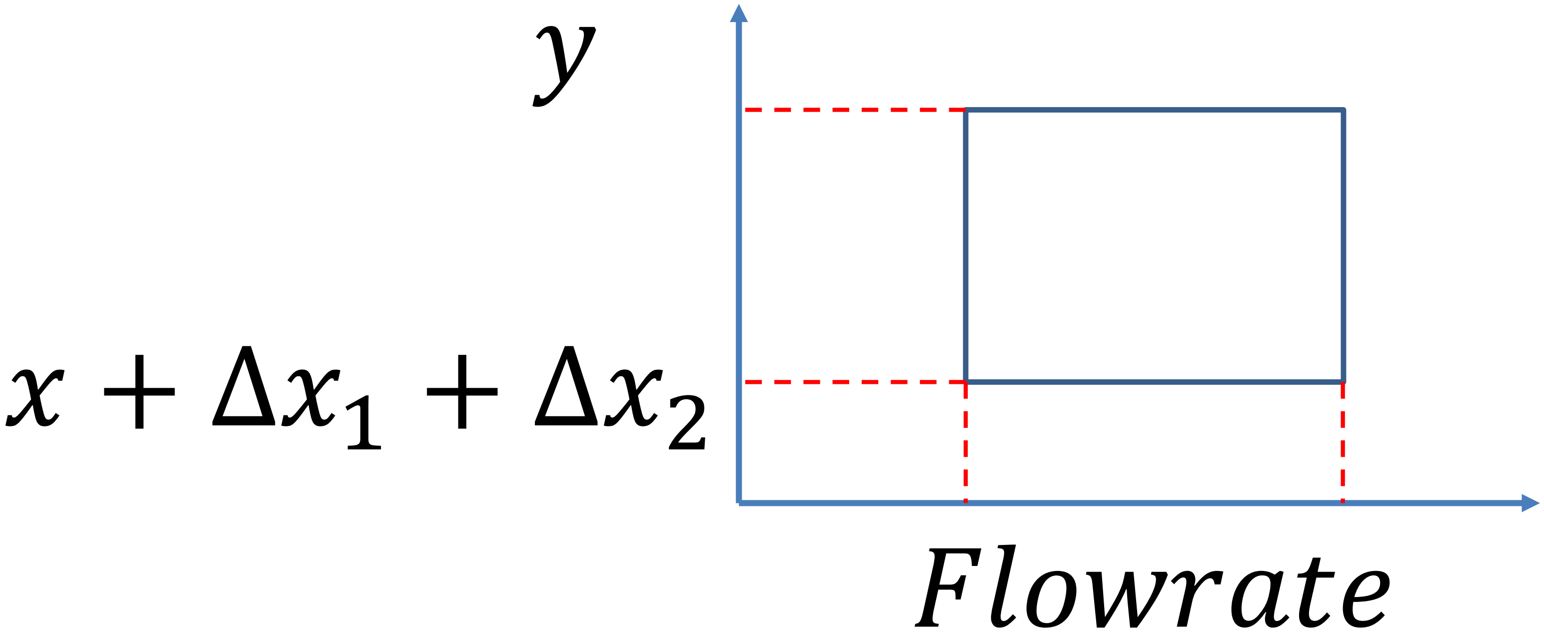
Marginal value: $y - (x + \Delta x_1 + \Delta x_2)$

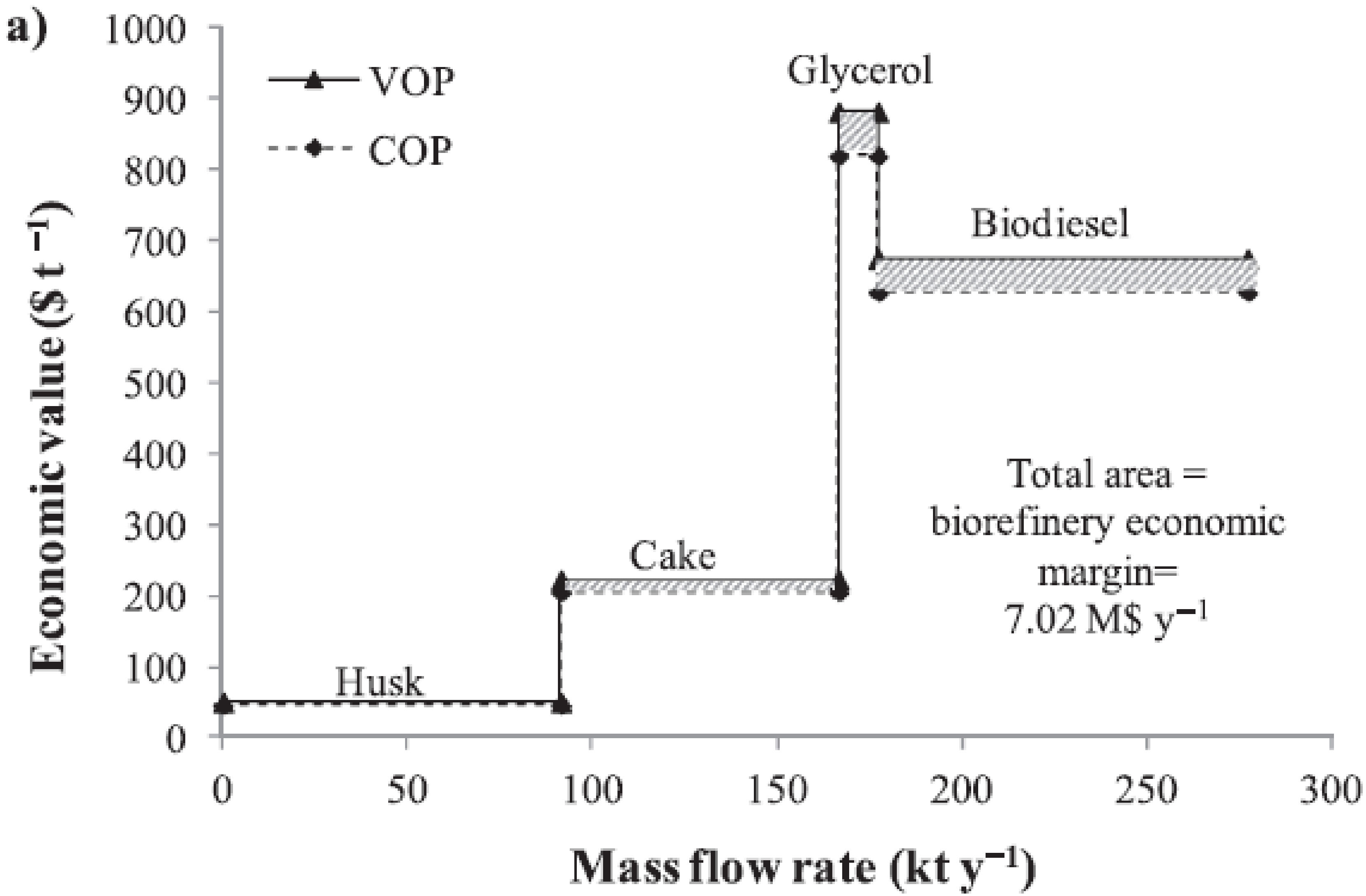
Concept of Value Analysis



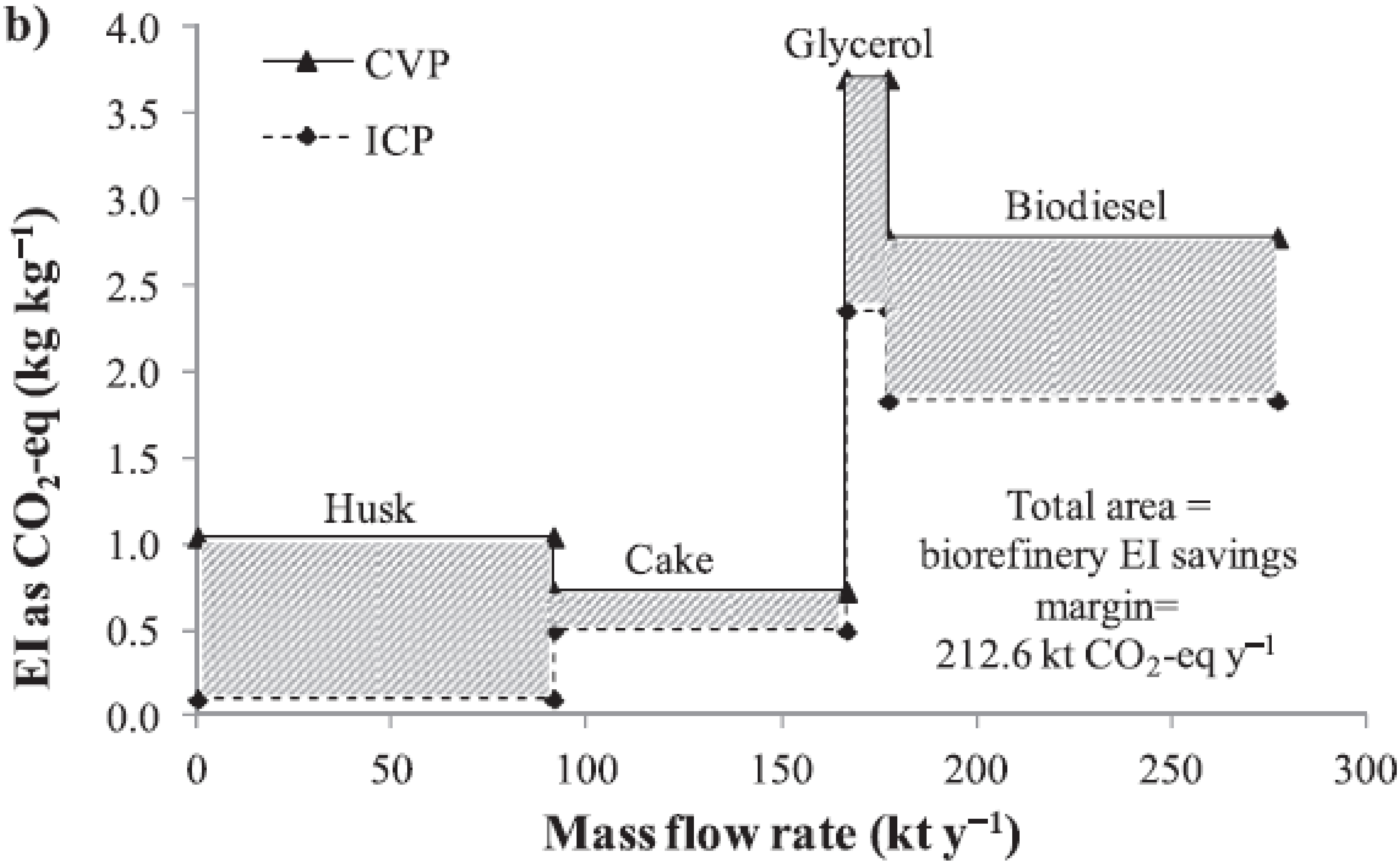
Marginal value: $y - (x + \Delta x_1 + \Delta x_2)$

Concept of Value Analysis





©Martinez-Hernandez, E., Campbell, G. M., & Sadhukhan, J. (2014). **Economic and environmental impact marginal analysis of biorefinery products for policy targets**. *Journal of Cleaner Production*, *74*, 74-85.



©Martinez-Hernandez, E., Campbell, G. M., & Sadhukhan, J. (2014). **Economic and environmental impact marginal analysis of biorefinery products for policy targets**. *Journal of Cleaner Production*, *74*, 74-85.

Literature

1. Sadhukhan J., Ng K.S. and Martinez-Hernandez E. 2016. Novel integrated mechanical biological chemical treatment (MBCT) systems for the production of levulinic acid from fraction of municipal solid waste: A comprehensive techno-economic analysis. *Bioresource Technology*, In press. http://dx.doi.org/10.1016/j.biortech.2016.04.030
2. Elias Martinez-Hernandez, Jhuma Sadhukhan. 2016. Process integration and design philosophy for competitive waste biorefineries. *Waste Biorefinery*. Elsevier. In press.
3. Ng K.S., Head, I., Premier, G.C., Scott, K., Yu, E., Lloyd, J., and Sadhukhan J. 2016. A multilevel sustainability analysis of zinc recovery from wastes. *Resources, Conservation & Recycling*. In press.
4. Martinez-Hernandez, E., Campbell, G.M., Sadhukhan, J., 2014. Economic and environmental impact marginal analysis of biorefinery products for policy targets. *J. Clean. Prod.* 74, 74-85.
5. Sadhukhan, J., Ng, K.S., Hernandez, E.M., 2014. *Biorefineries and Chemical Processes: Design, Integration and Sustainability Analysis*. Wiley, Chichester, UK.
6. E Martinez-Hernandez, GM Campbell, J Sadhukhan. 2013. Economic Value and Environmental Impact (EVEI) analysis of biorefinery systems. *Chemical Engineering Research Design*. 8(91), 1418-1426.
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8. Sadhukhan, J., Zhang, N., Zhu, X.X., 2004. Analytical optimisation of industrial systems and applications to refineries, petrochemicals. *Chem. Eng. Sci.* 59(20), 4169-4192.
9. Sadhukhan, J., Zhang, N., Zhu, X.X., 2003. Value analysis of complex systems and industrial application to refineries. *Ind. Eng. Chem. Res.* 42(21), 5165-5181.

Working Session 4.1 (Value Analysis) Questions

Report Value Analysis results of lignocellulose from MSW.

Working Session 4.1
- Solutions

COP of Products (Euro/T)

$$\frac{Flowrate\ of\ Lignocellulose\ (\frac{t}{h}) \times COP\ of\ Lignocellulose\ \left(\frac{Euro}{t}\right) \times 8000\ \left(\frac{h}{year}\right) + Total\ Annual\ Cost\ (million\ \frac{Euro}{year}) \times 10^6}{Flowrate\ of\ Lignocellulose\ (\frac{t}{h}) \times 8000 \left(\frac{h}{year}\right)}$$

VOP of Lignocellulose (Euro/t)

$$\frac{\sum Flowrate\ of\ Product\ \left(\frac{t}{h}\right) \times VOP\ of\ Product\ \left(\frac{Euro}{t}\right) \times 8000\ \left(\frac{h}{year}\right) - Total\ Annual\ Cost\ (million\frac{Euro}{year}) \times 10^6}{Flowrate\ of\ Lignocellulose\ (\frac{t}{h}) \times 8000\left(\frac{h}{year}\right)}$$

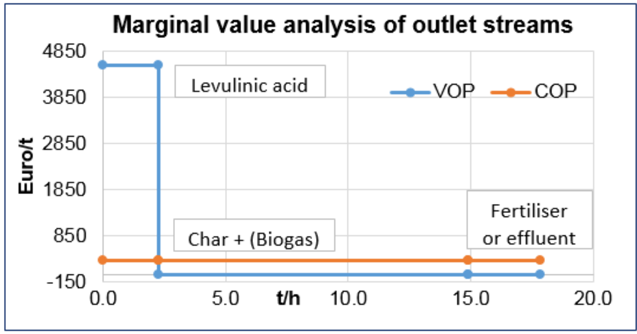
Value Analysis (Lignocellulose from MSW)

F	Flowrate, t/h
COP	Cost of production, €/t
VOP	Value on processing, €/t
EM	Economic margin, €/h
TC	Total annual cost (w/o variable operating cost), million €/y

Chemical conversion with CHP section

Stream	F	COP	VOP	EM
Lignocellulose	17.9	-7.3	266.3	4885.6
Fertiliser	3.0	301.7	4.7	-878.2
Char + Biogas used in internal heating	12.6	301.7	0.0	-3814.5
Levulinic acid	2.3	301.7	4550.0	9578.4

TC	44.1



Back to Home

To Flowsheet

Cost Components

- Capital cost
  - Delivered cost of equipment
  - Direct capital cost
  - Indirect capital cost
  - Working capital
  - Total capital investment or total CAPEX
  - Annualised capital charge (for annualised capital cost)

- Operating cost
  - Fixed
  - Variable
  - Miscellaneous
  - Total OPEX

Biorefineries and Chemical Processes: Design, Integration and Sustainability Analysis, First Edition.
Jhuma Sadhukhan, Kok Siew Ng and Elias Martinez Hernandez.

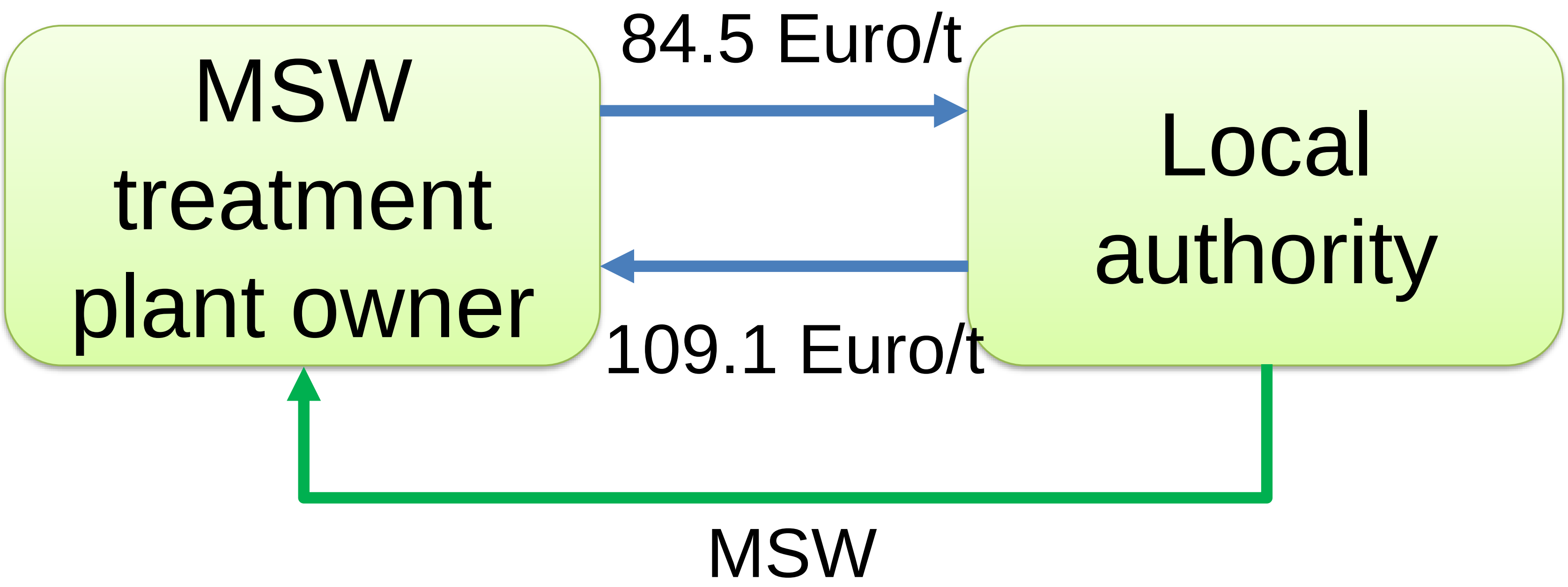
Companion Website: http://www.wiley.com/go/sadhukhan/biorefineries

Gate Fee

- An average waste collection fee of 84.5 Euro/t MSW is paid by the treatment plant owner to the local authority
- The treatment plant owner is eligible to receive a gate fee from the local authority, for treating MSW
- This rate is 109.12 Euro/t MSW (WRAP, 2015)
- Therefore, the cost of production (COP) of MSW is estimated (84.5 – 109.1) = −24.6 Euro/t
- This implies that the current business model allows 24.6 Euro/t revenue guaranteed for the MSW treatment plant owner
- This is a strong economic incentive for waste valorisation and thereby mitigation of environmental impacts of wastes and landfilling

COP of MSW

Income: 24.6 Euro/t



COP Of Lignocellulose Fraction of MSW

COP of MSW (Euro/t) + 17.3 Euro/t (Operating cost of MSW treatment)

When income from gate fees is considered:

$$= -24.6 + 17.3 = -7.3 \text{ Euro/t}$$

When income from gate fees is not considered and MSW priced at 50 Euro/t:

$$= 50 + 17.3 = 67.3 \text{ Euro/t}$$

Working Session 4.2
(Effect of biomass composition on economic performance)
Questions

Compare payback times, annual capital costs and cash flows between lignocellulose from MSW, sugarcane bagasse and blue agave bagasse using the default economic basis.

It may be useful to set up a table like this

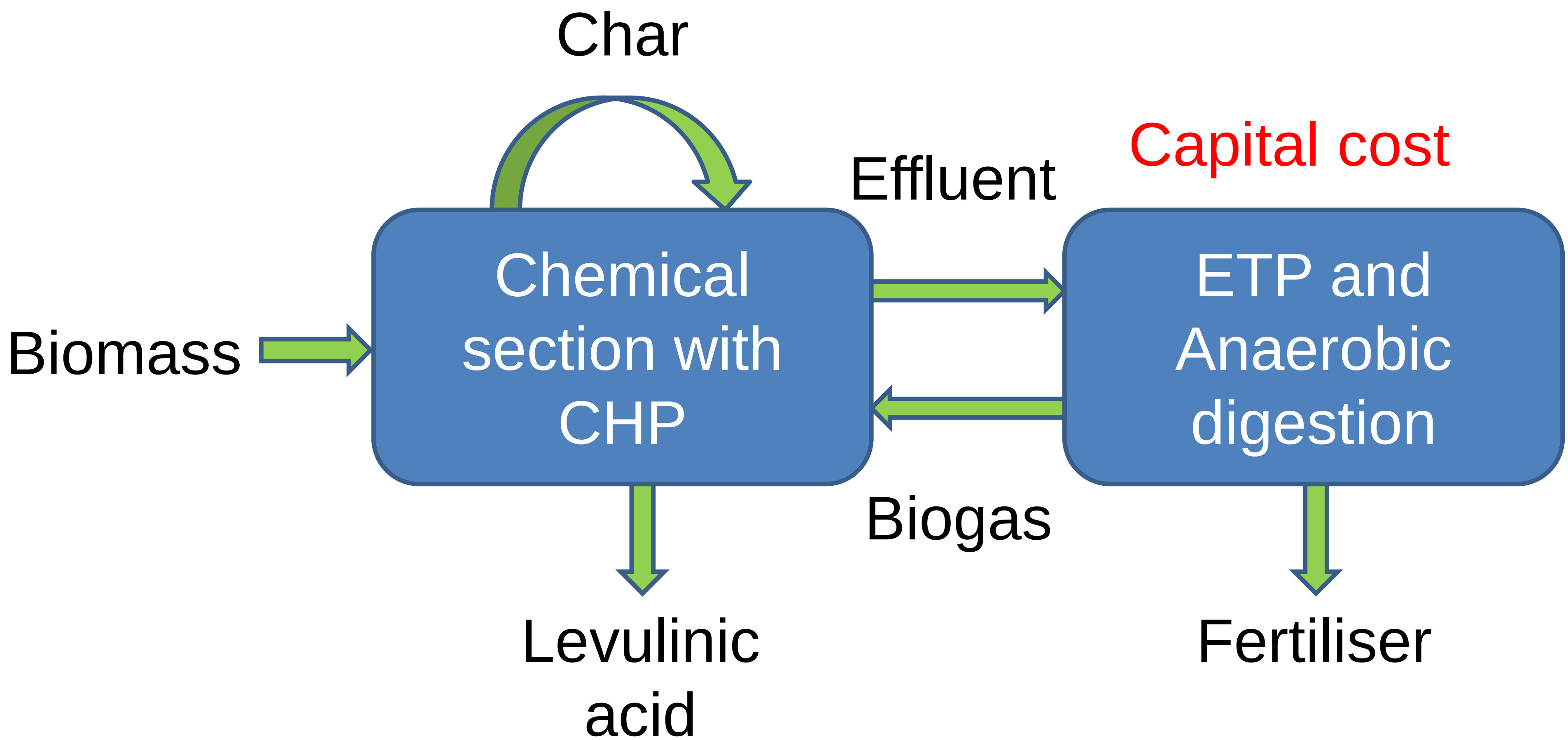
	Lignocellulose from MSW	Sugarcane bagasse	Blue agave bagasse
Payback time, years			
Annual capital cost, million Euro/y			
Cash flow, million Euro/y			

Working Session 4.2
- Solutions

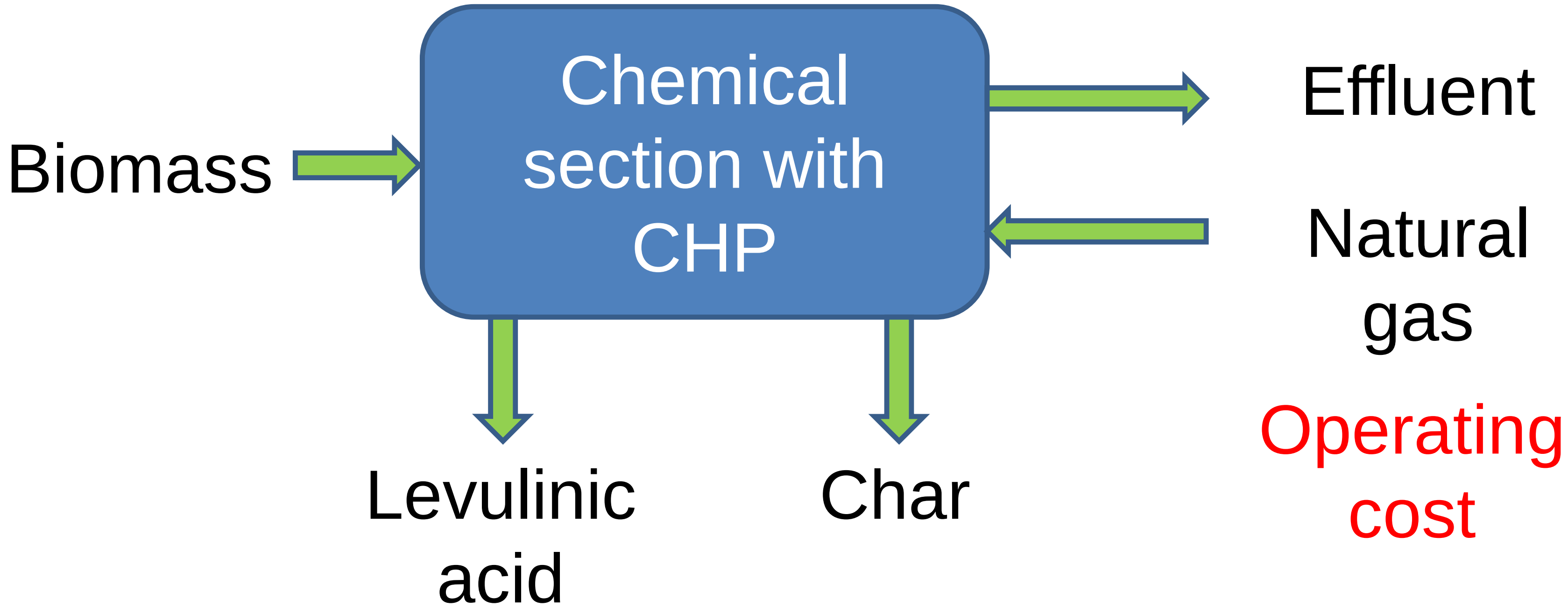
Results' table looks like this

	Lignocellulose from MSW	Sugarcane bagasse	Blue agave bagasse
Payback time, years	3.9	5	3.7
Annual capital cost, million Euro/y	39.9	42	41.8
Cash flow, million Euro/y	39.1	22.6	45.2

Case 1. CHP Supply from On-site Generation

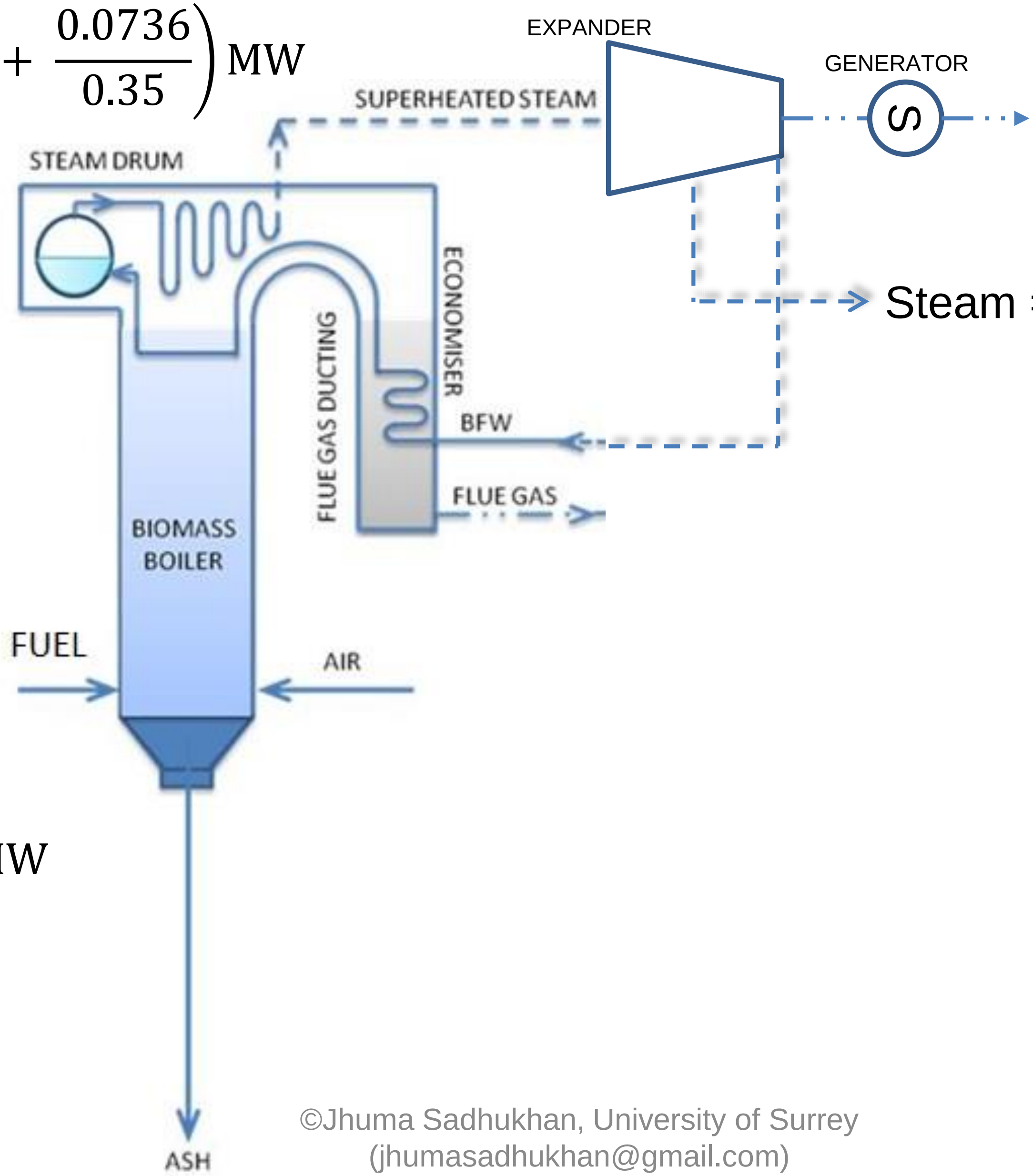


Case 2. CHP Supply from Natural Gas



CHP System

$$\left(60.1+\frac{0.0736}{0.35}\right)\text{MW}$$



Electricity = 0.0736 MW

Steam = 60.1 MW

Natural gas

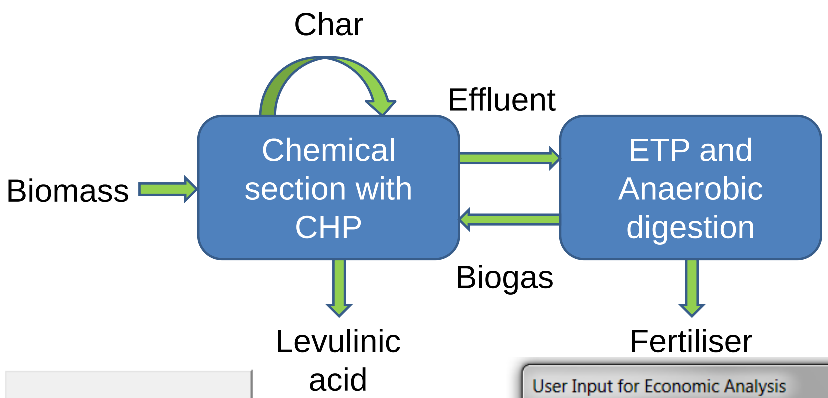
$$\frac{\left(60.1+\frac{0.0736}{0.35}\right)}{0.9}\text{MW}$$

Working Session 4.3
(Economic Analysis due to difference in CHP configuration)
Questions

Report Economic Analysis results of lignocellulose from MSW, due to difference in CHP configuration.

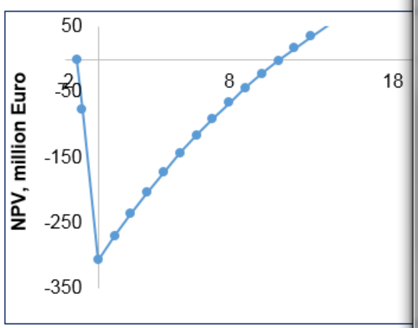
Working Session 4.3
- Solutions

Case 1: Economic Analysis (Lignocellulose from MSW)



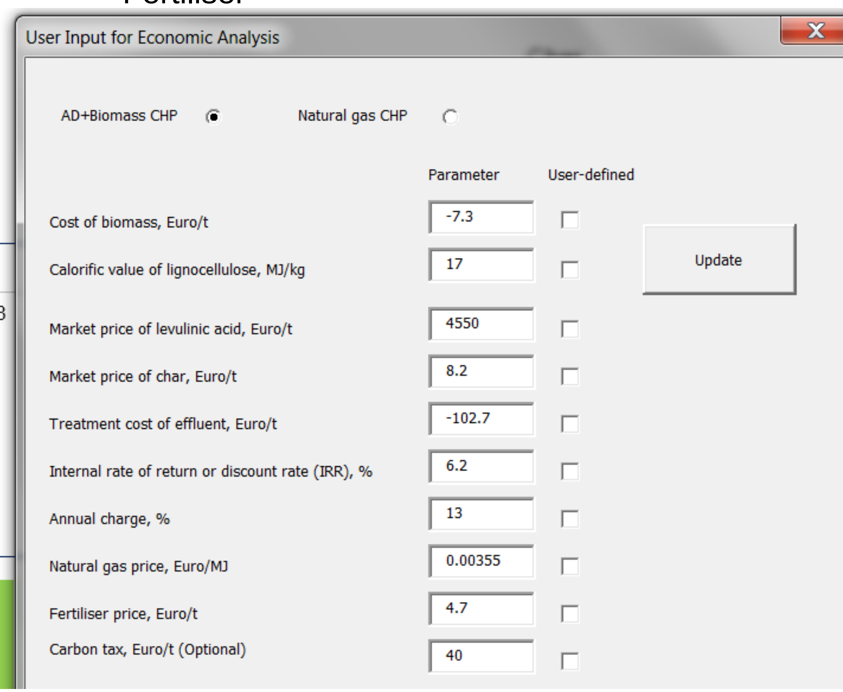
Back to Home | To Flowsheet | User Input

USER INPUT	
SELECT 1 FOR AD+BIOMASS CHP OR 0 FOR NATURAL GAS HEAT	1
USER INPUT	
Cost of biomass, Euro/h	-7.3
Calorific value of lignocellulose, MJ/kg	17
(OPTIONAL) USER INPUT	
Market price of levulinic acid, Euro/t	4550
Market price of char, Euro/t	8.2
Treatment cost of effluent, Euro/t	-102.7
Internal rate of return or discount rate (IRR), %	6.2
Annual charge, %	13
Natural gas price, Euro/MJ	0.0036
Fertiliser price, Euro/t	4.7
Carbon tax, Euro/t	40

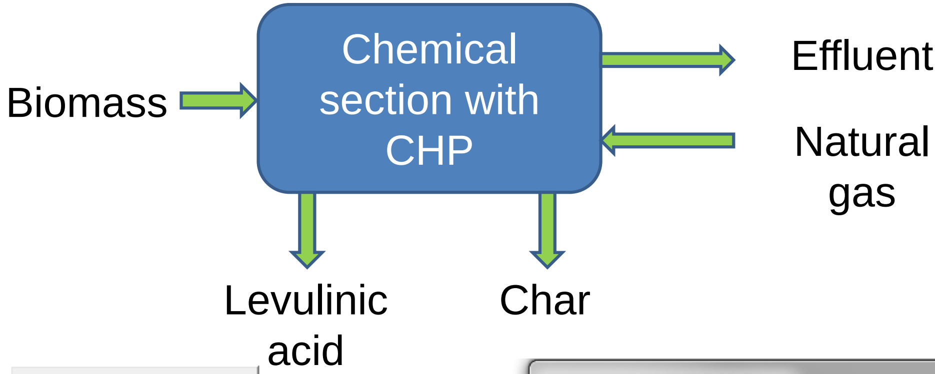


Discounted cash flow analysis

OUTPUT	
Payback time, years	3.9
Annual capital cost, million Euro/y	39.9
Cash flow, million Euro/y	39.1

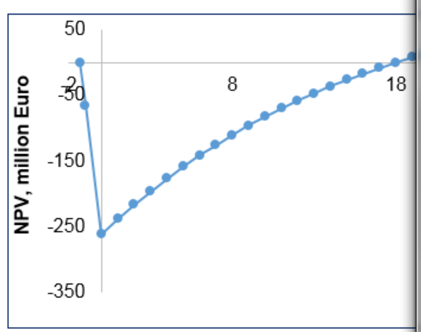


Case 2: Economic Analysis (Lignocellulose from MSW)

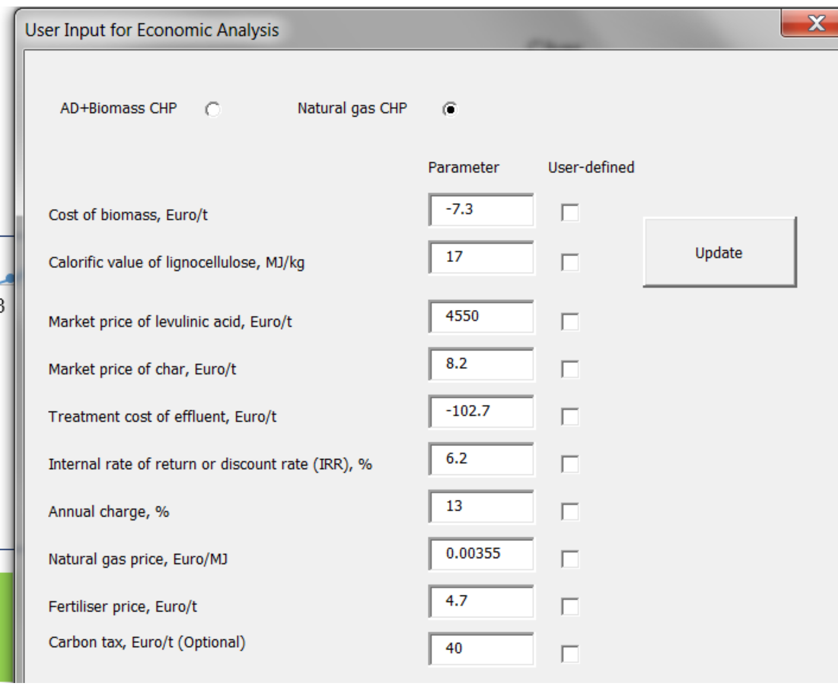


Back to Home | To Flowsheet | User Input

USER INPUT	
SELECT 1 FOR AD+BIOMASS CHP OR 0 FOR NATURAL GAS HEAT	0
USER INPUT	
Cost of biomass, Euro/h	-7.3
Calorific value of lignocellulose, MJ/kg	17
(OPTIONAL) USER INPUT	
Market price of levulinic acid, Euro/t	4550
Market price of char, Euro/t	8.2
Treatment cost of effluent, Euro/t	-102.7
Internal rate of return or discount rate (IRR), %	6.2
Annual charge, %	13
Natural gas price, Euro/MJ	0.0036
Fertiliser price, Euro/t	4.7
Carbon tax, Euro/t	40

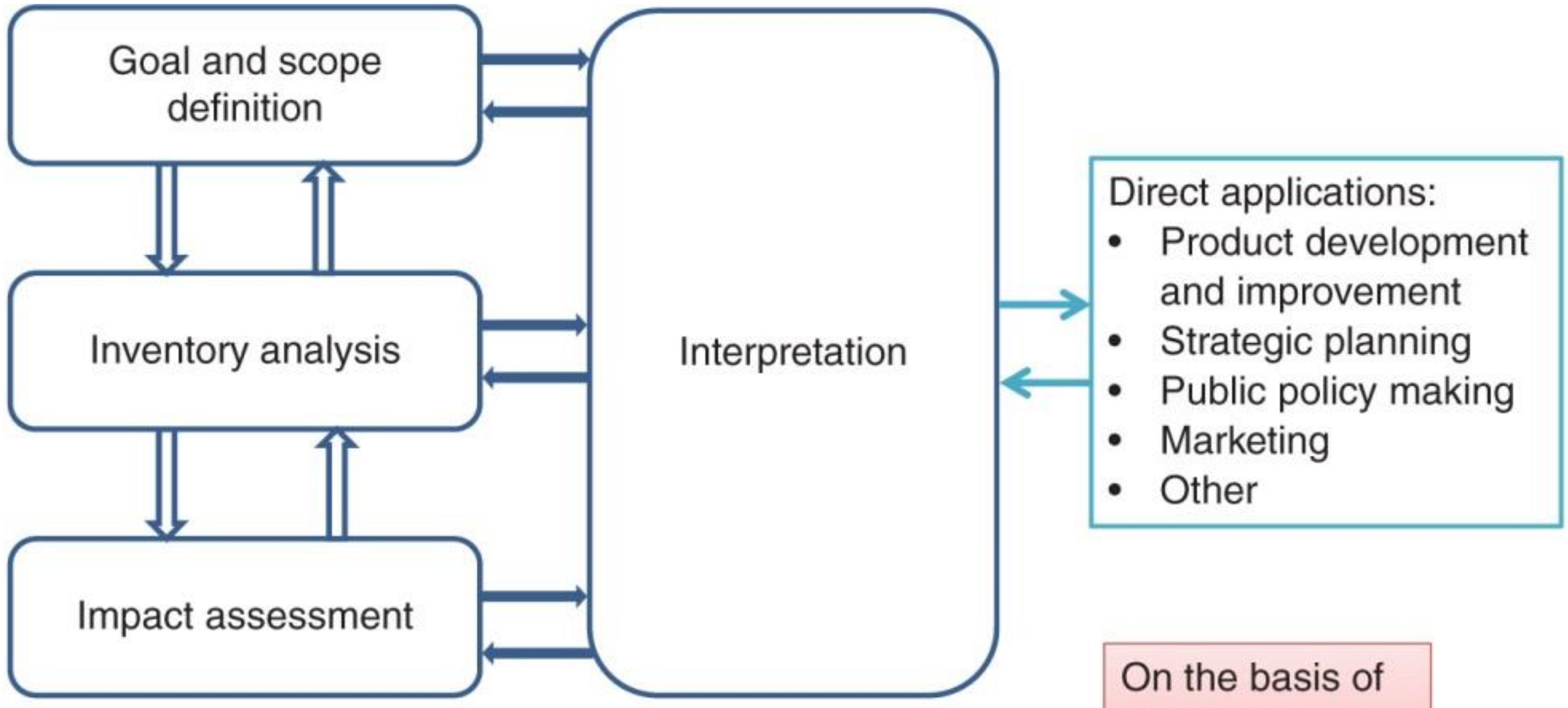


OUTPUT		Discounted cash flow analysis
Payback time, years	4.5	
Annual capital cost, million Euro/y	34.0	
Cash flow, million Euro/y	24.5	



Summary

- Variables for revenues include product values, feedstock costs, (credits, taxations, landfilling and gate fees, emission charges), etc.
- Influence of CHP configurations discussed
- Value analysis and EVEI analysis give graphical visualisation of comprehensive performance analysis of individual streams in a system



On the basis of ISO standards 14040, 14041 and 14044

Life Cycle Assessment (LCA)

Biorefineries and Chemical Processes: Design, Integration and Sustainability Analysis, First Edition.
Jhuma Sadhukhan, Kok Siew Ng and Elias Martinez Hernandez.

Companion Website: http://www.wiley.com/go/sadhukhan/biorefineries

Life Cycle Stages

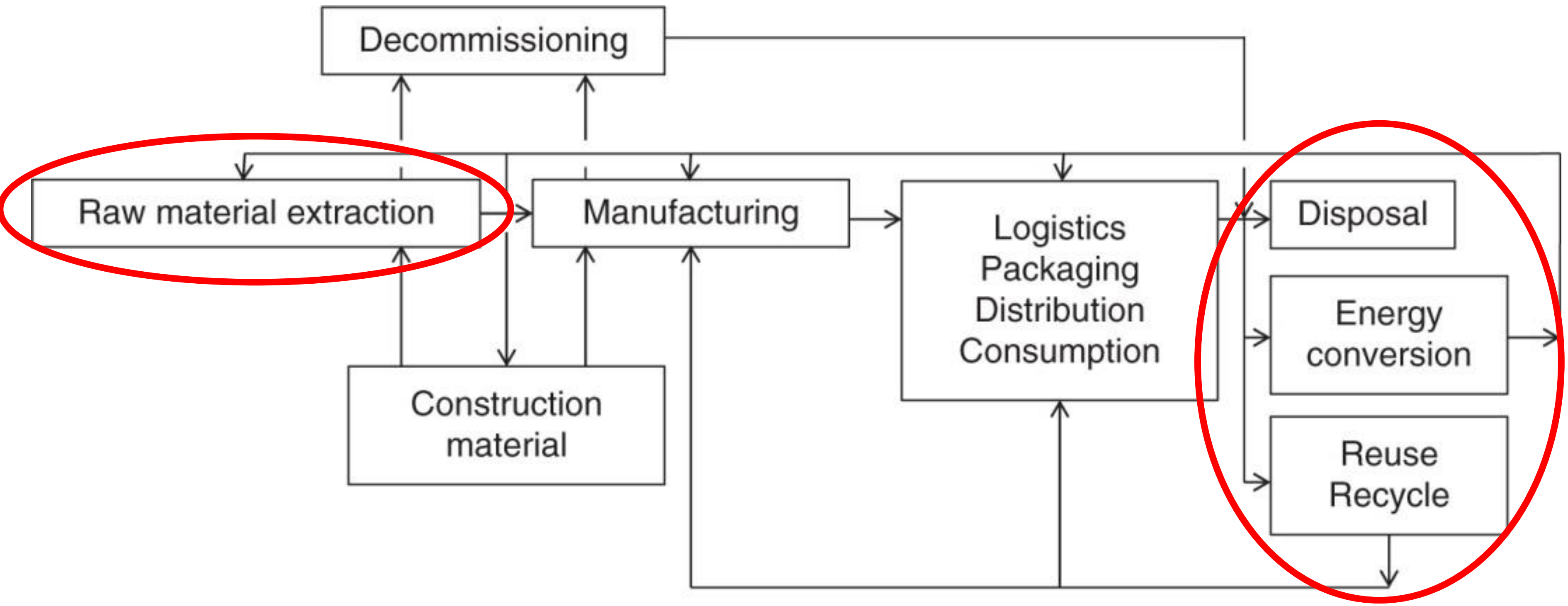


Figure 4.2 *Life cycle stages of a cradle to grave system.*

Biorefineries and Chemical Processes: Design, Integration and Sustainability Analysis, First Edition.
Jhuma Sadhukhan, Kok Siew Ng and Elias Martinez Hernandez.

Companion Website: http://www.wiley.com/go/sadhukhan/biorefineries

Life Cycle Stages

LCM stage impact	Material acquisition	R&D operations	Manufacturing operations	Customer needs	
				Use	Disposal
Environment					
Energy/Resources					
Health					
Safety					

Figure 4.6 *(above) LCA documents published by the International Organization for Standardization (ISO). (below) 3M, 1997, developed a Life Cycle Management framework for the assessment of risks and opportunities throughout the various stages of a product's life cycle.*

Biorefineries and Chemical Processes: Design, Integration and Sustainability Analysis, First Edition.
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Life Cycle Impact Assessment (LCIA) Methods

- Environmental quantities
  - CML 2001 - Nov. 2010
  - Earlier versions of methods
  - EDIP 2003
  - Impact 2002+
  - New impacts ILCD recommendation
  - ReCiPe 1.07
  - TRACI 2.1
  - UBP 2006
  - USEtox
  - Water
  - Primary energy demand from ren. and non ren. resources (gross cal. value)
  - Primary energy demand from ren. and non ren. resources (net cal. value)
  - Primary energy from non ren. resources (gross cal. value)
  - Primary energy from non ren. resources (net cal. value)
  - Primary energy from renewable raw materials (gross cal. value)
  - Primary energy from renewable raw materials (net cal. value)

Figure 4.20 *LCIA methodologies and their impact characterizations available in LCA software (a to h).* ***(a)*** *LCIA methodologies available in LCA software.*

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<u>Environmental impacts (</u>CML 2010 method gives primary impacts: **http://www.cml.leiden.edu/research/industrialecology/researchprojects/finished/new-dutch-lca-guide.html)**

1. **Global warming potential (kg CO_2 equivalent)**
2. **Ozone layer depletion potential (kg R-11 equivalent; Chlorofluorocarbon-11 or CFC-11 or Refrigerant-11)**
3. **Acidification potential (kg SO_2 equivalent)**
4. **Photochemical oxidant creation potential (kg Ethylene equivalent)**
5. **Eutrophication potential (kg Phosphate equivalent)**
6. **Freshwater aquatic ecotoxicity potential (kg DCB equivalent)**
7. **Marine aquatic ecotoxicity potential (kg DCB equivalent)**
8. **Human toxicity potential (kg DCB equivalent)**
9. **Terrestric ecotoxicity potential (kg DCB equivalent)**

DCB: 1, 4-dichlorobenzene

Impact 2002+

- I02+ v2.1 - Aquatic acidification - Midpoint
- I02+ v2.1 - Aquatic ecotoxicity - Midpoint
- I02+ v2.1 - Aquatic eutrophication - Midpoint
- I02+ v2.1 - Carcinogens - Midpoint
- I02+ v2.1 - Global warming 500yr - Midpoint
- I02+ v2.1 - Ionizing radiation - Midpoint
- I02+ v2.1 - Land occupation - Midpoint
- I02+ v2.1 - Mineral extraction - Midpoint
- I02+ v2.1 - Non-carcinogens - Midpoint
- I02+ v2.1 - Non-renewable energy - Midpoint
- I02+ v2.1 - Ozone layer depletion - Midpoint
- I02+ v2.1 - Photochemical oxidation - Midpoint
- I02+ v2.1 - Respiratory effects - Midpoint
- I02+ v2.1 - Terrestrial acidification/nutrification - Midpoint
- I02+ v2.1 - Terrestrial ecotoxicity - Midpoint

Figure 4.20(e) *Mid-point impact characterizations included in Impact 2002+.*

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- New impacts ILCD recommendation
  - Acidification, accumulated exceedance
  - CML2002 Resource Depletion, fossil and mineral, reserve Based
  - IPCC global warming, excl biogenic carbon
  - IPCC global warming, incl biogenic carbon
  - Particulate matter/Respiratory inorganics, RiskPoll
  - Terrestrial eutrophication, accumulated exceedance
  - Total freshwater consumption, including rainwater (acc. to UBP 2006)

Figure 4.20(f) *New impacts recommended in ILCD.*

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- TRACI 2.1
  - TRACI 2.1, Acidification Air
  - TRACI 2.1, Acidification Water
  - TRACI 2.1, Ecotoxicity (recommended)
  - TRACI 2.1, Eutrophication Air
  - TRACI 2.1, Eutrophication Water
  - TRACI 2.1, Global Warming Air
  - TRACI 2.1, Human Health Particulate Air
  - TRACI 2.1, Human toxicity, cancer (recommended)
  - TRACI 2.1, Human toxicity, non-canc. (recommended)
  - TRACI 2.1, Ozone Depletion Air
  - TRACI 2.1, Resources, Fossil fuels
  - TRACI 2.1, Smog Air
- UBP 2006
  - UBP 2006, Ecological scarcity method
- USEtox
  - USEtox, Ecotoxicity (recommended)
  - USEtox, Human toxicity, cancer (recommended)
  - USEtox, Human toxicity, non-canc. (recommended)
- Water
  - Blue water consumption
  - Blue water use
  - Total freshwater consumption (including rainwater)
  - Total freshwater use

Figure 4.20(h) *Primary impact characterizations included in TRACI, UBP, USEtox and Water.*

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Global Warming Potential Impact Characterisation

- The IPCC gives the following **classifications of pollutants** for global warming potential (GWP) impact assessment:
- Carbon dioxide, Methane, Nitrous oxide, Substances controlled by the Montreal Protocol, Hydrofluorocarbons, Perfluorinated compounds, Fluorinated ethers, Perfluoropolyethers, Hydrocarbons and other compounds – Direct Effects
- See: https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html

Types of LCA

- Stand-alone
  - Hot spot analysis of a technology or product life cycle
- Accounting
  - How does the sustainability of a technology compare against currently exploited technologies?
- Change oriented
  - How does the sustainability of a technology compare against future technologies in low carbon transition pathway through to 2050?
  - If the technology was integrated to an existing facility?

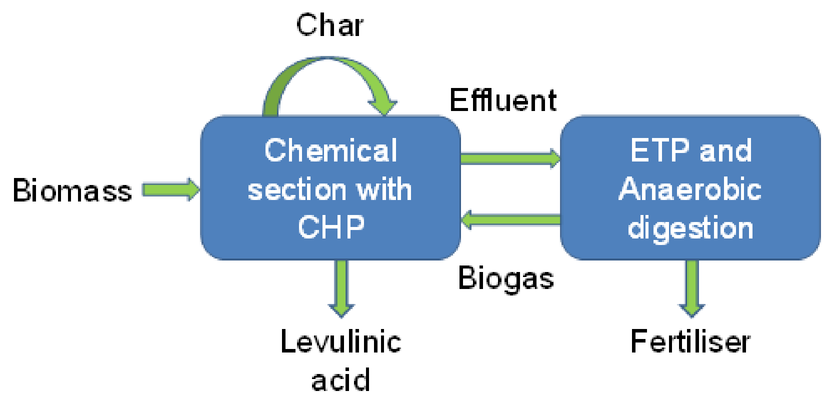
Working Session 4.4
(LCIA due to difference in CHP configuration)
Questions

Report LCIA results of lignocellulose from MSW, due to difference in CHP configuration.

Working Session 4.4
- Solutions

Case 1: LCIA (Lignocellulose from MSW)

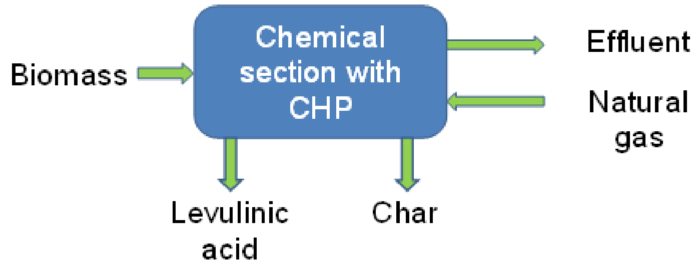
Back to Home | To Flowsheet



Data extracted for EU using Ecoinvent 3.0	Saving due to Levulinic Acid	Saving due to Fertiliser	Cost due to Biogas and Char	Net saving
Impact 2002+ Non-renewable energy savings - Midpoint [PJ/year]	1.0759	-0.0082	-0.1480	1.2157
CML				
Acidification Potential (AP) [kt SO_2-Equiv./year]	0.1719	0.2763	0.1815	0.2667
Eutrophication Potential (EP) [kt Phosphate-Equiv./year]	0.0493	0.0236	0.0503	0.0225
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kt DCB-Equiv./year]	3.7617	12.7284	3.2523	13.2378
Global Warming Potential (GWP 100 years) [kt CO_2-Equiv./year]	44.1477	31.0407	17.2873	57.9010
Human Toxicity Potential (HTP inf.) [kt DCB-Equiv./year]	43.5701	26.4997	7.8946	62.1753
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [Mt DCB-Equiv./year]	9.8209	40.2248	8.6174	41.4283
Ozone Layer Depletion Potential (ODP, steady state) [t R11-Equiv./year]	0.2621	0.0067	0.0008	0.2680
Photochem. Ozone Creation Potential (POCP) [kt Ethene-Equiv./year]	0.0326	0.0267	0.0109	0.0484
Terrestric Ecotoxicity Potential (TETP inf.) [kt DCB-Equiv./year]	0.2104	-0.5425	0.1480	-0.4800

Case 2: LCIA (Lignocellulose from MSW)

Back to Home | To Flowsheet



Data extracted for EU using Ecoinvent 3.0	Saving due to Levulinic Acid	Saving due to Char	Cost due to Natural Gas	Cost due to Effluent	Net saving
Impact 2002+ Non-renewable energy savings - Midpoint [PJ/year]	1.0759	1.9030E-04	2.2268	8.3335E-05	-1.1509
CML					
Acidification Potential (AP) [kt SO_2-Equiv./year]	0.1719	0.4171	0.1370	0.0577	0.3944
Eutrophication Potential (EP) [kt Phosphate-Equiv./year]	0.0493	0.1513	0.0347	0.6313	-0.4655
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kt DCB-Equiv./year]	3.7617	5.1168	3.8302	10.3781	-5.3298
Global Warming Potential (GWP 100 years) [kt CO_2-Equiv./year]	44.1477	33.7938	150.0887	72.8423	-144.9896
Human Toxicity Potential (HTP inf.) [kt DCB-Equiv./year]	43.5701	12.0959	5.8138	3.0134	46.8388
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [Mt DCB-Equiv./year]	9.8209	17.6787	11.0639	7.9629	8.4728
Ozone Layer Depletion Potential (ODP, steady state) [t R11-Equiv./year]	0.2621	0.0337	0.0212	5.2194E-04	0.2741
Photochem. Ozone Creation Potential (POCP) [kt Ethene-Equiv./year]	0.0326	0.0596	0.0275	0.0157	0.0490
Terrestric Ecotoxicity Potential (TETP inf.) [kt DCB-Equiv./year]	0.2104	0.2385	0.1396	0.1033	0.2061

Working Session 4.5
(Effect of biomass composition on environmental performance)
Questions

Compare EVEI between lignocellulose from MSW, sugarcane bagasse, blue agave bagasse and sago bark using the default economic basis.

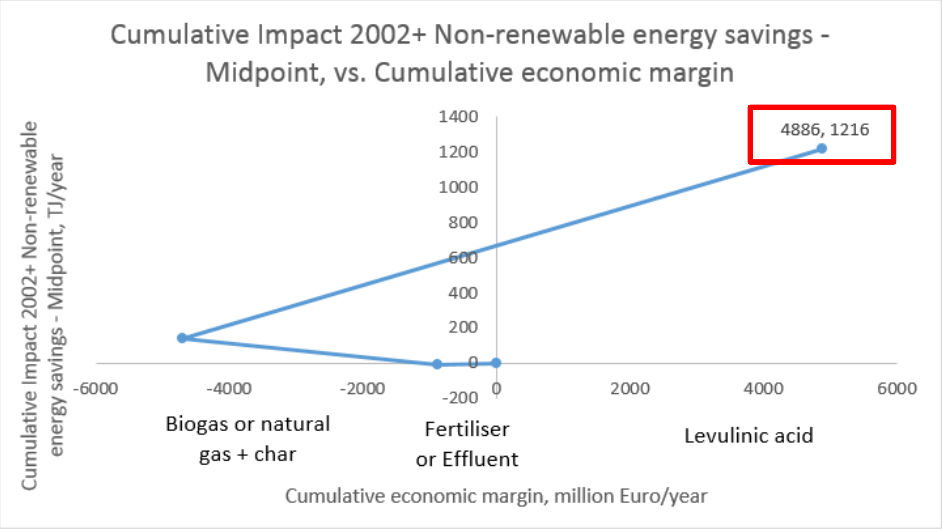
It may be useful to set up a table like this

	Lignocellulose from MSW	Sugarcane bagasse	Blue agave bagasse	Sago bark (runs on natural gas)

Working Session 4.5 - Solution

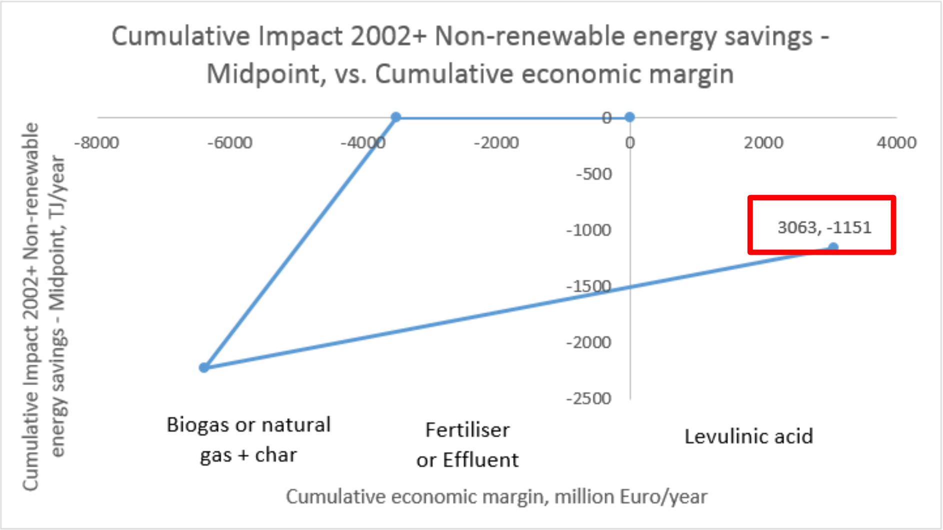
Case 1: EVEI Analysis (Lignocellulose from MSW)

	Cumulative economic margin million Euro/year	Cumulative Impact 2002+ Non-renewable energy savings - Midpoint TJ/year
	0	0
Saving due to Fertiliser	-878	-8
Saving due to biogas and char as fuel to CHP	-4693	140
Saving due to Levulinic Acid	4886	1216



Case 2: EVEI Analysis (Lignocellulose from MSW)

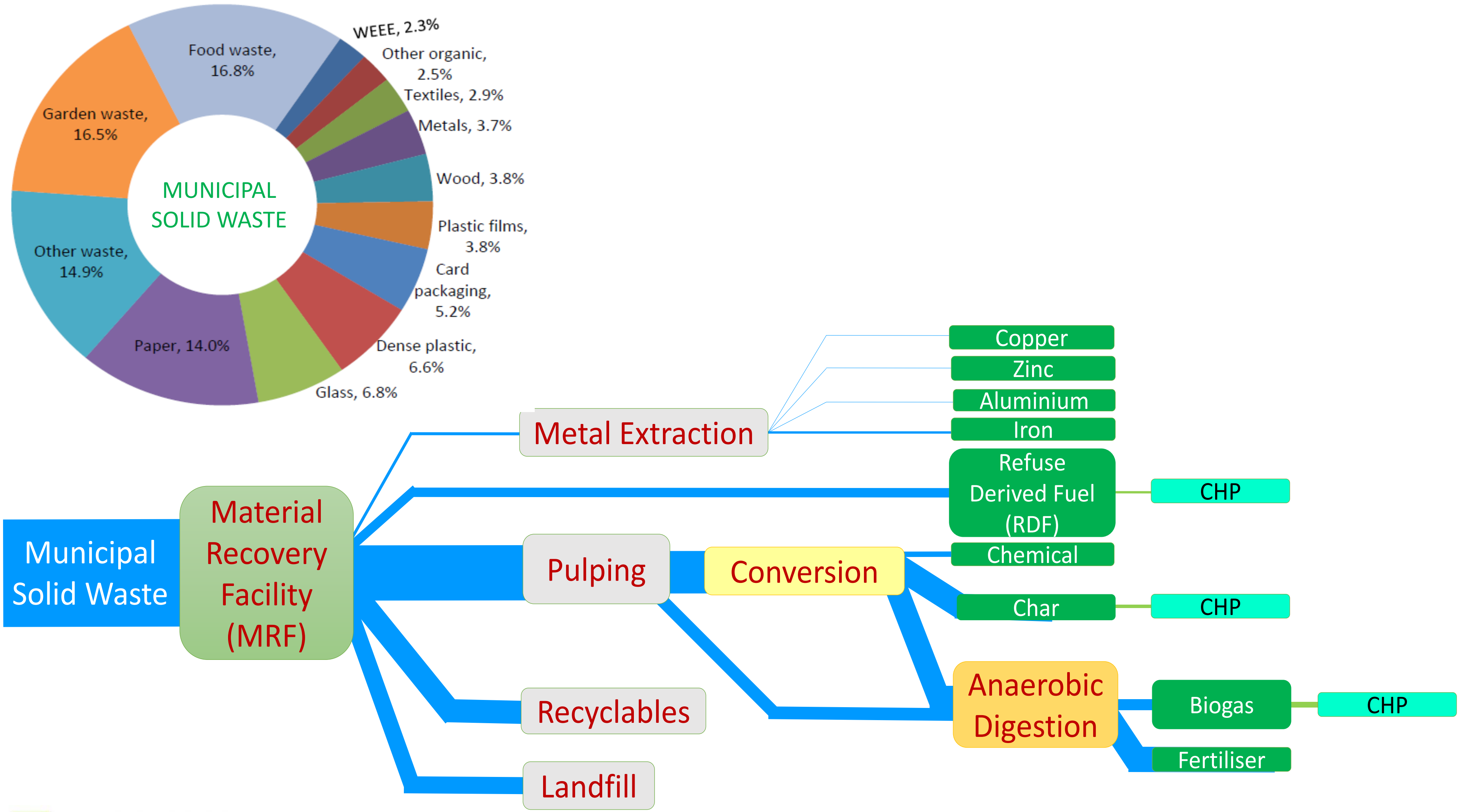
	Cumulative economic margin million Euro/year	Cumulative Impact 2002+ Non-renewable energy savings - Midpoint TJ/year
	0	0
Saving due to effluent	-3509	0
Saving due to natural gas as fuel to CHP and char as product	-6376	-2227
Saving due to Levulinic Acid	3063	-1151



Results' table looks like this

	Lignocellulose from MSW	Sugarcane bagasse	Blue agave bagasse	Sago bark (runs on natural gas)
Cumulative economic margin, million Euro/year	4886	2831	5650	1128
Cumulative Impact 2002+ fossil energy savings – Midpoint, TJ/year	1216	970	1262	-2247

Mass Transfer From Waste To Products



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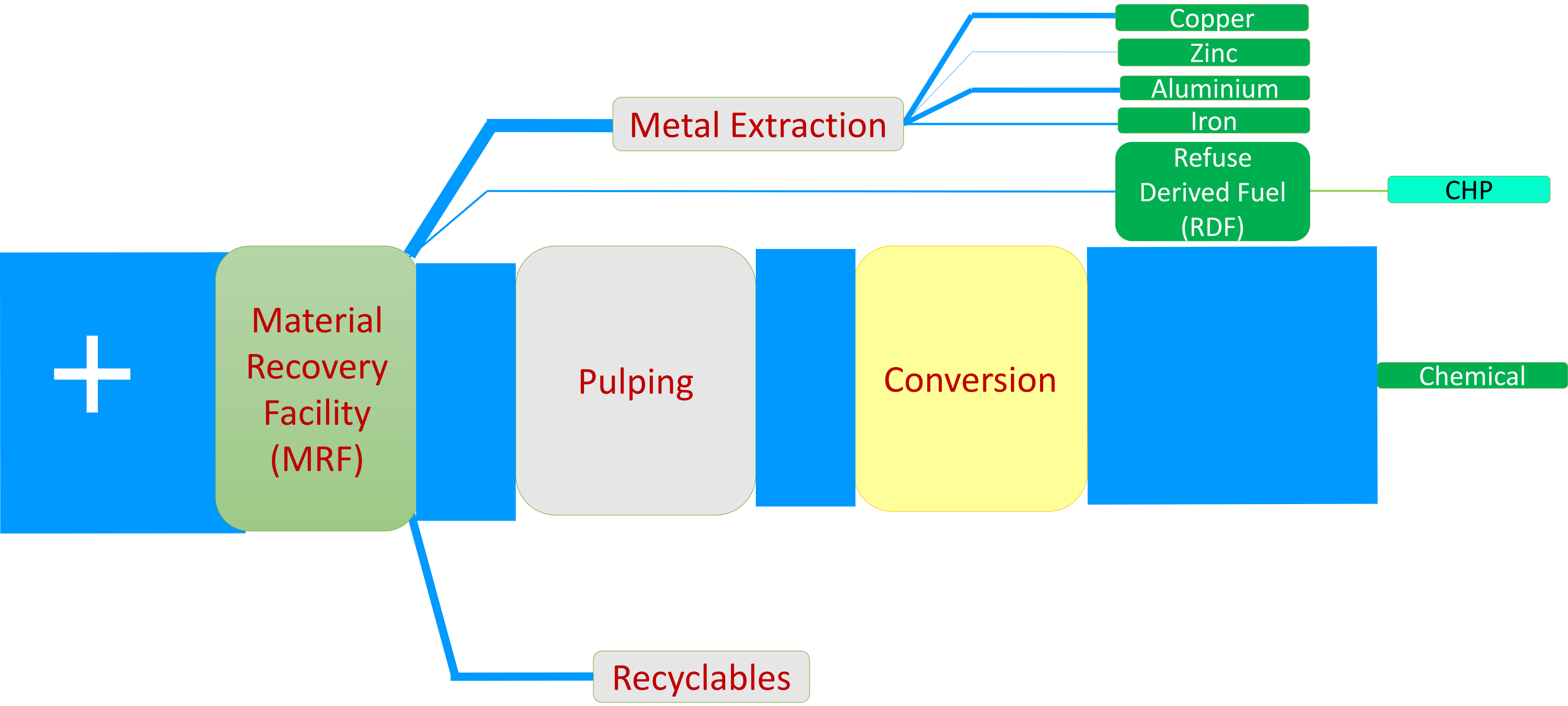
Value Analysis From Waste To Profitable Products



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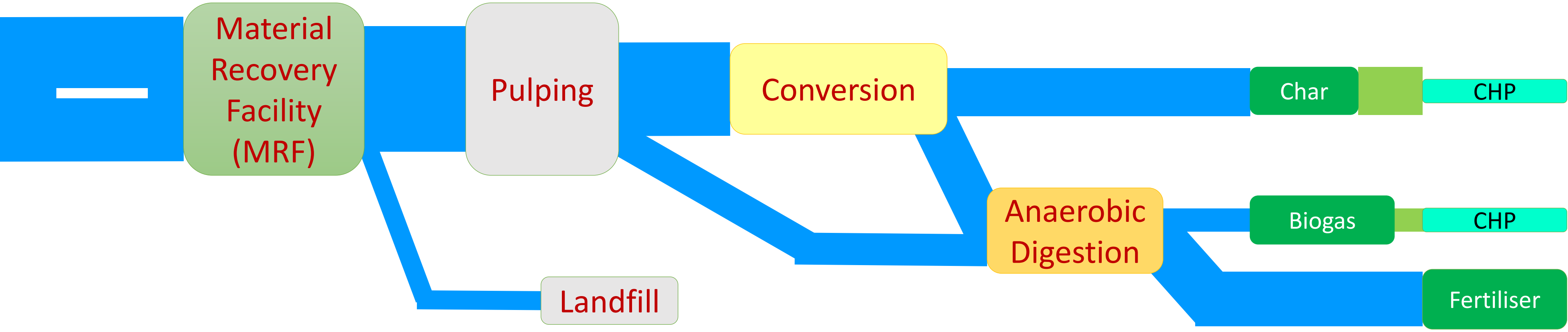
Value Analysis From Waste To Non-profitable Products



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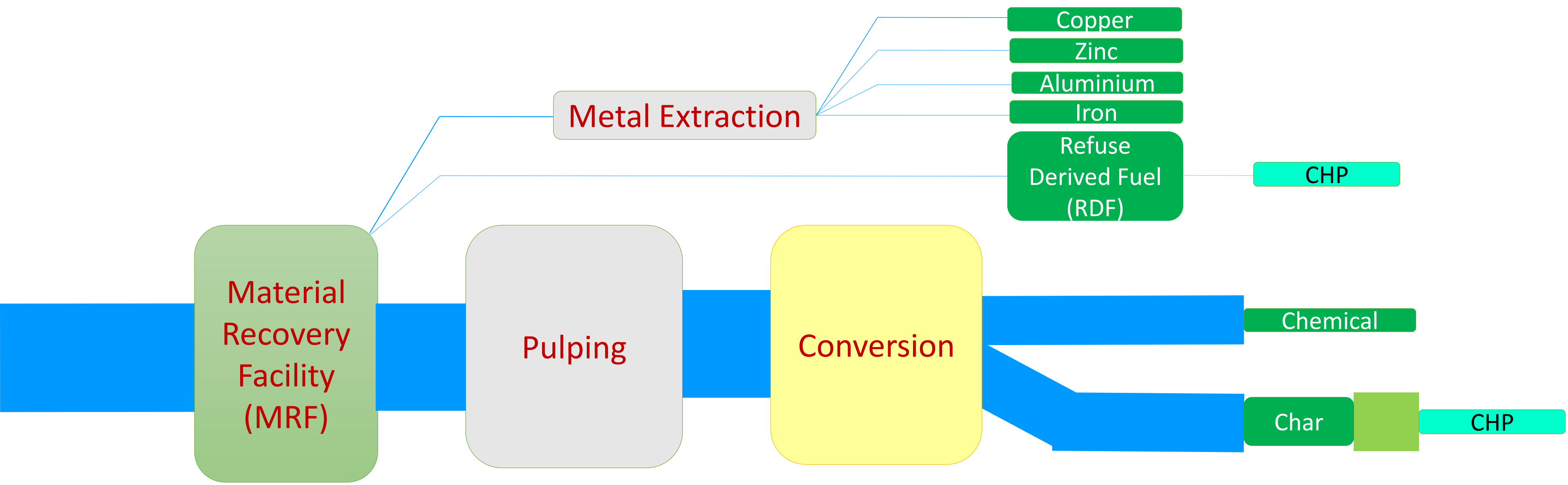
Fossil Energy Savings From Waste To Products



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Workshop on Sustainable Biorefineries

Lecture 5: Enhancing energy and resource efficiency by multi-platform biorefinery systems

Dr Kok Siew Ng
Dr Jhuma Sadhukhan
Dr Elias Martinez Hernandez

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Objectives

- To understand how in-process energy integration can be attained.
- To understand the structure and components in a utility system.
- To understand how multi-site integration can be attained.

Integrated Gasification Combined Cycle

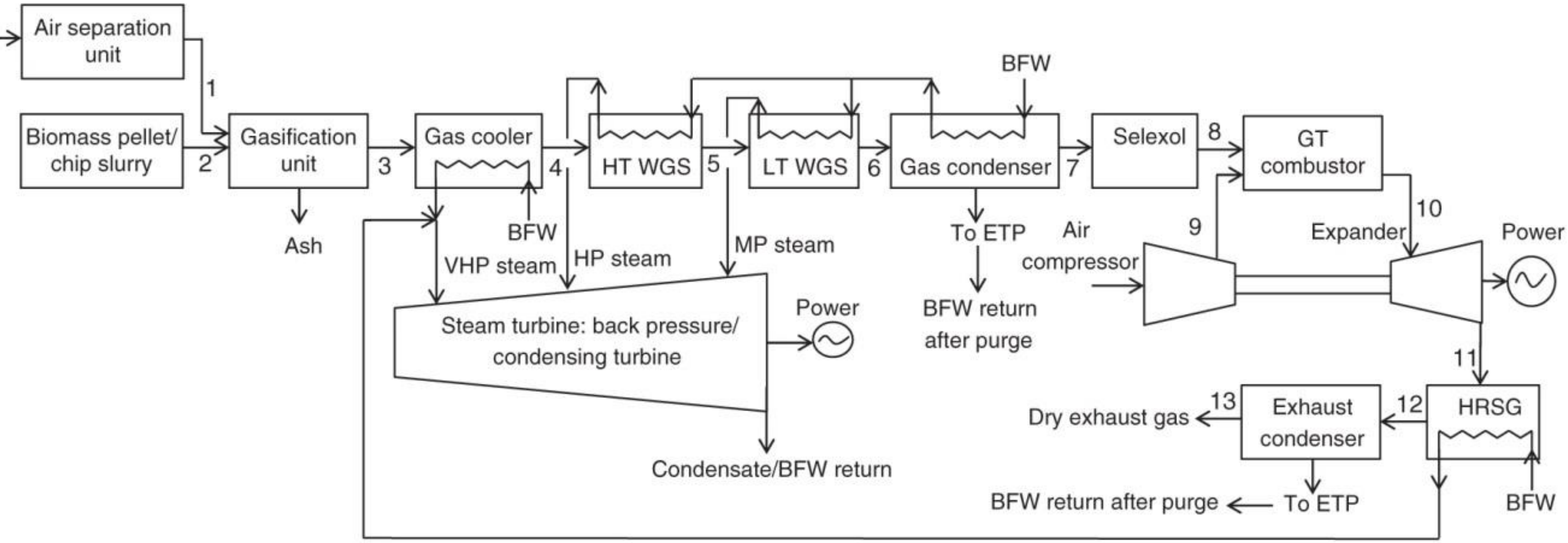

Figure 4.13 *Biomass integrated gasification combined cycle (BIGCC) flowsheet configuration. BFW, boiler feed water; ETP, effluent treatment plant; GT, gas turbine; HRSG, heat recovery steam generator; HP, high pressure; MP, medium pressure; VHP, very high pressure.*

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Biomass Gasification Fuel Cell System

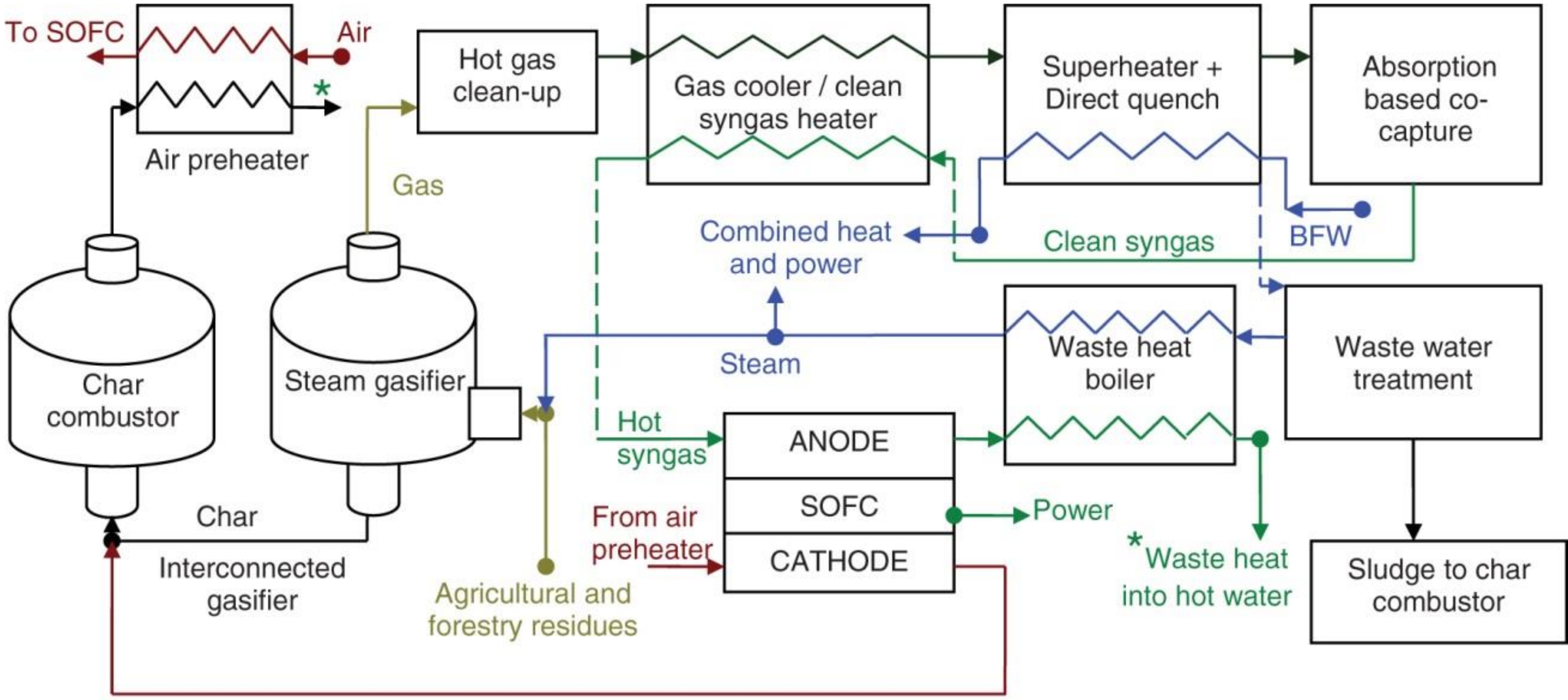

Figure 16.3 *BGFC schematic. (Reproduced with permission from Sadhukhan* et al. *(2010)*[3]. *Copyright © 2010, Elsevier.)*

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Utility System

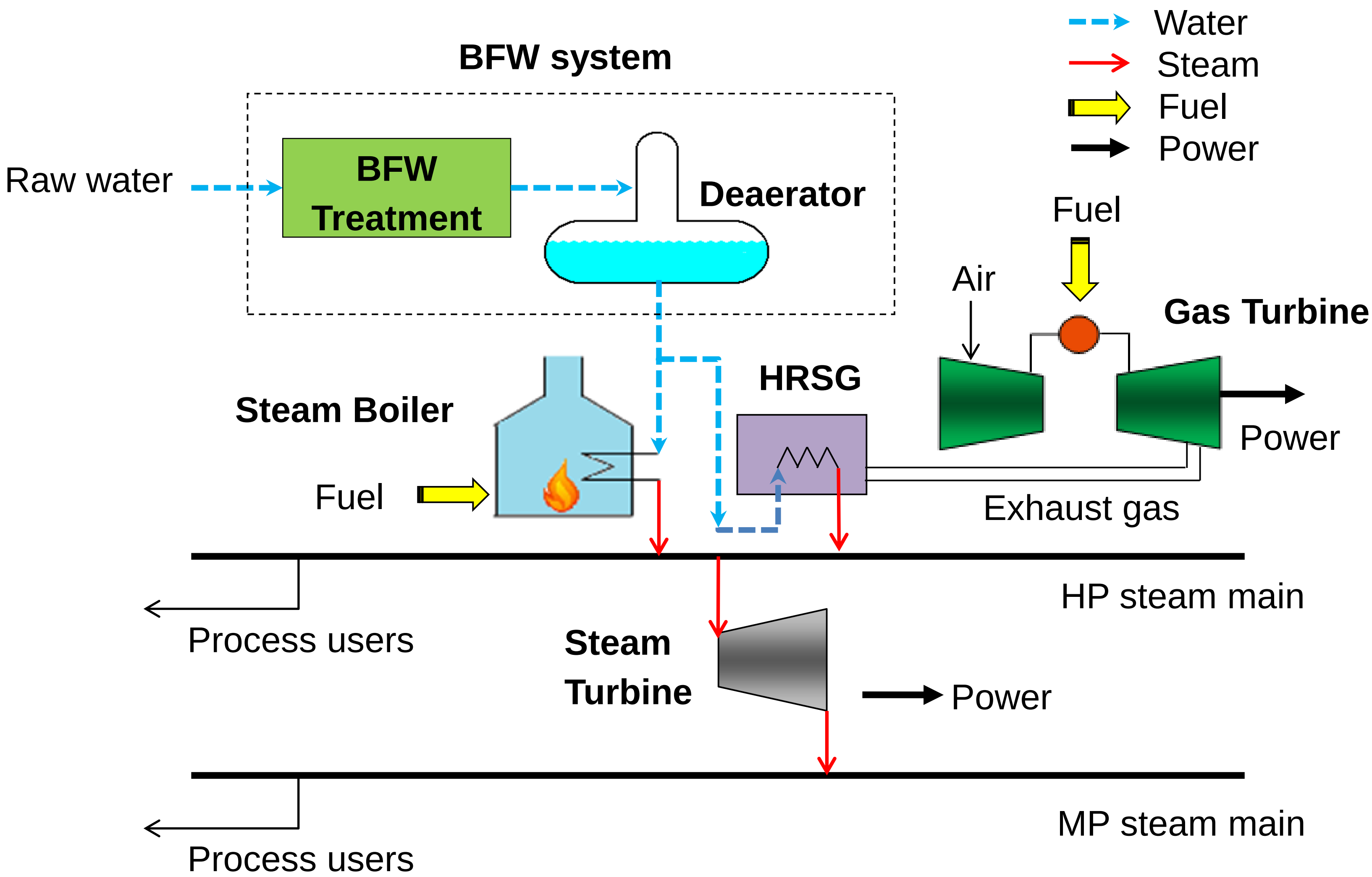
- Comprise all energy flows within the plant

- Intimate interaction between utility system and main processes

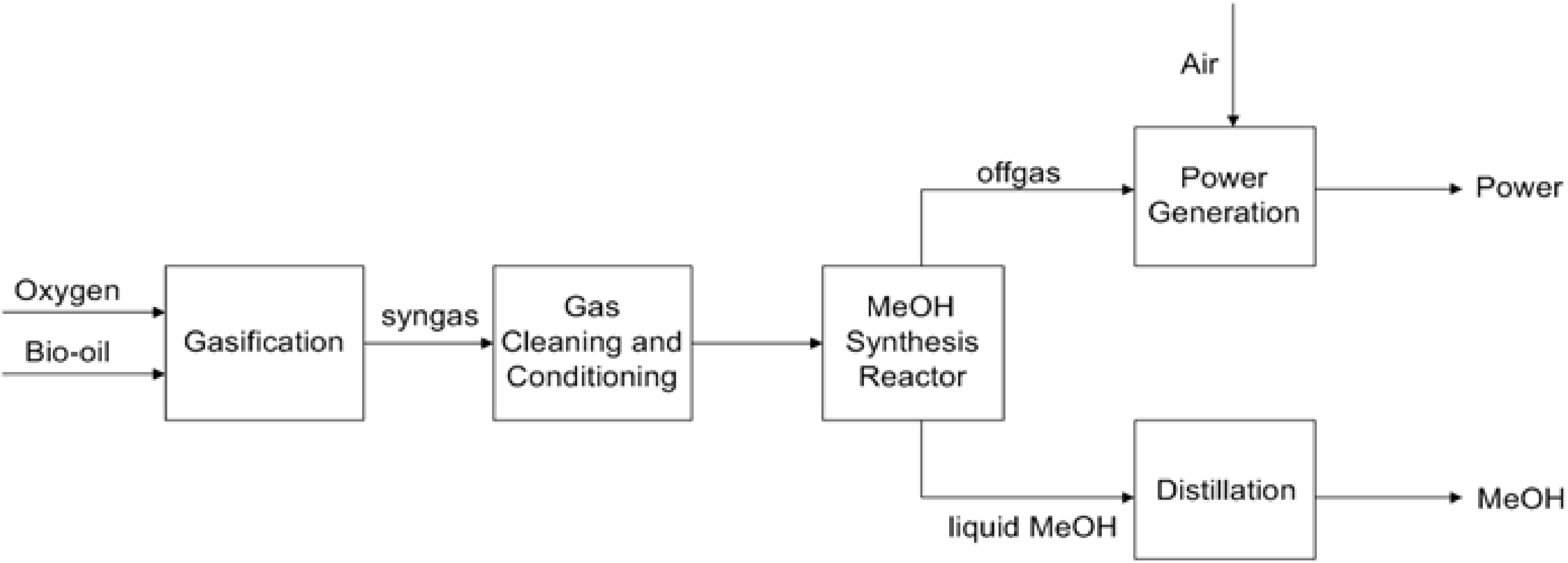
- The role of utility system in a process plant:
  - Supply heating and cooling demands
  - Supply power (from grid or on-site generation)
  - Meeting total site energy balance

- Highly efficient utility system would lead to
  - Minimum use of energy
  - Minimum energy cost

Utility System: Overview



Integrated Gasification of Bio-oil with Production of Methanol and CHP



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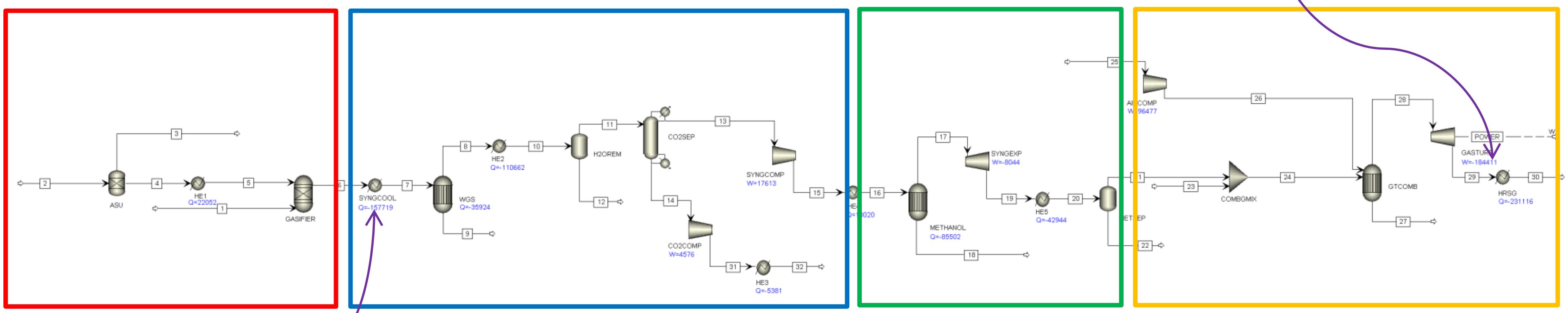
Integrated Gasification of Bio-oil with Production of Methanol and CHP

HRSG (730 – 100°C, ΔH = 230 MW)



Gasification

Gas cleaning and conditioning

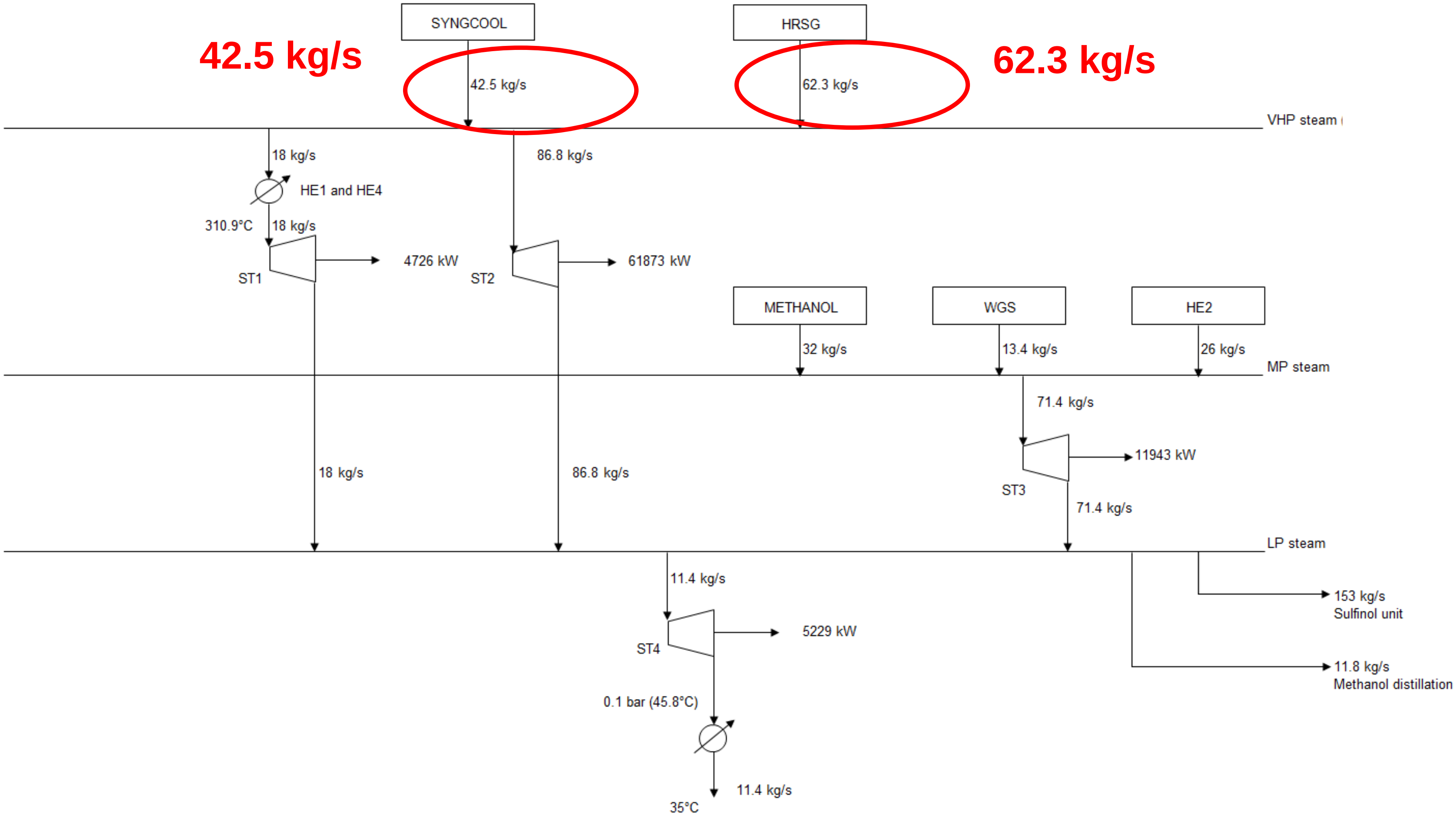
Methanol synthesis

Power generation

Syngas cooler (1100 – 450°C, ΔH = 158 MW)

©Ng, K.S., Sadhukhan, J. (2011). **Process integration and economic analysis of bio-oil platform for the production of methanol and combined heat and power.** *Biomass Bioenergy*, 35(3): 1153-1169.

Integrated Gasification of Bio-oil with Production of Methanol and CHP



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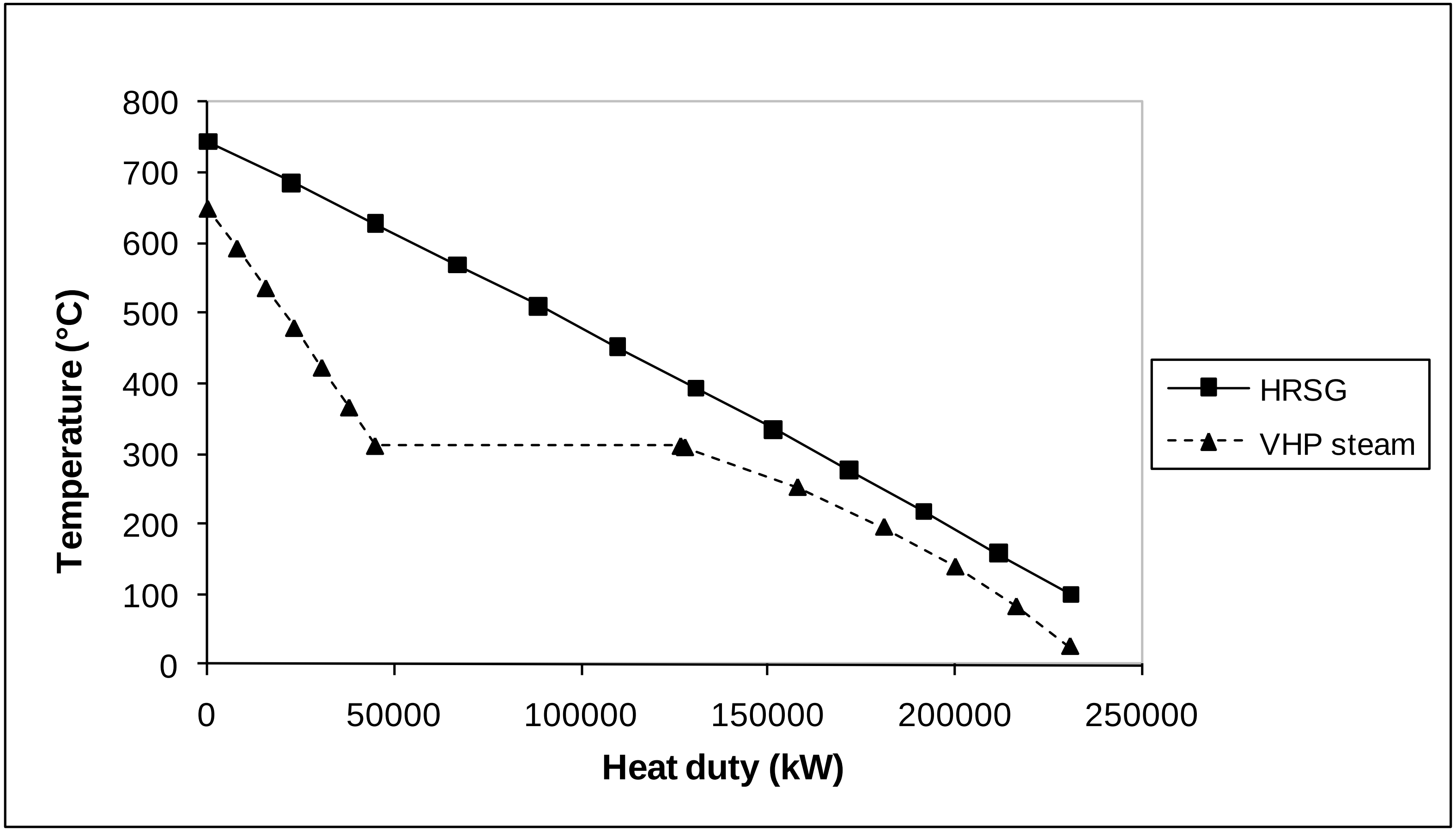
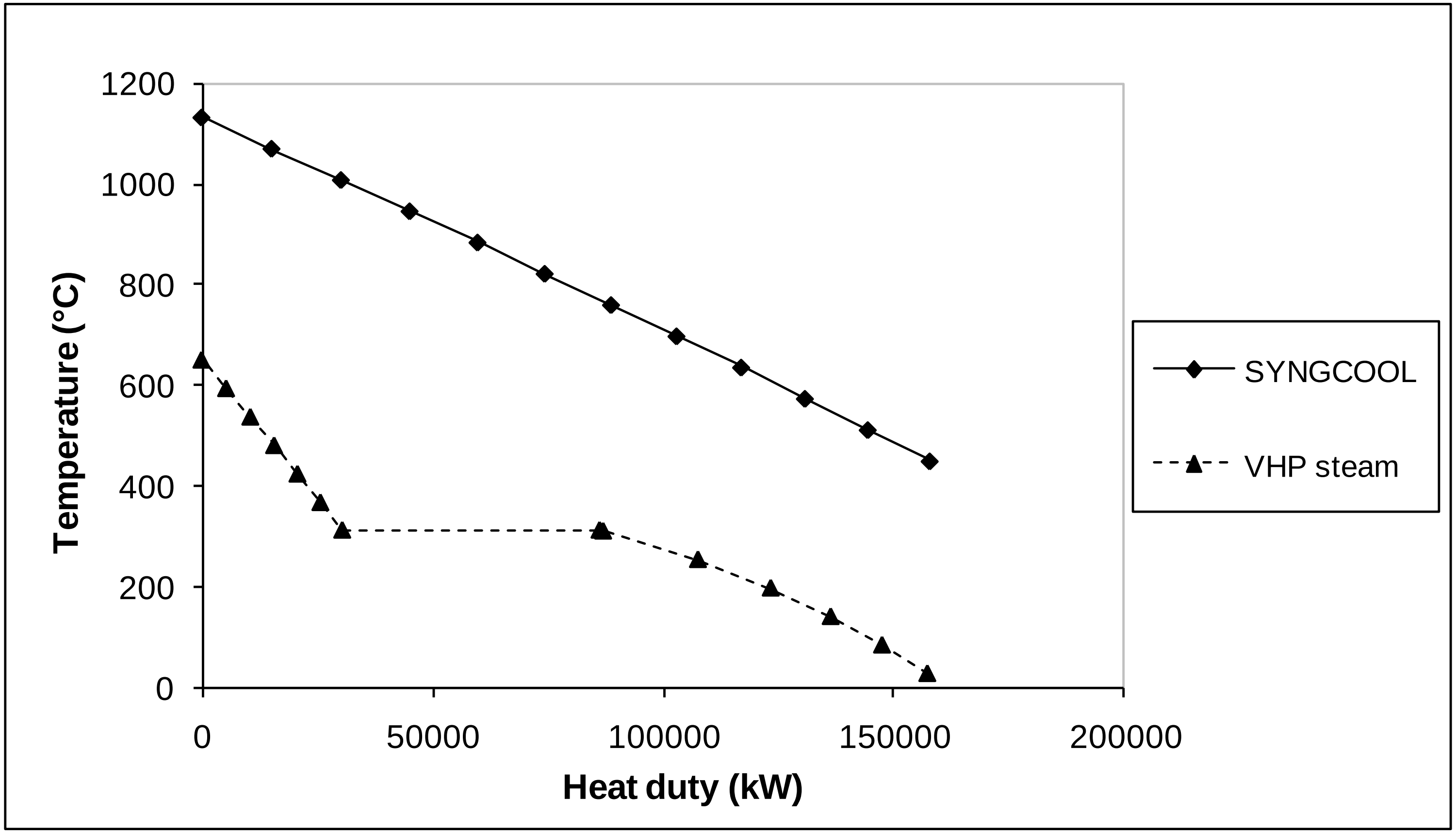
Integrated Gasification of Bio-oil with Production of Methanol and CHP

- Estimating maximum steam generation using composite curves.
- VHP steam generation from HRSG.
- ΔT_{min} = 20°C



Integrated Gasification of Bio-oil with Production of Methanol and CHP

- Estimating maximum steam generation using composite curves.
- VHP steam generation from syngas cooler.
- ΔT_{min} = 20°C



Advanced Biorefinery Options Based on Thermochemical Processing

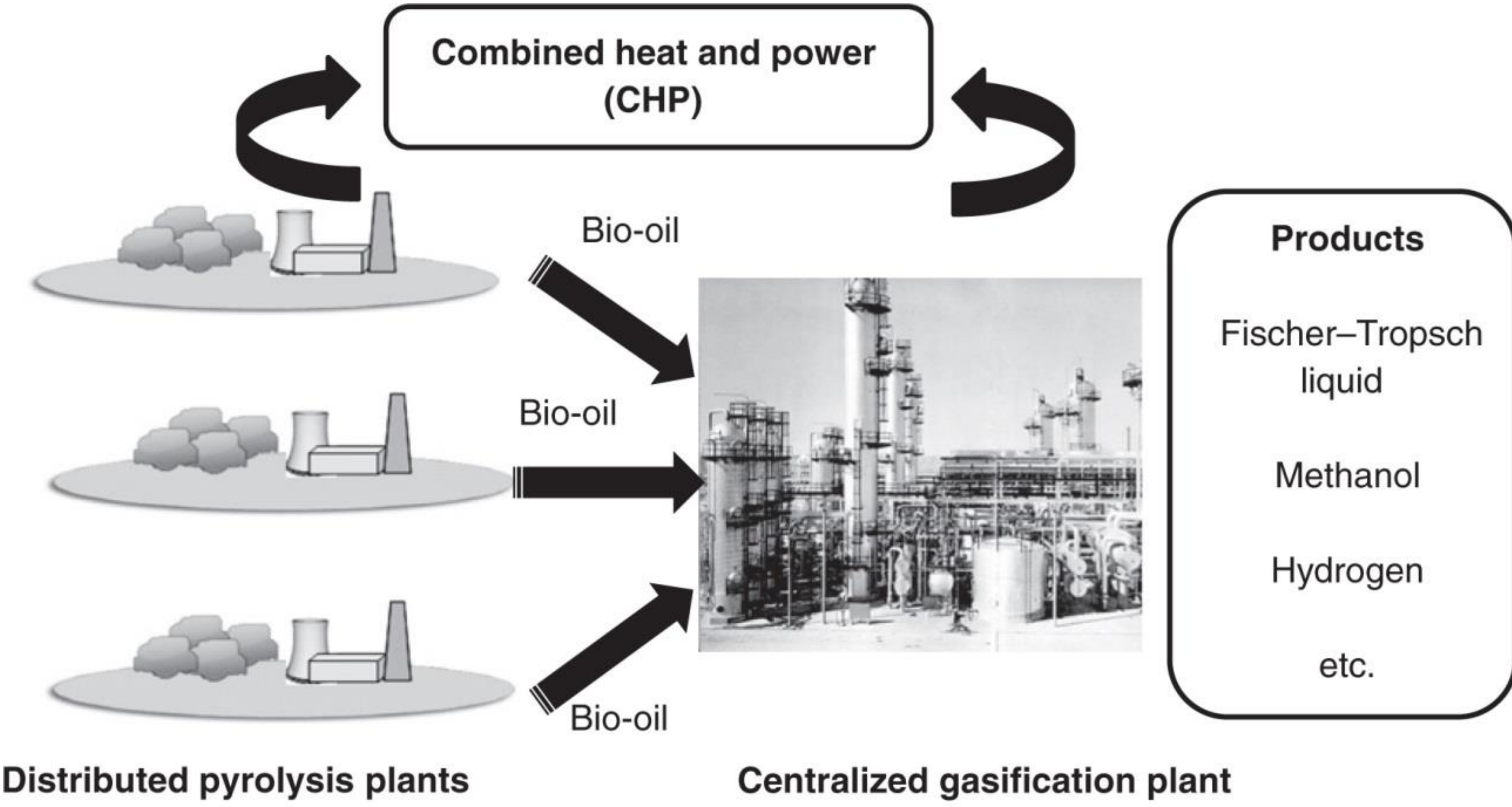


Figure 14.4 *Distributed processing of biomass and centralized processing of bio-oil.*

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Literature

BIOMASS AND BIOENERGY 35 (2011) 1153–1169

Available at www.sciencedirect.com

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Process integration and economic analysis of bio-oil platform for the production of methanol and combined heat and power

*Kok Siew Ng, Jhuma Sadhukhan**

Centre for Process Integration, School of Chemical Engineering and Analytical Science, University of Manchester, Manchester, M13 9PL, UK

Literature

BIOMASS AND BIOENERGY 35 (2011) 3218–3234

Available at www.sciencedirect.com

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http://www.elsevier.com/locate/biombioe

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Techno-economic performance analysis of bio-oil based Fischer-Tropsch and CHP synthesis platform

*Kok Siew Ng, Jhuma Sadhukhan**

Centre for Process Integration, Chemical Engineering, The University of Manchester, Manchester M13 9PL, UK

Literature

I&EC research
Industrial & Engineering Chemistry Research

ARTICLE

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Economic and European Union Environmental Sustainability Criteria Assesment of Bio-Oil-Based Biofuel Systems: Refinery Integration Cases

Jhuma Sadhukhan* and Kok Siew Ng

Process Integration, Chemical Engineering, The University of Manchester, Manchester M13 9PL, United Kingdom

ABSTRACT: The biofuel mix in transport in the U.K. must be increased from currently exploited 3.33% to the EU target mix of 10% by 2020. Under the face of this huge challenge, the most viable way forward is to process infrastructure-compatible intermediate, such as bio-oil from fast pyrolysis of lignocellulosic biomass, into biofuels. New facilities may integrate multiple distributed pyrolysis units producing bio-oil from locally available biomass and centralized biofuel production platforms, such as methanol or Fischer–Tropsch liquid synthesis utilizing syngas derived from gasification of bio-oil. An alternative to bio-oil gasification is hydrotreating and hydrocracking (upgrading) of bio-oil into stable oil with reduced oxygen content. The stable oil can then be coprocessed into targeted transportation fuel mix within refinery in exchange of refinery hydrogen to the upgrader. This Article focuses on the evaluation of economic and environmental sustainability of industrial scale biofuel production systems from bio-oils.

CO_2 Reuse

Chemical Engineering Journal 219 (2013) 96–108

Contents lists available at SciVerse ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

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Chemical Engineering Journal

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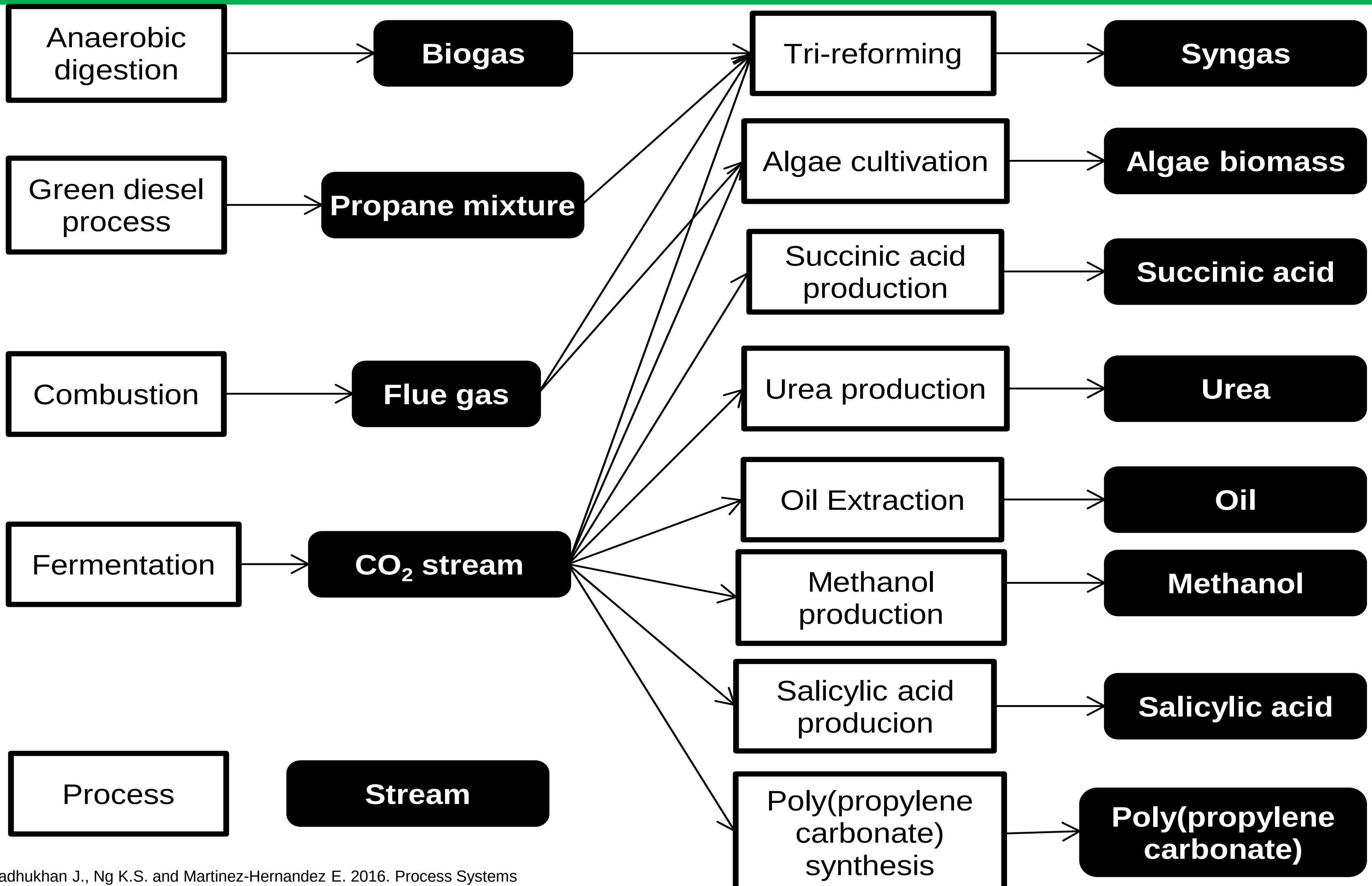
Techno-economic analysis of polygeneration systems with carbon capture and storage and CO_2 reuse

Kok Siew Ng[a], Nan Zhang[a], Jhuma Sadhukhan[b,*]

[a] *Centre for Process Integration, School of Chemical Engineering and Analytical Science, The University of Manchester, Manchester M13 9PL, UK*
[b] *Centre for Environmental Strategy, University of Surrey, Guildford GU2 7XH, UK*

Sadhukhan J., Ng K.S. and Martinez-Hernandez E. 2016. Process Systems Engineering Tools for Biomass Polygeneration Systems with Carbon Capture and Reuse. Chapter 9 in the Edited Book: *Process Design Strategies for Biomass Conversion Systems*, John Wiley & Sons, Inc.

CO_2 Reuse Roadmap



Sadhukhan J., Ng K.S. and Martinez-Hernandez E. 2016. Process Systems Engineering Tools for Biomass Polygeneration Systems with Carbon Capture and Reuse. Chapter 9 in the Edited Book: *Process Design Strategies for Biomass Conversion Systems*, John Wiley & Sons, Inc.

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CO_2 Reduction - Fuel and Chemical

Renewable and Sustainable Energy Reviews 56 (2016) 116–132

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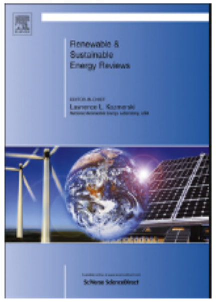

A critical review of integration analysis of microbial electrosynthesis (MES) systems with waste biorefineries for the production of biofuel and chemical from reuse of CO_2

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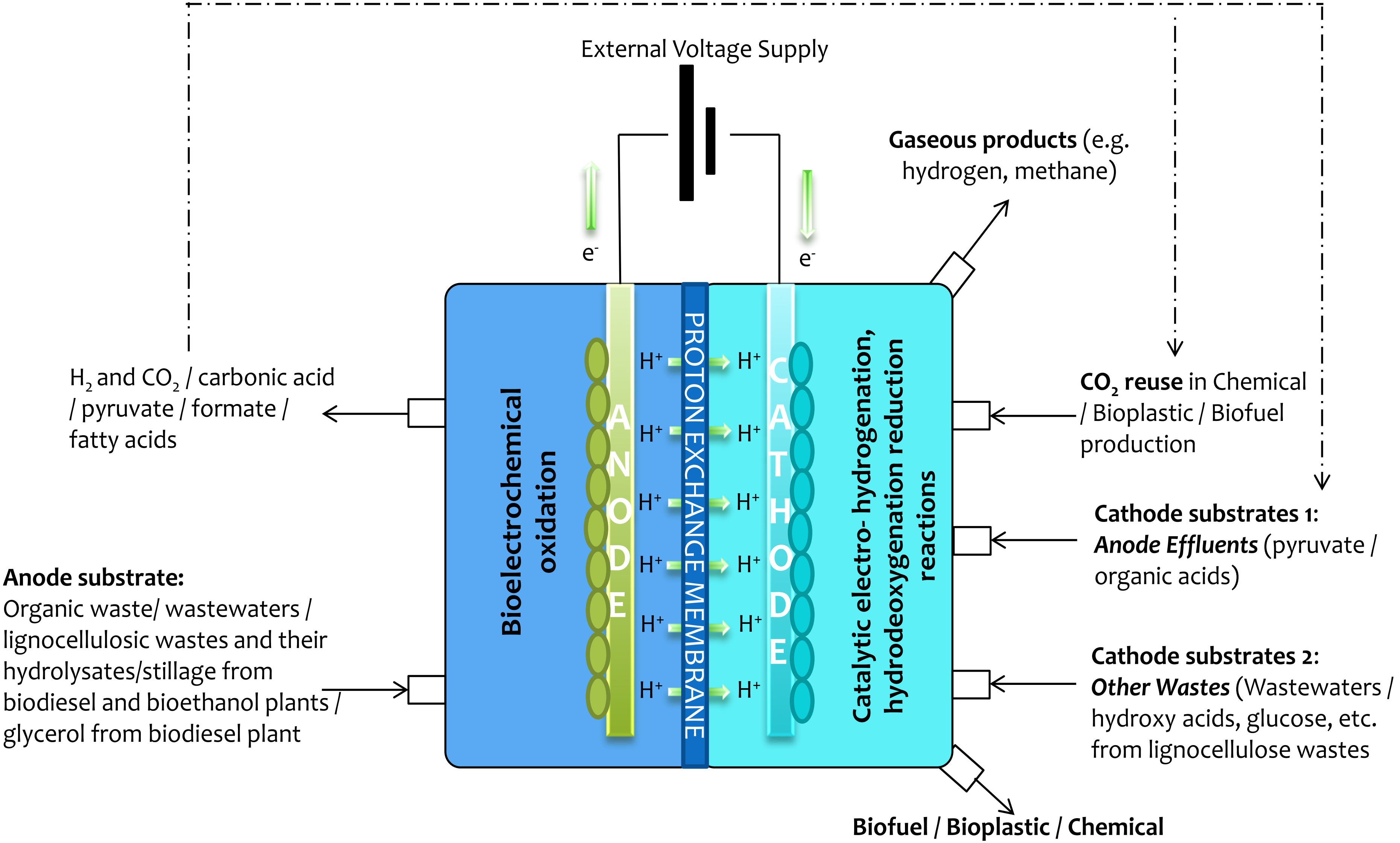
Jhuma Sadhukhan [a,*], Jon R. Lloyd [d], Keith Scott [c], Giuliano C. Premier [e], Eileen H. Yu [c], Tom Curtis [b], Ian M. Head [b]

[a] *Centre for Environmental Strategy, University of Surrey, Guildford, Surrey GU2 7XH, UK.*
[b] *School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne, Tyne and Wear NE1 7RU, UK.*
[c] *School of Chemical Engineering and Advanced Materials, Newcastle University, Newcastle upon Tyne, Tyne and Wear NE1 7RU, UK.*
[d] *Manchester Geomicrobiology Group, The University of Manchester, Oxford Road, Manchester M13 9PL, UK.*
[e] *Sustainable Environment Research Centre (SERC), Faculty of Computing, Engineering and Science University of South Wales, Pontypridd, Mid-Glamorgan CF37 1DL, UK*

MES Schematic



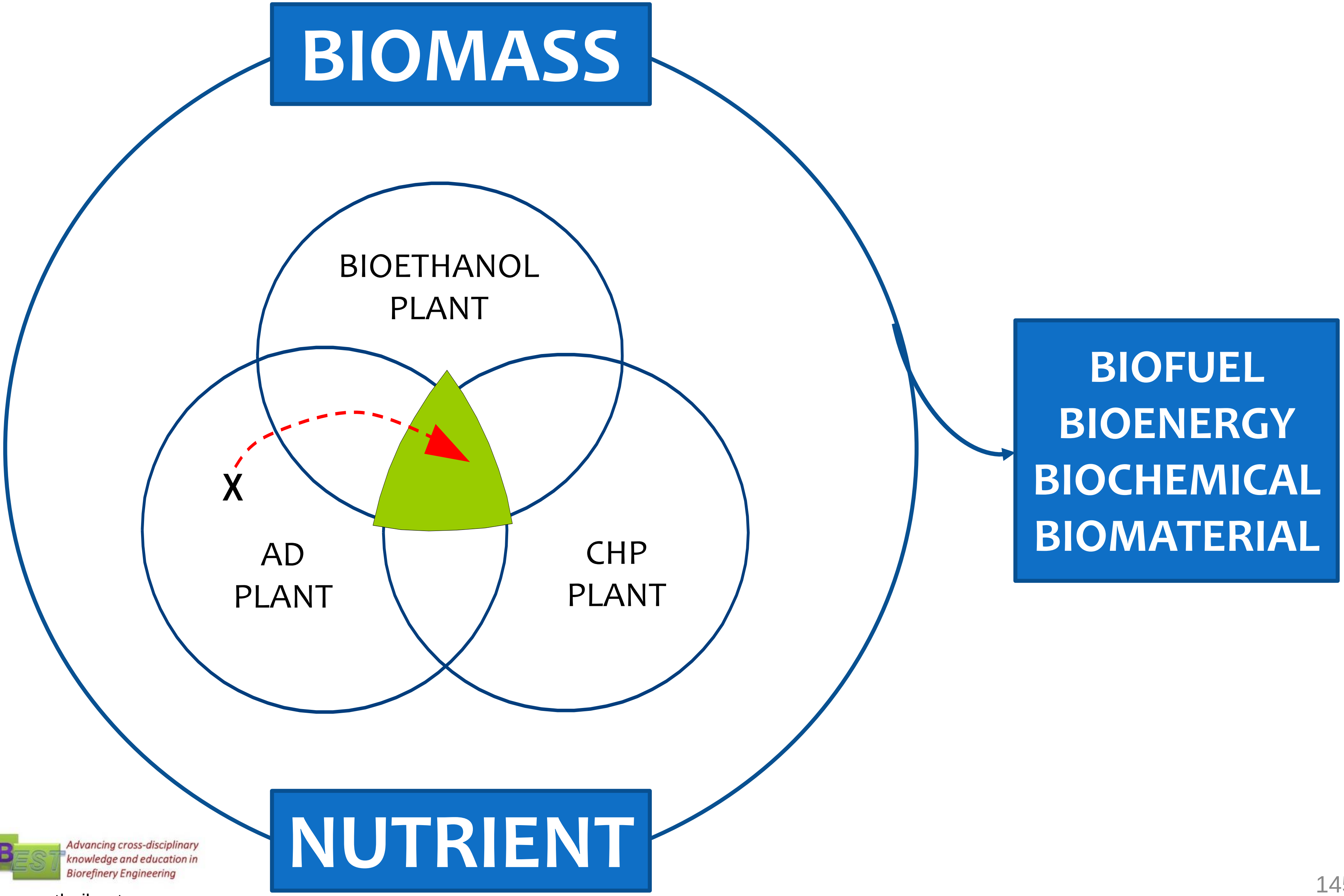
Sadhukhan, J., Lloyd, J., Scott, K., Premier, G.C., Yu, E., Curtis, T., and Head, I. (2016). **A Critical Review of Integration Analysis of Microbial Electrosynthesis (MES) Systems with Waste Biorefineries for the Production of Biofuel and Chemical from Reuse of CO_2**. *Renewable & Sustainable Energy Reviews*, 56, 116-132.

MES Products by CO_2 Reduction

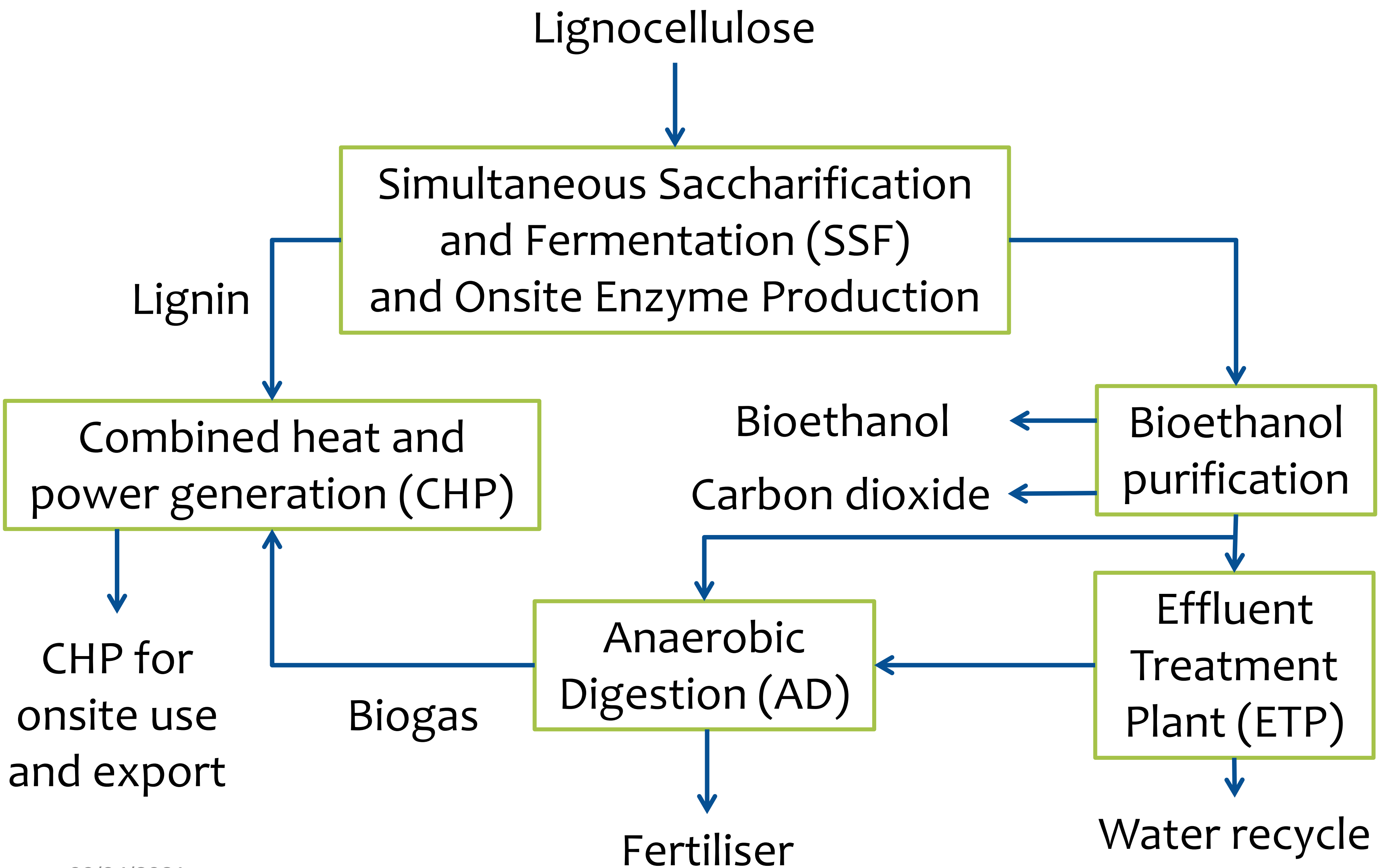
Product	Cathode reaction	$\Delta G^{\circ}_{cathode}$ (kJ/mol)
Formic acid	$HCO_3^- + H^+ + 2H_2 \rightarrow HCHO + 2H_2O$ (Formate dehydrogenase)	+21.8
Methane	$HCO_3^- + H^+ + 4H_2 \rightarrow CH_4 + 3H_2O$ (*Methanobacterium palustre*)	−135.6
Methanol	$HCO_3^- + H^+ + 3H_2 \rightarrow CH_3OH + 2H_2O$ Carbonic anhydrase, oxidoreductase enzymes	−23
Pyruvate	$3HCO_3^- + 2H^+ + 5H_2 \rightarrow Pyruvate^- + 6H_2O$	−57.3
Acetate	$2CO_2 + 4H_2 \rightarrow C_2H_3O_2^- + H^+ + 2H_2O$ (*Clostridium thermoaceticum*)	−94.96
Succinate	$Glycerol + CO_2 \rightarrow Succinate^{2-} + 2H^+ + H_2O$ (*Actinobacillus succinogenes*)	−44.5
Lactate	$Acetate^- + HCO_3^- + H^+ + 2H_2 \rightarrow Lactate^- + 2H_2O$	−4.2
Citrate	$Succinate^{2-} + 2HCO_3^- + H^+ + 2H_2 \rightarrow Citrate^{3-} + 3H_2O$	−23.8
Caproate, Caprylate	$3\ acetate^- + 2H^+ + 4H_2 \rightarrow Caproate^- + 4H_2O$ $Ethanol + Butyrate^- \rightarrow Caproate^- + H_2O$ (*Clostridium kluyveri*)	−96.6 −194
Butyrate	$2C_2H_3O_2^-(acetate) + H^+ + 2H_2 \rightarrow C_4H_7O_2^-(butyrate) + 2H_2O$ $Ethanol + Acetate^- \rightarrow Butyrate^- + H_2O$ (*Clostridium kluyveri*)	−48.3 −193

Sadhukhan, J., Lloyd, J., Scott, K., Premier, G.C., Yu, E., Curtis, T., and Head, I. (2016). **A Critical Review of Integration Analysis of Microbial Electrosynthesis (MES) Systems with Waste Biorefineries for the Production of Biofuel and Chemical from Reuse of CO_2**. *Renewable & Sustainable Energy Reviews*, 56, 116-132.

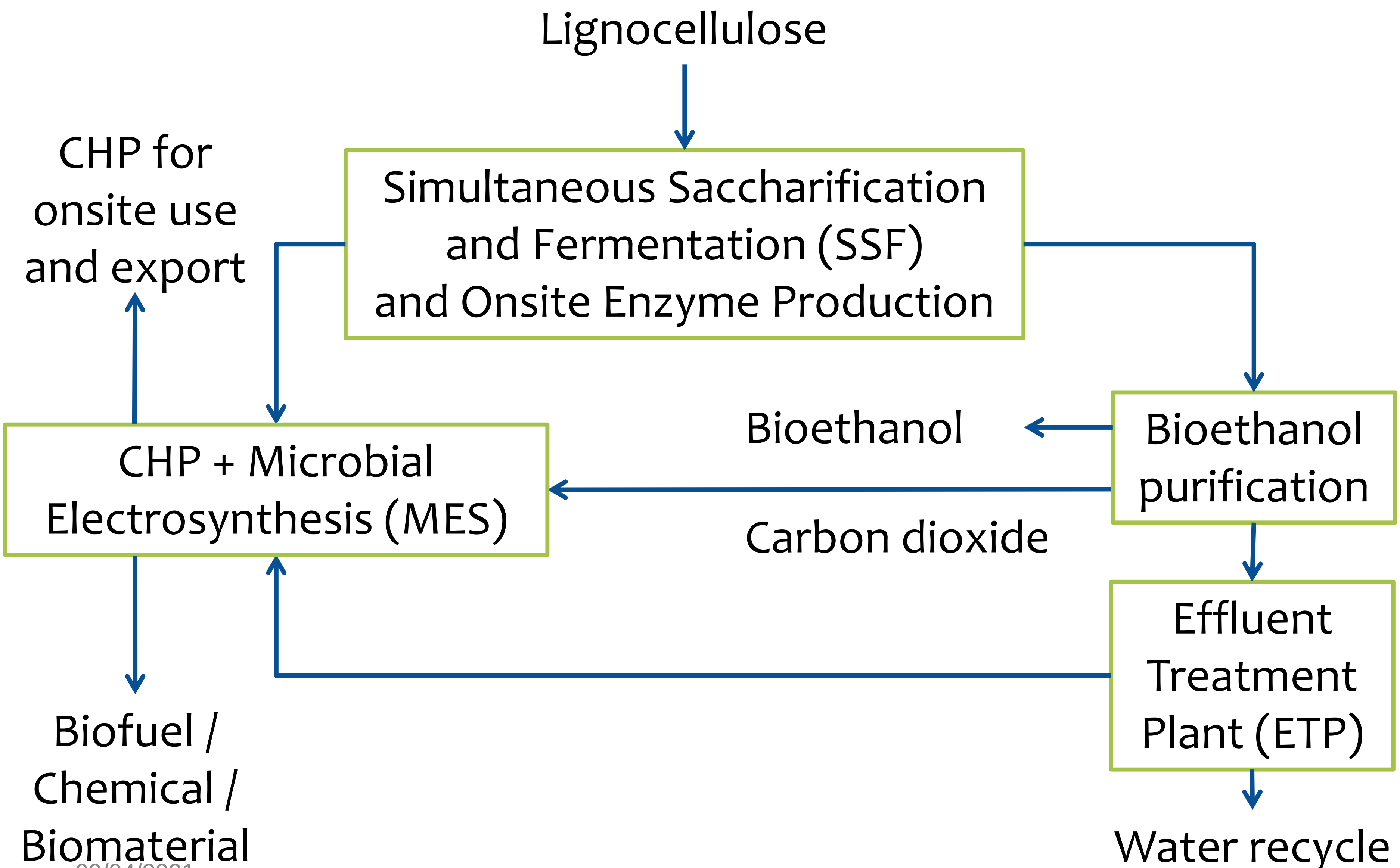
Multi-site Integration



Industrial Symbiosis



Industrial Symbiosis



Literature

1. Sadhukhan, J., Lloyd, J., Scott, K., Premier, G.C., Yu, E., Curtis, T., and Head, I. (2016). A Critical Review of Integration Analysis of Microbial Electrosynthesis (MES) Systems with Waste Biorefineries for the Production of Biofuel and Chemical from Reuse of CO_2. *Renewable & Sustainable Energy Reviews*, 56, 116-132.
2. Wan, Y.K., Sadhukhan, J., Ng, K.S. and Ng, D.K.S. (2016) Techno-economic evaluations for feasibility of sago-based biorefinery, Part 1: Alternative energy systems. *Chemical Engineering Research & Design*, Special Issue on Biorefinery Value Chain Creation, 107, 263-279.
3. Wan, Y.K., Sadhukhan, J., and Ng, D.K.S. (2016) Techno-economic evaluations for feasibility of sago-based biorefinery, Part 2: Integrated bioethanol production and energy systems. *Chemical Engineering Research & Design*, Special Issue on Biorefinery Value Chain Creation, 107, 102-116.

Life Cycle Sustainability Assessment (LCSA)

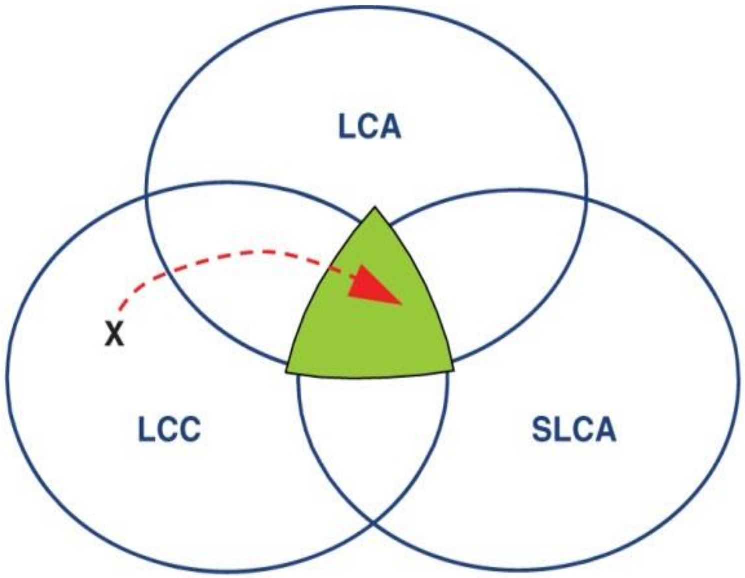


Figure 5.14 *Multicriteria analysis combining LCA, SLCA and LCC tools.*

Biorefineries and Chemical Processes: Design, Integration and Sustainability Analysis, First Edition.
Jhuma Sadhukhan, Kok Siew Ng and Elias Martinez Hernandez.

Companion Website: http://www.wiley.com/go/sadhukhan/biorefineries

Sustainable development calls for a multi-criteria analysis, called life cycle sustainability assessment (LCSA) including social, economic and environmental impact assessments. While LCA is a tool for environmental sustainability analysis, social and economic impacts can also be assessed over life cycles. These are called social LCA (SLCA) and life cycle cost (LCC), respectively. Similar to LCA, SLCA and LCC show corresponding hotspots and ways of mitigation. The hotspots can span across the time scale (life cycle) as well as geographic regions (supply chains).