Introduction to product-based bio-refinery concepts

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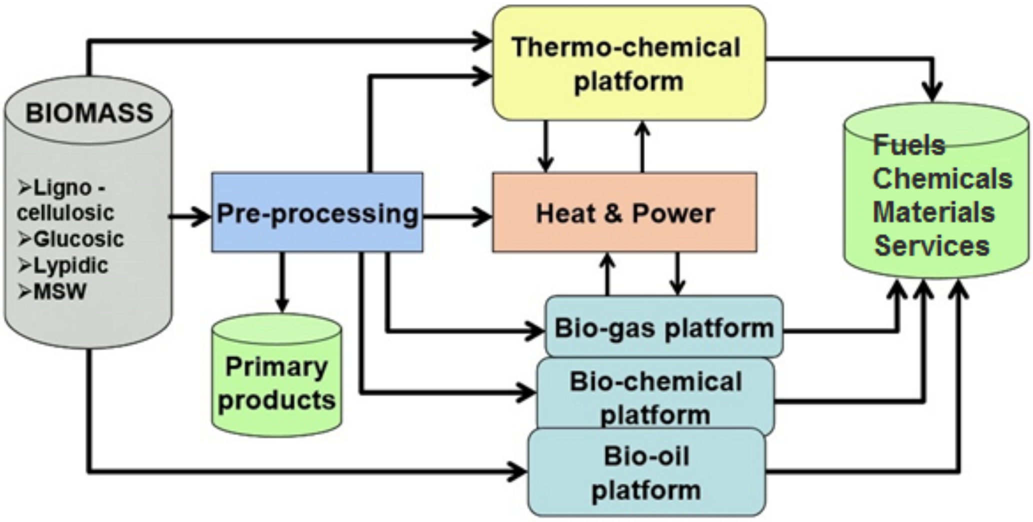
Outline

- Introduction
- Concept of biorefineries
- Conversion of Biomass
- Bio-Chemical Conversion Route
- Thermochemical Conversion Route
- Hybrid Conversion Process
- Process Integration
- Conclusions

Concept of biorefinery

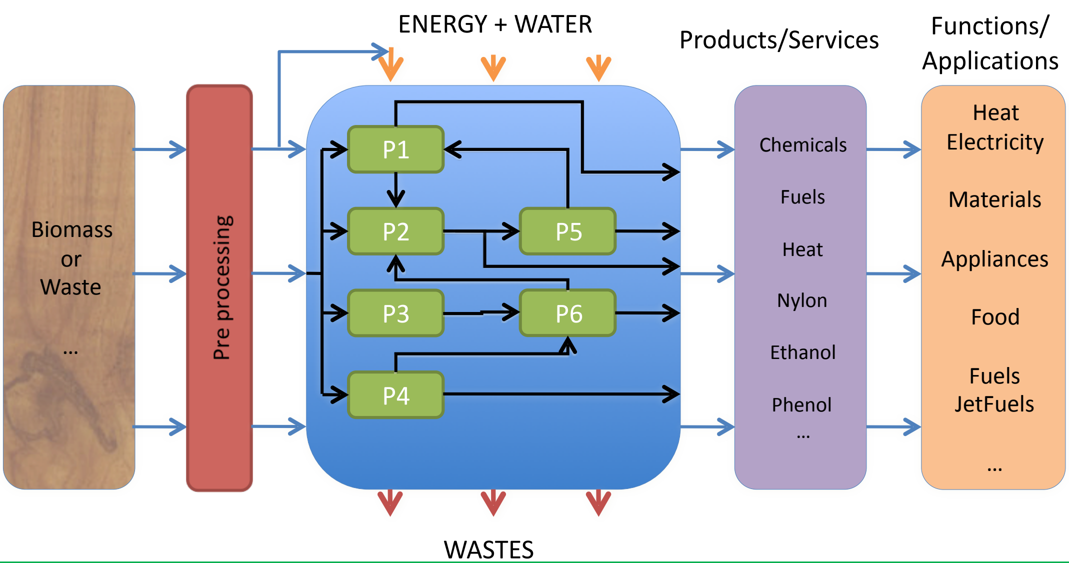
Adapted from: A. Dimian, Chemical Process Design, 2008



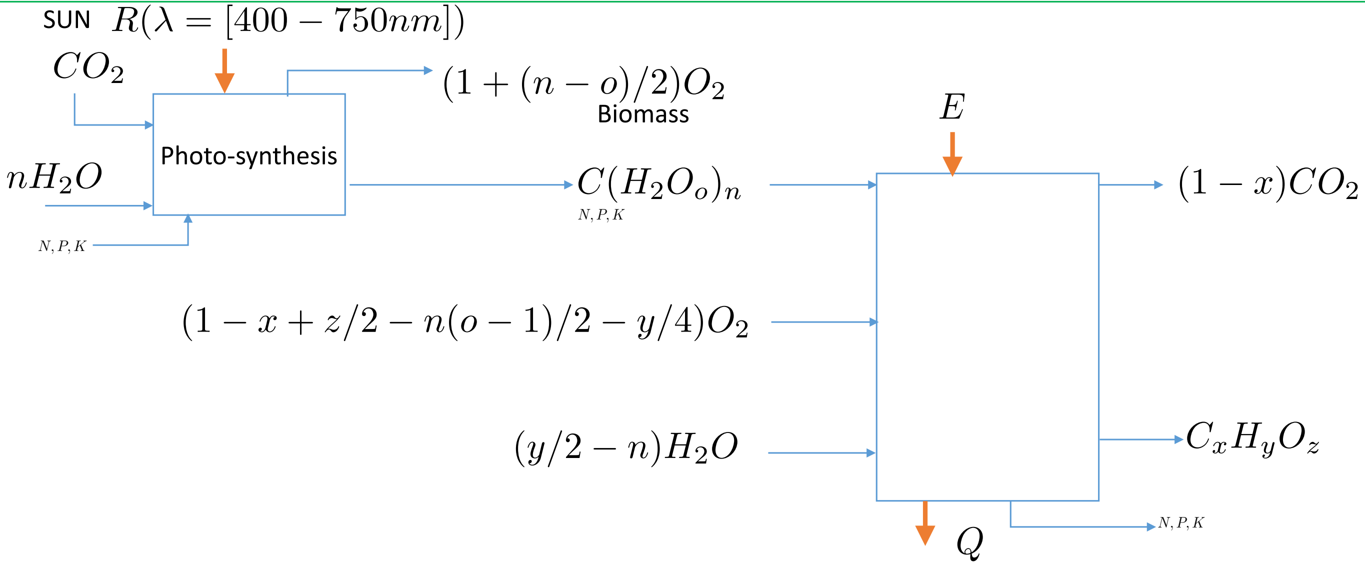
- Energy density
- Distribution
- Storage
- Conversion
- Utilisation

"A biorenefinery is an integrated processing facility that converts biomass into value-added products and energy."

Bio-refinery concept



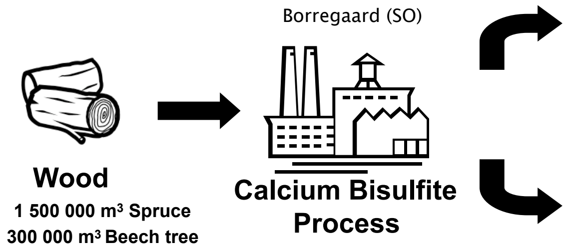
Conversion mass Atomic & Energy balance



WOOD | Natural Gas

Example $CH_{1.35}O_{0.63} + 0.3475H_2O \xrightarrow{\Delta H^0 = -10.5\ kJ/mol_{wood}} 0.51125CH_4 + 0.48875CO_2$

(OLD) Example of biorefinery : Sulfite pulp and paper process



Ligno sulfonate

- **Lignin 100 000 tons (70 MWy)**
- **Yeast 5300 tons**
- **Ethanol 8800 tons (7 MWy)**

Cellulose **128 000 tons (71 MWy)**

Table II. By-products repartition per ton of cellulose produced (t/tcp)

Sc.	Burned (t/tcp)	Ligsulf. (t/tcp)	Ethanol (t/tcp)	Yeast (t/tcp)
1*	0.959	0.937	0.0738	0.0464
2	0.959	0.937	0.0738	0.0464
3	0.641	1.011	0.1033	0.0547
4a	0.641	1.011	0.1033	0.0547
4b	0.753	1.011	0	0.0547
5	1.107	0.551	0.1033	0.0547

*Identification code is also used for Table III and Fig. 2.

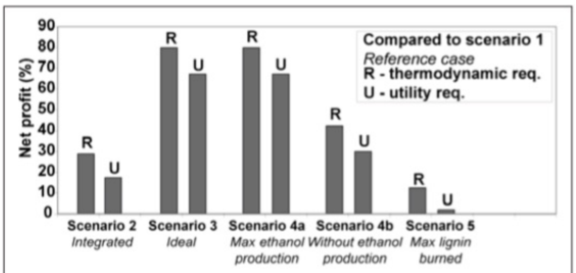
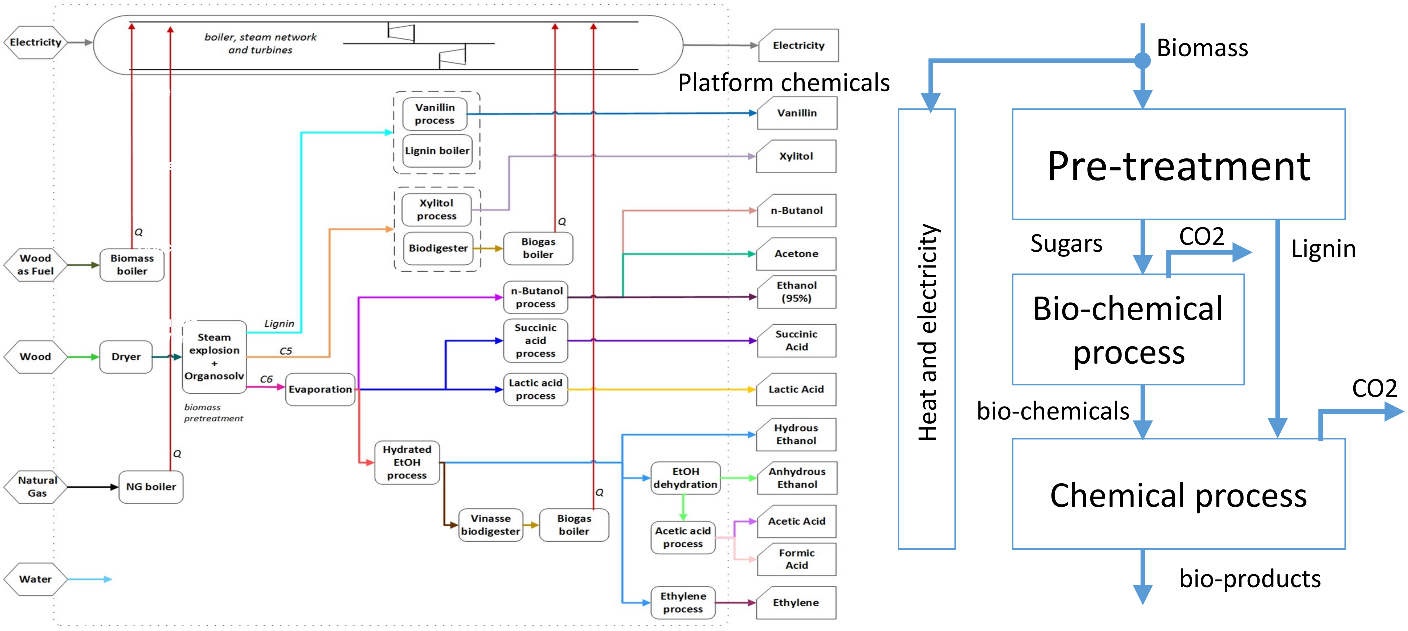


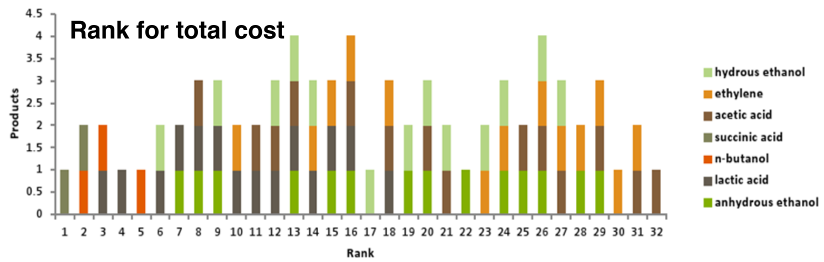
Fig. 2. Net profit difference for each scenario in comparison to the reference case (1).

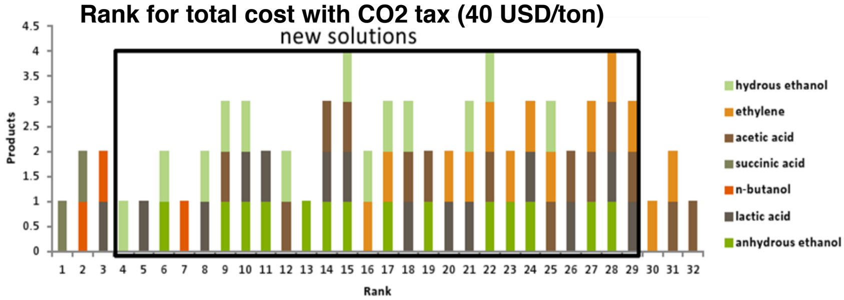
Perin-Levasseur, Zoe, Jean Paris, and François Marechal. "Analysis of a Biorefinery Integration in a Bisulfite Pulp Process." Pulp and Paper Canada may/june (2010): 31–33.

Bio-chemical plateform

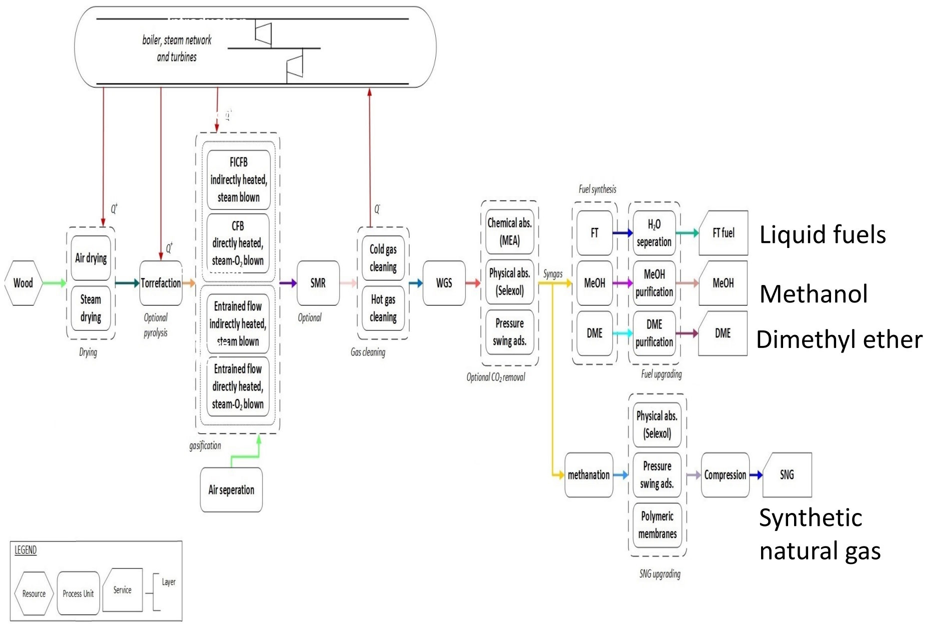


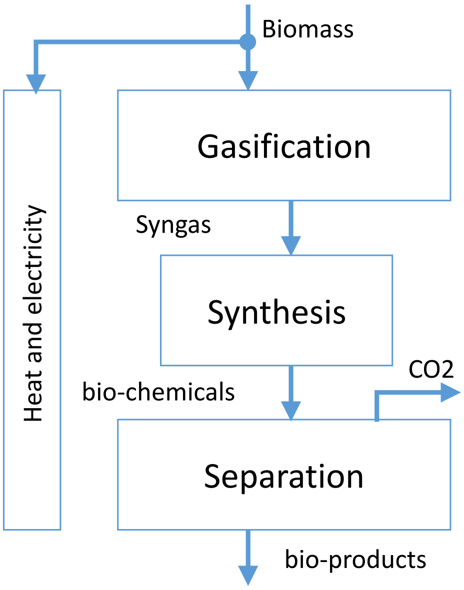
Multi-products : ranked with costs





Thermochemical Conversion Platform





Source: Tock et al., Thermochemical production of liquid fuels from biomass: Thermo-economic modeling, process design and process integration analysis, Biomass and Bioenergy, Vol. 34 (12), pp. 1838 - 1854, 2010.
Celebi et al., Computational platform for optimal design of biorefineries using energy and mass integration, ESCAPE25, Denmark, 2015.

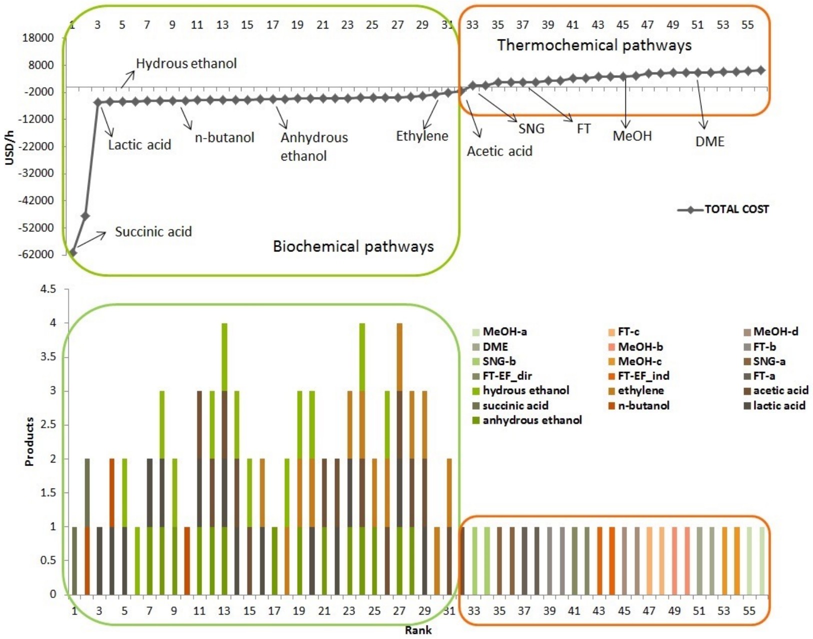
Bio-Fuel production

- Higher energy density
- Distribution network
  - Tank stations
  - Natural gas
- Conversion efficiency
  - Fuel cells => Heat pumps
  - Engines => Cogeneration
  - Combined cycle
- Decentralised systems
  - Cars - Airplanes
  - Small cogeneration

Table 7: Fossil CO_2 emissions reduction through the substitution of natural gas by biomass usage pathways for space heating (Reference value: 1.00 ≡ 0.165 $kg_{CO2}/kWh_{WoodyBiomass}$).

			Heat (Natural gas)					
Biomass to Fuel	Fuel to X	Elec. to Heat	Boiler	Cogen. engine	SOFC	SOFC & GT	CCGT	CCGT & CCS
–	Boiler	–	1.00	0.46	0.38	0.30	0.43	0.40
HTG	Boiler	–	1.02	0.47	0.39	0.31	0.44	0.41
Bio-SNG	Boiler	–	1.01	0.46	0.39	0.31	0.43	0.40
Bio-SNG & Electrolysis	Boiler	–	2.04	0.94	0.79	0.62	0.88	0.82
FT	Boiler	–	0.51	0.23	0.20	0.16	0.22	0.21
FT & Electrolysis	Boiler	–	0.99	0.46	0.38	0.30	0.43	0.40
HTG	Cogen eng	HP	1.93	0.89	0.74	0.59	0.84	0.78
Bio-SNG	Cogen eng	HP	1.98	0.91	0.76	0.60	0.86	0.80
Bio-SNG & Electrolysis	Cogen eng	HP	4.44	2.04	1.71	1.35	1.92	1.79
FT	Cogen eng	HP	1.02	0.47	0.39	0.31	0.44	0.41
FT & Electrolysis	Cogen eng	HP	1.97	0.91	0.76	0.60	0.85	0.79
HTG	SOFC	HP	2.26	1.04	0.87	0.69	0.98	0.91
Bio-SNG	SOFC	HP	2.33	1.07	0.90	0.71	1.01	0.94
Bio-SNG & Electrolysis	SOFC	HP	5.30	2.44	2.04	1.61	2.29	2.13
HTG	SOFC & GT	HP	2.80	1.29	1.08	0.85	1.21	1.13
Bio-SNG	SOFC & GT	HP	2.91	1.34	1.12	0.88	1.26	1.17
Bio-SNG & Electrolysis	SOFC & GT	HP	6.72	3.09	2.59	2.04	2.90	2.71
HTG	CCGT	HP	2.04	0.94	0.79	0.62	0.88	0.82
Bio-SNG	CCGT	HP	2.10	0.96	0.81	0.64	0.91	0.84
Bio-SNG & Electrolysis	CCGT	HP	4.72	2.17	1.82	1.43	2.04	1.90
HTG	CCGT & CCS	HP	2.68	1.61	1.46	1.30	1.56	1.50
Bio-SNG	CCGT & CCS	HP	2.78	1.68	1.53	1.37	1.63	1.57
Bio-SNG & Electrolysis	CCGT & CCS	HP	6.40	3.93	3.59	3.22	3.81	3.67
BIGCC		HP	2.08	0.96	0.80	0.63	0.90	0.84
Torrefaction	Supercritical plant	HP	1.91	0.88	0.73	0.58	0.82	0.77

Ranking the most promising pathways

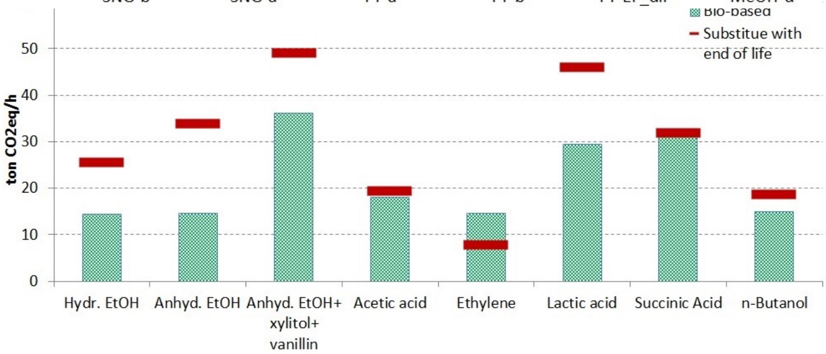


Rank of the most the promising pathways (economic objectives)

Reducing the CO2 emissions : LCA substitution

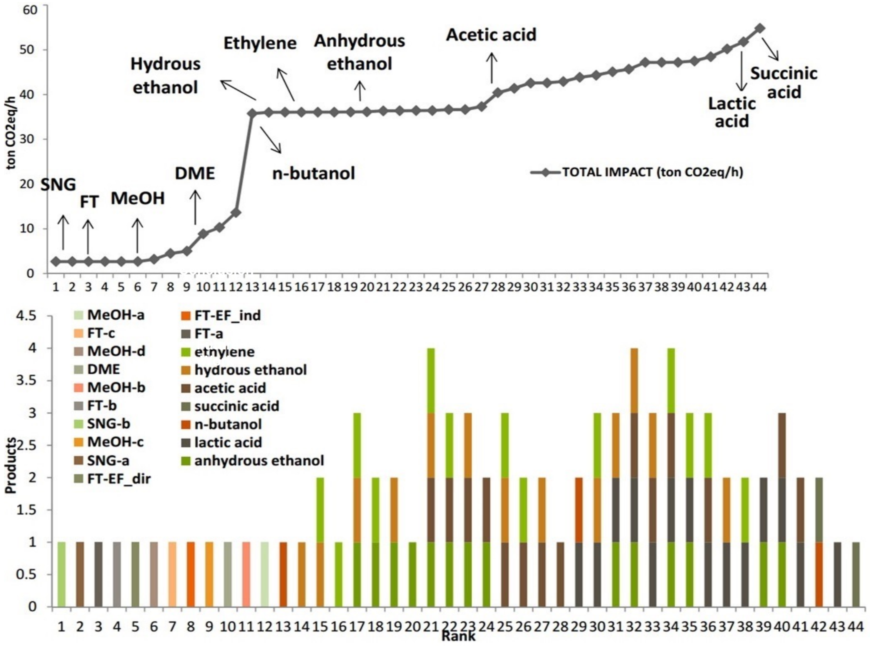
Thermo-chemical processes

Allocation when multi-products ?



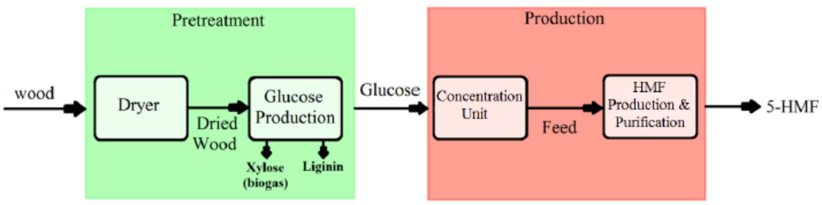
Bio-chemical processes

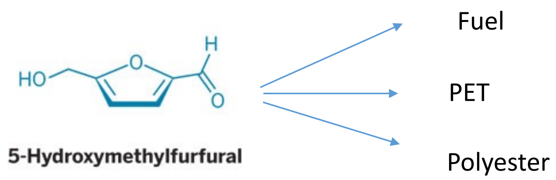
Global warming potential : impact reduction



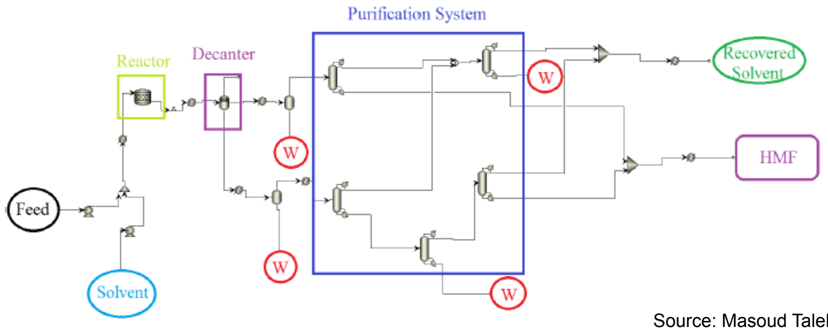
- Ranks with the CO2 savings potential
  - based on the same amount of biomass

Bio-Chemical Conversion Route : speciality/plateform chemicals





top 10 most valuable platform chemicals by the US (DOE, 2010)

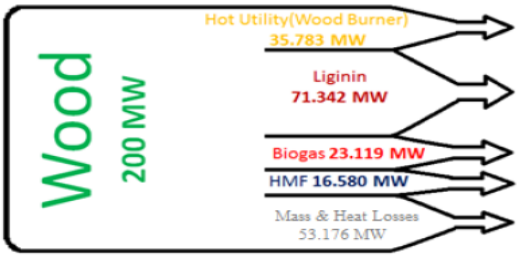


5-HMF Production Process

Source: Masoud Talebi Amiri, Process design of 5-hydroxymethlfurfural (HMF) process and integration in biorefineries, Master Thesis, IPESE, EPFL, July 2014.

Bio-Chemical Conversion Route : combined process

Energy balance for biphasic system



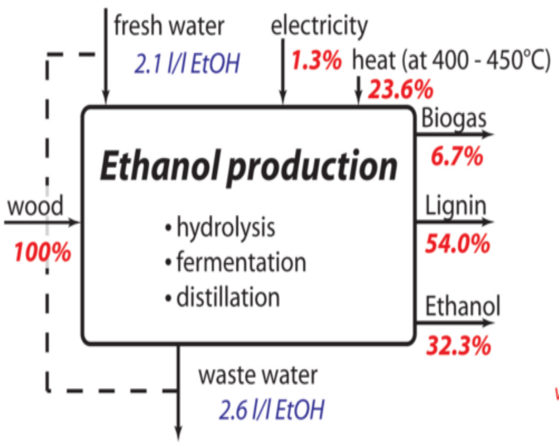
Economic analysis of biphasic system

Parameter	WO Cogeneration	With Cogeneration	Unit
Wood Available	200	200	MW
HMF Production	13641	10550	tons/yr
Equipment Cost (WO CHP)	97.57	91.53	MM USD
Equipment Cost (for CHP)	0	14.62	MM USD
Total Capital Cost	399	434	MM USD
Total Production Cost	375	366	MM USD/yr
Total Profit	1437	1273	MM USD/yr
Break Even Point	2.57	2.66	yr

Technology	Feed Water Content (wt%)	Reactor Temp.(°C)/Press.(atm)	Catalyst	Glucose Conv.	HMF Yield	HMF Purity wt%	HMF Mass (Kg/h)
Biphasic	70.7%	130 / 4.5	$Ag_3PW_{12}O_{40}$	0.9	0.77	0.991	3030

Source: Masoud Talebi Amiri, Process design of 5-hydroxymethlfurfural (HMF) process and integration in biorefineries, Master Thesis, IPESE, EPFL, July 2014.

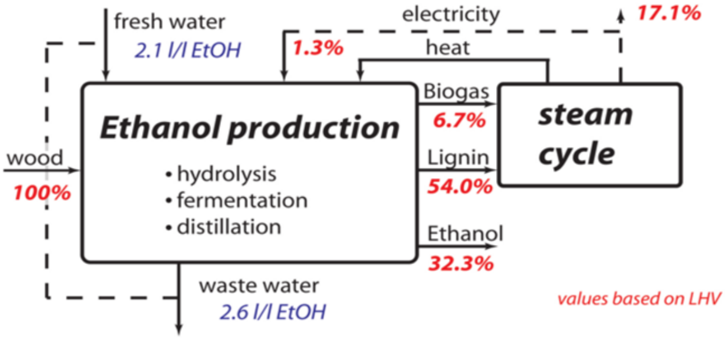
Process Integration in Biorefineries

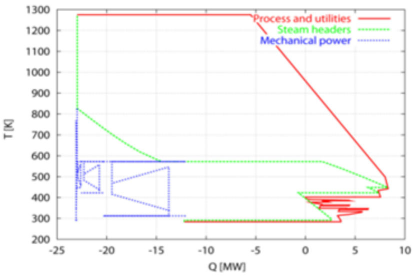


values based on LHV

Gassner, Martin, and François Maréchal. "Increasing Efficiency of Fuel Ethanol Production from Lignocellulosic Biomass by Process Integration." Energy & Fuels 27, no. 4 (April 18, 2013): 2107–2115. doi:10.1021/ef301952u.

Process Integration in Biorefineries



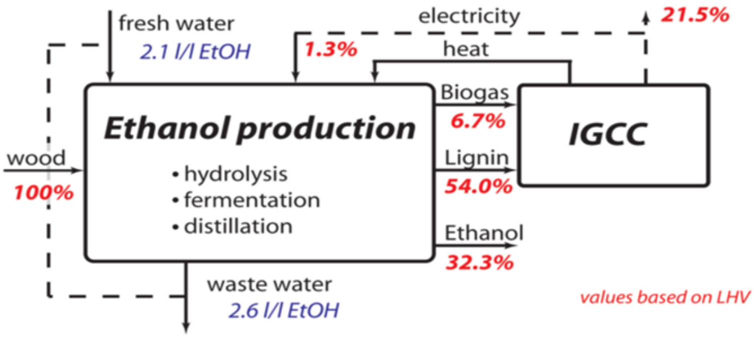


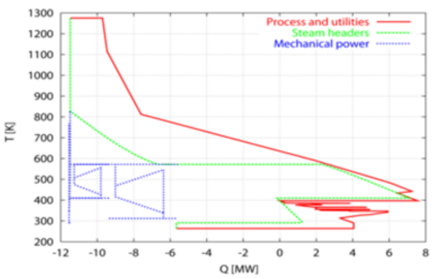
input: 58 $MW_{th,wood}$

		steam cycle
Input	wood	100 %
Output	ethanol	32.3 %
	SNG	-
	electricity	17.1 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %
total efficiency		49.4 %

Energy balance for different process integration options (without seed train, non-optimised).

Process Integration in Biorefineries

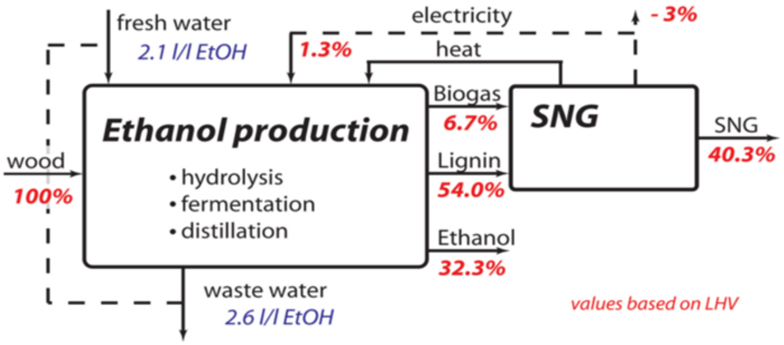


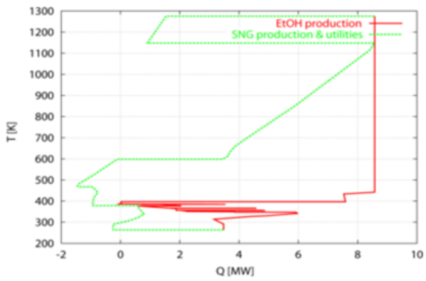


input: 58 $MW_{th,wood}$

		steam cycle	IGCC
Input	wood	100 %	100 %
Output	ethanol	32.3 %	32.3 %
	SNG	-	-
	electricity	17.1 %	21.5 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %	70.0 %
total efficiency		49.4 %	53.8 %

Energy balance for different process integration options (without seed train, non-optimised).



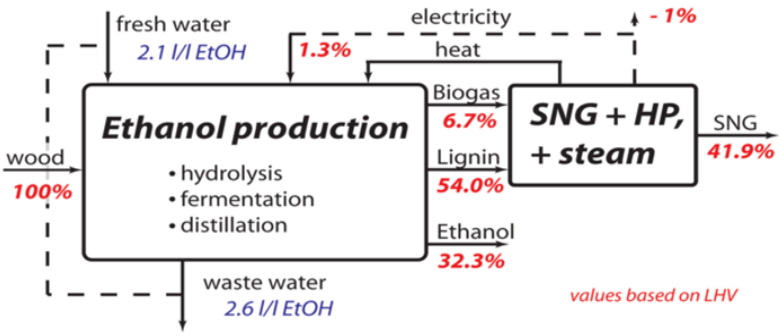


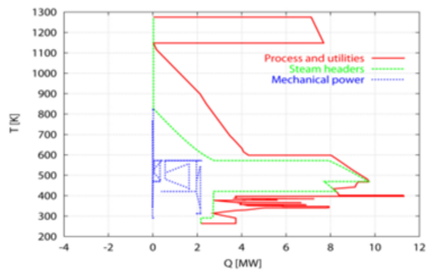
input: 58 $MW_{th,wood}$

		steam cycle	IGCC	SNG
Input	wood	100 %	100 %	100 %
Output	ethanol	32.3 %	32.3 %	32.3 %
	SNG	-	-	40.3 %
	electricity	17.1 %	21.5 %	-3.0 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %	70.0 %	67.3 %
total efficiency		49.4 %	53.8 %	70.5 %

Energy balance for different process integration options (without seed train, non-optimised).

Combined production of bio-fuels : 32 % -> 74%





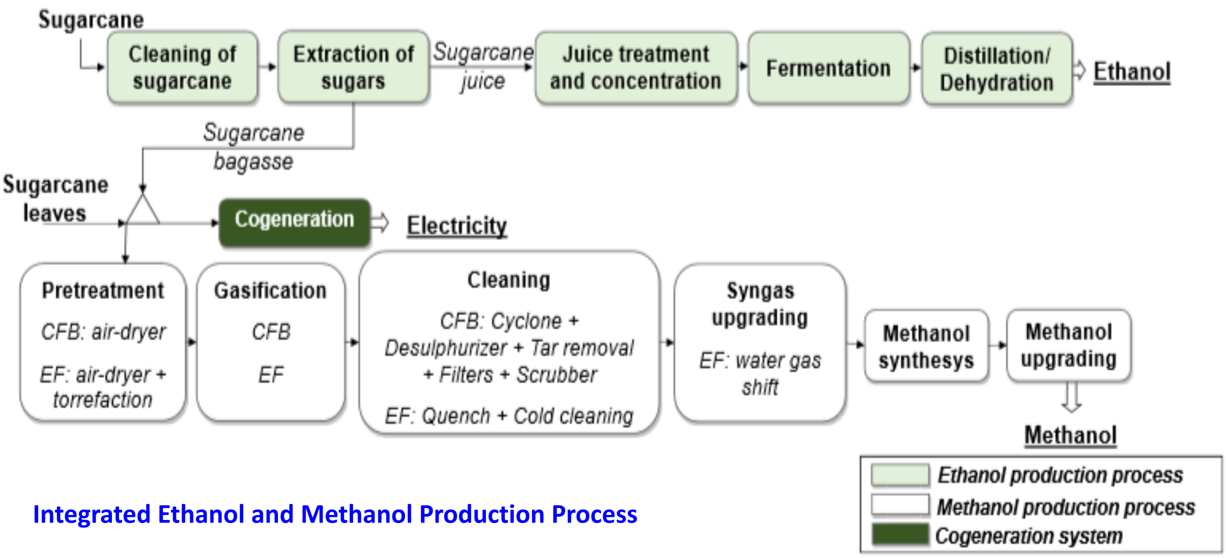
input: 58 $MW_{th,wood}$

		steam cycle	IGCC	SNG	+ steam	+ HP
Input	wood	100 %	100 %	100 %	100 %	100 %
Output	ethanol	32.3 %	32.3 %	32.3 %	32.2 %	32.2 %
	SNG	-	-	40.3 %	30.5 %	41.9 %
	electricity	17.1 %	21.5 %	-3.0 %	1.5 %	-1.0 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %	70.0 %	67.3 %	65.3 %	72.3 %
total efficiency		49.4 %	53.8 %	70.5 %	64.2 %	73.1 %

Energy balance for different process integration options (without seed train, non-optimised).

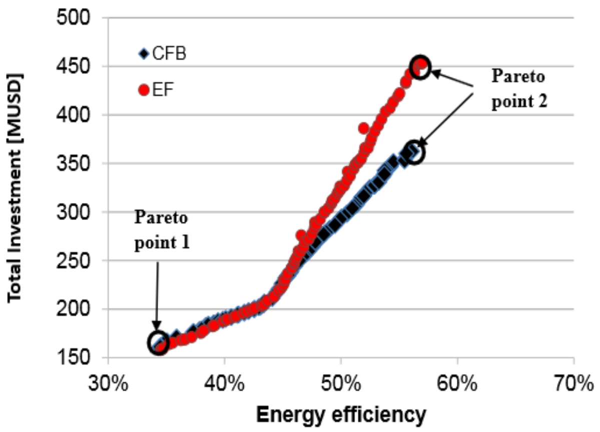
Gassner, Martin, and François Maréchal. "Increasing Efficiency of Fuel Ethanol Production from Lignocellulosic Biomass by Process Integration." Energy & Fuels 27, no. 4 (April 18, 2013): 2107–2115. doi:10.1021/ef301952u.

Hybrid (Bio-Chemical & Thermochemical) Process



Integrated Ethanol and Methanol Production Process

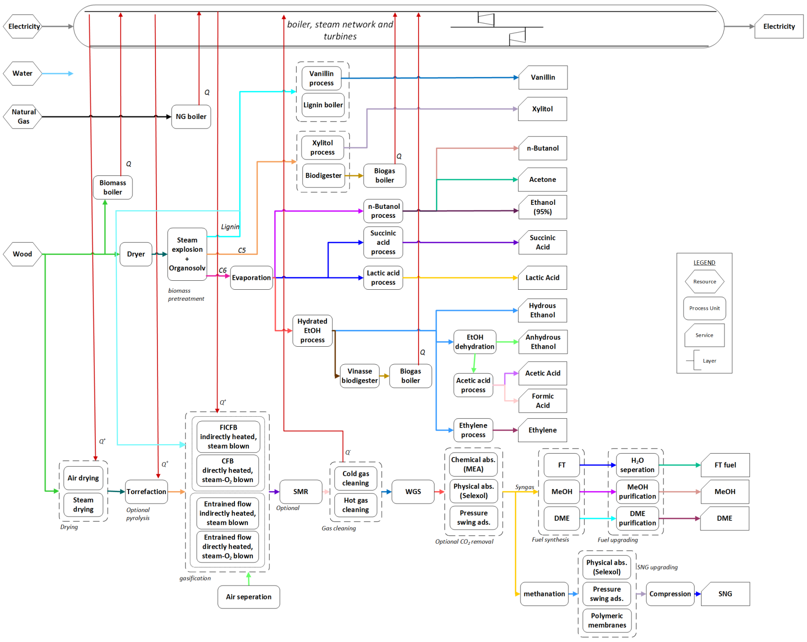
Combined chemicals and electricity



	Pareto point		Pareto point 2		
	CFB	EF	CFB	EF	
Power Input					
Sugar cane input power	633	633	633	633	[MW]
Leaves input power	147	147	147	147	[MW]
Power Output					
Total net electricity	−2.5	−13.1	−36.8	−34.9	[MW]
Ethanol production	265	265	265	265	[MW]
Methanol production	0	0	211	218	[MW]
Efficiencies					
Energy efficiency	34	33	58	59	[%]
Exergy efficiency	24	24	48	49	[%]
Global carbon conversion efficiency	16	16	33	34	[%]
Economic parameters					
Total investment cost	161.2	158.2	362.5	453.0	MUSD
Operational cost	87.3	87.0	262.9	279.3	MUSD/y
Methanol production cost	–	–	0.83	0.93	USD/kg

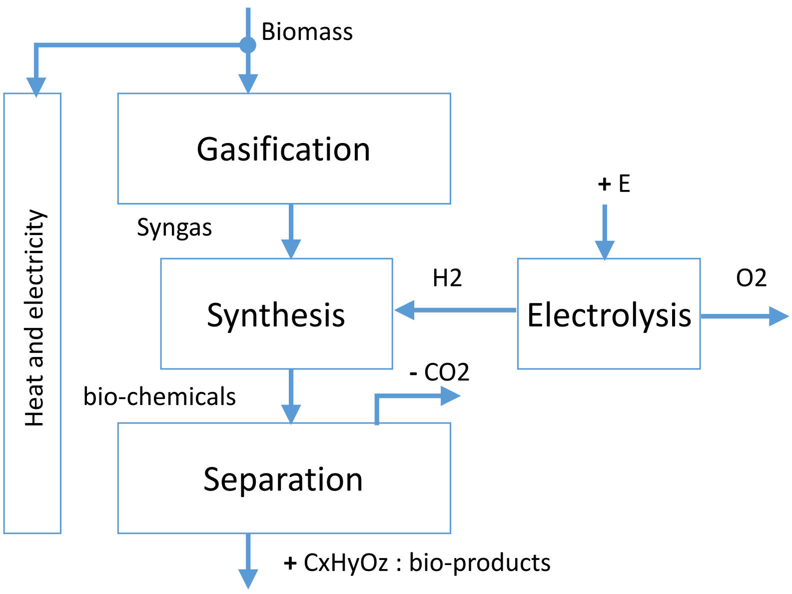
Source: Albarelli et al., Multi-objective optimization of a sugarcane biorefinery for integrated ethanol and methanol production, Energy, In Press, 2015.

Hybrid Thermo-chemical/bio-chemical platform



- Integrated system
  - Base chemicals
  - Chemicals
  - Fuels/ fuel additives
  - Electricity
- Goal : maximise the use of biogenic energy

The role in the energy system



- Long term energy storage

Reference : 100 MJ of biomass

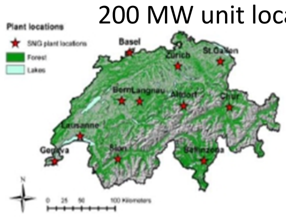
	Reference	Max electricity	Max Fuel
	MJ	MJe	MJ
Synthetic Natural Gas	72.4	144.5	170.0
Fisher- Tropsh Fuel	43.4	54.2	84.2

E. Peduzzi, F. Maréchal and G. Boissonnet (Dirs.). *Biomass To Liquids: Thermo-Economic Analysis and Multi-Objective Optimisation.* Thèse EPFL, n° 6529 (2015)
Gassner, Martin, and François Maréchal. "Thermo-Economic Optimisation of the Integration of Electrolysis in Synthetic Natural Gas Production from Wood." Energy 33, no. 2 (February 2008): 189–198. doi:10.1016/j.energy.2007.09.010.

Biomass supply chain & biorefinery plant size

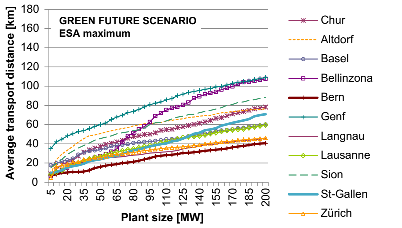
Area = 40 km2

200 MW unit location



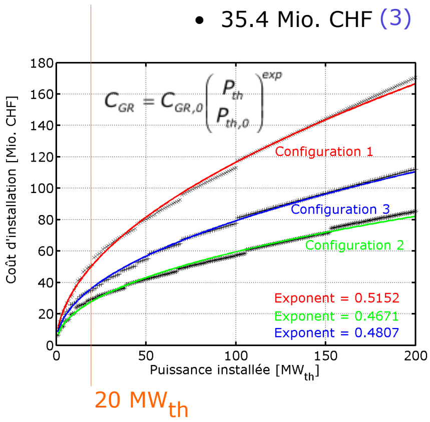
B. Steubing et al. /Renewable Energy 61 (2014) 57-68

Transport = 10 % of the energy



Process Size => Investment

20 MW_{th}:
- 51.4 Mio. CHF (1)
- 29.5 Mio. CHF (2)
- 35.4 Mio. CHF (3)



- Biomass supply chain
- Process intensification

Productivity : 5000 Wyear/year/ha

Conclusions : why biorefineries ?

- **Bio chemicals**
  - Green products => Image
  - High value/low impact products
  - Life cycle green house gas emissions substitution
- **Biogenic carbon support**
  - Fuels : stored & easily distributed energy
  - Fuel additives
  - Long term electricity storage
- **Importance of system integration**
  - Bio-chemical/thermo-chemical/catalytic reactions integrated
  - Grid services
  - District heating
- **Difficulties**
  - Supply chains
  - Economy of scale => process intensification
  - Cost of the ressources : wood vs fossil fuels