Process integration aspects in the design of biofuel processes

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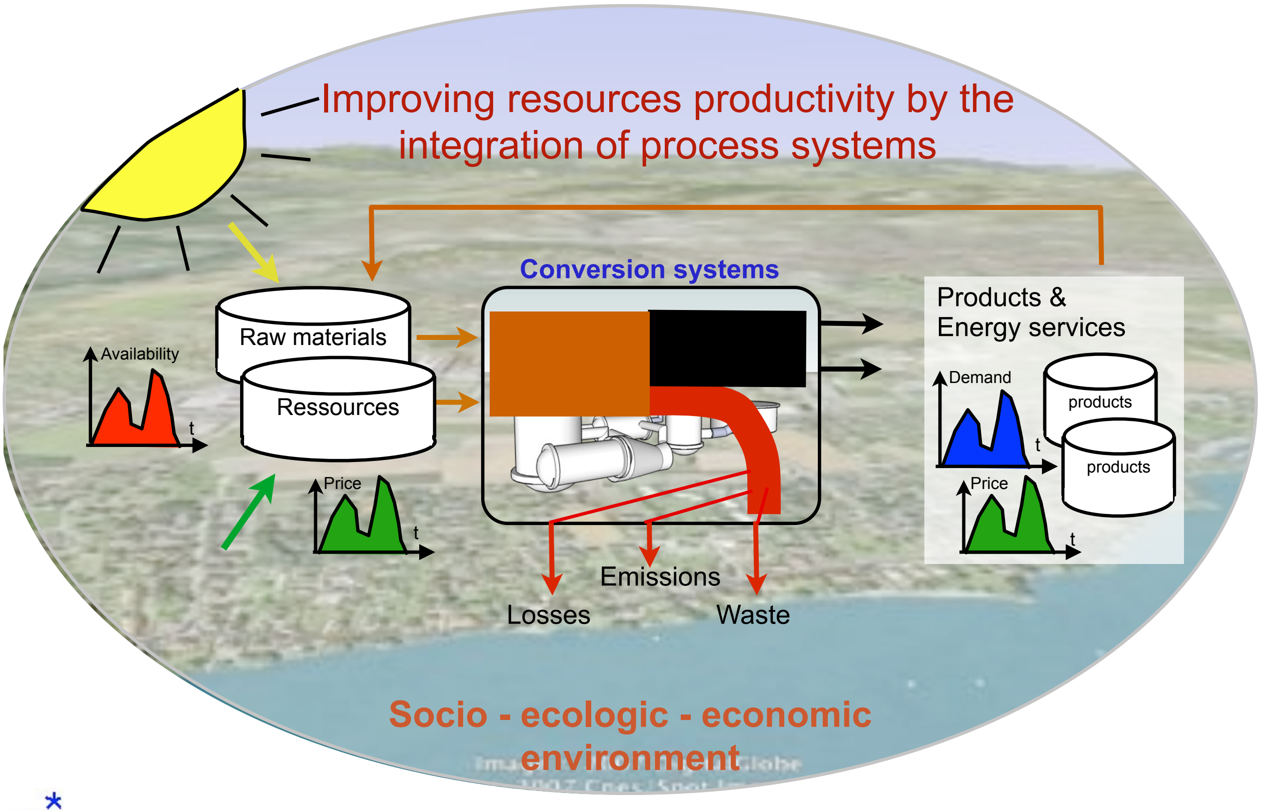
Goals of my talk

1. Motivations
2. Process integration
3. Process system design method
4. Integrating Sustainability in design
5. Multi-objective optimization
6. System analysis
7. Computer aided design framework

Energy Conversion Systems



Improving resources productivity by the integration of process systems

Conversion systems

Raw materials

Ressources

Products & Energy services

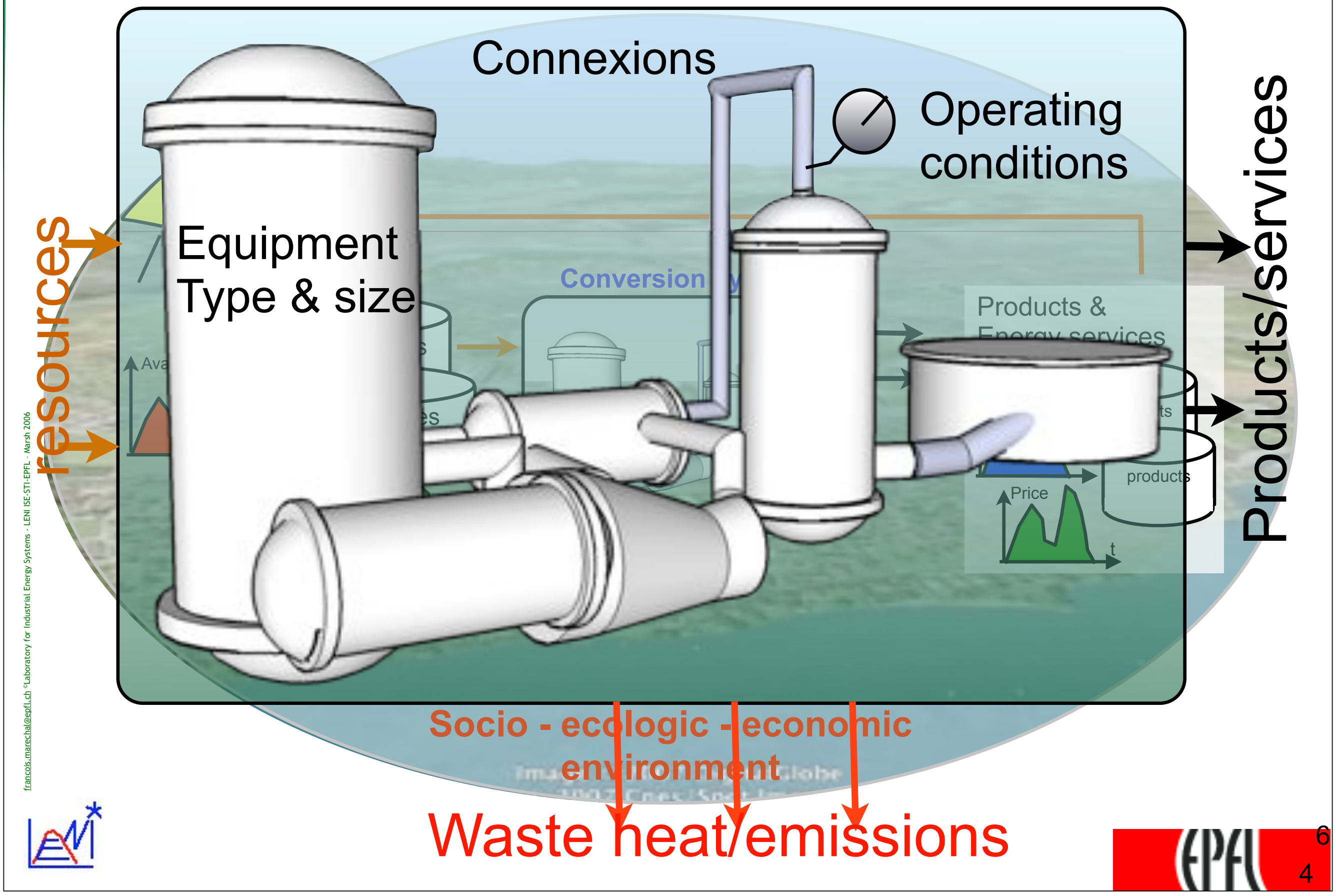
Emissions

Losses

Waste

Socio - ecologic - economic environment

Energy system analysis and design



Connexions

Operating conditions

Equipment Type & size

resources

Products/services

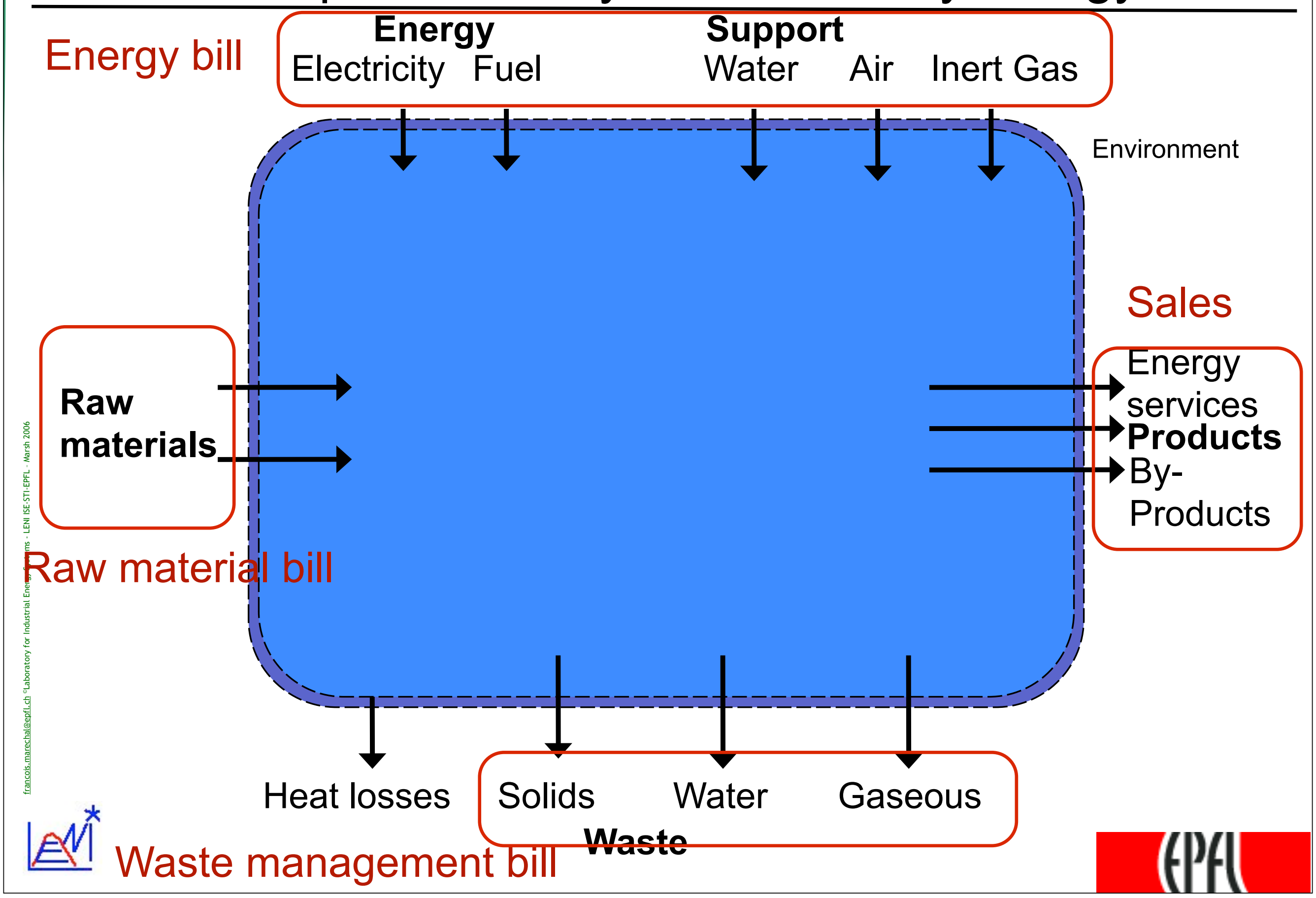
Waste heat/emissions

Process integration

Process integration is the engineering action of assembling process equipments to form a process system

- Understanding the interactions between the process units
  - Mass flows
  - Heat exchange
  - Coproduction
  - Waste management
- Adopt a system (holistic) vision
- Reach the “optimal” design
  - the one that makes sense for the engineer

Industrial processes system driven by energy



Energy bill

Energy
Electricity Fuel

Support
Water Air Inert Gas

Environment

Raw materials

Raw material bill

Sales

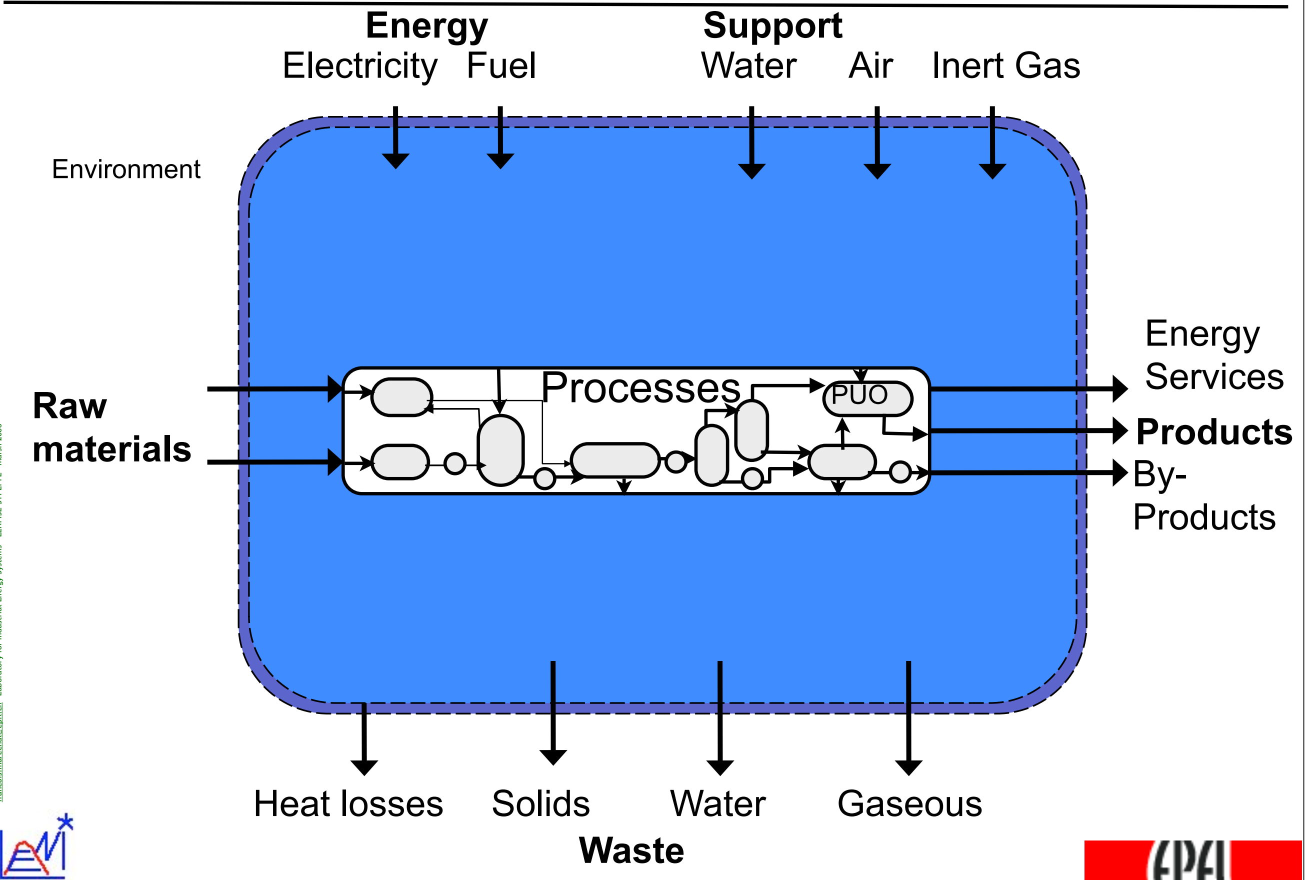
Energy services
Products
By-Products

Heat losses

Solids Water Gaseous
Waste

Waste management bill

1. Reduce : analyse process requirement



Energy
Electricity Fuel

Support
Water Air Inert Gas

Environment

Raw materials

Processes

PUO

Energy Services

Products

By-Products

Heat losses Solids Water Gaseous

Waste

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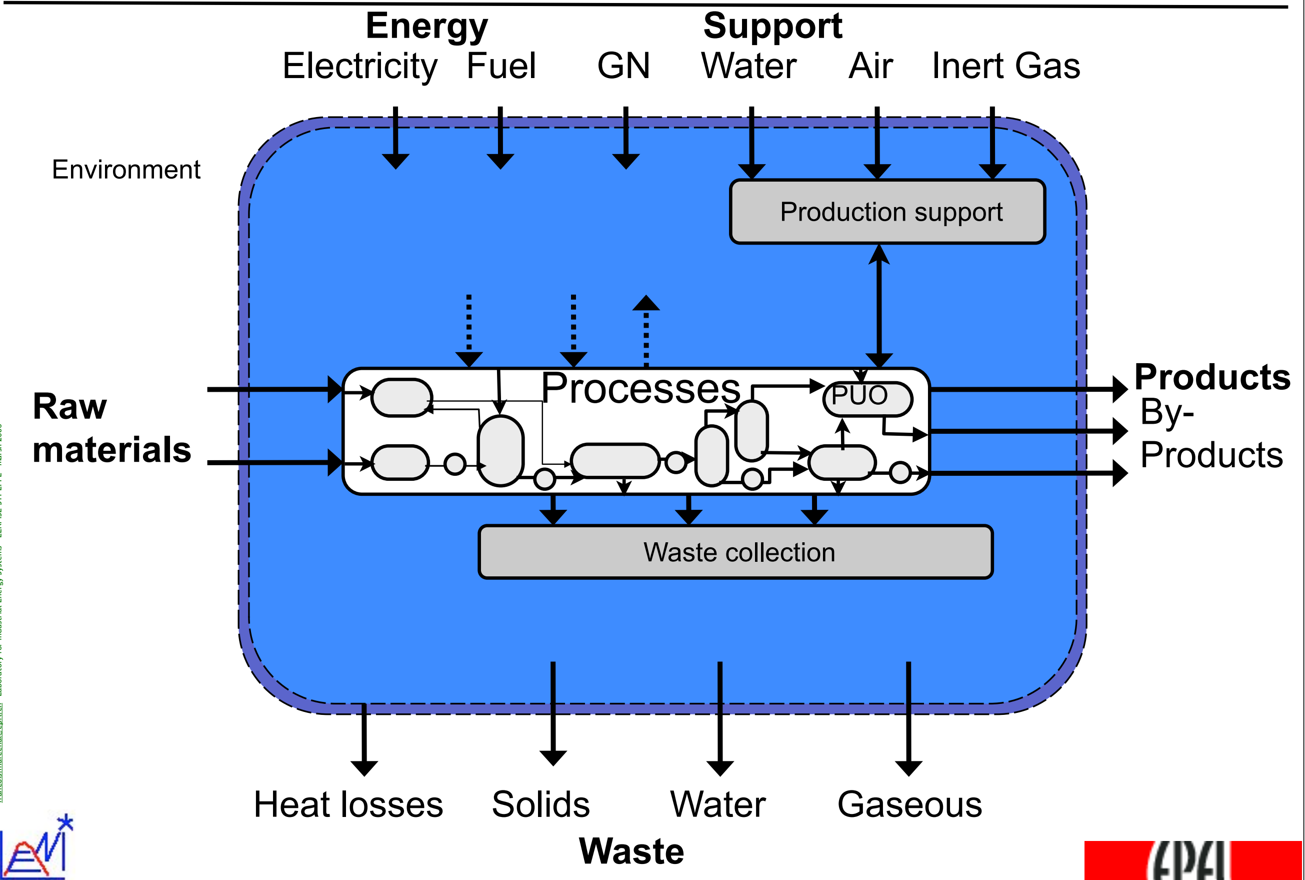
2. Recycling : heat and mass recovery



Energy
Electricity Fuel GN

Support
Water Air Inert Gas

Environment

Production support

Raw materials

Processes

PUO

Waste collection

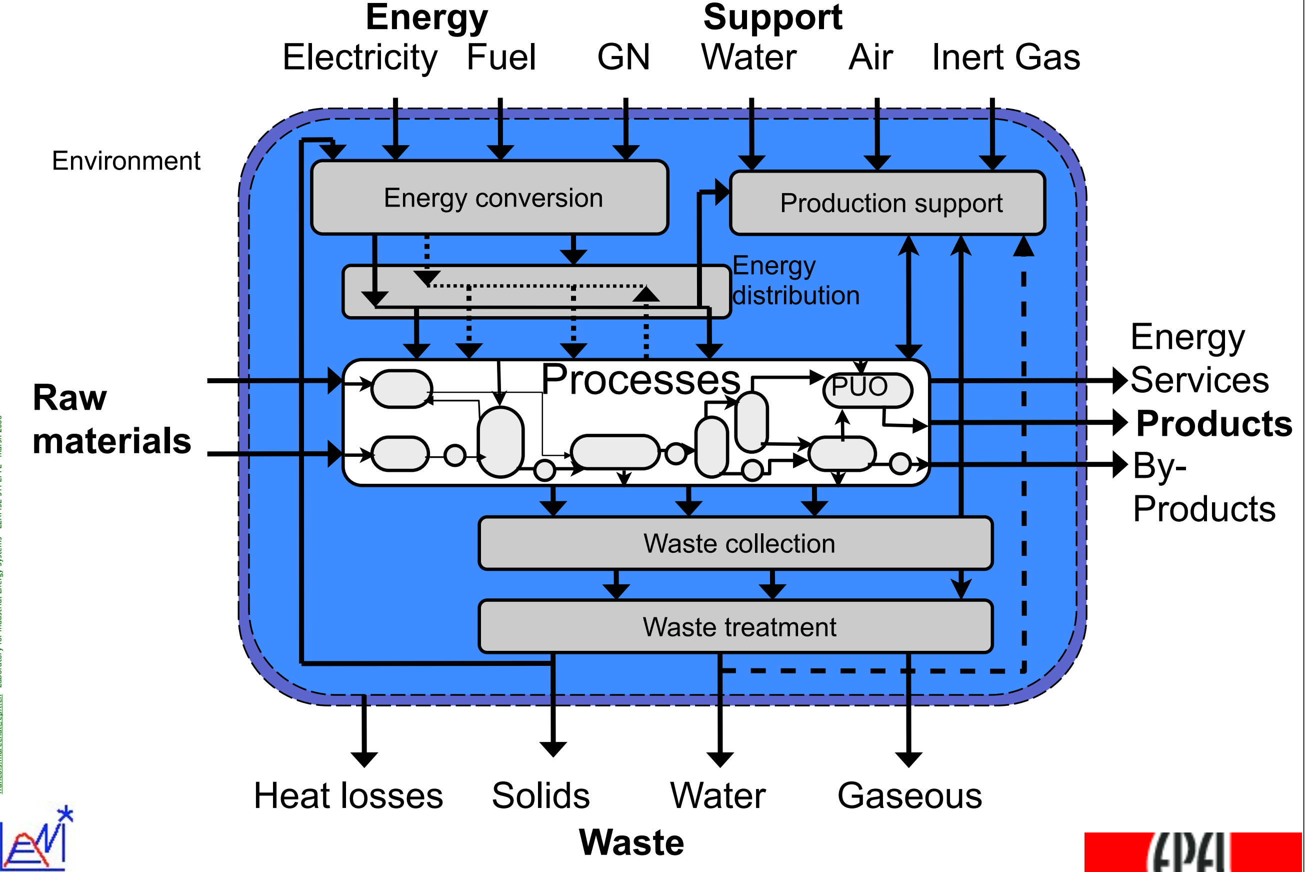
Products

By-Products

Heat losses Solids Water Gaseous

Waste

3. Reuse : Optimal conversion and waste treatment



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3 R approach for process integration

1. Reduce

- Analyse processing requirements
- Analyse process units requirements
- System boundaries

Exergy analysis

Simulation/ optimisation

Pinchlight.epfl.ch

2. Recycle

- Mass recovery (production support)
- Heat recovery

Heat transfer & mass requirement

Pinch analysis

3. Reuse

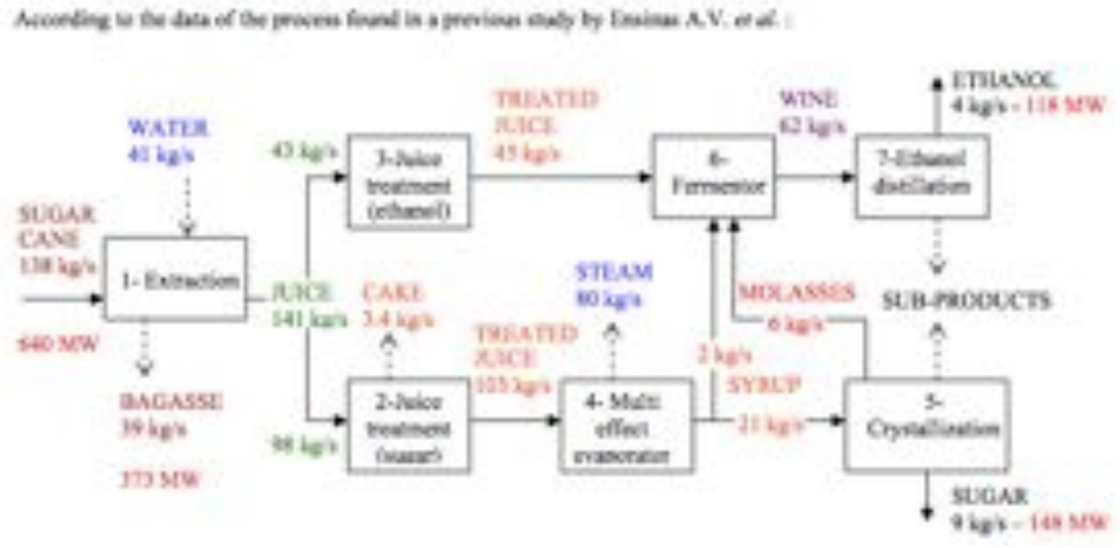
- Combined heat and power
- Heat pumping
- Waste conversion/valorisation
- Extend System boundaries

Optimization

Large scale system integration

Example sugar-ethanol process

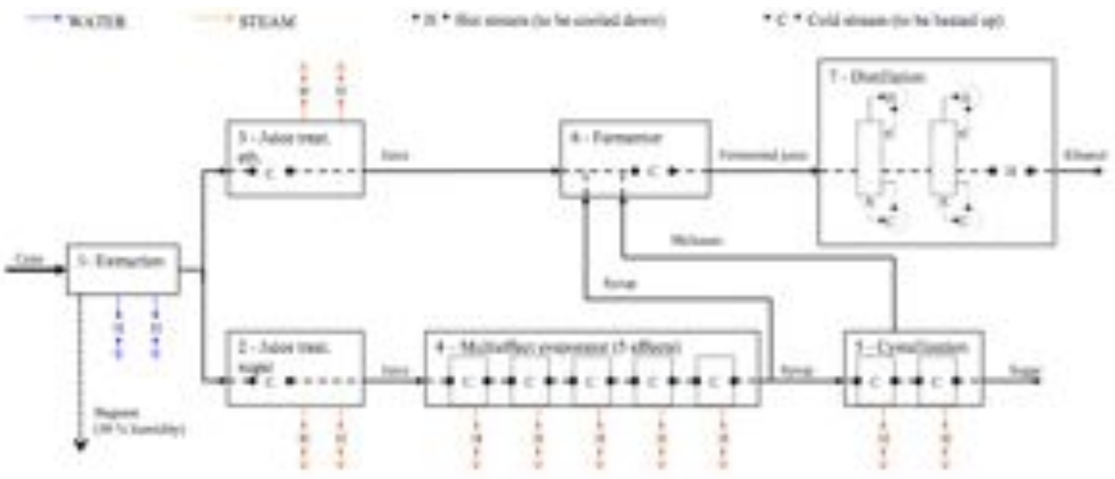
- **Present consumption 138 MW of heat**
  - optimize the process operation
  - Simulation of the process



Morandin, Matteo, Andrea Toffolo, Andrea Lazzaretto, François Maréchal, Adriano V. Ensinas, and Silvia a. Nebra. "Synthesis and parameter optimization of a combined sugar and ethanol production process integrated with a CHP system." *Energy* 36, no. 6 (December 8, 2010): 3675-3690.

Process heat integration

- **Define the hot streams and cold streams**



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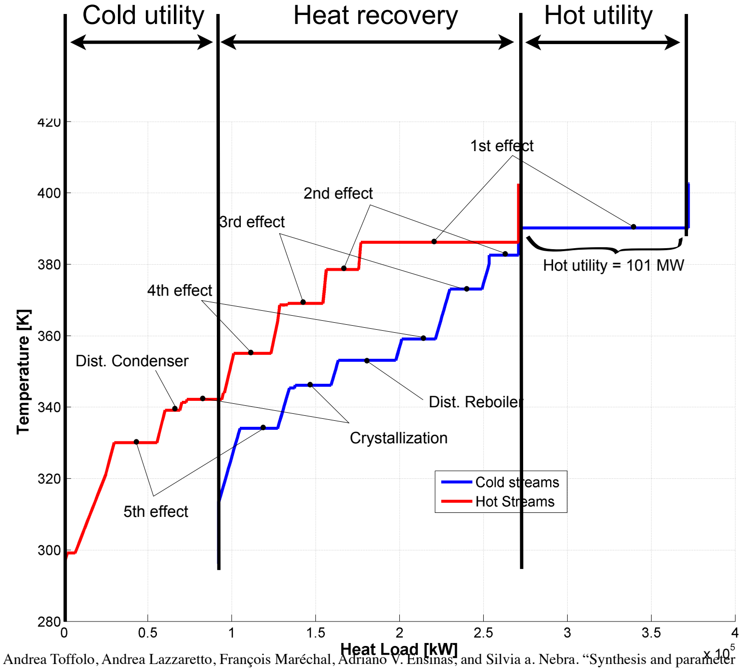
Maximum heat recovery in the system

Process composite curves

- Heat : 138 MW -> 101 MW (73%)

Ethanol 4.19 kg/s (118 MW), sugar 9.21 kg/s (148 MW)



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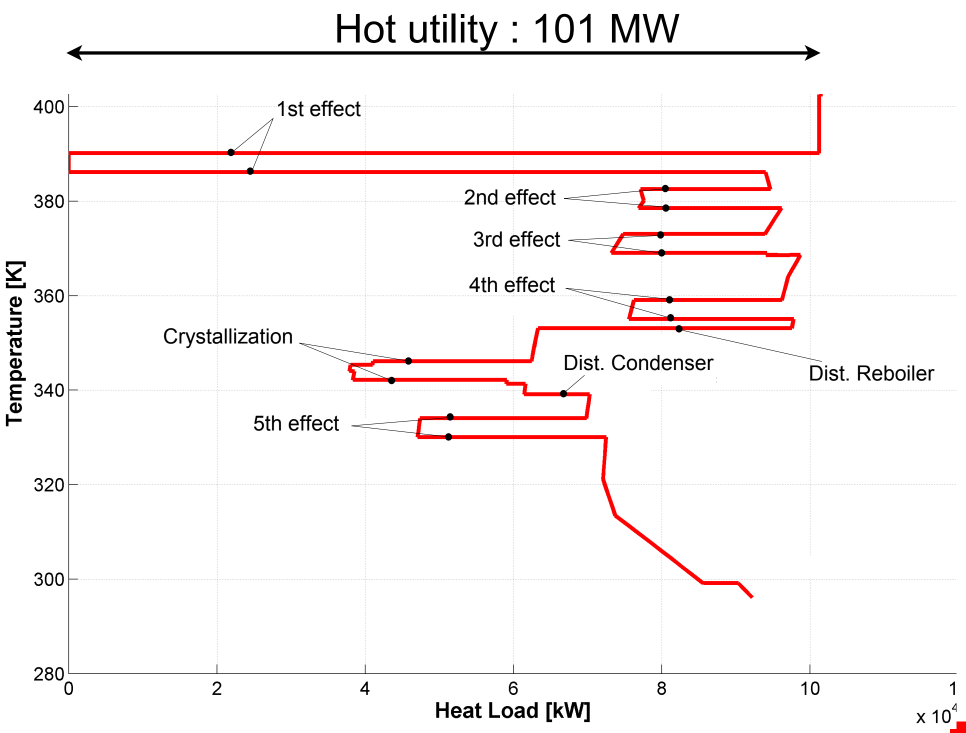
Enthalpy temperature profile of the heat requirement



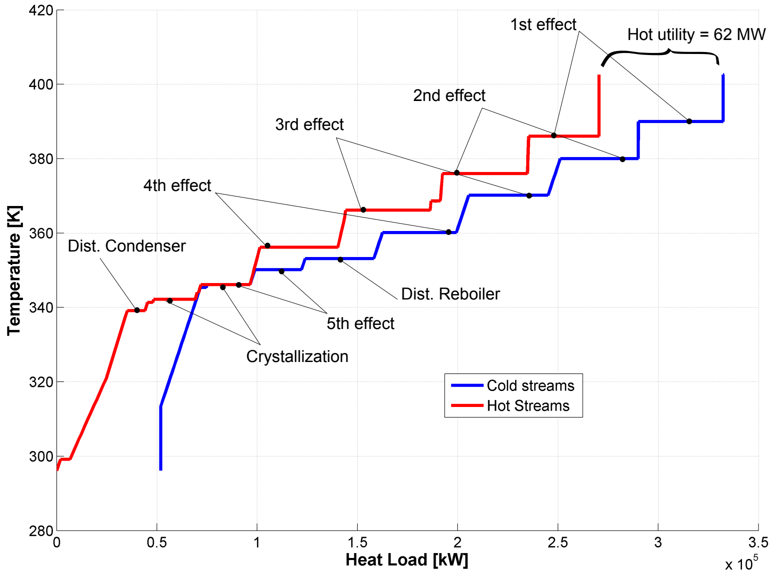
Ethanol 4.19 kg/s (118 MW), sugar 9.21 kg/s (148 MW)

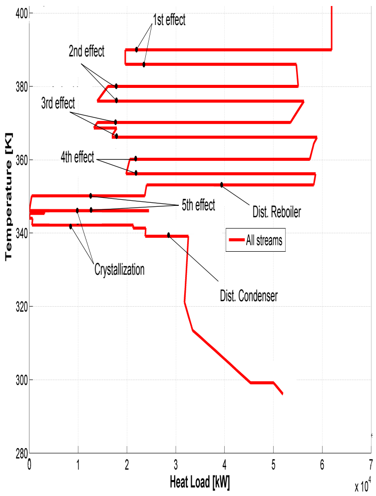
Optimize the operating conditions of the process

Changing the pressures of the evaporation

- Heat : 138 MW -> 101 MW (73%) -> 62 MW (45%)

Ethanol 4.19 kg/s (118 MW), sugar 9.21 kg/s (148 MW)





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Optimizing the energy conversion

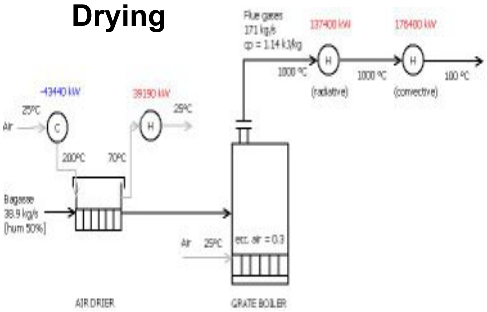
Bagasse conversion (373 MW$_{HHV}$ available)

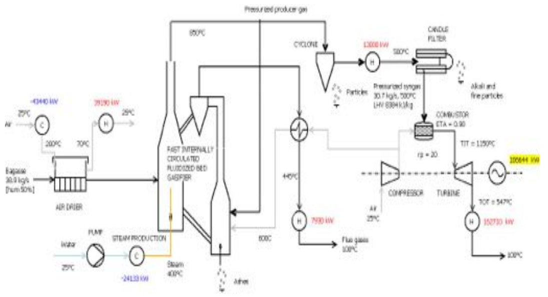
- Full potential ?

Combustion

IGCC

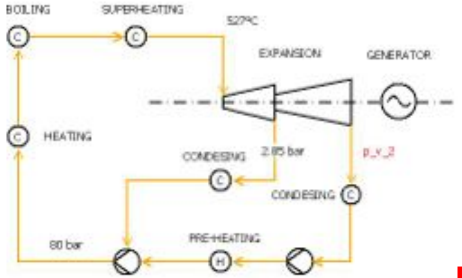
Drying





Steam Cycle

Pressures to be optimized



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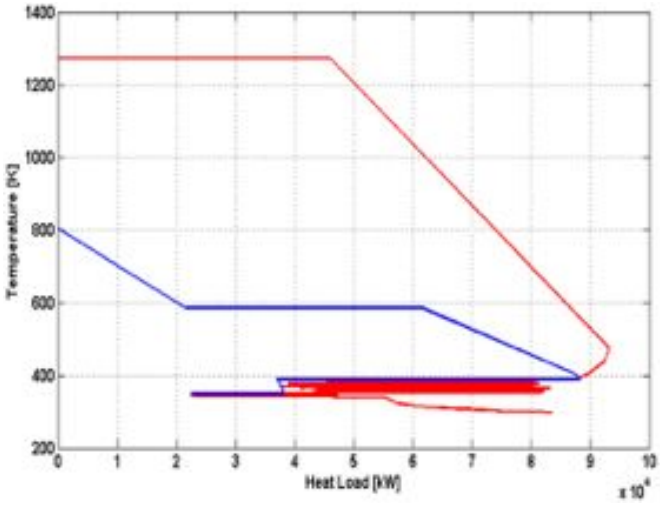
Result : combustion + CHP

- **30% of bagasse used**
  - Marginal electricity production efficiency = 82 %



Case 1 results – CHP system 1
(30.2% bagasse combustion)

Rankine cycle net power = 22562 kW
HP turbine section power = 21593 kW
LP turbine section power = 1281 kW
Process power requirement = 15165 kW
Total site net power = 7397 kW
(14.79 kWh/t_{cane})
Cold utility requirement = 61416 kW
Bagasse input power = 89830 kW
Total site net thermal efficiency = 8.23 %

Ethanol 4.19 kg/s (118 MW), sugar 9.21 kg/s (148 MW)

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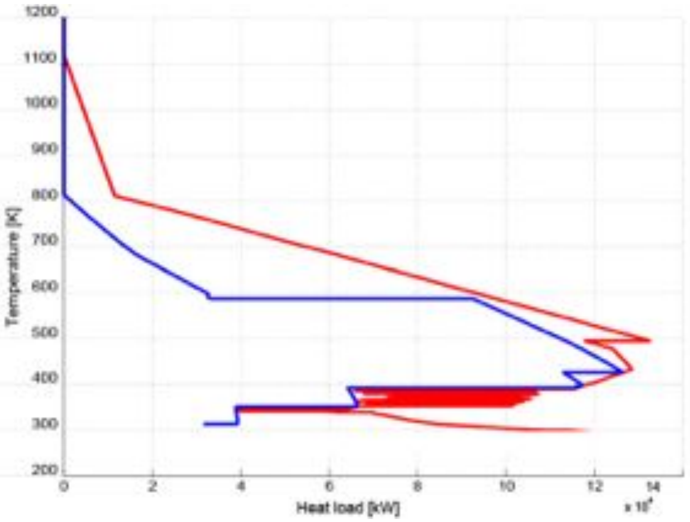
Optimized system

- **Total power produced : 137.8 MWe**
  - Marginal electricity production efficiency = 59 %



Case 1 results – advanced CHP system
(combined cycle + heat pump across crystallization temperature level)

Gas turbine net power = 106644 kW
Rankine cycle net power = 31196 kW
Process power requirement = 15165 kW
Total site net power = 122675 kW
(245.35 kWh/t_{cane})
Cold utility requirement = 87995 kW
Bagasse input power = 297450 kW
Total site net thermal efficiency = 41.24 %
Steam cycle pressures:
p_{high} = 101 bar; p_{extr1} = 5.32 bar; p_{extr2} = 1.92 bar
p_{extr3} = 0.47 bar; p_{out} = 0.1 bar;

Ethanol 4.19 kg/s (118 MW), sugar 9.21 kg/s (148 MW)

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Process integration comparing solutions

	Bagasse (MW)	Electricity (MW)	Marginal eff.
Combustion	89.8	22.6	82 %
CHP full	297.4	99	42 %
IGCC full + CHP + RMV	297.4	137.8	58.7 %

Ethanol 4.19 kg/s (118 MW), sugar 9.21 kg/s (148 MW)

Process system design : a larger perspective

- A Simple problem ?

  Produce Synthetic Natural Gas from Wood

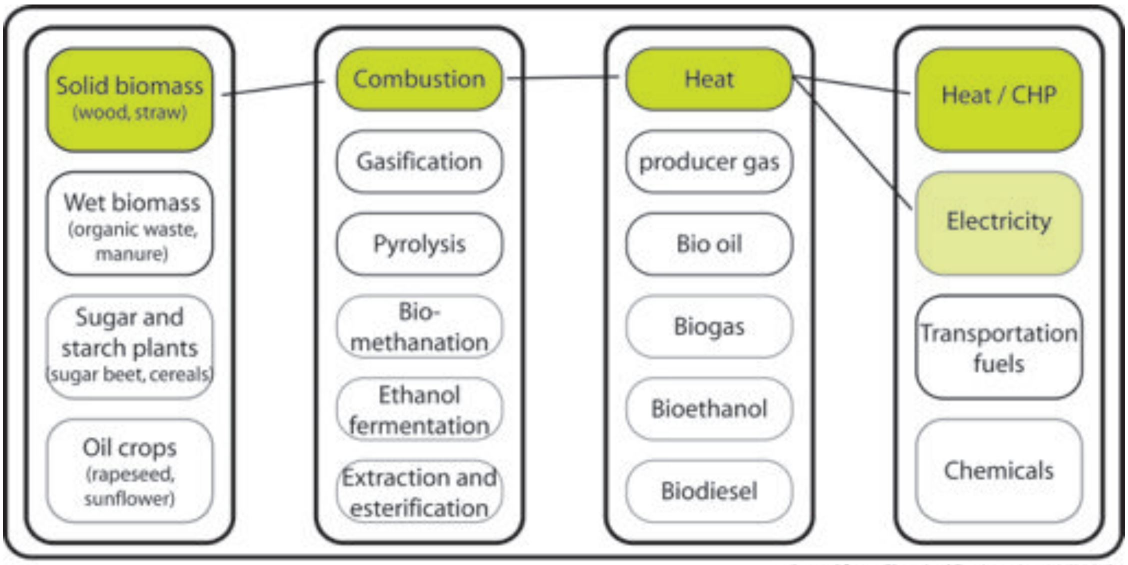
$$CH_{1.35}O_{0.63} + 0.3475H_2O \xrightarrow{\Delta H^0=-10.5\ kJ/mol_{wood}} 0.51125CH_4 + 0.48875CO_2$$

Process system design

What are the options ?

Biomass conversion

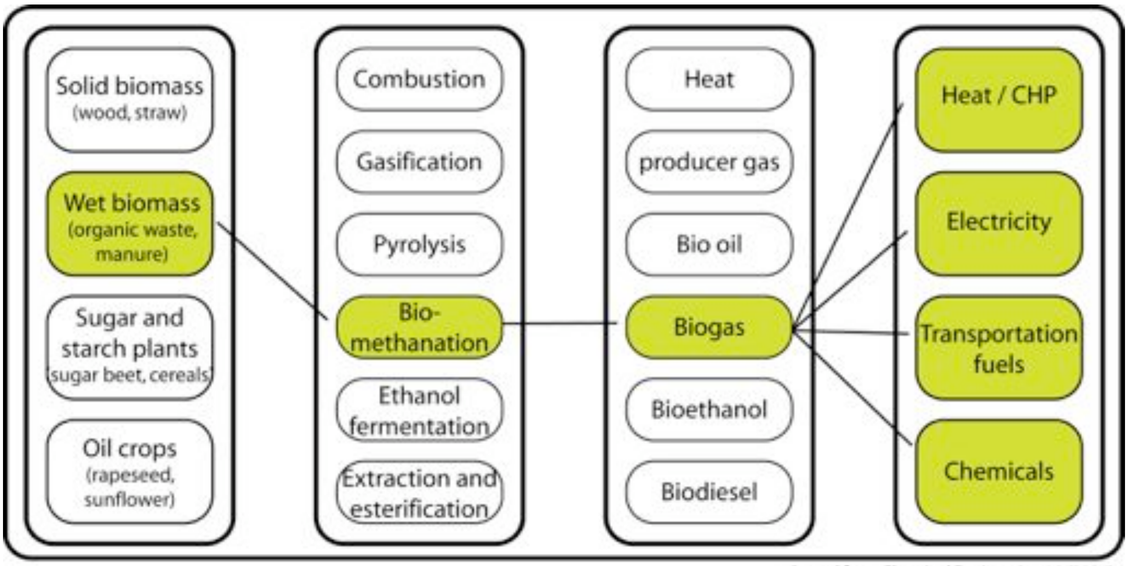
Combustion



Solid biomass (wood, straw)	**Combustion**	**Heat**	**Heat / CHP**
Wet biomass (organic waste, manure)	Gasification	producer gas	Electricity
Sugar and starch plants (sugar beet, cereals)	Pyrolysis	Bio oil	Transportation fuels
Oil crops (rapeseed, sunflower)	Bio-methanation	Biogas	Chemicals
	Ethanol fermentation	Bioethanol	
	Extraction and esterification	Biodiesel	

adapted from Chemical Engineering 10 (2006)

Biomass conversion
Biomethanation



Solid biomass (wood, straw)

Wet biomass (organic waste, manure)

Sugar and starch plants (sugar beet, cereals)

Oil crops (rapeseed, sunflower)

Combustion

Gasification

Pyrolysis

Bio-methanation

Ethanol fermentation

Extraction and esterification

Heat

producer gas

Bio oil

Biogas

Bioethanol

Biodiesel

Heat / CHP

Electricity

Transportation fuels

Chemicals

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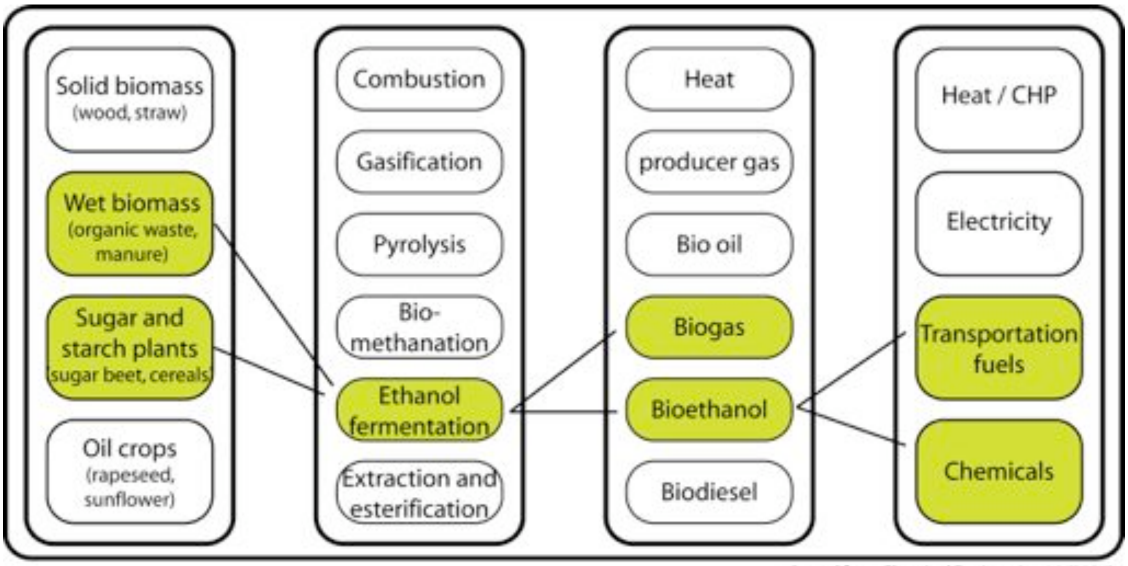
Biomass conversion
Ethanol fermentation



Solid biomass (wood, straw)

Wet biomass (organic waste, manure)

Sugar and starch plants (sugar beet, cereals)

Oil crops (rapeseed, sunflower)

Combustion

Gasification

Pyrolysis

Bio-methanation

Ethanol fermentation

Extraction and esterification

Heat

producer gas

Bio oil

Biogas

Bioethanol

Biodiesel

Heat / CHP

Electricity

Transportation fuels

Chemicals

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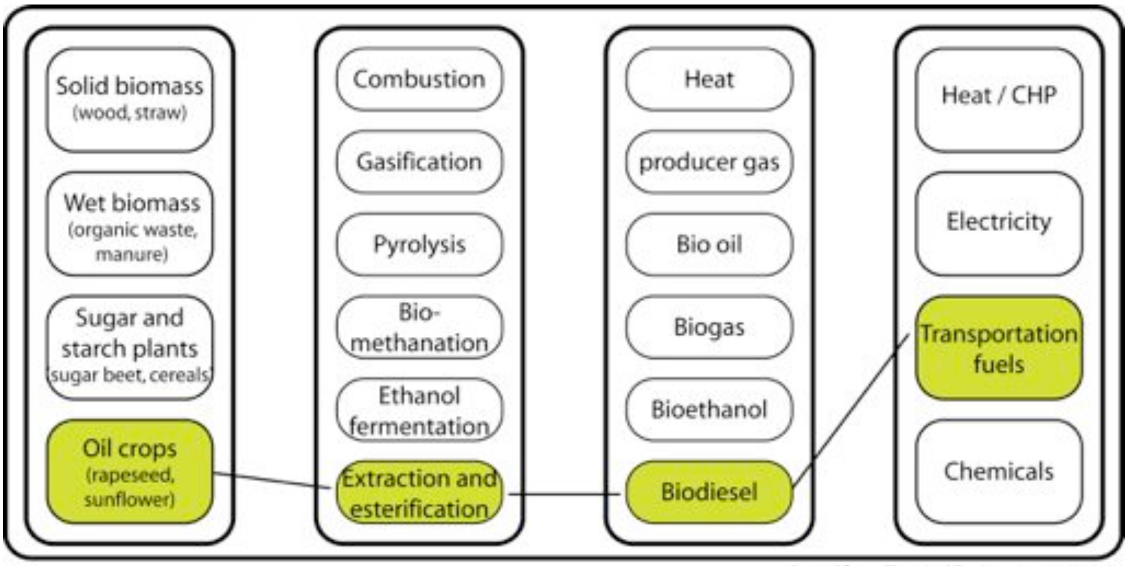
Biomass conversion

Transesterification



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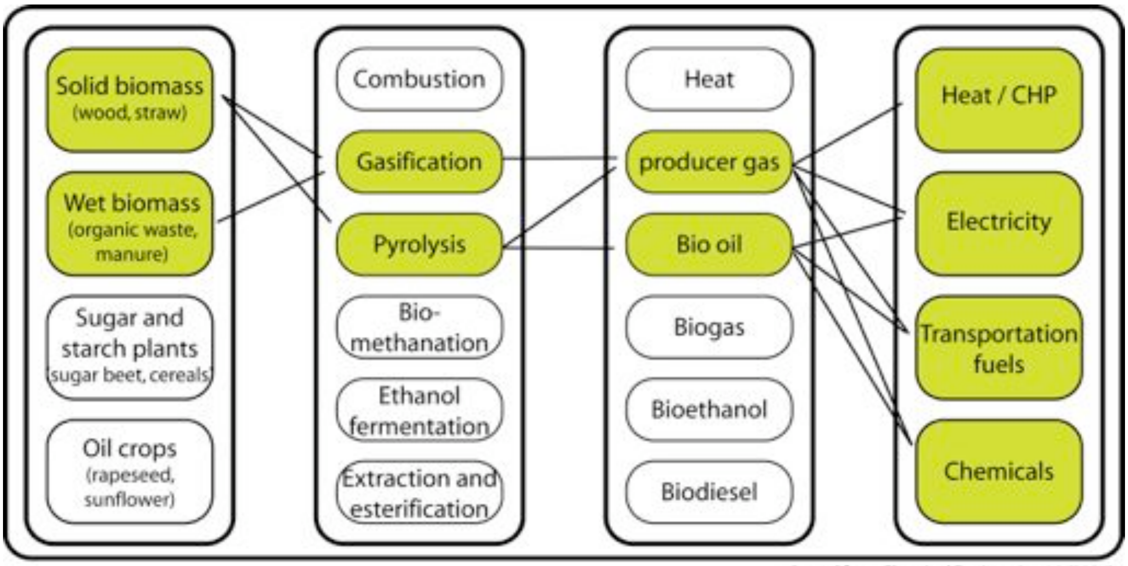
Biomass conversion

Thermochemical routes



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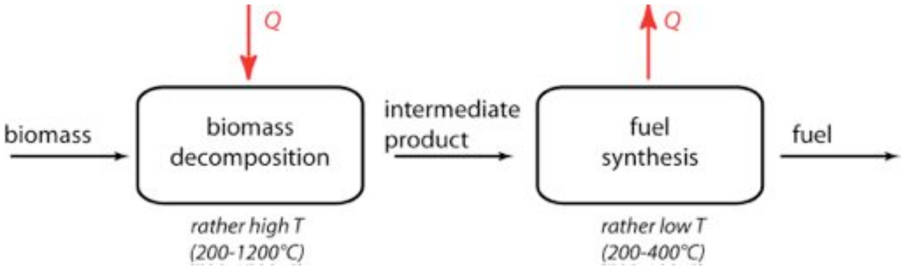
Thermochemical biomass conversion

Principle of conventional thermochemical routes

Thermochemical biomass to fuel reforming proceeds typically in two (or more) reaction steps:



- gasification
- pyrolysis

non-condensable/
condensable
substances
(H_2, CO, CO_2, H_2O,
CH_4, C_xH_y,
char, tars)

- methanation
- FT synthesis
- DME synthesis
- methanol synthesis

Process system design

What are the processing options ?

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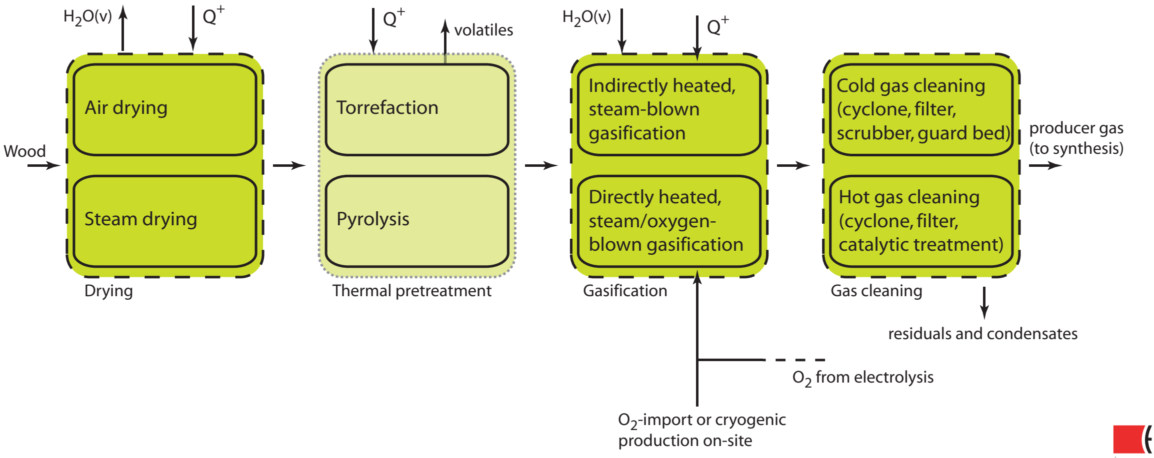
Block flow superstructure

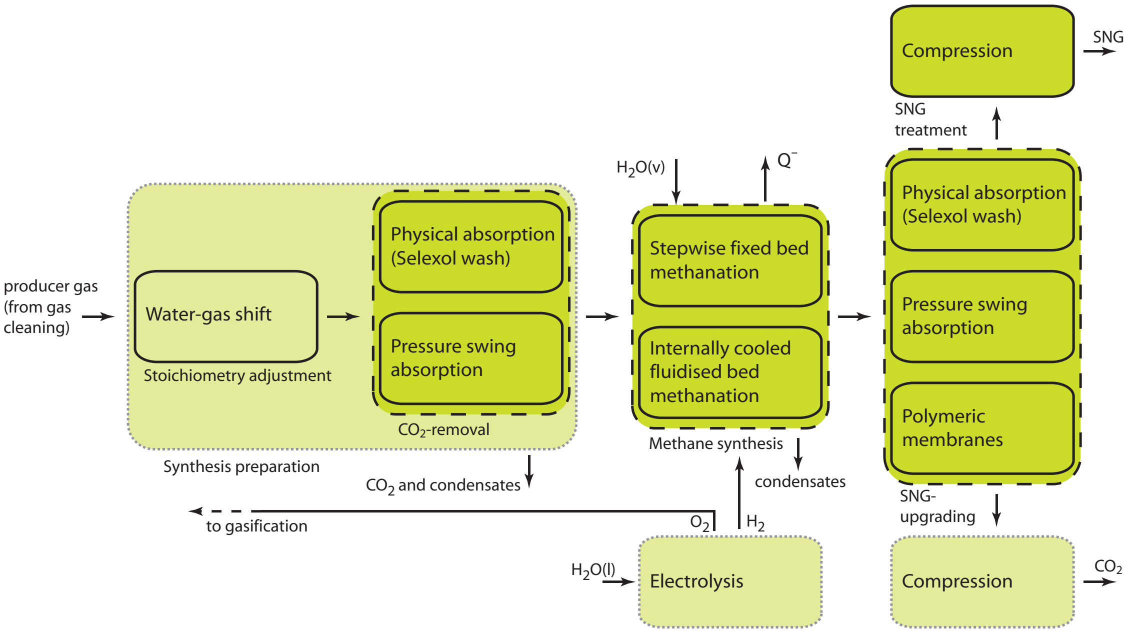
Conventional route (gasification & methanation): decomposition



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

Block flow superstructure

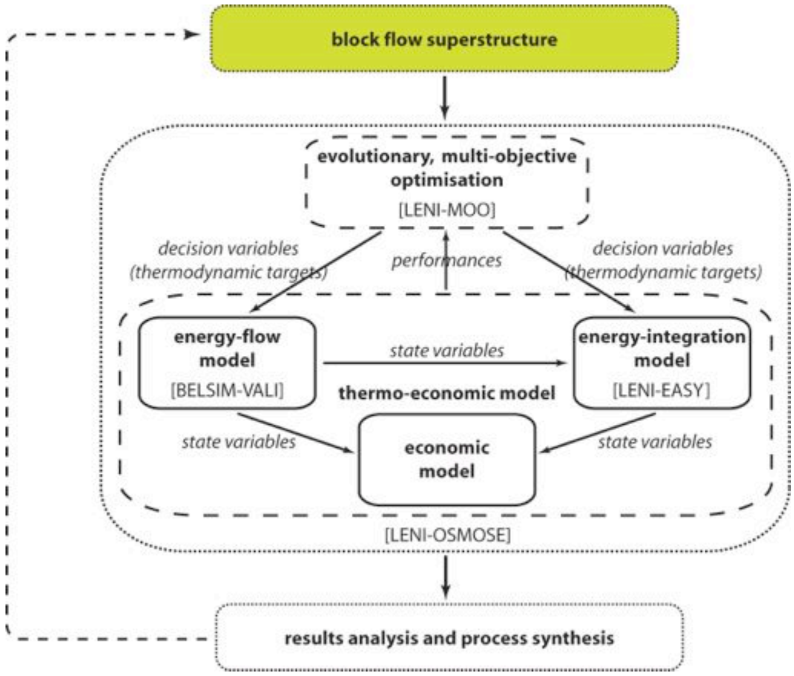
Conventional route (gasification & methanation): synthesis



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

Methodology

Block flow superstructure



Process system design

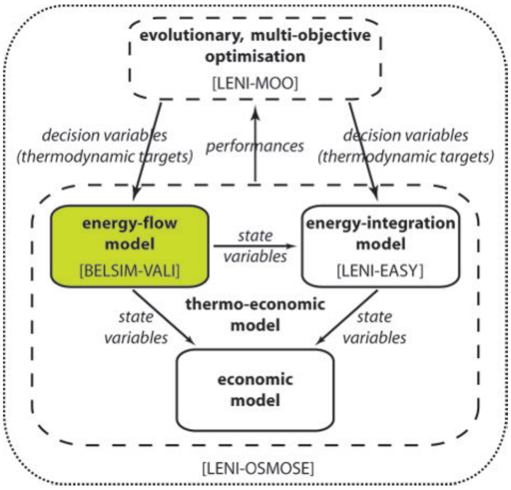
Process unit models?

Simple models but not too simple ...

- Levels of detail
- Developed for the design
  - i.e allow for thermo-economic evaluations
    - Flowsheet calculation
    - Unit size optimization
    - Cost estimation
    - Environmental impact assessment

Flowsheet generation (1)
Energy-flow model

Calculation of the thermodynamic transformations in the process units



use of

- conservation principles
- model equations

to determine

- power requirements
- heat transfer requirements
    - T-h profile of hot and cold streams

Process system design

Interconnections ?

Mass interactions -> flow superstructure

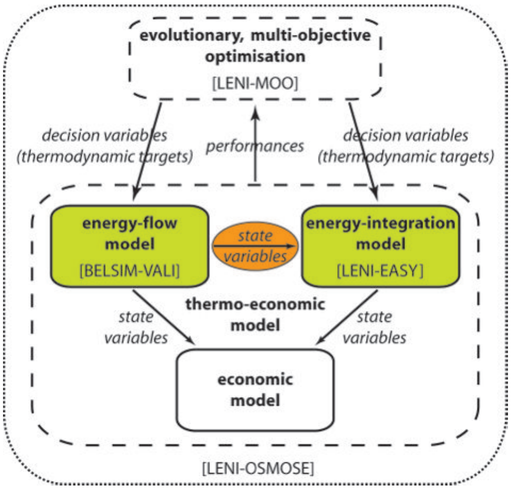
Heat interactions -> Heat cascade

Energy balance -> energy conversion integration

Flowsheet generation (1)

Energy-flow model

Calculation of the thermodynamic transformations in the process units



use of

- conservation principles
- model equations

to determine

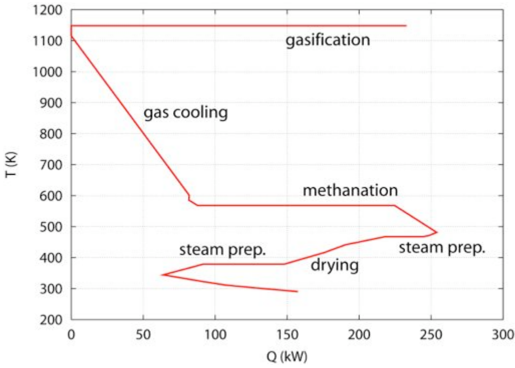
- power requirements
- heat transfer requirements
  - T-h profile of hot and cold streams

Flowsheet generation (2)

Energy-integration model

How to satisfy the MER?

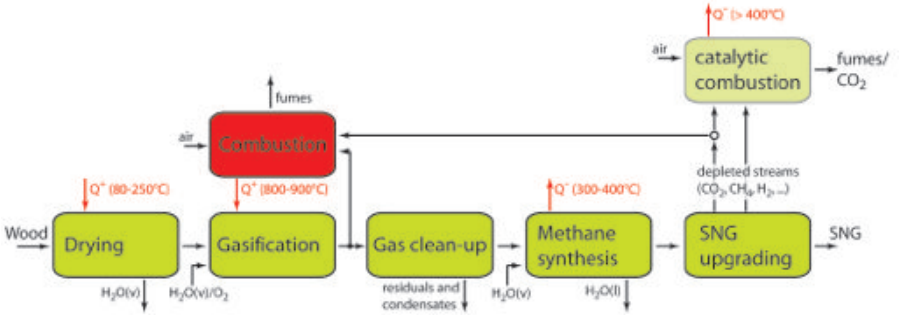
- MER of crude production



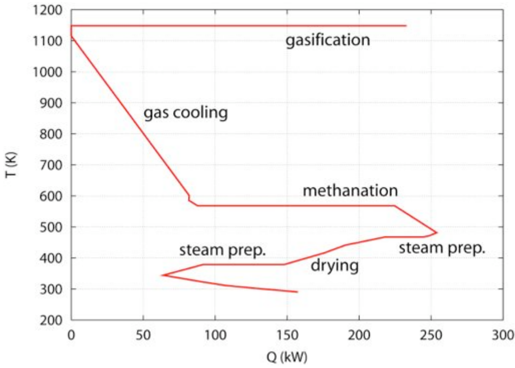
Flowsheet generation (2)

Energy-integration model

How to satisfy the MER?



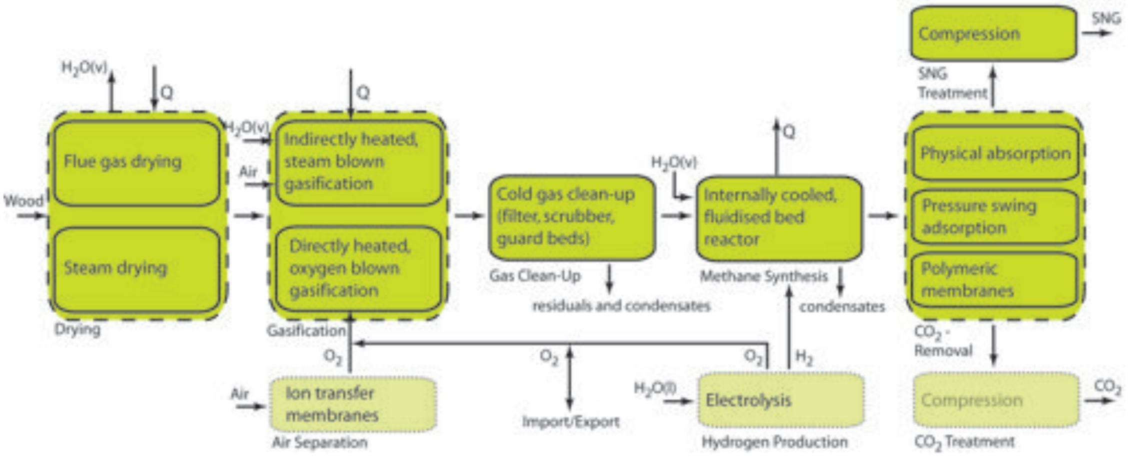
- MER of crude production
- hot utility: combustion
- fuel choice?
    - waste streams
    - intermediate products



Flowsheet generation (2)

Energy-integration model

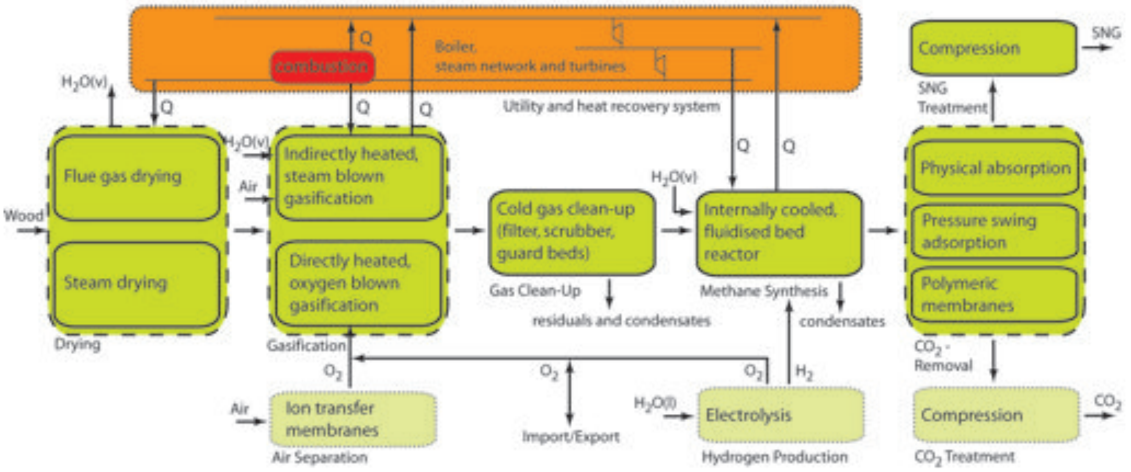
Integrating heat recovery technologies in the superstructure



Flowsheet generation (2)

Energy-integration model

Integrating heat recovery technologies in the superstructure



Flowsheet generation (2)

Energy-integration model

Math. problem formulation: MILP programming...

$$\min_{\dot{R}_r, y_s, f_s} \sum_{s=1}^{n_s} \dot{L}_s = \sum_{s=1}^{n_s} (f_s \cdot (\sum_{f=1}^{n_{fuel,s}} \dot{m}_{f,s} \Delta k_f^0 + \dot{w}_s^+ - \sum_{r=1}^{n_r} (\dot{e}_{q,s,r}^-)_{\Delta T_{min}} - \dot{w}_s^-))$$

subject to:

1. Existence of subsystem s:

$$fmin_s y_s \leq f_s \leq fmax_s y_s \qquad y_s \in \{0,1\}, \ \forall s = 1, \ldots, n_s$$

2. Heat balance of the temperature intervals r:

$$\sum_{s=1}^{n_s} f_s \dot{q}_{s,r}^- + \dot{R}_{r+1} - \dot{R}_r = 0 \qquad R_r \geq 0 \ \ \forall r = 1, \ldots, n_r$$

3. Overall heat balance:

$$R_1 = 0, \ R_{n_r+1} = 0$$

Flowsheet generation (2)
Energy-integration model

Math. problem formulation: MILP programming...

$$\min_{\dot{R}_r, y_s, f_s} \sum_{s=1}^{n_s} \dot{L}_s = \sum_{s=1}^{n_s} (f_s \cdot (\sum_{f=1}^{n_{fuel,s}} \dot{m}_{f,s} \Delta k_f^0 + \dot{w}_s^+ - \sum_{r=1}^{n_r} (\dot{e}^-_{q,s,r})_{\Delta T_{min}} - \dot{w}_s^-))$$

subject to:

4 Electricity consumption:

$$\sum_{s=1}^{n_s} f_s \dot{w}_s^- + \epsilon_d \dot{W}^+ - \dot{W}_c \geq 0 \qquad \dot{W}^+ \geq 0$$

5 Electricity exportation:

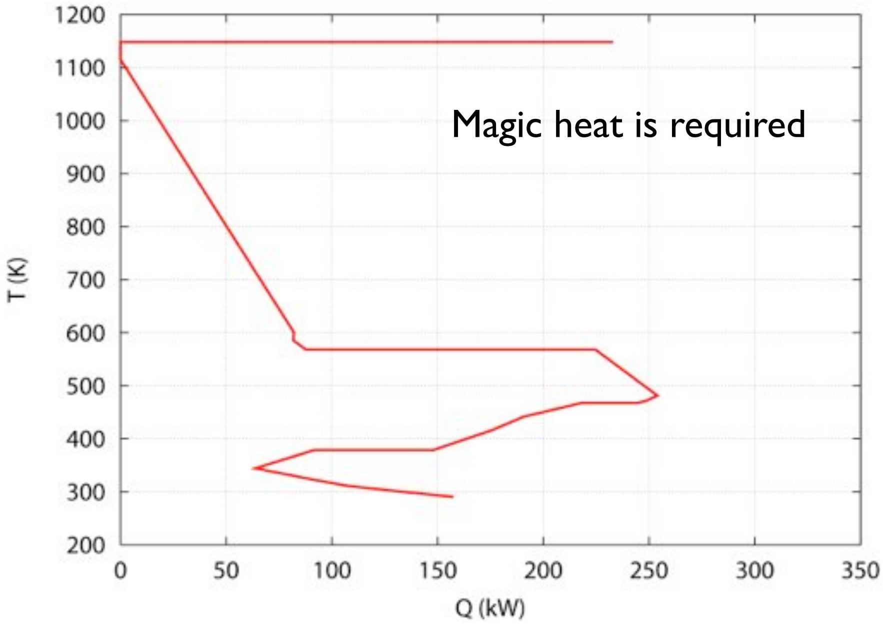
$$\sum_{s=1}^{n_s} f_s \dot{w}_s^- + \epsilon_d \dot{W}^+ - \frac{\dot{W}^-}{\epsilon_g} - \dot{W}_c = 0 \qquad \dot{W}^+ \geq 0, \ \dot{W}^- \geq 0$$

6 Superstructure model:

$$Af = b \qquad A : (n_s \times n_s), \ f, b : (n_s \times 1)$$

Flowsheet generation (2)
Energy-integration model

MILP resolution: from MER ...

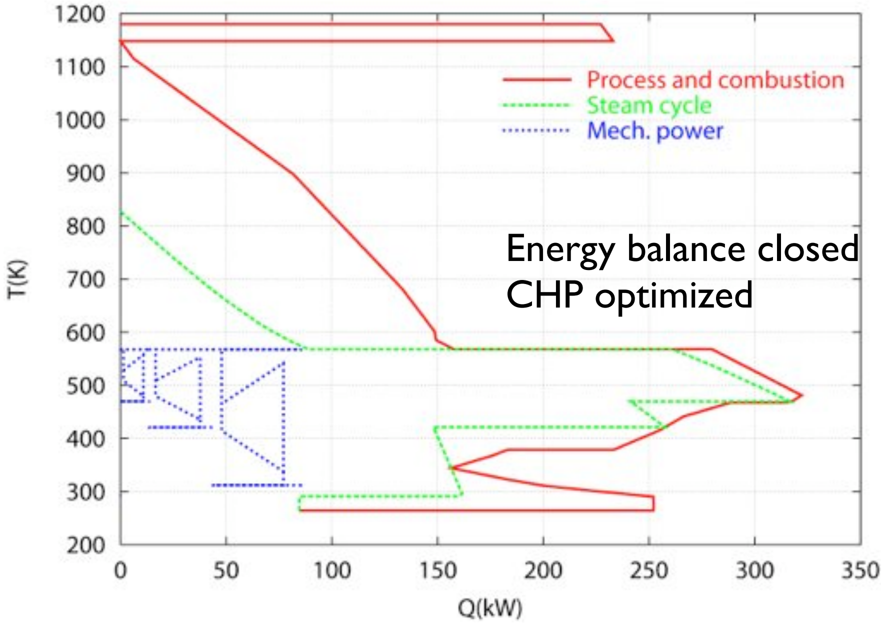


Magic heat is required

Flowsheet generation (2)

Energy-integration model

MILP resolution: ... to an integrated solution



Energy balance closed
CHP optimized

Process system design

Process performances ?

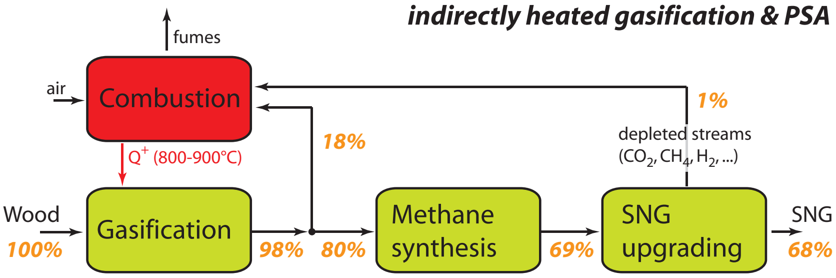
Thermodynamic performances
System balanced

Process performance

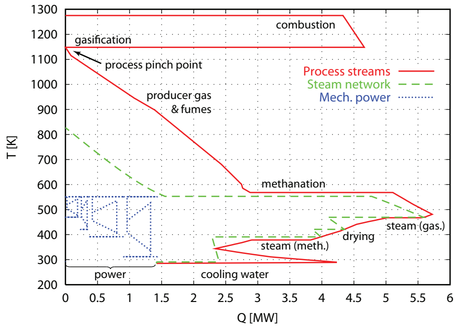
conventional SNG

Some (non-optimised) scenarios for conventional SNG production:

indirectly heated gasification & PSA



(only the chemical energy flow of the main product conversion is shown)



input: 20 $MW_{th,wood}$

		FICFB				CFB	
		(base)	(torr)	(pM)	(pM, SA)	(pGM)	(pGM, hot)
Consumption	Wood	100%	100%	100%	100%	100%	100%
	Biodiesel	1.8%	1.6%	1.8%	1.8%	0.1%	-
	Electricity	-	0.5%	-	-	0.9%	-
Production	SNG	67.7%	72.1%	67.5%	67.8%	74.0%	74.0%
	Electricity	2.9%	-	2.6%	3.3%	-	1.6%
Overall efficiency		69.4%	70.7&	68.8%	69.8%	73.2%	75.6%

Process system design

Process performances ?

Economics :

Investment

- Design equipments
- Sizes
- Cost estimations

Incomes

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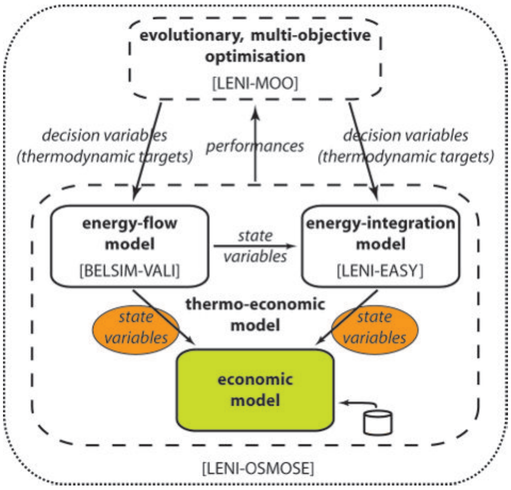
Equipment sizing and costing

Meeting the thermodynamic design target for the flowsheet



Rate the equipment with

- design heuristics
- pilot plant data

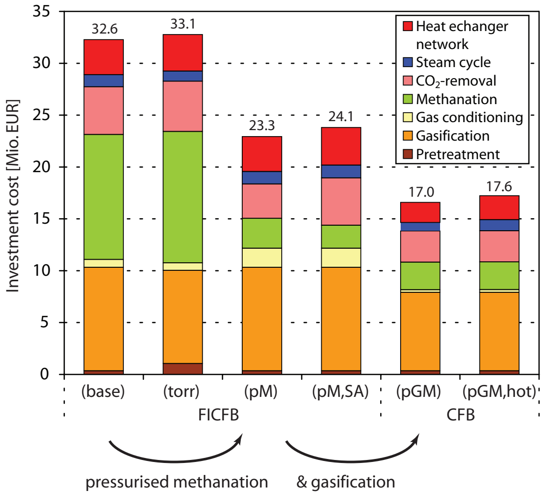
Assessment of investment cost considering the specific operating conditions

$$C_{GR} = f\,(T, p, size\,(T, p, \ldots)) \qquad (1)$$

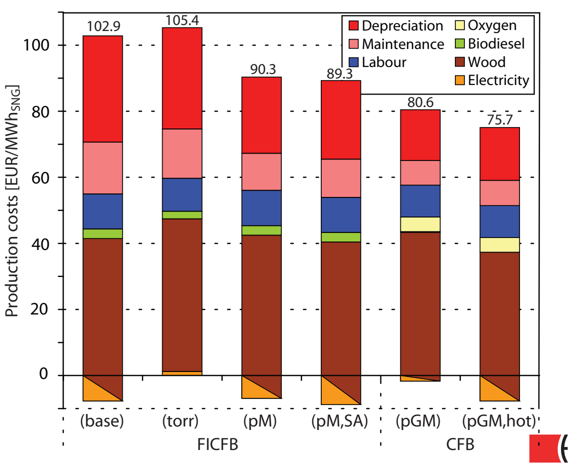
Process performance
conventional SNG

Some (non-optimised) scenarios for conventional SNG production:

Investment cost



Total production costs

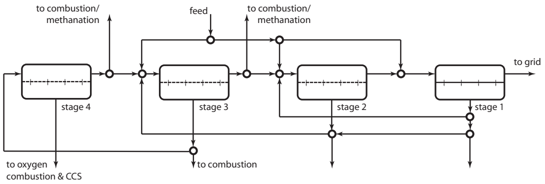


Technology integration example

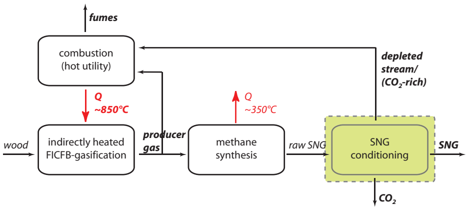
Gas upgrading by membrane

Membrane system upgrading superstructure

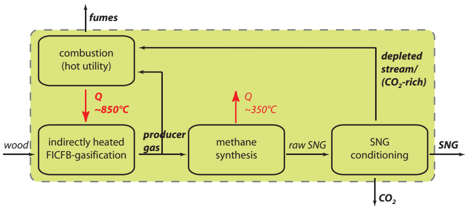
CH4/CO2
separation



"isolated": separation only



"integrated": total system



- Maximise SNG recovery
- Permeate stream is lost

- Permeate stream valorised
- Overall system performance

Technology integration example

Gas upgrading by membrane

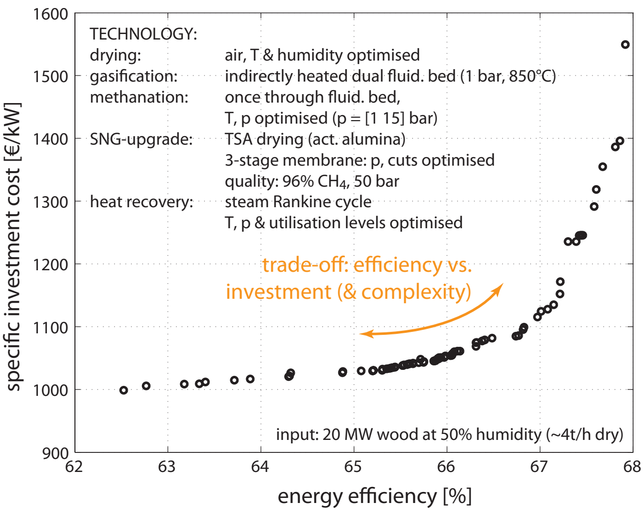
Results : Isolated vs integrated design

		isolated	integrated	overshoot
system		**3-stage CC**	**3-stage, 1 rec**	
r_{SNG}	%	**93.2**	**84.1**	+ 10.8%
e^{sep}_{spec}	$kW_{el}/MW_{th,in}$	**76.9**	**55.9**	+ 37.6%
$\tilde{c}_{CO2,p}$	%	86.6	79.9	+ 8.4%
$\tilde{c}_{H2,p}$	%	10.3	9.4	+ 9.6%
$\tilde{c}_{CH4,p}$	%	3.0	10.4	– 71.2%
A	m^2	**4675**	**2928**	+ 59.7%
C^{sep}_I	M€	**5.7**	**4.1**	+ 39.0%
ϵ^{sep}	%	86.6	80.7	+ 8.8%
ϵ_{cg}	%	69.0	63.5	+ 8.7%
ϵ	%	66.0	66.2	– 0.3%
C_I	M€	30.7	29.9	+ 2.7%
C_P	€/MWh	105.6	102.9	+ 2.6%

Thermo-economic optimisation

Trade-offs: efficiency and scale vs. investment

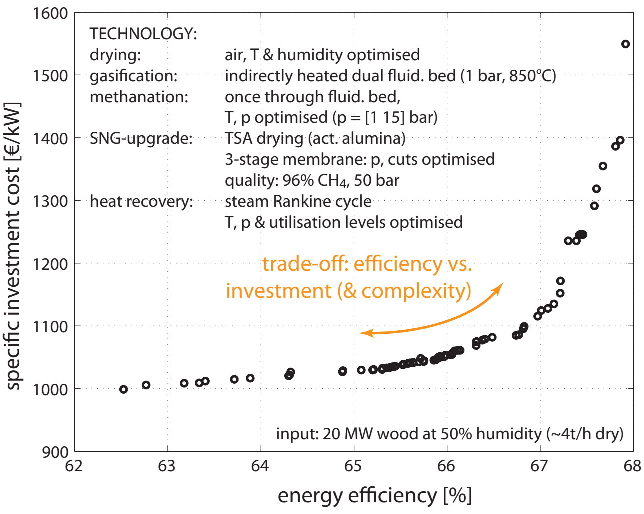
Efficiency vs. investment:

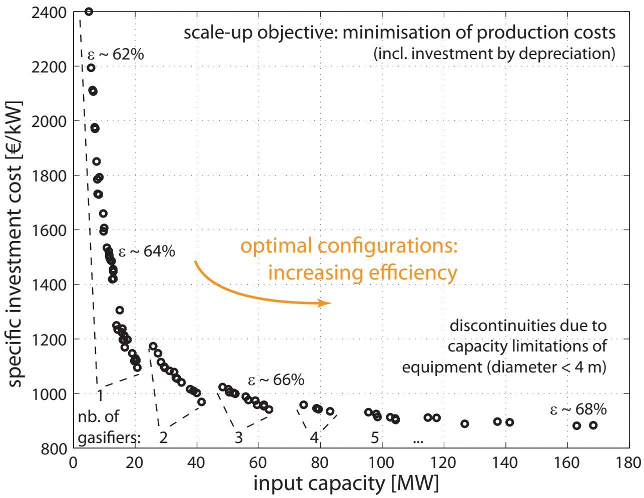


Thermo-economic optimisation

Trade-offs: efficiency and scale vs. investment

Efficiency vs. investment and optimal scale-up:



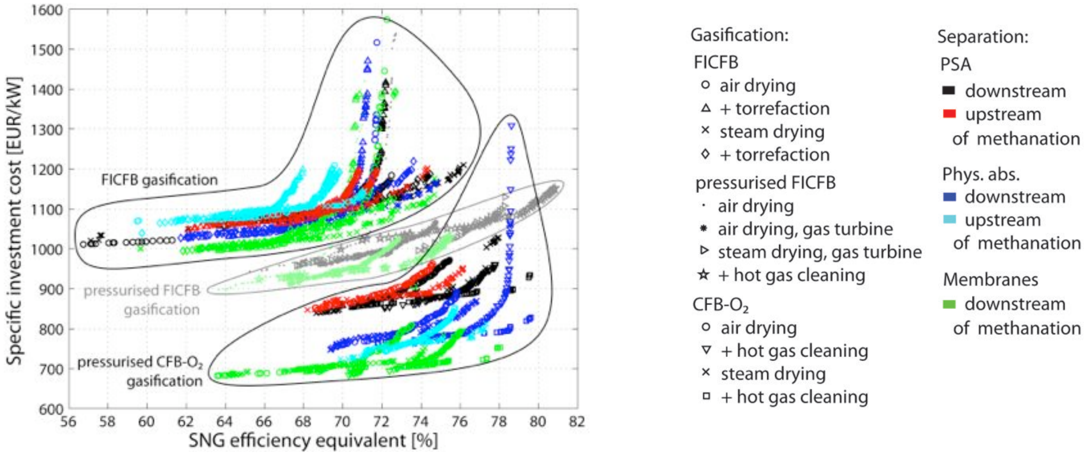


Some results

Cmparing technologies and processes

comprehensive way of comparing design options in an uncertain world

Thermo-economic Pareto front (cost vs efficiency):



→ *The best solution is the pressurised directly heated gasifier*

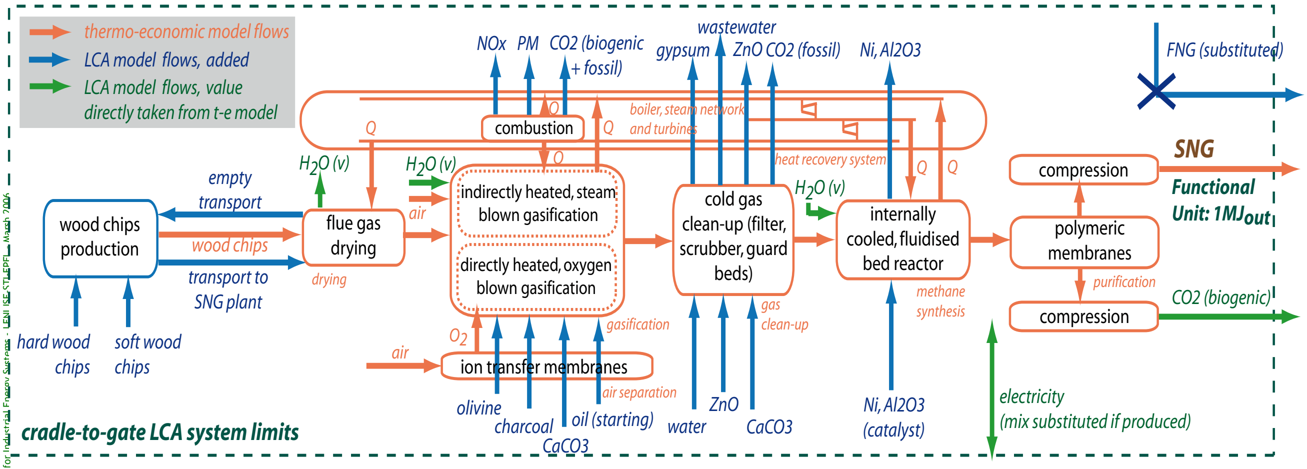
Sustainability and process integration

- Process integration of supply chains
  - What is the size of the process wrt to biomass availability ?
  - How to minimize the environmental impact ?

Environmental Process performance indicators

Identification of Life Cycle Inventory elements

- Process superstructure, extended with LCI



➡ use of ecoinvent emission database (1) for each LCI element, to take into account off-site emissions

(1) http://www.ecoinvent.org

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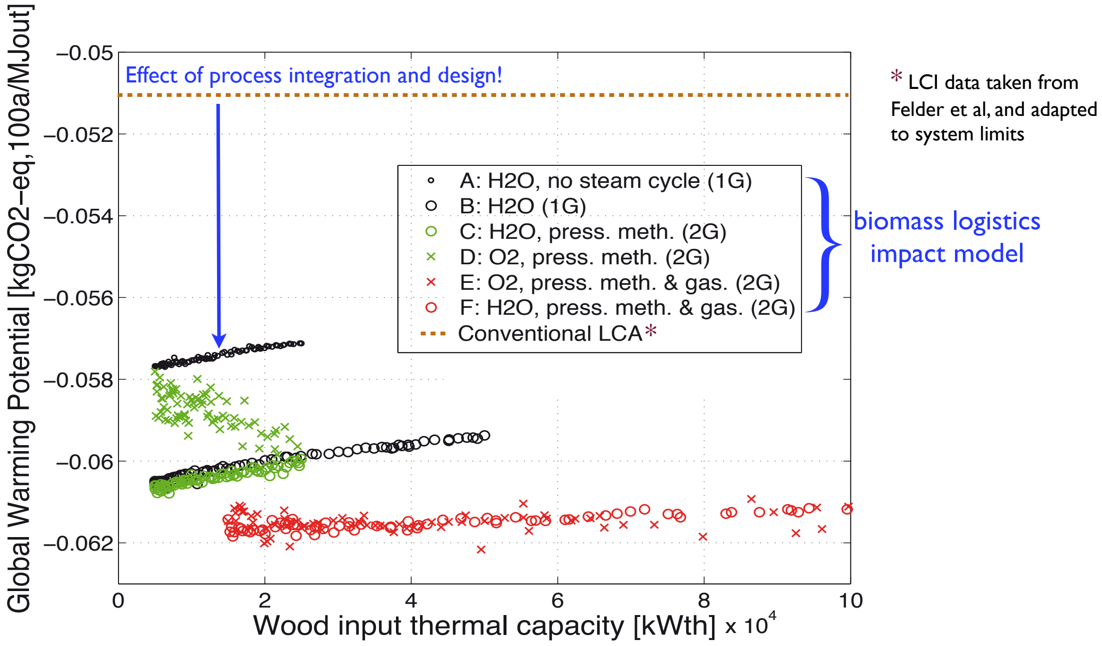
Gerber, L. et al., 2010 Comp & Chem Eng., 1405-1410

Integration of LCIA in the methodology

Perspective: plant scale-up vs. biomass logistics

The biomass Logistics has an influence on the plant impact



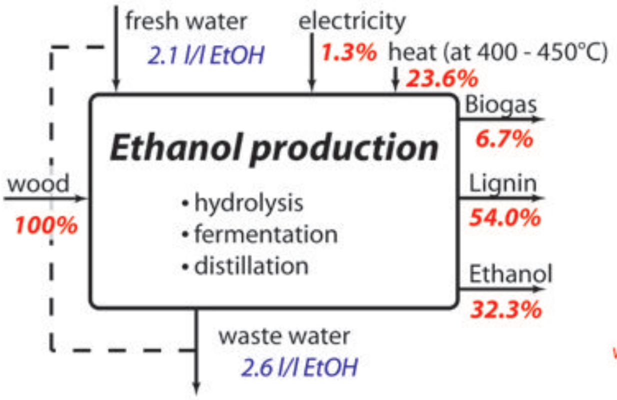
* LCI data taken from Felder et al, and adapted to system limits

→ *Optimal plant size with respect to biomass logistics*

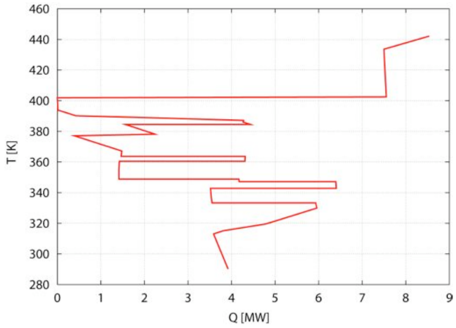
Site integration: process couplings

EtOH & SNG

Ethanol production from lignocellulosic biomass:



values based on LHV

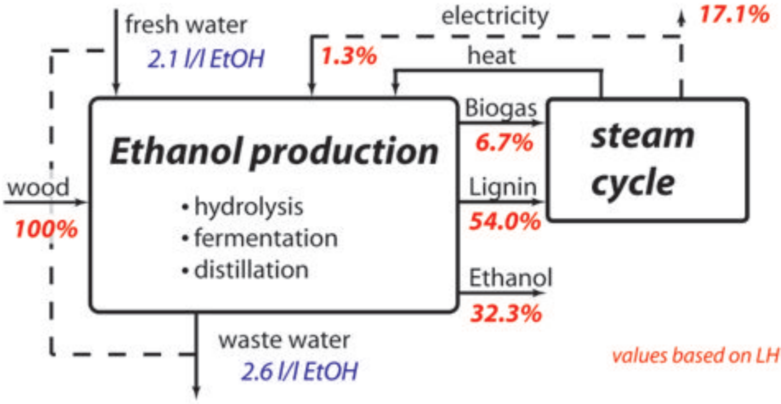


input: $58\ MW_{th,wood}$

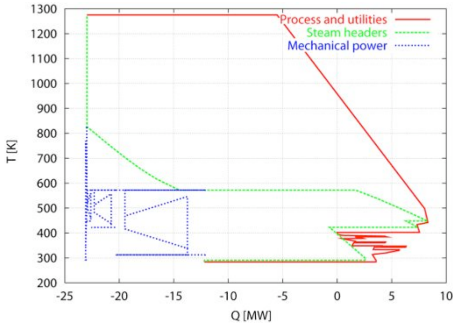
Site integration: process couplings

EtOH & SNG

Ethanol production from lignocellulosic biomass:



values based on LHV



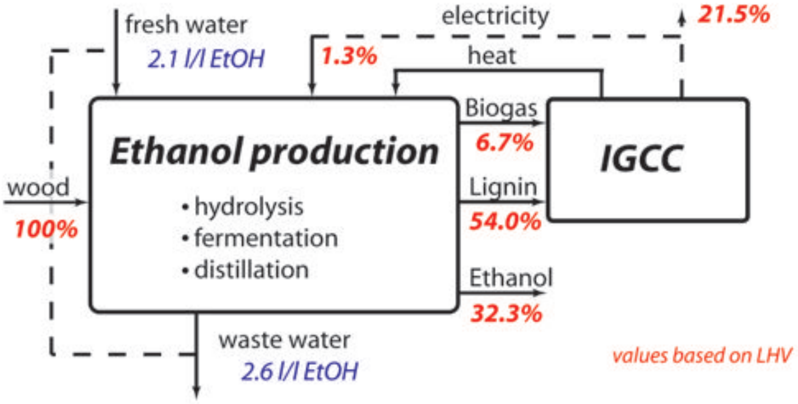
input: $58\ MW_{th,wood}$

		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 %

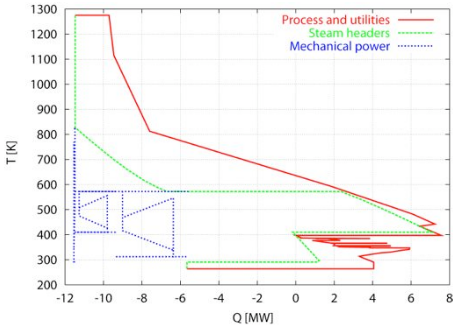
Energy balance for different process integration options (without seed train, non-optimised).

Site integration: process couplings
EtOH & SNG

Ethanol production from lignocellulosic biomass:


fresh water
2.1 l/l EtOH
1.3%
electricity
21.5%
heat
wood
100%
Ethanol production
- hydrolysis
- fermentation
- distillation

Biogas
6.7%
Lignin
54.0%
Ethanol
32.3%
IGCC
waste water
2.6 l/l EtOH
values based on LHV



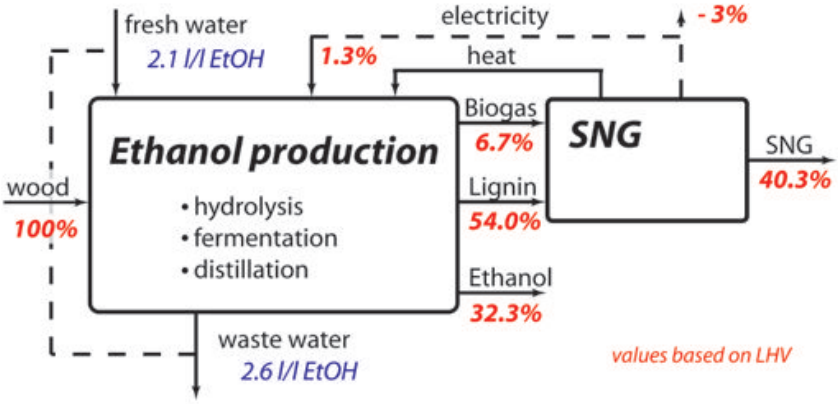
input: 58 $MW_{th,wood}$

		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 %

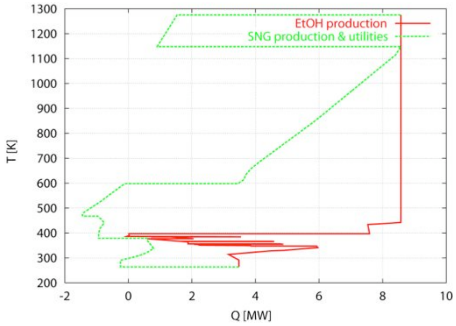
Energy balance for different process integration options (without seed train, non-optimised).

Site integration: process couplings
EtOH & SNG

Ethanol production from lignocellulosic biomass:


fresh water
2.1 l/l EtOH
1.3%
electricity
- 3%
heat
wood
100%
Ethanol production
- hydrolysis
- fermentation
- distillation

Biogas
6.7%
Lignin
54.0%
Ethanol
32.3%
SNG
SNG
40.3%
waste water
2.6 l/l EtOH
values based on LHV



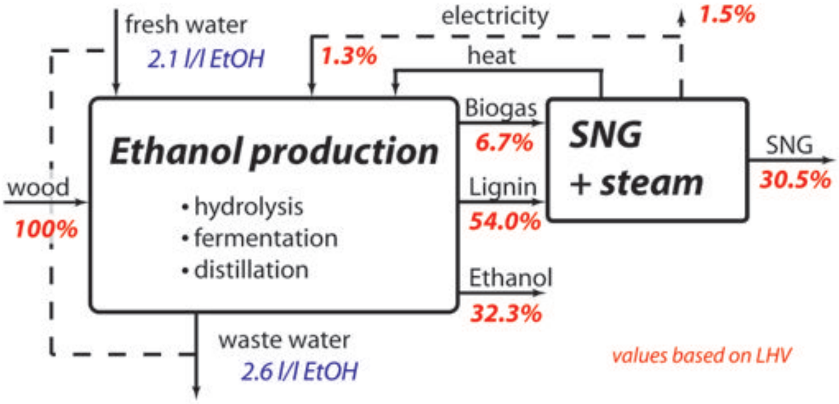
input: 58 $MW_{th,wood}$

		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).

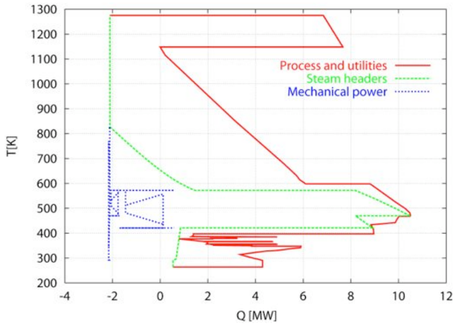
Site integration: process couplings
EtOH & SNG

Ethanol production from lignocellulosic biomass:



fresh water
2.1 l/l EtOH
electricity
1.5%
1.3%
heat
Biogas
6.7%
Ethanol production
- hydrolysis
- fermentation
- distillation

SNG + steam
SNG
30.5%
wood
100%
Lignin
54.0%
Ethanol
32.3%
waste water
2.6 l/l EtOH
values based on LHV



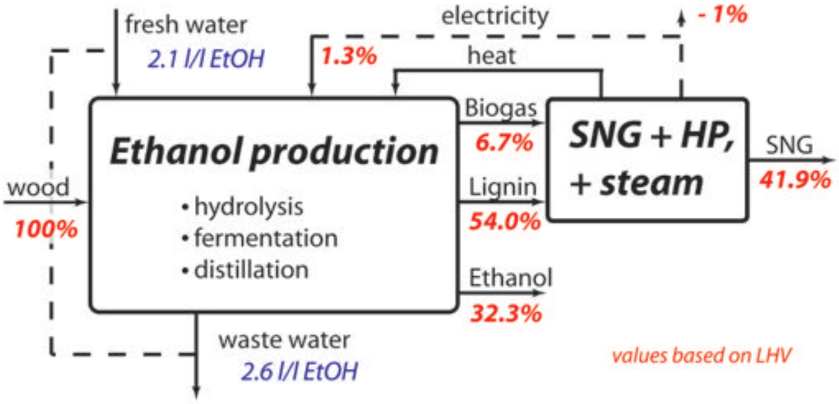
input: 58 $MW_{th,wood}$

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

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

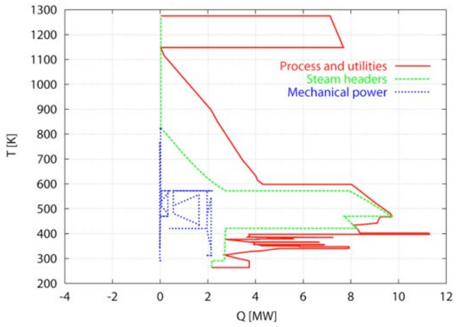
Site integration: process couplings
EtOH & SNG

Ethanol production from lignocellulosic biomass:



fresh water
2.1 l/l EtOH
electricity
- 1%
1.3%
heat
Biogas
6.7%
Ethanol production
- hydrolysis
- fermentation
- distillation

SNG + HP, + steam
SNG
41.9%
wood
100%
Lignin
54.0%
Ethanol
32.3%
waste water
2.6 l/l EtOH
values based on LHV



input: 58 $MW_{th,wood}$

		steam cycle	IGCC	SNG	+ steam	+ HP
Input	wood	100 %	100 %	100 %	100 %	100 %
	ethanol	32.3 %	32.3 %	32.3 %	32.2 %	32.2 %
Output	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).

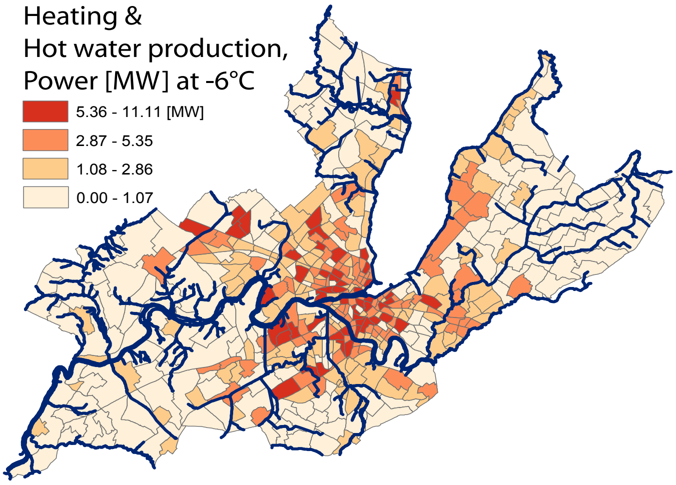
Gassner, M. and Maréchal F. ECOS2010 proceedings, Suping Zang et al. *Energy and fuels* 23, no. 3 (2009): 1759-1765

Motivations

6. Overall System analysis

Extending system boundaries

Locate the plant for CHP

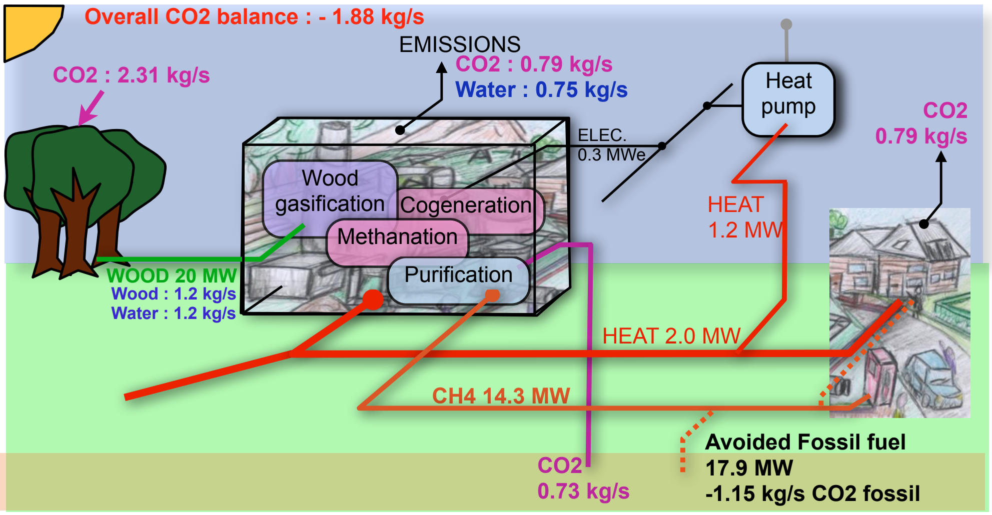


Heating requirement in the Canton of Geneva

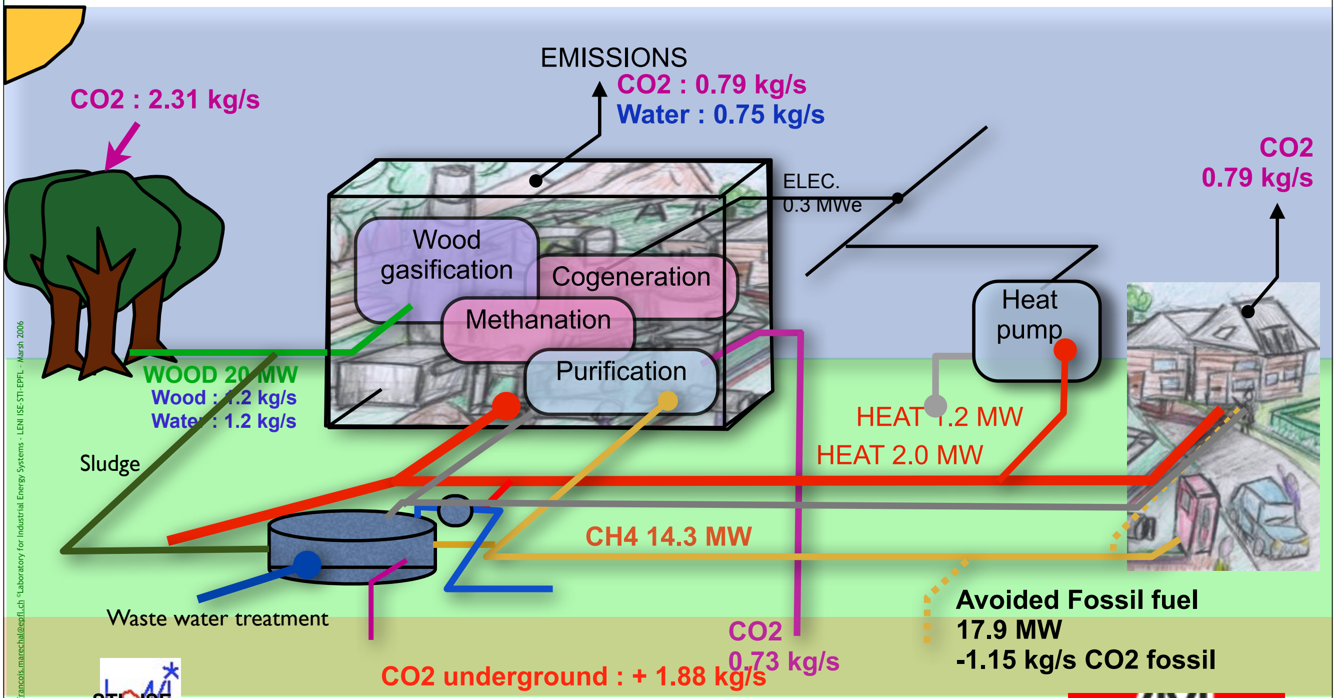
Girardin, et al., Energy, (2010)

The System vision of the bio SNG plant

1 Swiss familly of 4 person with hybrid SNG car and SIA standard house require 2 Ha of forest and ... sucks CO_2 from the environment.



Towards Industrial ecology

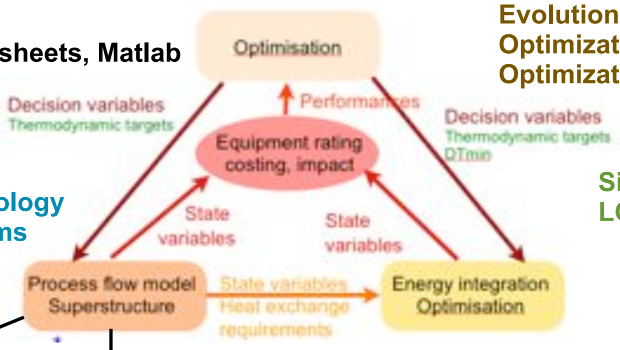


Motivations

7. Computer aided design framework

OSMOSE
developed by the LENISYSTEM group

OSMOSE : A process system design platform



Grid computing

Multi-objective optimization
Evolutionary - Hybrid
Optimization problem decomposition
Optimization under uncertainty

GUI : Spreadsheets, Matlab

GIS data base
Industrial ecology
Urban systems

Sizing/costing data base
LCIA database (ECOINVENT)

Optimal control models
(MILP/ AMPL or GLPK)
Multi-period problems

Flowsheeting tools
- •BELSIM-VALI
- •gPROMS
- •ASPEN plus
- •HYSYS
- •Matlab
- •Simulink
- •(CITYSIM)
- •Others possible
  - •CAPE-OPEN ?
  - •PROSIM
  - •MODELICA ?
  - •UNISIM ?

Energy technology data base
- •Data/models interfaces
- •Simulation
- •Process integration interface
- •Costing/LCIA performances
- •Reporting/documentation
- •Certified dev procedure

MILP/MINLP models
AMPL
Heat/mass integration
Sub systems analysis
BonMin
HEN synthesis models

PinchLIght interface
- •Web service tool to access models via the web
- • Web interface + workflow
- • Reporting

Conclusions

- **Process integration and design methods for sustainable biofuel systems**
  - Energy system analysis
  - Thermo-economic models
  - Process integration techniques
  - Life cycle assessment methods
  - Multi-objective optimization techniques
  - Systems “thinking”
- from **multi-disciplinarity** to **inter-disciplinarity**

Thanks to my team and co-workers

Dr Martin Gassner, Dr Matteo Morandin, Dr Alexis Duret, Dr Raffaele Bolliger, Dr Leandro Salgueiro

Leda Gerber, Suping Zang, Laurence Tock, Luc Girardin, Emanuela Peduzzi, Matthias Dubuis, Helen Becker

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http://leni.epfl.ch

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