Process design methods for sustainable energy systems

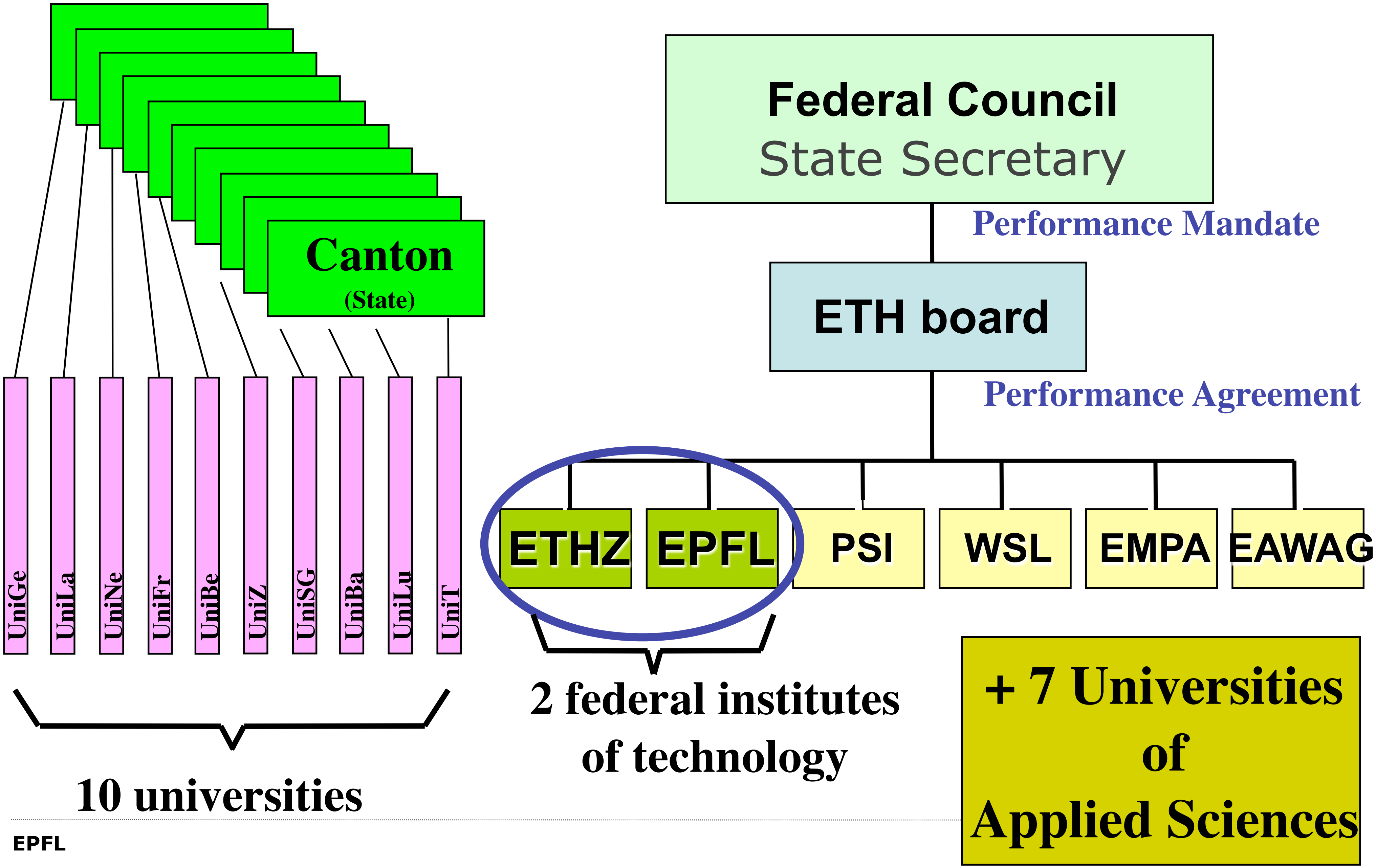
Dr François Marechal

Ecole Polytechnique Fédérale de Lausanne

EPFL
today and tomorrow

Dr A. Fromentin

Head International Relations Affairs

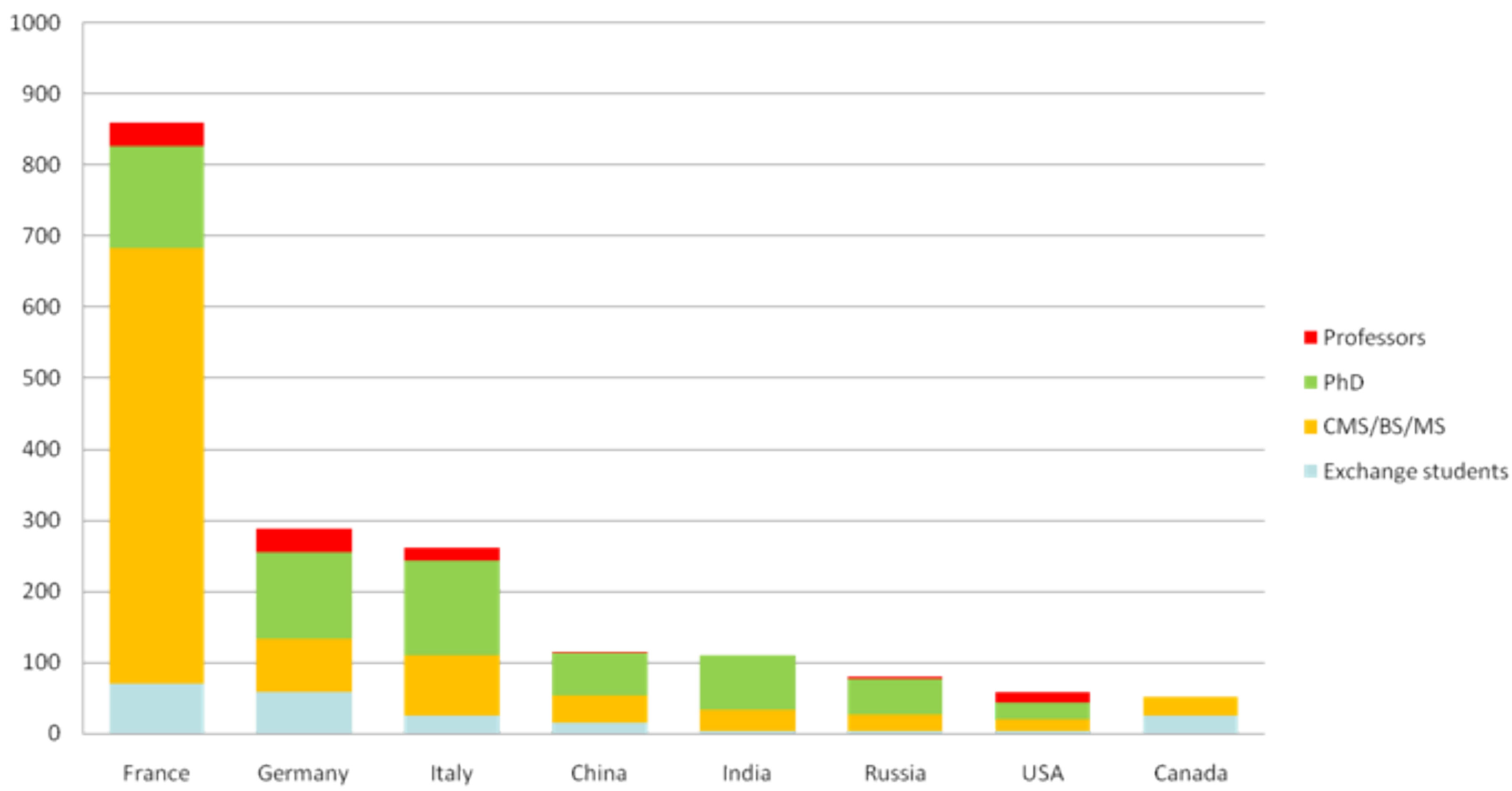

Canton
(State)
UniGe
UniLa
UniNe
UniFr
UniBe
UniZ
UniSG
UniBa
UniLu
UniT
10 universities
Federal Council
State Secretary
Performance Mandate
ETH board
Performance Agreement
ETHZ
EPFL
PSI
WSL
EMPA
EAWAG
2 federal institutes
of technology
+ 7 Universities
of
Applied Sciences

10'000	People on the campus
7178	Students, of which
1785	PhD students
900	teachers and educators
320	Faculty members (Prof)

Confederation Budget	**548 Million CHF (2009)**
External Financing	**194 Million CHF (2009)**

World@epfl

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE



Non-exhaustive list!

vendredi, 18 février 2011

Academic Ranking of World Universities by Broad Subject Field - 2009

Shanghai Jiao Tong University
Institute of Higher Education

Shanghai Jiao Tong ARWU 2009 Engineering, Technology and Computer Science		
1	Massachusetts Inst Tech (MIT)	USA
2	Stanford Univ	USA
3	Univ Illinois - Urbana Champaign	USA
4	Univ California - Berkeley	USA
5	Carnegie Mellon Univ	USA
6	Univ Michigan - Ann Arbor	USA
7	Univ Texas - Austin	USA
8	Georgia Inst Tech	USA
9	Univ California - San Diego	USA
10	Penn State Univ - Univ Park	USA
11	Univ Southern California	USA
12	California Inst Tech	USA
13	Univ California - Santa Barbara	USA
14	Univ Maryland - Coll Park	USA
15	EPFL	Switzerland
15	Univ Cambridge	UK
17	Purdue Univ - West Lafayette	USA
18	Cornell Univ	USA
19	University of Toronto	Canada
20	Tohoku Univ	Japan

EPFL in the top 20 in Engineering, Technology and Computer Science

No 1 in Europe !

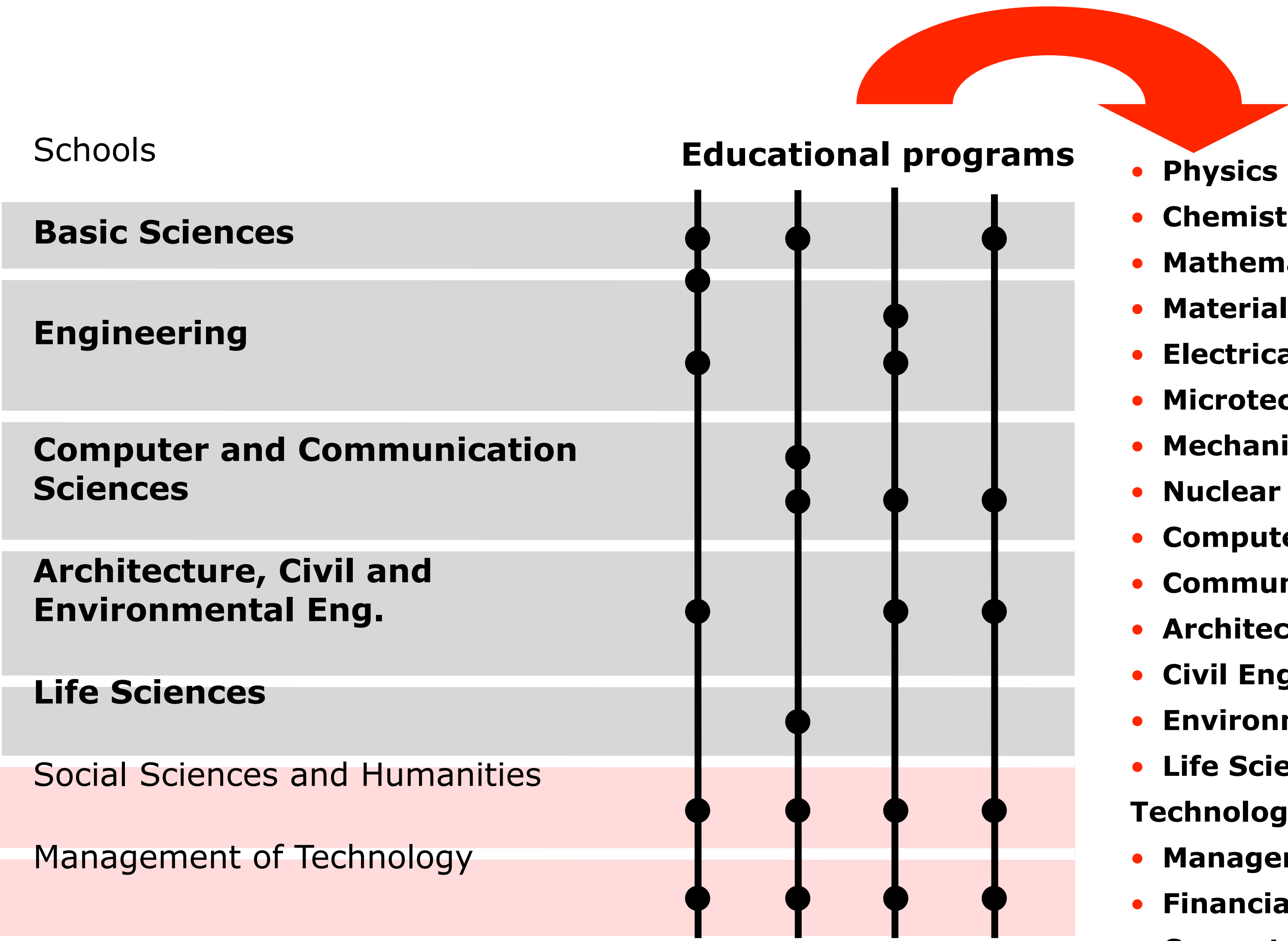


Educate and train future scientists, engineers and architects

Conduct cutting-edge research

Transfer knowledge to create jobs and companies

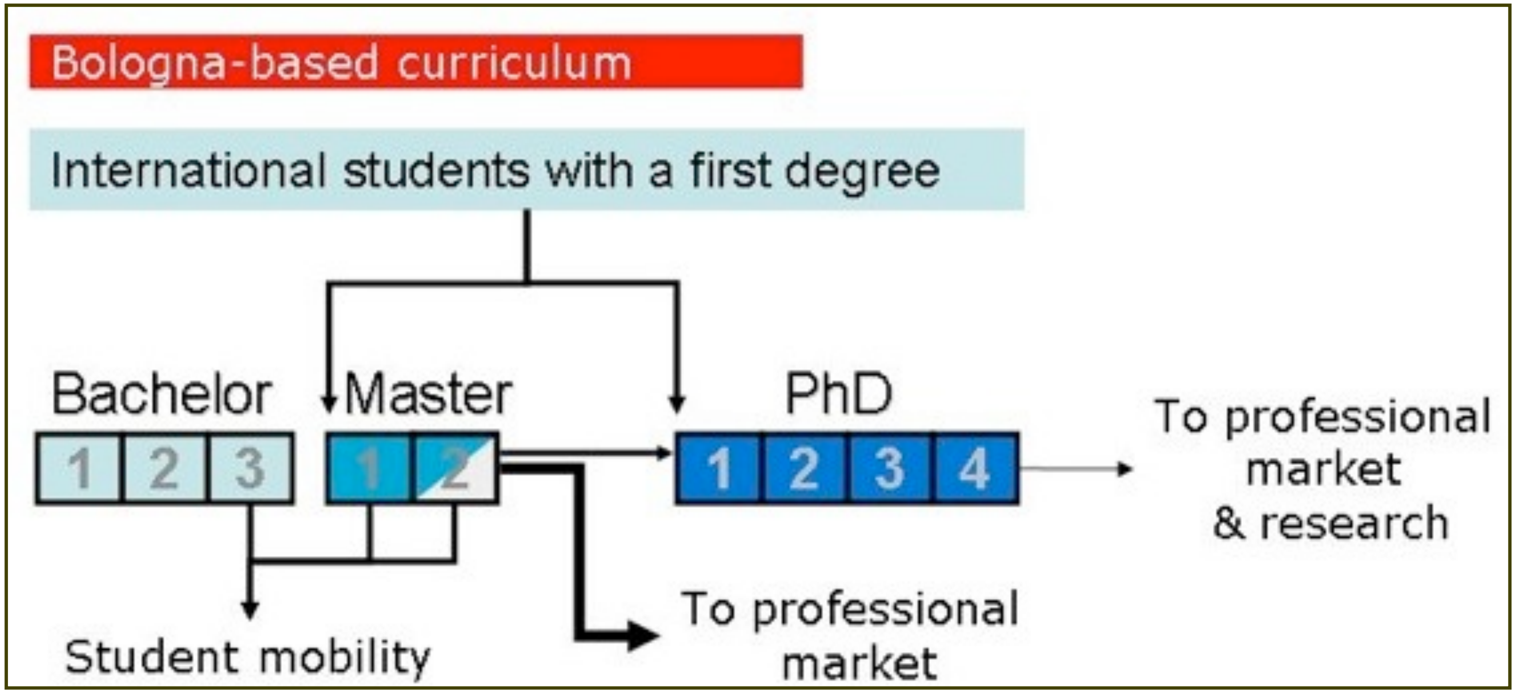
A wide range of knowledge



- Physics
- Chemistry / Chemical Eng.
- Mathematics
- Material Sciences
- Electrical Engineering
- Microtechnology
- Mechanical Engineering
- Nuclear Engineering
- Computer science
- Communication systems
- Architecture
- Civil Engineering
- Environmental Science & Eng.
- Life Sciences & Technology
- Management of Technology
- Financial Engineering
- Computational Science & Eng.

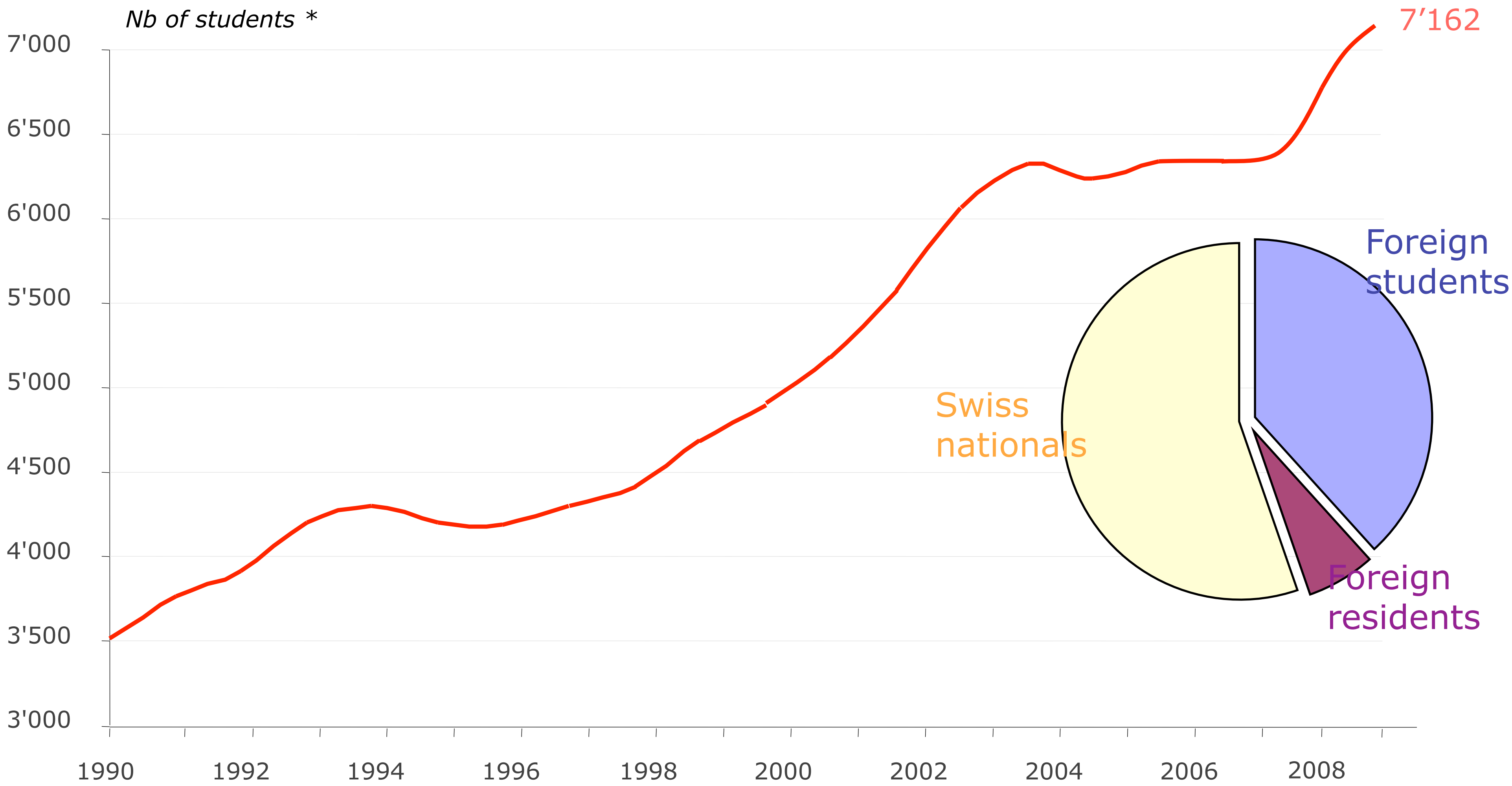
A curriculum with international compatibility

Undergraduate	Graduate	Graduate
Bachelor (BS)	Master (MS)	Doctoral Studies (PhD)



+ Postgraduate studies: Executive Master (EM) - Master of Advanced Studies (MAS) - Continuing Education

A steady increase



* Bachelor, Master, PhD, Postgraduate (CMS not included)

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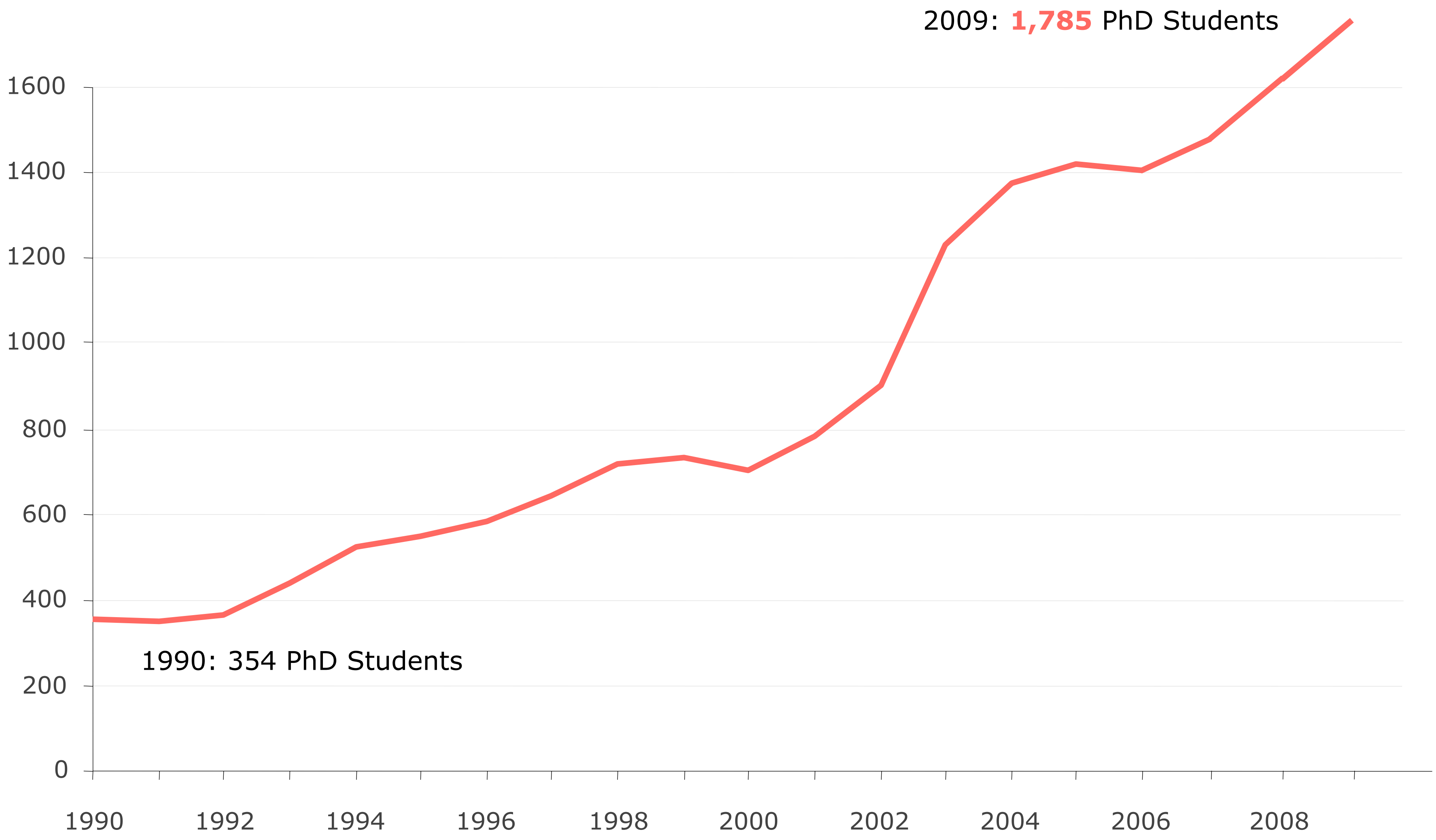
Steady increase of PhD students



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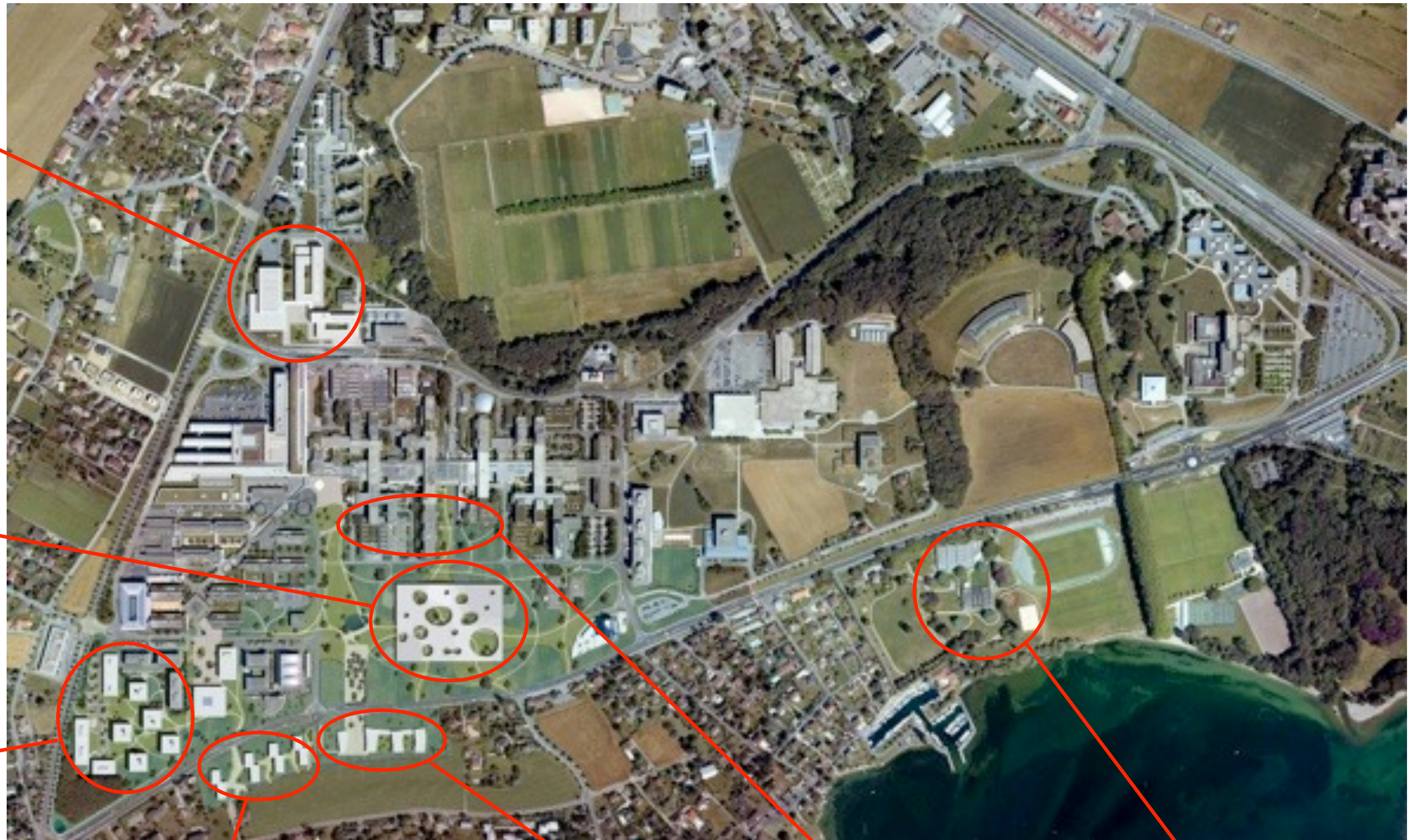
Infrastructure: Main projects

Conference Centre

Rolex Learning Centre

Innovation Square



Students Housing

Hotel

Message 2009

Sport centre

Laboratoire d'énergétique industrielle
Industrial Energy Systems Laboratory
LENI -IGM-STI-EPFL

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

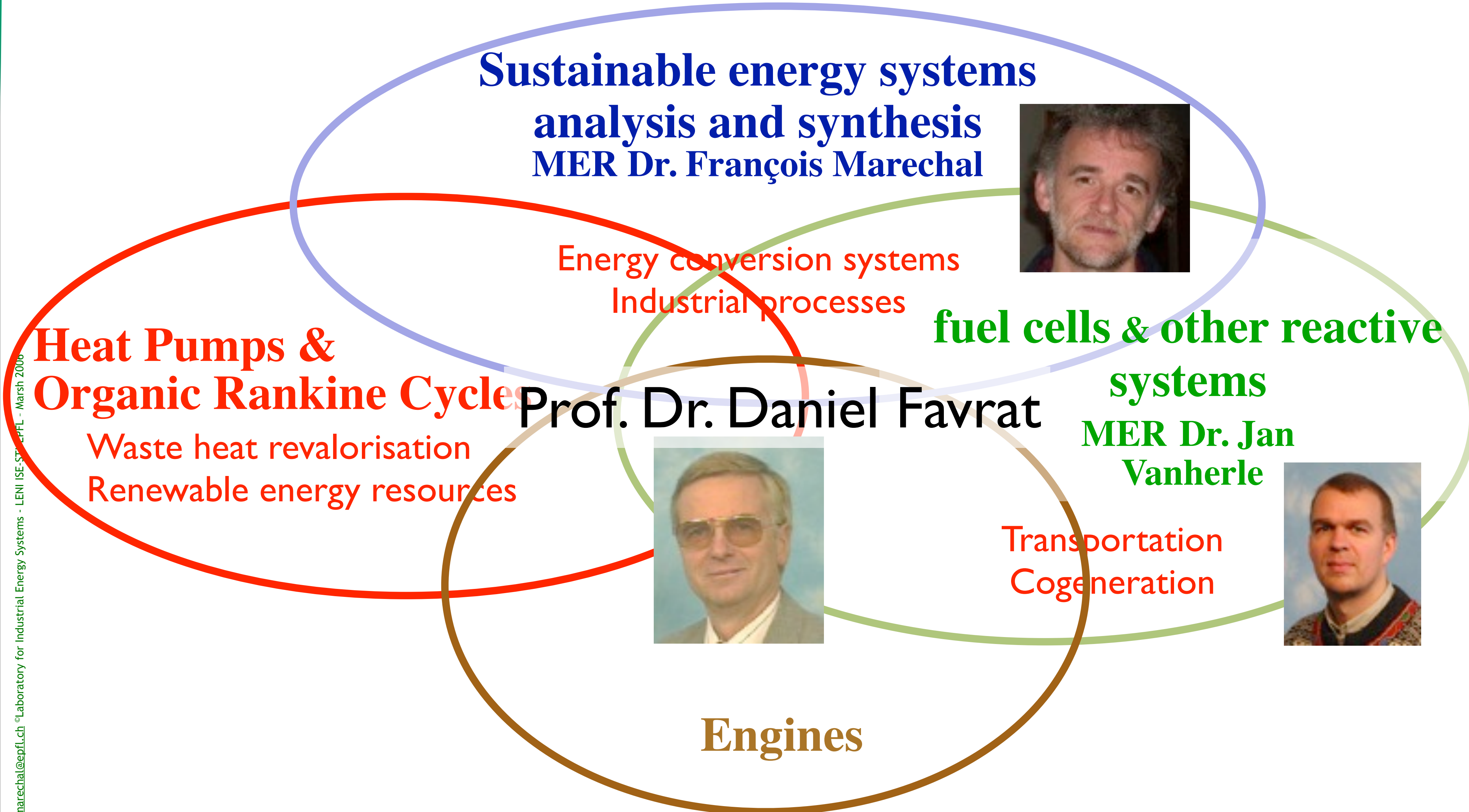
Industrial Energy Systems Laboratory

Mechanical Engineering Institute
School of Engineering

Ecole Polytechnique Fédérale de Lausanne

Prof Dr. Daniel Favrat
MER Dr. F. Marechal
MER Dr. Jan Vanherle
http://leni.epfl.ch

Industrial Energy Systems Laboratory



approx. 30 people , 3 seniors, 4 groups

Industrial Energy Systems Laboratory Reseach

- Goals
  - Develop **methods**, **tools** and **technologies** for the Rational Use and Conversion of Energy in Industrial Energy Systems
- Keywords
  - Advanced energy conversion **technologies**
  - Energy efficiency
  - **Systems integration**
  - Sustainable development
  - 2000 W society

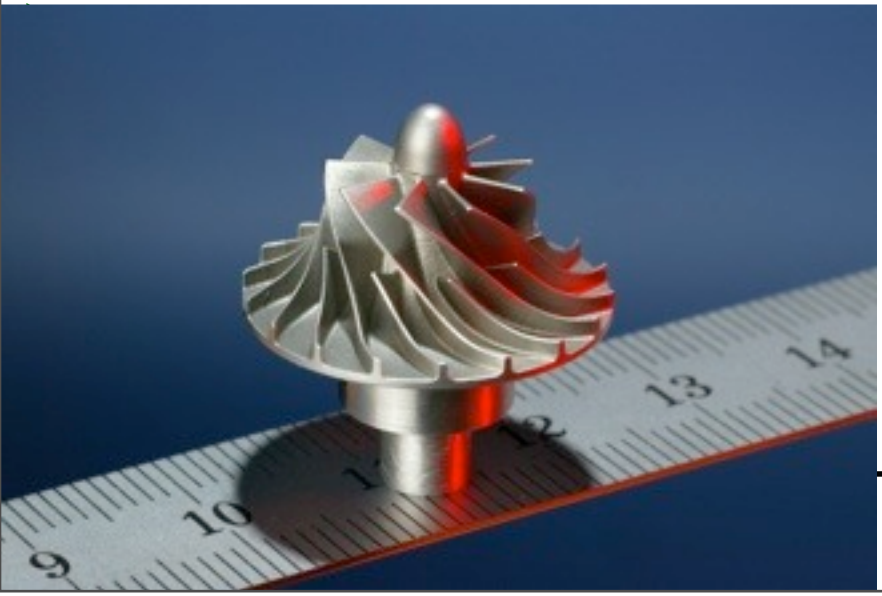
Oil-free Turbo with direct high speed electric drive

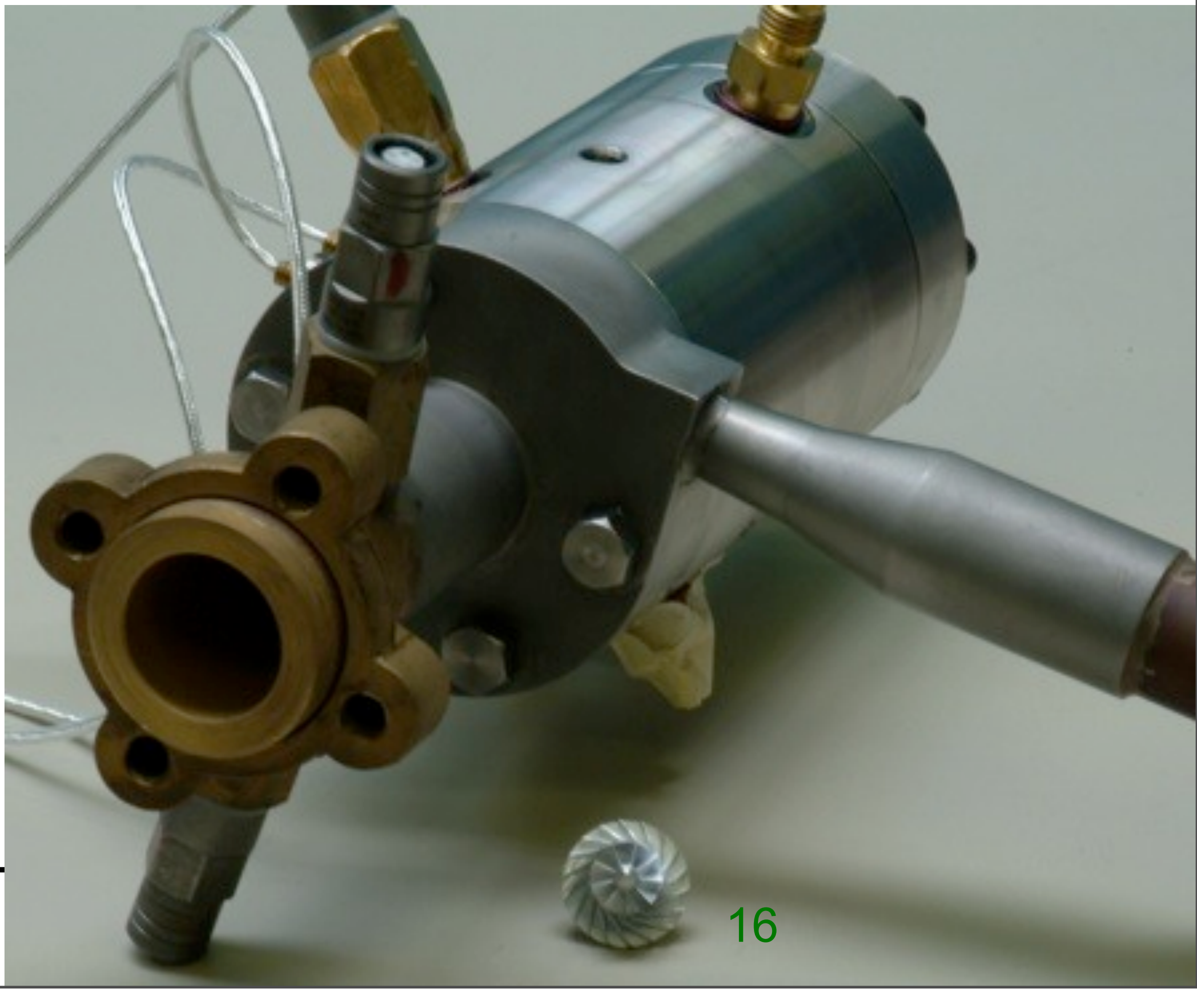
HIGH SPEED (240’000 RPM) - Oil Free Compressors (gas bearings)

- Coefficient of performance better (in 2 stages)
- Continuous power regulation (high performance and variable speed permanent magnet motor)
- No oil, ease of refrigerant recycling, fluid compatibility ..
- Miniature, low material content
- Smaller and better evaporator

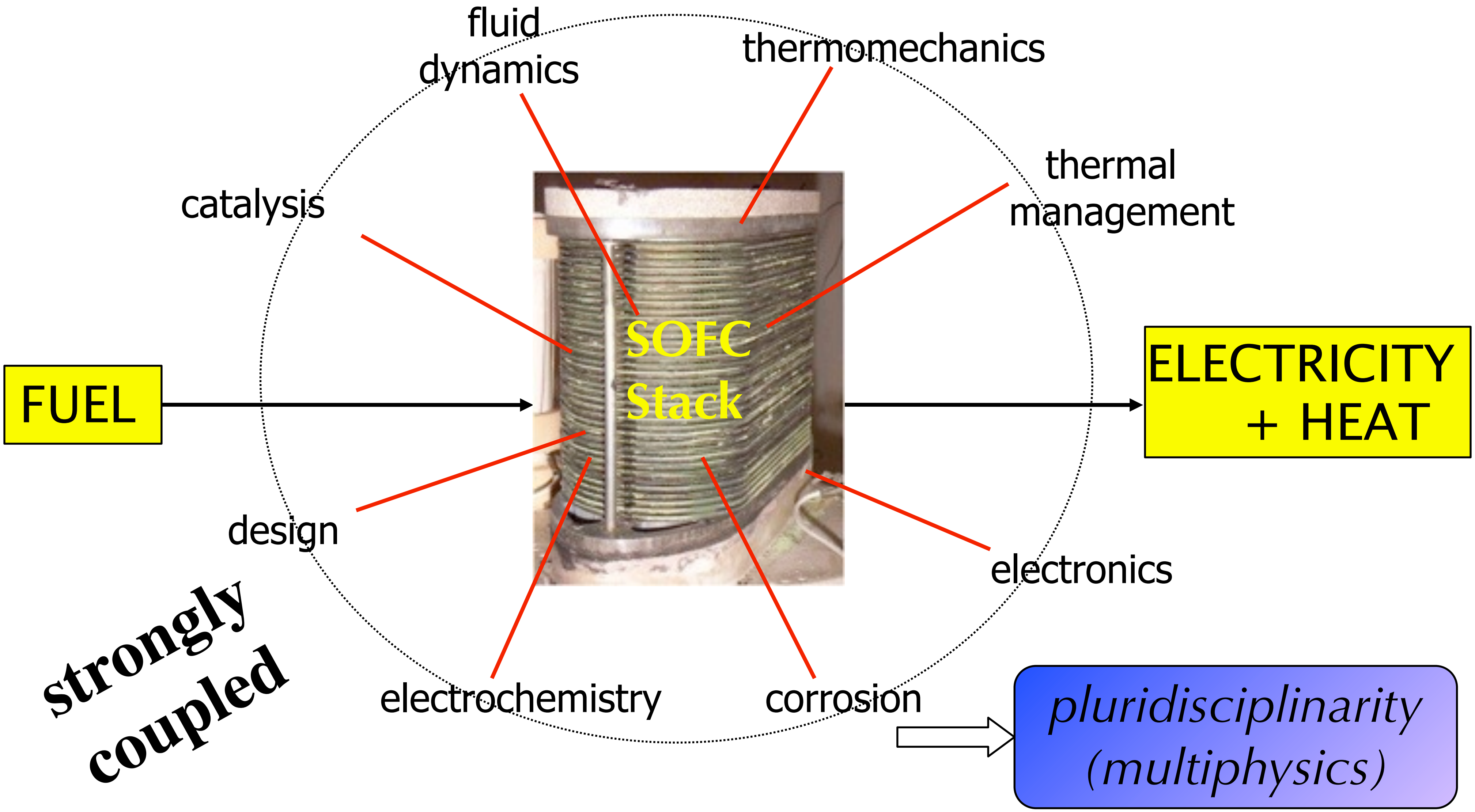
(better oil-free heat transfer

coefficient with enhanced surfaces)





Industrialisation of SOFC systems



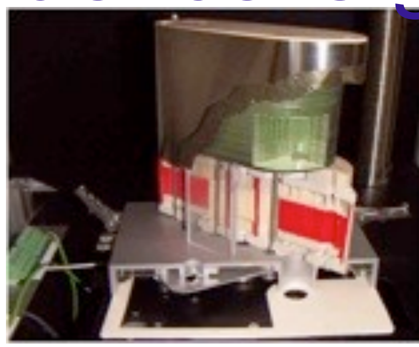
Modeling & Experiments

Systems integration : SOFC+µT hybrid

System group

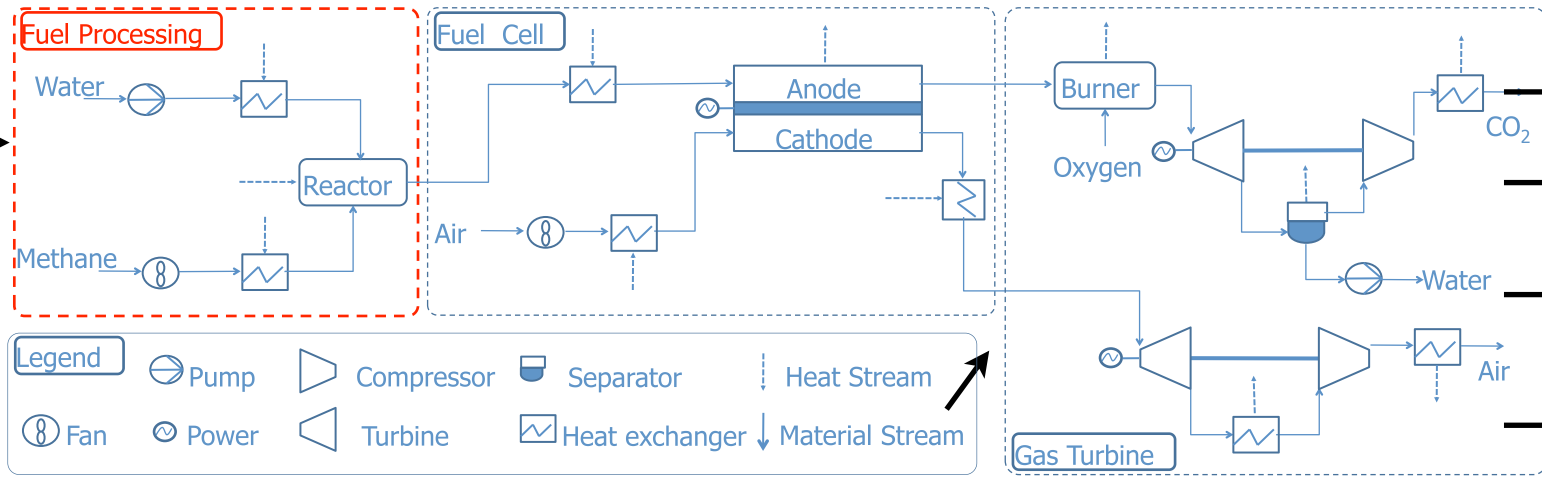
Fuel cells group

Efficiency up to 80 %
Size 21 kWe



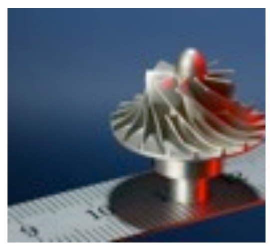
15 kWe

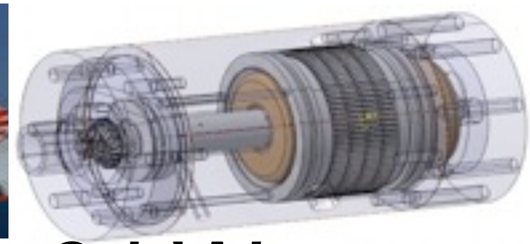
CH4
Bio CH4



CO2
Elec
Heat
H2O

Cycles group

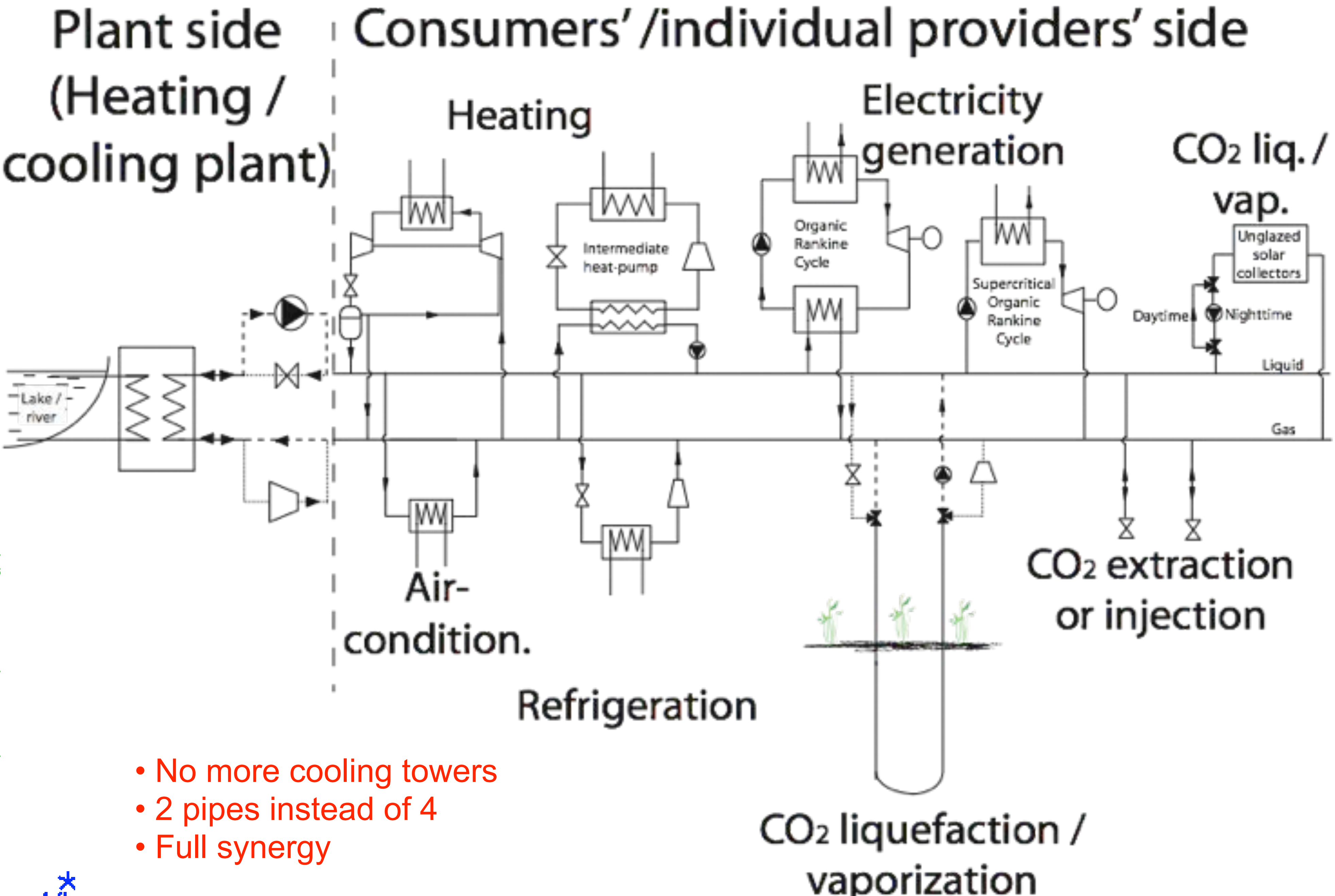




6 kWe

Patent EU : PCT/IB2010/052558

System integration the LENI concept : CO2 district heating system



- No more cooling towers
- 2 pipes instead of 4
- Full synergy

Le groupe

Analyse et synthèse des systèmes énergétiques assistées par ordinateurs

Sustainable energy systems

Analysis and Synthesis group

MER Dr. François Marechal (francois.marechal@epfl.ch)

Industrial Energy Systems Laboratory

Laboratoire d'énergétique industrielle

LENI - IGM - STI - EPFL

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http://leni.epfl.ch + 41 21 693 35 06

- Francois Marechal's CV
  - 1986 Chem Eng. Univ. Liège (B)
  - 1995 Ph D. Univ Liège
    - prof Kalitventzeff, Energy Analysis and Synthesis of Industrial Processes
  - 2001 EPFL / LENI
  - 2005 MER (EPFL /LENI)
- Other
  - Scientific committee of IFP Energie Nouvelles
  - Advisor Energy efficiency VEOLIA
  - ECLEER (EDF/ Mines/EPFL)
  - Responsable for the minor in energy (EPFL)
  - ESCAPE comitee (repr. CH)
- http://people.epfl.ch/francois.marechal

the LENI SYSTEM group

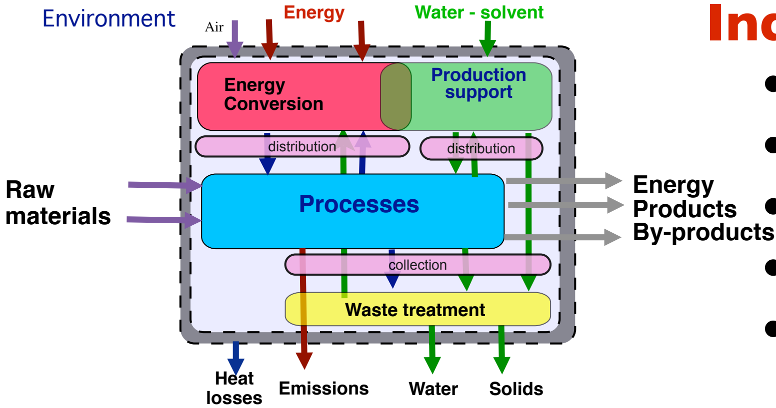
4 Post docs - 12 Ph D. students

A team who develops **computer aided process system engineering** tools and methods for the **analysis** and the **synthesis** of efficient processes and energy conversion systems

- **Thermo-economic & environomic models** of sub-systems
  - Data base concept
- **System integration modeling**
  - Modeling the possible interactions between sub-systems
- **Multi-objective optimization** for decision support
  - Thermo-Economic Pareto fronts
- **Thermodynamic insights** for systems analysis and synthesis

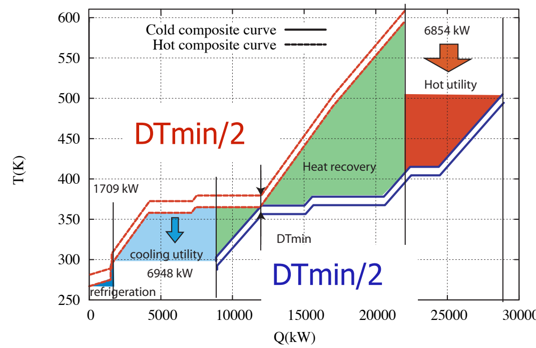
*with the goal of understanding the **system's energetics***

Domain of applications and partners



Industrial Processes

- Pinch analysis
- Exergy analysis
- Energy conversion
- Integrated systems
- Water & Waste

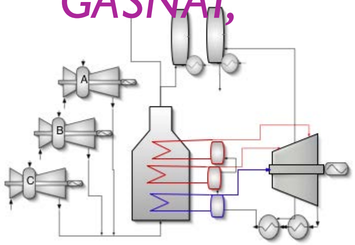


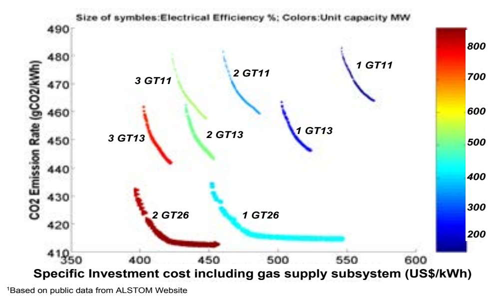
NESTLE, EDF, OFEN, VEOLIA, RHODIA, SYNGENTA, SNF, Borregaard

Process system design

- Fuel cells systems
- Power plants, Biofuels,...
- Water prod., Waste water
- CO_2 capture

VEOLIA, CCEM, ALSTOM, SWISSELECTRIC, GASNAT,

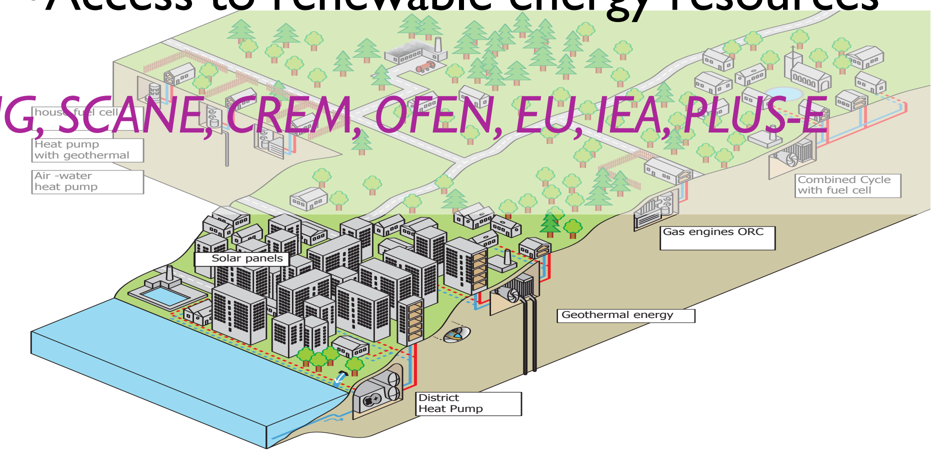




Urban systems

- District networks : CO_2 swiss knife
- Polygeneration : Virtual power plants
- Integrated services and technologies
- Access to renewable energy resources

SIG, SCANE, CREM, OFEN, EU, IEA, PLUS-E



Process design methods for sustainable energy systems

Dr François Marechal

Ecole Polytechnique Fédérale de Lausanne

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

Motivations

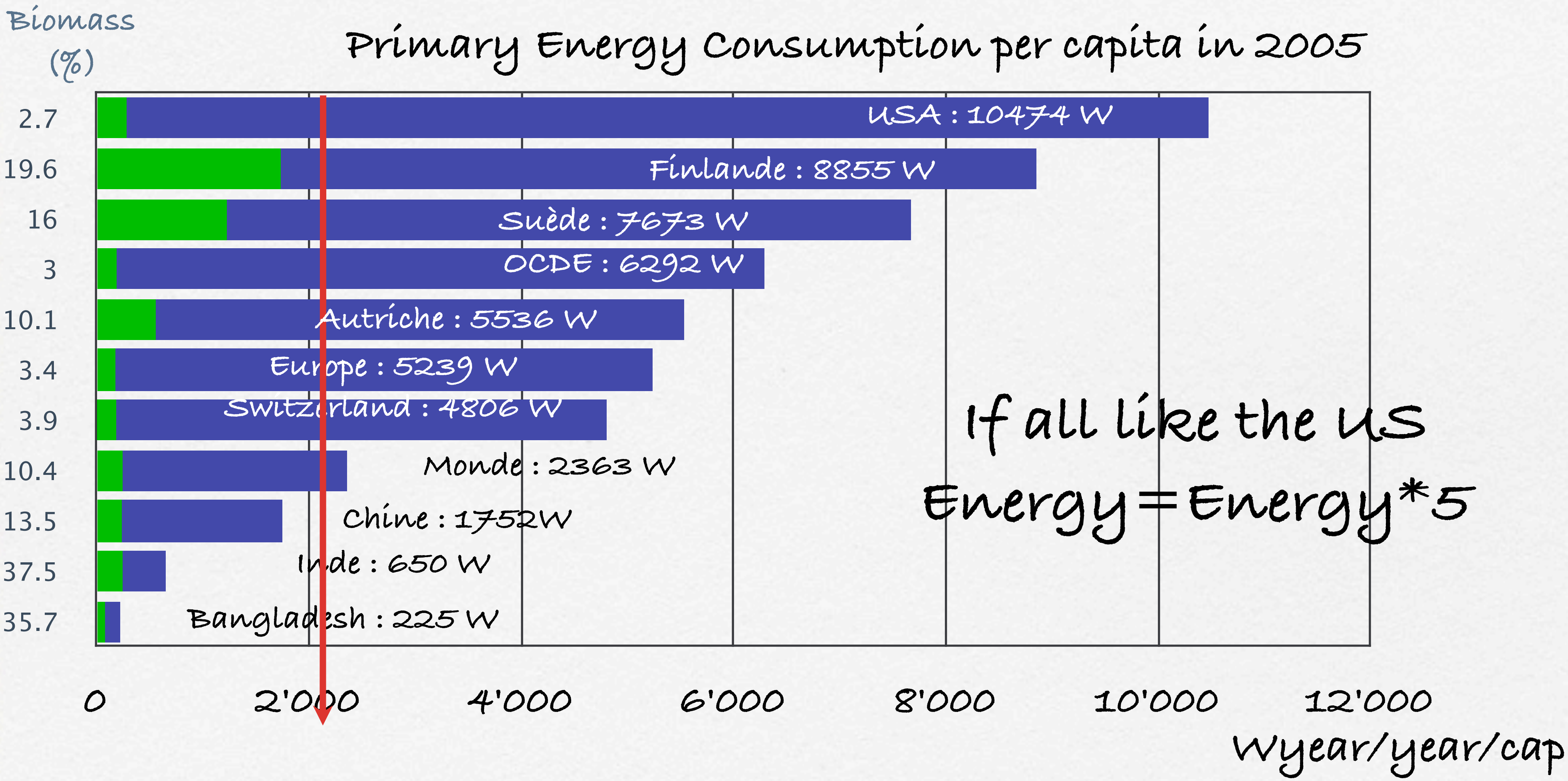
Sustainable energy systems

The 2000 W society challenge

2000 Wyear/year/cap

1tCO2/year/cap

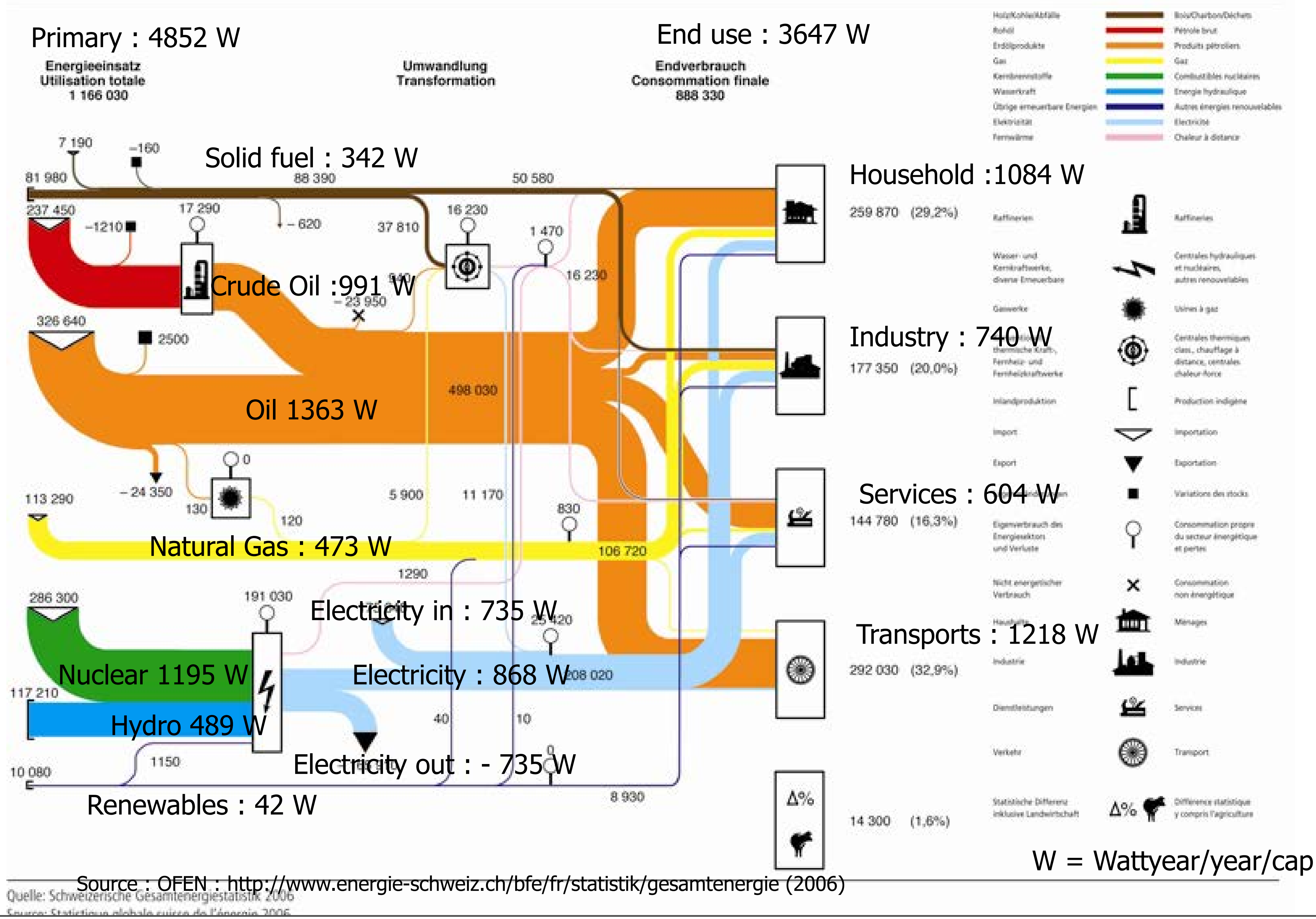
2000 W society concept



Source: Key World Energy Statistics, IEA, edition 2007, Renewables Information IEA, edtion 2007

Energieflussdiagramm der Schweiz im Jahre 2006 in Terajoule
Flux énergétique de la Suisse en 2006 en térajoule

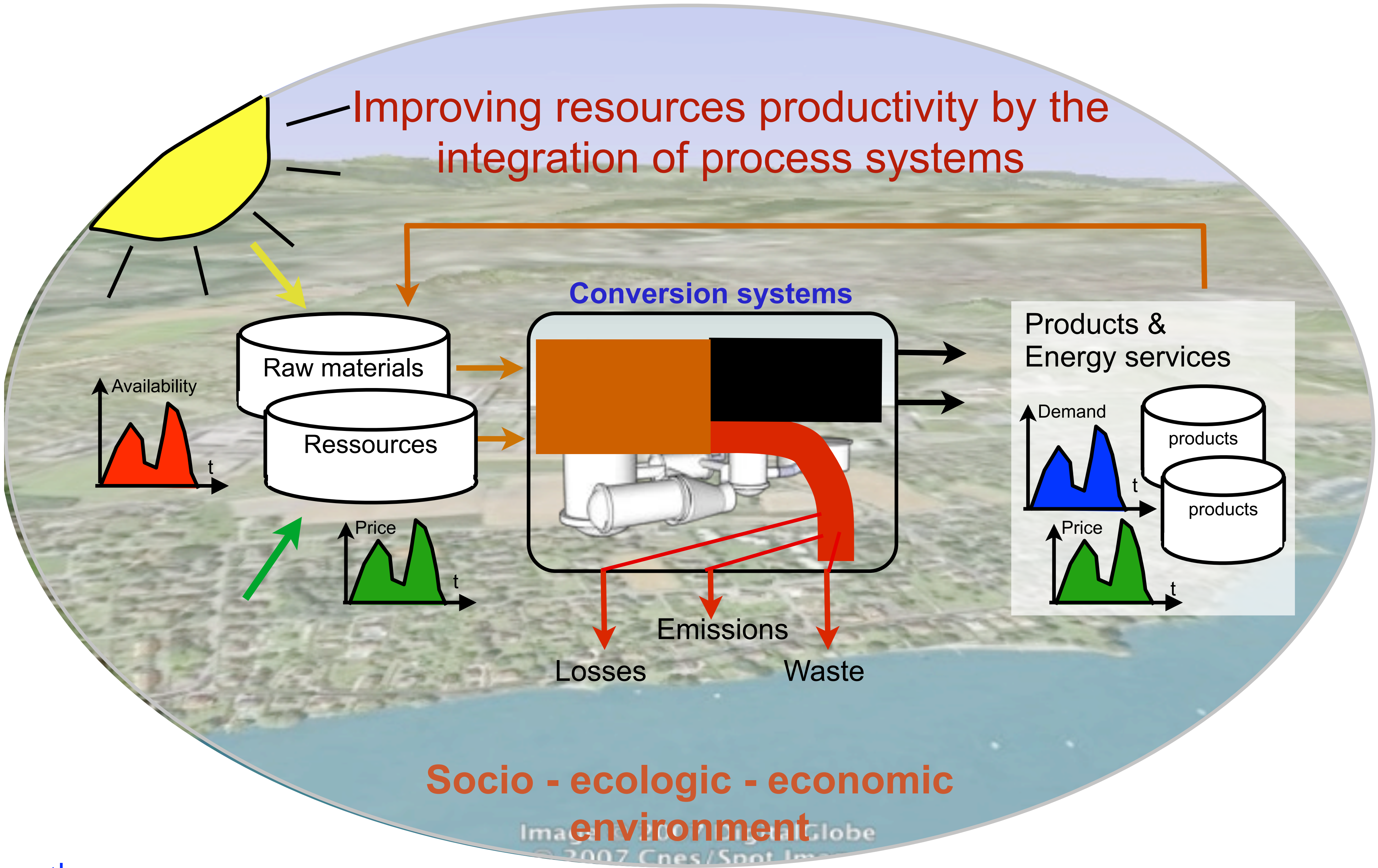
Energy usage in Switzerland



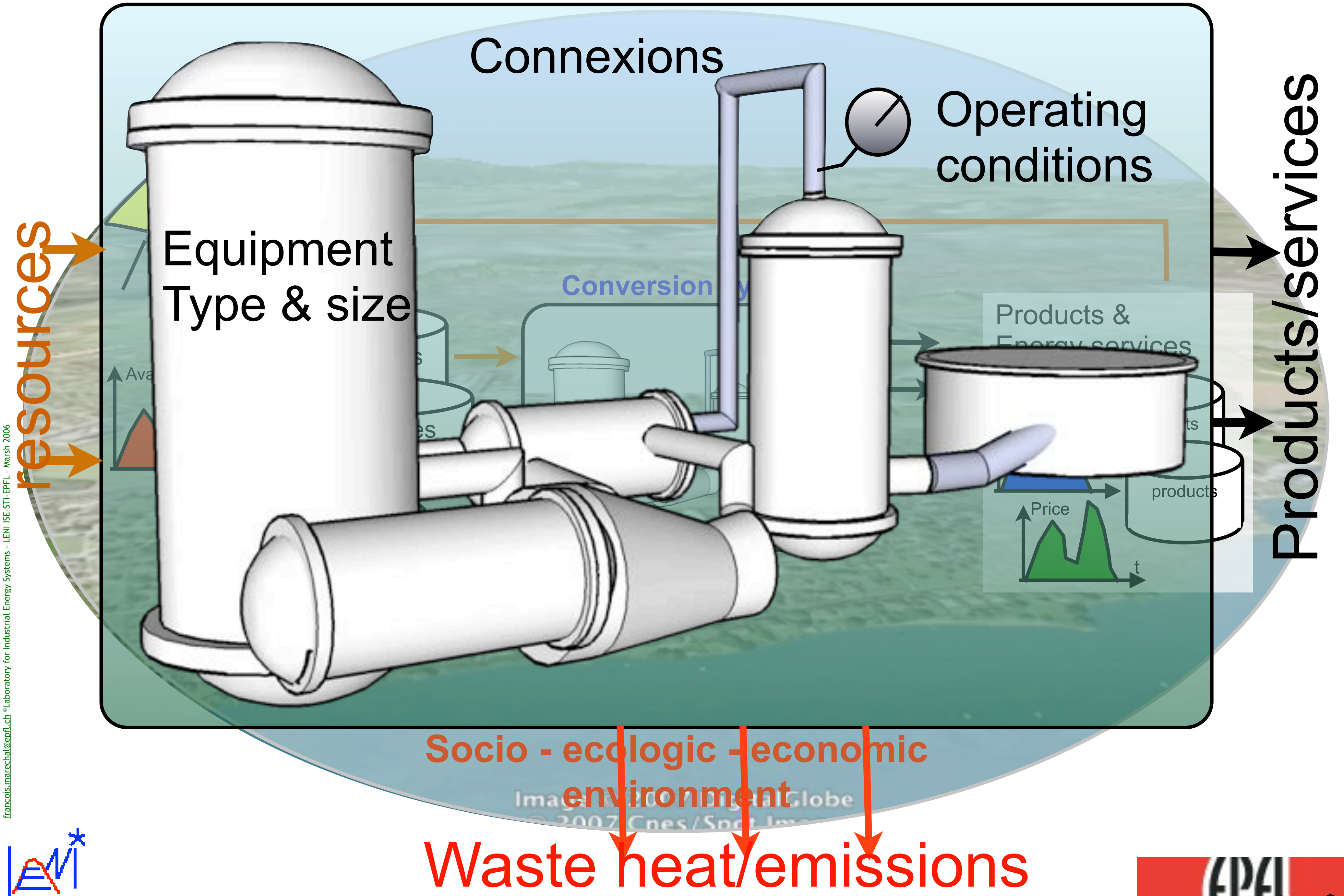
vendredi, 18 février 2011

- Process design
  - an easy definition ;-)

Energy Conversion Systems



Energy system analysis and design

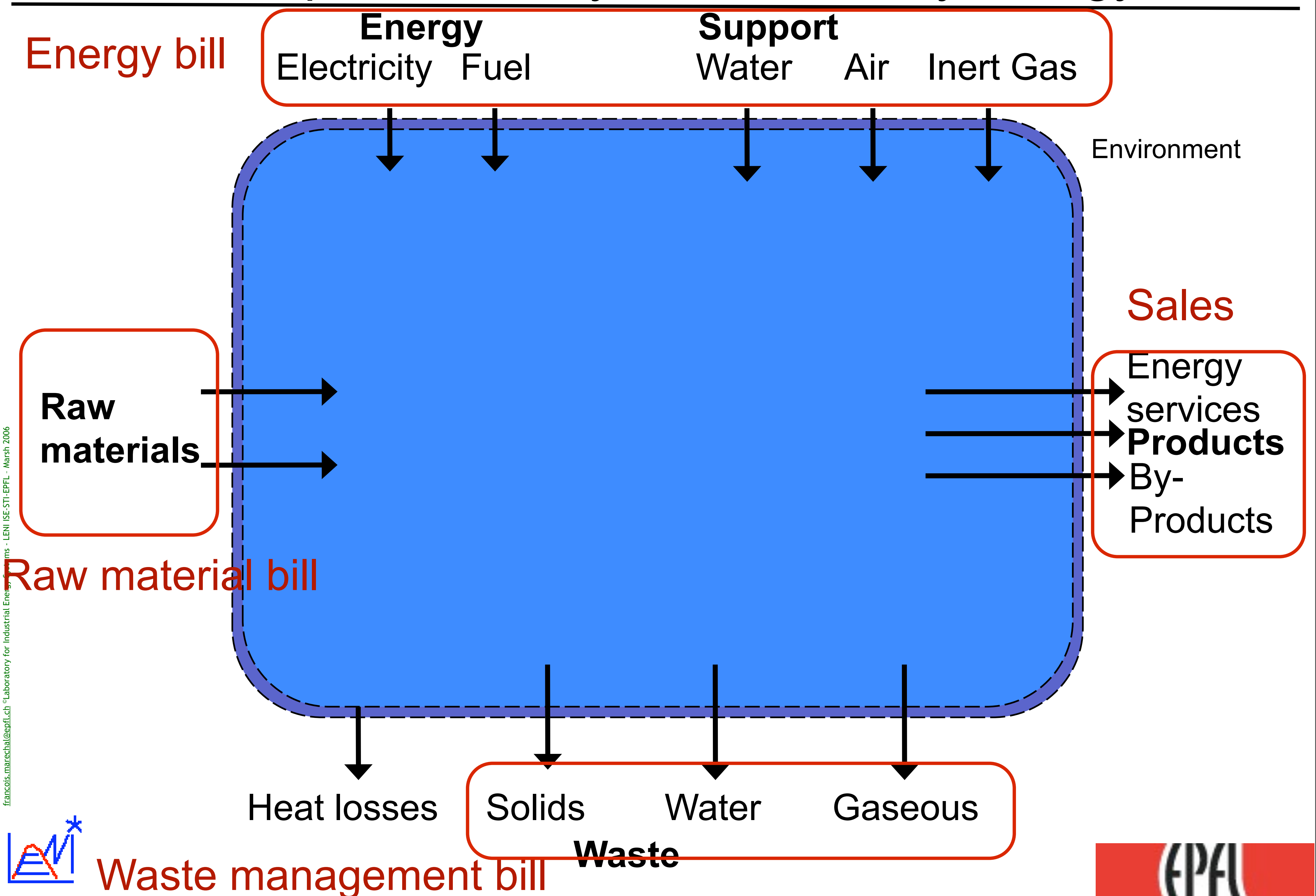


Motivations

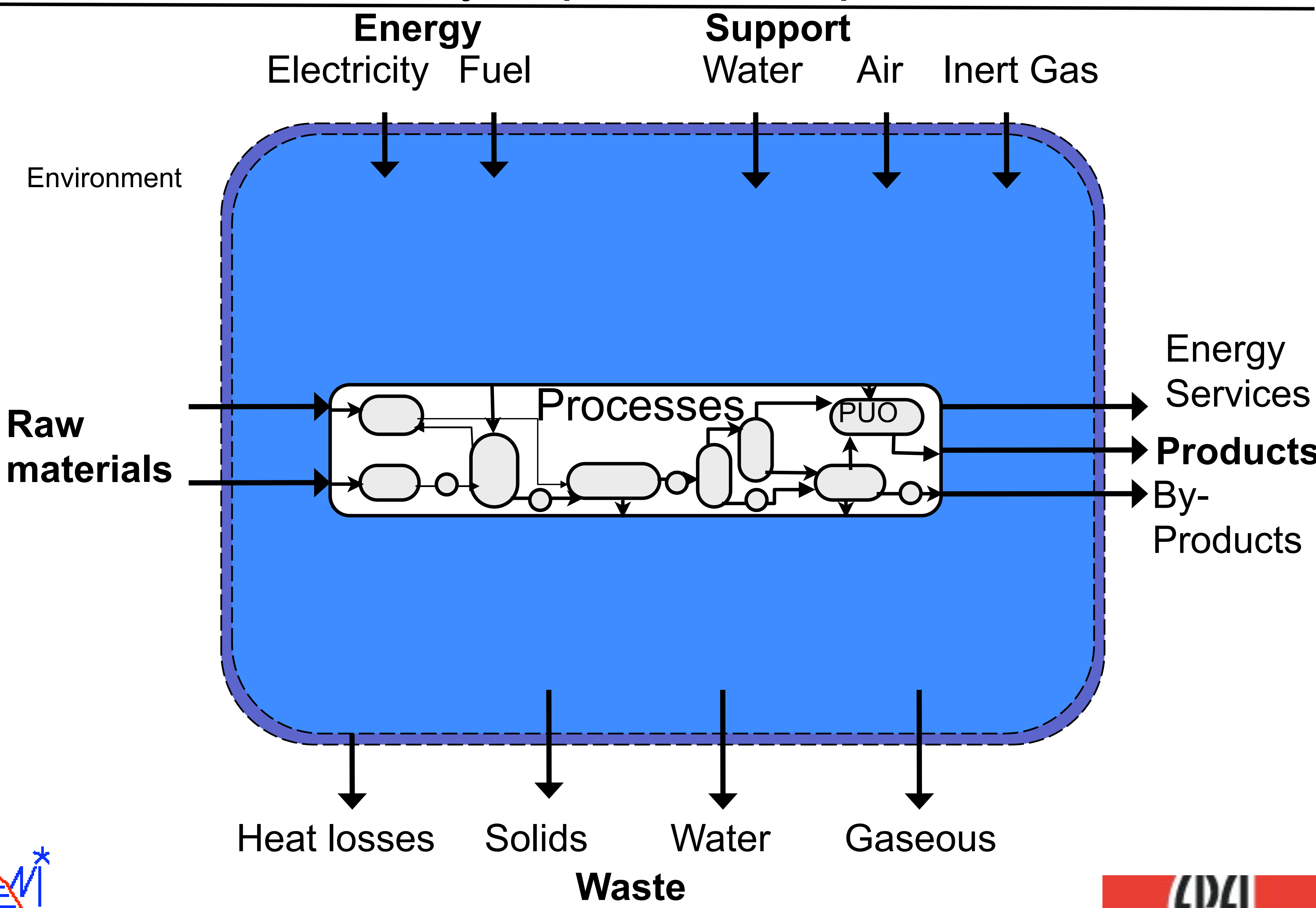
Reducing the demands in the industry

- Process integration challenge
  - Rational use of resources in industry
    - Energy and Water
  - Minimize the environmental impact

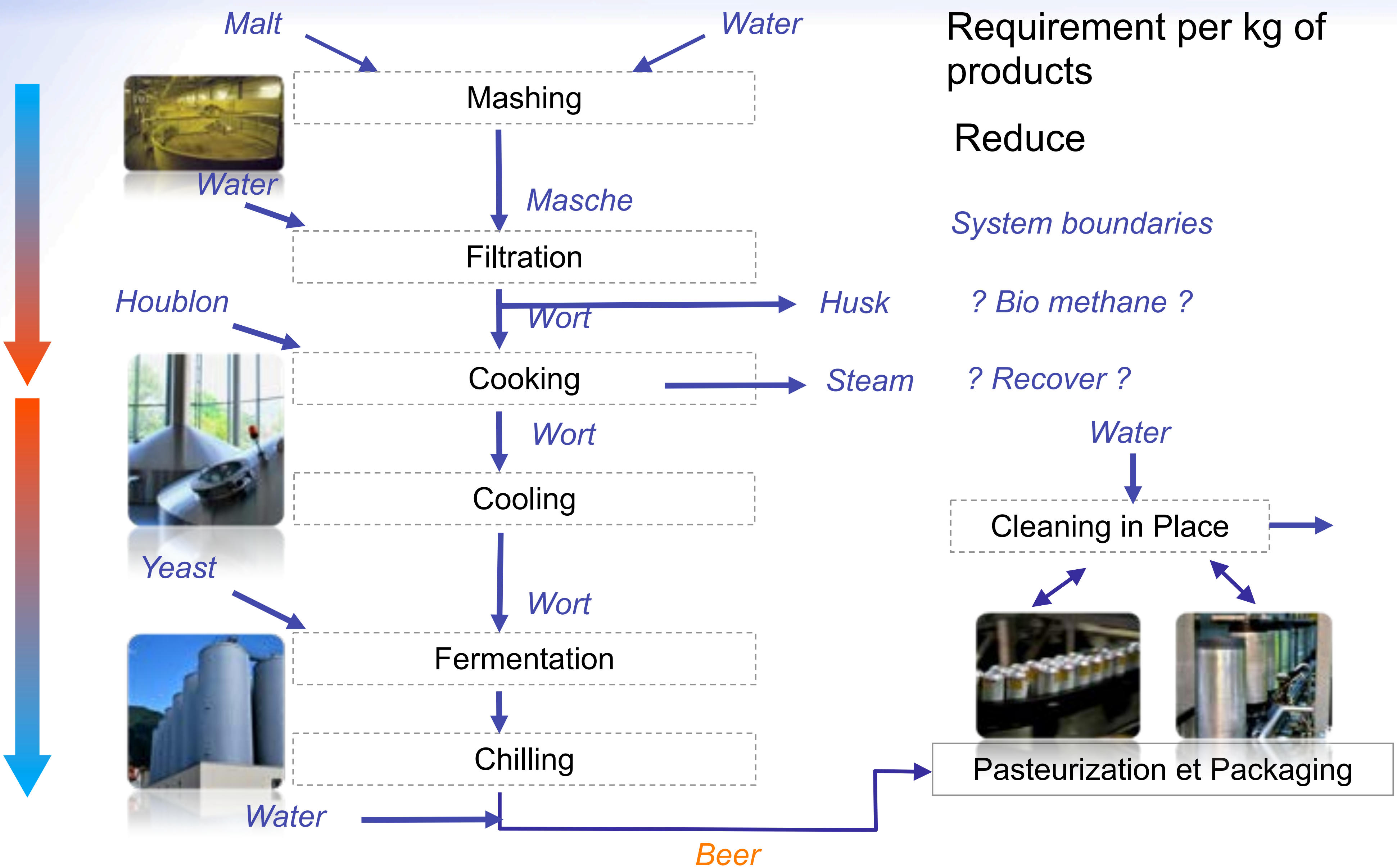
Industrial processes system driven by energy



1. Reduce : analyse process requirement

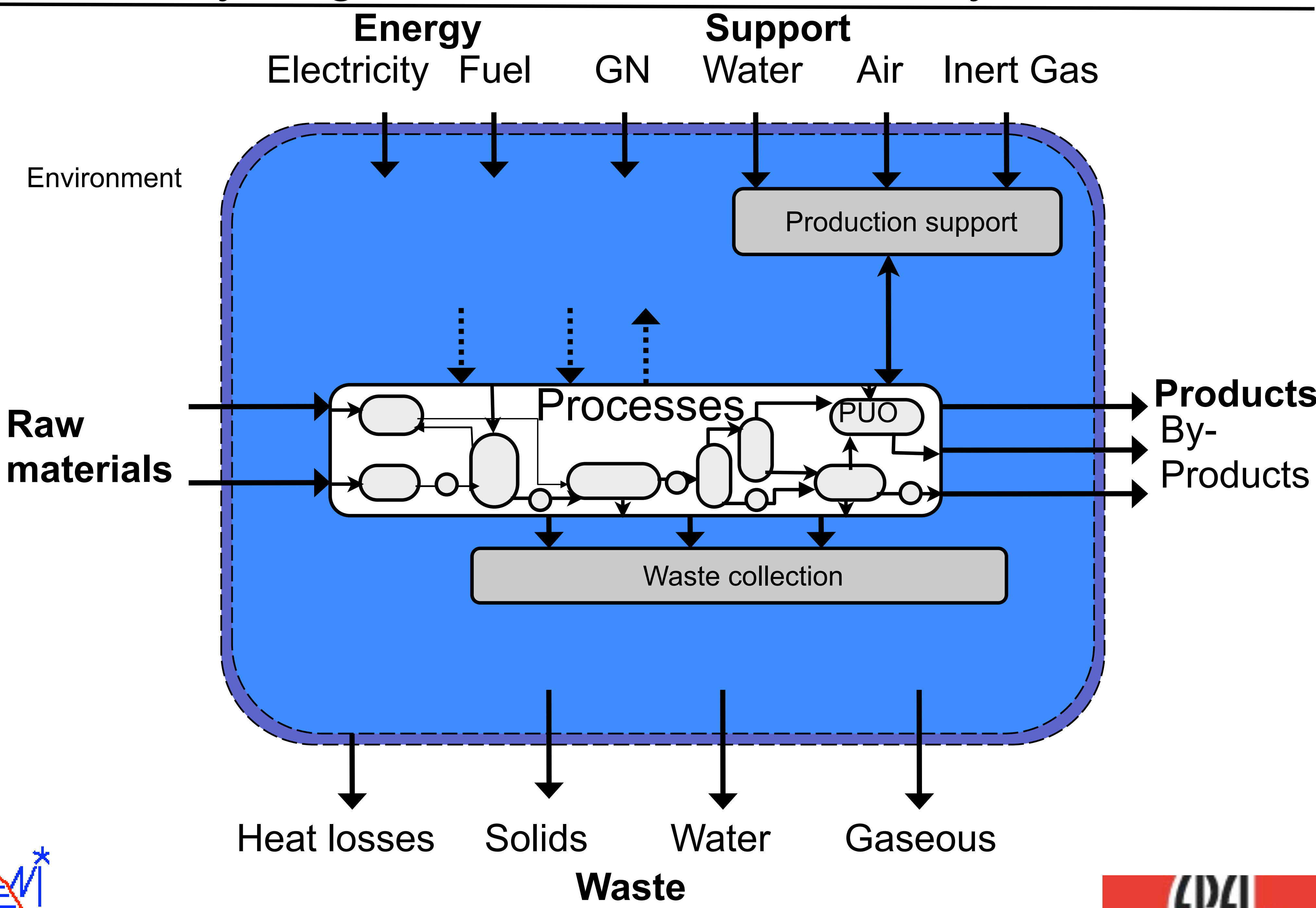


1. Reduce : Process requirement analysis :unit operations

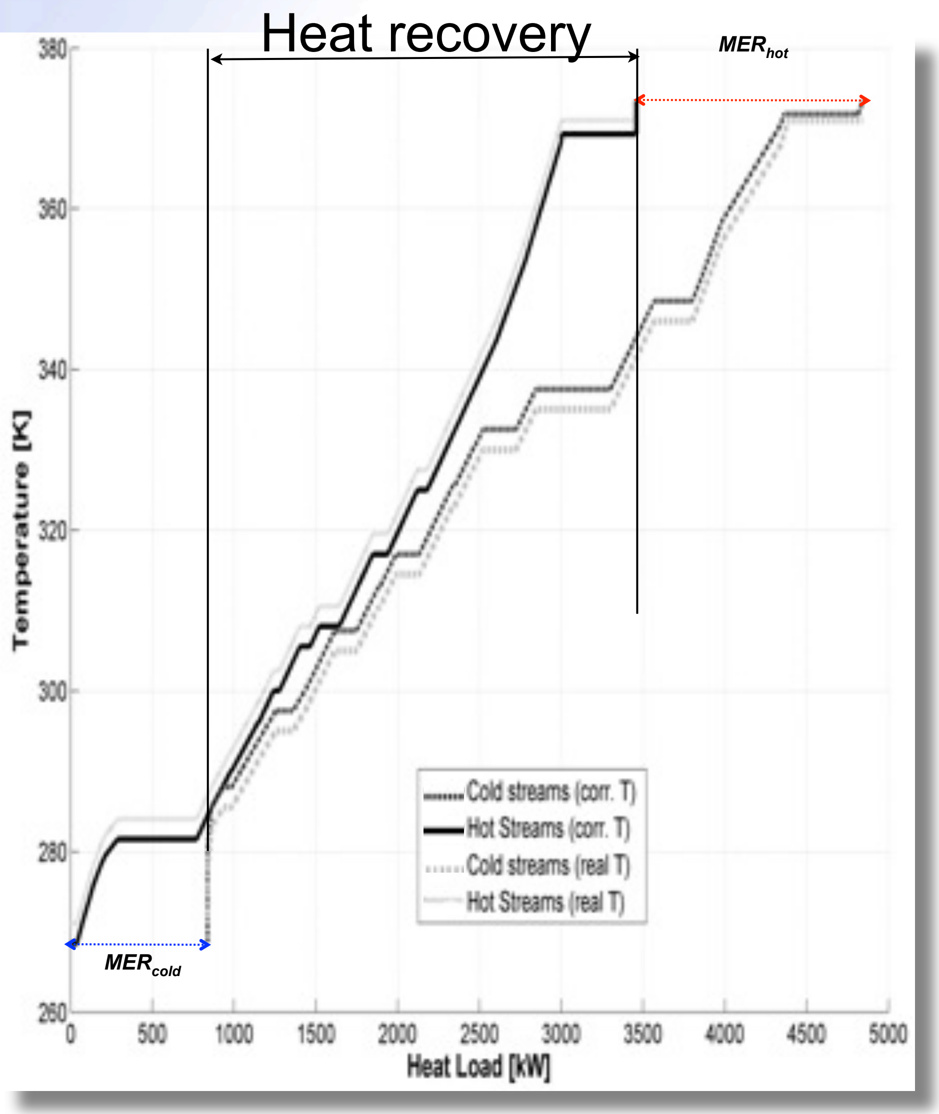


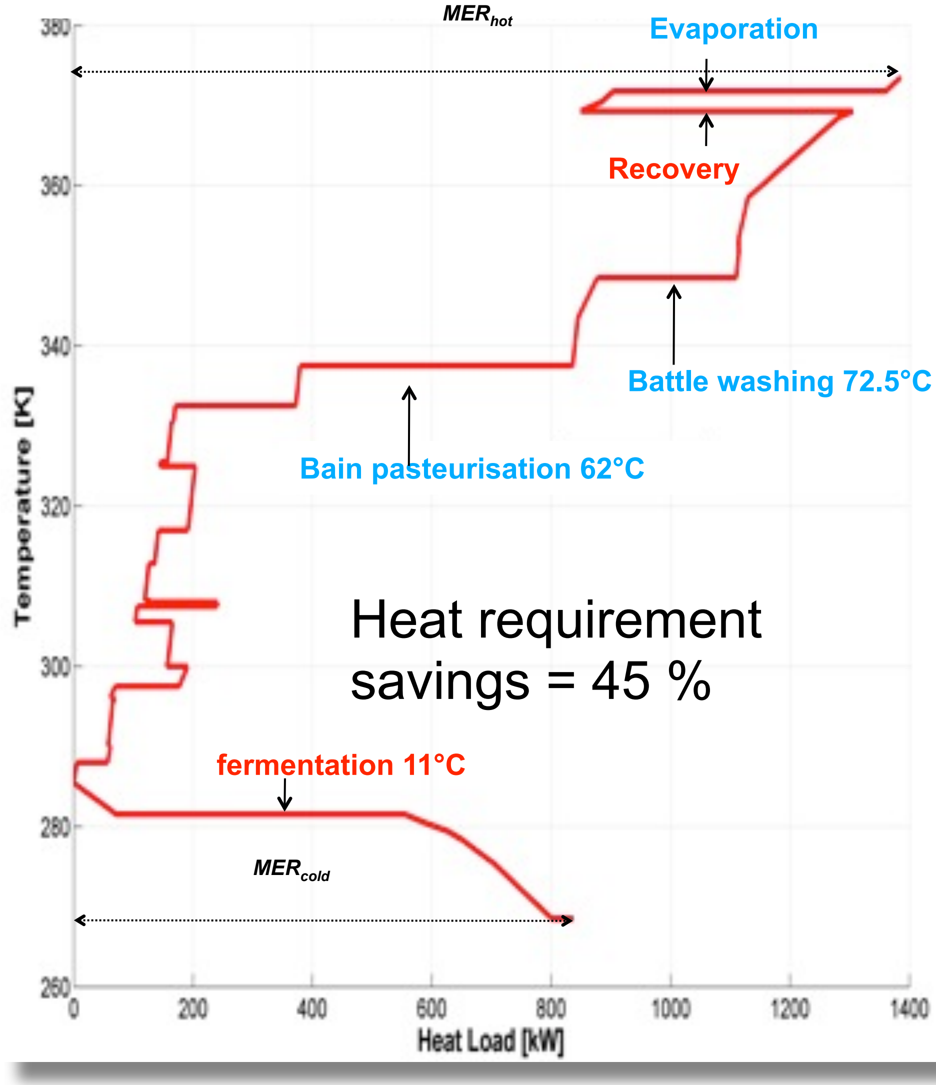
Analyse du pincement et intégration optimale des utilitaires en vue d'améliorer l'efficacité énergétique des procédés brassicoles
Monika DUMBLIAUSKAITE, ingénieur ENPC

2. Recycling : heat and mass recovery



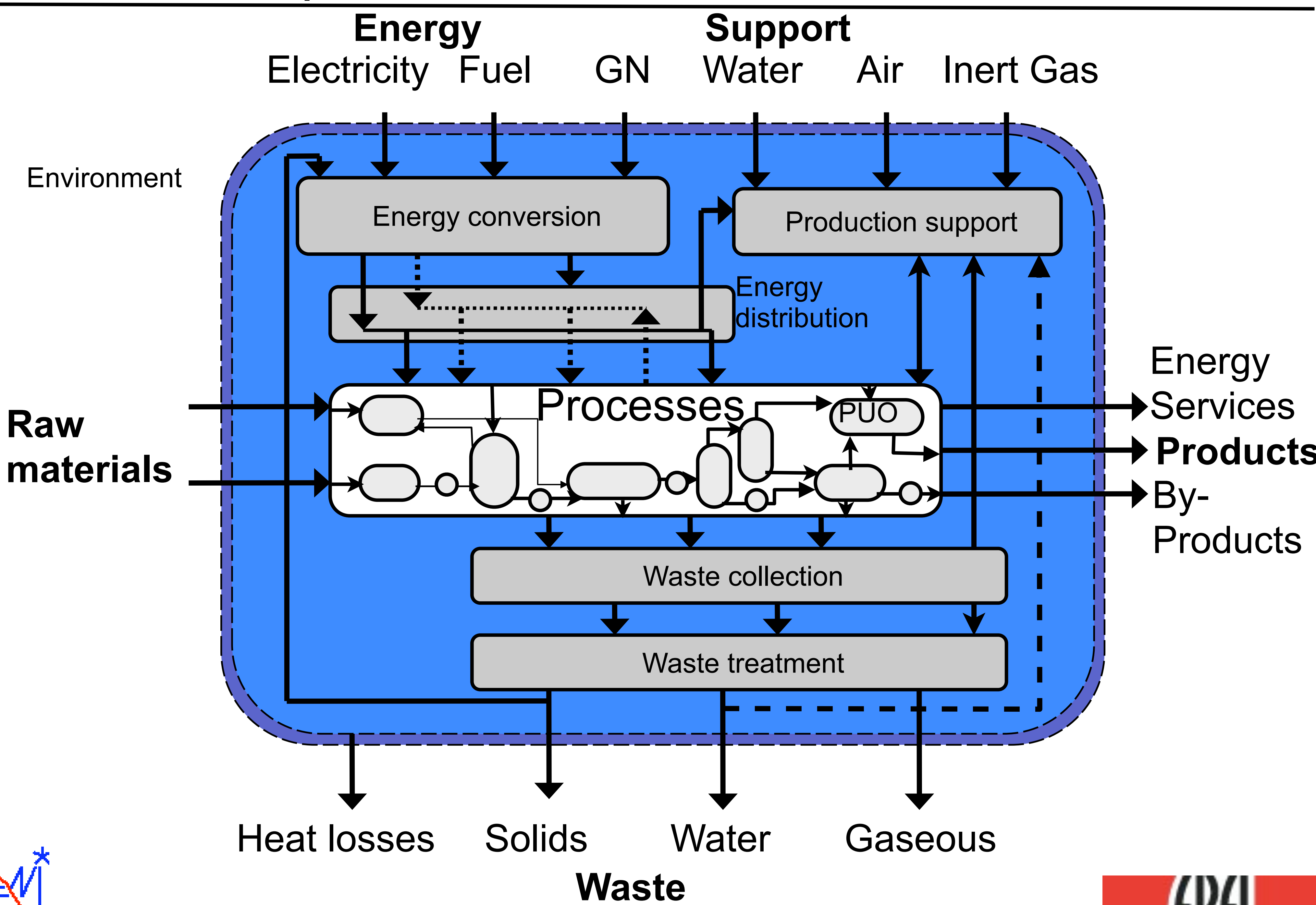
2. Reuse : Heat recovery -> Pinch analysis
Water recovery -> Pinch analysis





Heat requirement savings = 45 %

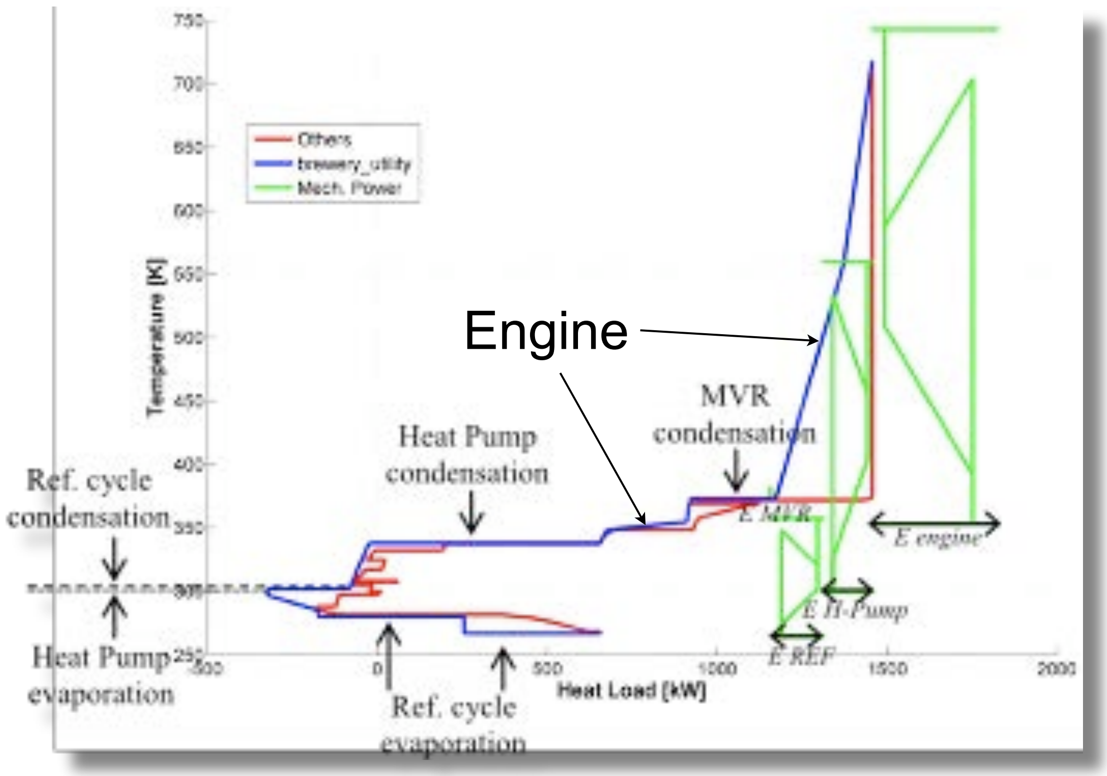
3. Reuse : Optimal conversion and waste treatment



3. Reuse : Energy conversion system

Combined heat and power integration

- Cogeneration
- Heat pumping (refrigeration + heat pump + mechanical vapour recompression)
- Husk Biomethanization (1664 kW) -> Cogeneration



Results (Maximum Heat Recovery)

	Unit	0. Reference	1. Heat recovery	2. MVR + HP + COGEN	3. MVR + HP + COGEN + Waste biomethane
Fuel	kW	3133	2088	1140	200
Electricity	kW_e	184	184	212	-219
Water	kg/s	32.0	17.1	0.2	0.2
Run. Costs FR	k€/yr	500	332	212	-32
Run. Costs GER	k€/yr	780	520	336	-60
TOTAL Costs FR	k€/yr	500	332	274	115
TOTAL Costs GER	k€/yr	780	520	398	88
TOTAL CO_2 FR*	ton/yr	3690	2459	1372	170
TOTAL CO_2 GER*	ton/yr	4400	2987	1976	-452

Grid electricity mix: FR=55 kgCO2/MWh, GER=624 kgCO2/MWh

M. Dumbliauskaite, H. Becker, F. Maréchal

3 R approach for process integration

- **Reduce**
  - •Analyse processing requirements
  - •Analyse process units requirements
  - •System boundaries
- **Recycle**
  - •Mass recovery (production support)
  - •Heat recovery
- **Reuse**
  - •Combined heat and power
  - •Heat pumping
  - •Waste conversion/valorisation
  - •Extend System boundaries

Exergy analysis

Simulation/ optimisation

Pinchlight.epfl.ch

Heat transfer & mass requirement

Pinch analysis

Optimization

Large scale system integration

Motivations

- Energy conversion system design
  - an easy definition ;-)

Sustainable energy systems

- **Energy conversion system design : an easy definition but ...**
  - Growing number of (advanced) technologies
  - Multi-services approaches
  - Need to valorize synergies
  - Uncertain environment
    - Energy services
    - Energy prices + investment
    - Environmental pressure
    - Technologies performances
  - Renewable energy resources
  - Energy is the driver **and** the raw material **and** the product
- **Need for a comprehensive method to drive engineers towards good solutions**

The energy system engineering methodology

Energy services
Resources
Context & Constraints

System Boundaries

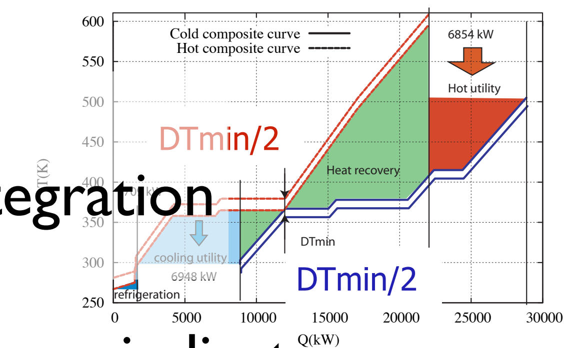
Technology options

Technologies
Thermodynamics
Economics
Environmental impact

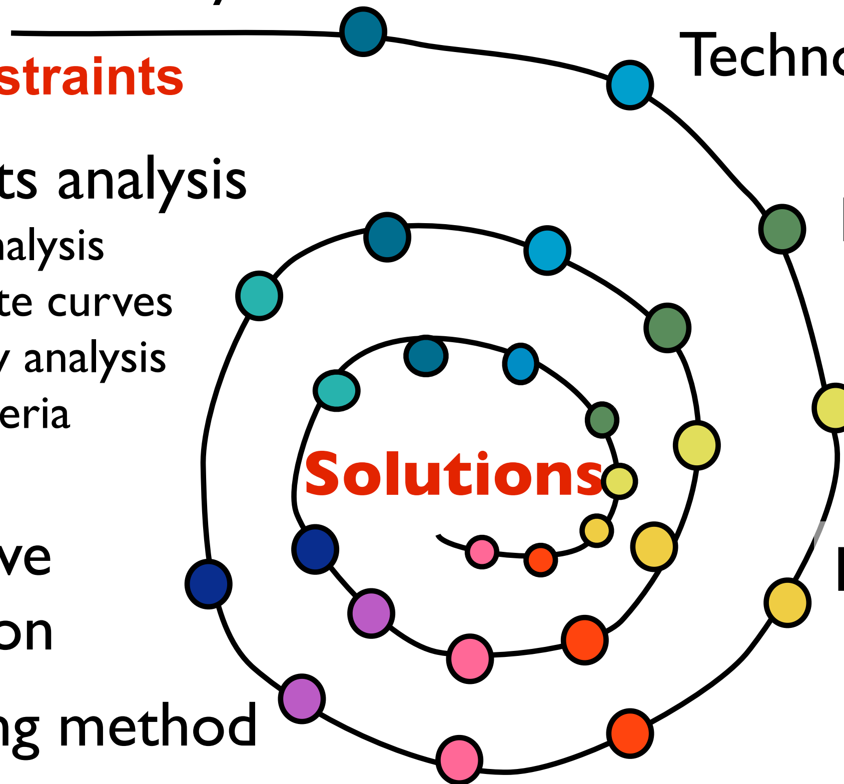
Models

Process Superstructure

Heat & Mass integration



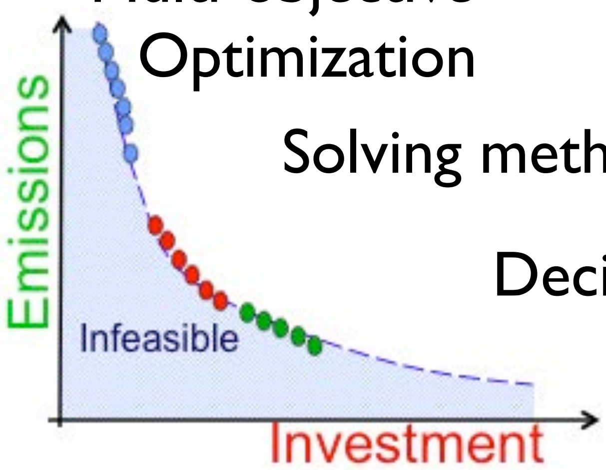
System performances indicators
- Economic
- Thermodynamic
- Life cycle environmental impact



Decision variables

Solving method

Multi-objective Optimization



Thermo-economic Pareto

Results analysis
- Exergy analysis
- Composite curves
- Sensitivity analysis
- Multi-criteria

Process system design :

- A Simple problem ?

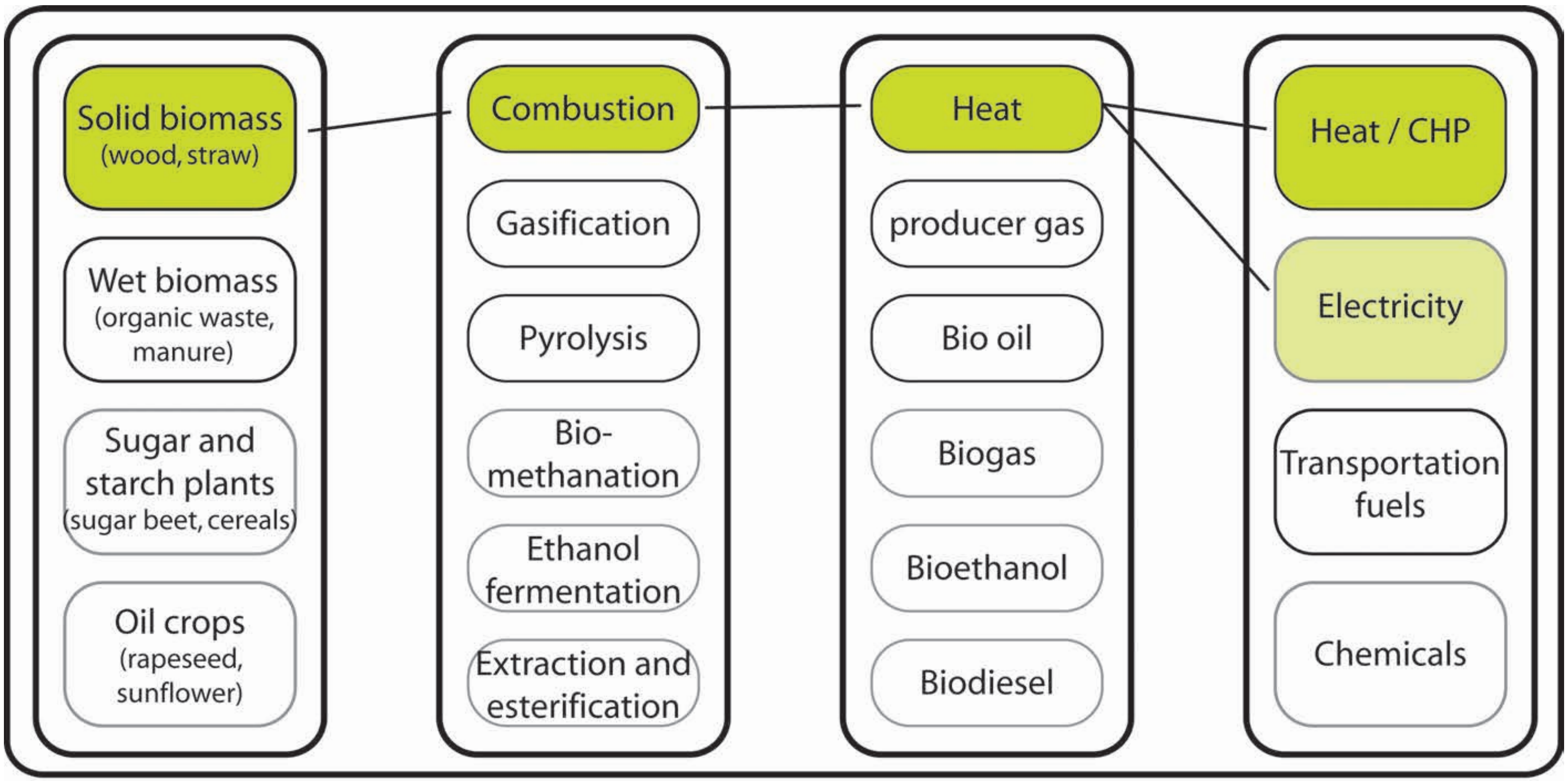
Produce Synthetic Natural Gas from Wood

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

Process system design

What are the options ?

Biomass conversion
Combustion



adapted from Chemical Engineering 10 (2006)

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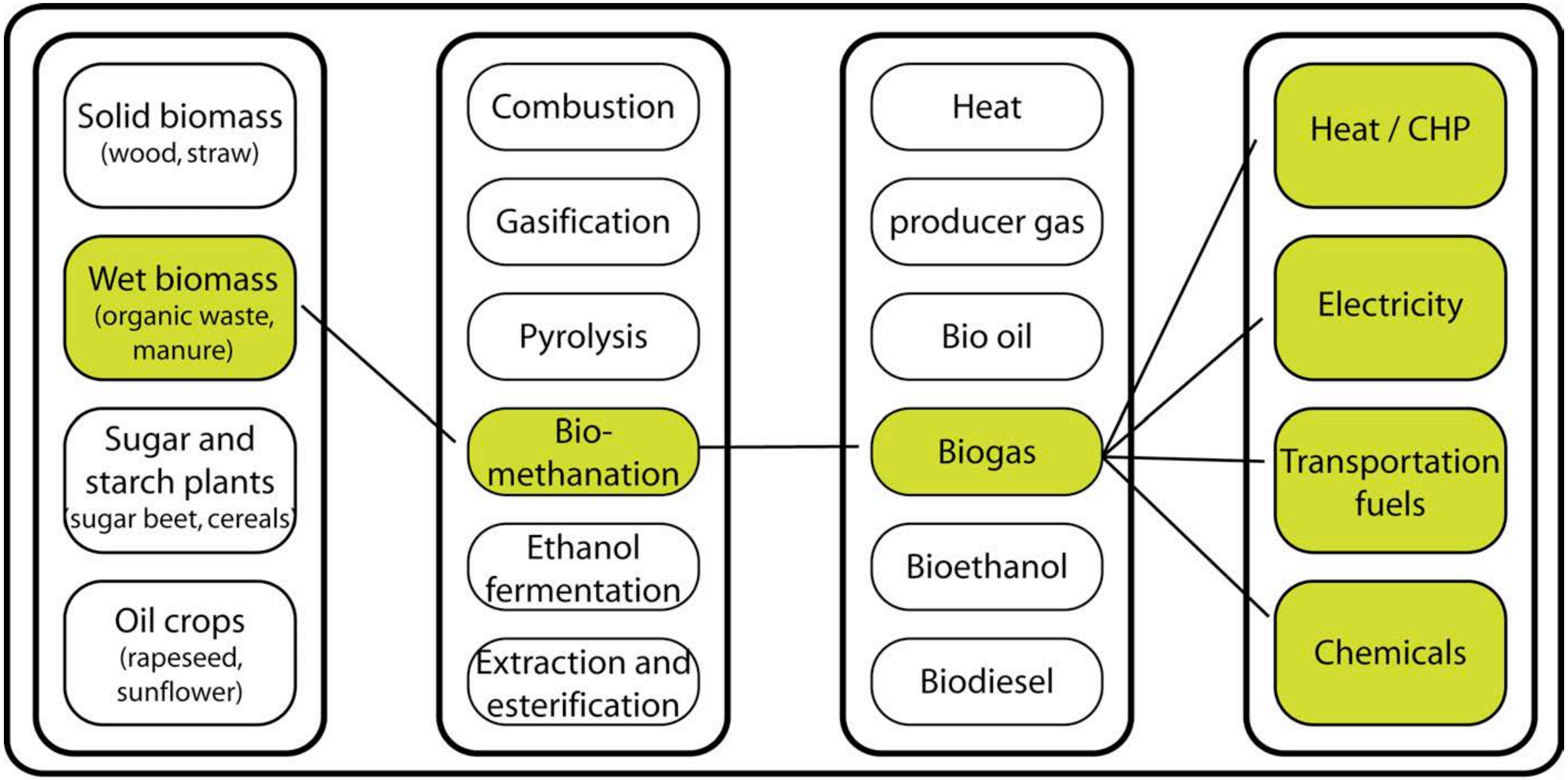
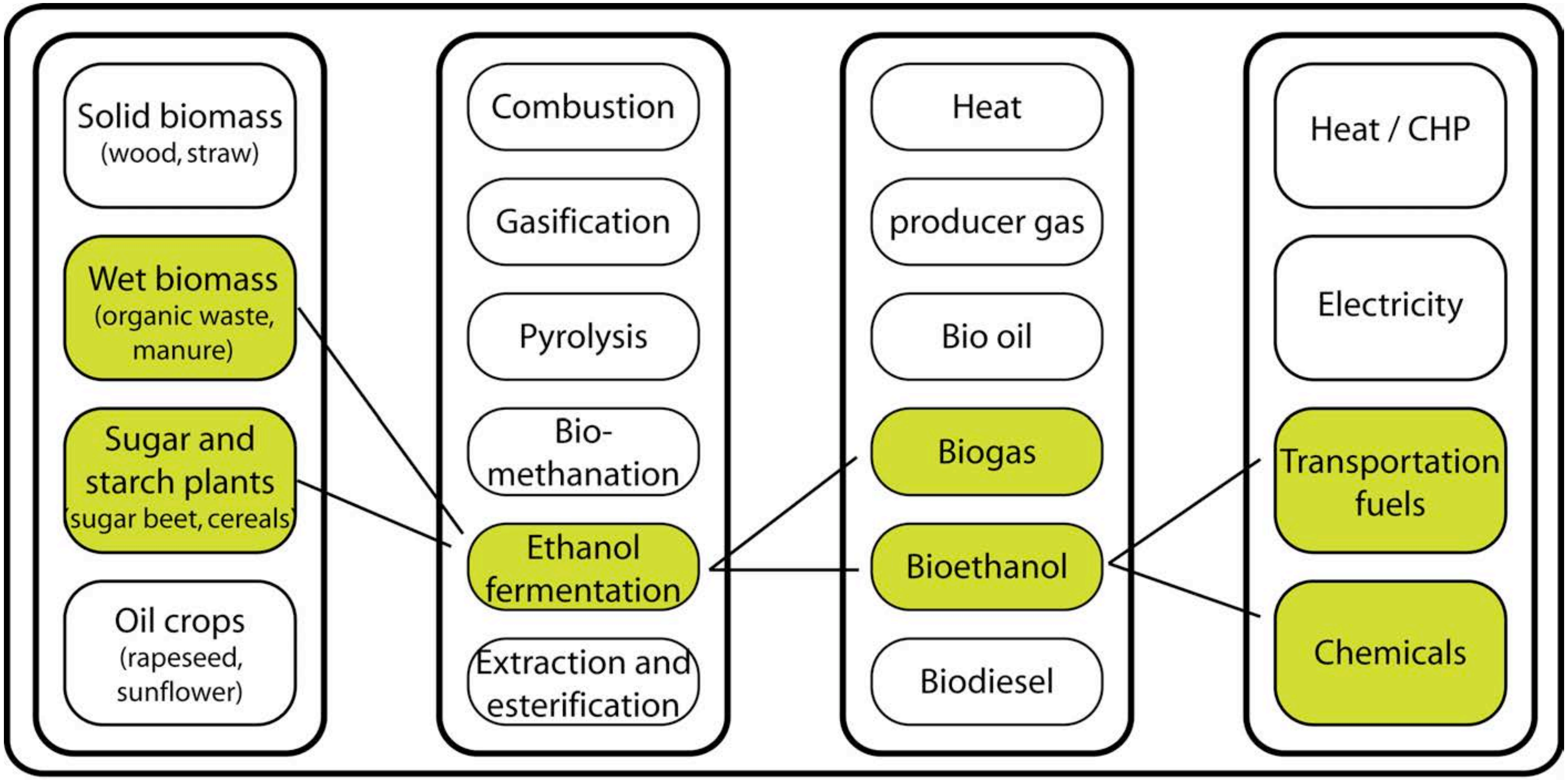
Biomass conversion
Biomethanation



adapted from Chemical Engineering 10 (2006)

Biomass conversion
Ethanol fermentation



adapted from Chemical Engineering 10 (2006)

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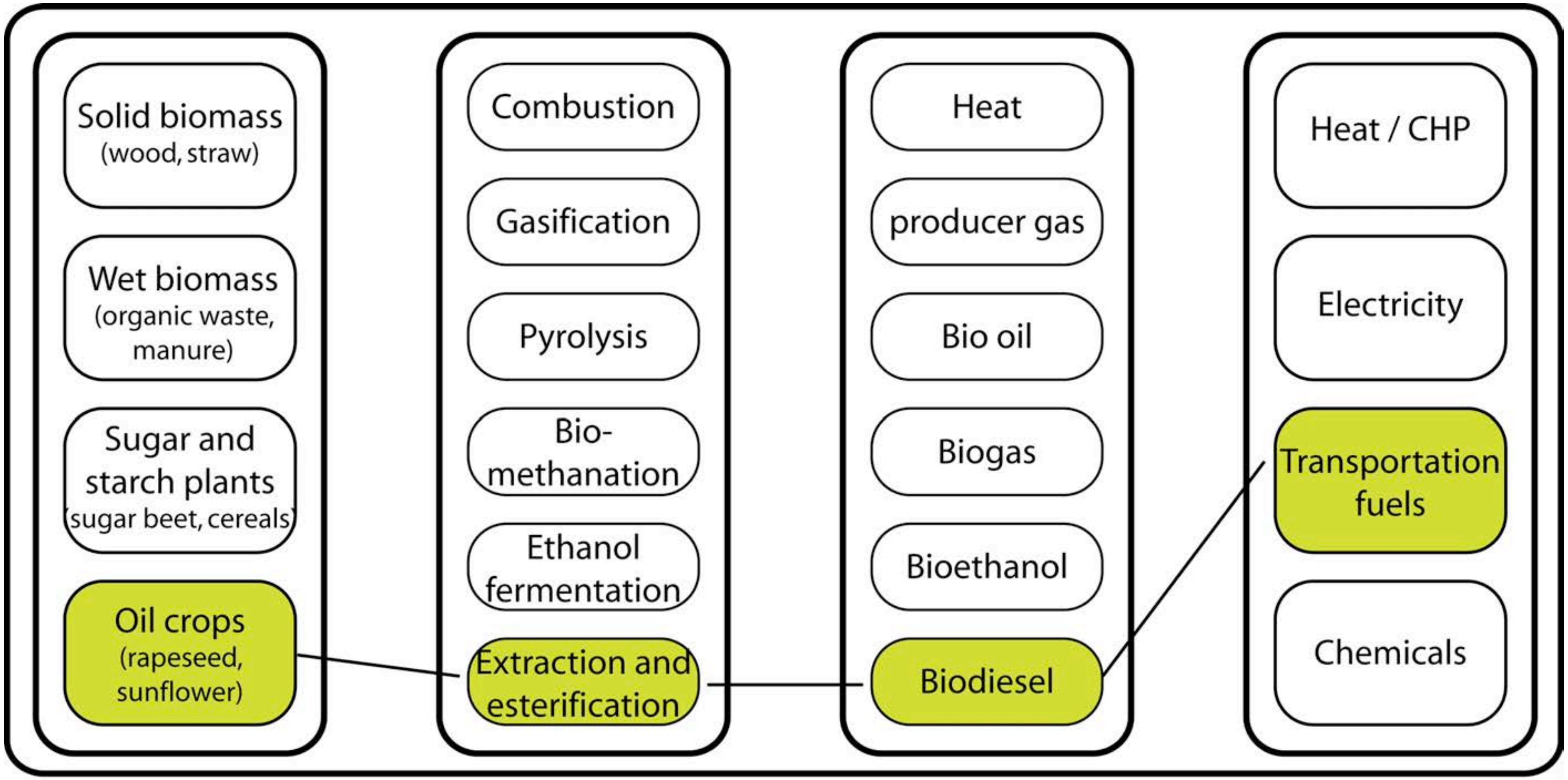
Biomass conversion
Transesterification



adapted from Chemical Engineering 10 (2006)

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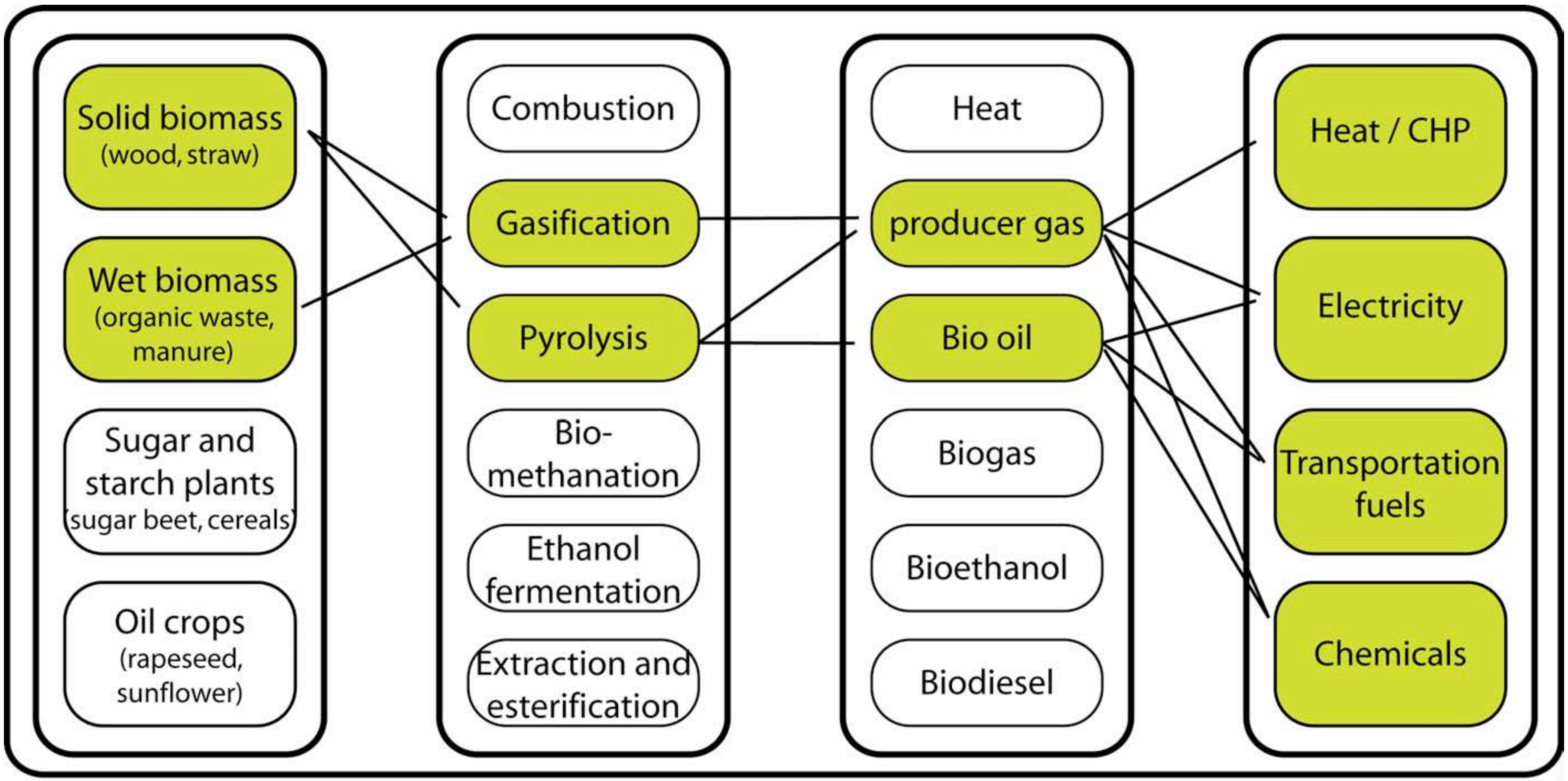
Biomass conversion
Thermochemical routes

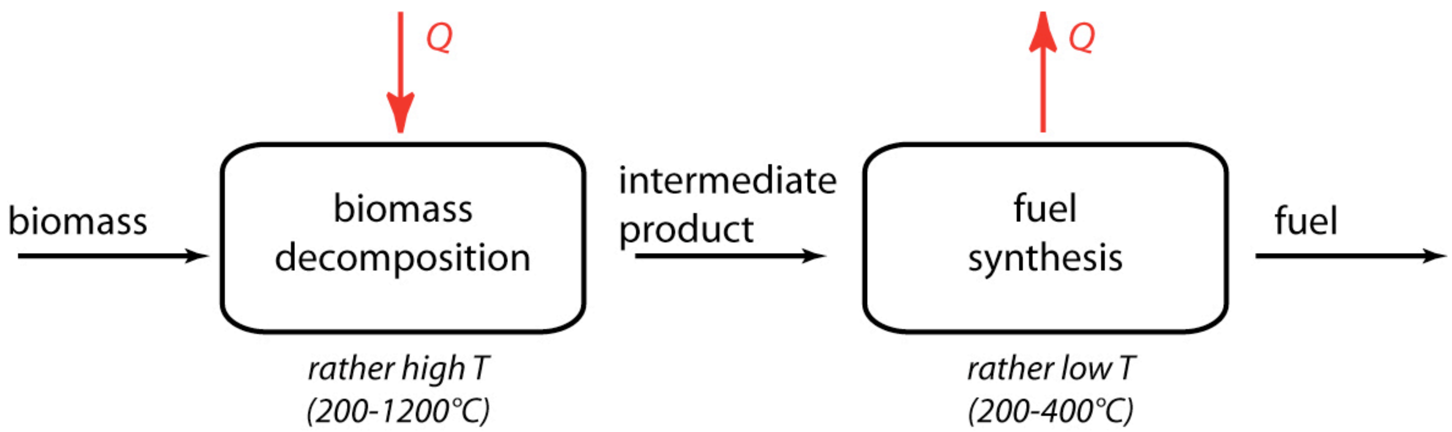


adapted from Chemical Engineering 10 (2006)

Thermochemical biomass conversion

Principle of conventional thermochemical routes

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



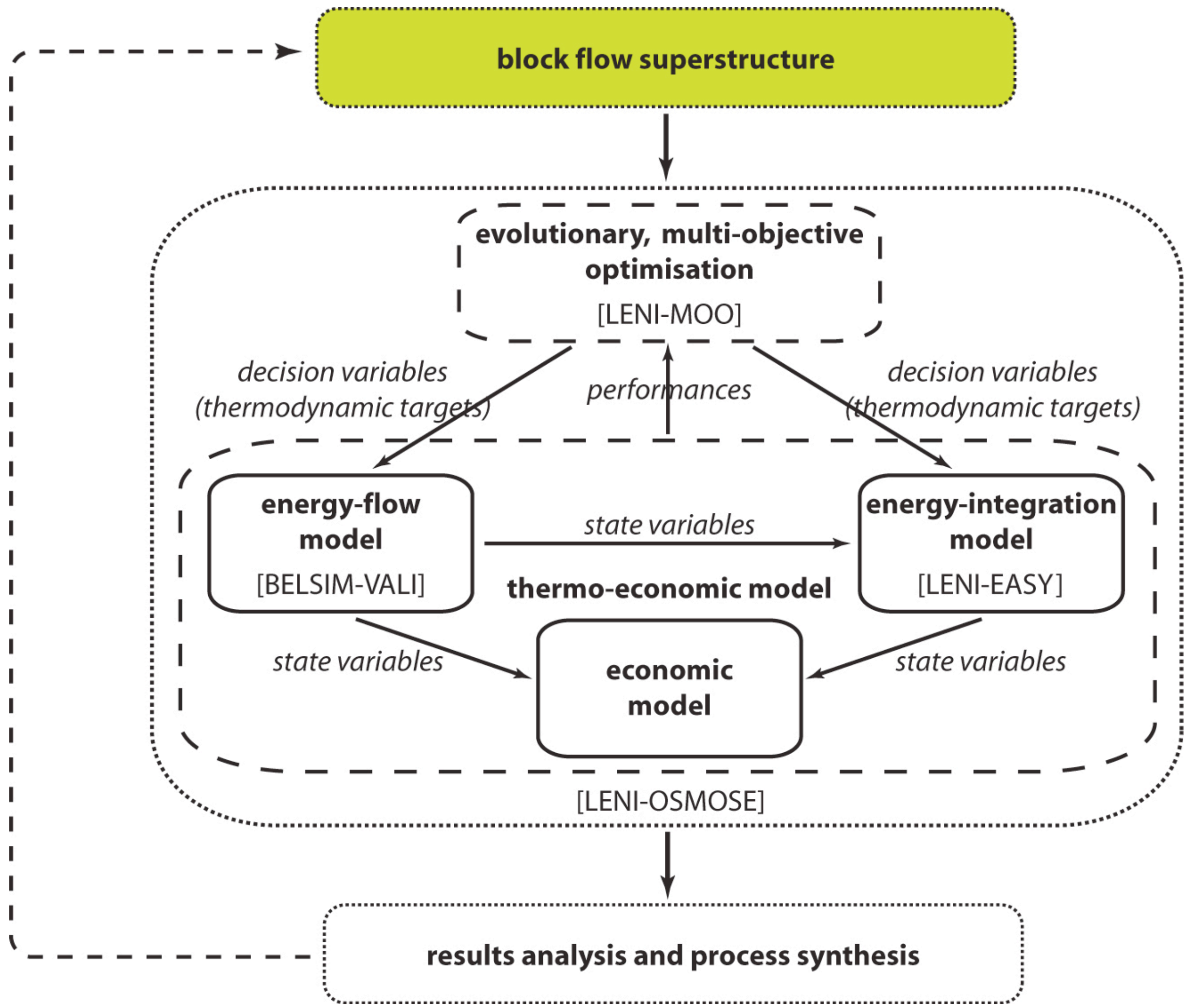
- gasification
- pyrolysis

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

Methodology

Block flow superstructure



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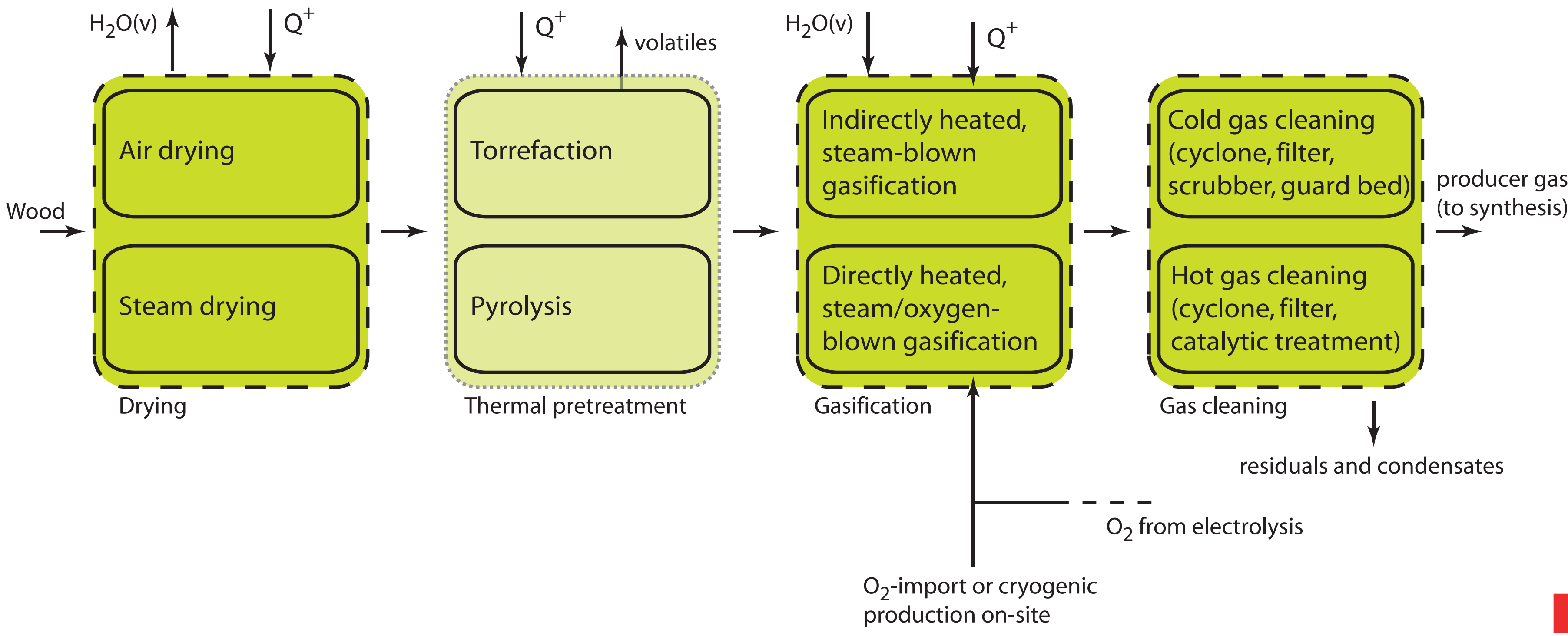
Process system design

What are the processing options ?

Block flow superstructure

Conventional route (gasification & methanation): decomposition



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

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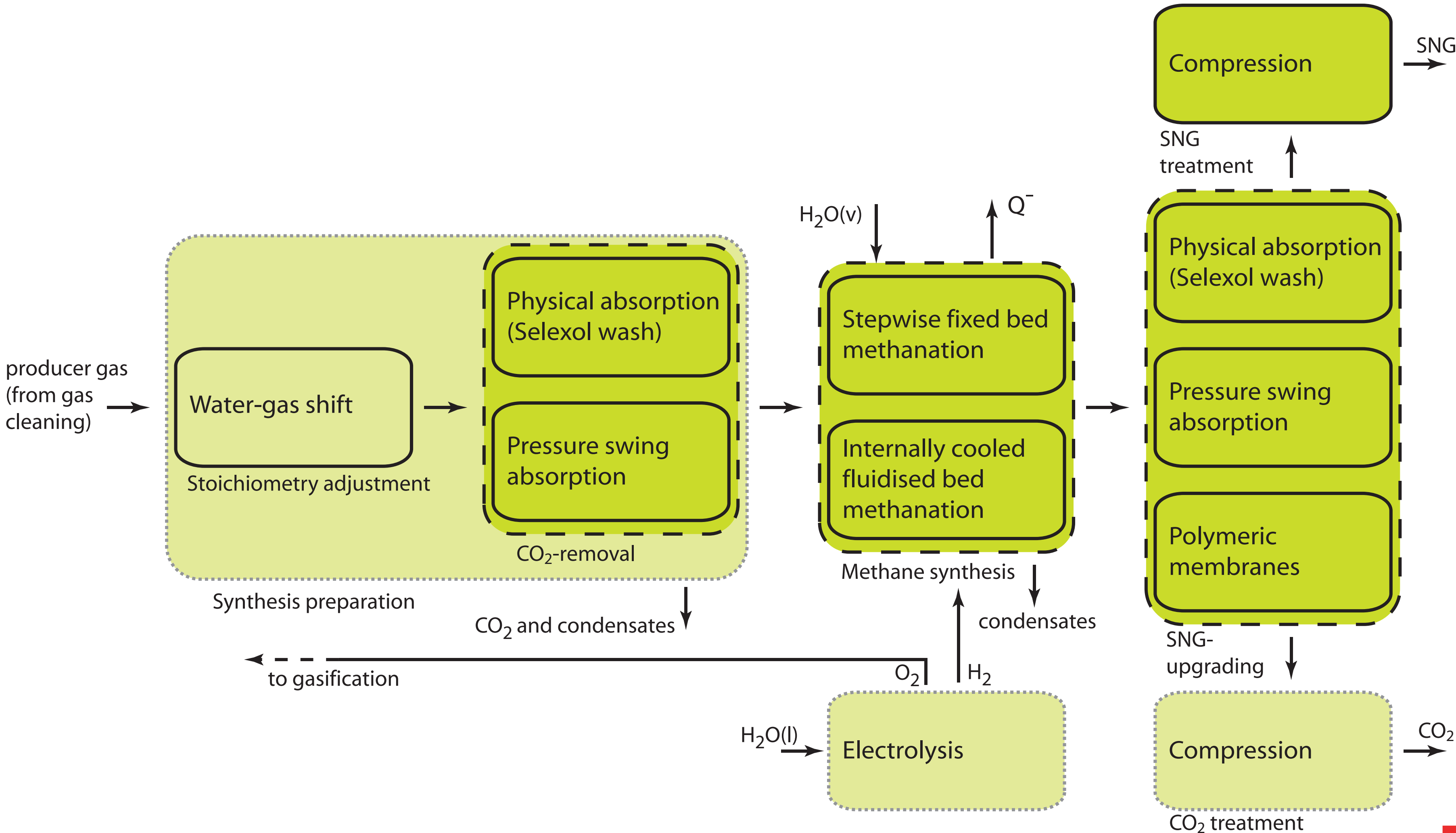
Block flow superstructure

Conventional route (gasification & methanation): synthesis



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

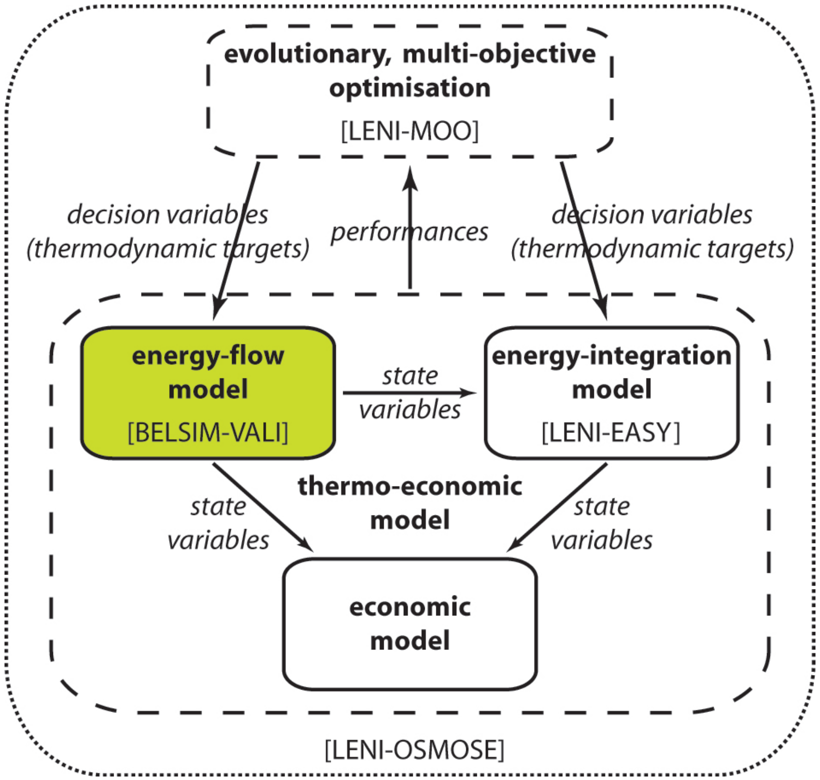
Process system design

Modeling processing options ?

Simple models but not too simple ...

- Levels of detail
- Developed for the design
  - allow for thermo-economic evaluations

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

Gasification unit models

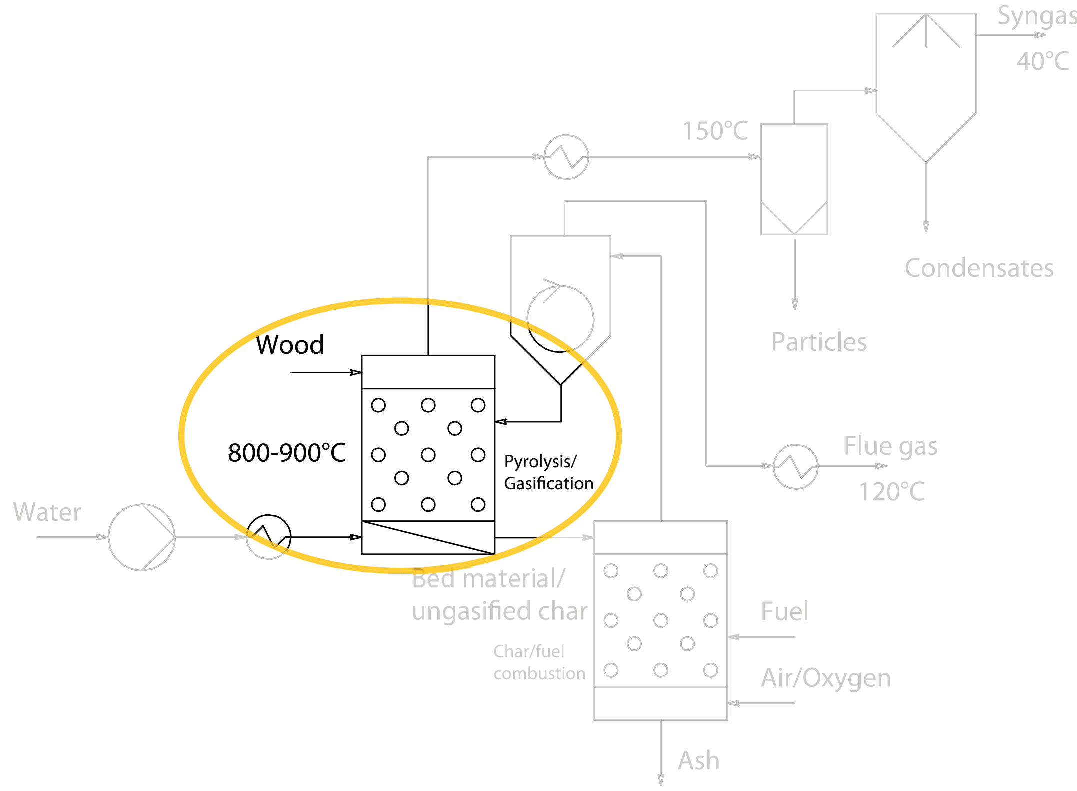
Problem set-up

Gasification modelling problem:

- 8 bulk species:

  CH_4, CO, CO_2, H_2, H_2O, N_2, C_2H_4, $C(s)$
- 4 atomic mass balances

⇒ 4 model equations required



Gasification unit models
Model equations

- 3 adjusted equilibrium equations

$$\hat{K}_{p,i} = K_{p,i}(T_g + \Delta T_i)$$

where: T_g gasification temperature
ΔT_i artificial temperature difference

- constant ratio between CH_4 and higher hydrocarbons

$$p_{C2H4} = k_p \cdot p_{CH4}$$

		Δh_r^0
hydrogenating gasification	$C(s) + 2H_2 \rightleftharpoons CH_4$	-75 kJ/mol
Boudouard equilibrium	$C(s) + CO_2 \rightleftharpoons 2CO$	173 kJ/mol
water-gas shift	$CO + H_2O \rightleftharpoons CO_2 + H_2$	-41 kJ/mol

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Model reconciliation

Gas composition (%vol) & model constants

Process	FICFB		Viking		
Reactor	gasification		pyrolysis	gasification	
State	wet	dry	wet	wet	dry
CH_4	8.8 / 9.0	- / 9.3	- / 35.7	- / 1.2	1.2 / 1.2
CO	29.4 / 28.0	- / 28.9	- / 3.0	- / 18.3	19.6 / 19.0
CO_2	16.2 / 15.3	- / 15.9	- / 33.2	- / 14.2	15.4 / 14.7
H_2	37.3 / 39.5	- / 41.0	- / 4.9	- / 30.4	30.5 / 31.4
H_2O	3.6 / 3.5	- / -	- / 23.0	- / 3.2	- / -
N_2	2.9 / 2.9	- / 3.0	- / 0.2	- / 32.7	33.3 / 33.7
C_2H_4	1.8 / 1.8	- / 1.9	- / -	- / -	- / -

measures (Rauch, R. (2004), Goebel, B. et al. (2004)) / calculation

⇒ accurate reproduction of gas composition & heat demand

Process	FICFB	Viking	
Reactor	gasification	pyrolysis	gasification
ΔT_{hg}	-260°C	-289°C	-11°C
ΔT_{bd}	-201°C	-	-123°C
ΔT_{wg}	-112°C	+12°C	-126°C
k_p	4.9	-	-

reconciled model constants

⇒ part. oxidation at high T gets closer to equilibrium

Process system design

Interconnections ?

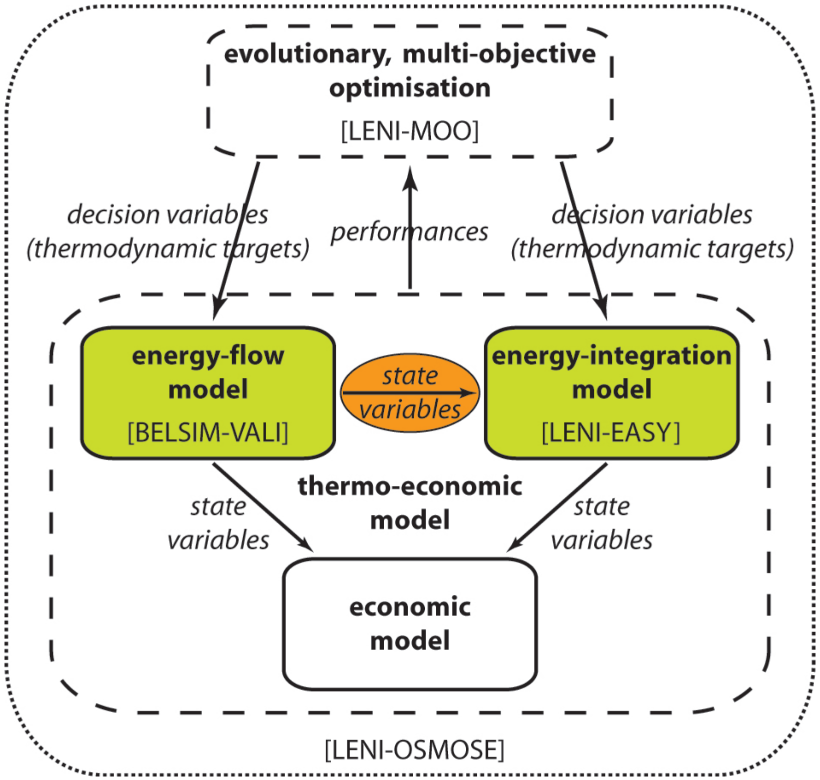
Mass interactions -> flow superstructure

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

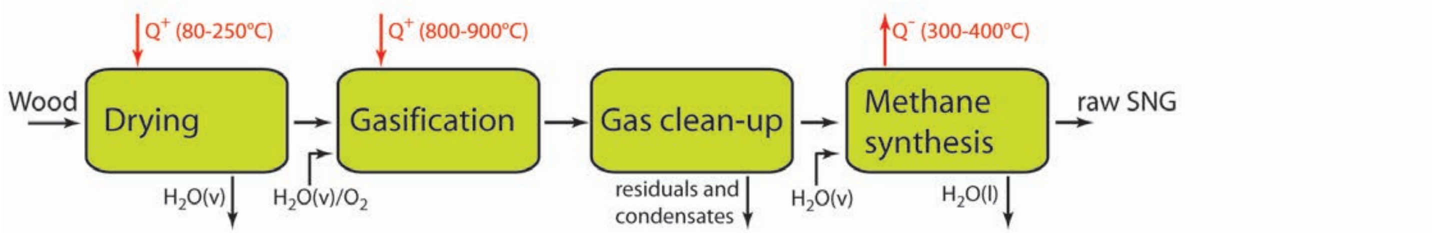
to determine

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

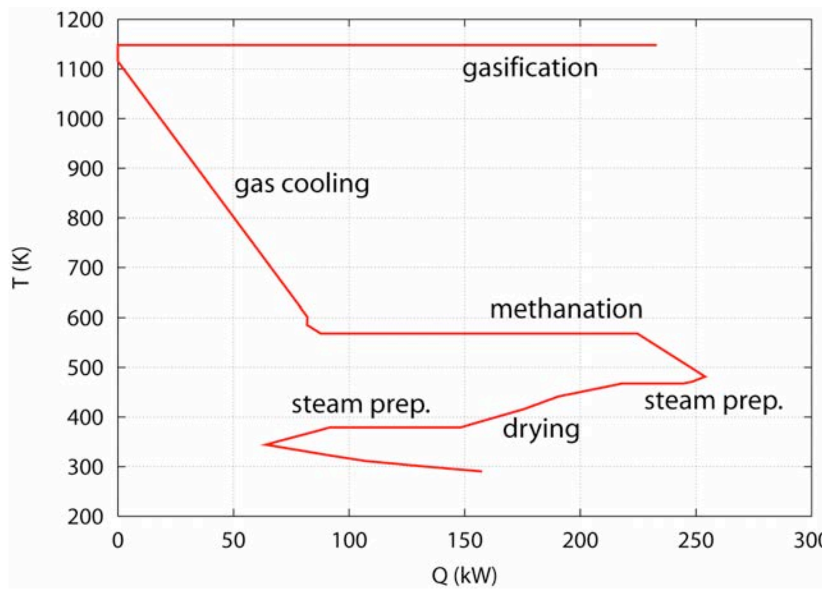
Flowsheet generation (2)

Energy-integration model

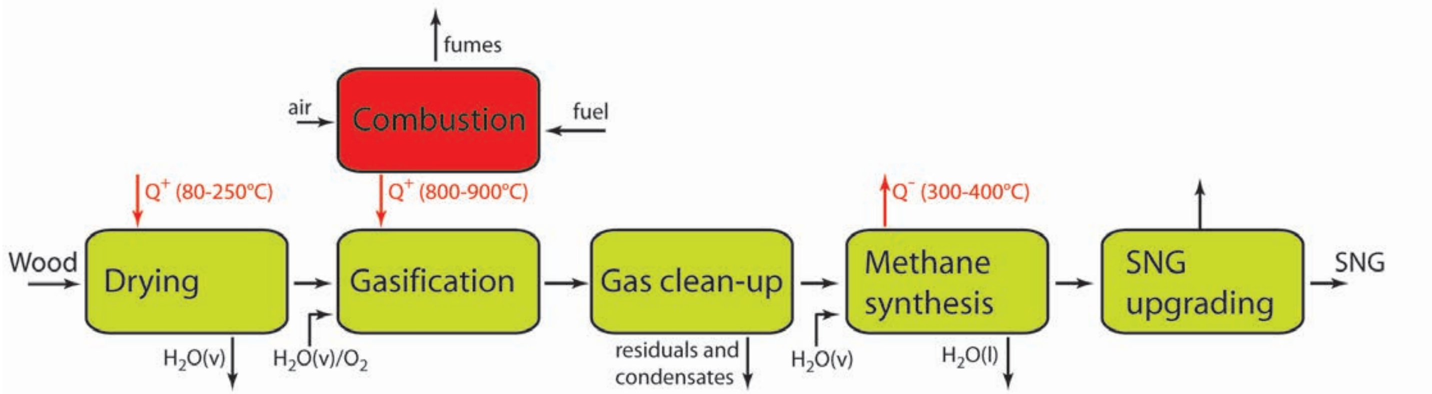
How to satisfy the MER?



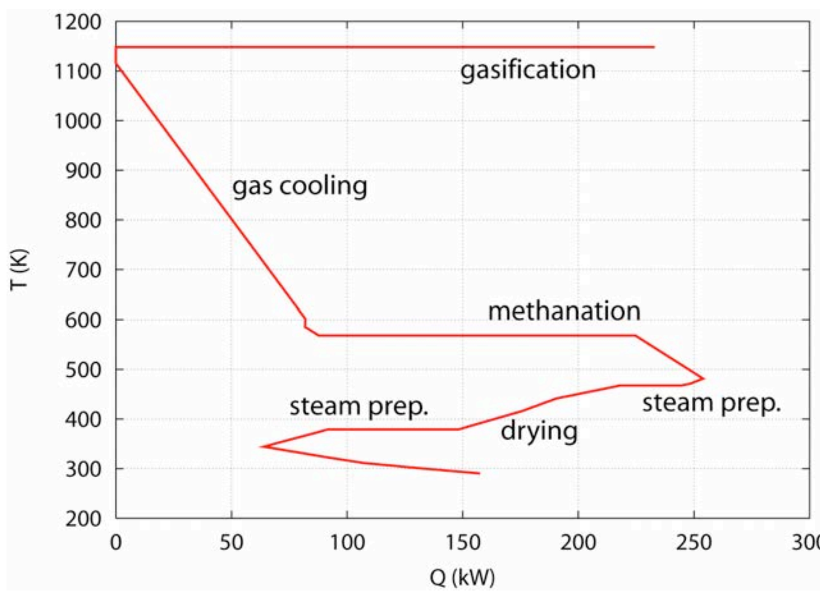
- MER of crude production



How to satisfy the MER?



- MER of crude production
- hot utility: combustion



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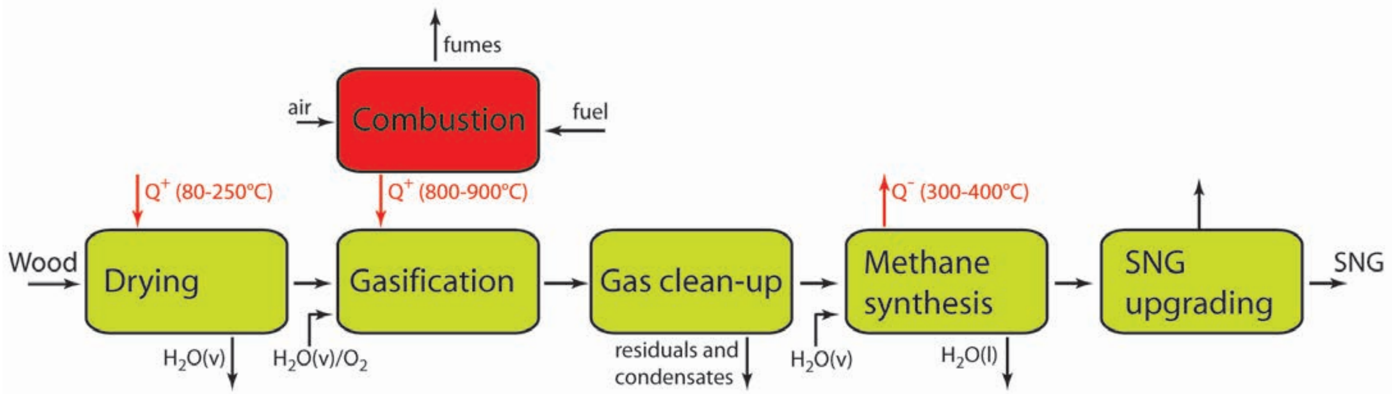
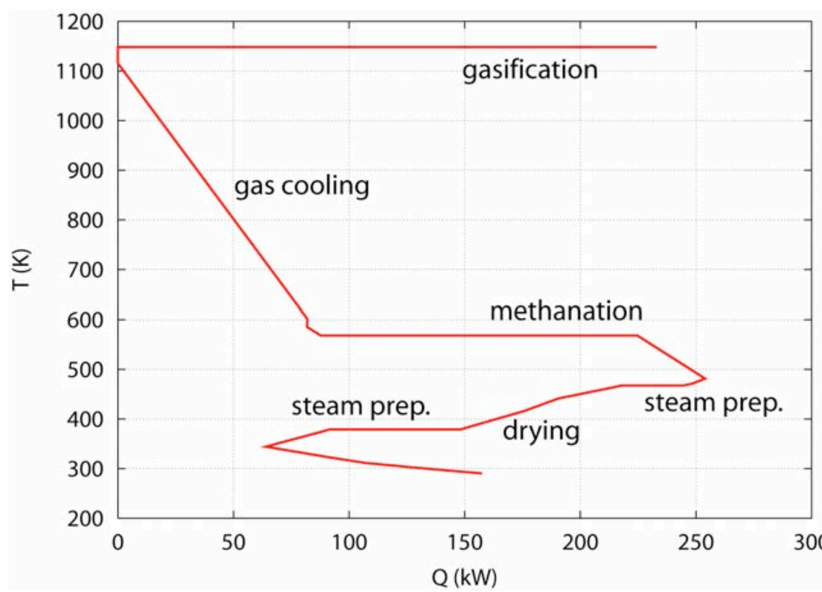
Flowsheet generation (2)

Energy-integration model

How to satisfy the MER?



- MER of crude production
- hot utility: combustion
- fuel choice?



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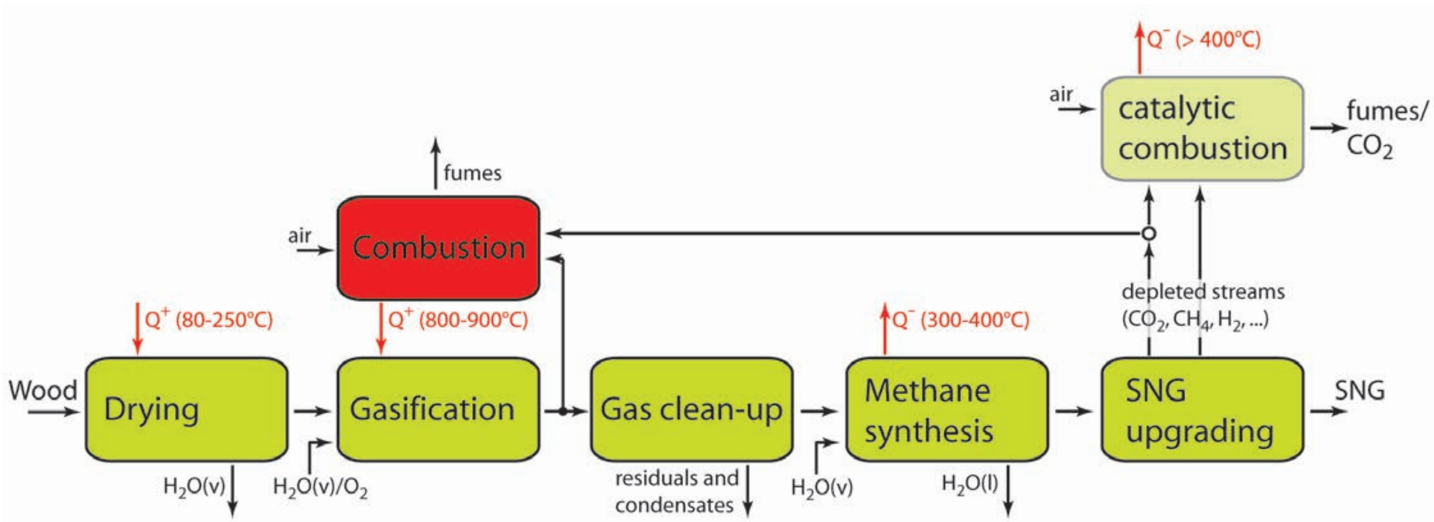
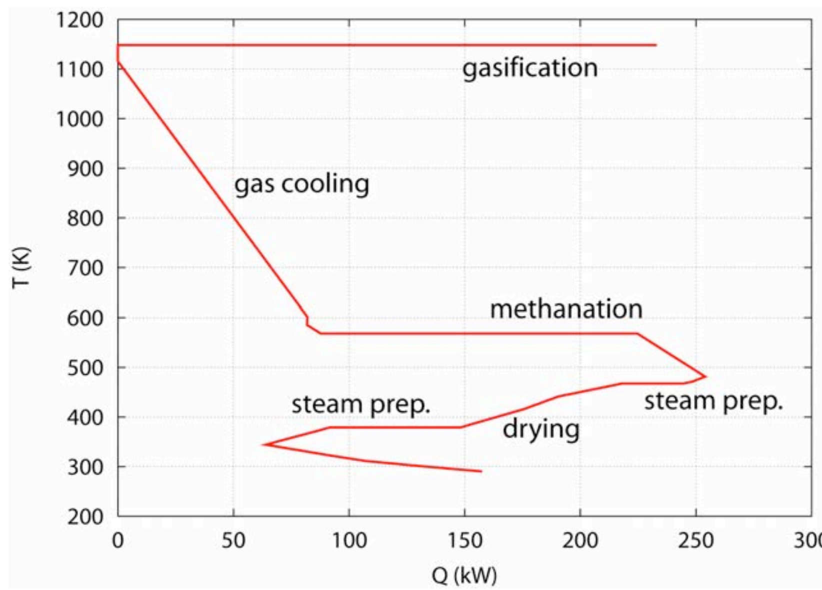
Flowsheet generation (2)

Energy-integration model

How to satisfy the MER?



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



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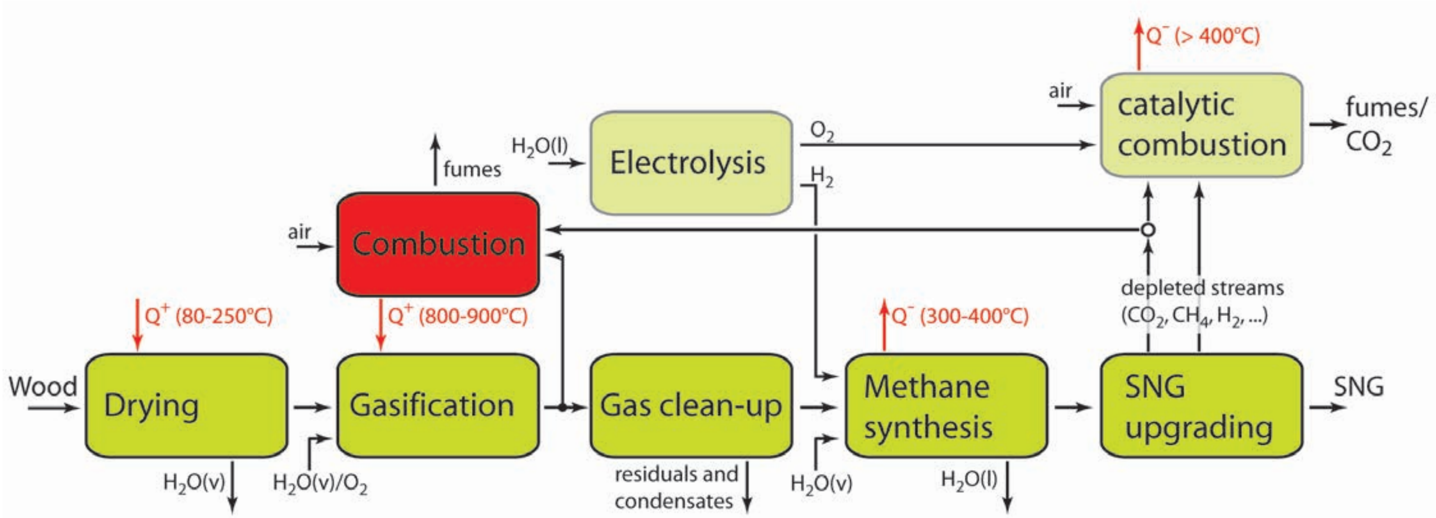
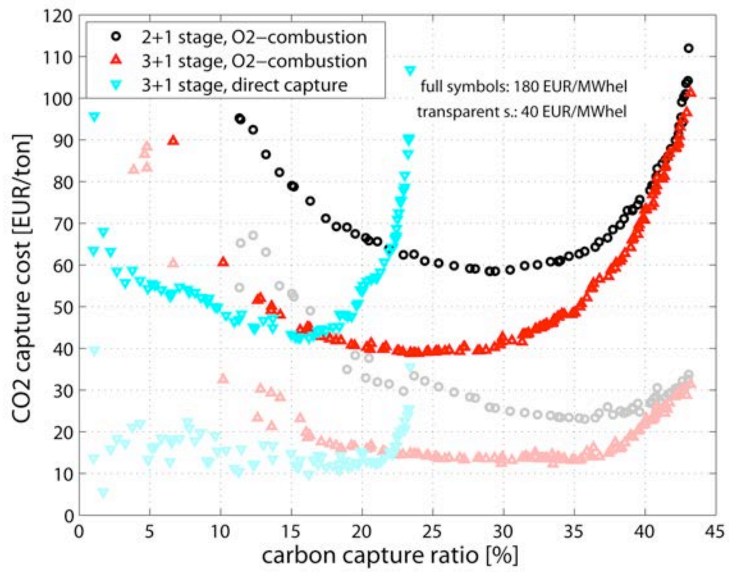
Flowsheet generation (2)
Energy-integration model

How to satisfy the MER (while by-producing pure CO_2)?



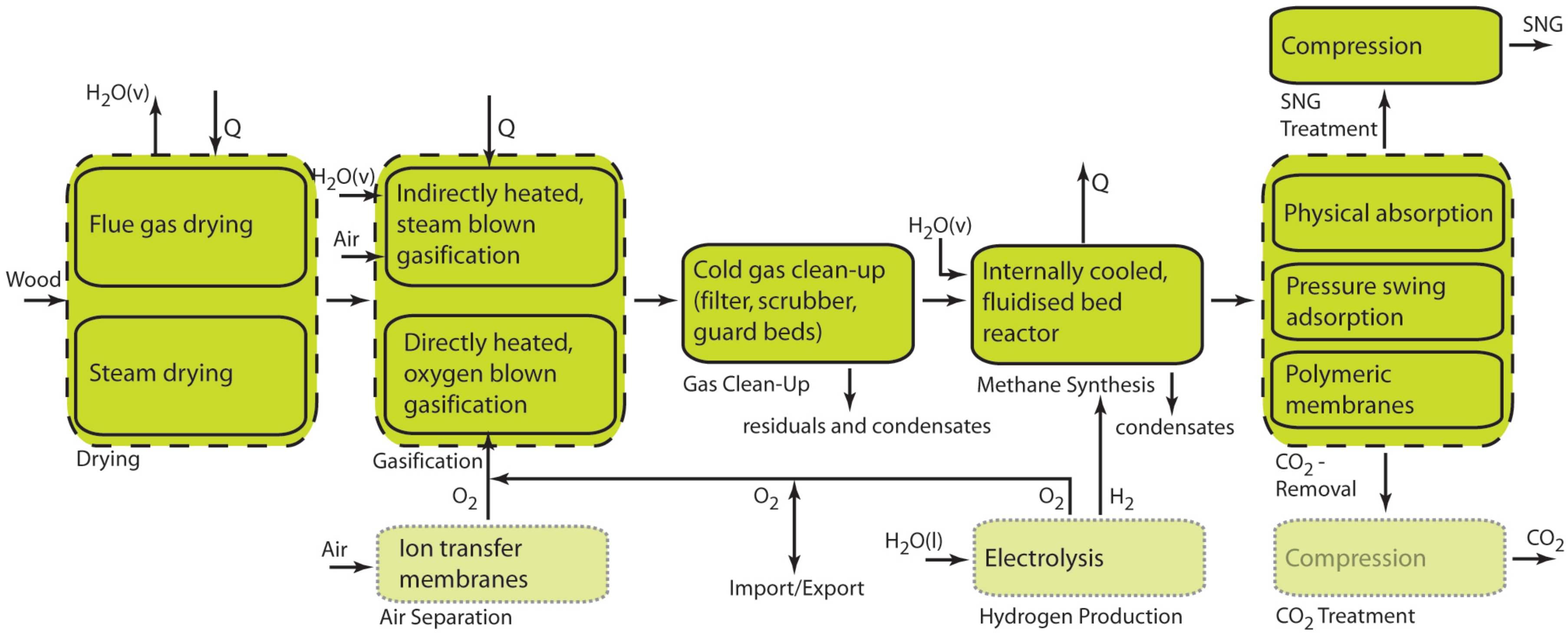
- MER of crude production
- hot utility: combustion
- fuel choice?
- perspective: CCS at < 15 €/t



Flowsheet generation (2)

Energy-integration model

Integrating heat recovery technologies in the superstructure



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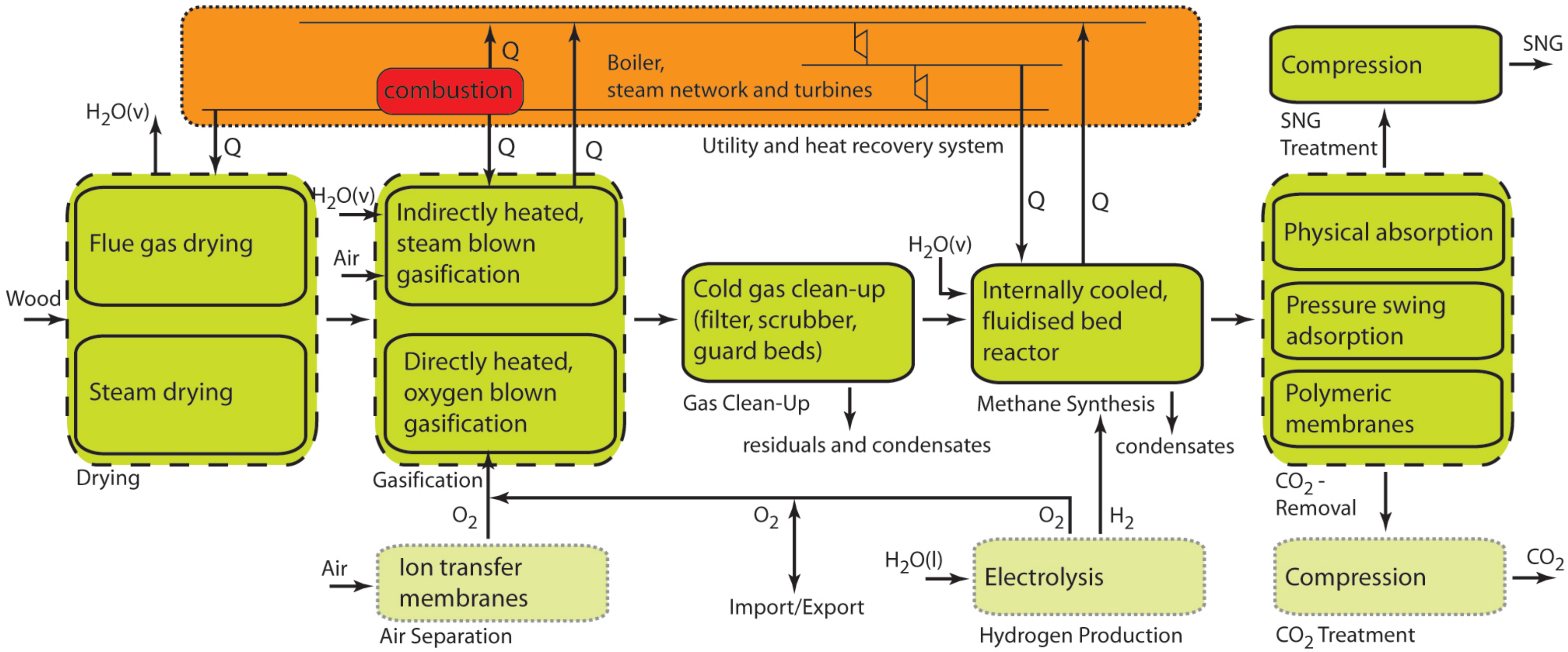
Integrating heat recovery technologies in the superstructure



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Flowsheet generation (2)
Energy-integration model

Math. problem formulation: MILP programming...

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

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Flowsheet generation (2)

Energy-integration model

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subject to:

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:

$$R_1 = 0, \ R_{n_{r+1}} = 0$$

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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:

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

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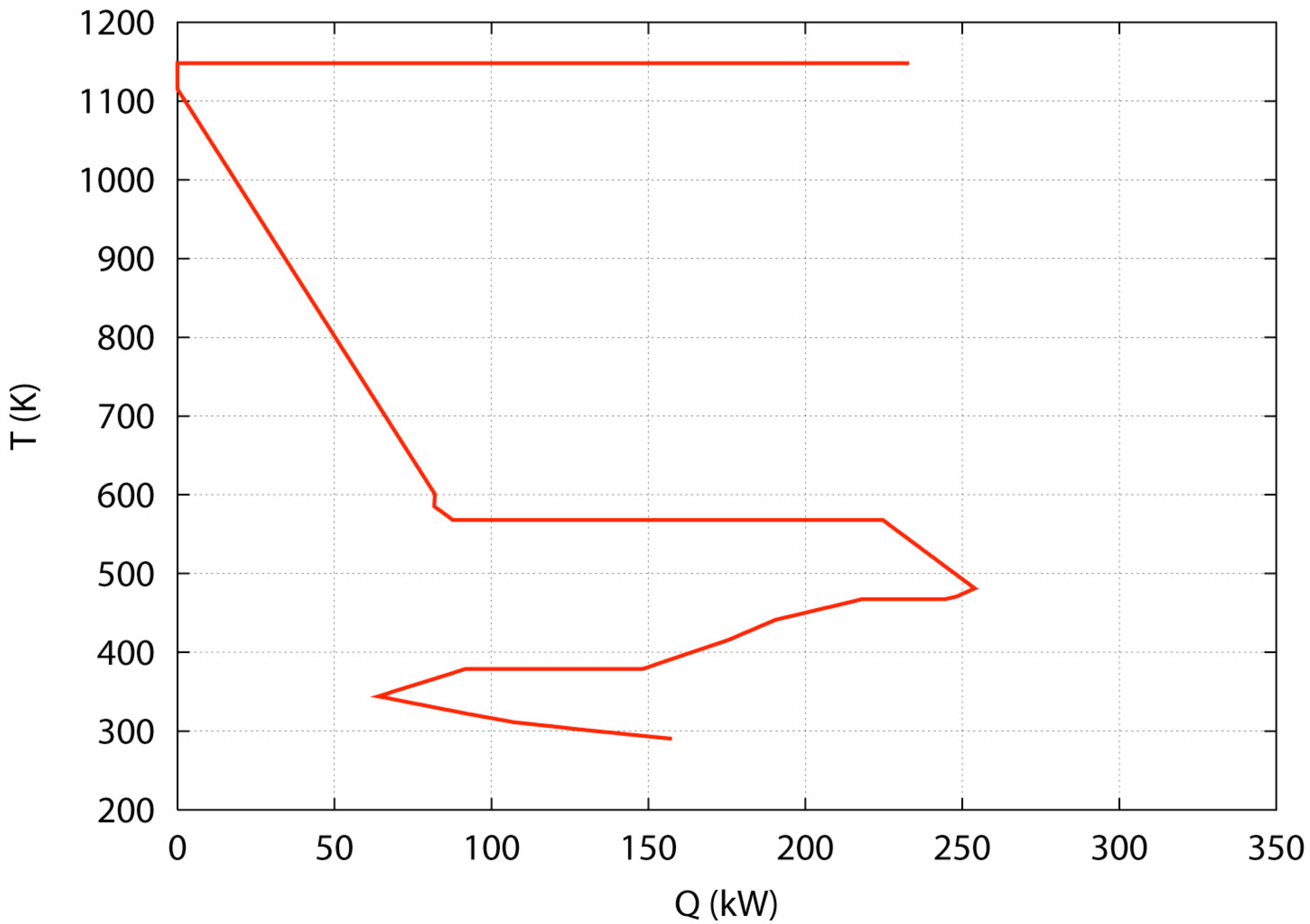
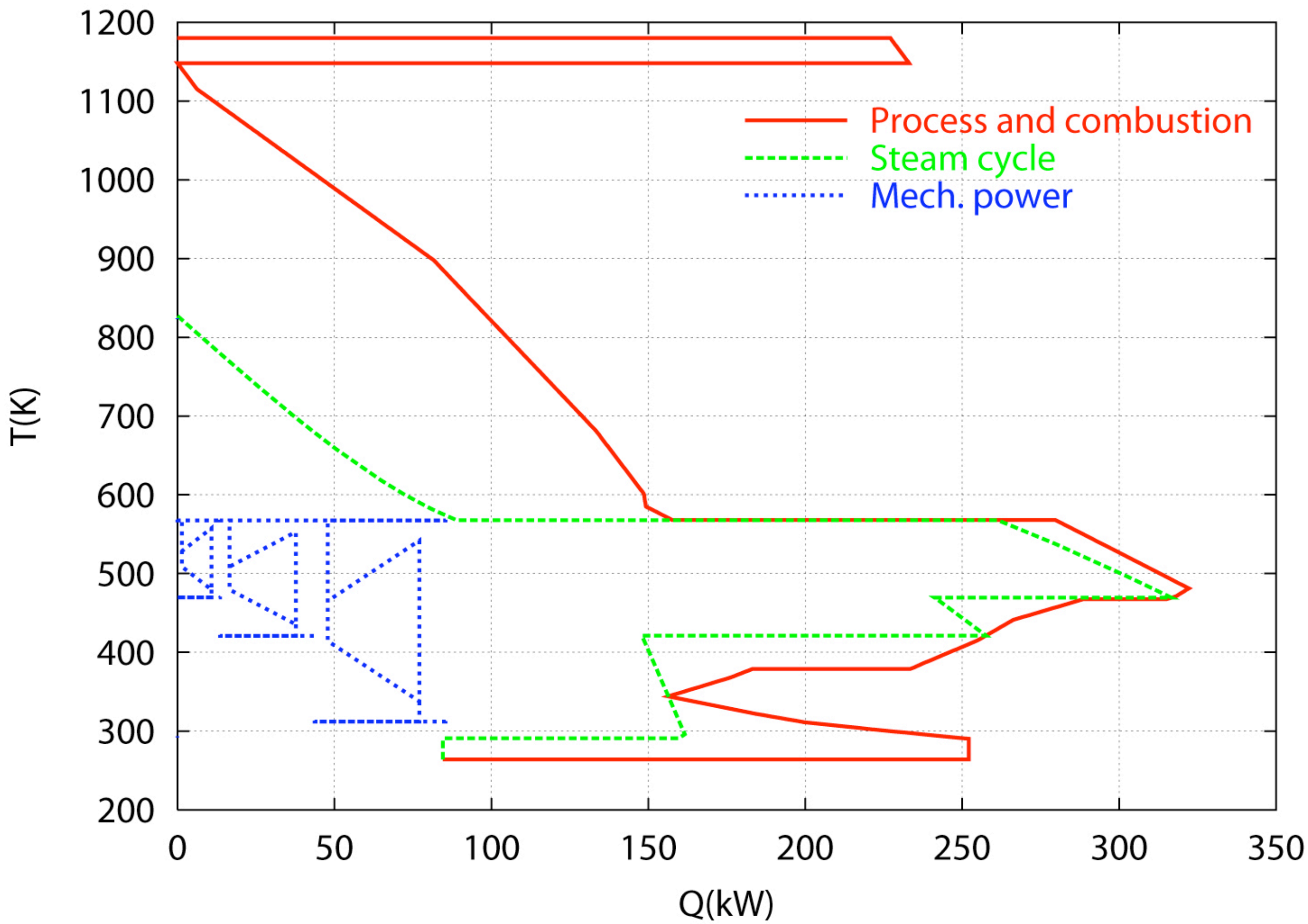
Flowsheet generation (2)
Energy-integration model

MILP resolution: from MER ...

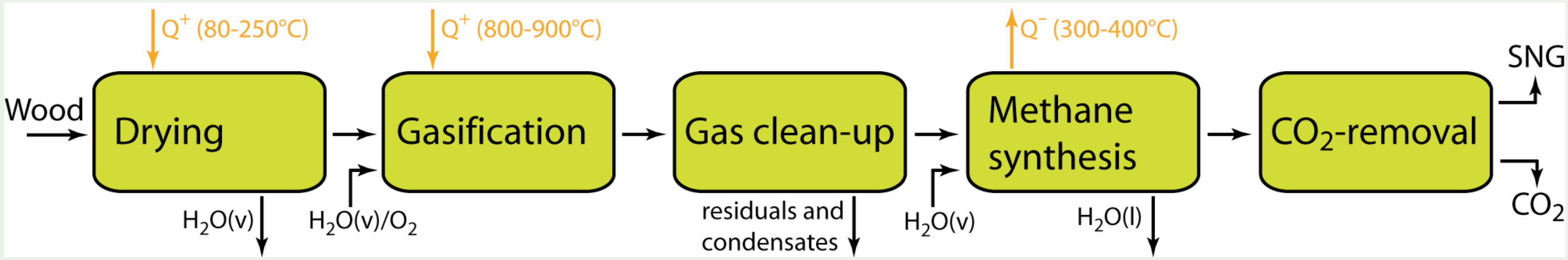


MILP resolution: ... to an integrated solution



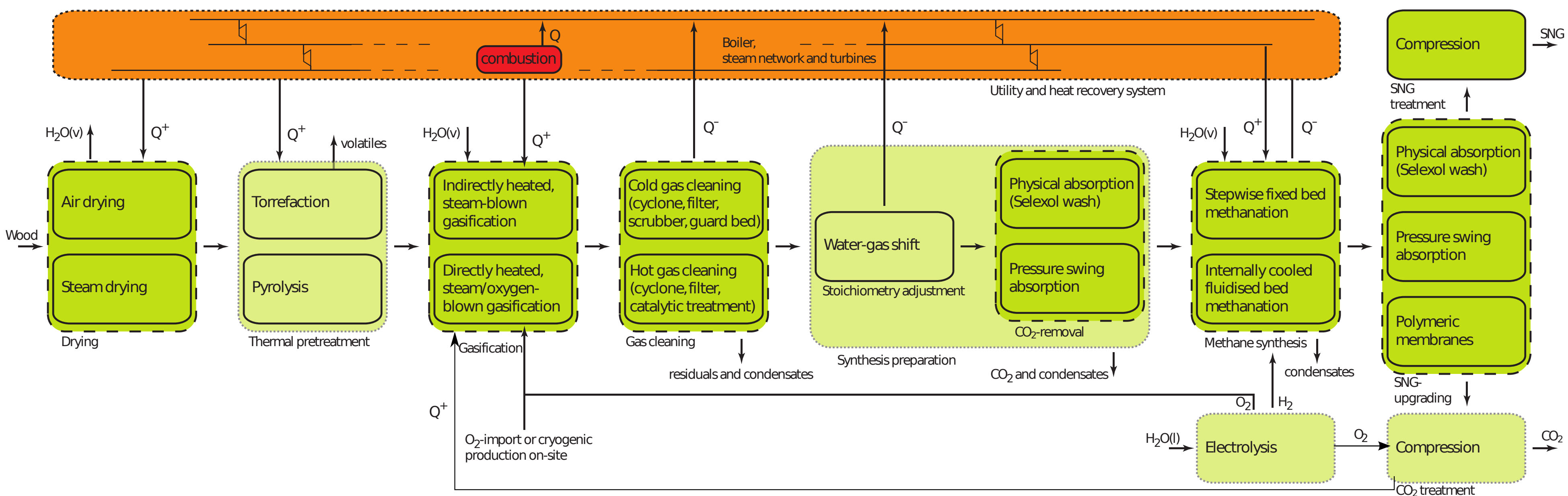
Biofuel process design

Example: Common wood to SNG route



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

Process superstructure

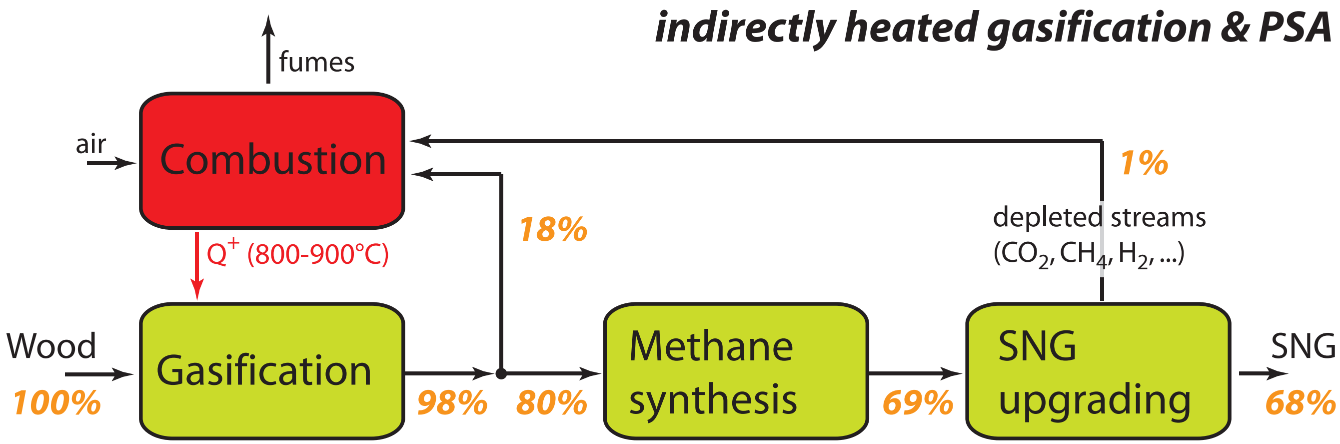


Process system design

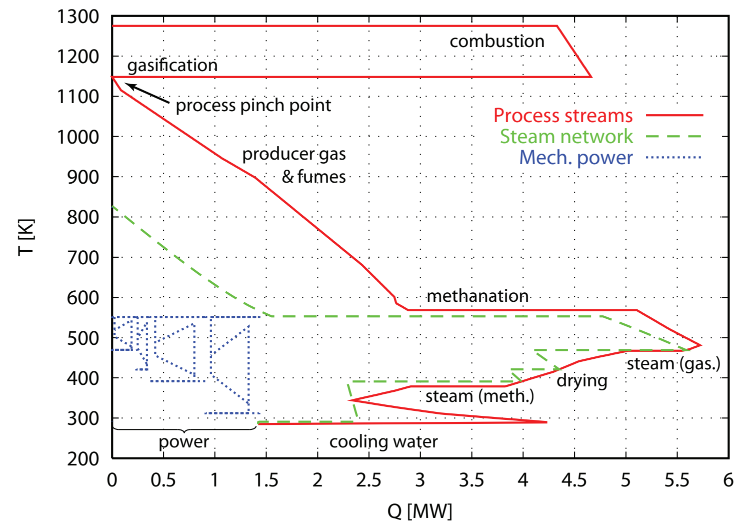
Process performances ?

Thermodynamic performances
System balanced

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



(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%

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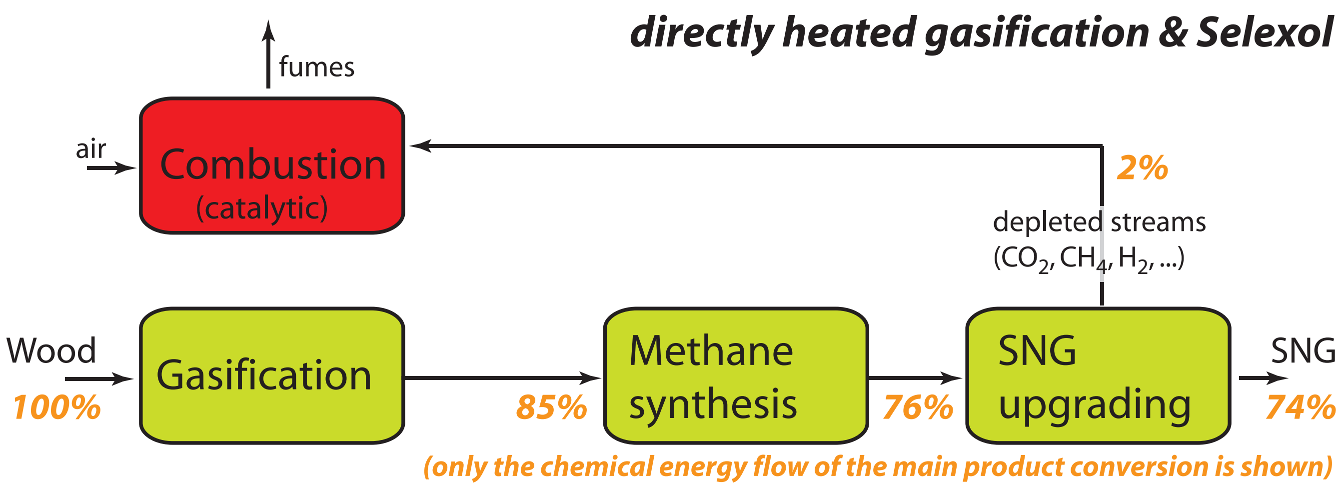
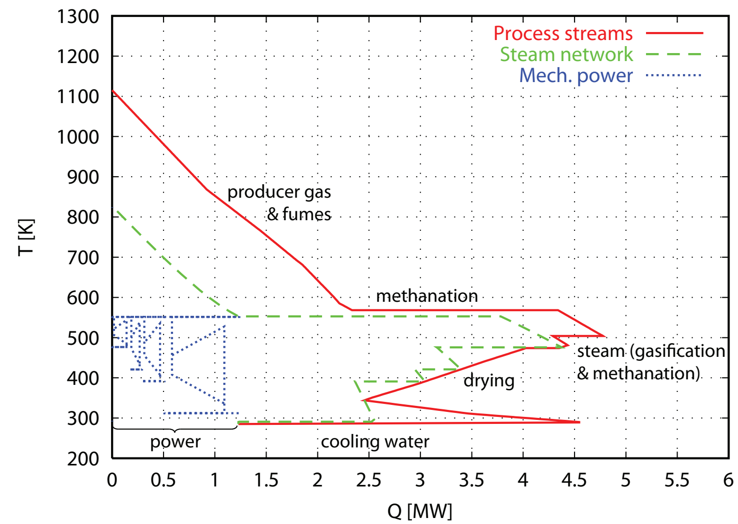
Some (non-optimised) scenarios for conventional SNG production:





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Overall efficiency		69.4%	70.7&	68.8%	69.8%	73.2%	75.6%

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Process system design

Process performances ?

Economics :

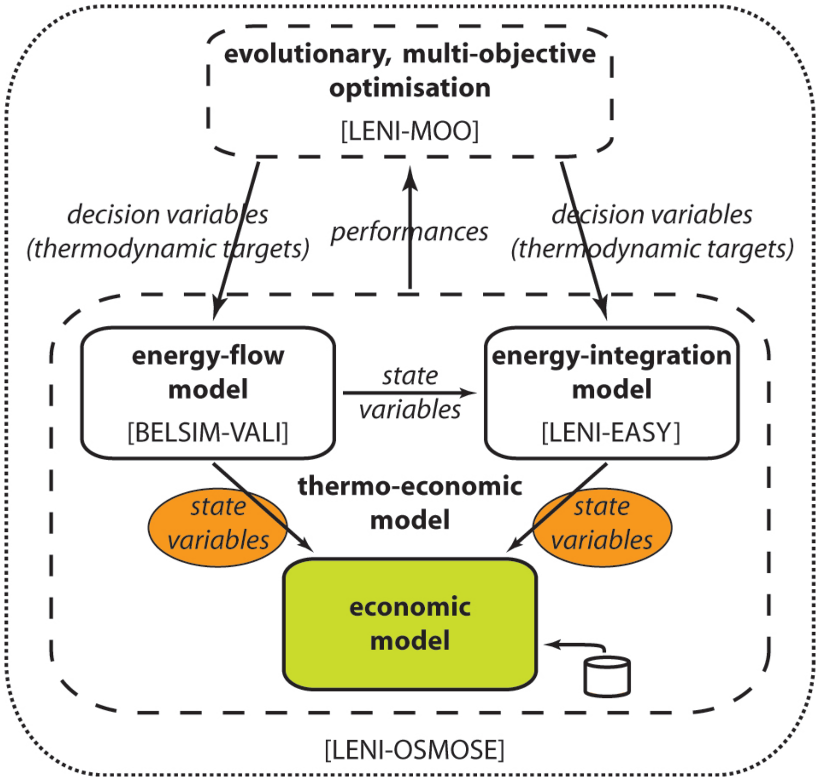
Investment

- Design equipments
- Sizes
- Cost estimations

Incomes

Equipment sizing and costing

Meeting the thermodynamic design target for the flowsheet



Rate the equipment with

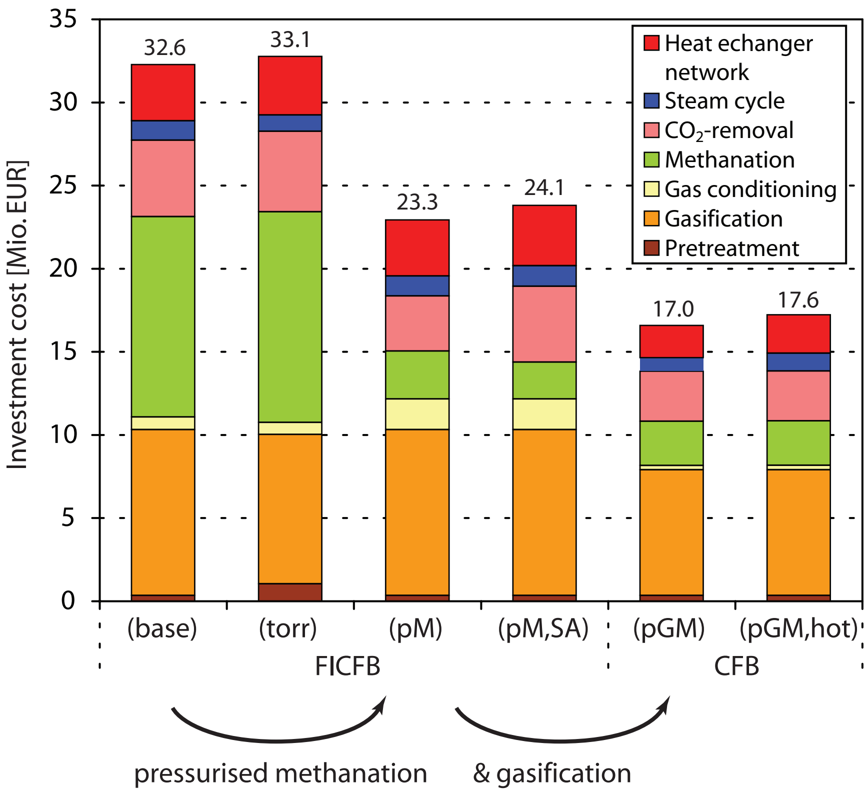
- design heuristics
- pilot plant data

Assessment of investment cost considering the specific operating conditions

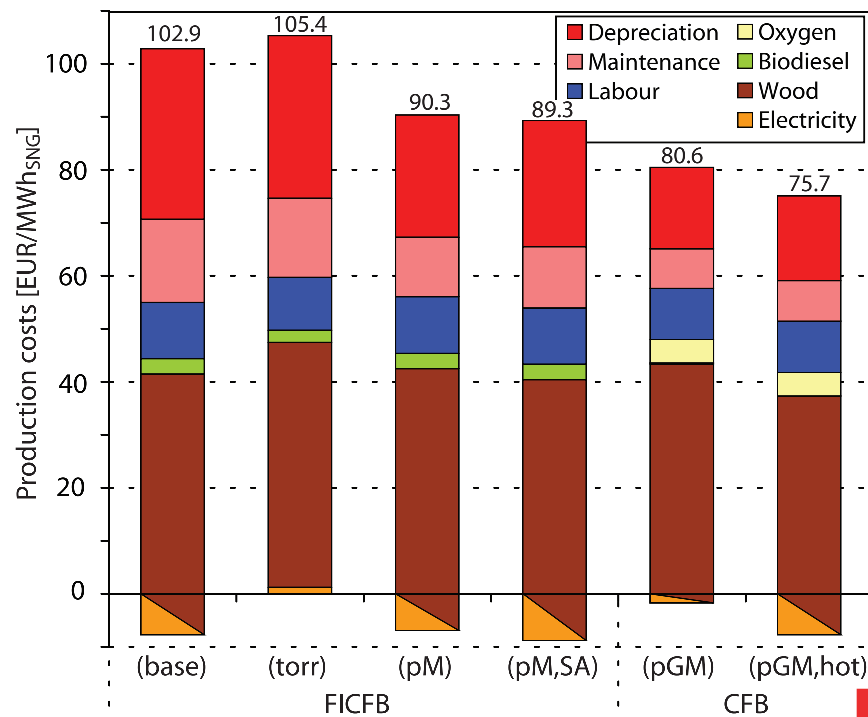
$$C_{GR} = f\left(T, p, size\left(T, p, \ldots\right)\right) \quad (1)$$

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

Investment cost



Total production costs



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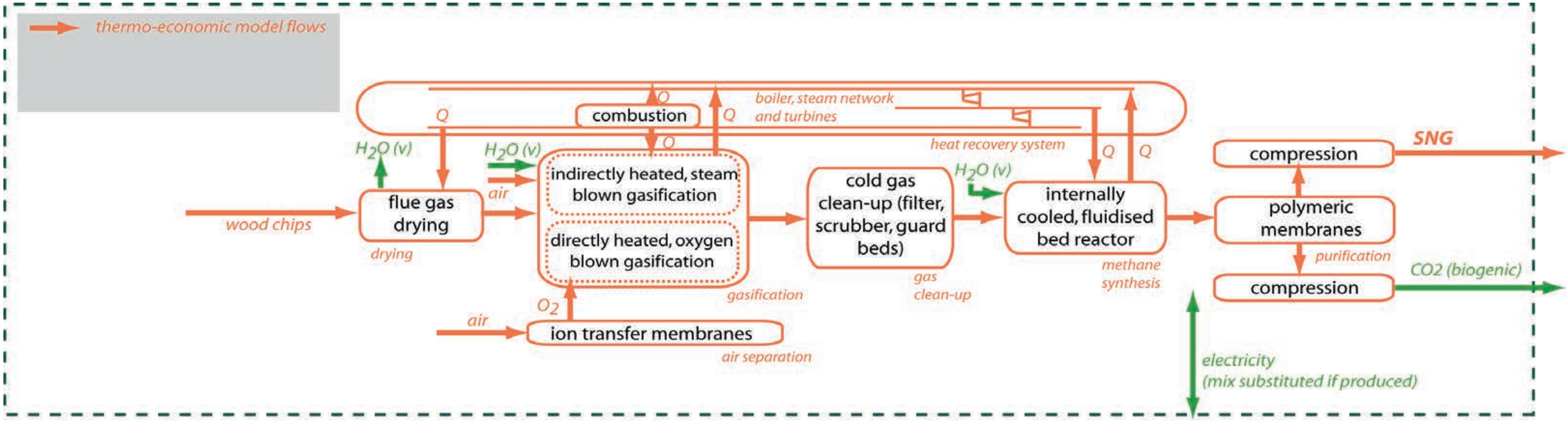
4. Integrating sustainability in design

Process superstructure: thermo-economic model



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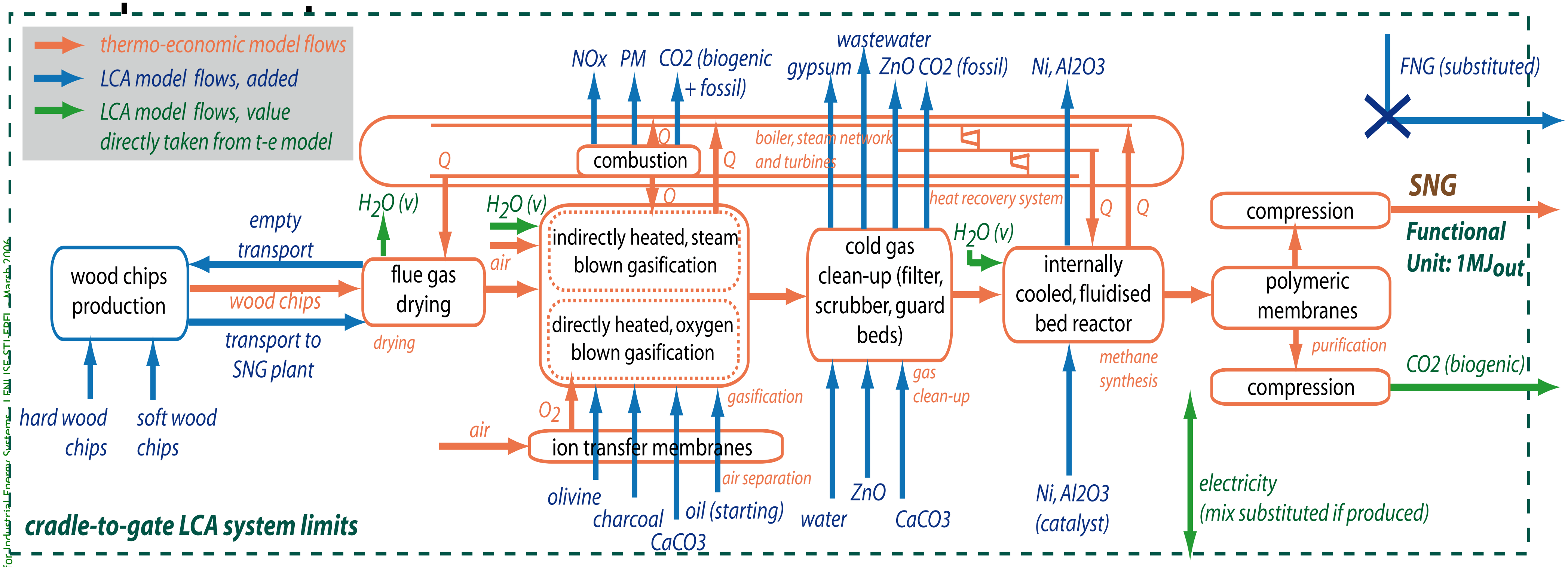
Environmental Process performance indicators

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

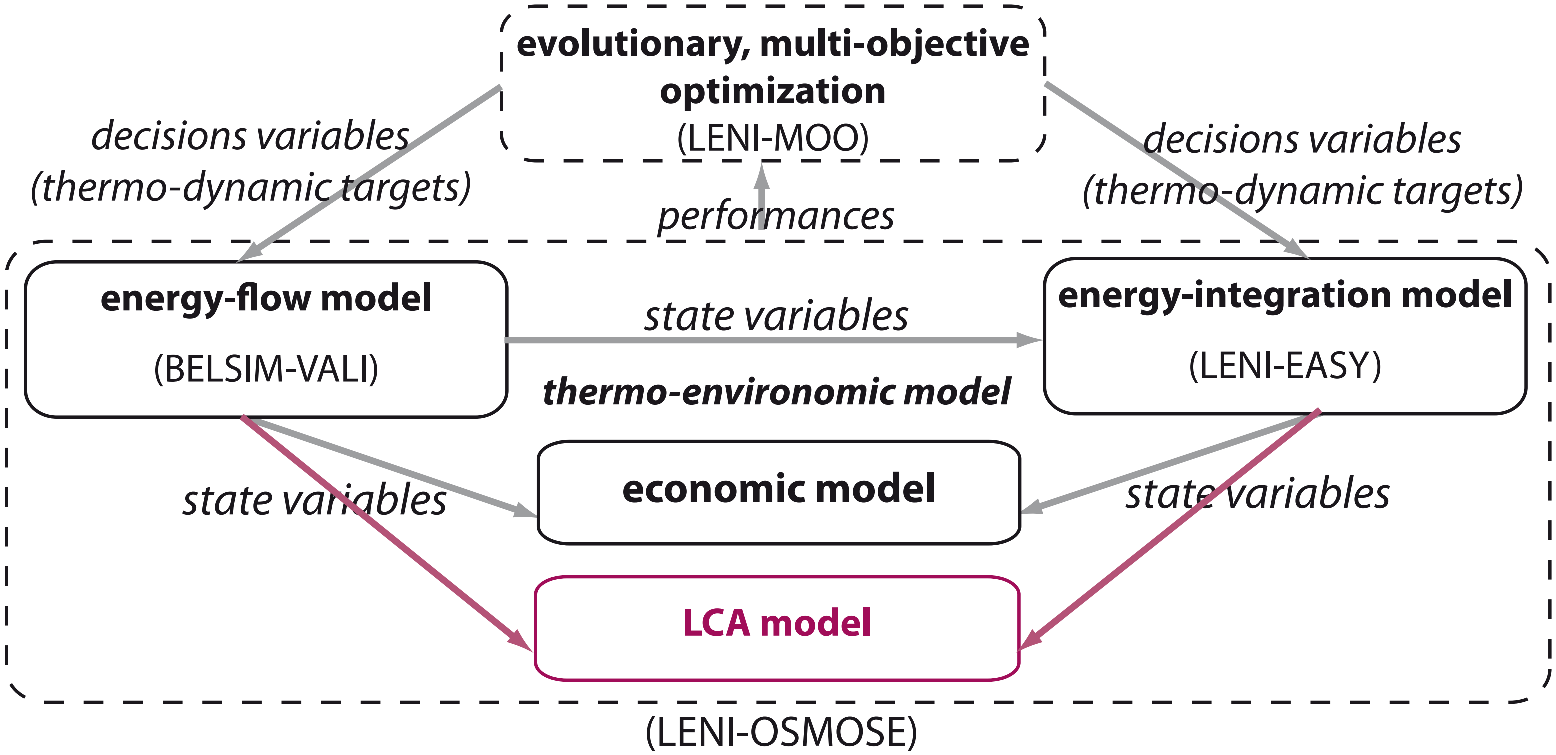
Gerber, L., Gassner, M., and Maréchal, F. (2009). Integration of LCA in a thermo-economic model for multi-objective process optimization of SNG production from woody biomass, , (), 1405-1410

Motivation

- Analysing the decision space
- Take the “best decision”
  - Multi-objective optimization
  - Thermo-economic or environomic Pareto front

Solving method : problem decomposition

MINLP non differentiable problem



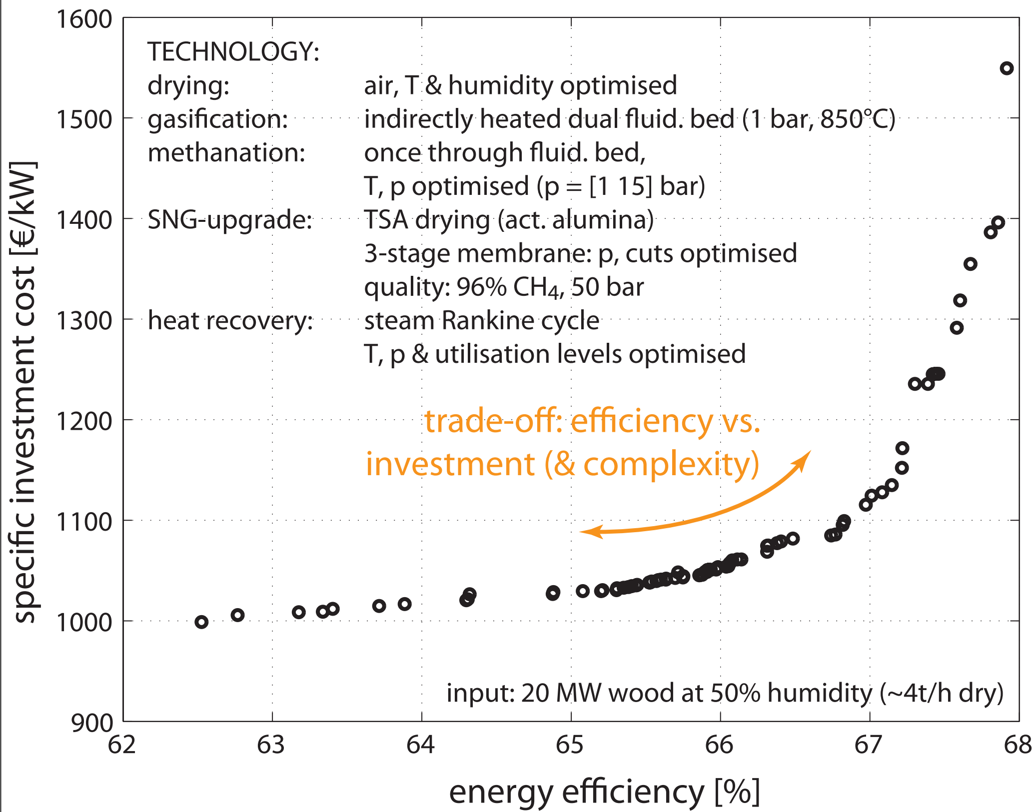
Non linear eq.

MILP problem

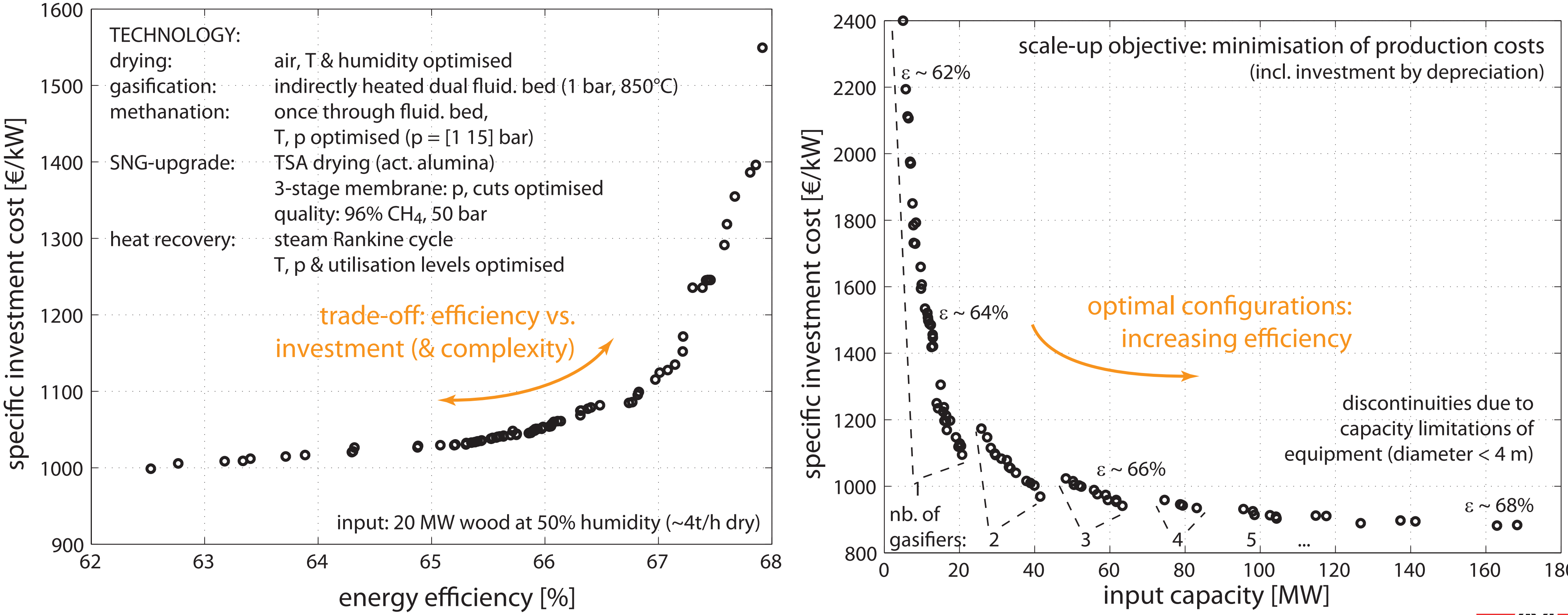
combinatorial

Gassner, M. and Marechal, F. (2009). Methodology for the optimal thermo-economic, multi-objective design of thermochemical fuel production from biomass, Computers and Chemical Engineering, 33(3), 769-781

Efficiency vs. investment:



Efficiency vs. investment and optimal scale-up:



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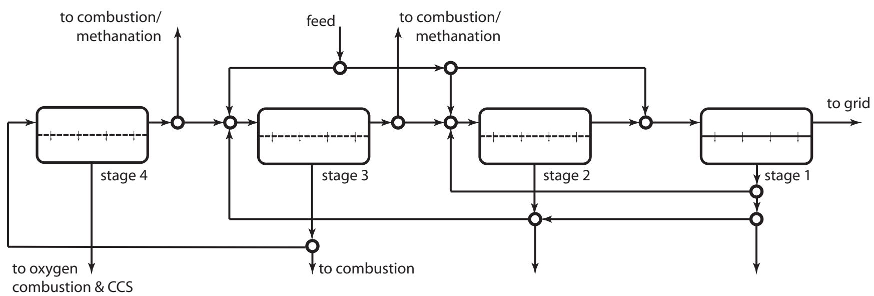
Technology integration example

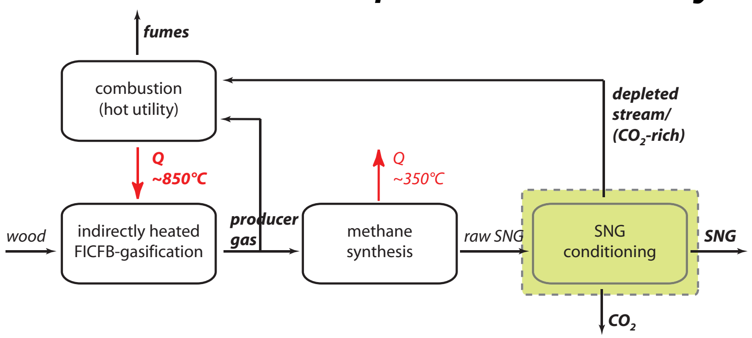
Gas upgrading by membrane

Membrane system upgrading superstructure

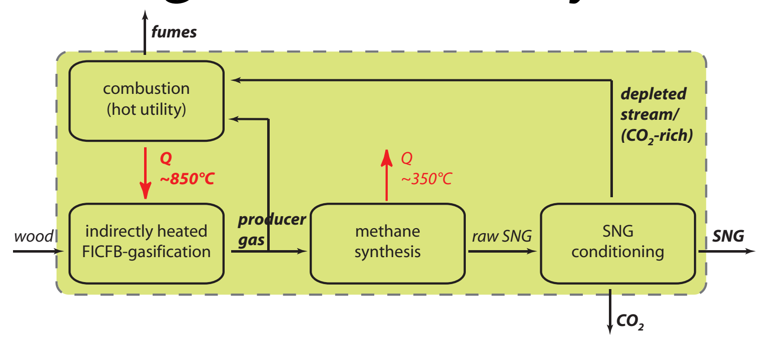
CH_4/CO_2 separation



"isolated": separation only



"integrated": total system



- Maximise SNG recovery
- Permeate stream is lost

- Permeate stream valorised
- Overall system performance

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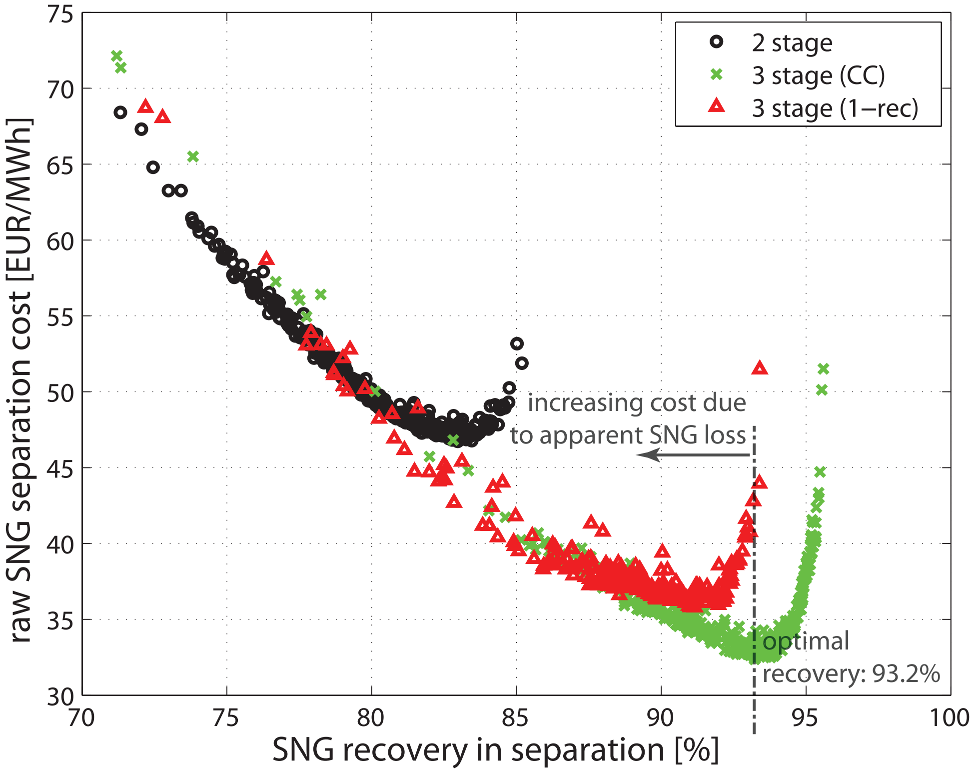
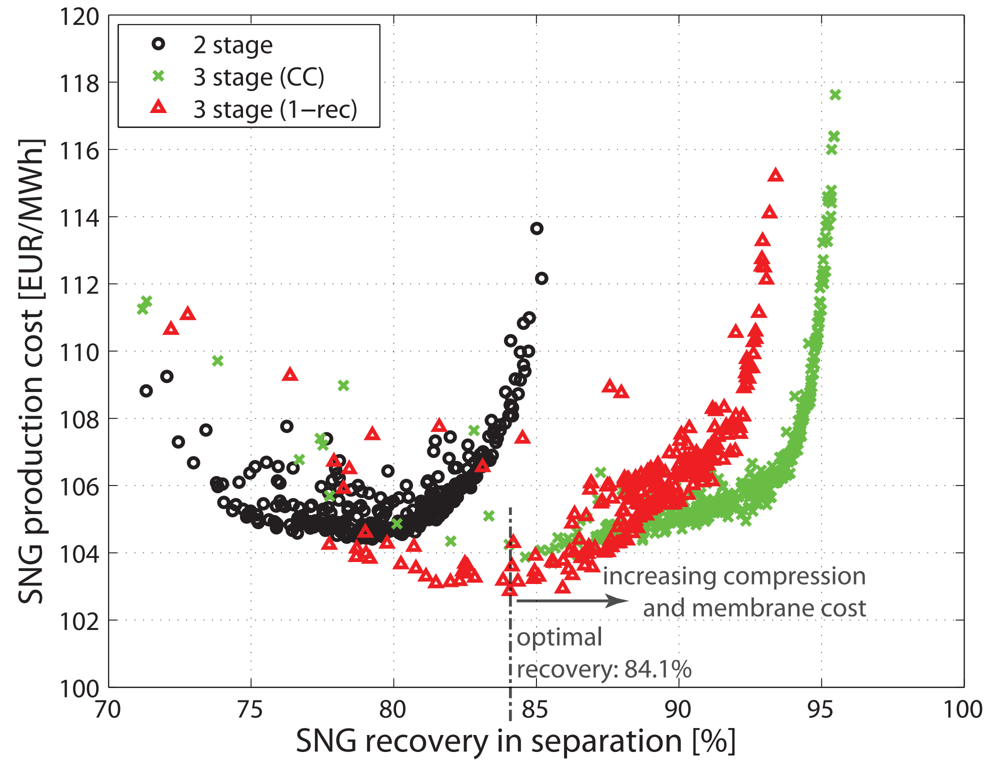
Production costs:

separation only



total system



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Results : Isolated vs integrated design

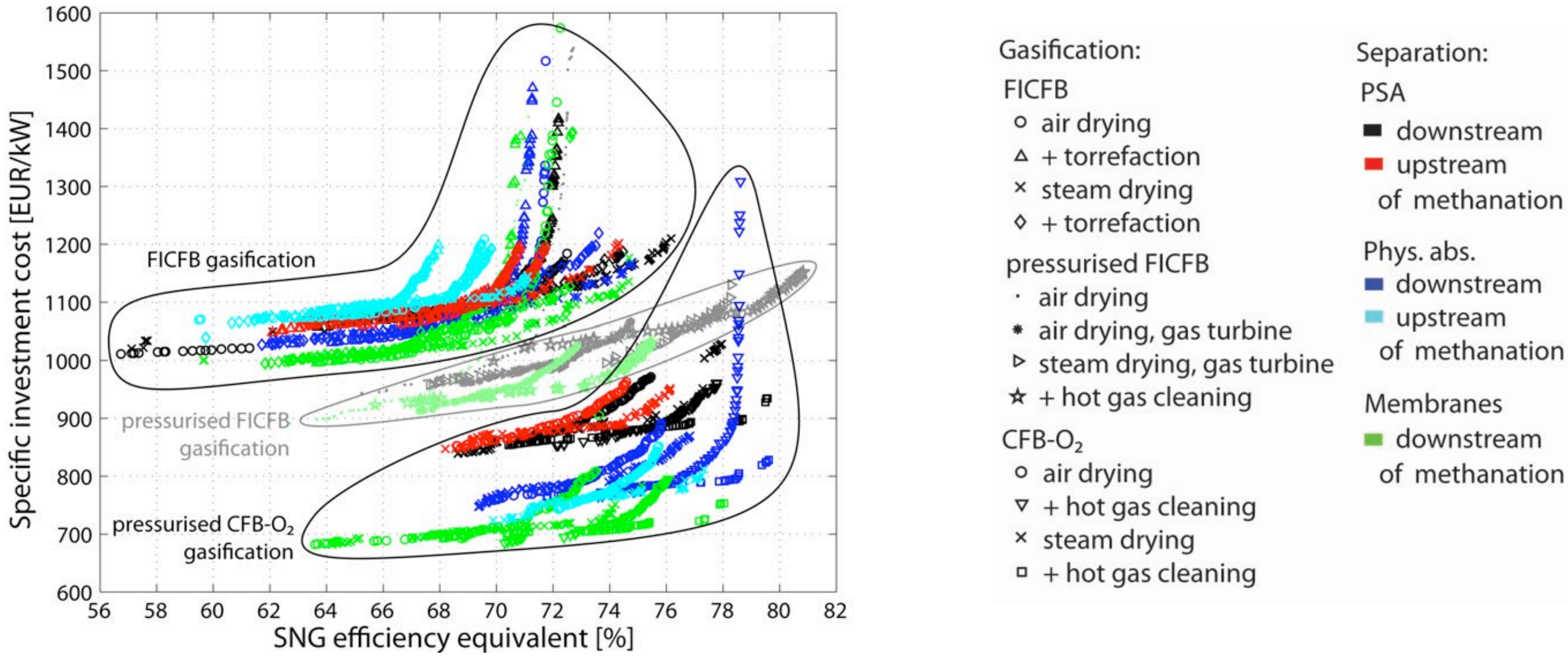
		isolated	integrated	overshoot
system		**3-stage CC**	**3-stage, 1 rec**	
r_{SNG}	%	**93.2**	**84.1**	+ 10.8%
e^{sep}_{spec}	$kW_{el}/MW_{th,in}$	**76.9**	**55.9**	+ 37.6%
$\tilde{c}_{CO2,p}$	%	86.6	79.9	+ 8.4%
$\tilde{c}_{H2,p}$	%	10.3	9.4	+ 9.6%
$\tilde{c}_{CH4,p}$	%	3.0	10.4	− 71.2%
A	m^2	**4675**	**2928**	+ 59.7%
C_I^{sep}	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%

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Some results

Cmparing technologies and processes

Thermo-economic Pareto front (cost vs efficiency):



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

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Comparing performances and design

Drying	technology	steam drying	
	$T_{d,in}$	188°C	181°C
	p_d	5 bar	5 bar
	$\Phi_{d,wood}$	13.8%wt	10.2%wt
Gasification	technology	**FICFB**	**CFB-O_2**
	p_g	1 bar	30 bar
Gas cleaning	technology	cold	
Methanation	$T_{m,in}$	396°C	344°C
	$T_{m,out}$	326°C	303°C
	p_m	12.2 bar	30 bar
Separation	technology	Membranes	
	...		
Efficiencies	ϵ_{SNG}	65.9%	68.1%
	ϵ_{el}	1.8%	3.0%
	ϵ_{th}	16.9%	19.8%
	ϵ	84.6%	90.9%
	ϵ_{chem}	78.7%	84.6%
Costs	c_I	1096 €/kW	751 €/kW
	c_p	70.4 €/MWh	50.9 €/MWh
	$c_{biomass,break-even}$	66.6€/MWh	80.4€/MWh

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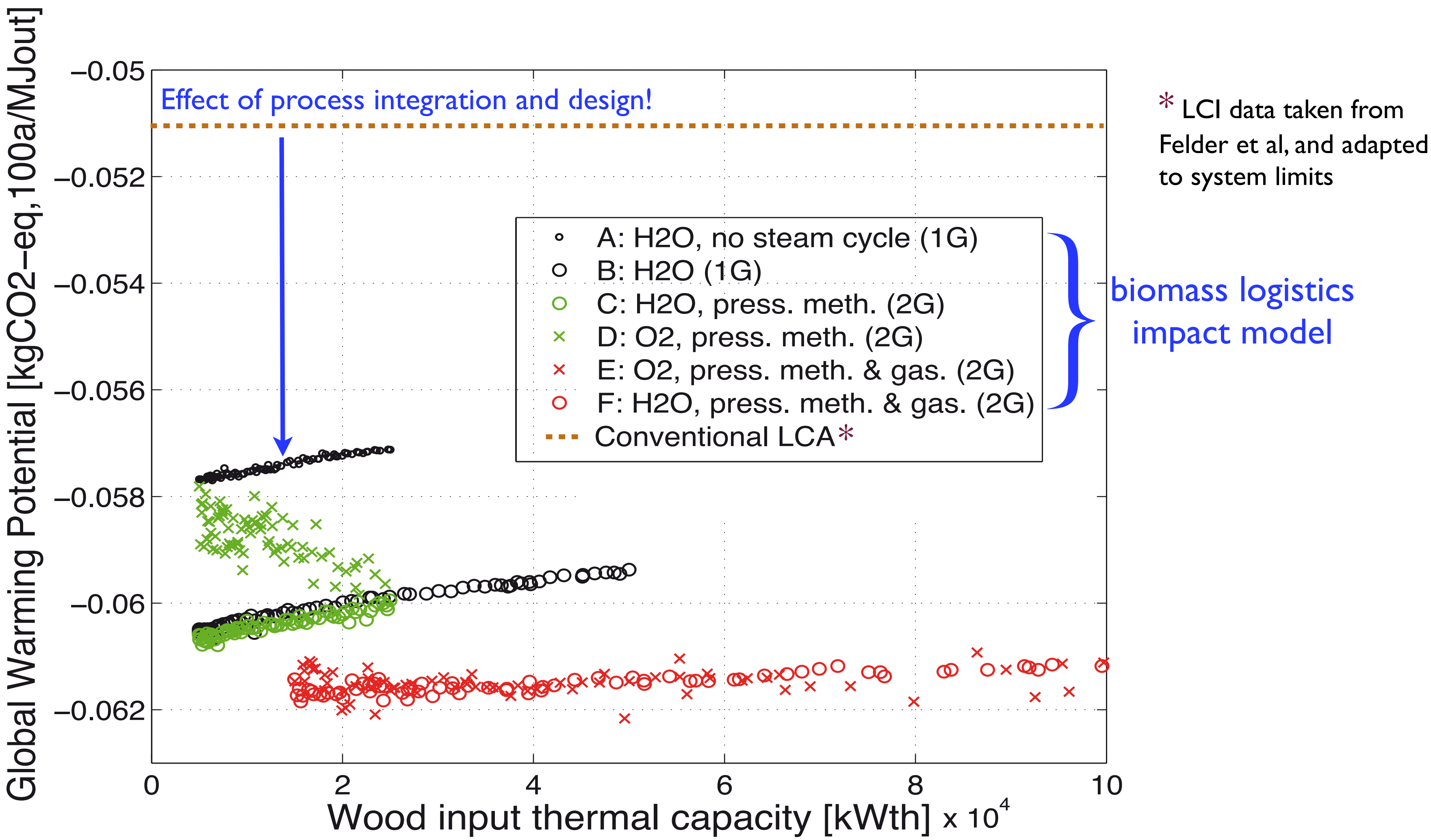
Integration of LCIA in the methodology

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*

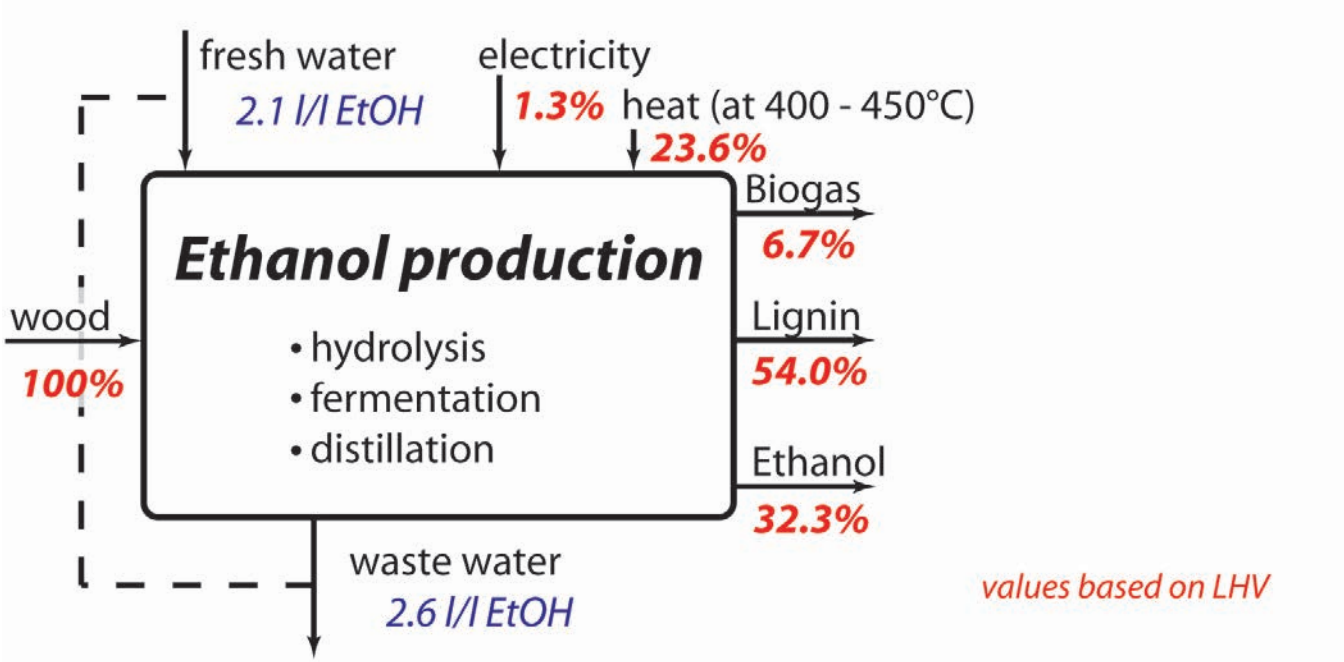
Motivation

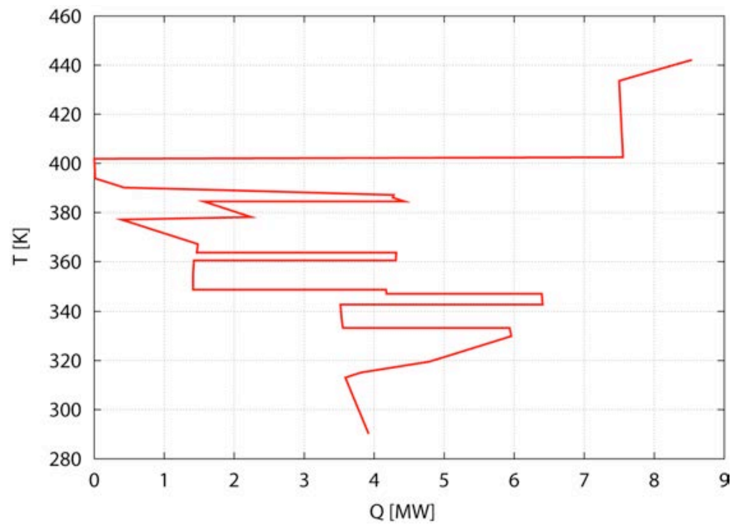
6. Overall System analysis

Discover synergies

Site integration: process couplings
EtOH & SNG

Ethanol production from lignocellulosic biomass:

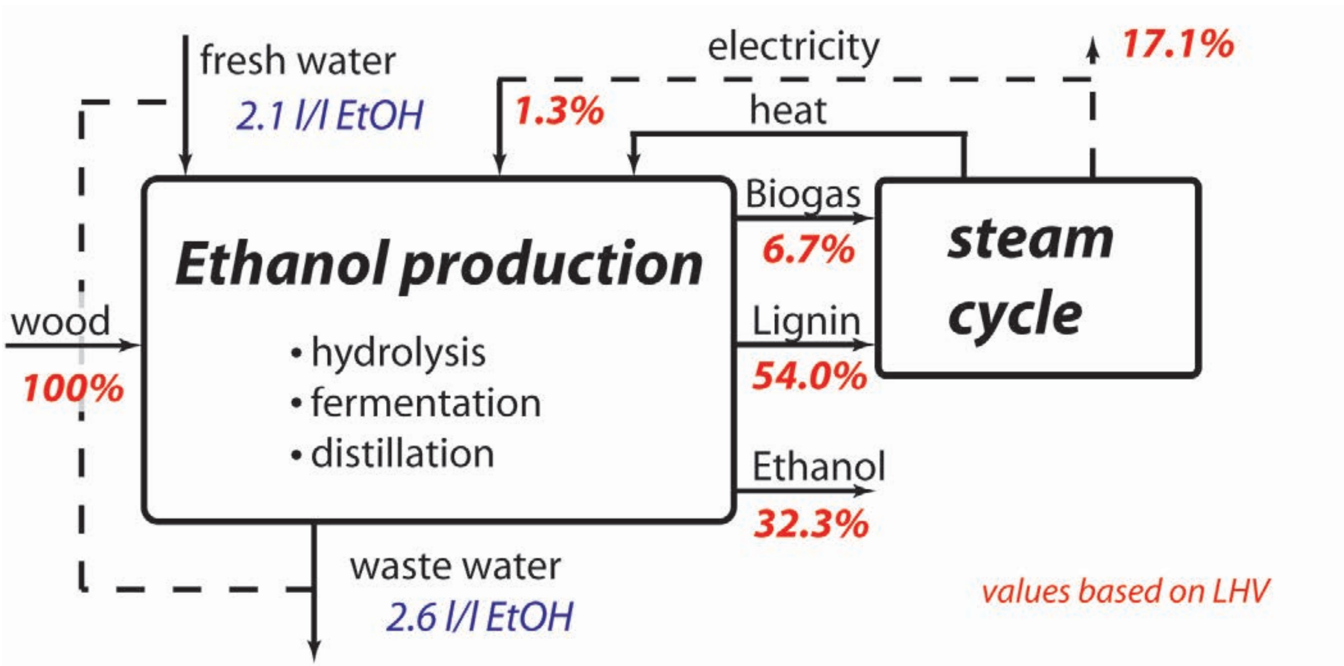


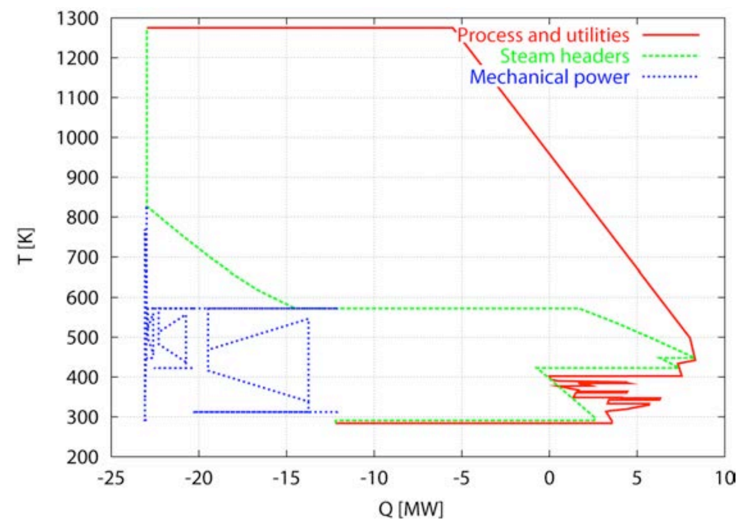


input: $58\ MW_{th,wood}$

Site integration: process couplings
EtOH & SNG

Ethanol production from lignocellulosic biomass:





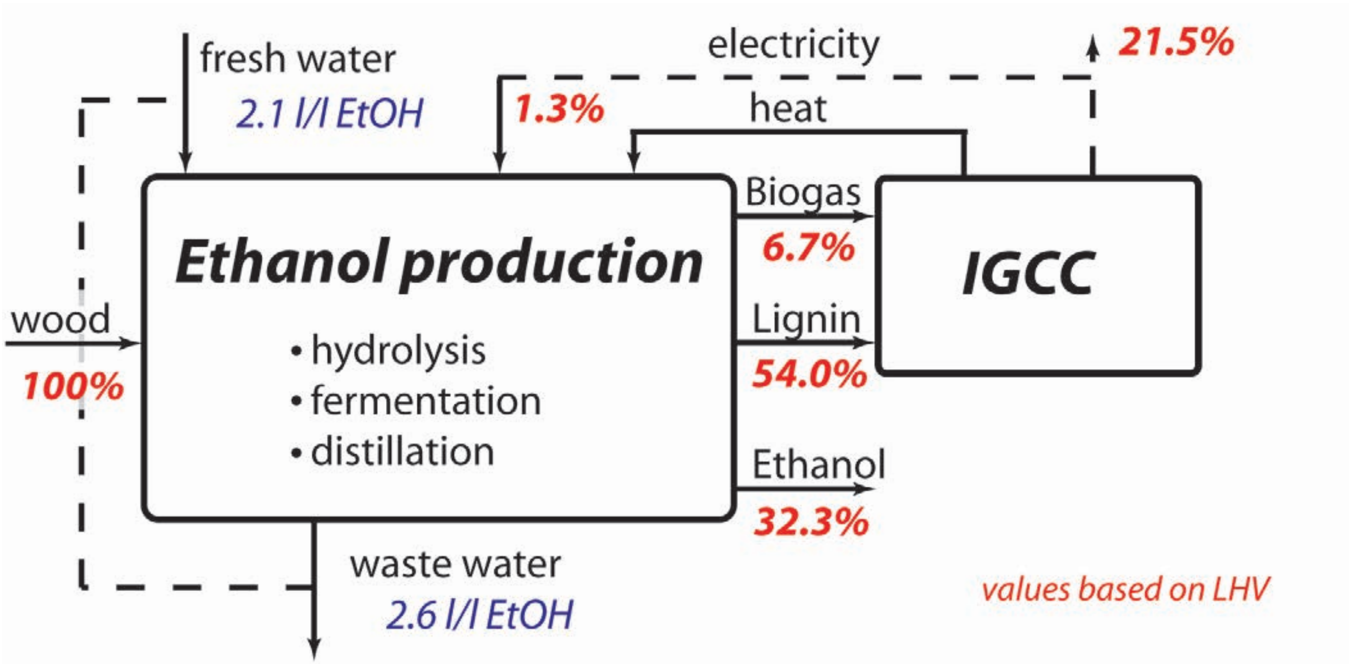
input: $58\ MW_{th,wood}$

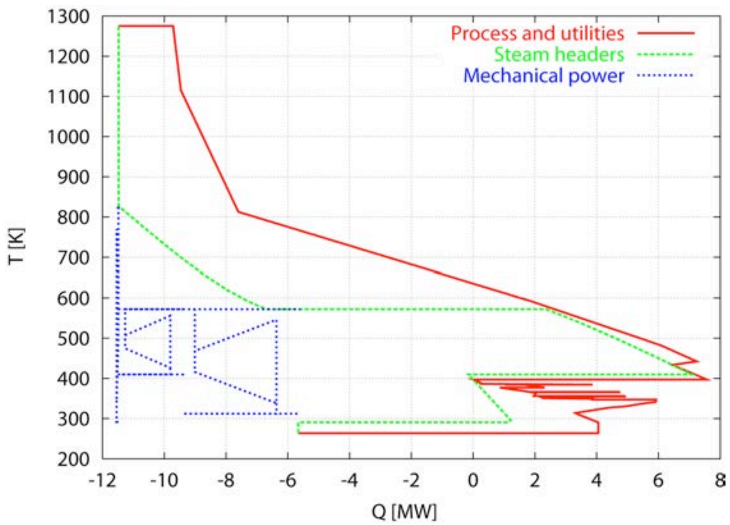
		steam cycle
Input	wood	100 %
	ethanol	32.3 %
Output	SNG	-
	electricity	17.1 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %
total efficiency		49.4 %

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

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Ethanol production from lignocellulosic biomass:





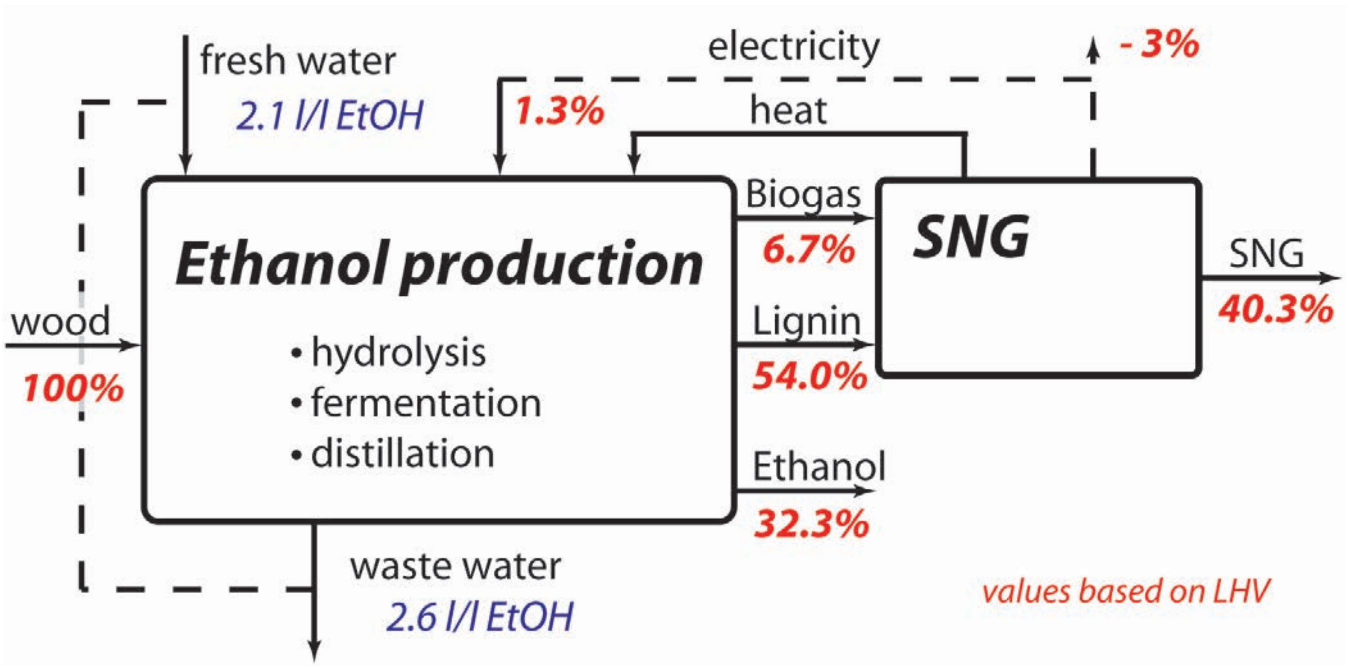
input: $58\ MW_{th,wood}$

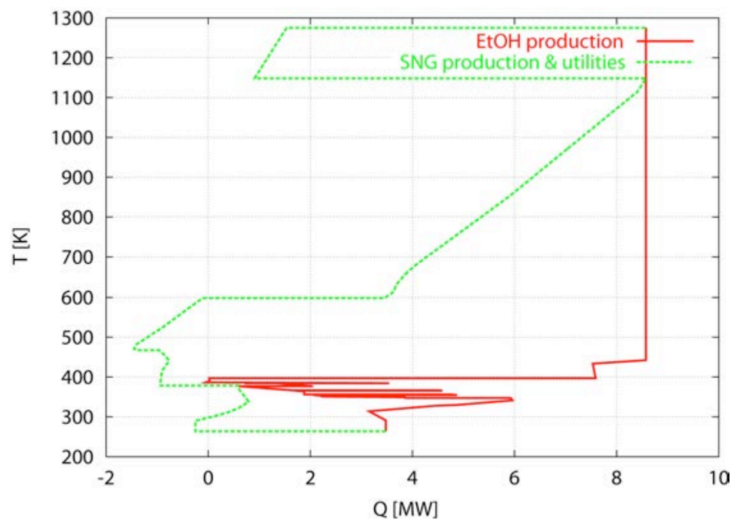
		steam cycle	IGCC
Input	wood	100 %	100 %
Output	ethanol	32.3 %	32.3 %
	SNG	-	-
	electricity	17.1 %	21.5 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %	70.0 %
total efficiency		49.4 %	53.8 %

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

Site integration: process couplings
EtOH & SNG

Ethanol production from lignocellulosic biomass:





input: 58 $MW_{th,wood}$

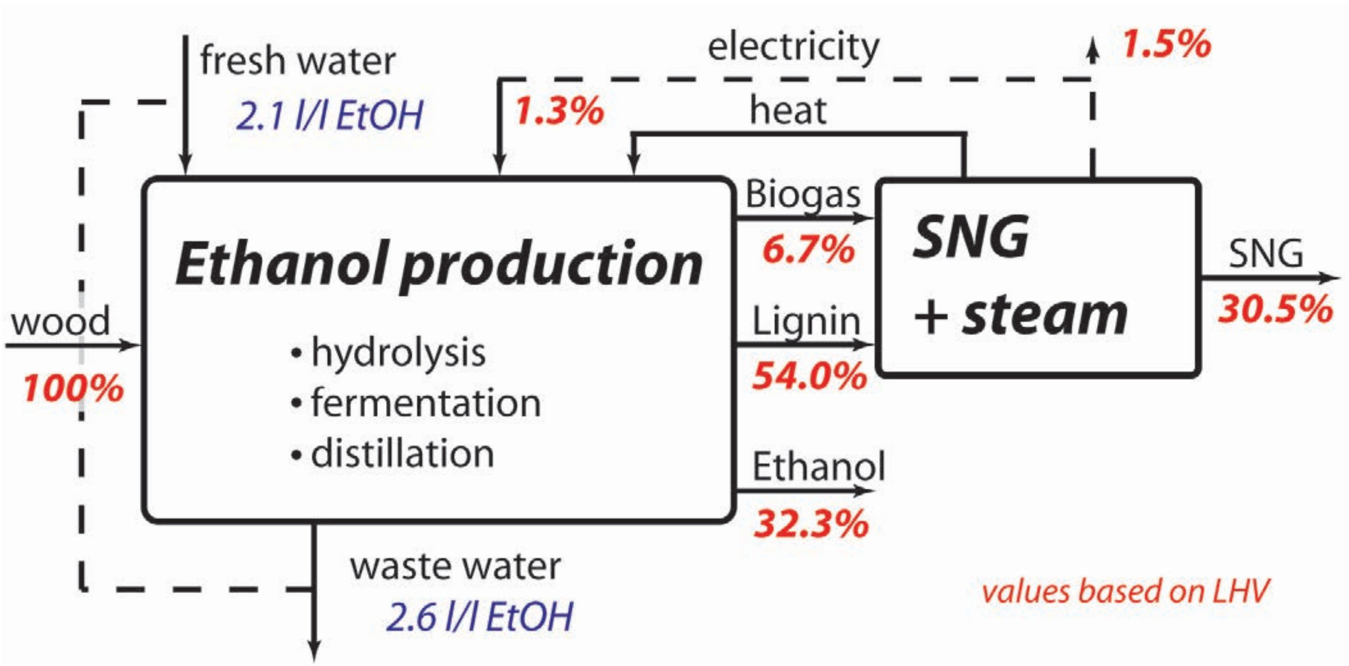
		steam cycle	IGCC	SNG
Input	wood	100 %	100 %	100 %
	ethanol	32.3 %	32.3 %	32.3 %
Output	SNG	-	-	40.3 %
	electricity	17.1 %	21.5 %	-3.0 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %	70.0 %	67.3 %
total efficiency		49.4 %	53.8 %	70.5 %

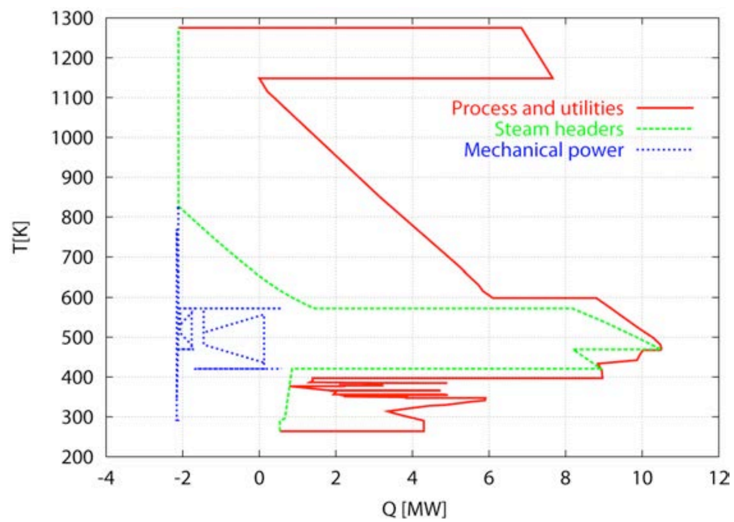
Energy balance for different process integration options (without seed train, non-optimised).

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Site integration: process couplings
EtOH & SNG

Ethanol production from lignocellulosic biomass:





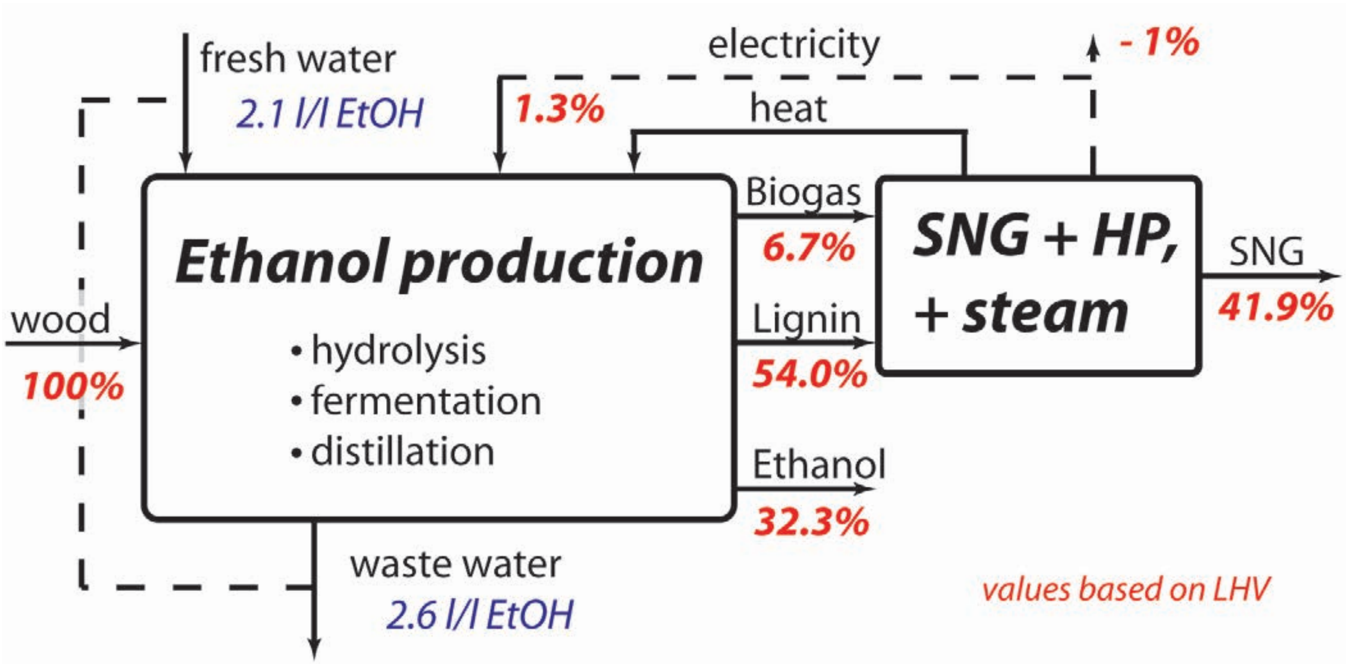
input: $58\ MW_{th,wood}$

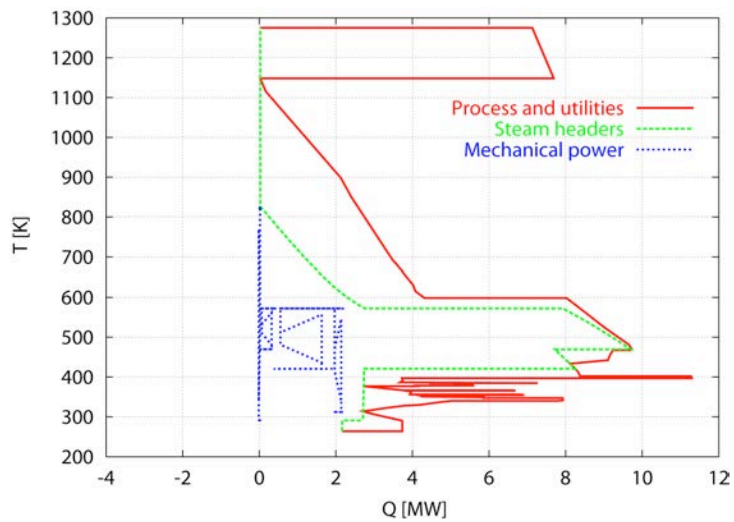
		steam cycle	IGCC	SNG	+ steam
Input	wood	100 %	100 %	100 %	100 %
	ethanol	32.3 %	32.3 %	32.3 %	32.2 %
Output	SNG	-	-	40.3 %	30.5 %
	electricity	17.1 %	21.5 %	-3.0 %	1.5 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %	70.0 %	67.3 %	65.3 %
total efficiency		49.4 %	53.8 %	70.5 %	64.2 %

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

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Ethanol production from lignocellulosic biomass:





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).

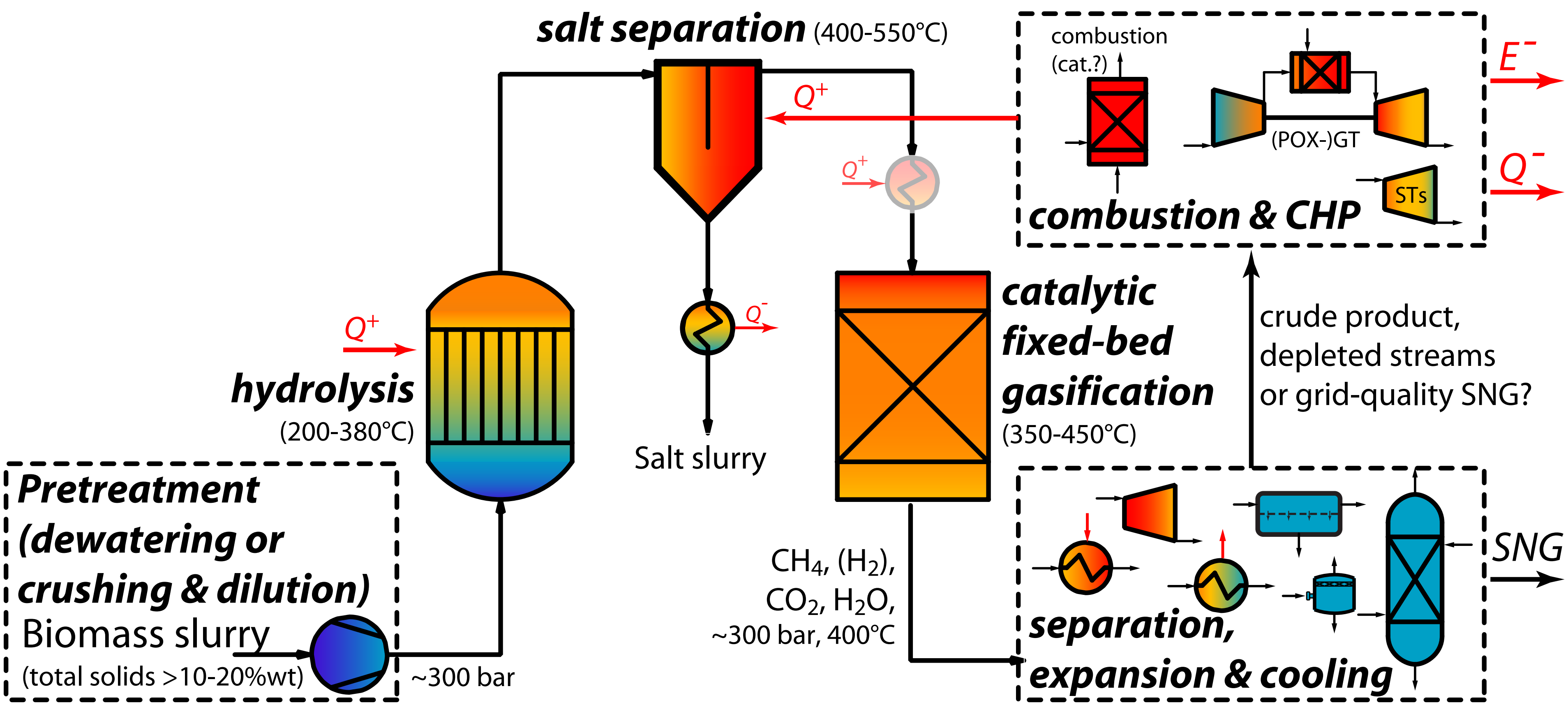
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Motivations

6. Overall System analysis

competing technologies

Hydrothermal supercritical gasification



Martin Gassner, Frederic Vogel, Georges Heyen and Francois Marechal , *Process design of SNG production by hydrothermal gasification of waste biomass: Thermo-economic process modelling and integration,* submitted to Energy & Environmental Science (2010)

Motivations

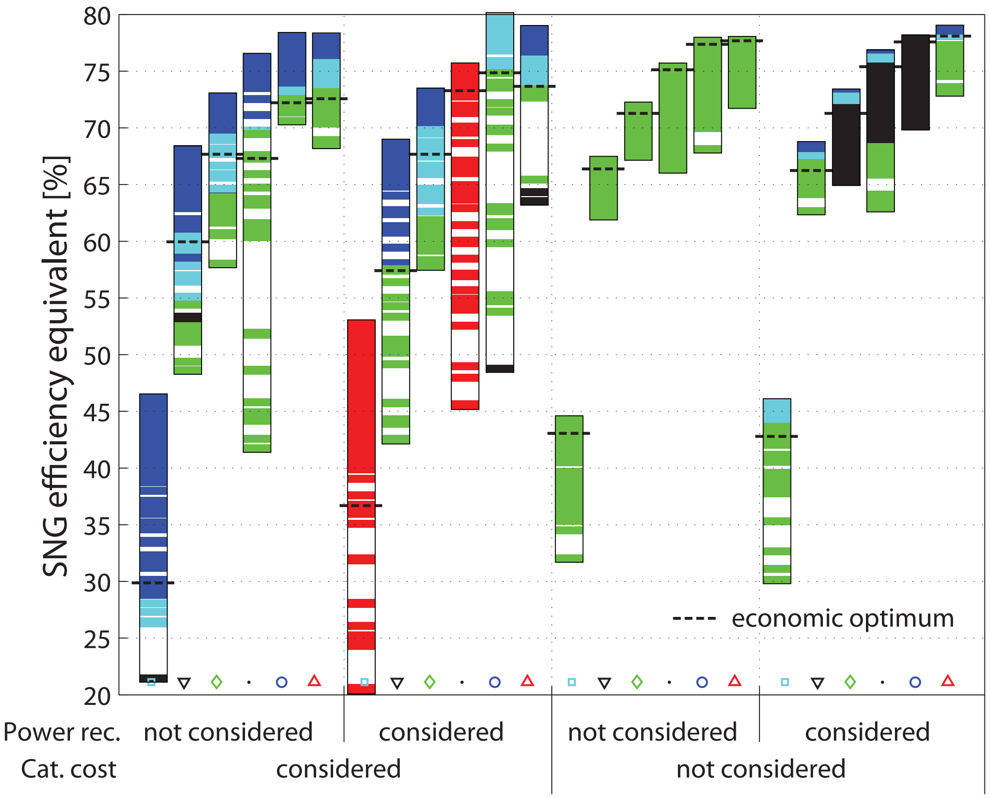
6. Overall System analysis

other feedstocks (waste biomass)

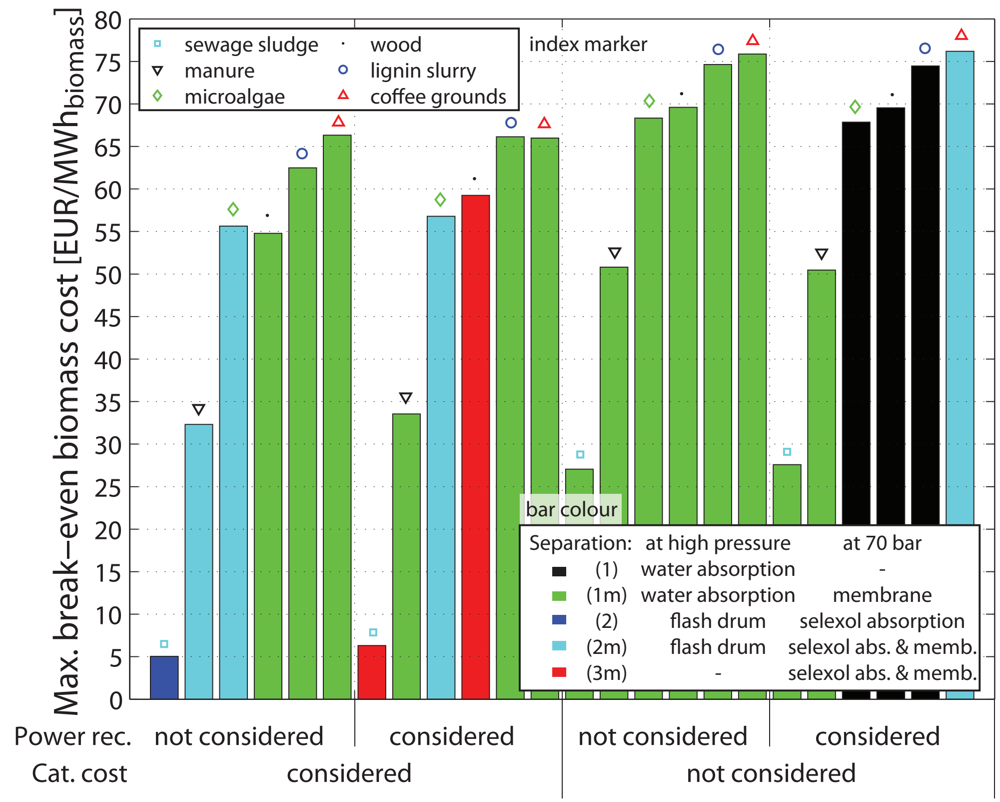
Process optimisation

(2) Thermo-economic performance for different substrates

Optimal plant configurations



evolution on Pareto front



most economic conf. at 20 MW_{th}

Martin Gassner, Frederic Vogel, Georges Heyen and Francois Marechal, *Process design of SNG production by hydrothermal gasification of waste biomass: Process optimisation for selected substrates*, submitted to Energy & Environmental Science (2010)

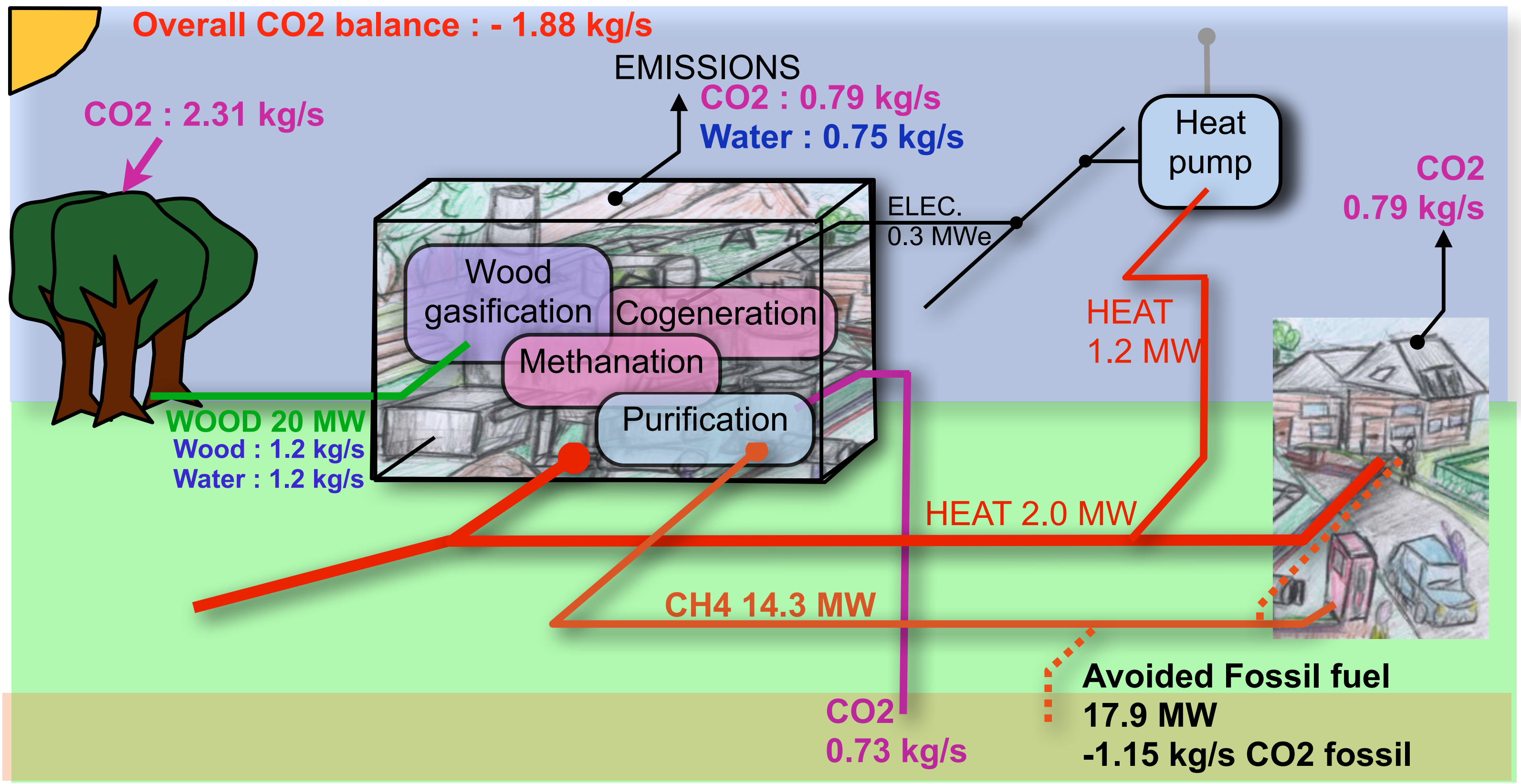
Motivations

6. Overall System analysis

Extending system boundaries

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.



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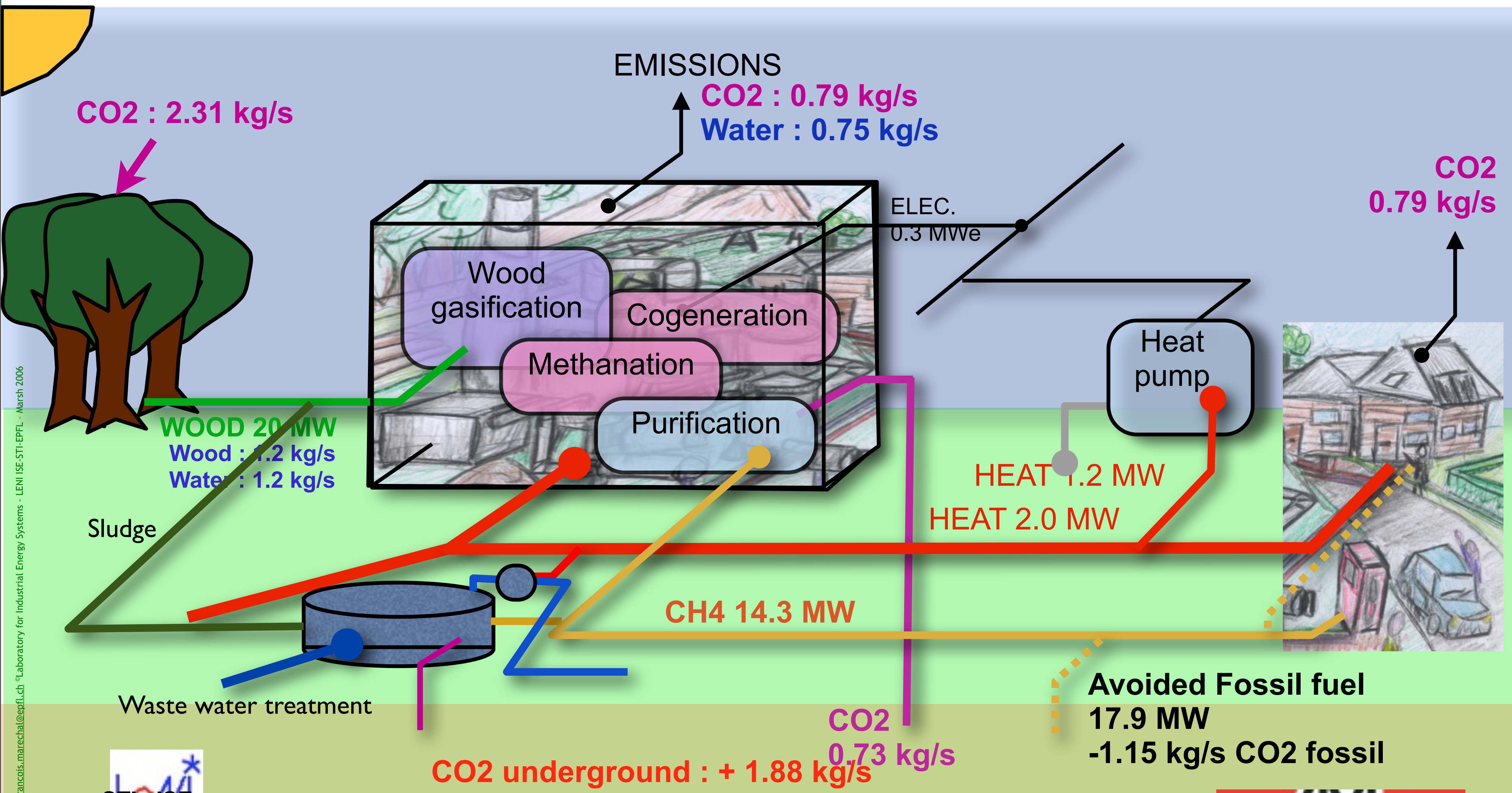
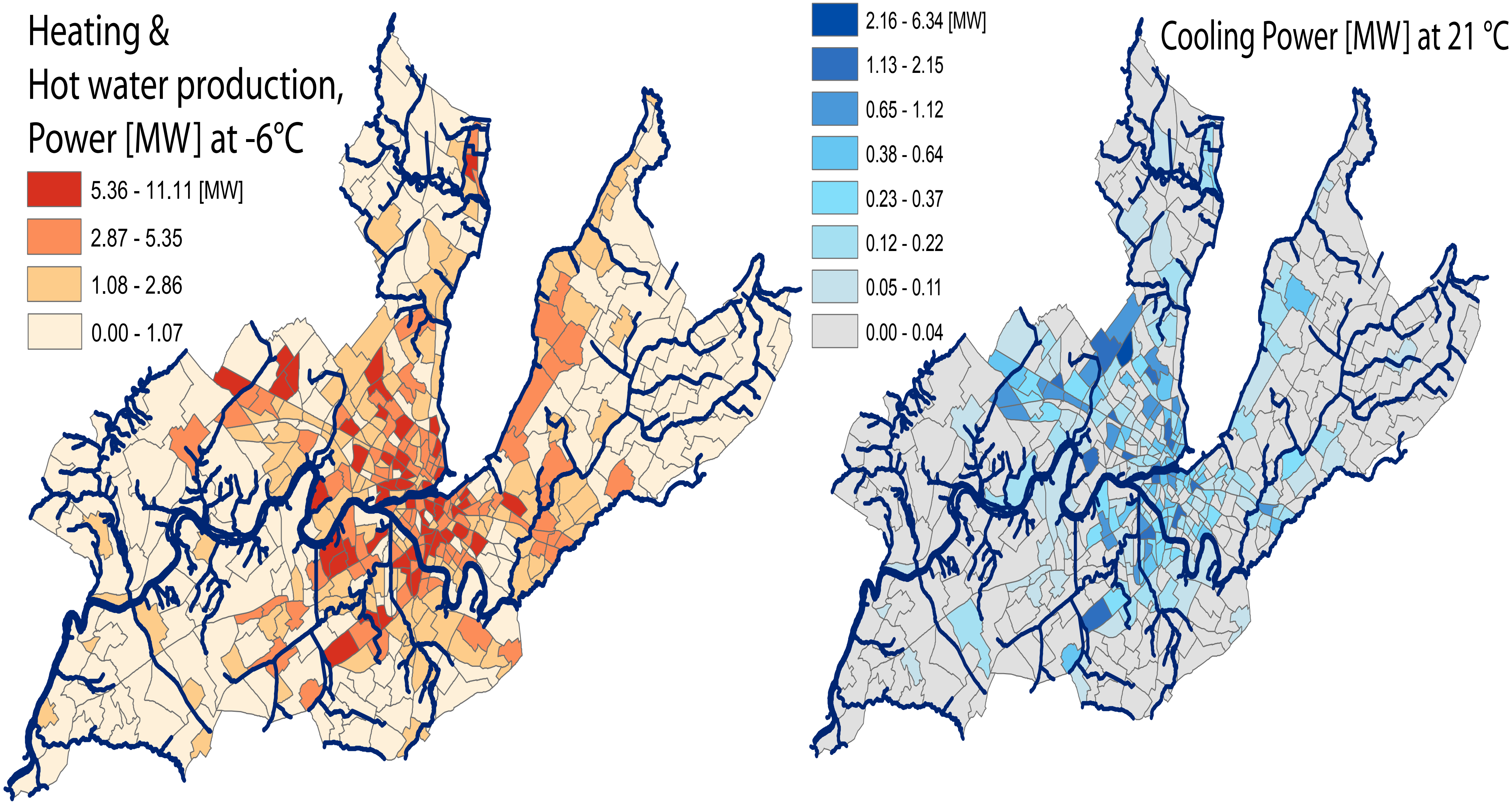
Towards Industrial ecology

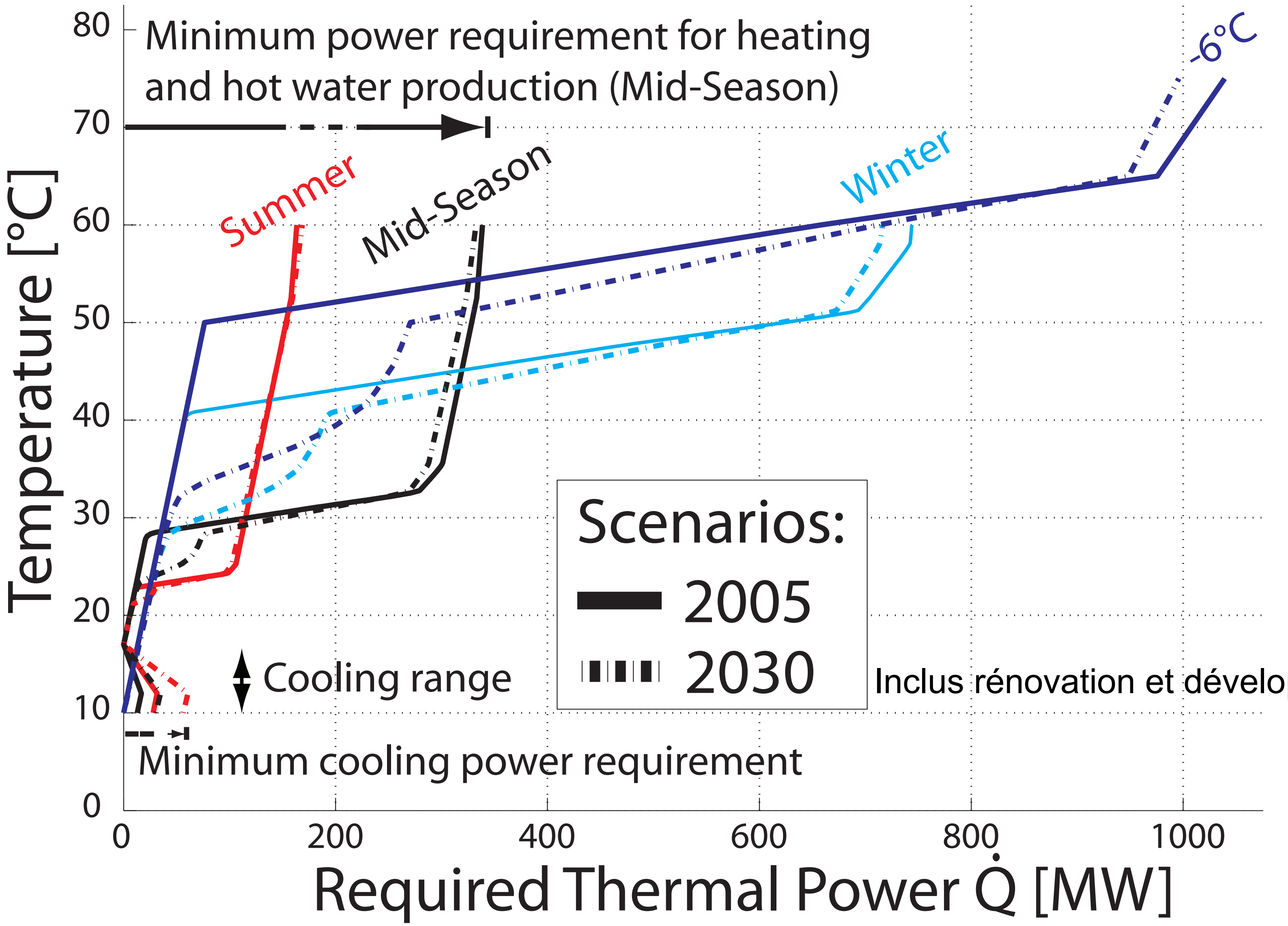


STI ISE LENI

Large scale integration

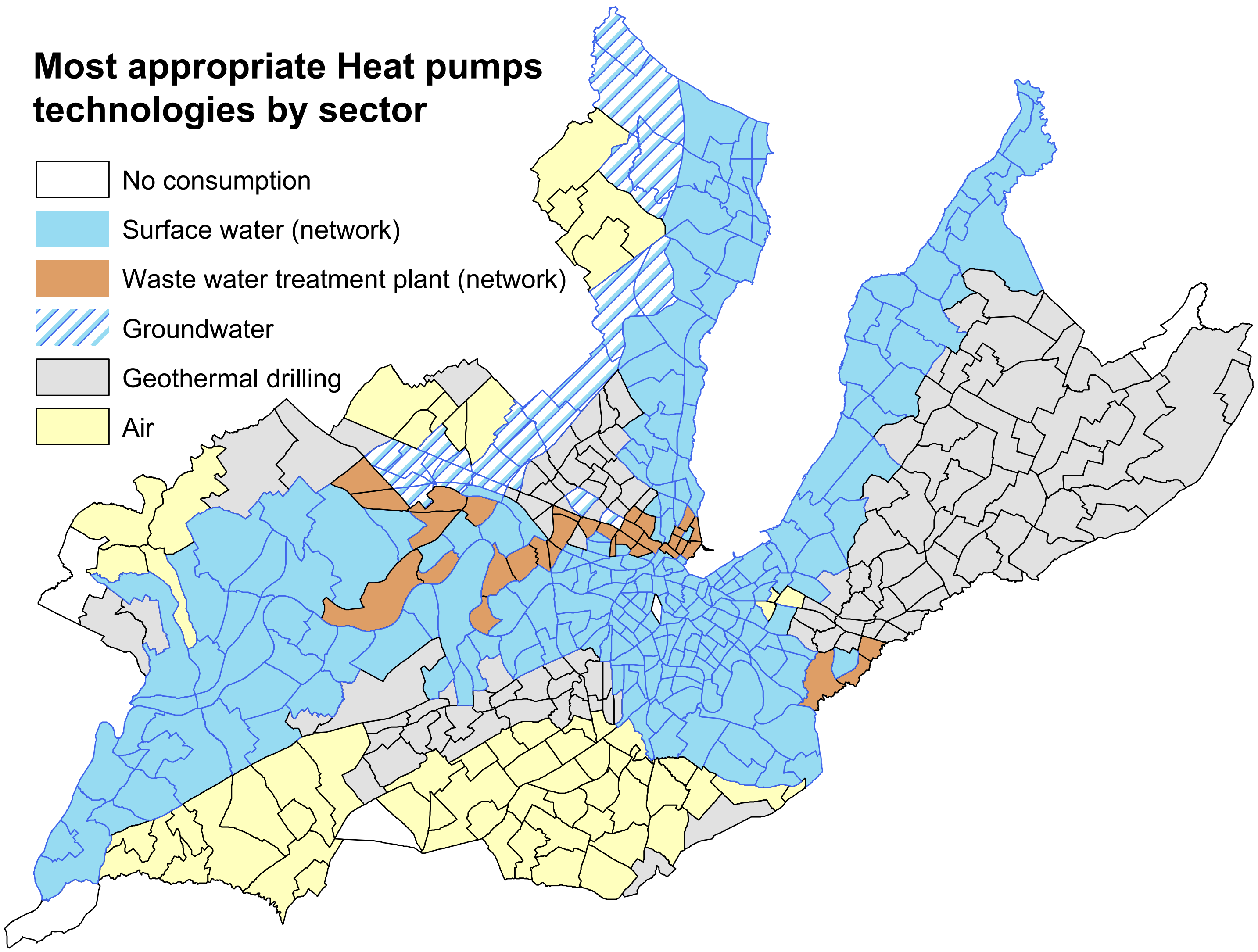


Zone aggregation for district study



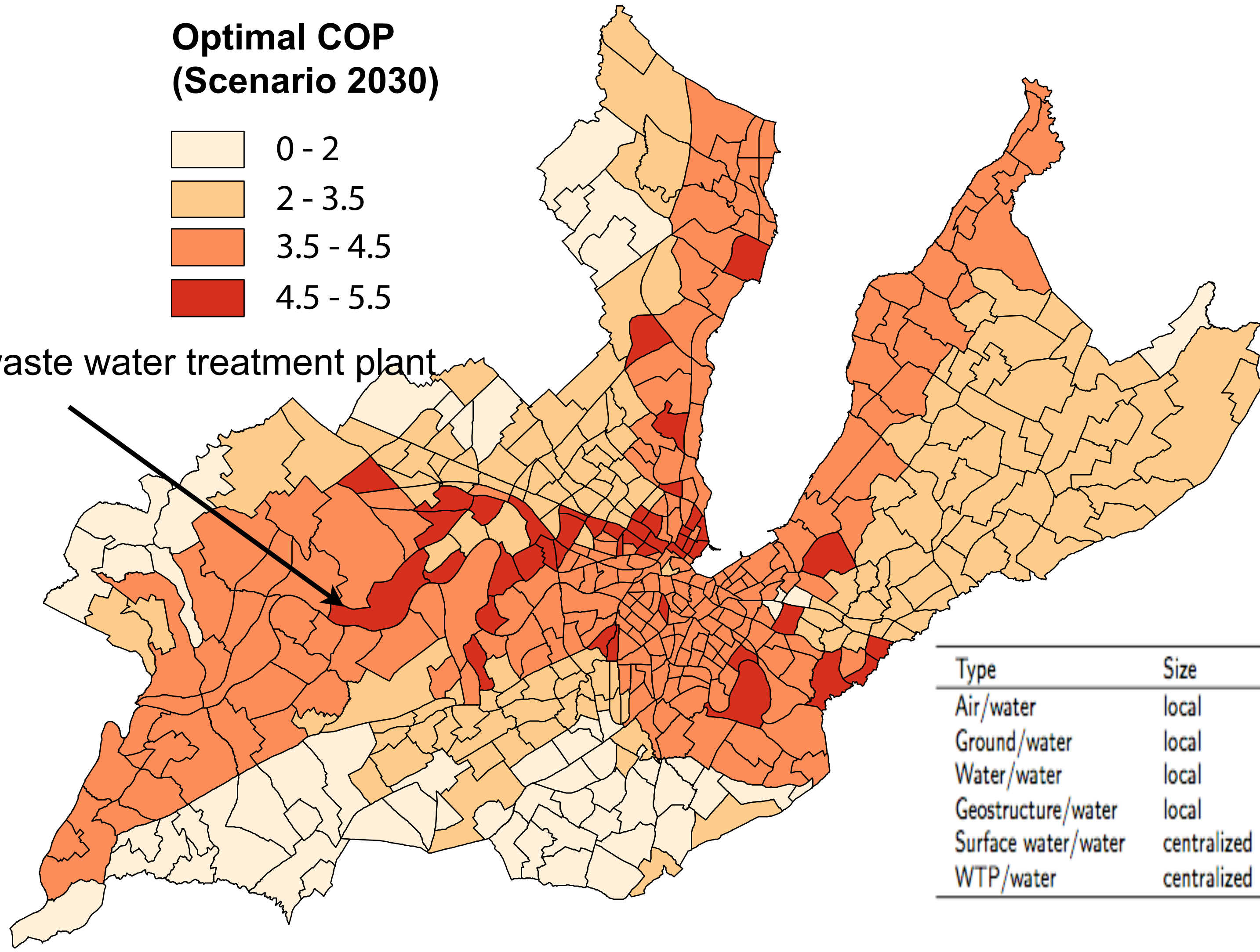
Inclus rénovation et développement zone

Matching with the ressources



Heat pump potential

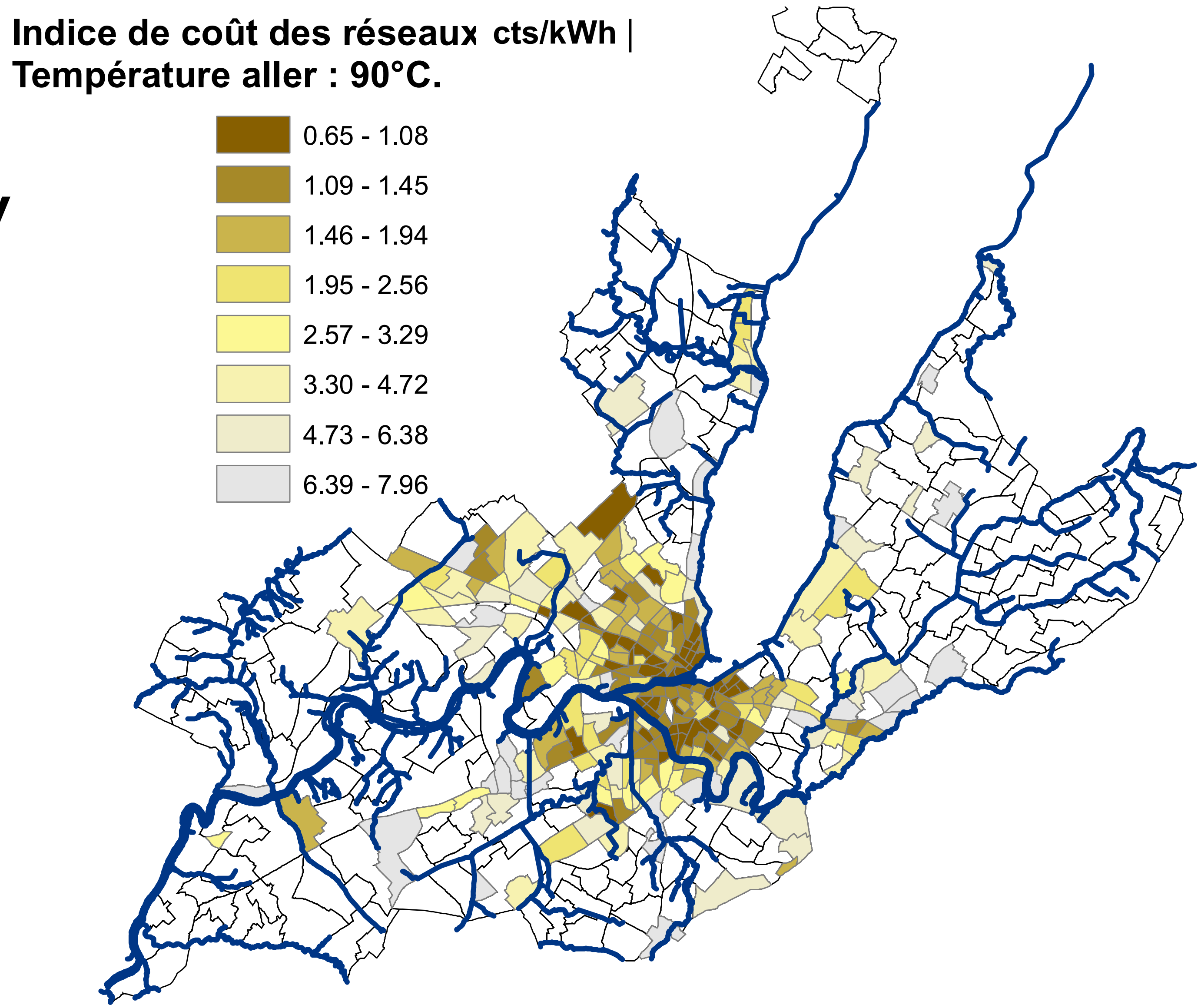
Combining resources/requirements



Type	Size	T_{lm}^{cold}	$\eta_{COP}(2005)$	$\eta_{COP}(2030)$
Air/water	local	$T^{out} - 5$	0.34	0.38
Ground/water	local	2	0.43	0.48
Water/water	local	3	0.43	0.48
Geostructure/water	local	6	0.43	0.48
Surface water/water	centralized	6	0.55	0.60
WTP/water	centralized	12	0.55	0.60

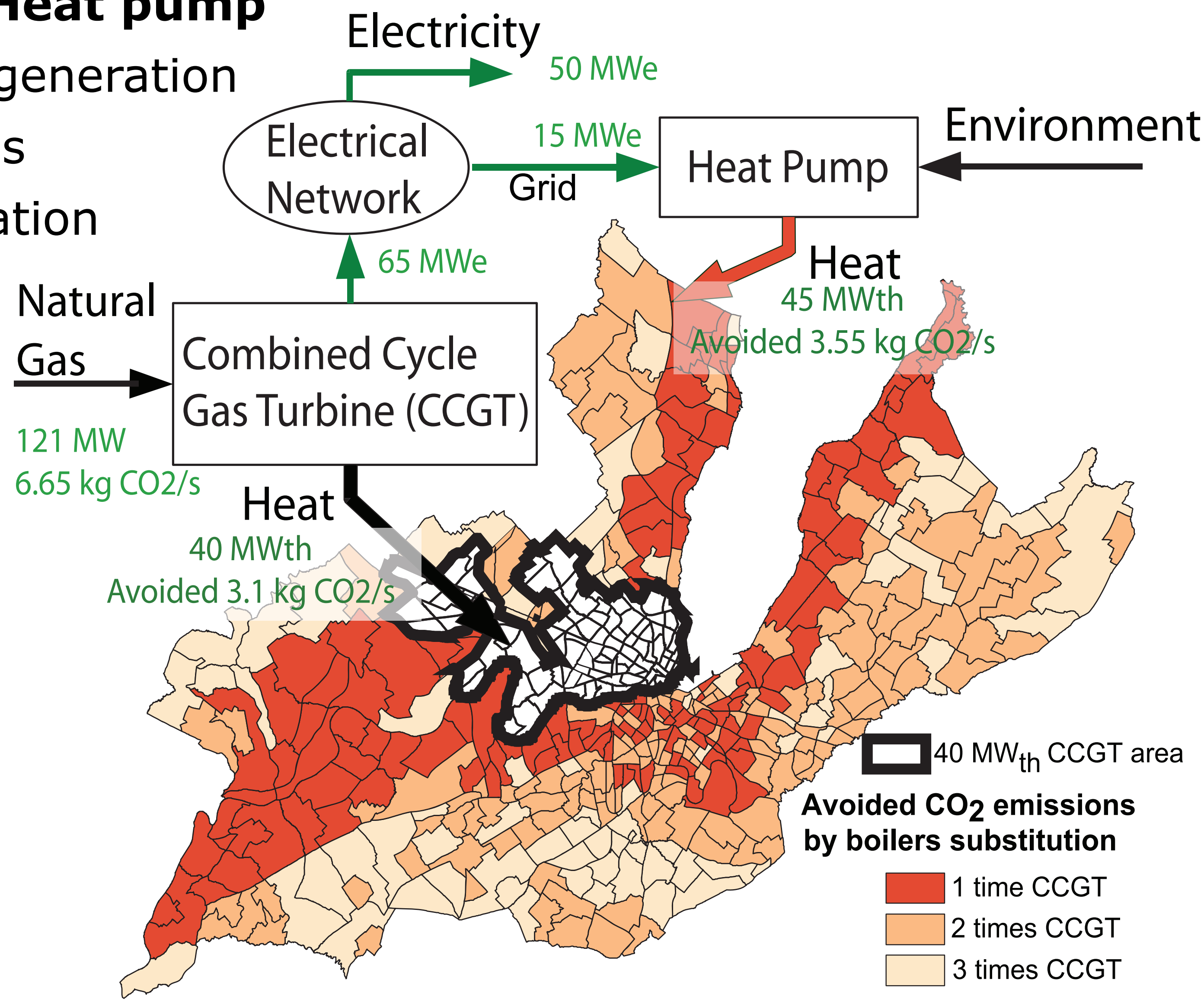
Heat distribution cost : cts/annual kWh

- **Building density**
  - nb + m2
- **Power density**
- **Annual energy**



Integration strategy?

- **CCGT or SNG+ Heat pump**
  - Centralised cogeneration
  - Prioritary zones
  - CO2 compensation



Global integration heat distribution system

Given a set of energy conversion technologies :

- Where to locate the energy conversion technologies ?
- How to connect the buildings ?
- How to operate the energy conversion technologies ?

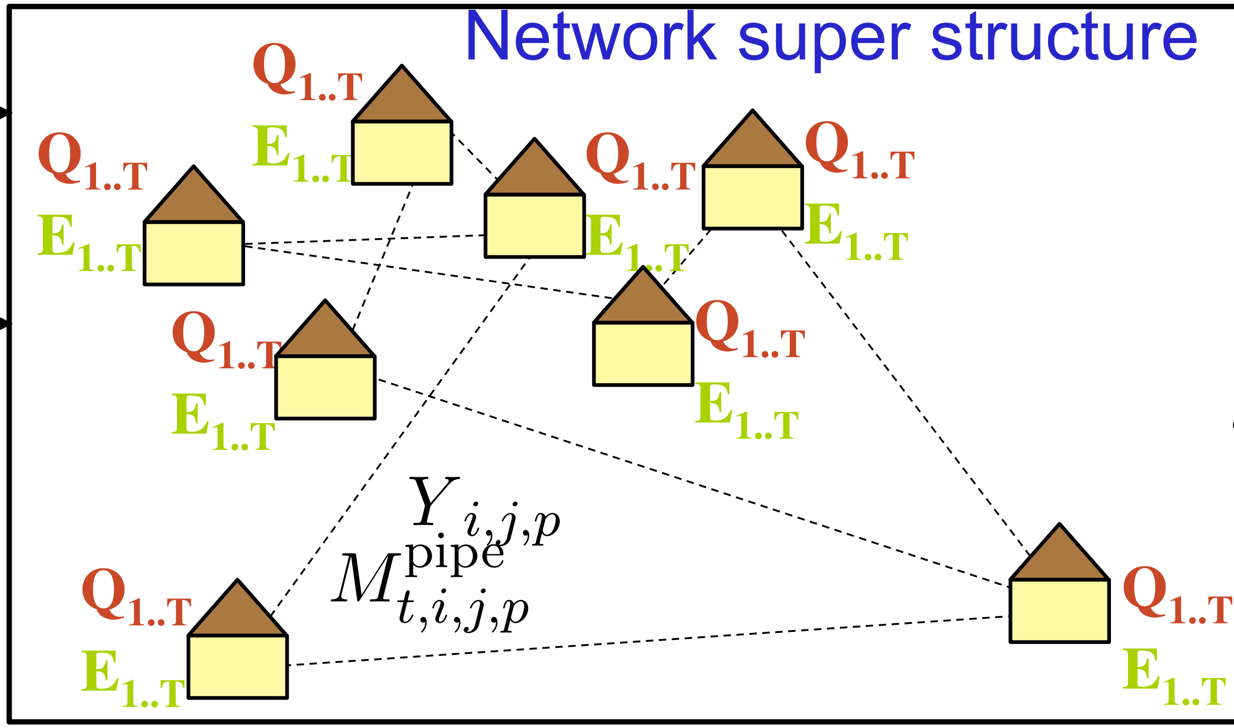
Operating cost

Gas

$$C^{gas} = \sum_{e=1}^{n_e}\sum_{k=1}^{n_k}\sum_{t=1}^{n_p} H_t \frac{Q_{e,k,t}}{\epsilon_e^{th}}$$

Electricity

C^{grid}



Electricity

C^{grid}

Emissions

$CO_2{}^{\text{gas}}$

$CO_2{}^{\text{grid}}$

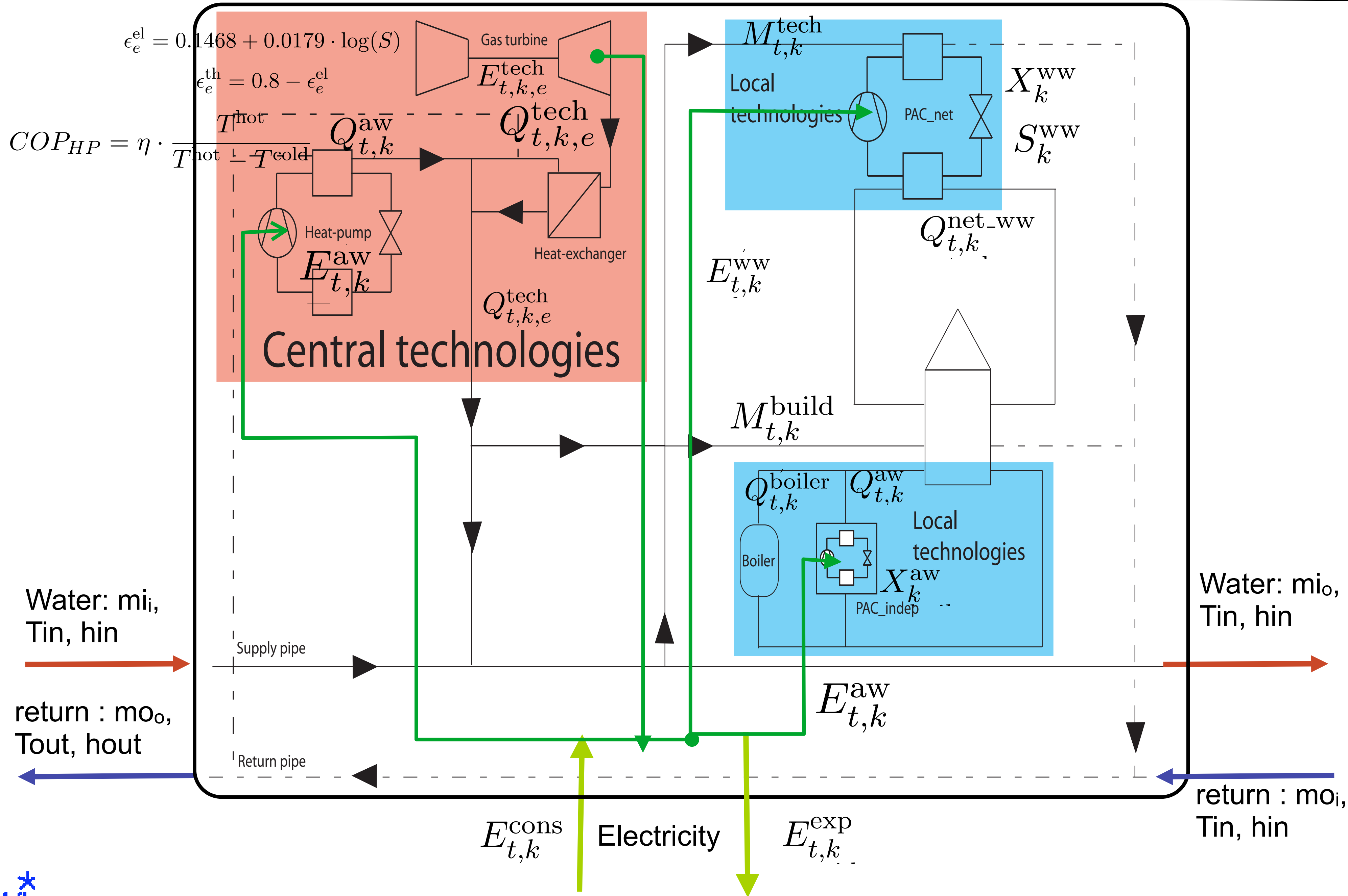
Investment

C^{pipes}

Maintenance

$$C^{inv} = \sum_{e=1}^{n_e}\sum_{k=1}^{n_k} a_e + a_e * S_{e,k}$$

Superstructure & process integration at each node



Thesis C. Weber (2007)

Motivations

7. Computer aided design framework

OSMOSE

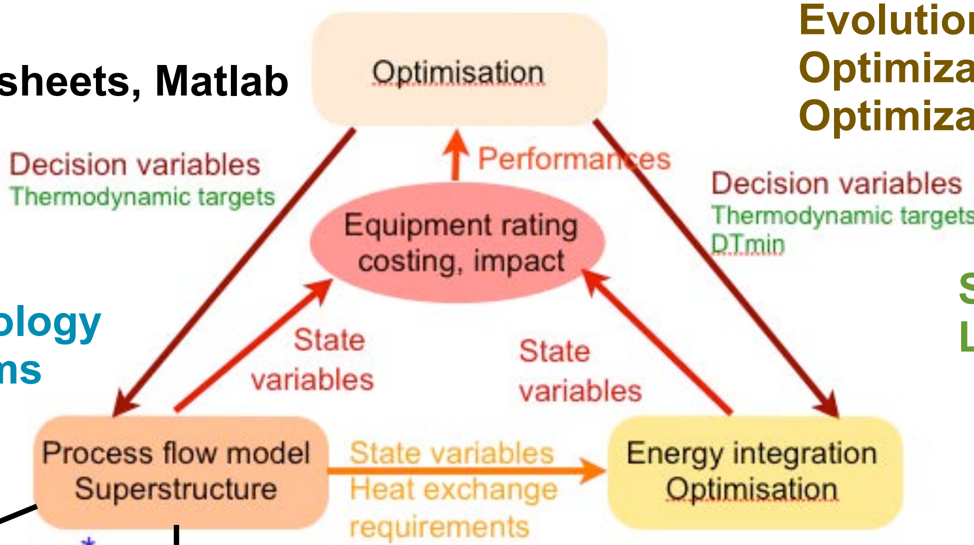
developed by the LENISYSTEM group

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

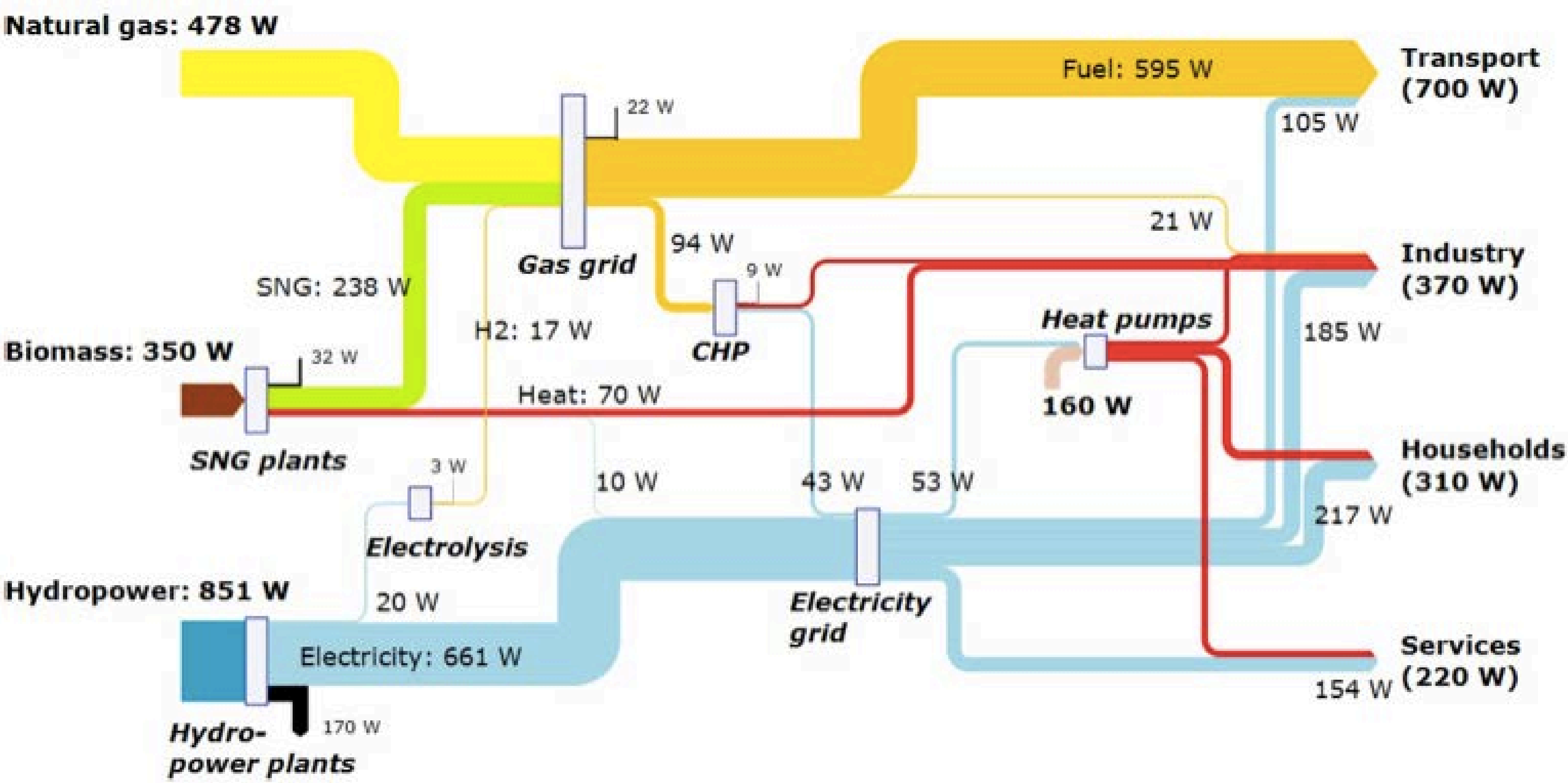
Conclusions

- **Process design methods for sustainable energy 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**

On the way towards the 2000 Watt society

2000 Watt society + 1 tCO2 : YES we can !



francois.marechal@

vendredi, 18 février 2011

More information on http://leni.epfl.ch

Contact : francois.marechal@epfl.ch

Industrial Energy Systems Laboratory

Laboratoire d'énergétique industrielle

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