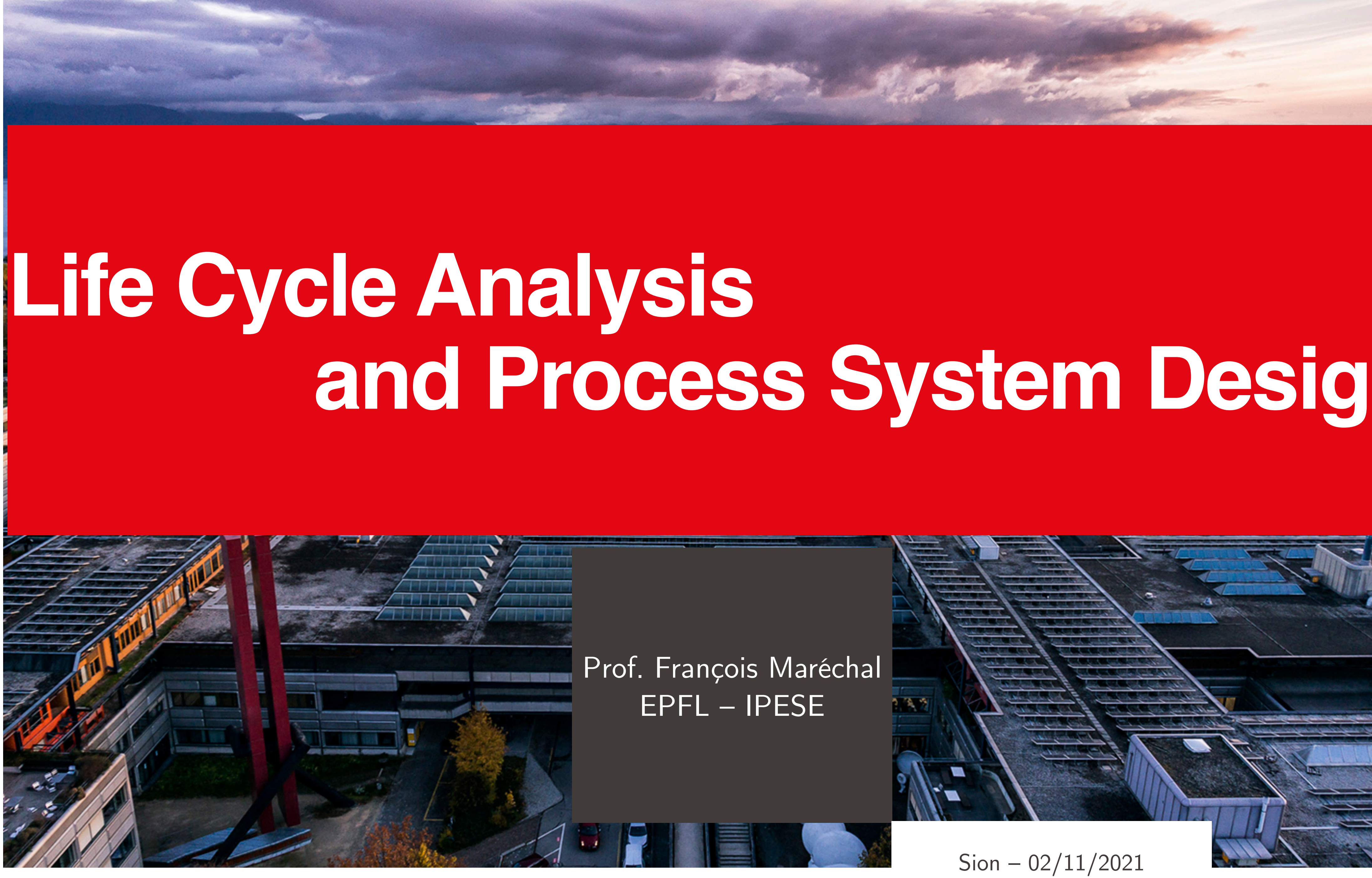


Life Cycle Analysis and Process System Desig

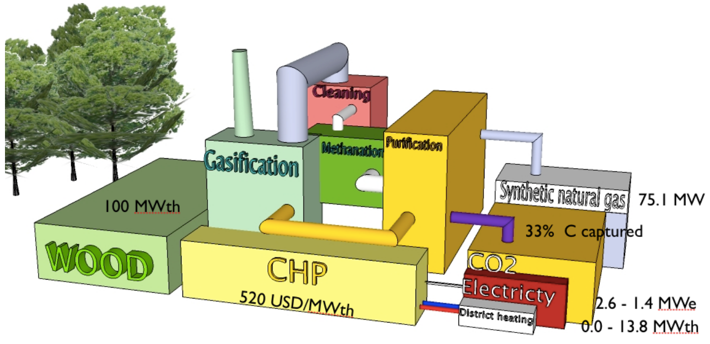
Prof. François Maréchal
EPFL – IPESE

Sion – 02/11/2021

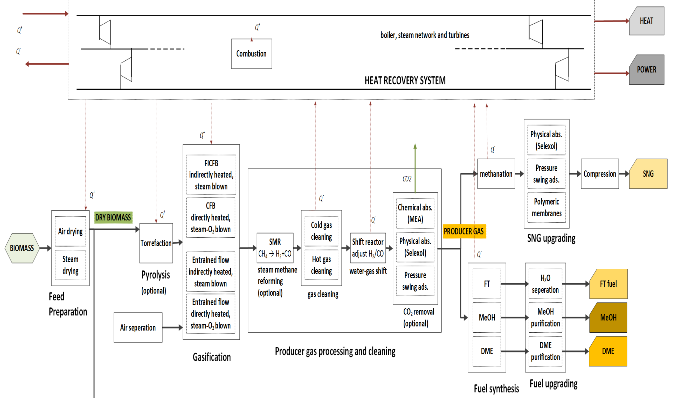
École
polytechnique
fédérale
de Lausanne

Systematic method for process system design options

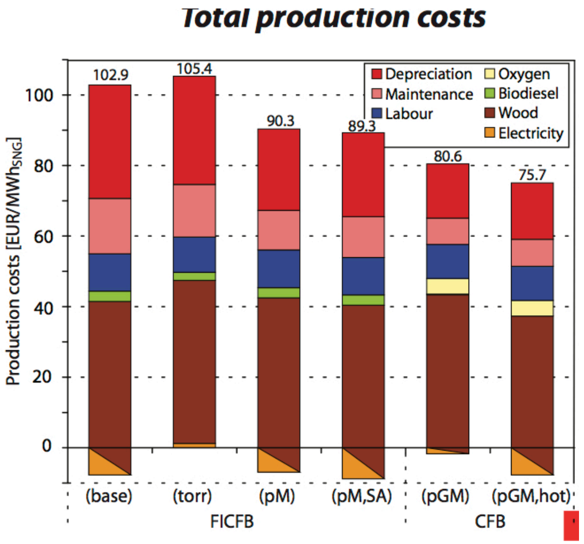
2C(H2O) -> CH4 + CO2

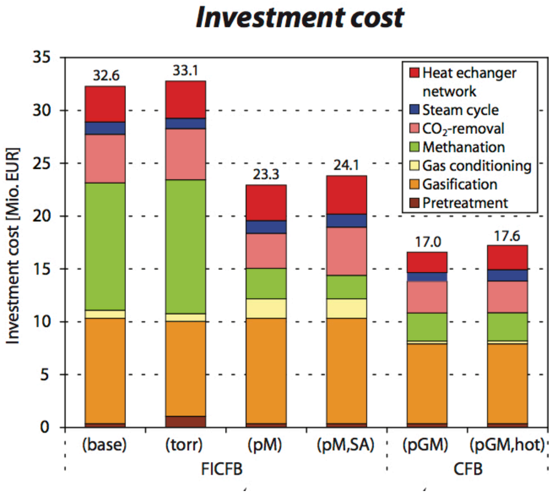


Process superstructure



Comparing options





Systematic generation

Gasification:

FICFB
- ○ air drying
- △ + torrefaction
- × steam drying
- ◇ + torrefaction

pressurised FICFB
- · air drying
- ● air drying, gas turbine
- ▷ steam drying, gas turbine
- ★ + hot gas cleaning

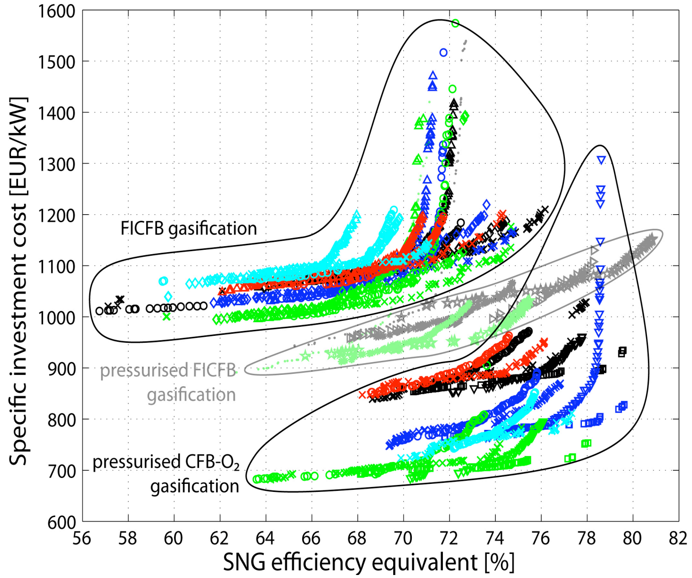
CFB-O_2
- ○ air drying
- ▽ + hot gas cleaning
- × steam drying
- ▫ + hot gas cleaning

Separation:

PSA
- ■ downstream
- 🟥 upstream of methanation

Phys. abs.
- 🟦 downstream
- ■ upstream of methanation

Membranes
- 🟩 downstream of methanation

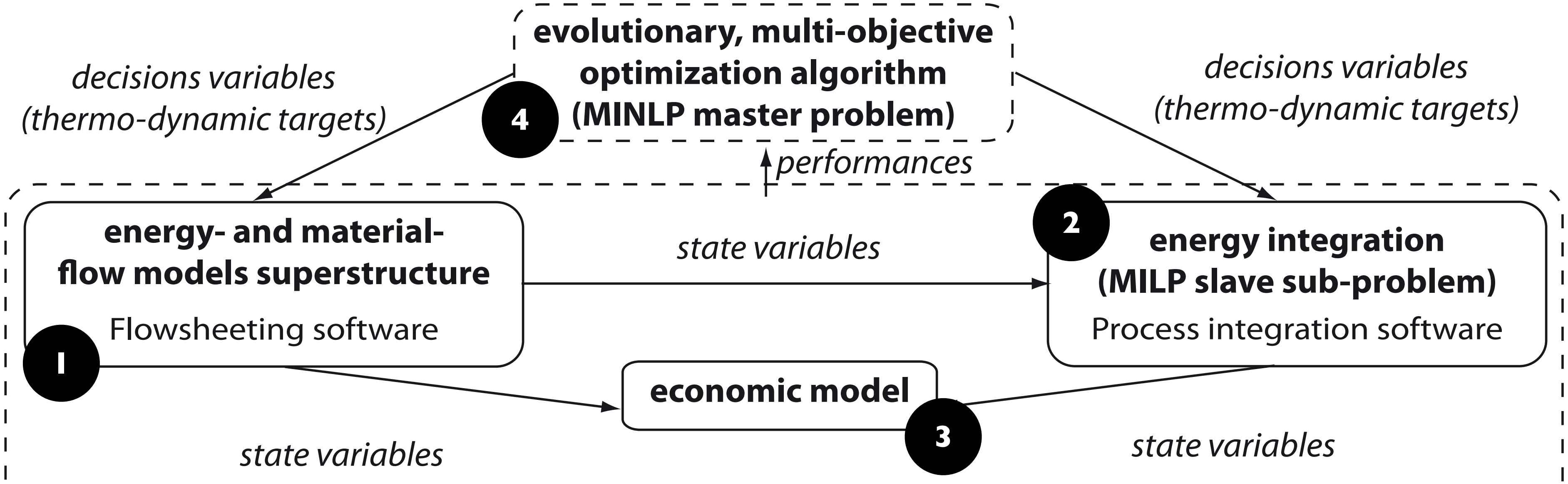


Gassner, Martin, and François Maréchal. *Energy & Environmental Science* 5, no. 2 (2012): 5768 – 5789.

Note : 1.5 years of calculation time !

IPESE
Industrial Process and Energy Systems Engineering

Using optimisation to extract solutions



evolutionary, multi-objective optimization algorithm (MINLP master problem) ④

decisions variables (thermo-dynamic targets)

decisions variables (thermo-dynamic targets)

performances

① **energy- and material-flow models superstructure**
Flowsheeting software

② **energy integration (MILP slave sub-problem)**
Process integration software

state variables

③ **economic model**

state variables

state variables

Gerber, Léda, Martin Gassner, and François Maréchal. "Systematic Integration of LCA in Process Systems Design: Application to Combined Fuel and Electricity Production from Lignocellulosic Biomass." *Computers & Chemical Engineering* 35, no. 7 (December 9, 2010): 1265–1280. http://linkinghub.elsevier.com/retrieve/pii/S0098135410003595.

Thermo-economic optimisation

Trade-offs: efficiency and scale vs. investment

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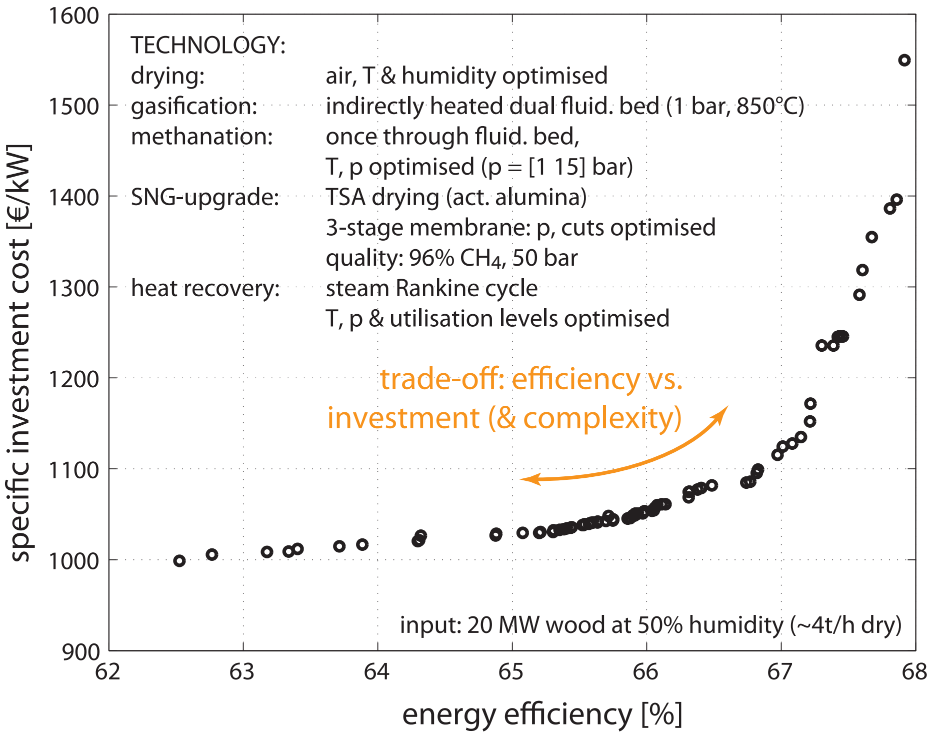
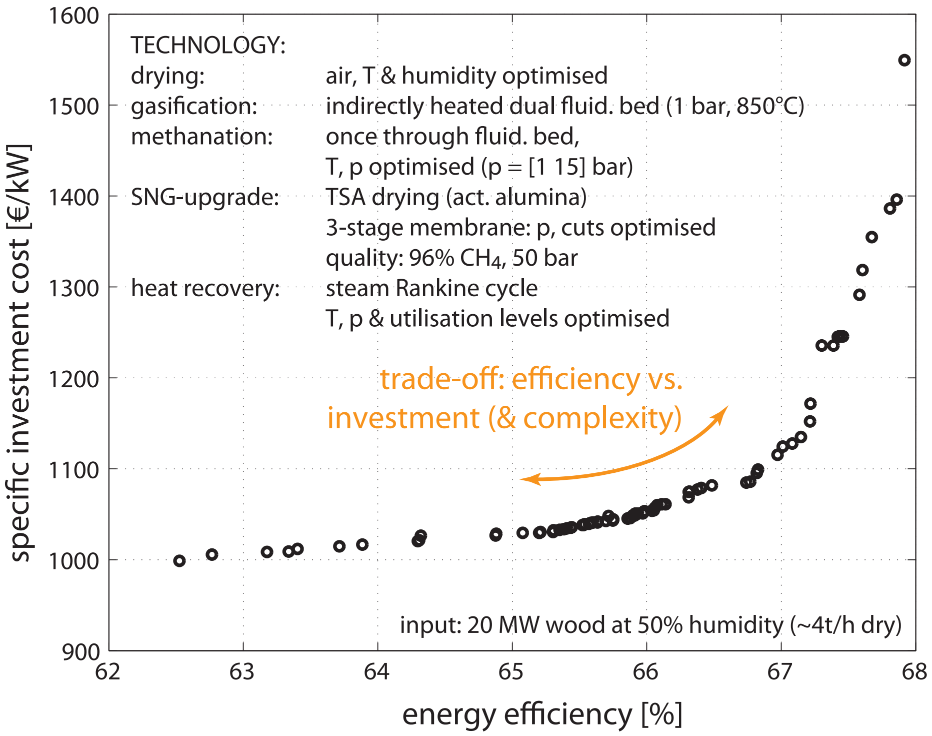
Efficiency vs. investment:



Thermo-economic optimisation

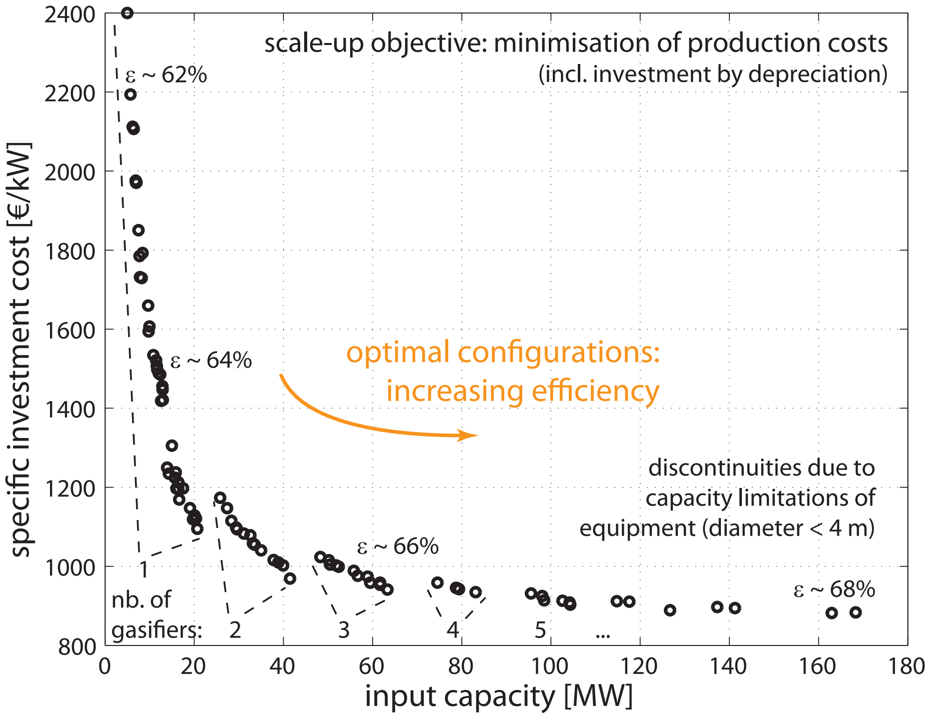
Trade-offs: efficiency and scale vs. investment

Efficiency vs. investment and optimal scale-up:



TECHNOLOGY:

drying:	air, T & humidity optimised
gasification:	indirectly heated dual fluid. bed (1 bar, 850°C)
methanation:	once through fluid. bed, T, p optimised (p = [1 15] bar)
SNG-upgrade:	TSA drying (act. alumina) 3-stage membrane: p, cuts optimised quality: 96% CH_4, 50 bar
heat recovery:	steam Rankine cycle T, p & utilisation levels optimised



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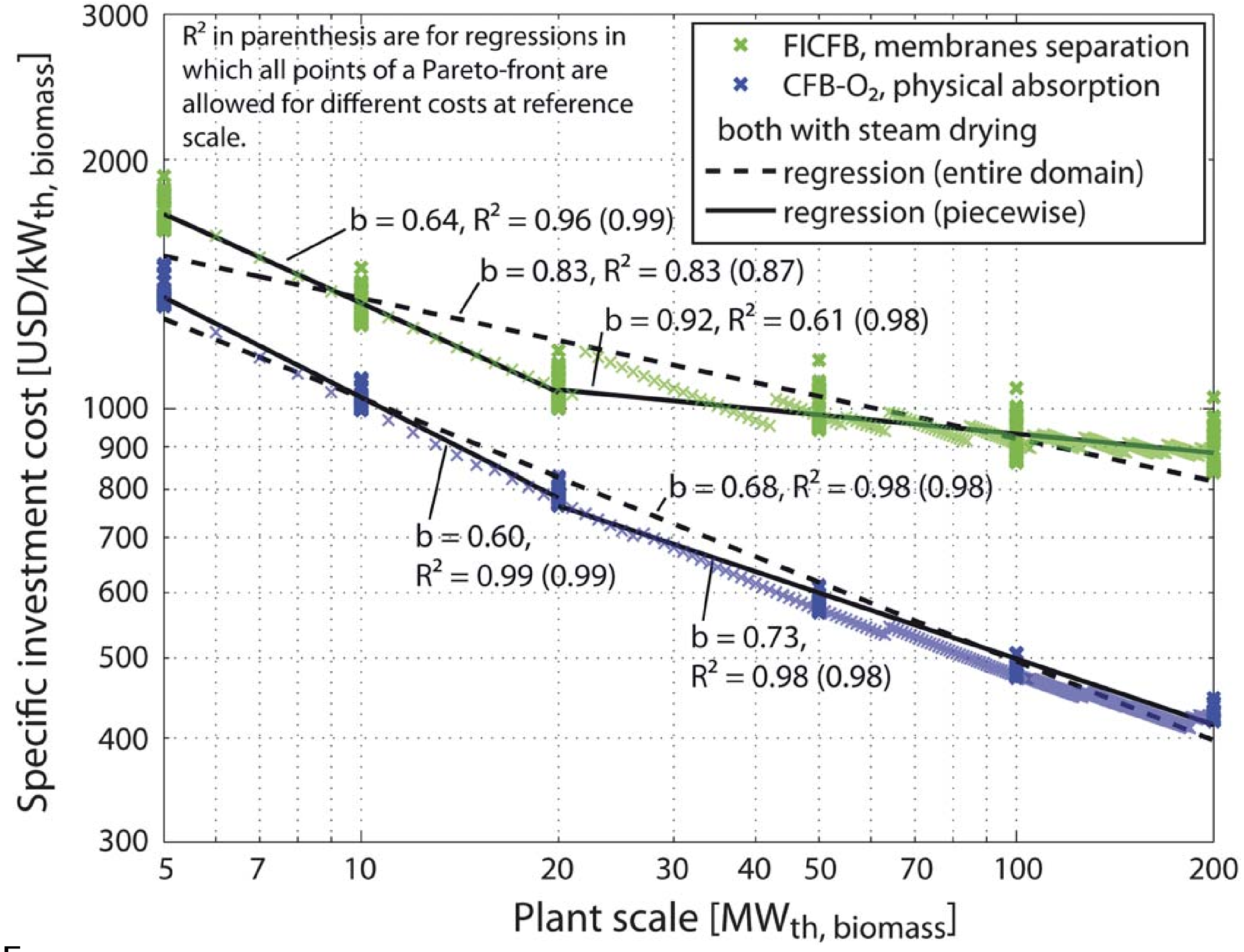
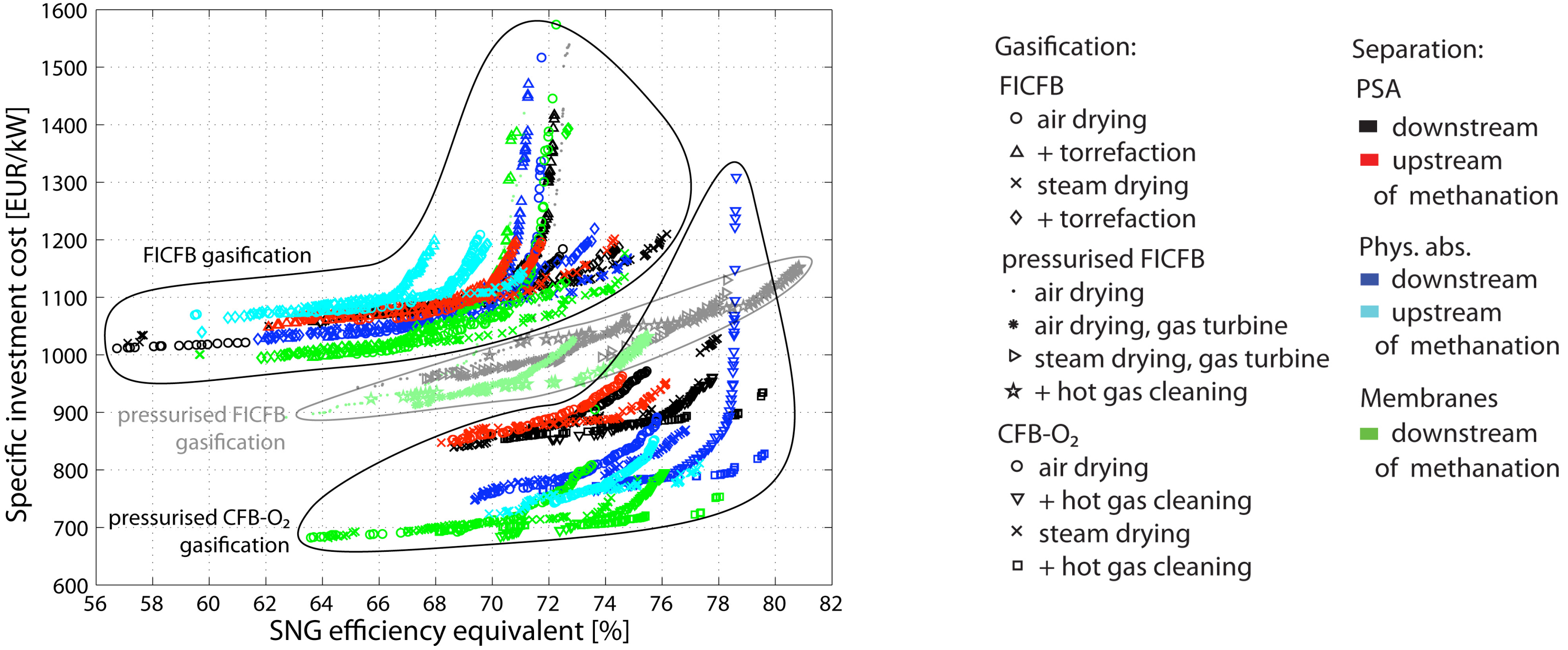
Investment as a function of biomass feed



8. Analysing the results

- Each point of the Pareto is a process design

Thermo-economic Pareto front (cost vs efficiency):



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

Martin Gassner , Ph D Thesis, EPFL, 2010

Plant location

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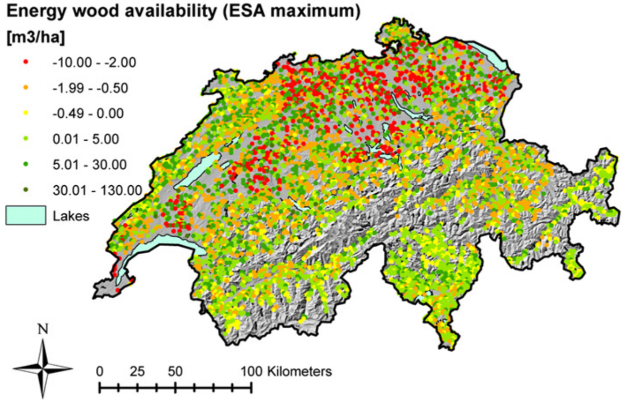
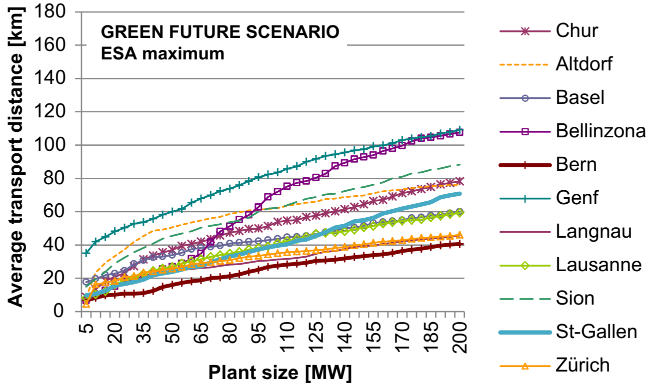
Area = 40 km2

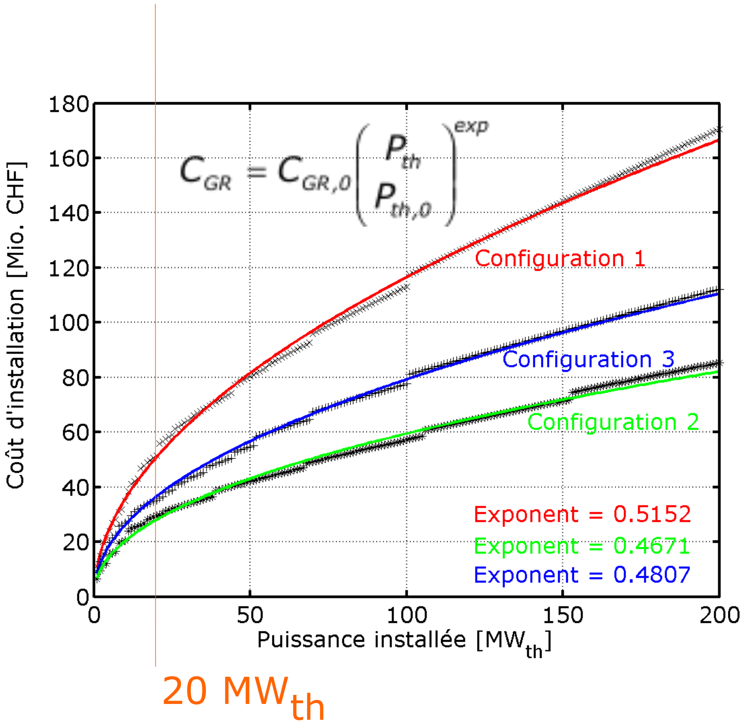


Transport = 10 % of the energy



Process Size => Investment

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

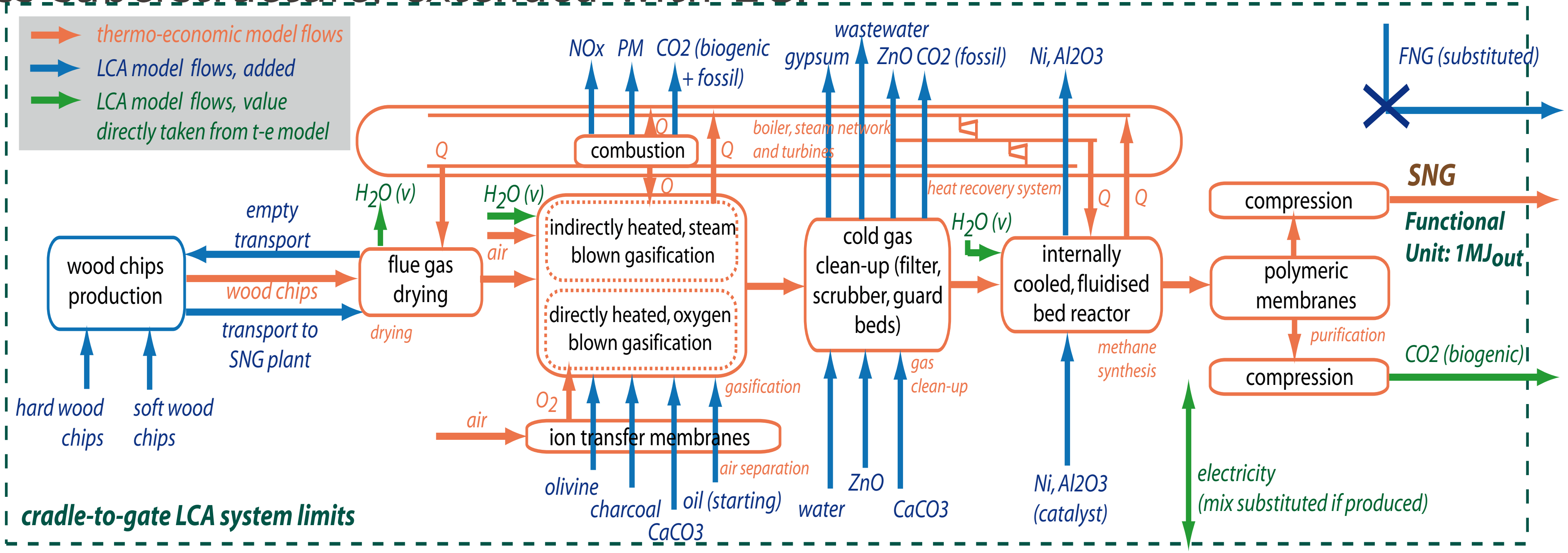


Efficiency : 5000 Wyear/year/ha

Environmental Process performance indicators

Identification of Life Cycle Inventory elements

- Process superstructure, extended with LCI

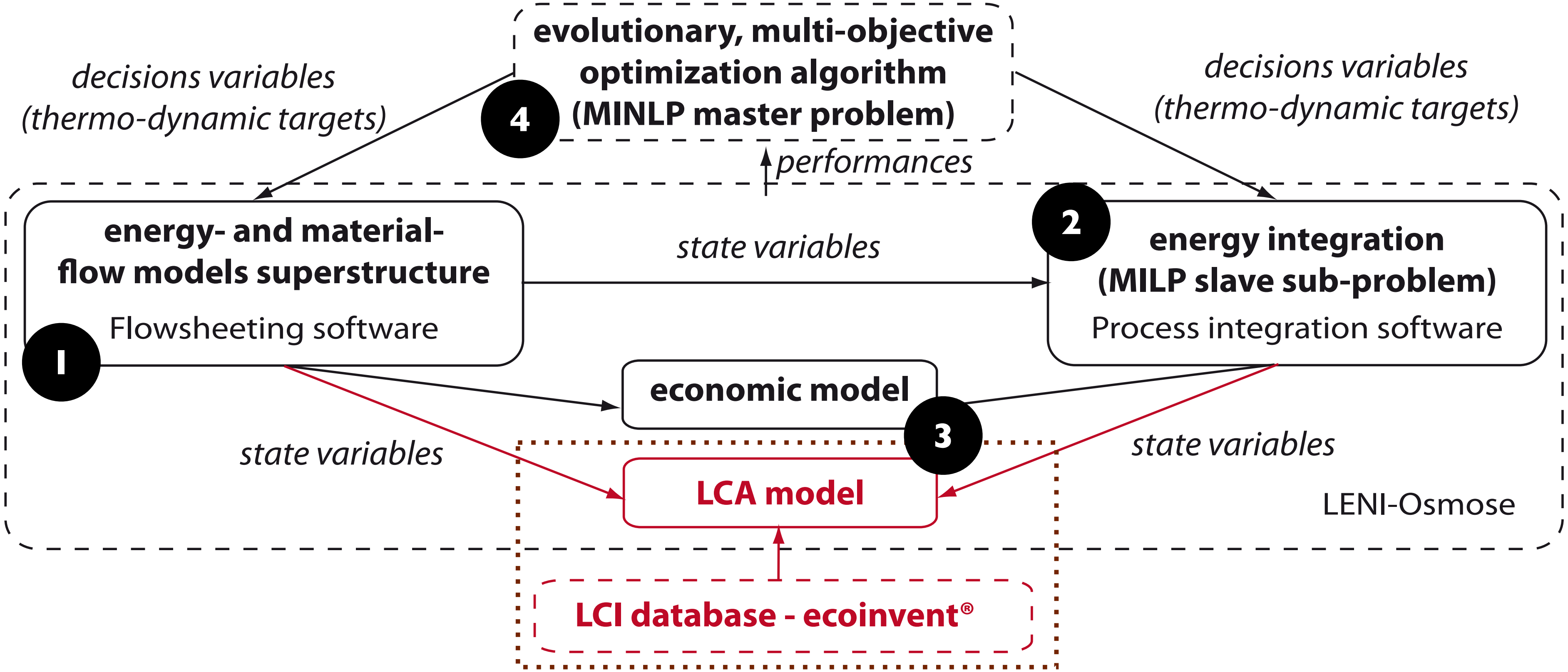


➡ use of ecoinvent emission database (1) for each LCI element, to take into account off-site emissions

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

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

Computational framework



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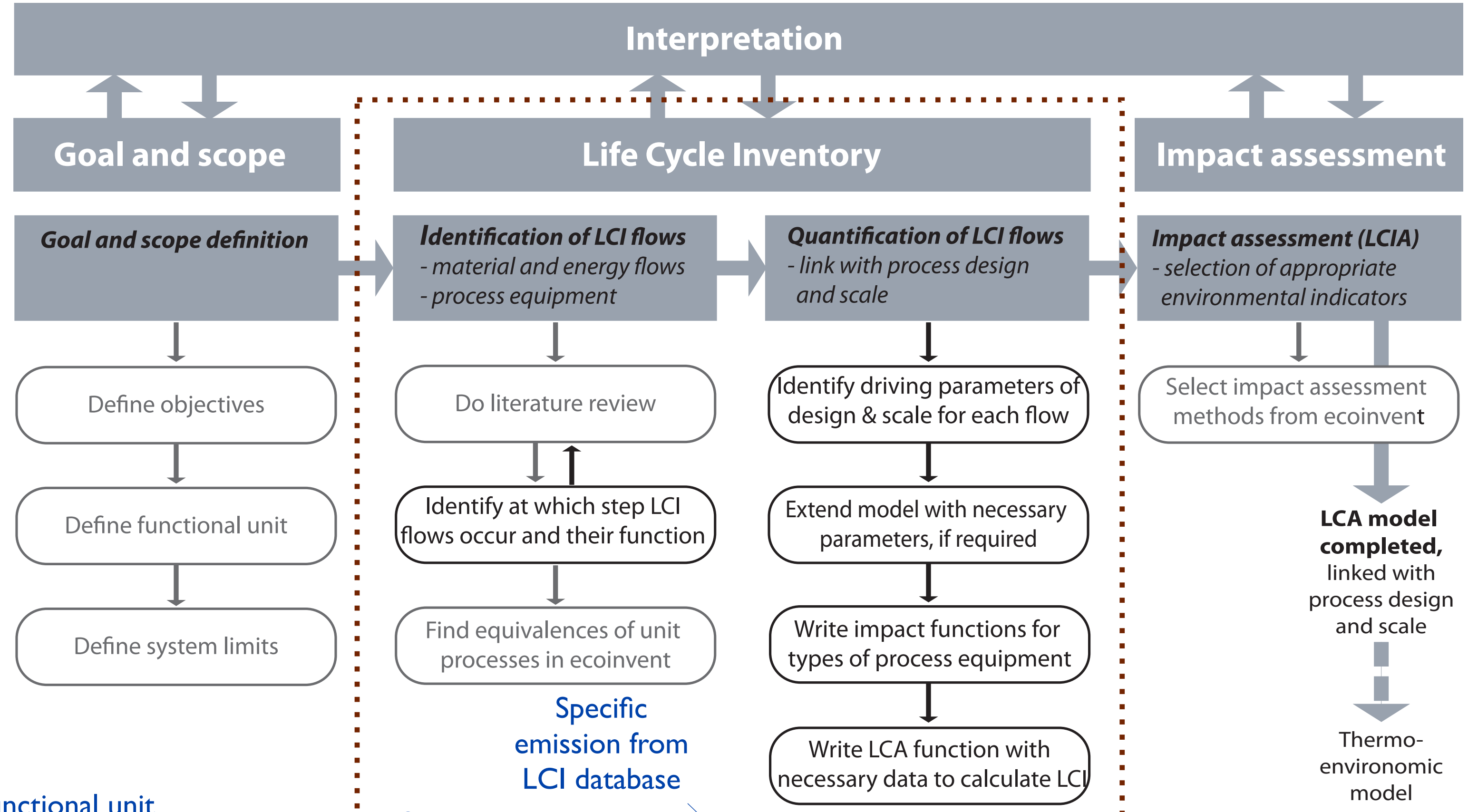
LCA in Osmose

- 3 elements type can be declared in the LCI:

	Components	Unit processes	Elementary flows
Definition	corresponds to a piece of process equipment	contains the cumulated life cycle inventory emissions and extractions	a single emission (or extraction) generated by the model
Database equivalence	in the «components» database, listed in EnergyTechnologies documentation	in the «unit processes» category	in the «elementary flows» category

In multi-model: pay attention to the risk of double-counting (ex: electricity balance) or intermediate flows (ex: logistics)

Guidelines for LCA model



Interpretation

Goal and scope

Goal and scope definition

- Define objectives
- Define functional unit
- Define system limits

Life Cycle Inventory

Identification of LCI flows
- material and energy flows
- process equipment

- Do literature review
- Identify at which step LCI flows occur and their function
- Find equivalences of unit processes in ecoinvent

Quantification of LCI flows
- link with process design and scale

- Identify driving parameters of design & scale for each flow
- Extend model with necessary parameters, if required
- Write impact functions for types of process equipment
- Write LCA function with necessary data to calculate LCI

Impact assessment

Impact assessment (LCIA)
- selection of appropriate environmental indicators

- Select impact assessment methods from ecoinvent

LCA model completed, linked with process design and scale

Thermo-environomic model

Total functional unit quantity

$$FU_{tot} = FU(x_d) \cdot t_{yr} \cdot r$$

Decision variables of optim. problem

Specific emission from LCI database

Scaled emission i of LCI

$$Em_{j,i}^{FU} = \mathbf{em_i} \cdot V_j^{FU}(x_d$$

Quantity of element j of LCI

$$\forall i = 1...n_i : \ Em_i^{FU} = \sum_{j=1}^{n_j} Em_{j,i}^{FU}$$

$$\begin{matrix} \mathbf{F_{1,1}} & ... & \mathbf{F_{1,n_i}} \\ ... & ... & ... \\ \mathbf{F_{n_l,1}} & ... & \mathbf{F_{n_l,n_i}} \end{matrix}] \cdot [\begin{matrix} Em_1^{FU} \\ ... \\ Em_{n_i}^{FU} \end{matrix}] = [\begin{matrix} I_1^{FU} \\ ... \\ I_{n_l}^{FU} \end{matrix}$$

LCI scaling of process equipment

- Analogy with economies of scale for equipment investment estimation

Scaled emission of element j of LCI

Functional parameter of element j

Impact exponent

Correction factor if necessary

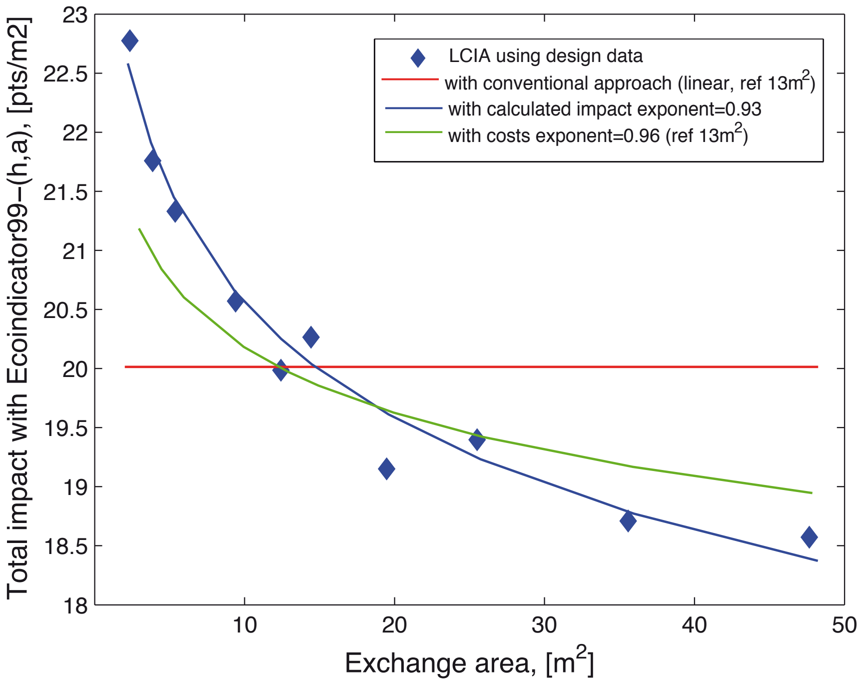
$$\frac{Em_{j,i}}{\mathbf{Em_{j,ref,i}}} = n \cdot \left(\frac{A_j(x_d)}{n \cdot \mathbf{A_{j,ref}}}\right)^{\mathbf{k_{j,i}}} \cdot \mathbf{c_j}, A_j \in [A_{j,min}; A_{j,max}$$

$$n = [int(\frac{A_j}{\mathbf{A_{j,max}}}) + 1$$

Reference emission of element j

Decision variables of MOO problem

- Example of heat exchanger
  - shell and tube heat exchanger
  - functional parameter: exchange area, in m²



LCI scaling of process flowsheet and auxiliary flows

- Process flowsheet

Quantity directly calculated
by the process flowsheet,
varies as a function of d.v. of MOO problem

$$V_j^{FU} = \frac{V_j(x_d) \cdot t_{yr} \cdot r_c}{FU_{tot}(x_d)}$$

- Example: quantity of RME for scrubbing at gas cleaning
  - *volumetric flow rate from gasification...*
  - *... gasification pressure (d.v.)*

- Auxiliary flows
  - No systematic formulation but in general:

$$V_j^{FU} \sim V_{j,init}(x_d), \dot{\alpha}_j, t_{yr}, r_c$$

Initial quantity

Turnover

- Example: auxiliary flows for reactors (olivine, charcoal, ...)

$$\dot{m}_{j,reac} = V_{reac}(x_d) \cdot \dot{v}_{j,reac}$$

reactor volume, scaled
non-linearly

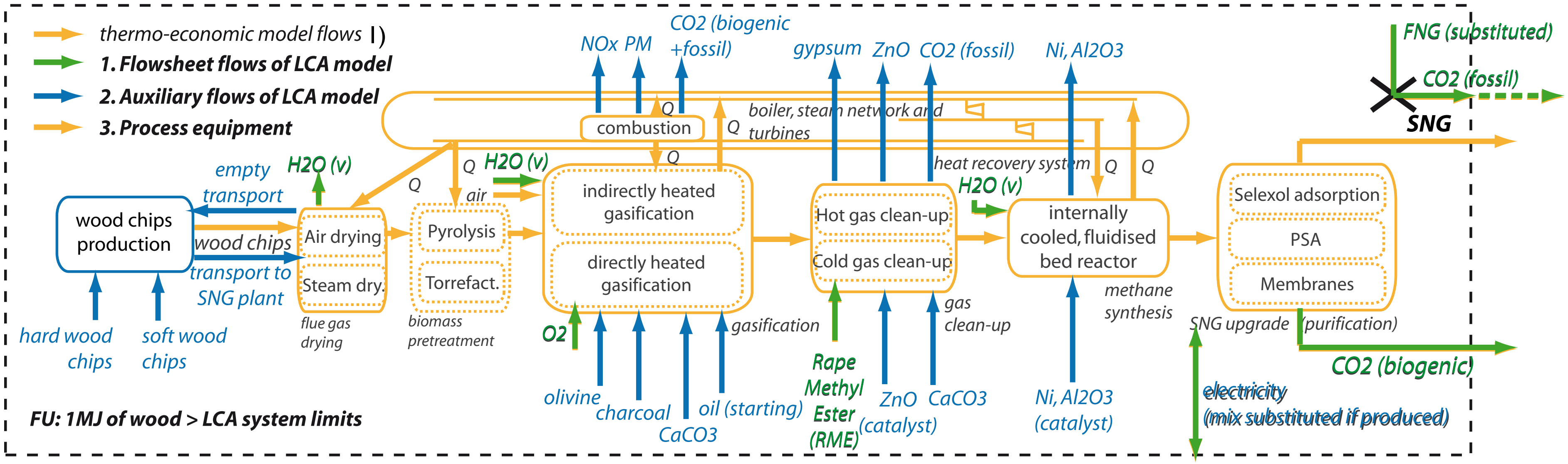
specific mass
consumption rate of
material per unit volume

- *Method better than conventional LCA?*

Multi-objective optimisation

- Residual wood for combined Synthetic Natural Gas (SNG) and electricity production:

functional unit is the wood processed at plant entry



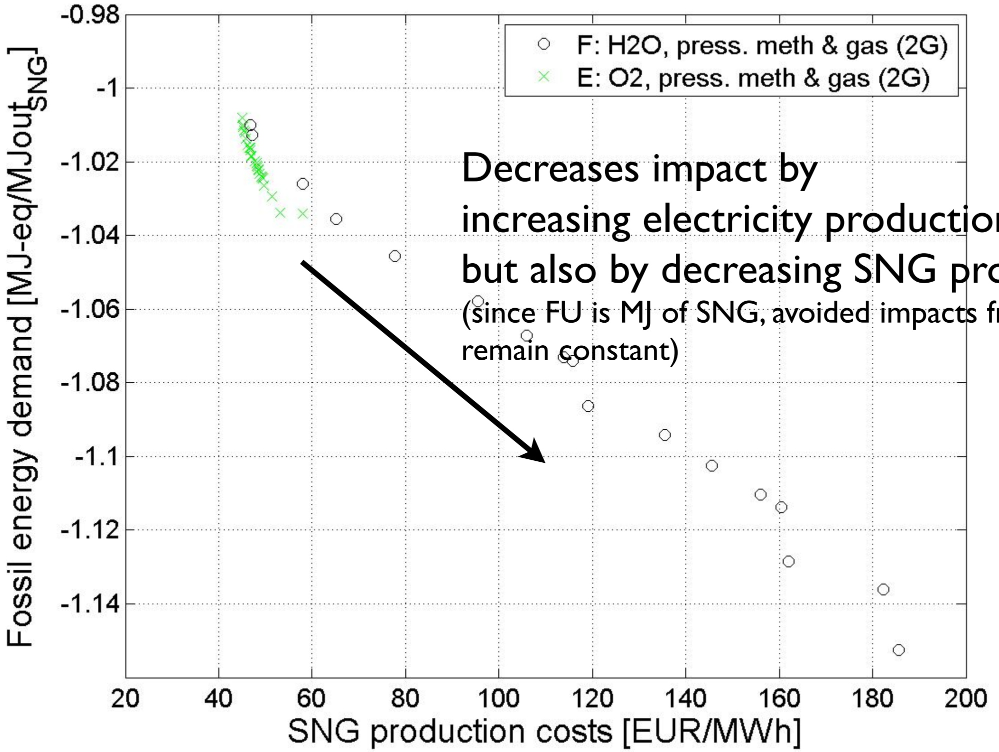
Objectives

- Wood processing benefit
- Environmental impact
- Size of the plant

1) M. Gassner, 2010, *Process design methodology for thermochemical production of fuels from biomass. Application to the production of synthetic natural gas from lignocellulosic resources.* PhD thesis, EPFL

LCI: a few traps to avoid

- Definition of system function and thus FU
  - Example: for SNG production, FU taken was first the MJ of SNG



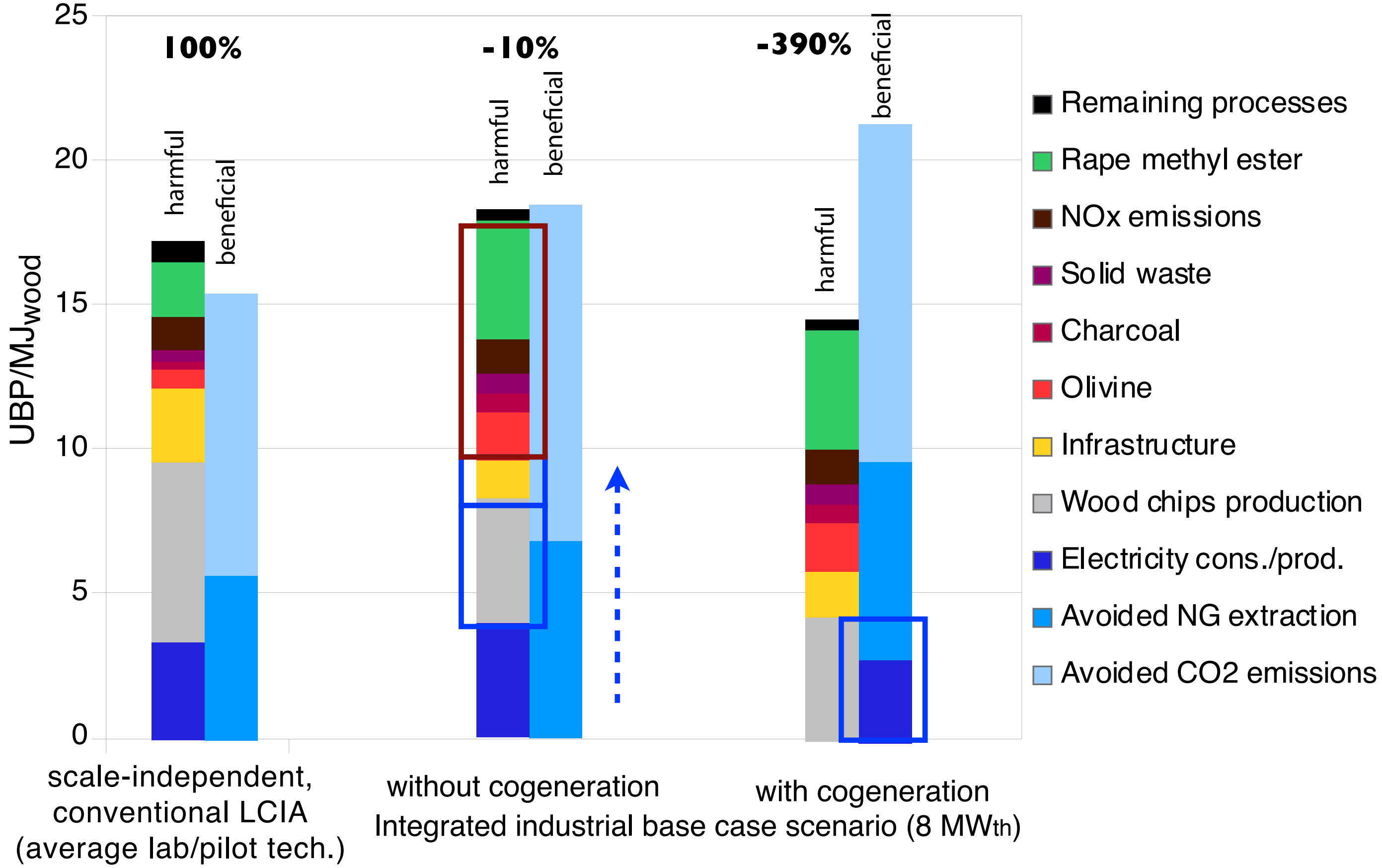
Decreases impact by
increasing electricity production ...
but also by decreasing SNG production!
(since FU is MJ of SNG, avoided impacts from SNG remain constant)

Function of the process
is actually to convert biomass in
multiple energy services!

- new FU: MJ of wood!

Comparison with conventional LCA

- pilot-scale vs integrated process for wood conversion to SNG & electricity (Ecoscarcity06)



- *Significant differences due to developed methodology*
- *Generation of optimal scenarios?*

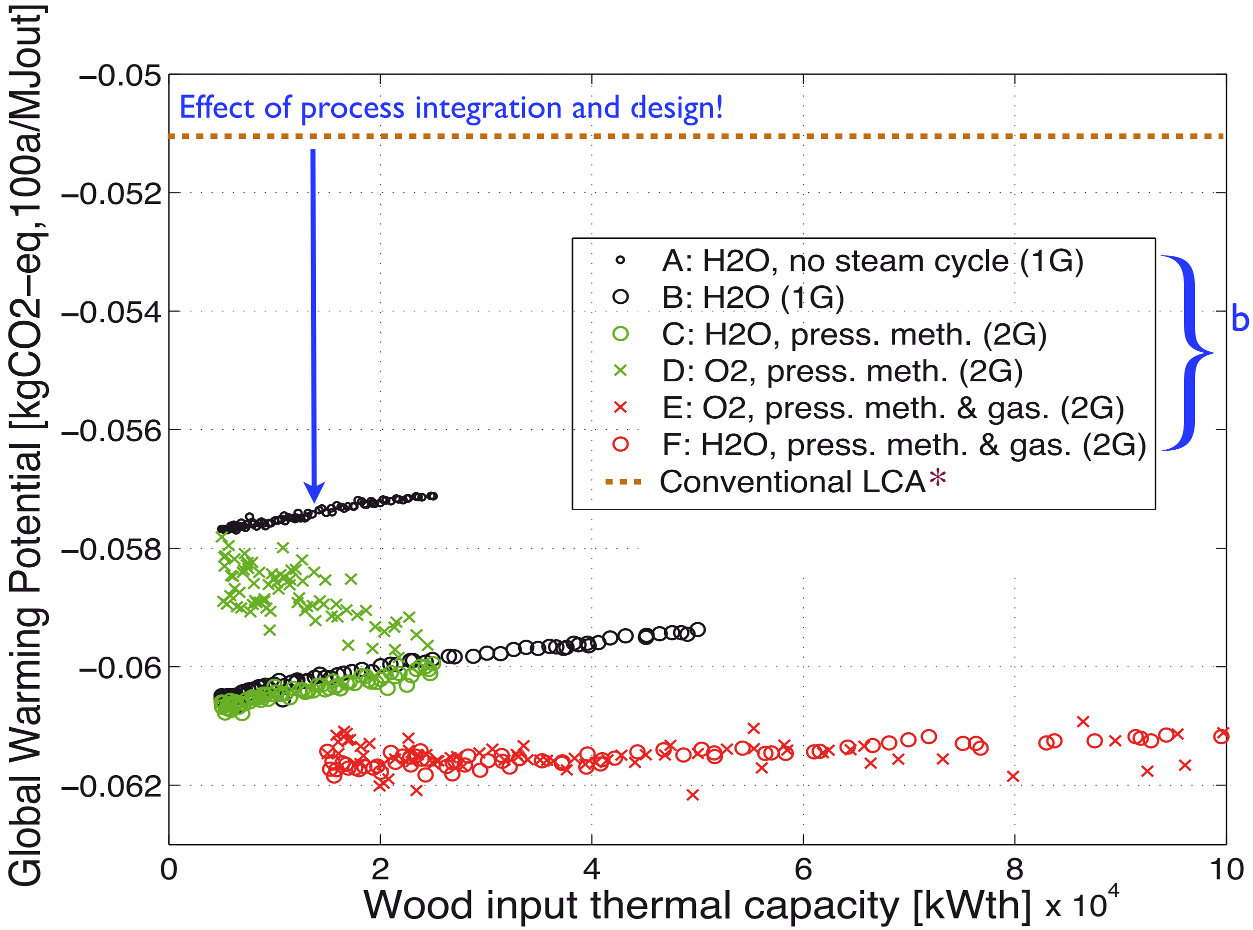
Multi-objective optimization

- Environomic optimal process design
  - ➡ 2 objectives
    - economic → *Biomass profitability*
    - environmental → *Ecoscarcity06 (Single score)*; *Ecoindicator99-(h,a) (Single score)*
- Effect of technology and scale
  - 6 technological alternatives (clusters)
  - 19-21 decisions variables
    - process scale [5-200 MWth]
    - operating conditions

Integration of LCIA in the methodology

Perspective: plant scale-up vs. biomass logistics

The biomass Logistics has an influence on the plant impact



biomass logistics
impact model

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

→ *Optimal plant size with respect to biomass logistics*

Gerber, Léda, Martin Gassner, and François Maréchal. "Integration of LCA in the optimal design of energy conversion systems: The example of SNG production from lignocellulosic biomass." *Comput .Chem. Eng*. In press (2011).

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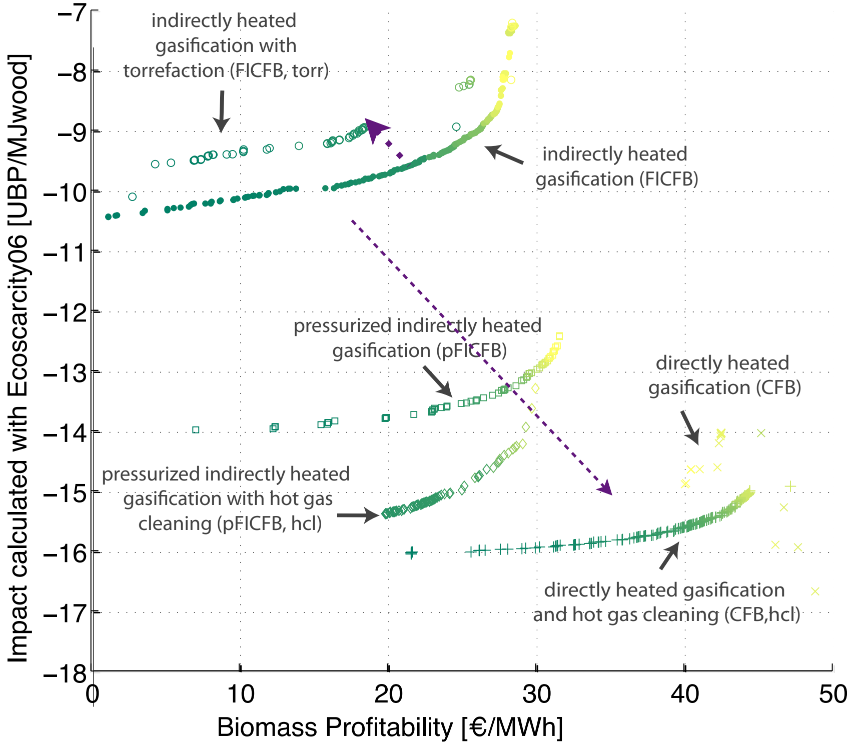
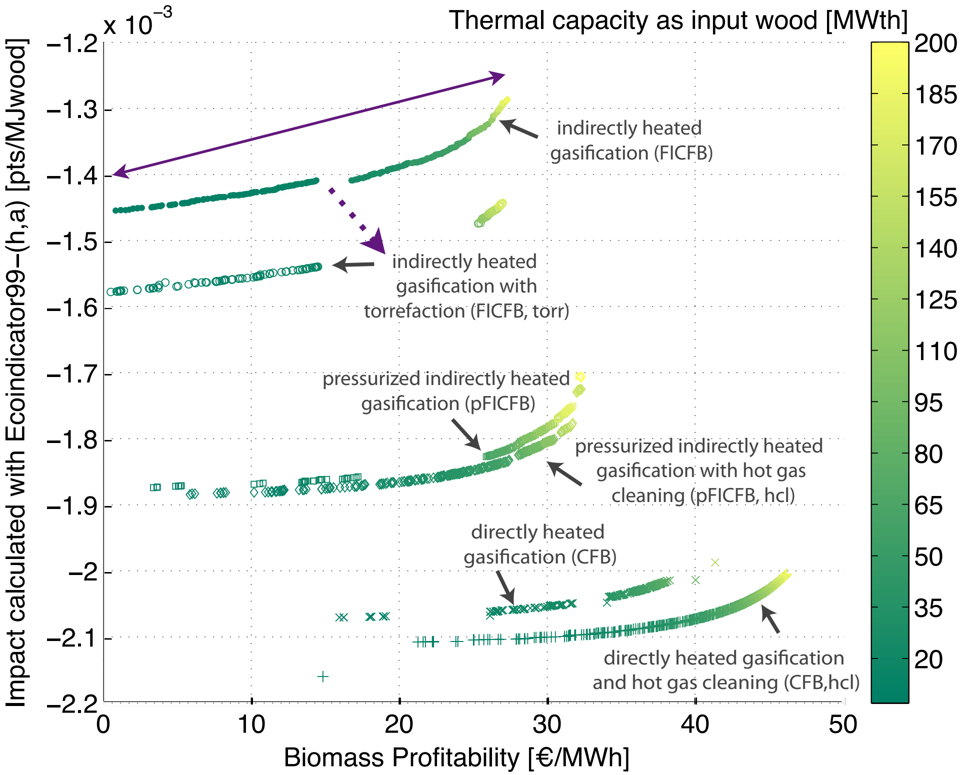
Multi-objective optimization results

- Optimal configurations





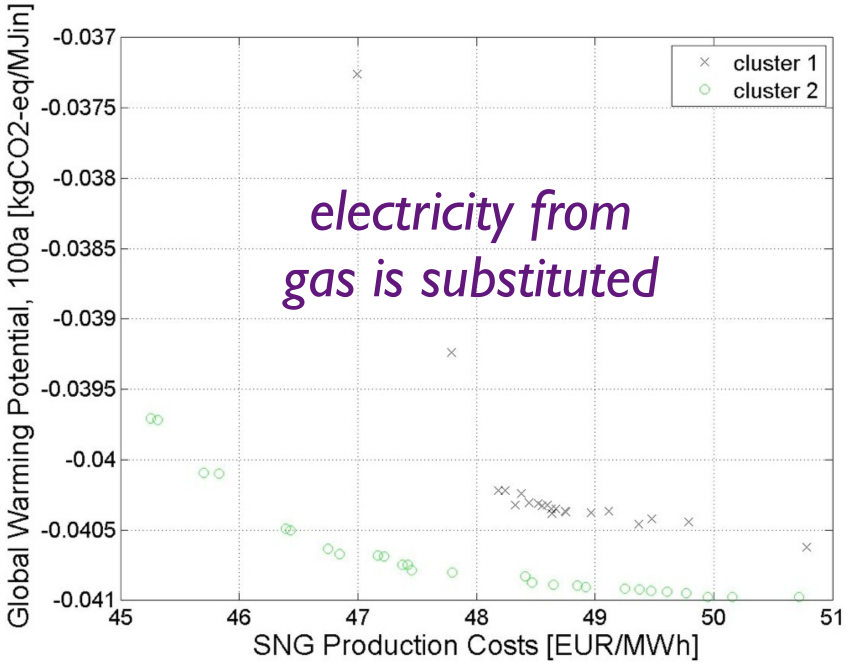
1. Process scale

2. Technology evolution

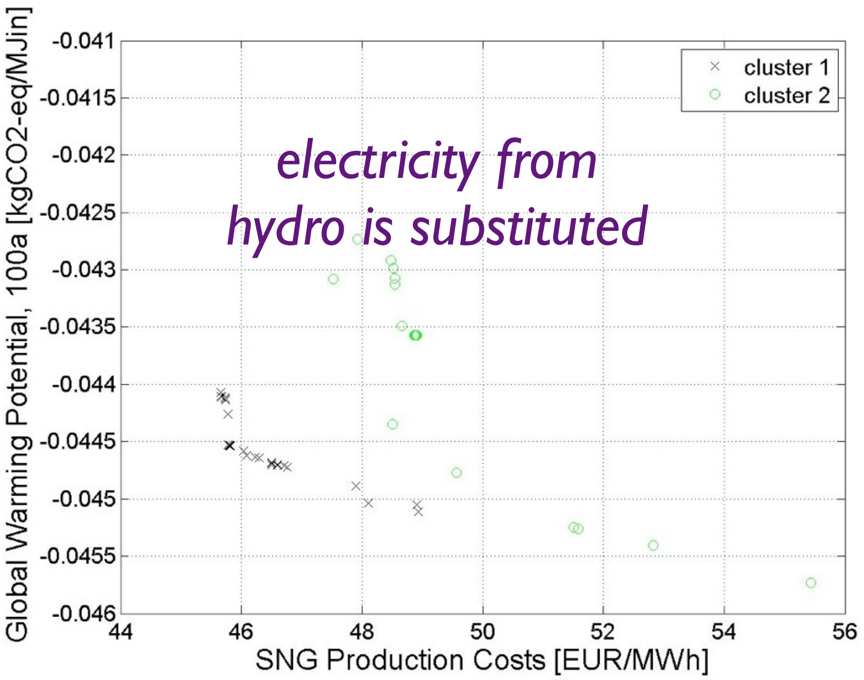
3. Environmental objective function

LCI: a few traps to avoid

- Assumptions regarding the mix greatly influe on the decision making...



electricity from gas is substituted



electricity from hydro is substituted

Best technology changes in function of avoided impacts!

Take home message

- Impact is not only local emissions
- Renewable energy means harvesting
  - Impact is associated to investment
- People define the needs
  - functional unit definition
- Efficiency define the energy consumption
  - Investment in efficiency creates impact
- The energy system is used to produce the investment
  - Solar panels will be created by renewable based energy mix