Integration of LCA in a thermo-economic model for multi-objective process optimization of SNG production from woody biomass

Léda Gerber, Martin Gassner, François Maréchal

Ecole Polytechnique Fédérale de Lausanne, Industrial Energy Systems Laboratory

ESCAPE19, 14-17 June 2009, Cracow

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Context

- Conceptual process design for renewable energy conversion in biofuels
  - Environmental impact is one key performance indicator
    - Life Cycle Assessment (LCA) (1)
    - Based on average technology (2)
- Decision variables in process design and technology evolution should reflect in LCA

➡ LCA to be integrated in the conceptual design methodology

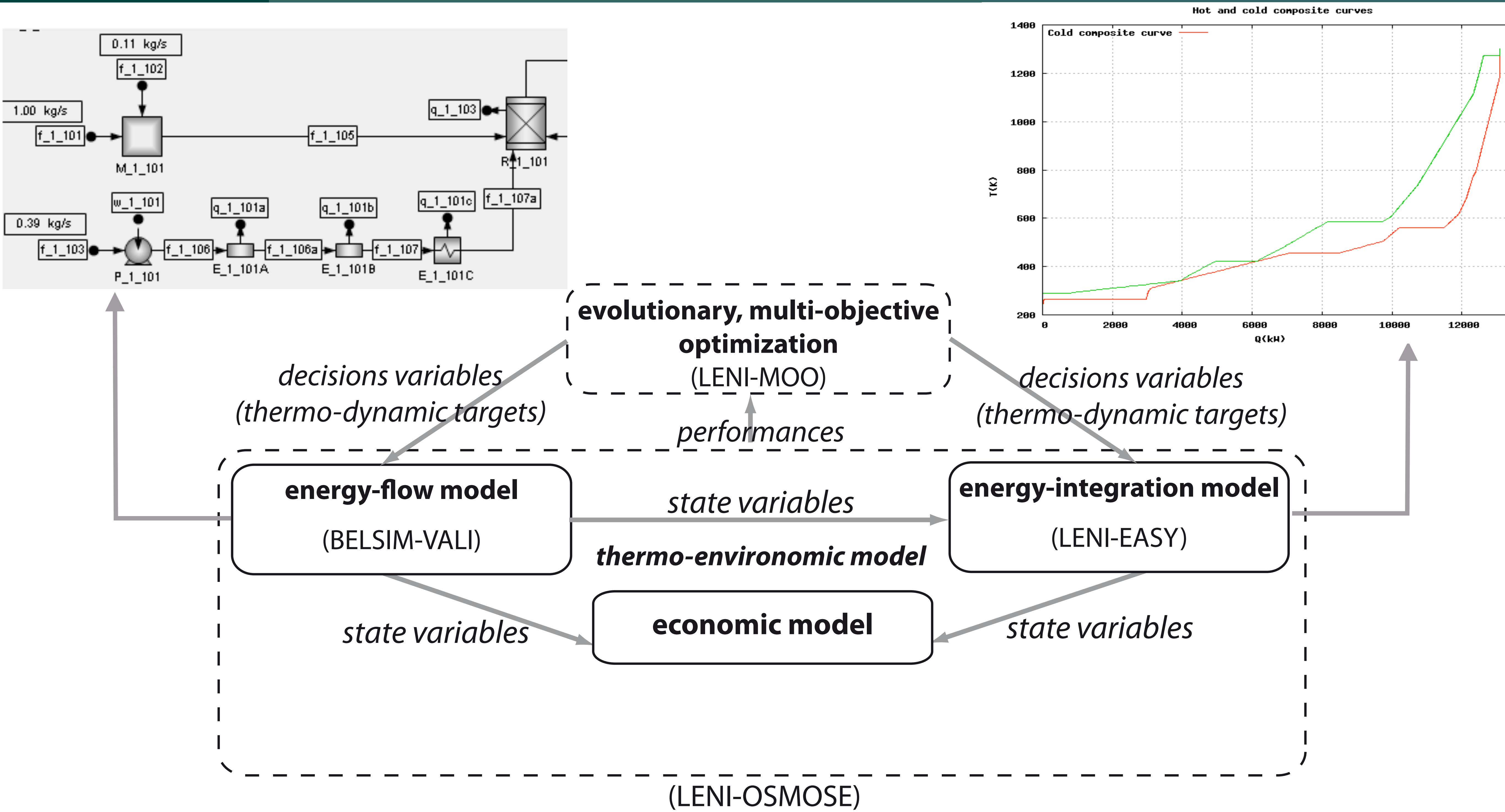
(1) ISO. Environmental management - life cycle assessment - principles and framework. International Standard, ISO 14'040, 2006
(2) Felder R., Dones R., *Evaluation of ecological impacts of synthetic natural gas from wood used in current heating and car systems*, Biomass and bioenergy 31, 403-415, 2007

Goal of the study

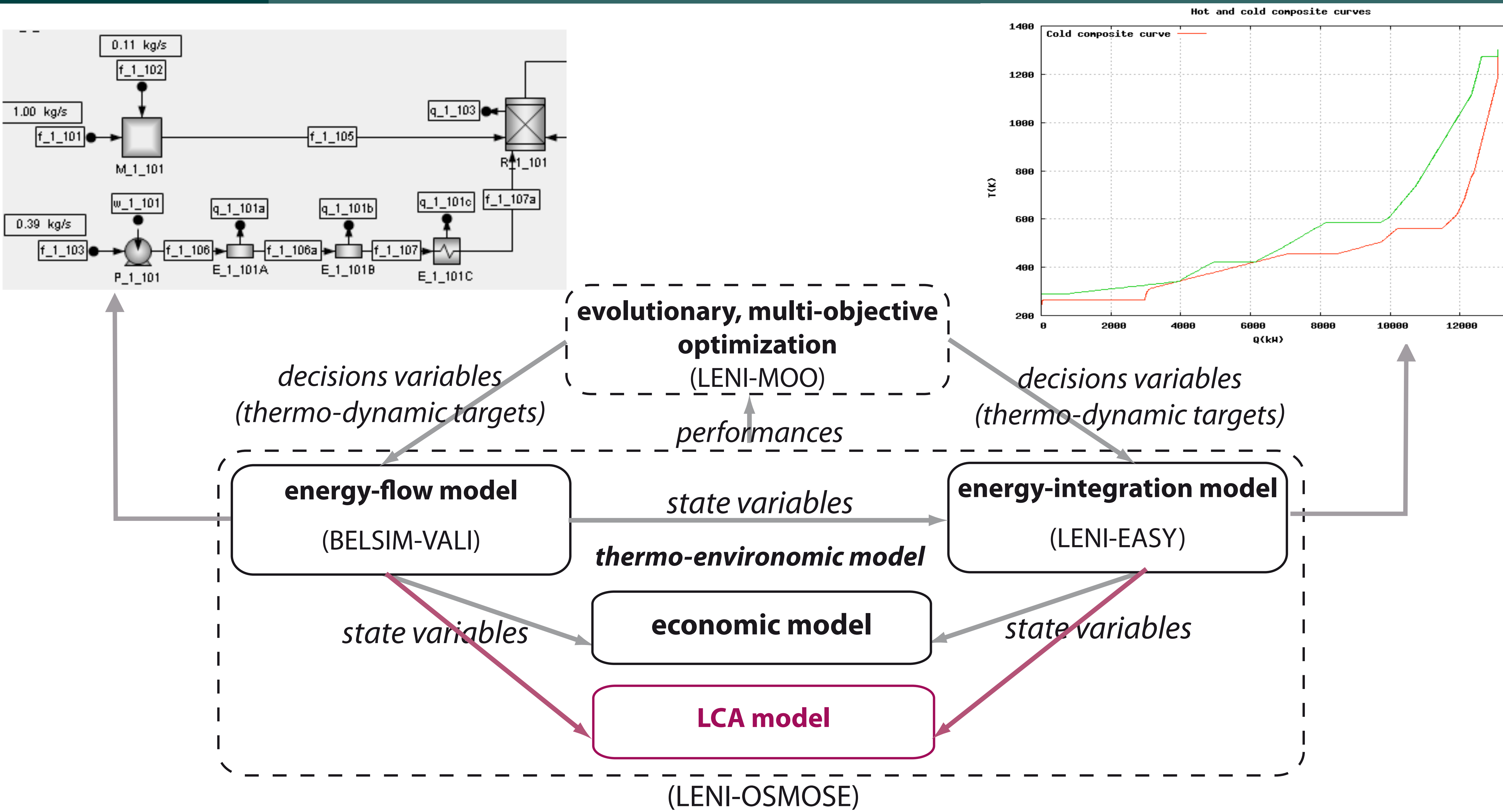
- Develop a methodology to integrate LCA in conceptual process design
    - Represent impact of engineering decisions
    - Model plant scale-up effects
- Application to synthetic natural gas (SNG) production process from woody biomass
    - Thermo-economic model existing (1)
    - ➡ Extension to LCA
    - ➡ Use LCA in multi-objective optimization

(1) Gassner M., Maréchal F., *Thermo-economic model of a process converting wood to methane*, Accepted by Biomass and Bioenergy, 2009

Process design environment

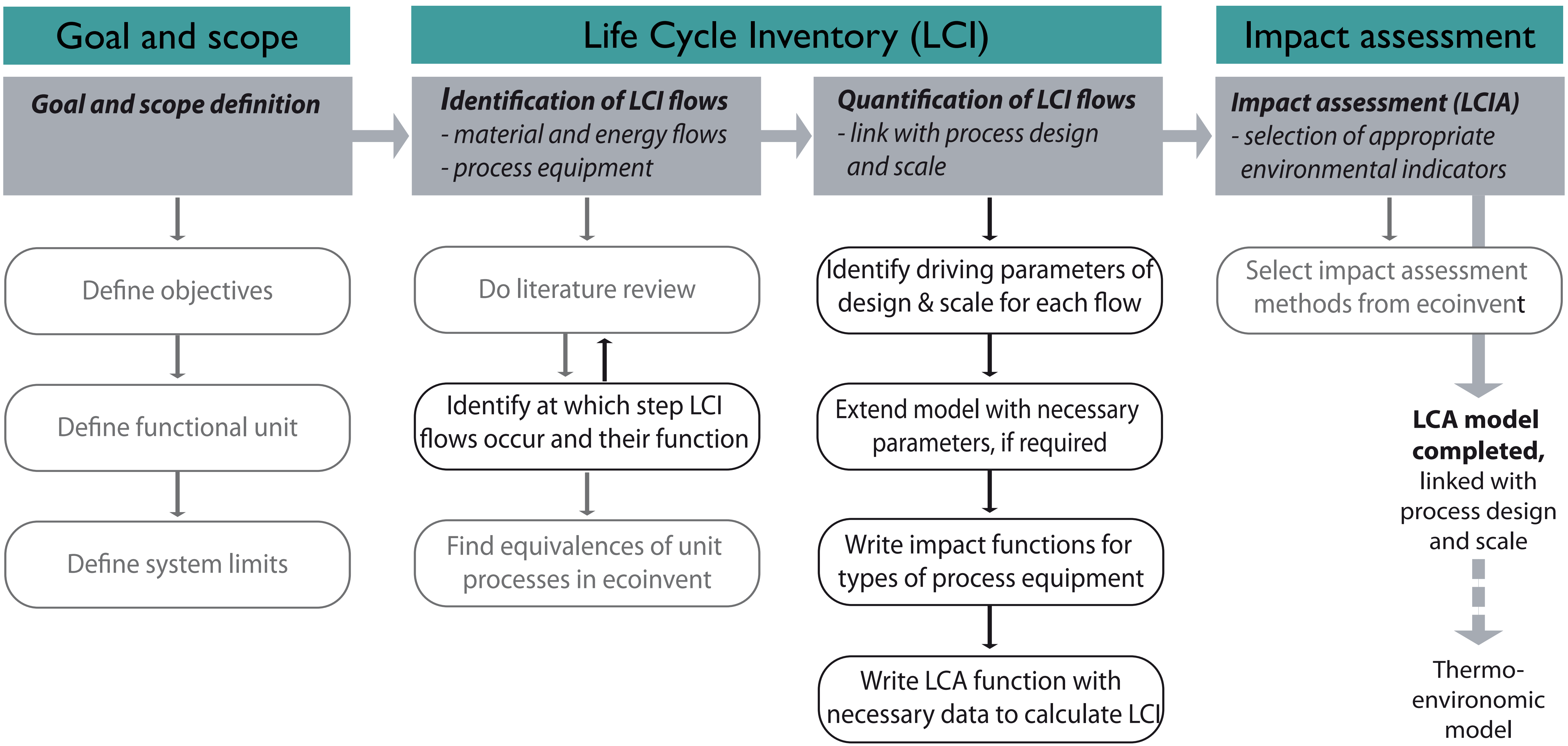


Process design environment



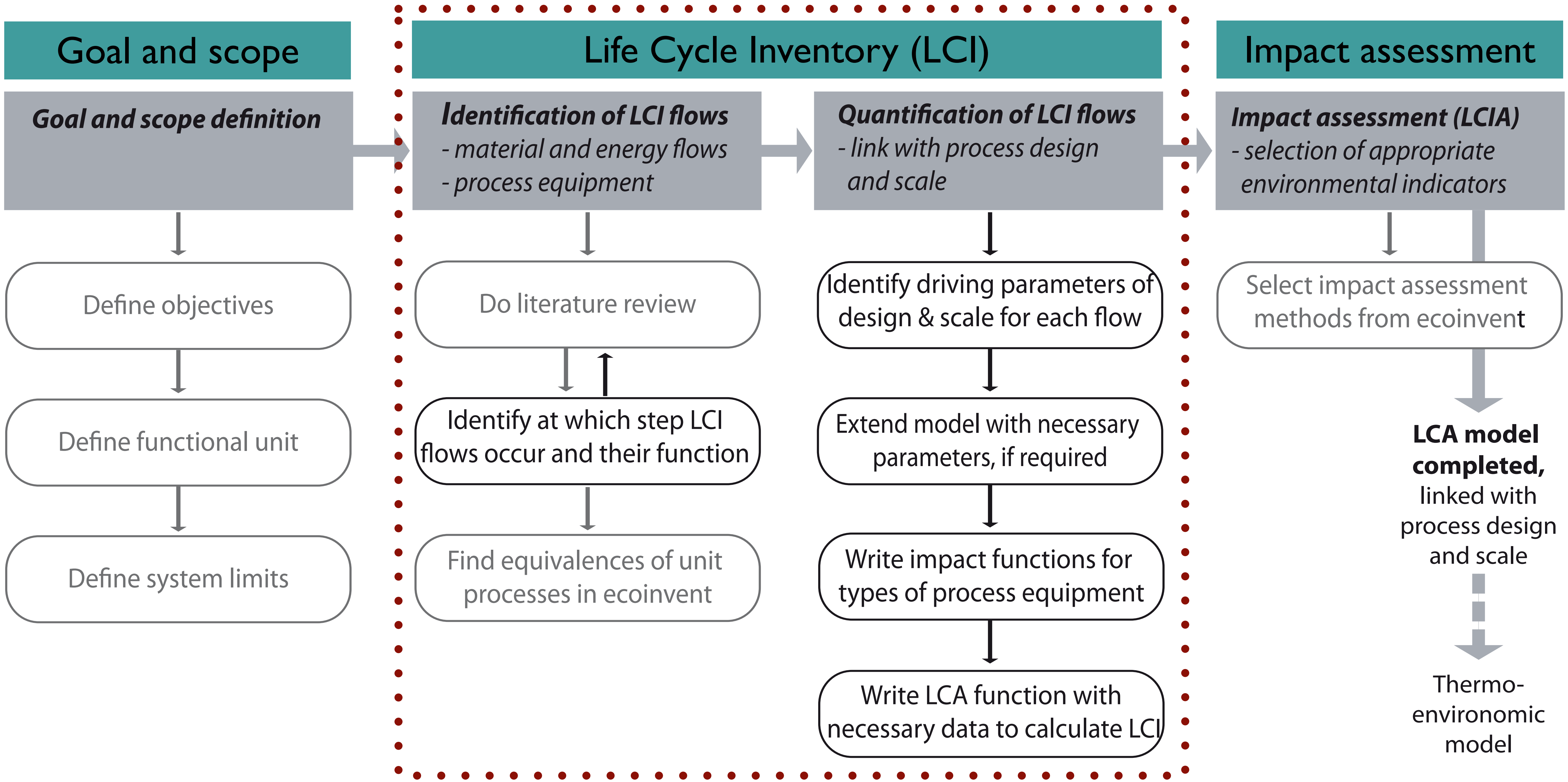
General methodology

- LCA model development steps



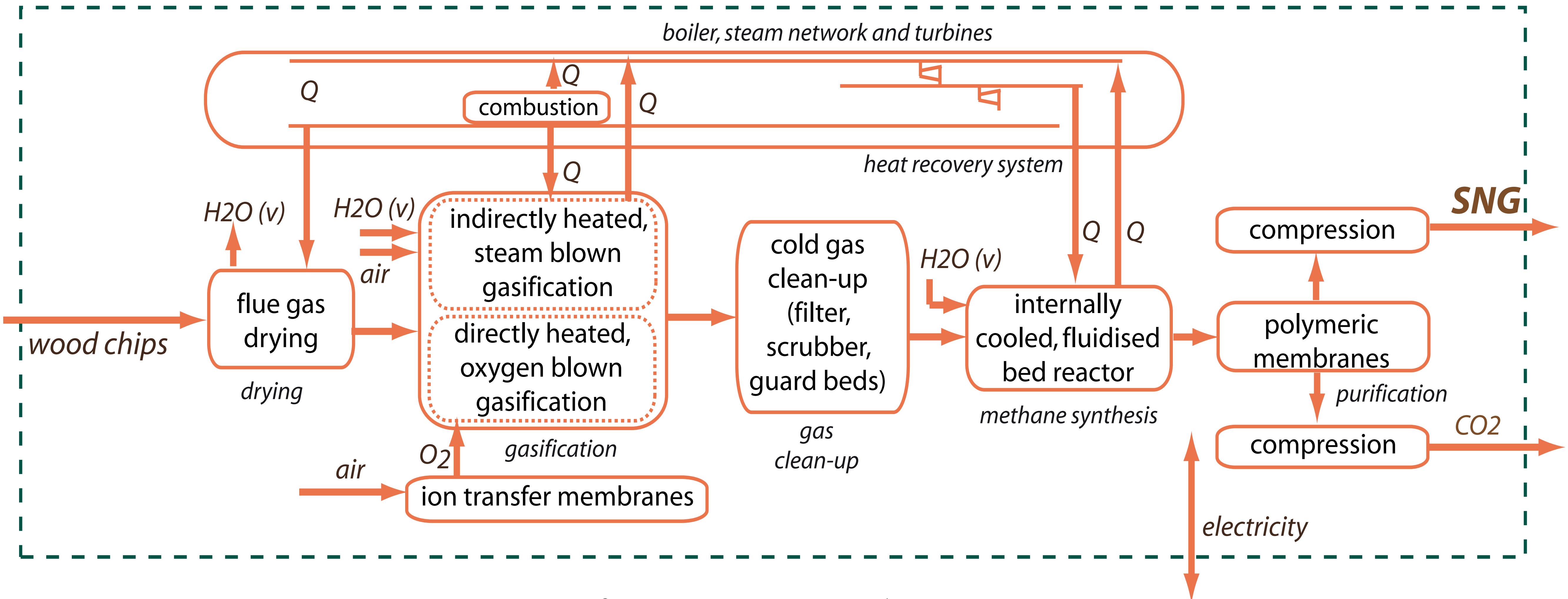
General methodology

- LCA model development steps



Identification of LCI elements

- Process superstructure of the thermo-economic model (1)

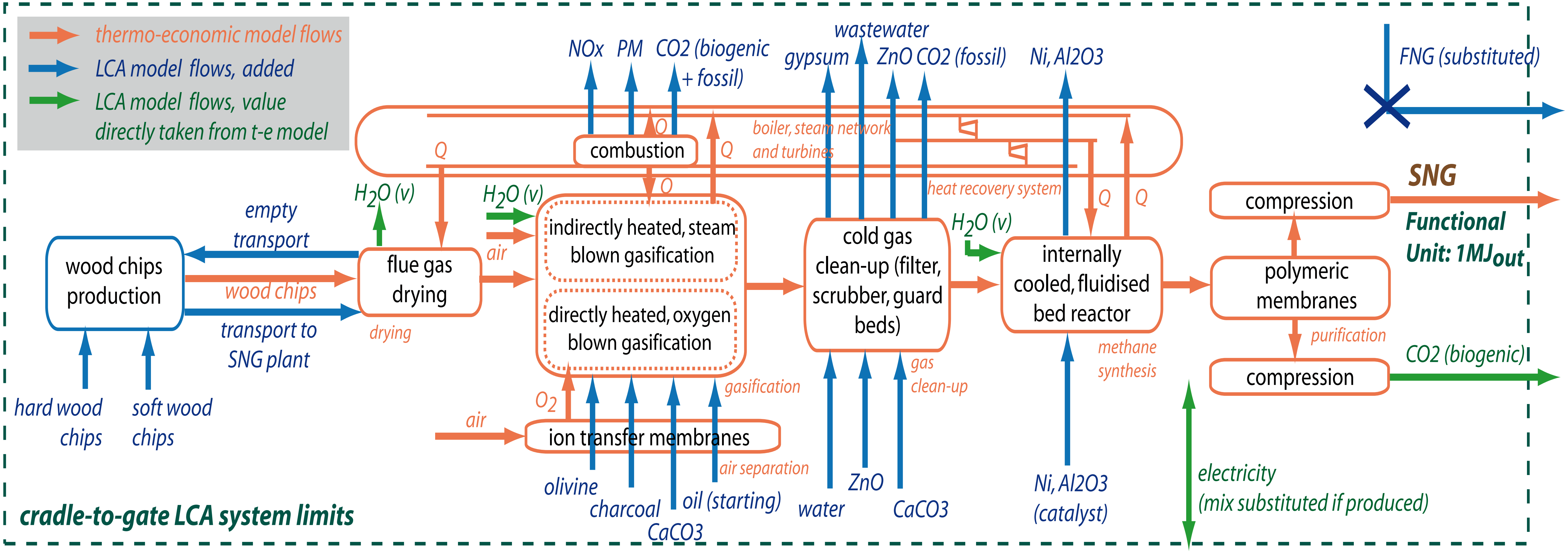


$$CH_{1.35}O_{0.63} + 0.3475H_2O \xrightarrow{\Delta H^0 = -10.5kJ*mol^{-1}wood} 0.51125CH_4 + 0.48875CO_2$$

(1) Gassner M., Maréchal F., *Thermo-economic model of a process converting wood to methane*, Accepted by Biomass and Bioenergy, 2009

Identification of LCI elements

- Process superstructure, extended with LCI elements



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

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

LCI scaling of process equipment

- Analogy with equipment cost estimation
  - Costs and impacts both linked to material quantity

$$\frac{E_{A,i}}{E_{ref,i}} = \left(\frac{A}{A_{ref}}\right)^k * c$$

$E_{ref,i}$: emission/extraction i of the reference dataset

$E_{A,i}$: scaled emission/extraction i

A : functional parameter related to the size of the process equipment

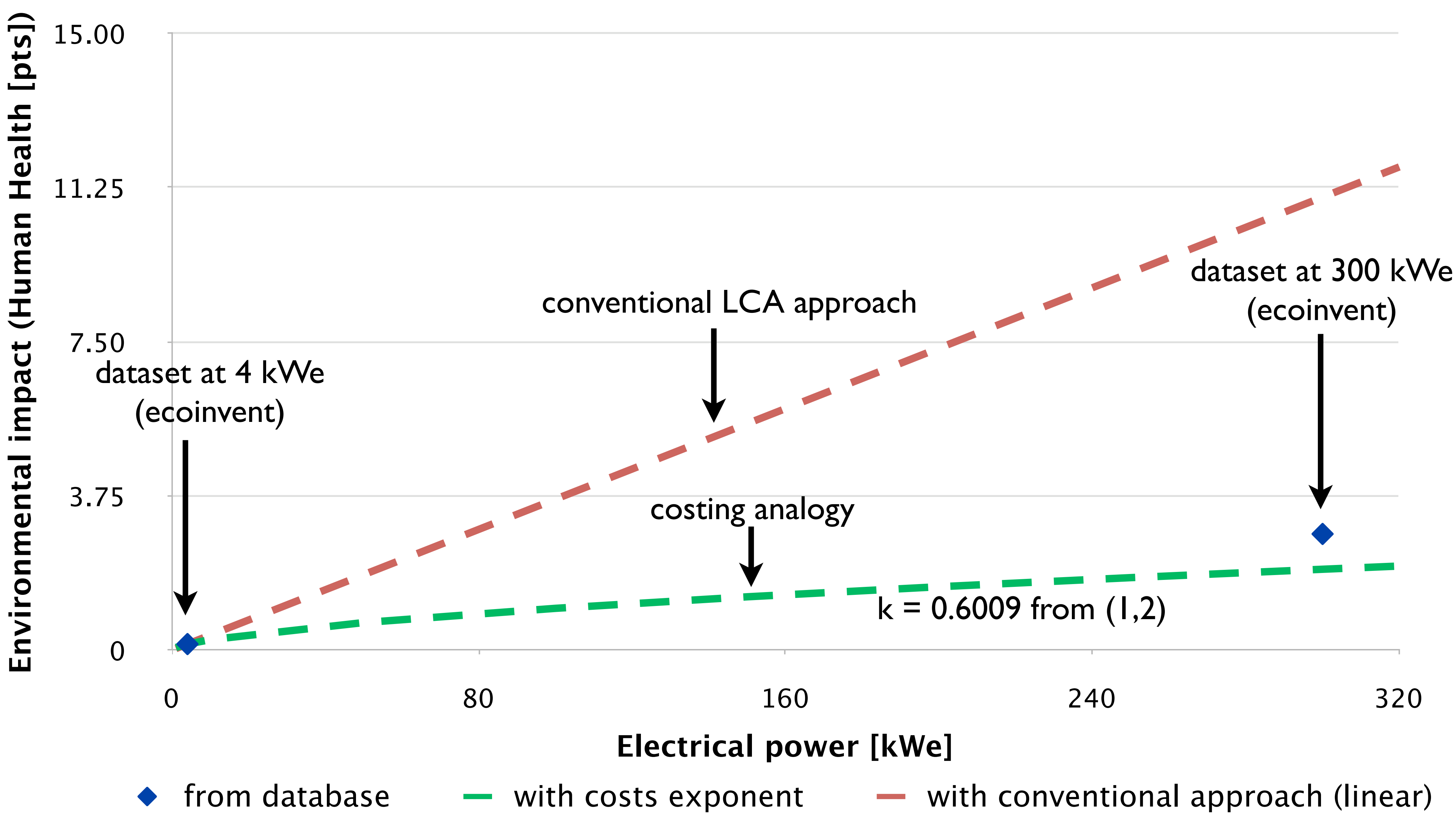
A_{ref} : value of the functional parameter for the reference dataset

k : exponent calculated for different values of A_{ref} from available LCI datasets

c : correction factor, function of the operating pressure, the material and the type

LCI scaling of process equipment

- Relevance of the approach - example for a compressor



(1) Turton R., Bailie R.C., Whiting W.B., Shaiewitz J.A., *Analysis, synthesis and design of chemical processes*, Prentice Hall, New Jersey, 1998
(2) Ulrich G.D., *A guide to chemical engineering process design and economics*, Wiley, New York 1984

LCI scaling of process equipment

- Similar scaling laws developed for the following types of process equipment

Type	A (functional parameter)	c (correction factor)
Boiler	Thermal power [kW_{th}]	-
Compressor	Electrical power [kW_e]	type (axial, centrifugal)
Filter	Volume flow [Nm^3/s]	-
Heat exchanger	Exchange area [m^2]	operating pressure
Membrane	Membrane area [m^2]	-
Pump	Electrical power [kW_e]	operating pressure
Reactor	Volume (height/diameter) [m^3]	operating pressure

LCI scaling of process flows

- No generic formulation for LCI flows - Case by case approach
  - Example of a heat carrier for gasification (olivine):

$$LCI_{olivine} = V_{gasif}(x_d) * \boldsymbol{\alpha}_{olivine}$$

$LCI_{olivine}$: total olivine required (over lifetime) $[kg]$

$V_{gasif}(x_d)$: gasifier volume $[m^3]$

$\alpha_{olivine}$: olivine constant filling rate $[\frac{kg}{m^3 * s}]$

(1) Gassner M., Maréchal F., *Thermo-economic model of a process converting wood to methane*, Accepted by Biomass and Bioenergy, 2009

LCI scaling of process flows

- No generic formulation for LCI flows - Case by case approach
  - Example of a heat carrier for gasification (olivine):

$$LCI_{olivine} = V_{gasif}(x_d) * \boldsymbol{\alpha}_{olivine}$$

$LCI_{olivine}$: total olivine required (over lifetime) $[kg]$

$V_{gasif}(x_d)$: gasifier volume $[m^3]$

$\alpha_{olivine}$: olivine constant filling rate $[\frac{kg}{m^3 * s}]$

$$d_g = 2 * \sqrt{\frac{Vflow_{gas}}{\pi * U_{mean,gas}}}$$

$$h_g = c1 * (Vflow_{gas})^{c2}$$

from (1)

d_g : diameter of gasifier $[m]$

h_g : height of gasifier $[m]$

(1) Gassner M., Maréchal F., *Thermo-economic model of a process converting wood to methane*, Accepted by Biomass and Bioenergy, 2009

Impact assessment

- Aggregation of LCI to indicators: →
  - Different impact assessment methods

$$\begin{bmatrix} F_{1,1} & \dots & F_{1,n} \\ \dots & \dots & \dots \\ F_{m,1} & \dots & F_{m,n} \end{bmatrix} * \begin{bmatrix} E_1 \\ \dots \\ E_n \end{bmatrix} = \begin{bmatrix} I_1 \\ \dots \\ I_m \end{bmatrix}$$

Impact assessment method	Impact categories included
CML2001	• Acidification potential, average european • Eutrophication potential, average european • Global warming potential, 100a • Ozone Depletion potential, steady-state
Ecoindicator99 - (H,A)	• Human Health • Ecosystem Quality • Resources
Ecoscarcity06	• Air emissions • Surface water emissions • Groundwater emissions • Top soil emissions • Energy resources • Natural resources • Deposited waste
Cumulative Energy Demand	• Fossil, non-renewable

F : weightings (impact factors)

E : emissions/extractions

I : impact categories

n : number of emissions/extractions taken into account in LCI

m : number of impact categories

Environomic multi-objective optimization

- 6 scenarios evaluated

Scenario	Gasification technology	Rankine cycle	Gasification pressure	Methanation pressure	Installation size
A	Indirect	Without	Atmospheric	Atmospheric	5-25 MW
B	Indirect	With	Atmospheric	Atmospheric	5-50 MW
C	Indirect	With	Atmospheric	$\leq$ 30 bar	5-25 MW
D	Direct	With	Atmospheric	$\leq$ 30 bar	5-25 MW
E	Direct	With	$\leq$ 30 bar	$\leq$ 30 bar	15-100 MW
F	Indirect	With	$\leq$ 30 bar	$\leq$ 30 bar	15-100 MW

Environomic multi-objective optimization

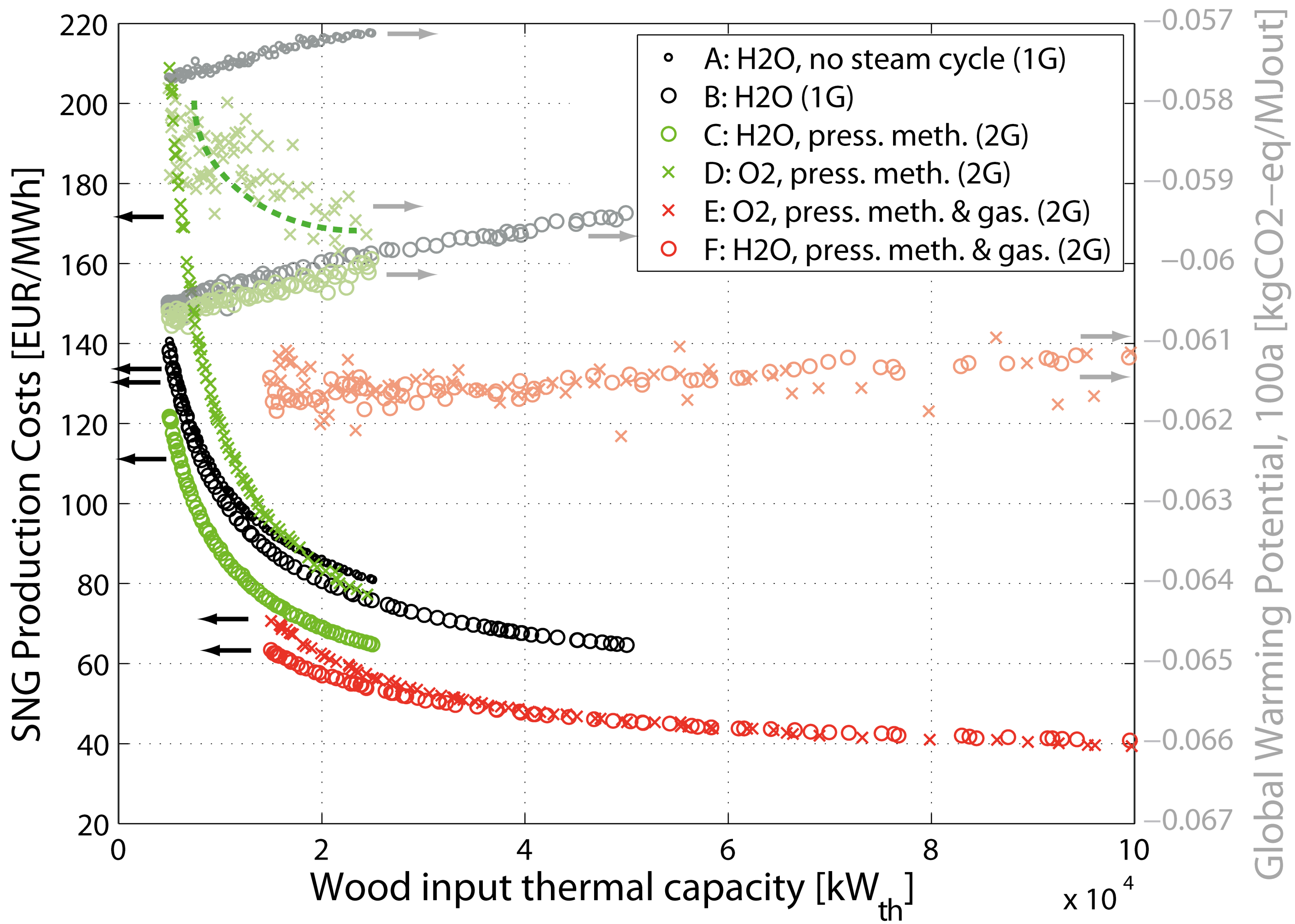
- Engineering decision variables

Variable	Name	Unit	Range	Used for
pth	Nominal thermal capacity	kW_{th}	[5'000 : 100'000]	all
T_{airdry}	Air drying temperature	°K	[453.15 : 513.15]	all
w_{hum}	wood humidity	-	[0.05 : 0.35]	all
p_g	gasification pressure	bar	[1.15 : 30.15]	E,F
p_m	methanation pressure	bar	[1.15 : 30.15]	C,D,E,F
T_m	methanation temperature	°K	[573.15 : 673.15]	all
θ_2	Molar stage cut of membrane stage 2	-	[0.3 : 0.6]	all
P_{steam}	Steam production pressure (Rankine param.)	bar	[40 : 100]	all
T_{steam}	Steam production temperature (Rankine param.)	°K	[623.15 : 823.15]	B,C,D,E,F
ΔT	DT factor (heat exchanger network parameter)	-	[1 : 2]	B,C,D,E,F

- 3 conflicting objectives: size, economic and environmental

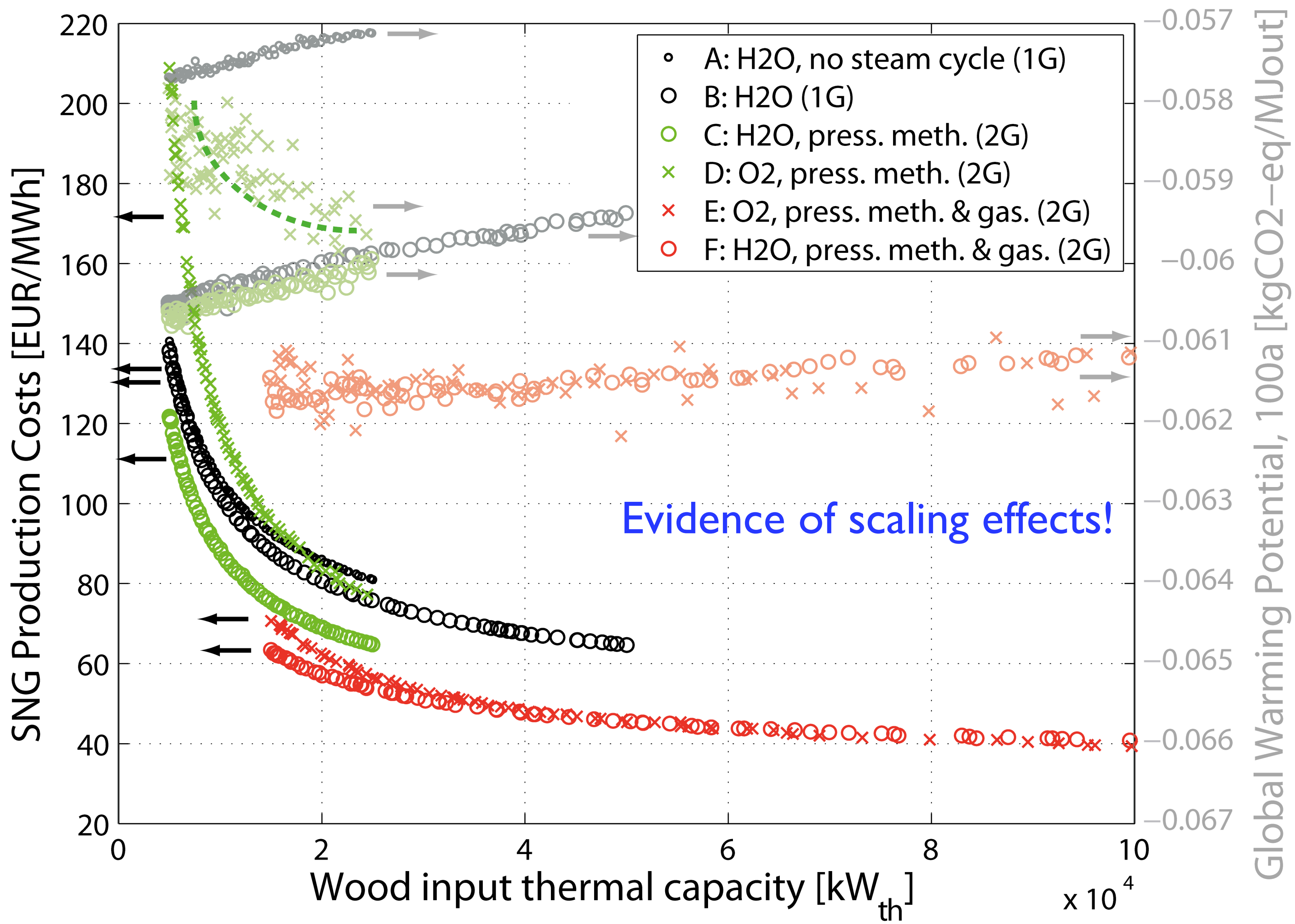
Objectives: size vs production costs

- Economic optimization at multiple scale, and associated environmental impacts

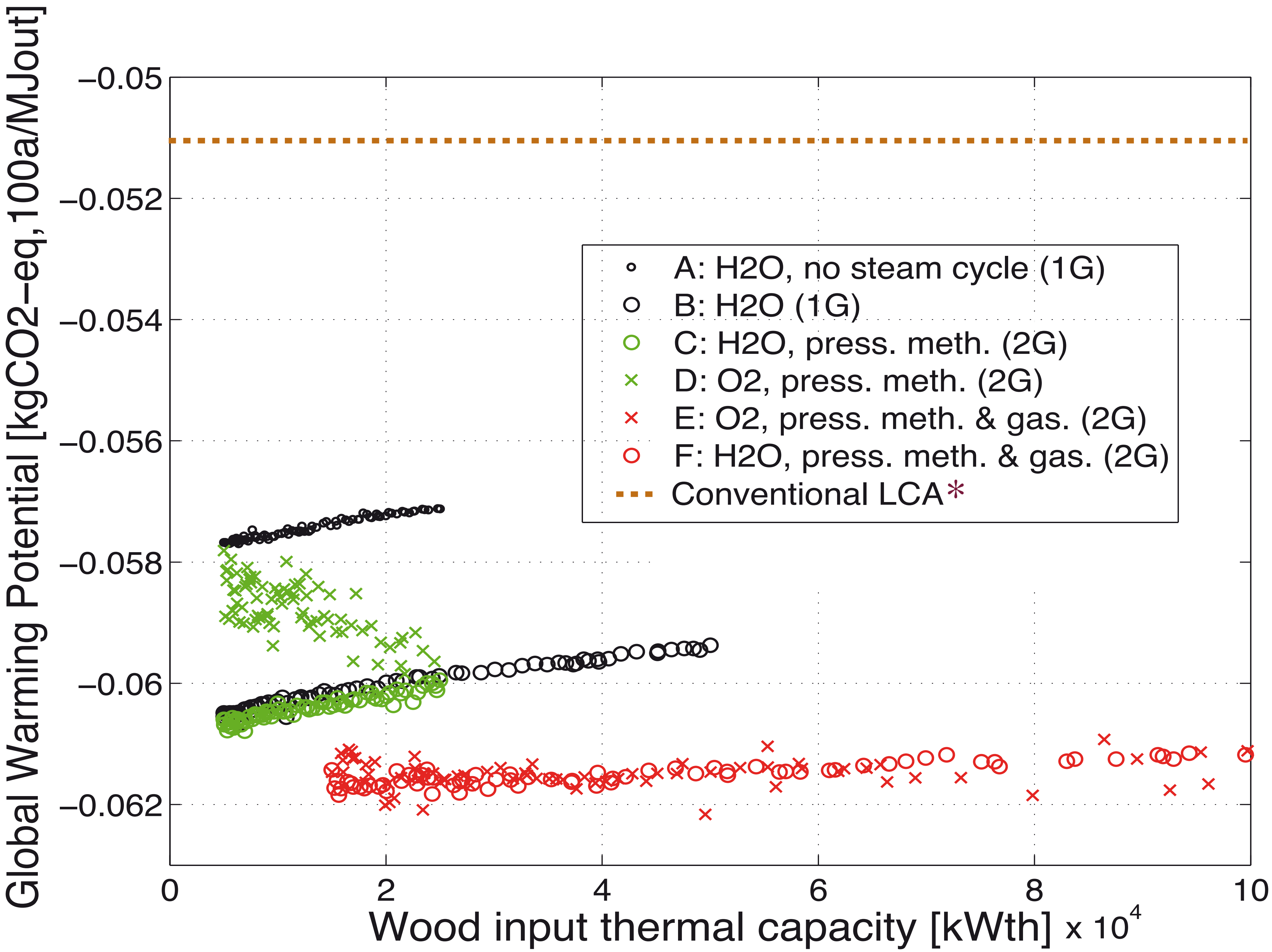


Objectives: size vs production costs

- Economic optimization at multiple scale, and associated environmental impacts

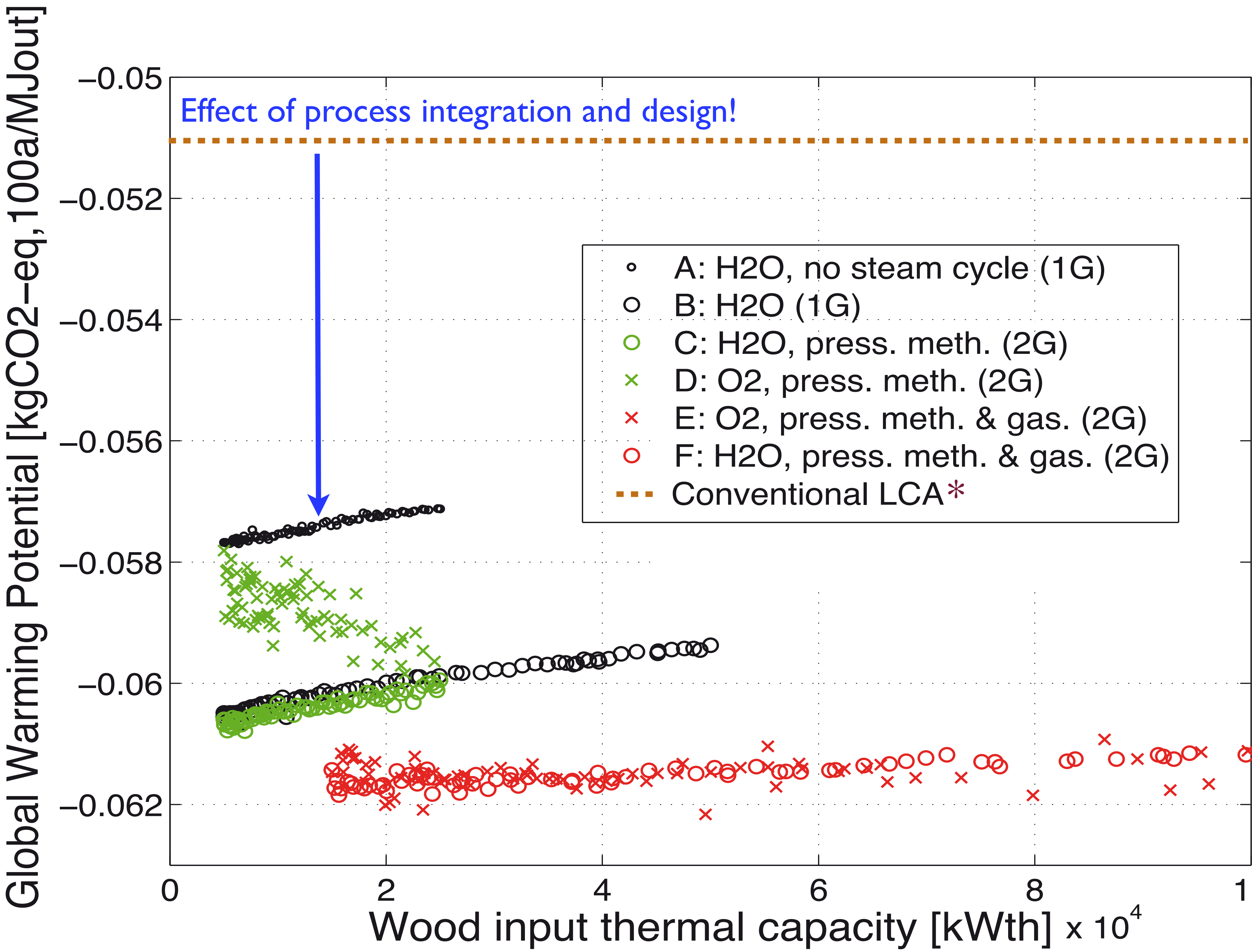


Comparison with conventional LCA



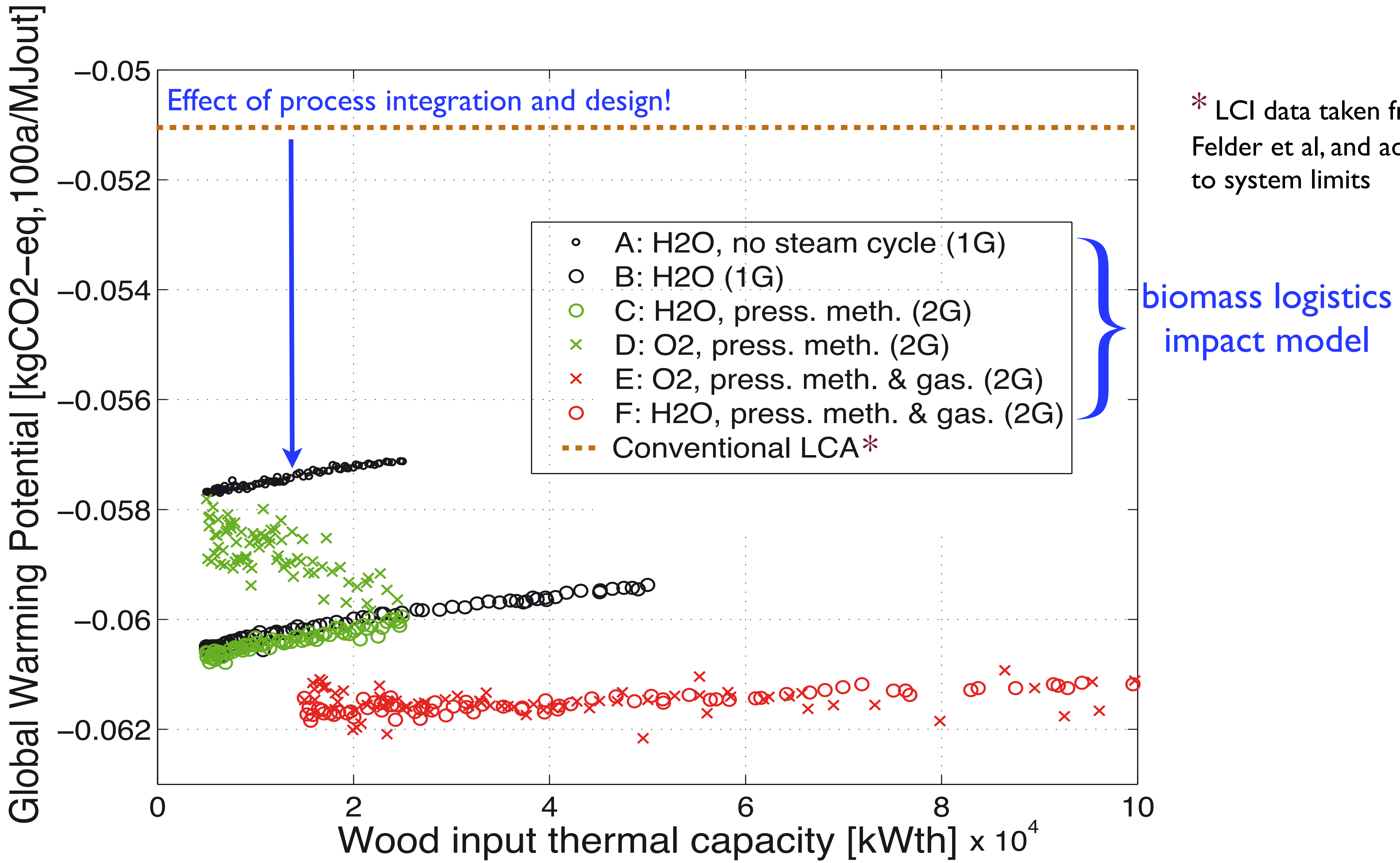
* LCI data taken from Felder et al, and adapted to system limits

Comparison with conventional LCA



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

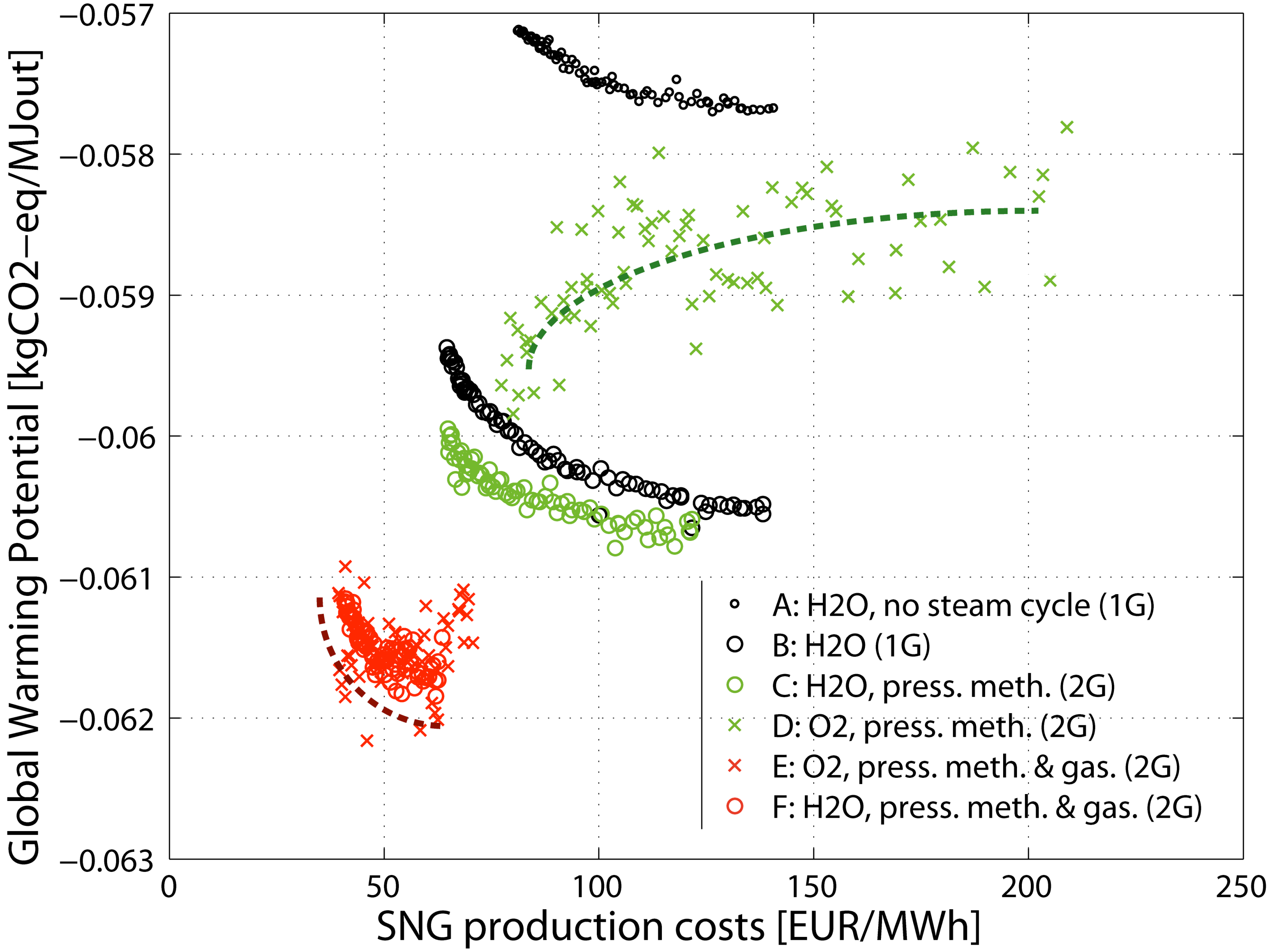
Comparison with conventional LCA



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

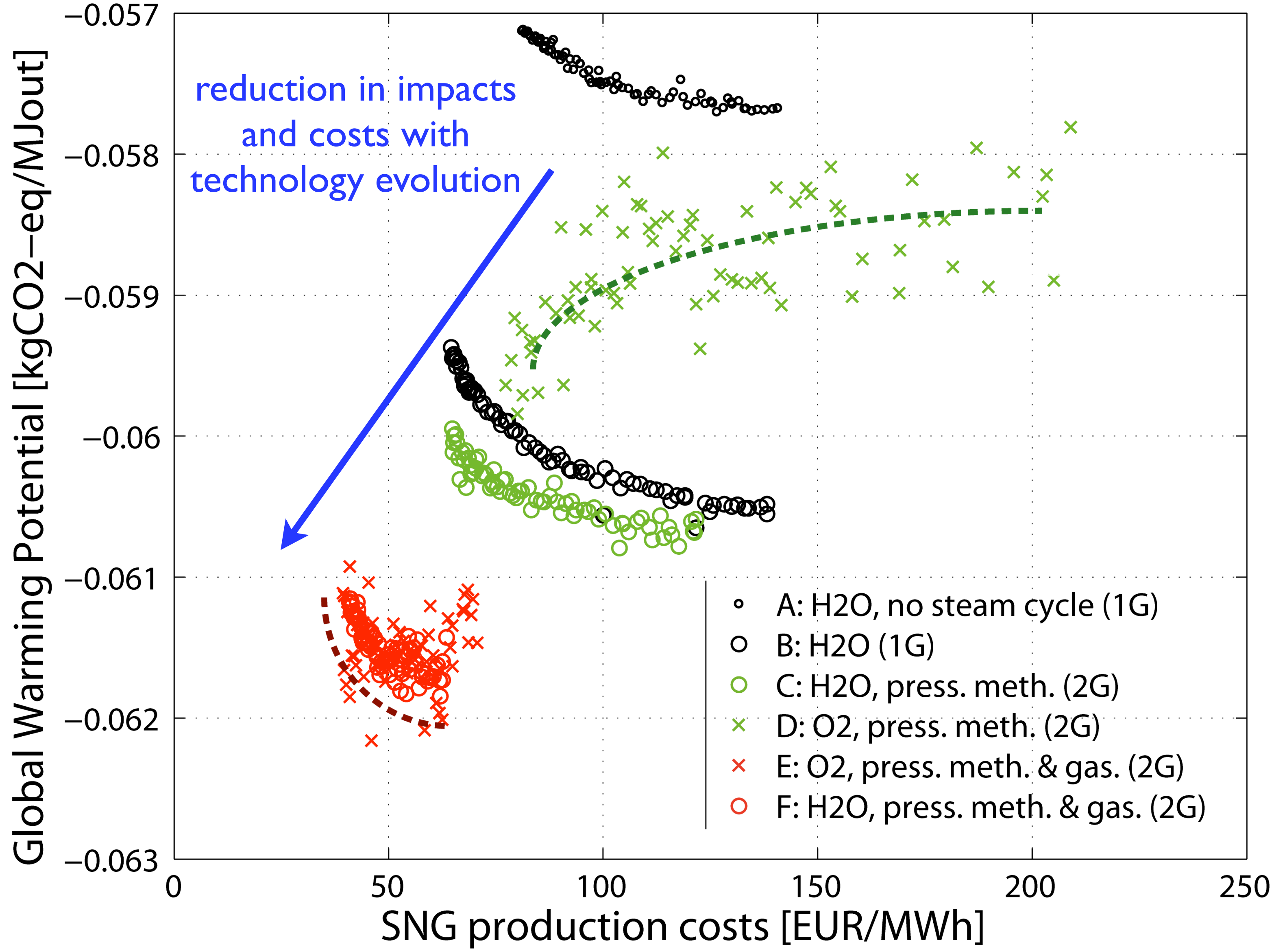
Environomic optimization

- Trade-off between costs and impacts



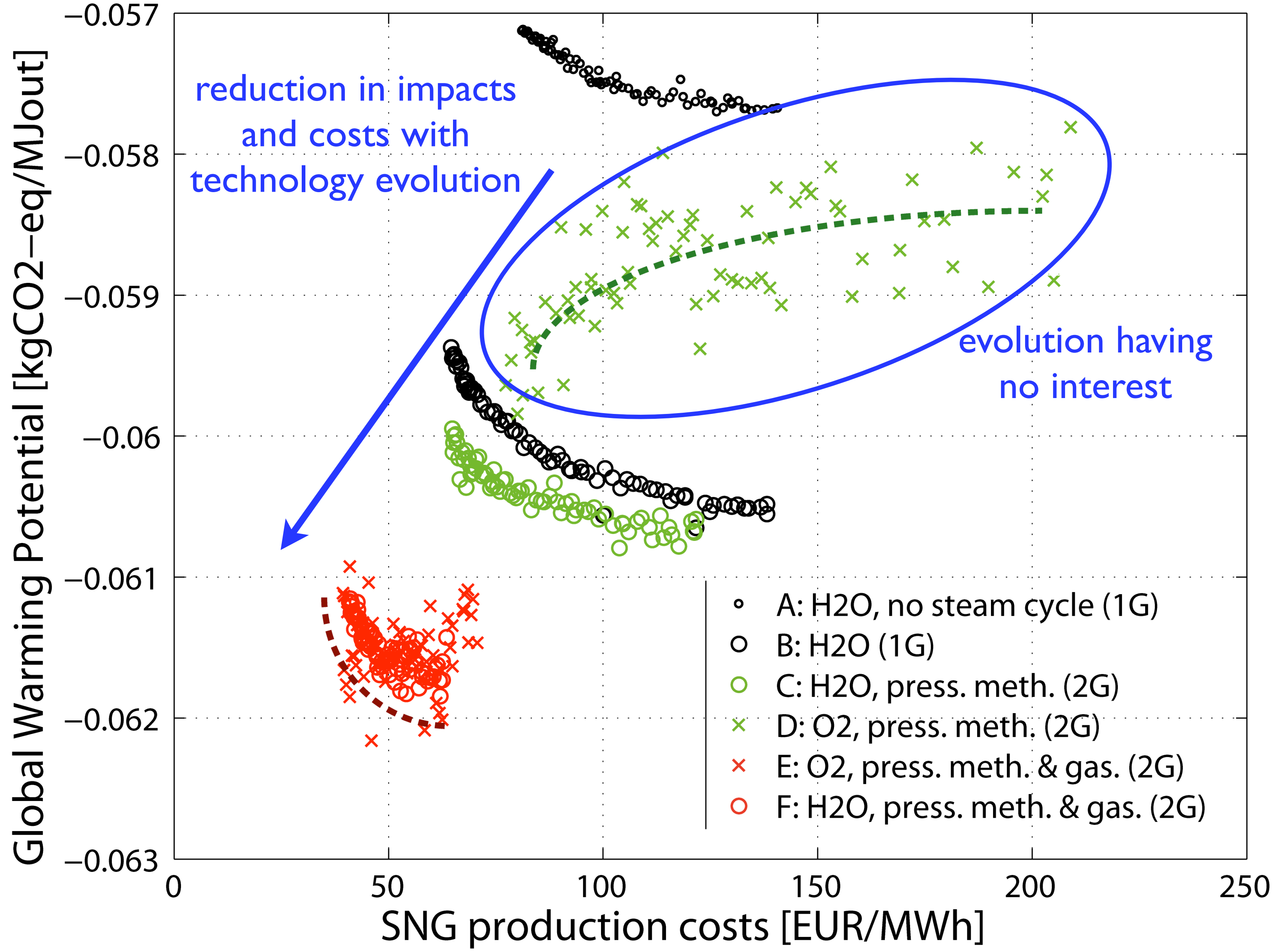
Environomic optimization

- Trade-off between costs and impacts



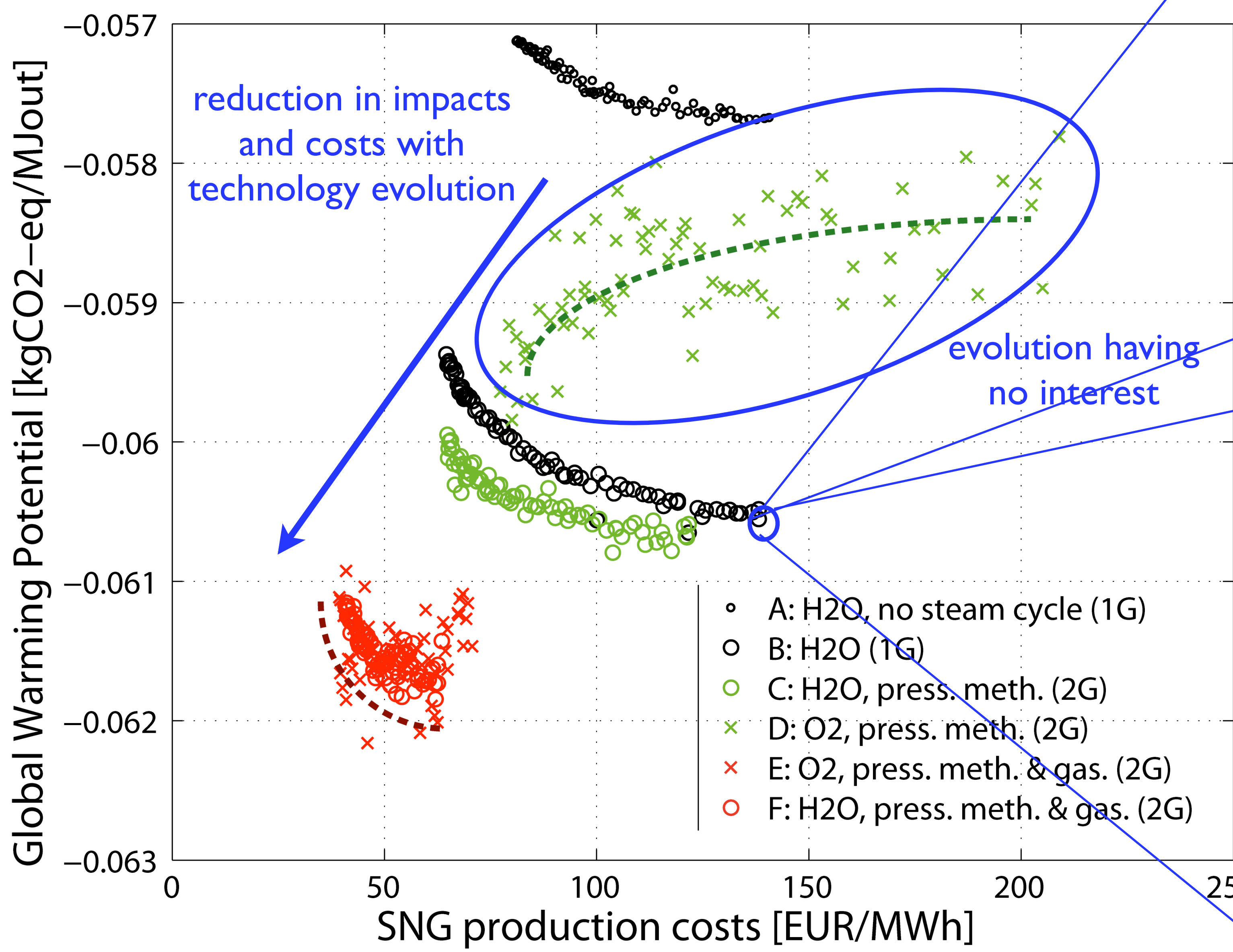
Environomic optimization

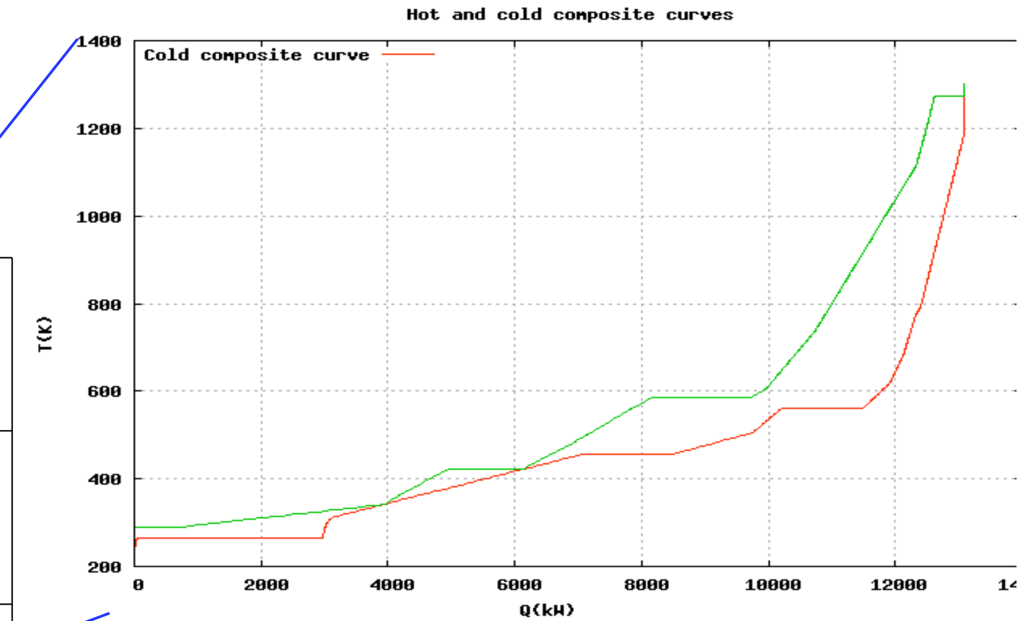
- Trade-off between costs and impacts



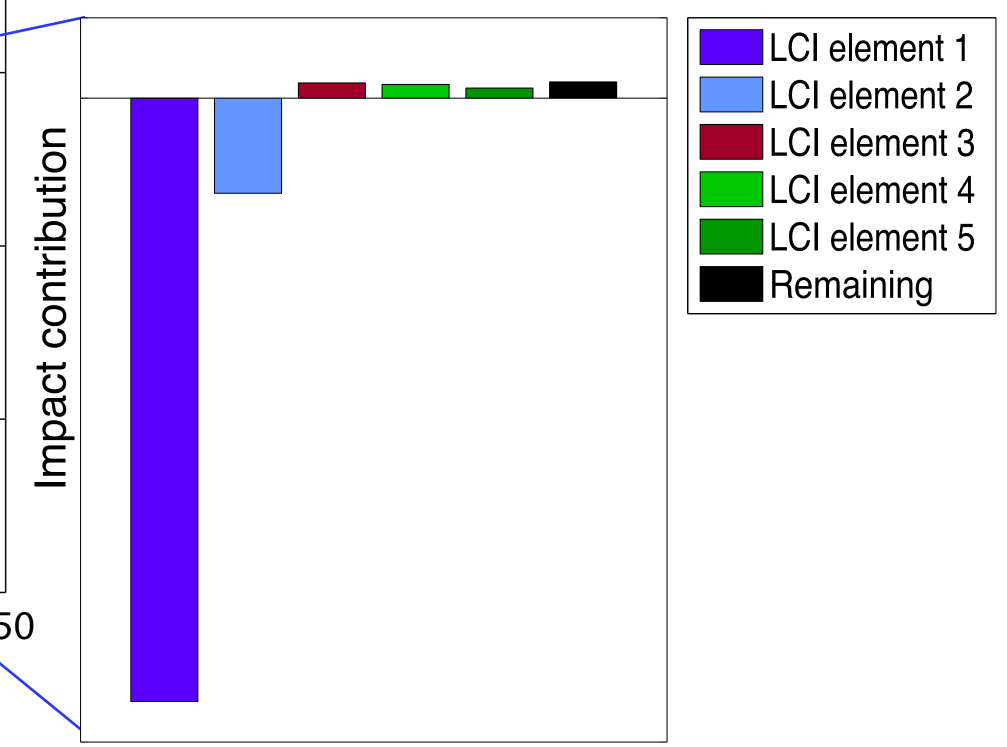
Environomic optimization

- Trade-off between costs and impacts





Detailed contribution of LCI elements



Conclusions

- Methodology to integrate LCA in conceptual process design
  - Systematic method in process design framework (LENI-Osmose, EPFL)
  - Successful implementation in a thermo-economic model for SNG production from woody biomass
- Future work
  - Systematic integration in the 2nd generation biofuel process design platform
    - Bioethanol(1), DME(2), MeOH(2), Fischer-Tropsch(2), Hydrothermal gasification(3)
  - Logistic costs model

(1) Suping, Z., Maréchal, F., Gassner, M., Périn-Levasseur, Z. ,Qi, W., Ren, Z., Yongjie, Y., Favrat, D. Process modeling and integration of fuel ethanol production from lignocellulosic biomass based on double acid hydrolysis, Energy and Fuels, 23 (3), pp. 1759-1765, 2009
(2) Tock L., Thermo-economic evaluation of the production of liquid fuels from biomass, EPFL master thesis, 2009
(3) Luterbacher J. et al, Hydrothermal gasification of waste biomass: process design and life cycle assessment, Environmental Science and Technology, 43 (5), pp. 1578-1583, 2009

Thank you for your attention!

Hope to see you next year in Lausanne after the ESCAPE conference at the ECOS 2010 conference!

www.ecos2010.ch