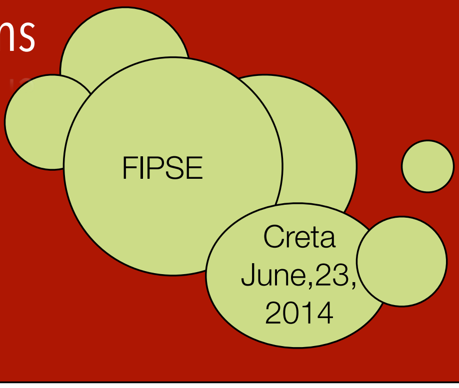
Process System Engineering and the energy transition

Smart engineers for smart systems

- Prof. François Marechal
- http://ipese.epfl.ch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Creta
June,23,
2014

Industrial Process and Energy Systems Engineering
Institute of Mechanical Engineering
Sciences et Techniques de l'Ingénieur
Ecole Polytechnique fédérale de Lausanne

Industrial Process and Energy Systems Engineering

Computer Aided methods for **Energy Systems Engineering**

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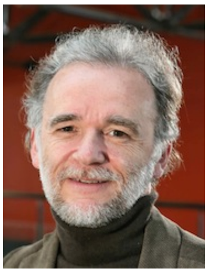
EPFL-STI-IGM-IPESE



- Speciality Chief Editor :
  - Frontiers in Energy : Process and energy systems engineering section.
  - http://www.frontiersin.org/Process_and_Energy_Systems_Engineering
- Scientific committee of IFP Energie Nouvelle
- Board of ECOINVENT

My scientific challenge :

Develop systemic approaches for the Rational Use and Conversion of Energy and Resources in Industrial Energy Systems

Industrial Process and Energy Systems Engineering

- **15 Researchers developing research in Computer aided energy systems engineering**
  - Thermo-economic-environomic modeling
  - Process and Energy Systems Integration
    - Modeling the system’s interactions
    - Energy-Water-Waste
    - Renewable Energy Integration
  - Multi-objective optimisation for decision support
    - Thermo-Economic and Environomic Pareto
    - Life Cycle Environmental Impact Assessment
  - Understanding the energetics of complex systems
    - Thermodynamic methods and metrics for system analysis and design

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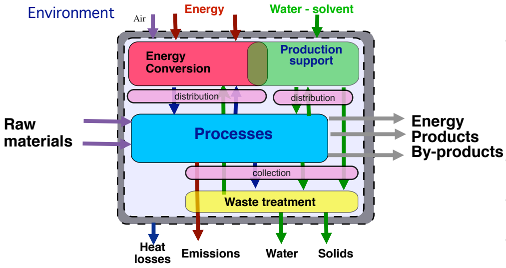
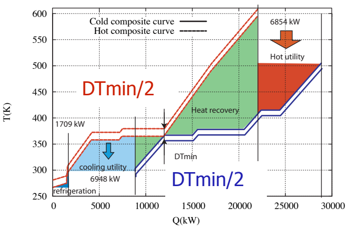
3 Domains of application

Energy and resource efficiency in industrial processes

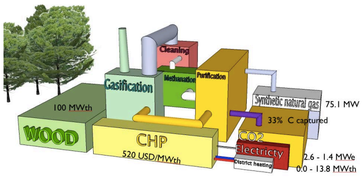


- Process integration
  - Pinch analysis
  - Exergy analysis
- Energy conversion
- Site Scale Integration
- Water & Waste

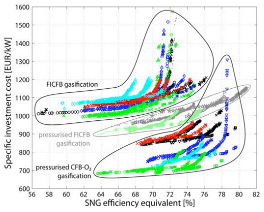


Process system design

- Fuel cells systems
- Power plants, Biomass & Biofuels,...
- Water prod., Waste water
- CO2 capture
- Electricity Storage

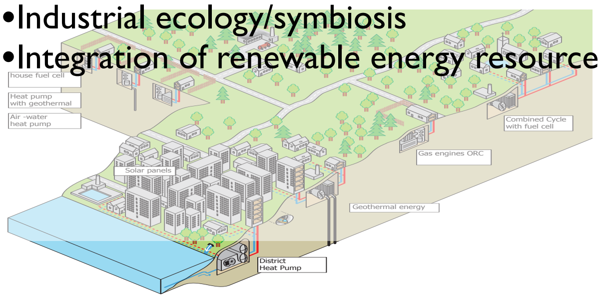


Thermo-economic Pareto front (cost vs efficiency):



Urban systems

- District networks : CO2 swiss knife
- Smart grid : Virtual power plants
- Industrial ecology/symbiosis
- Integration of renewable energy resources



> *“System Engineering :*
> *Treatment of Engineering Design as a decision making process”*

Hazelrigg, 2012

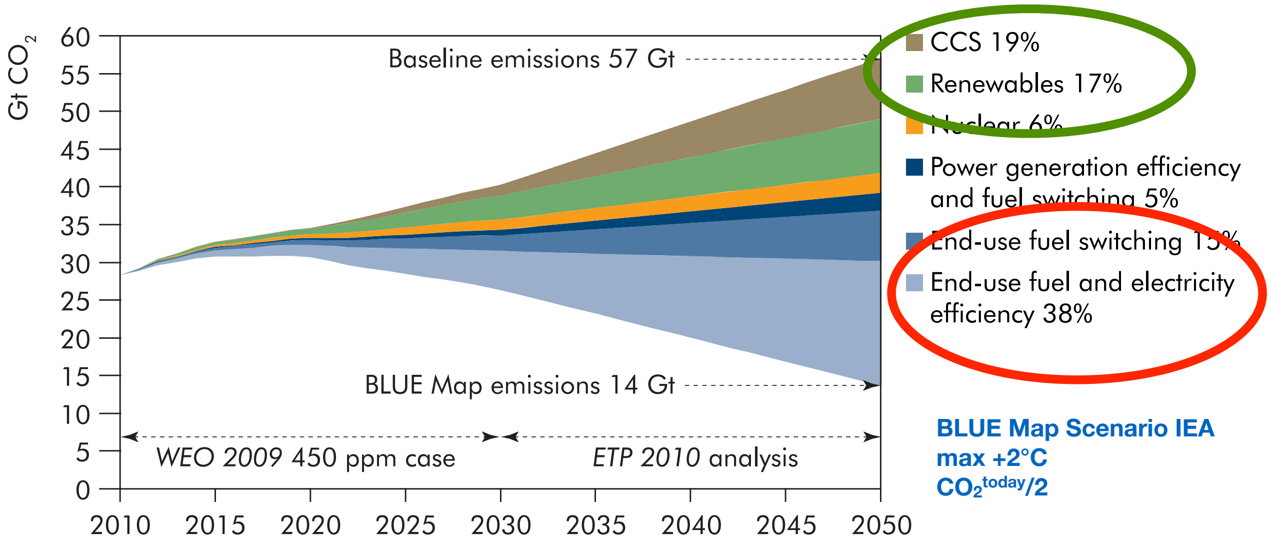
What is the Role of Process System Engineering for the energy transition ?

- Problem Statement
- Open Questions

Smart Engineers for Smart Systems ?

The Energy Transition

Figure ES.1 ▶ **Key technologies for reducing CO_2 emissions under the BLUE Map scenario**



BLUE Map Scenario IEA
max +2°C
$CO_2^{today}/2$

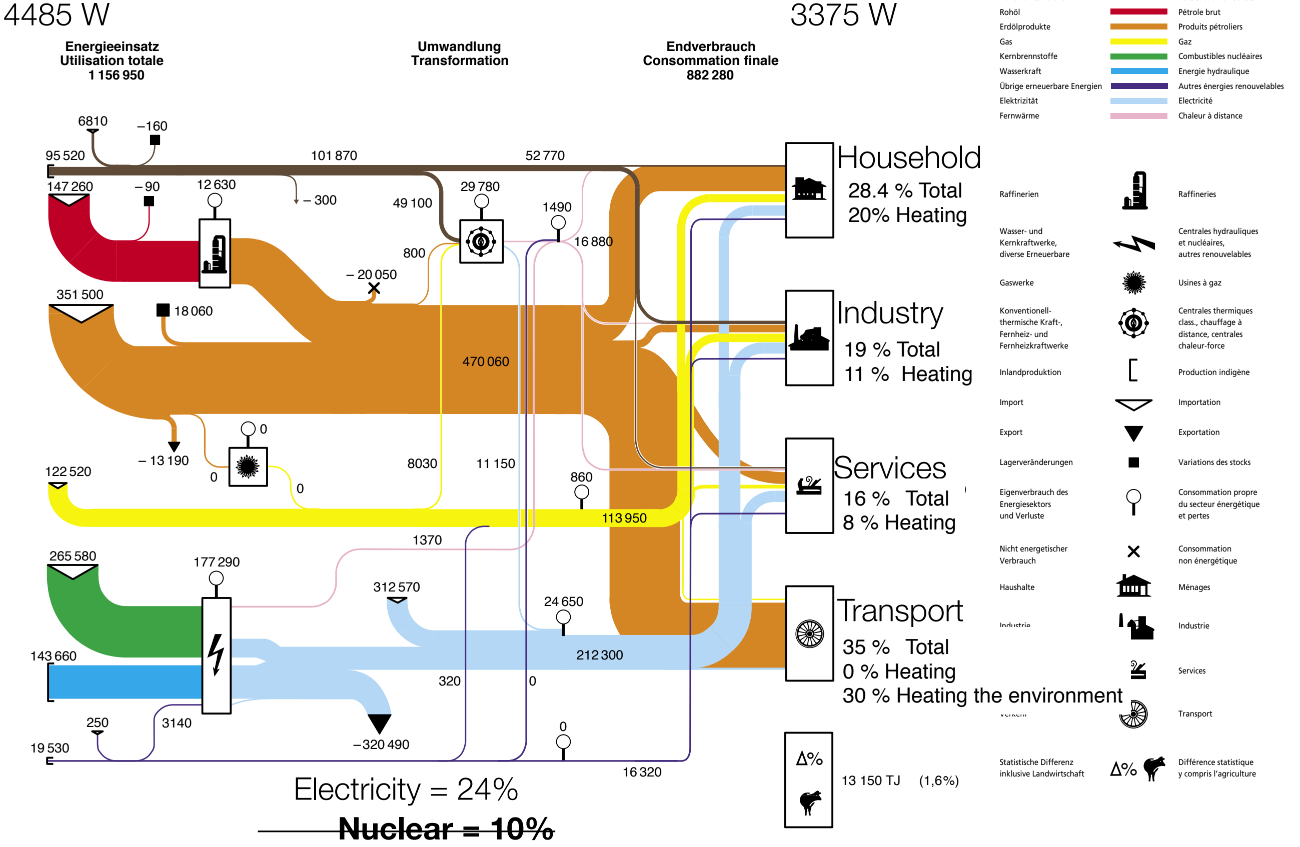
- Efficient energy and resources use and reuse
- Efficient energy conversion
- Integration of renewable energy resources
- Large Scale and Complex System integration
- Sustainable processes & Environmental impact

Energy Technology Perspective 2010, *International Energy Agency , 2010*

The Swiss Energy system today

Fig. 5 *Detailliertes Energieflussdiagramm der Schweiz 2012 (in TJ)*
Flux énergétique détaillé de la Suisse en 2012 (en TJ)

W means Wyear/year/cap



Household
28.4 % Total
20% Heating

Industry
19 % Total
11 % Heating

Services
16 % Total
8 % Heating

Transport
35 % Total
0 % Heating
30 % Heating the environment

Holz/Kohle/Abfälle	🟫	Bois/Charbon/Déchets
Rohöl	🟥	Pétrole brut
Erdölprodukte	🟧	Produits pétroliers
Gas	🟨	Gaz
Kernbrennstoffe	🟩	Combustibles nucléaires
Wasserkraft	🟦	Energie hydraulique
Übrige erneuerbare Energien	🟪	Autres énergies renouvelables
Elektrizität	🟦	Electricité
Fernwärme	🟥	Chaleur à distance
Raffinerien		Raffineries
Wasser- und Kernkraftwerke, diverse Erneuerbare	ϟ	Centrales hydrauliques et nucléaires, autres renouvelables
Gaswerke	✹	Usines à gaz
Konventionell-thermische Kraft-, Fernheiz- und Fernheizkraftwerke	◎	Centrales thermiques class., chauffage à distance, centrales chaleur-force
Inlandproduktion	[	Production indigène
Import	▽	Importation
Export	▼	Exportation
Lagerveränderungen	■	Variations des stocks
Eigenverbrauch des Energiesektors und Verluste	⚲	Consommation propre du secteur énergétique et pertes
Nicht energetischer Verbrauch	×	Consommation non énergétique
Haushalte		Ménages
Industrie		Industrie
		Services
		Transport
Statistische Differenz inklusive Landwirtschaft	Δ%	Différence statistique y compris l'agriculture

Electricity = 24%

~~Nuclear = 10%~~

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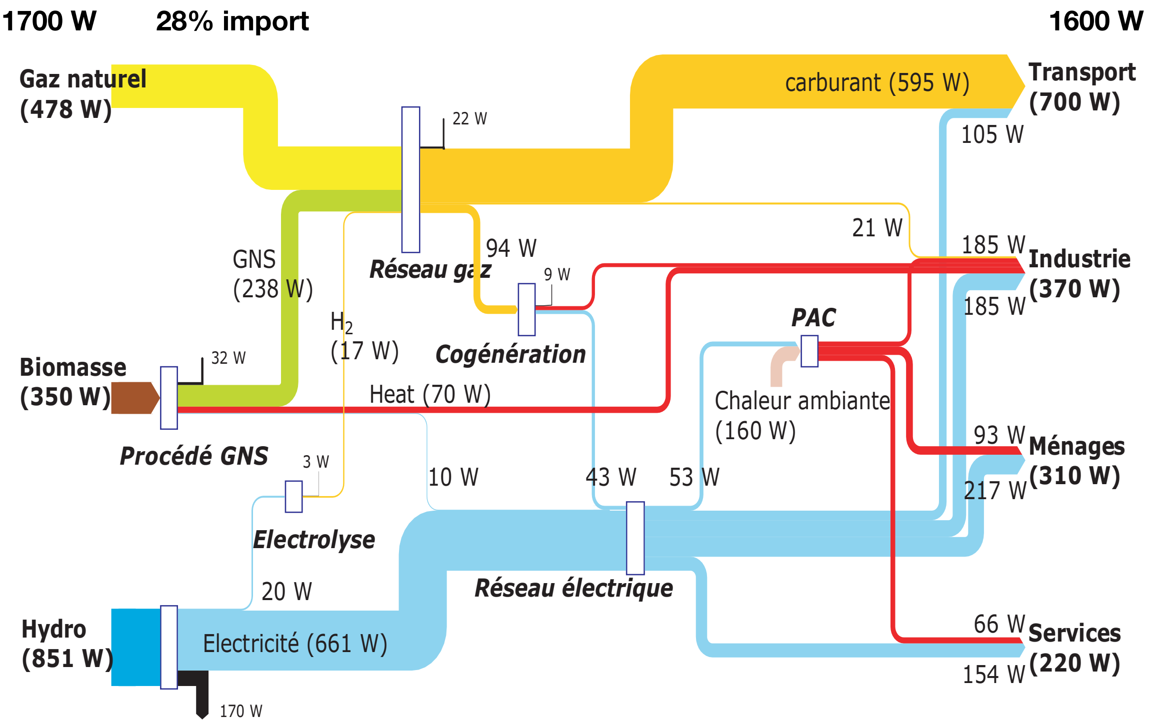
And One future One : 2000 W Society

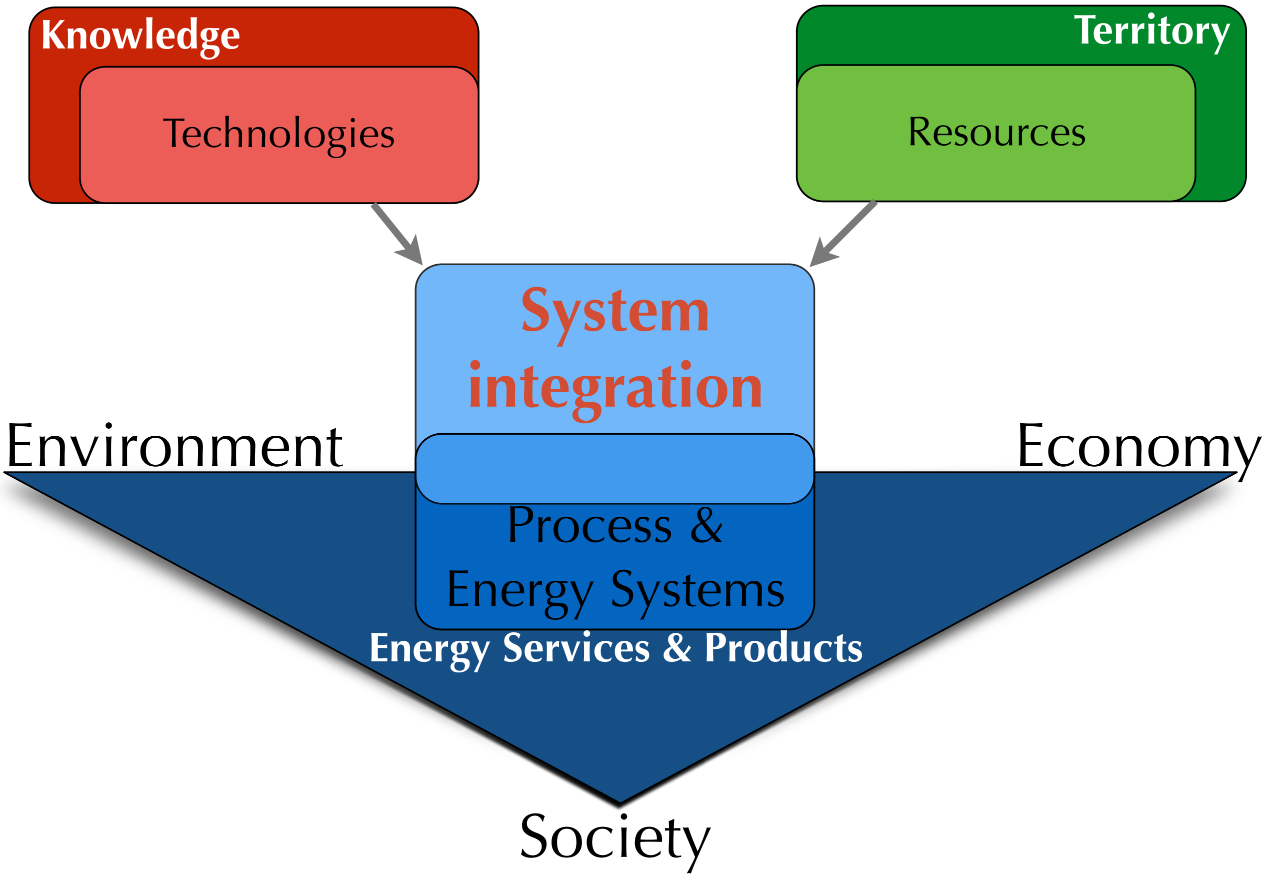


W means Wyear/year/cap

Gassner, et al. *Energy and Environmental Science* 4, no. 5 (2011): 1742–1758.

©Francois Marechal -IPESE-IGM-STI-EPFL Marechal, Francois, Daniel Favrat, and Eberhard Jochem. *Resources, Conservation and Recycling* 44, no. 3 (2005): 245–262.

Sustainable Energy System design



Knowledge

Technologies

Territory

Resources

System integration

Process & Energy Systems

Energy Services & Products

Environment

Economy

Society

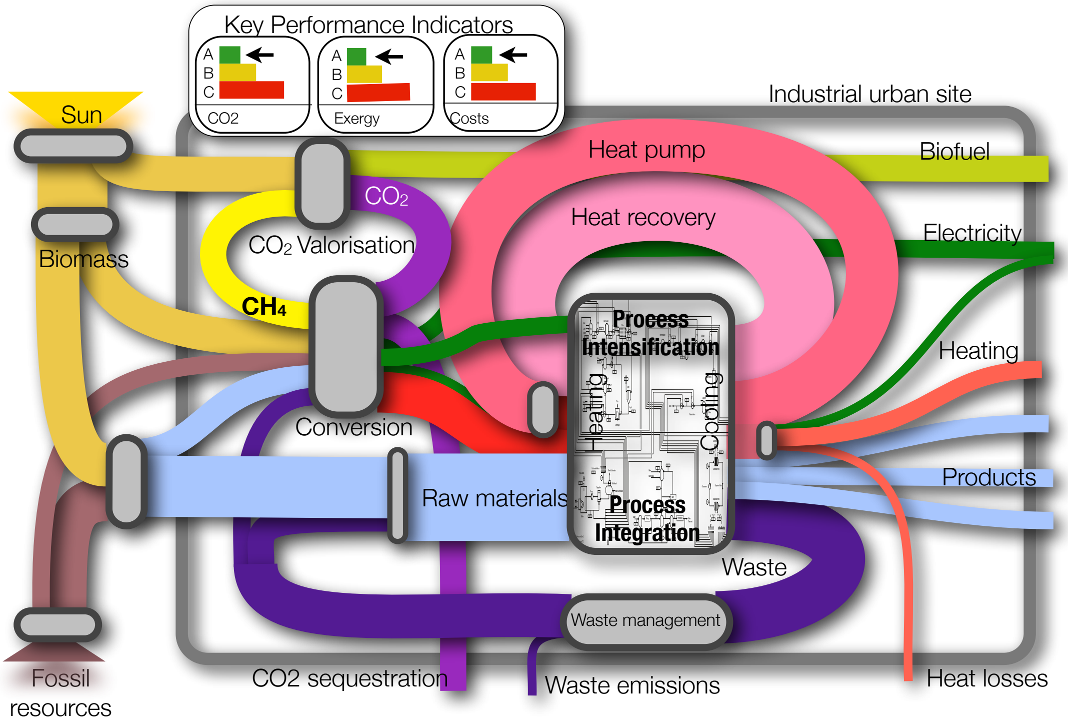
Energy Transition

- **Actions**
  - Sobriety => ask less for the same services
  - Efficiency => do more from the resources
  - Integrate => Look for synergies, define the right system boundaries
  - Renewables => Integrate the endogenous resources
  - Invest => Capital for equipments

The Vision : energy transition by system integration

Process system engineering

Selection, Integration, Sizing and optimal Operation in industrial system



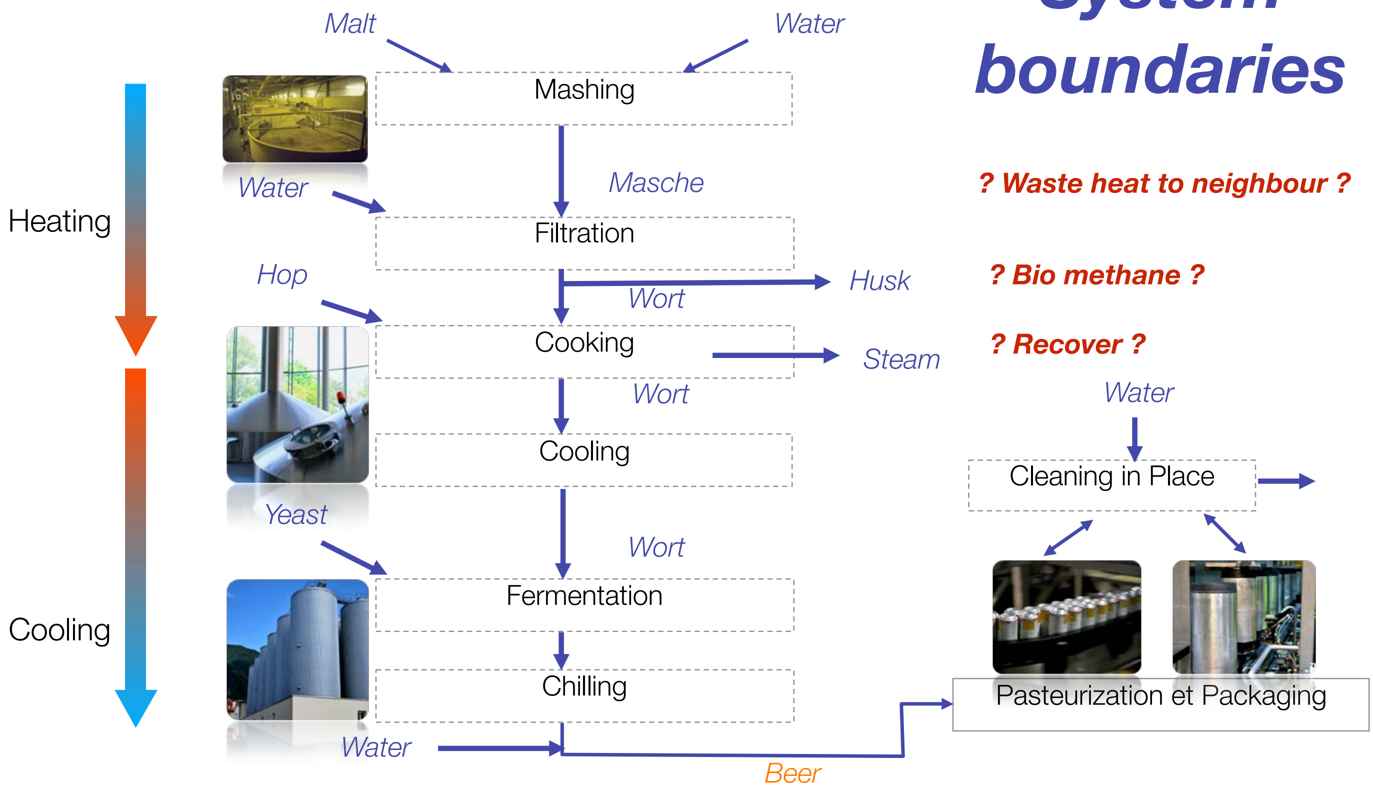
Process efficiency

Example in a brewing process

Analysing the process requirement

Beer Production Process

System boundaries



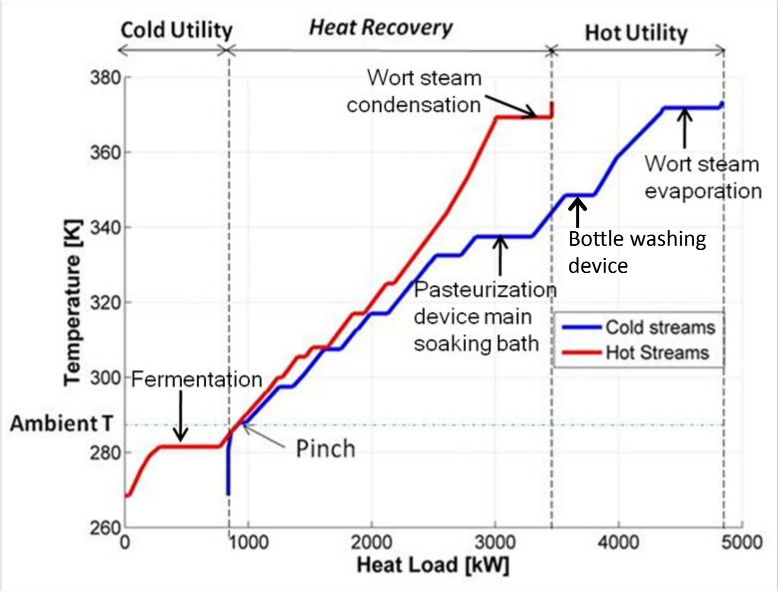
? Waste heat to neighbour ?

? Bio methane ?

? Recover ?

Maximum heat recovery by process integration

- **Heat recovery but magic heat input/output**
  - 2700 kW out of 4000 kW can be recovered by heat exchange

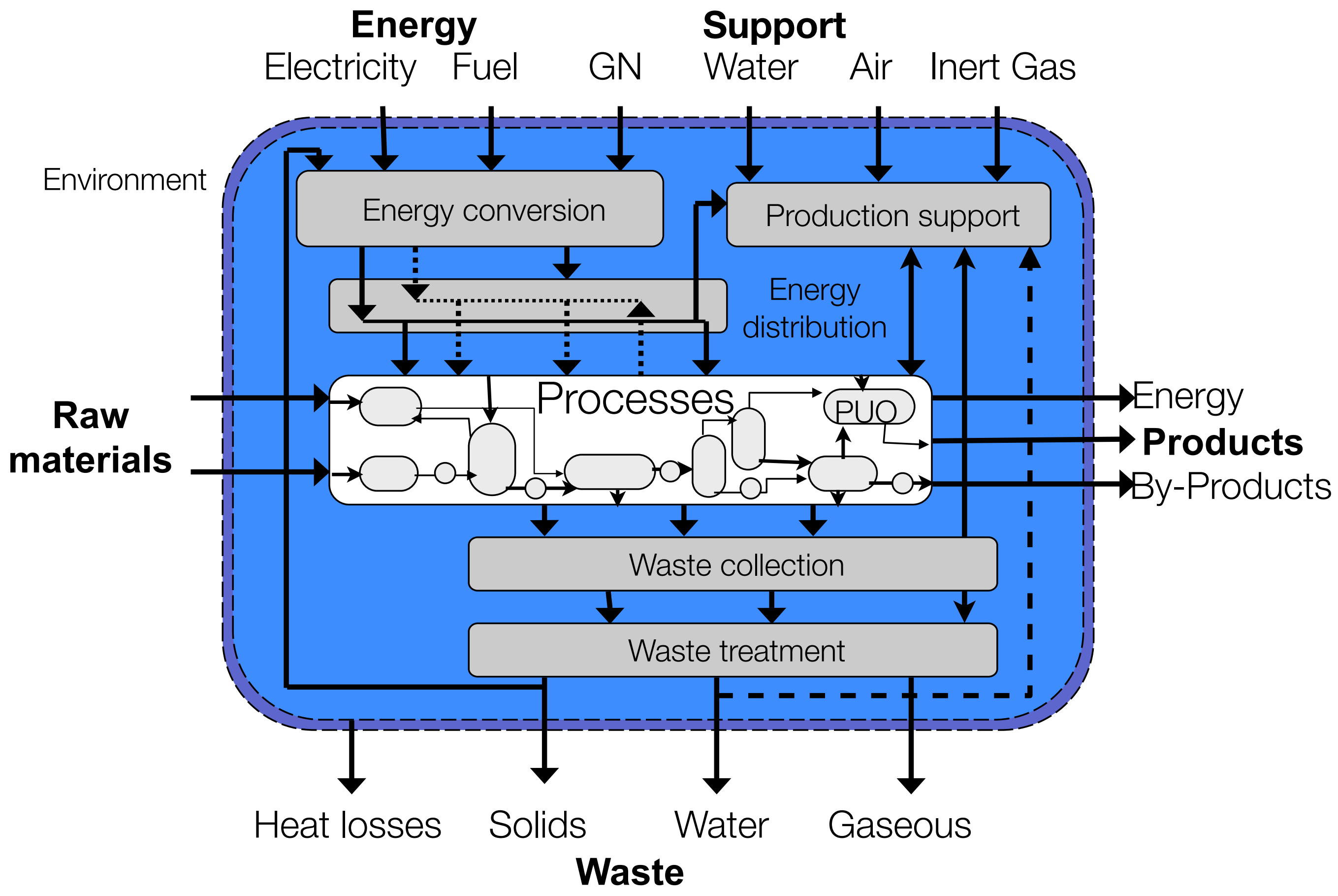


Pinch analysis based on ΔTmin assumption

Utility	MER [kW]	Current [kW]
Hot utility	1386	2220
Cold utility	-	**16**
Refrigeration utility	837	**1200**

Heat recovery leads to 37 % energy savings

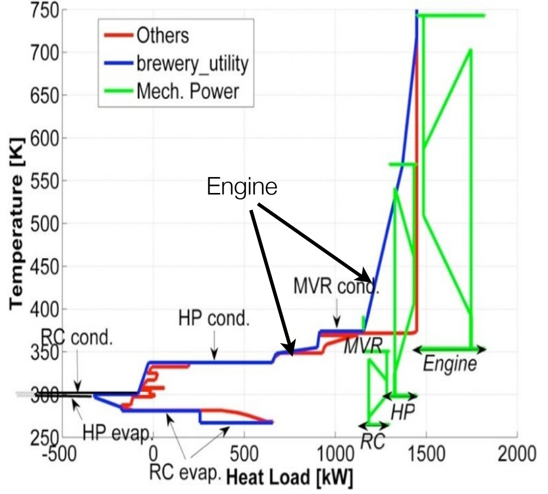
The process system integration

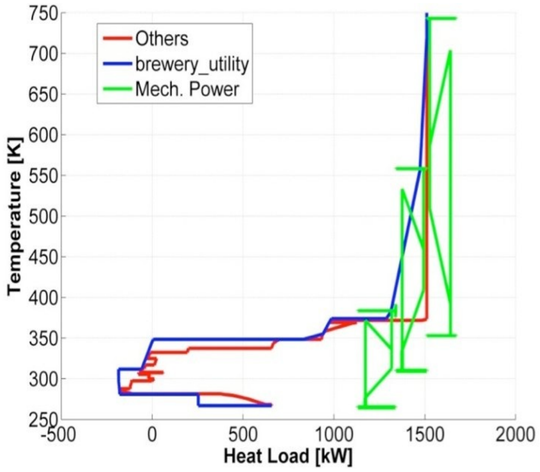


Energy conversion system integration

- **2 heat pumps + 1 cogeneration engine**
  - HP1 set up 1 (Tcond=340K)

HP 2 set up (T$_{cond}$=351K)





Fuel	1677 kW
CHP	**-374 kWe**
« Heat Pumps »	**295 kWe**
Cooling Water	3.0 kg/s

Fuel	1140 kW
CHP	**-166 kWe**
« Heat Pumps »	**379 kWe**
Cooling Water	0.2 kg/s

Becker H., Spinato G. and Marechal F., 2011b, A multi objective optimization method to integrate heat pumps in industrial processes, Computer Aided Chemical Engineering 29, 1673–1677.

Energy conversion with Maximum Heat Recovery

Waste heat

	Unit	1.	2.	3.	4.
Natural Gas	kW	2088	3279	1677	1140
Electricity	kW	184	-863	-80	212
Cooling Water	kg/s	17.1	17.1	3.2	0.2
Run. Costs FR	k€/yr	332	210	205	212
Run. Costs GER	k€/yr	520	283	312	336
TOTAL Costs FR	k€/yr	332	308	274	274
TOTAL Costs GER	k€/yr	520	380	381	398
TOTAL CO	ton/yr	2459	3544	1912	1372
TOTAL CO	ton/yr	2987	1094	1686	1976

1. Gas Boiler 2.Gas CHP 3.Gas CHP+MVR+HP (T_{cond}=66.5°C) 4.Gas CHP+MVR+HP (T_{cond}=77.5°C)

Energy /Resource	Unit Cost 2007 (Without Taxes)	CO_2 Emissions
France		
Electricity	0.0541€/kWh_e	55g_{CO2}/kWh_e
Natural Gas	0.0271€/kWh_{LHV}	231g_{CO2}/kWh_{LHV}
Water	0.00657€/m^3	-
Germany		
Electricity	0.0927€/kWh_e	624g_{CO2}/kWh_e
Natural Gas	0.0417€/kWh_{LHV}	231g_{CO2}/kWh_{LHV}

Waste management integration

- **Organic waste (husk) bio-methanation**
  - 75 Nm^3 CH_4/t husk
- **However…**
  - Extra investment (digester), increased electric consumptions (blender, pumps)
  - Heating requirement (Cold stream @ 35 °C)

- **Available : 1660 kW as LHV of CH_4**

Evaluation : Bio-Methane integration : Results

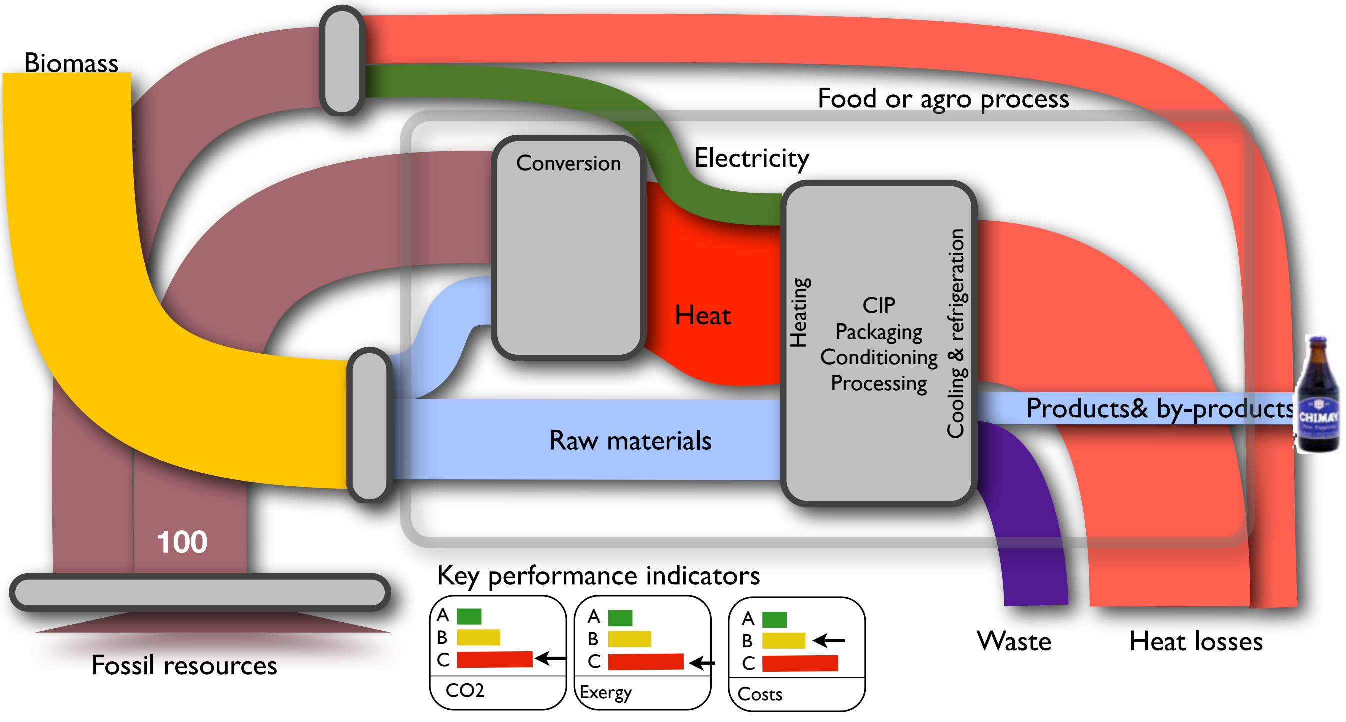
	Unit	1.	2.	3.	4.
Biogas	kW	1660	1660	1660	1660
Natural Gas	kW	664 (2088)	711 (3279)	480 (1677)	200 (1140)
Electricity	kW	264 (184)	-924 (-863)	-298 (-80)	-219 (212)
Water	kg/s	17.1	17.1	3.2	0.2
Run. Costs FR	k€/yr	161 (332)	-31 (210)	-16 (205)	-32 (212)
Run. Costs GER	k€/yr	260 (520)	-280 (283)	-38 (312)	-60 (336)
TOTAL Costs FR	k€/yr	238 (332)	145 (308)	124 (274)	115 (274)
TOTAL Costs GER	k€/yr	338 (520)	-105 (380)	101 (381)	88 (398)
TOTAL CO	ton/yr	839 (2459)	566 (3544)	471 (1912)	170 (1372)
TOTAL CO	ton/yr	1588 (2987)	-2060 (1094)	-377 (1686)	-452 (1976)

- **Natural gas = -95 %**
- **Electricity = -147 %**

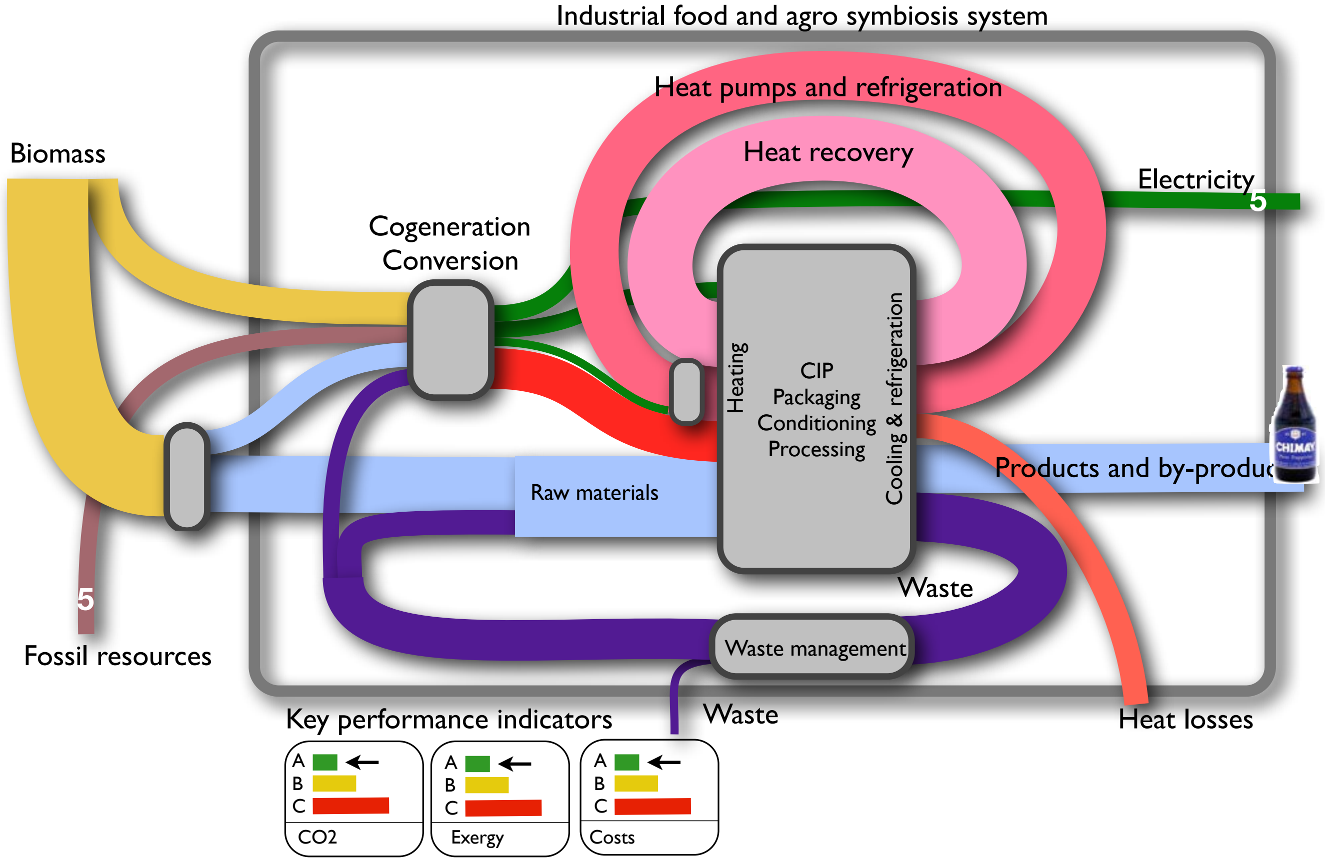
Import : 200 kW_{NG}
Export : 220 kWe

Becker H., Spinato G. and Marechal F., 2011b, A multi objective optimization method to integrate heat pumps in industrial processes, Computer Aided Chemical Engineering 29, 1673–1677.

Conclusions : Before the analysis



Conclusion : if you use the hidden fuel



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Open questions : Process energy efficiency

- Holistic system approach
  - Think globally - act locally
- Heat exchanger network design
  - Start-up & Shutdown
  - Flexibility
- Combined heat/mass integration
- Systematically extend the system boundaries
  - Urban / Industrial symbiosis
- Decision support
  - Energy price uncertainty
  - Utility - Process interface
    - *Utility => Energy bill*
    - *Process => Product quality*
- Energy service companies
  - Define a business from the integration ?

Site Scale integration

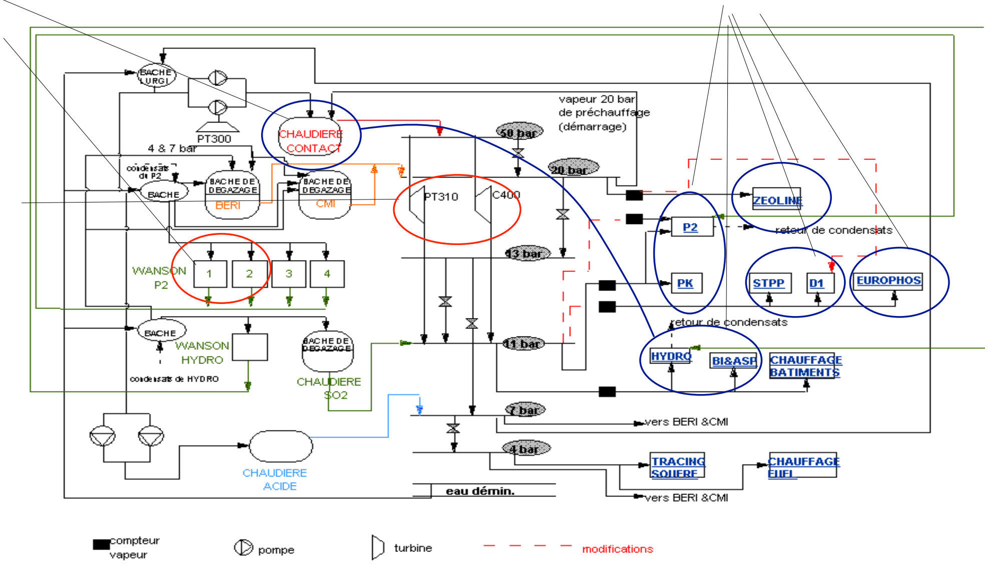
Steam Network

Heat recovery

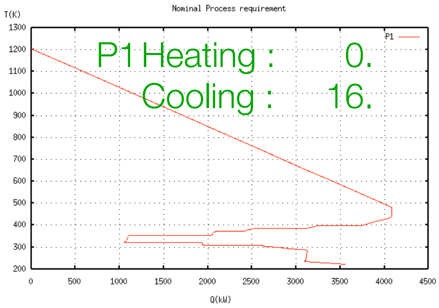
Boilers

CHP Turbines

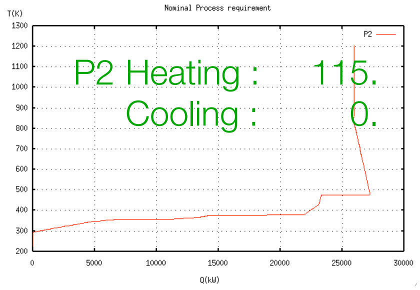
Processes



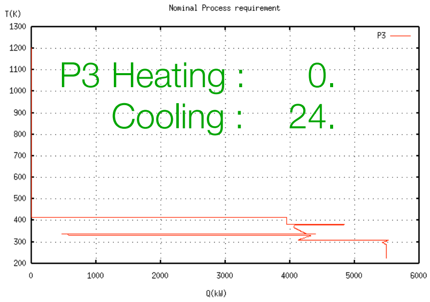
Industrial site integration (symbiosis)



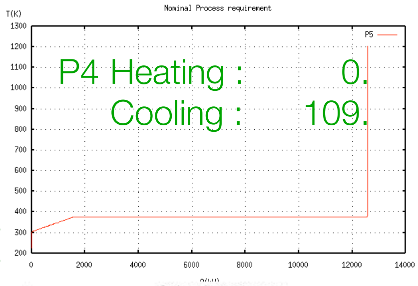
P1 Heating : 0.
Cooling : 16.



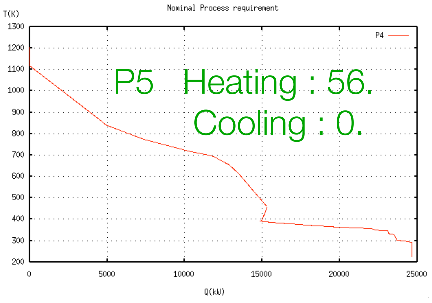
P2 Heating : 115.
Cooling : 0.



P3 Heating : 0.
Cooling : 24.

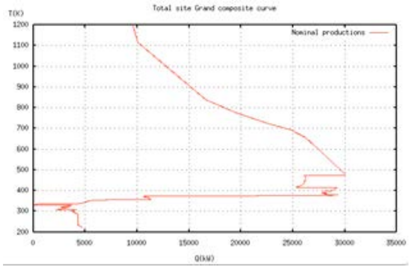


P4 Heating : 0.
Cooling : 109.



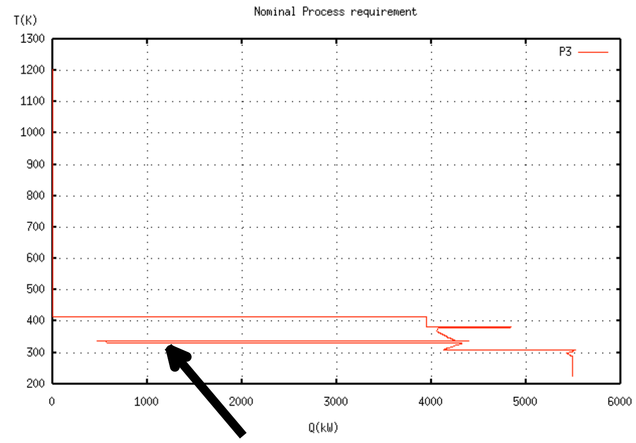
P5 Heating : 56.
Cooling : 0.

SITE reference
Heating : 100.
(171.)
Cooling : 78.
(150.)

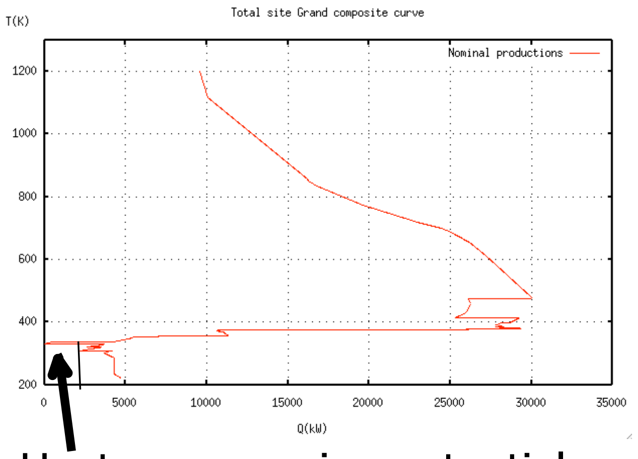


Integrated SITE Heating integration
Heating : 42.
with Heat Pump : 30.

Heat recovery



Heat pump not useful for P3

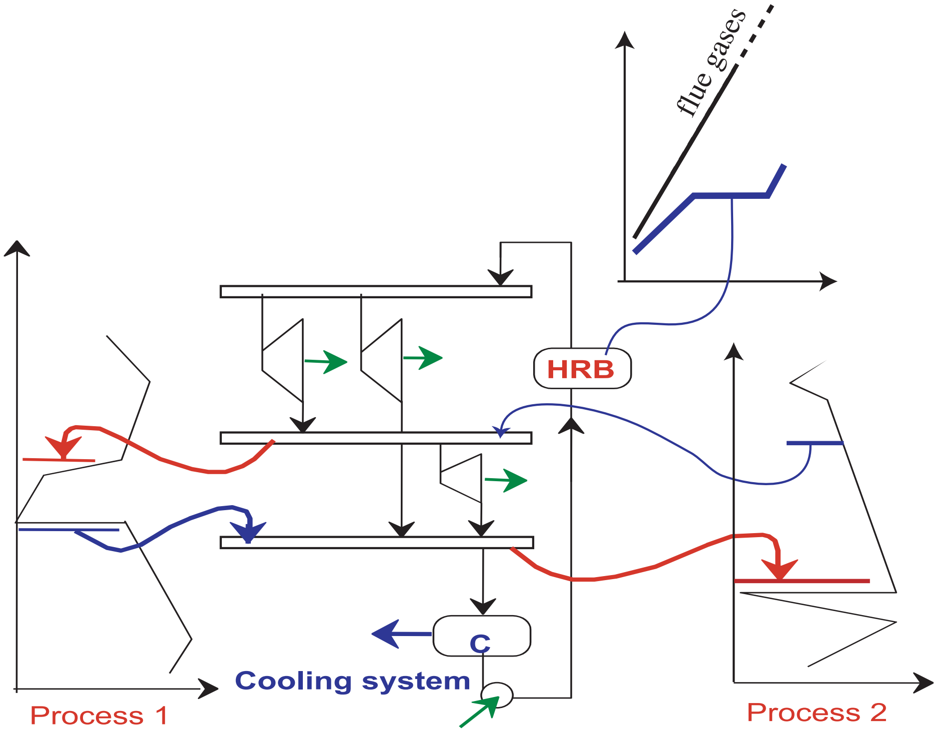


Heat pump saving potential
for total site : 2957 kW (30%)

- **Representation with all the hot and cold streams**
  - System sub-divisions
  - No abstraction of pockets potentials

Steam network integration

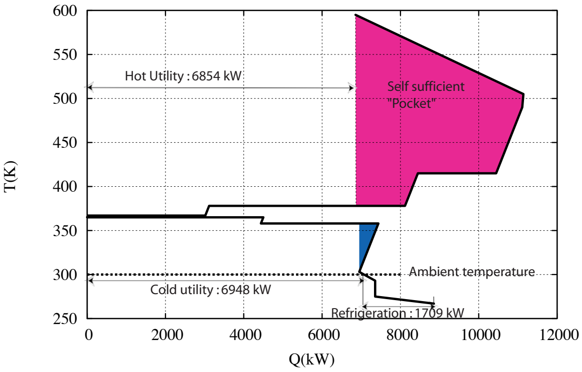
Combined heat and power production



Application : the engineer creativity

Maximum energy recovery

	Energy	Exergy
Heating (kW)	+6854	+567
Cooling (kW)	-6948	- 1269
Refrigeration (kW)	+1709	+ 157



Hot utility

Boiler house : NG (44495 kJ/kg)

Air Preheating

Gas turbine : NG (el. eff = 32%)

Steam cycle

Header	P (bar)	T (K)	Comment
HP2	92	793	superheated
HP1	39	707	superheated
HPU	32	510	condensation
MPU	7.66	442	condensation
LPU	4.28	419	condensation
LPU2	2.59	402	condensation
LPU3	1.29	380	condensation
DEA	1.15	377	deaeration

Heat pumps
Fluid R123

	P_{low} (bar)	T_{low} (°K)	P_{high} (bar)	T_{high} (K)	COP -	kWe
Cycle 3	5	354	7.5	371	15	130
Cycle 2	6	361	10	384	12	323
Cycle 0	6	361	7.5	371	28	34

Refrigeration

Refrigerant	R717	Ammonia
Reference flowrate	0.1	kmol/s
Mechanical power	394	kW

	P (bar)	T_{in} (°K)	T_{out} (°K)	Q kW	$\Delta T min/2$ (°K)
Hot str.	12	340	304	2274	2
Cold str.	3	264	264	1880	2

Results

$$Total1 = \dot{m}_{fuel} * LHV_{fuel} + \frac{(E^+ - E^-)}{\eta_{el}} (= 55\%(NGCC))$$

$$Total2 = \dot{m}_{fuel} * LHV_{fuel} + \frac{(E^+ - E^-)}{\eta_{el}} (= 38\%(EUmix))$$

Table 9

Energy consumption and exergy efficiency of the different options

Option	Fuel $[kW_{LHV}]$	$\dot{E}^+_{grid}$ [kWe]	Total 1 $[kW_{LHV}]$	Total 2 $[kW_{LHV}]$	η_{ex} %	Losses [kW]
Comb. + frg	7071.0	371.0	7745.5	8029.7	34.9	8868.0
Comb. + stm + frg	10086.0	-2481.0	5575.1	3675.1	44.5	8830.0
GT + stm + frg	16961.0	-7195.0	3879.2	$\boxed{-1630.7}$	51.3	11197.2
hpmp + frg	0.0	832.0	1512.7	2149.9	72.4	2408.1
hpmp + stm + frg	666.0	125.0	$\boxed{893.3}$	989.0	72.6	$\boxed{1831.6}$

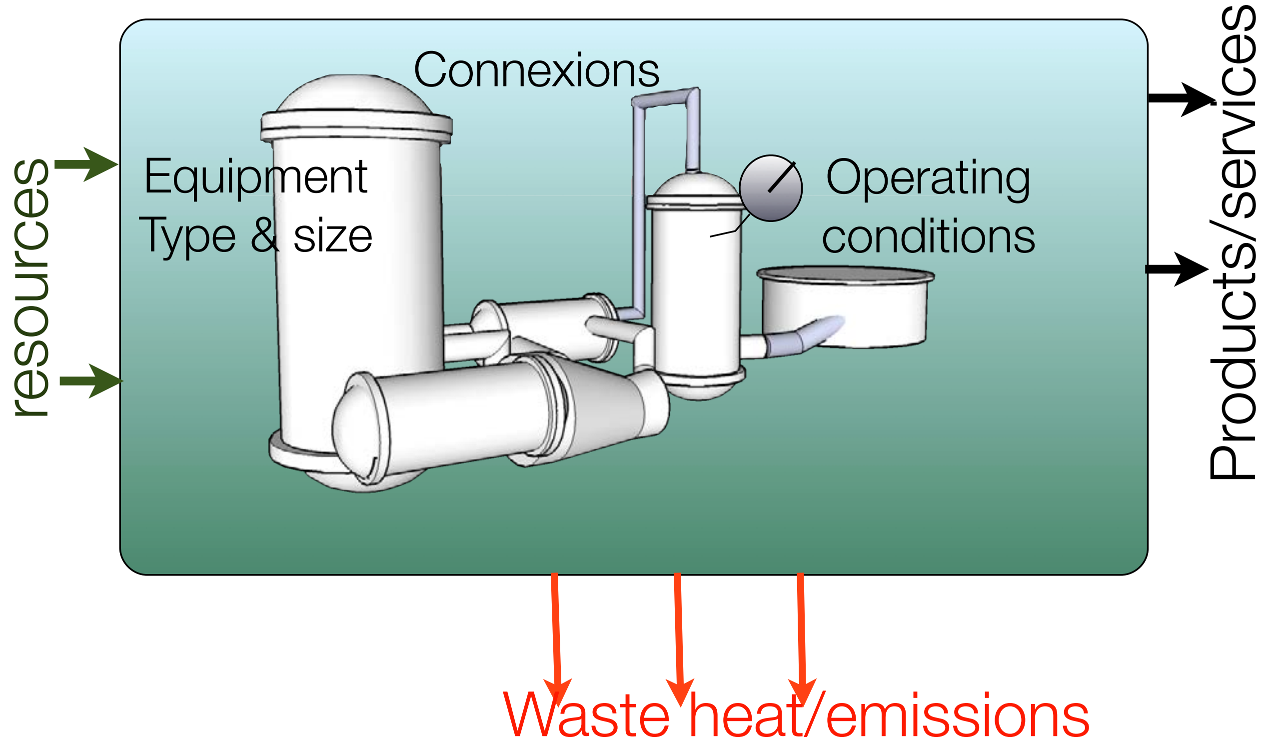
11% wrt combustion

5 % of reference

Total site integration : Open questions

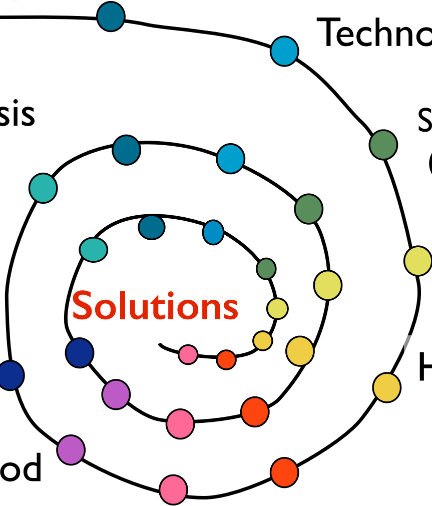
- **How to organise heat transfer between processes**
  - Third Party : ESCO ?
    - Process interfaces
      - *contract + confidentiality*
  - Restricted matches & HEN design
- **How to realise a holistic system design ?**
  - Energy conversion
    - Combined Heat - Cold and power production
    - Waste management integration
    - Combined Water/Solvent/Hydrogen integration
  - Multiperiod
    - Processes operating scenarios
  - Robustness & flexibility
    - Operation
    - Robust design / backup equipment

Process system design



The energy system engineering methodology

Energy services
Resources
Context & Constraints



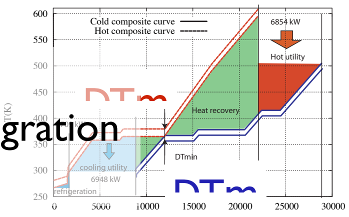
System Boundaries

Technology options

System interfaces models
(Lego bricks)

Thermo chemical
Economics
Environmental impact

Process Superstructure



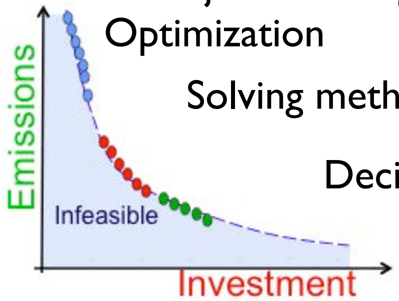
Heat &
Mass integration

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

Solutions

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

Multi-objective
Optimization



Thermo-economic Pareto

Solving method

Decision variables

OSMOSE : Computer Aided Platform

Grid computing

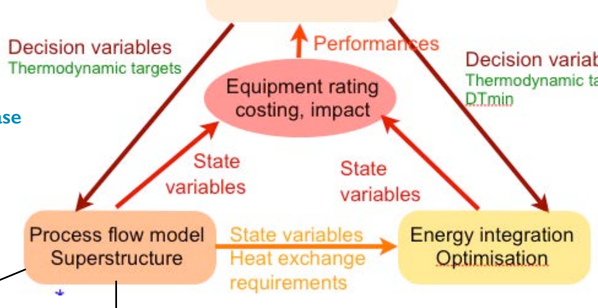
Decision support

Multi-objective optimisation
- Evolutionary - Hybrid
- Problem decomposition
- Uncertainty

Data Structuring

GIS data base
- Industrial ecology
- Urban systems

GUI : Spreadsheets, Matlab



Technology models data base
- Energy conversion
- Sharing knowledge

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)
- MODELICA
- Others possible
  - CAPE-OPEN ?
  - PROSIM
  - UNISIM ?

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

MILP/MINLP models
- Heat/mass integration
- Sub systems analysis
- Superstructure
- HEN synthesis models

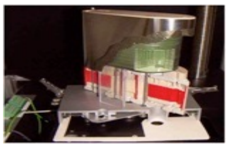
Process integration

Modeling tools integration

Process synthesis of a fuel cell hybrid system

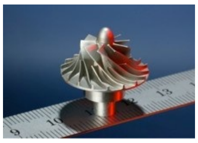
$$\eta_d = \frac{E^-}{CH4^+_{LHV}} = 80\%$$

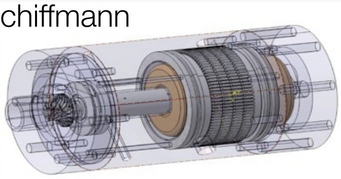
MER Jan Vanherle



15 kWe

Prof. Favrat/Schiffmann



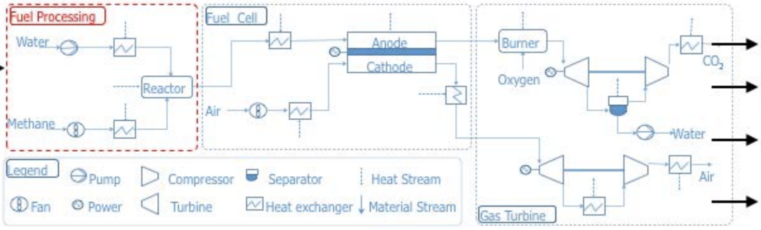


6 kWe

Flowsheet

CH4 →
Bio CH4

26.3 kWe **100%**



→ CO2

→ Elec 80 - 82% 21 kWe

→ Heat 12- 10% 5.3 kWth

→ H2O

Facchinetti, M, Daniel Favrat, and Francois Marechal. "Sub-atmospheric Hybrid Cycle SOFC-Gas Turbine with CO2 Separation." *PCT/IB2010/052558, 2011*.

Heat integration

2 kWth/kWel

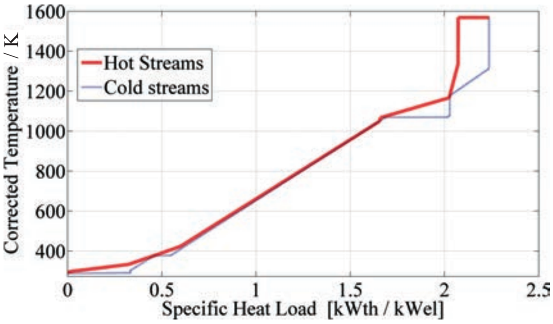


Fig. 7 HCox composite curves of optimal solution with π = 3 and max TIT = 1,573 K

Facchinetti, Emanuele, Daniel Favrat, and François Marechal. *Fuel Cells*, no. 0 (2011): 1-8.

A paradigme for the energy system ?

- **Replace centralised power plants**
  - 1 unit of 750 MWe / 61% elec

- **by ...**
  - 75000 units of 10 kWe / 80% elec
  - Distributed
  - 13% cogeneration

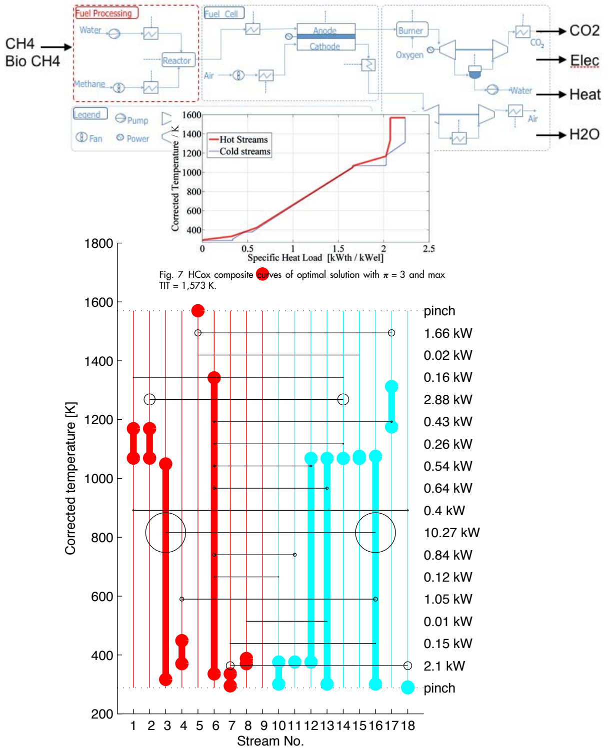
Process system design Challenge

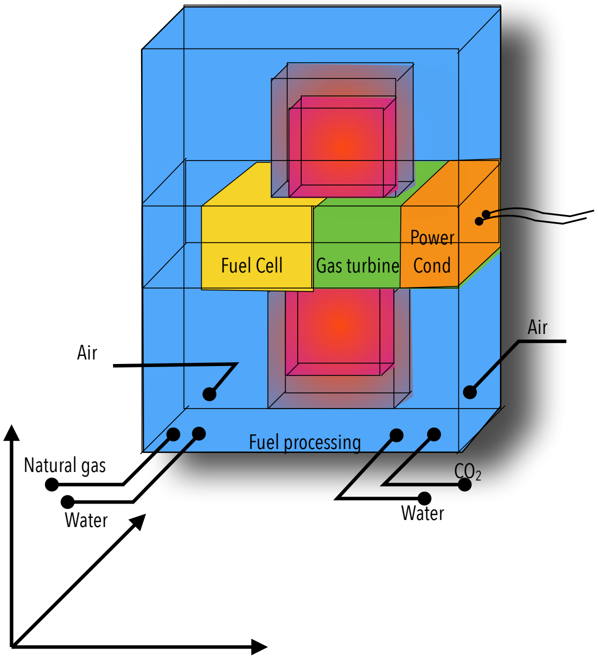
- **3D design + Lego ?**
  - 3D Design
  - 3D Models
  - Sensors
  - 4D Control
  - Grids Connected
  - or Mobile => Range extender in cars

Smart system design ?

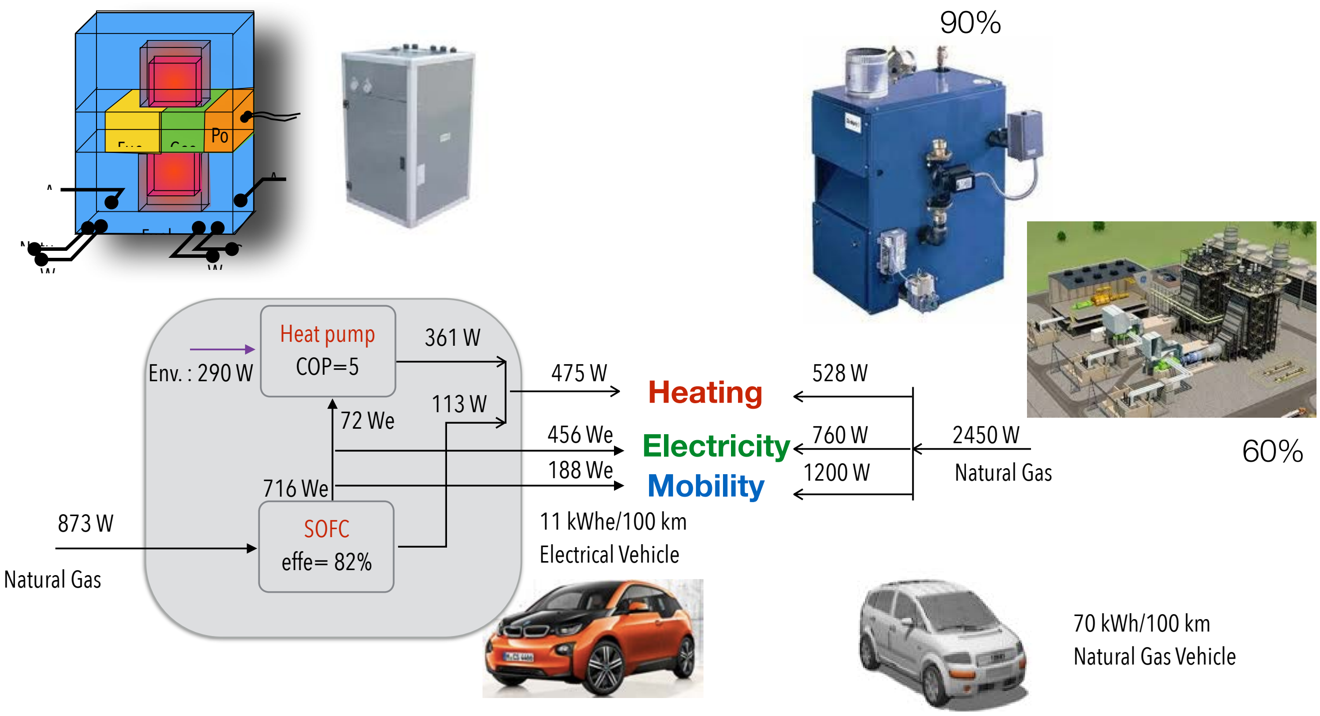
- **3D designs for 3D printing ?**

3D Design
3D Modeling
3D System control





Motivation : for a typical Swiss household



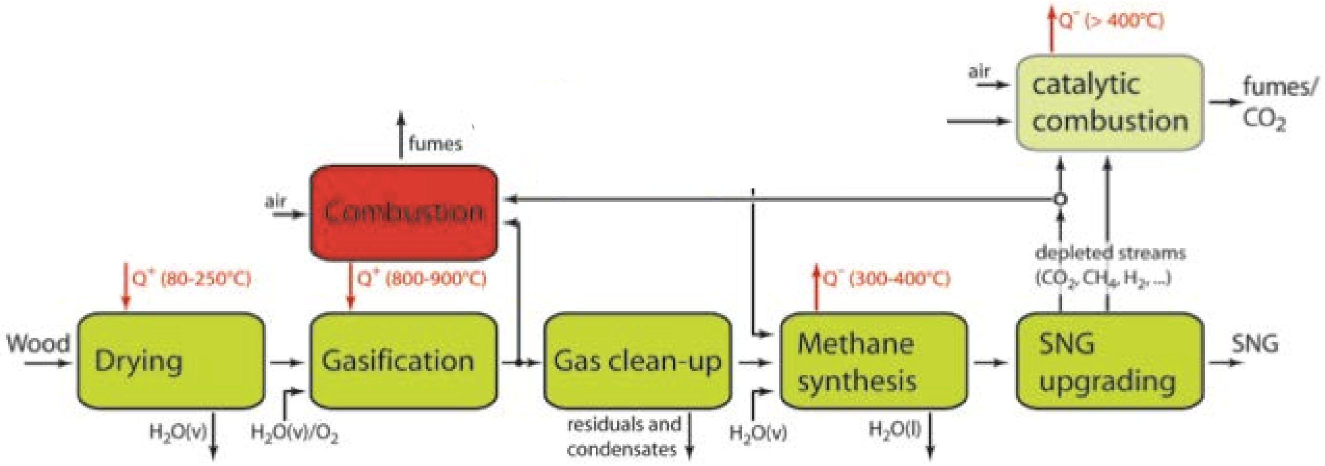
Savings : 65 %

W means Wyear/year/cap

- **Smart engineers:**
  Renewable energy integration

Producing Natural gas from Wood

Renewable natural gas : Synthetic natural gas from biomass



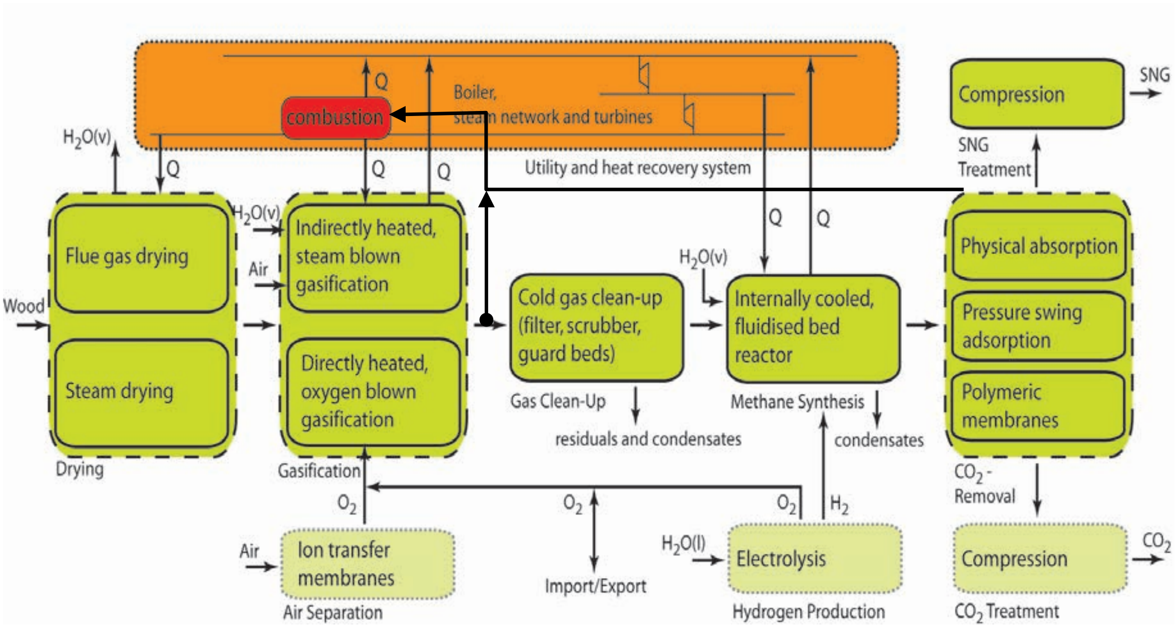
WOOD Natural Gas (SNG) CO2 (pure)

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

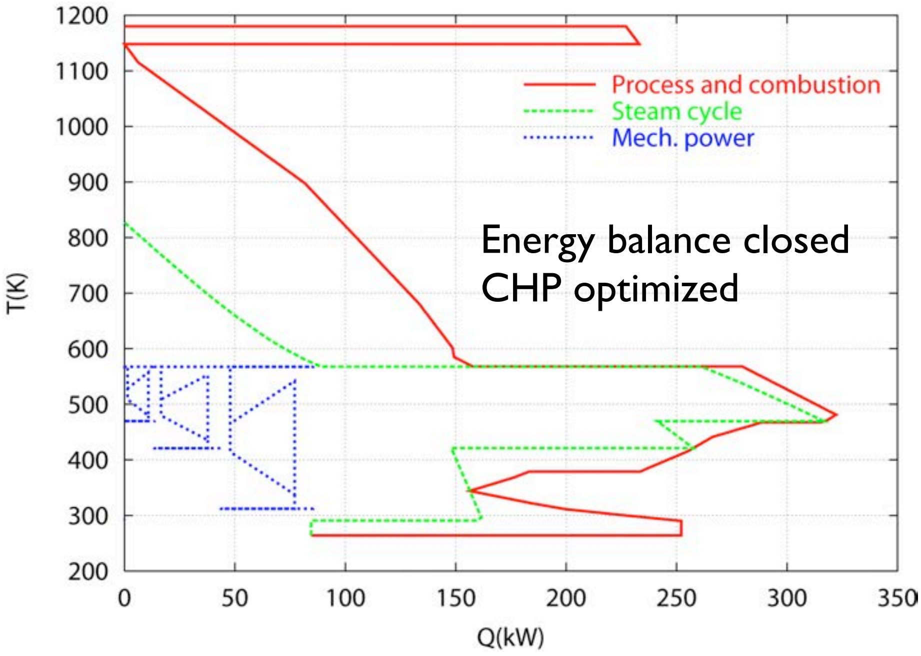
Gassner, M., and F. Maréchal. “Thermo-economic optimisation of the integration of electrolysis in synthetic natural gas production from wood.” *Energy* 33, no. 2 (February 2008): 189-198.

Closing the energy balance

Integrating heat recovery technologies in the superstructure



Process integration of the energy usage

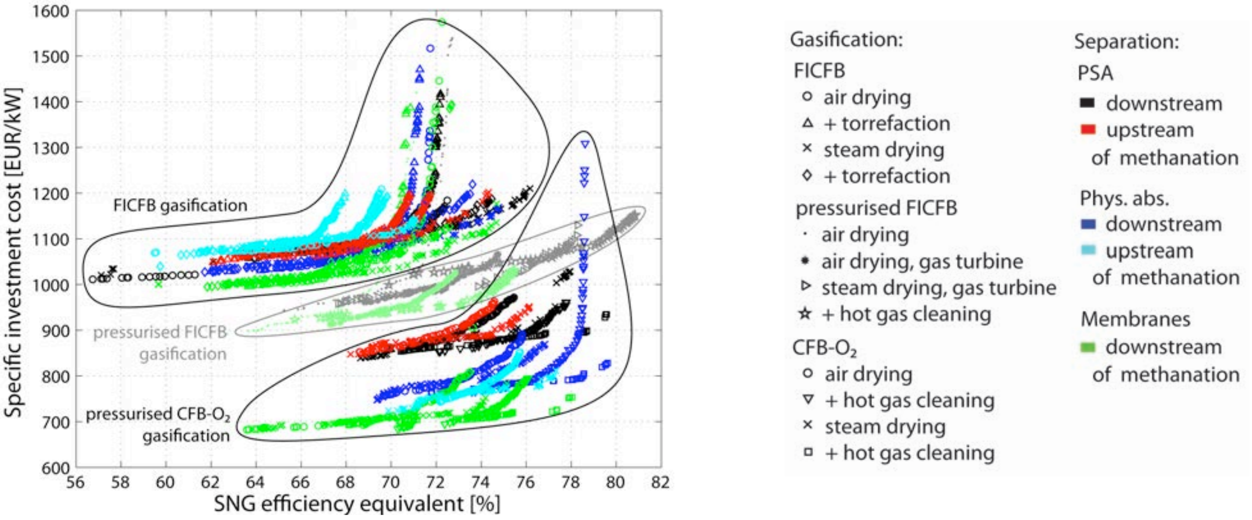


Energy balance closed
CHP optimized

Comparing options

- **Each point of the Pareto is a process design**

Thermo-economic Pareto front
(cost vs efficiency):

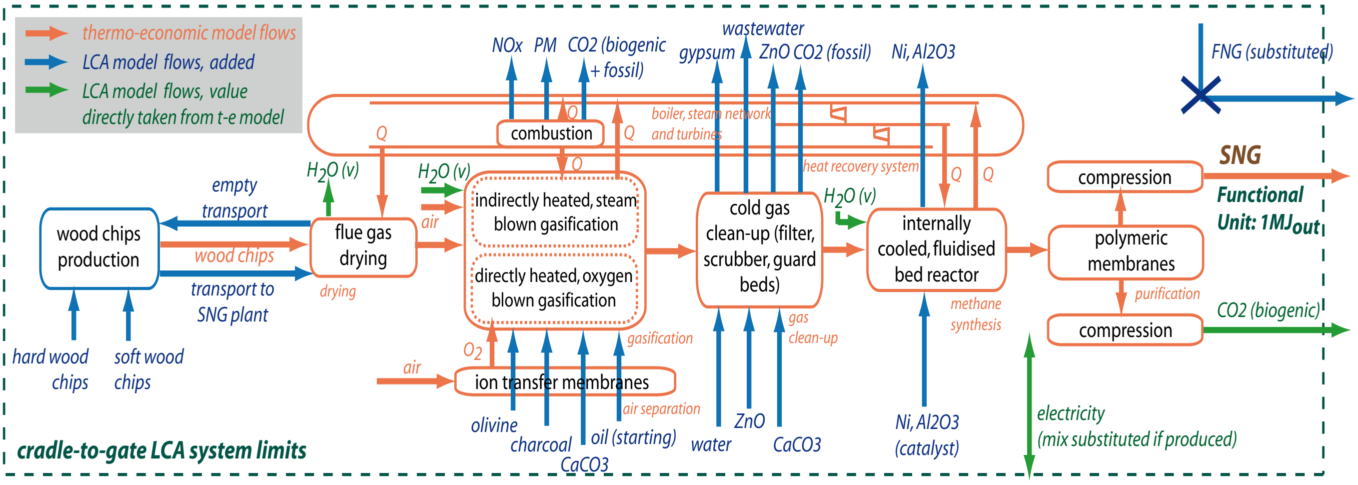


Note : 1.5 years of calculation time !

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

Identification of Life Cycle Inventory elements

- **Process superstructure, extended with LCI**

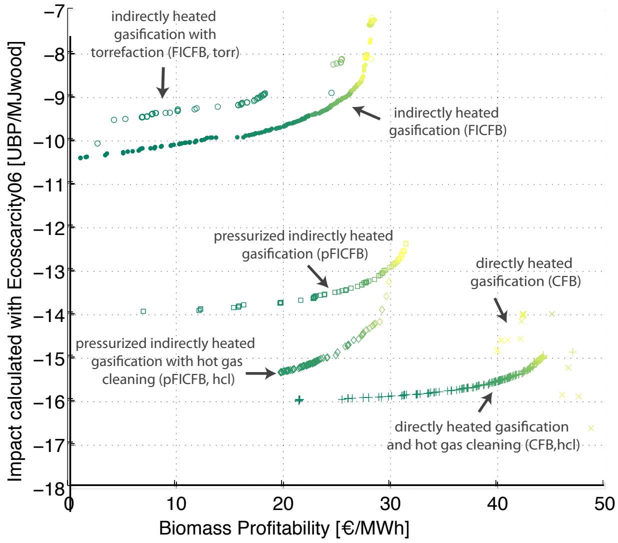


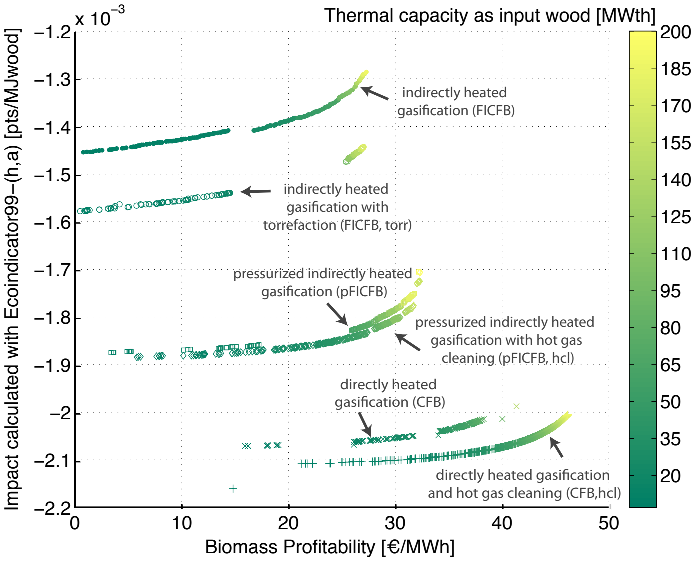
➡ **use of ecoinvent emission database (1) for each LCI element, to take into account off-site emissions**

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

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

- **Optimal configurations**



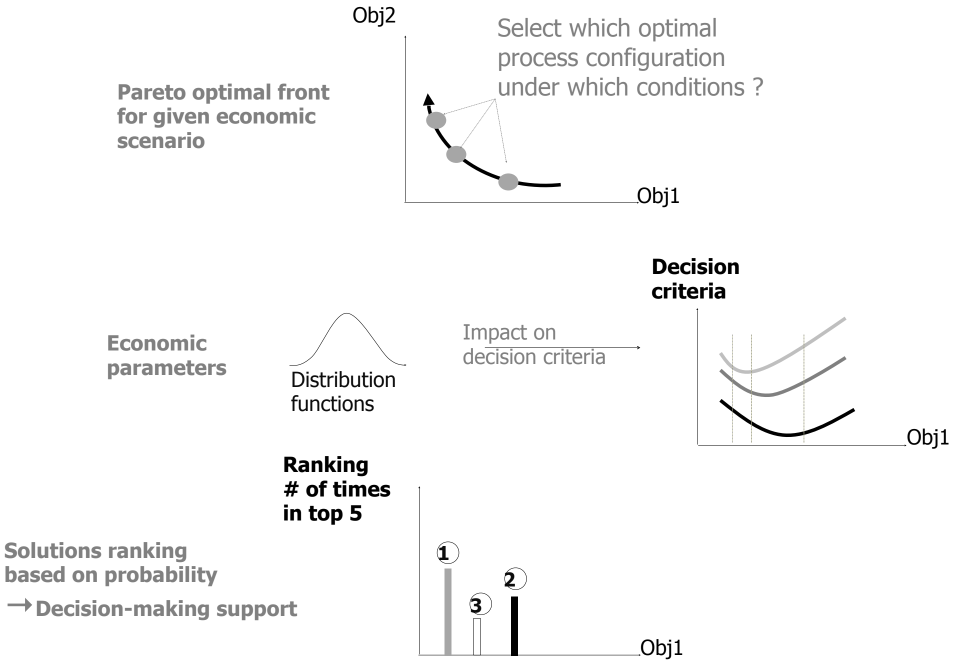


Land & supply chain are constraints

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

Decision-making

- **Selecting the process in the Pareto set**



Pareto optimal front for given economic scenario

Select which optimal process configuration under which conditions ?

Economic parameters

Distribution functions

Impact on decision criteria

Decision criteria

Ranking # of times in top 5

Solutions ranking based on probability
→Decision-making support

Decision-making

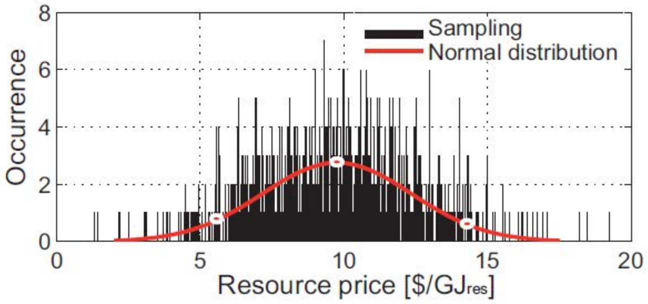
- **Uncertainty of the economical conditions**
  - Economic assumptions probability distribution functions
    - Normal, uniform, beta distribution

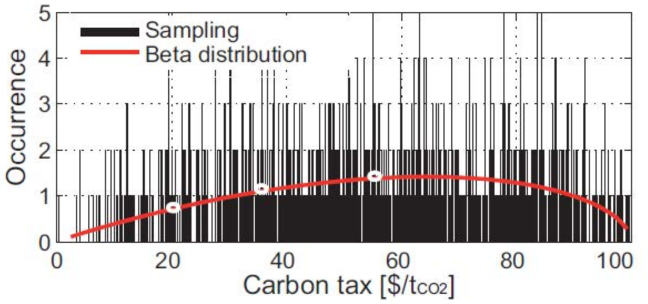
Scenario [IEA, EU, ZEP,...]	Base	Low	High
Resource price [\$/GJ$_{res}$]	9.7	14.2	5.5
Carbon tax [\$/t$_{CO2}$]	35	20	55
Yearly operation [h/y]	7500	4500	8200
Expected lifetime [y]	25	15	30
Interest rate [%]	6	4	8
Investment cost [%]	-30%	-	+30%

$$f(x;\mu,\sigma^2) = \frac{1}{\sigma\sqrt{2\Pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

$$f(x) = \frac{1}{a-b}$$

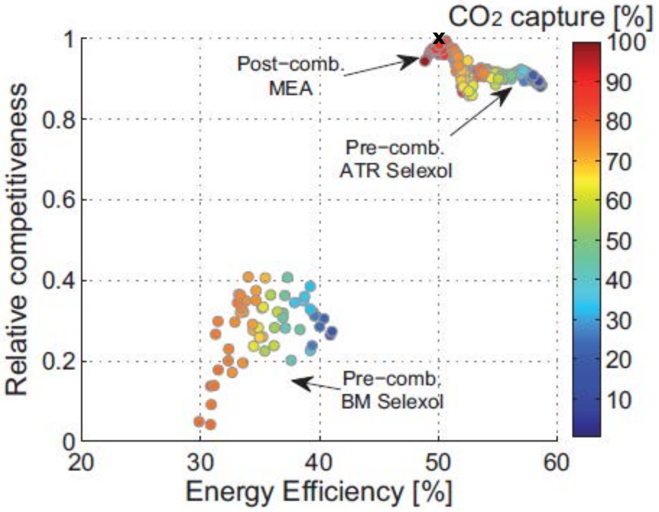
$$f(x;a,b) = cst \cdot x^{a-1} \cdot (1-x)^{b-1}$$





Decision-making

- **Relative competitiveness of Pareto solutions**
  - Ranking with regard to most economically competitive solution



  - CO_2 capture is economically competitive for capture rates between 70 and 85%!

Laurence Tock, Thesis, 2013

Open questions

- **How to deal with engineers creativity ?**
  - Combinatorial
- **Models sharing**
  - Documentation
  - Consistency
  - Transferability
- **Model interoperability**
  - Different softwares
- **Data base of models**
  - Interface ontology
  - Meta-models : e.g. from Pareto sets
  - Systematic superstructure definition
    - e.g. biorefineries
- **Integration of supply chains**
- **Integration of Life cycle Impact assessment metrics**
- **Robustness & uncertainty**

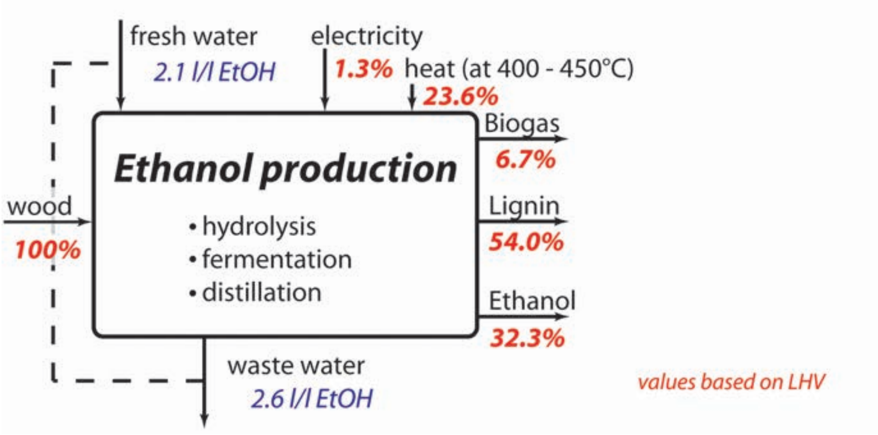
Extending the system boundaries

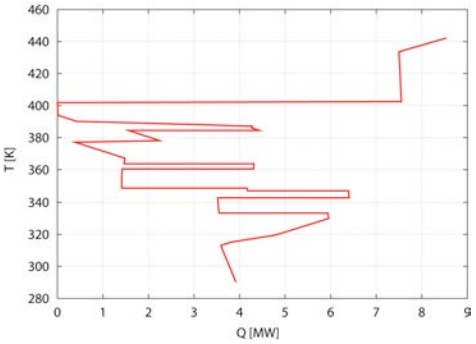
- **Biorefinery concept**
  - **Integrated biofuel system**

Site integration: process couplings

EtOH & SNG

Ethanol production from lignocellulosic biomass:

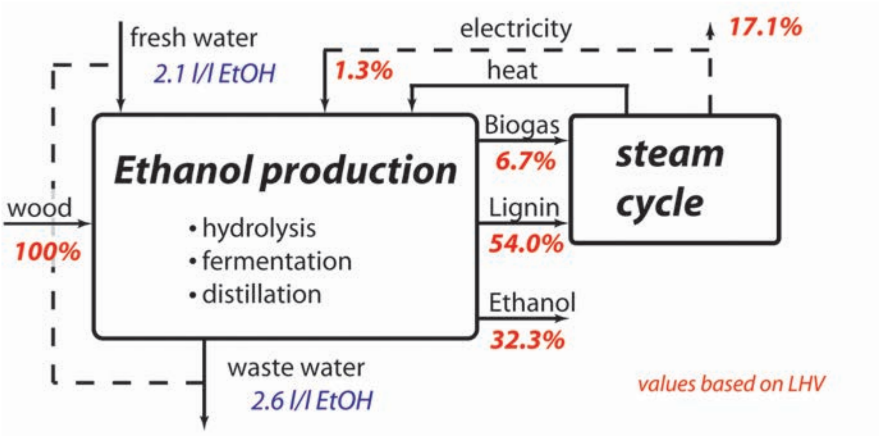


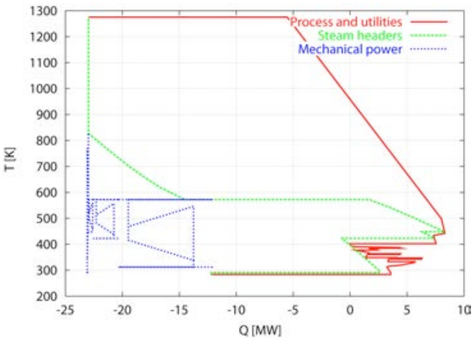


input: 58 $MW_{th,wood}$

Site integration: process couplings
EtOH & SNG

Ethanol production from lignocellulosic biomass:





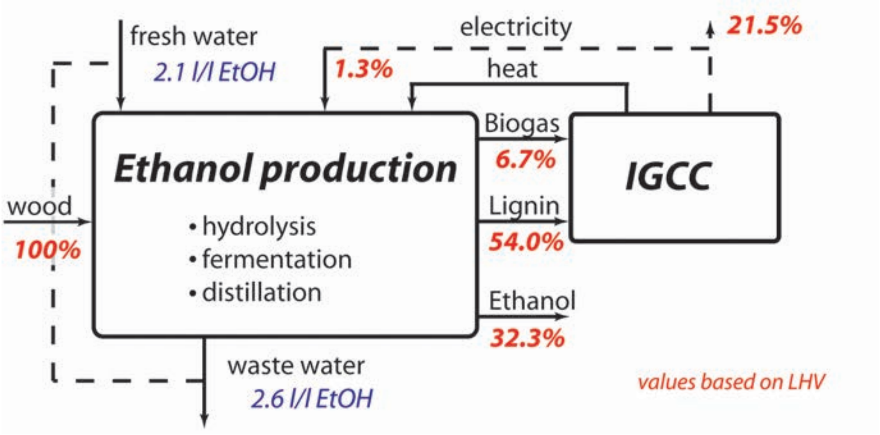
input: 58 $MW_{th,wood}$

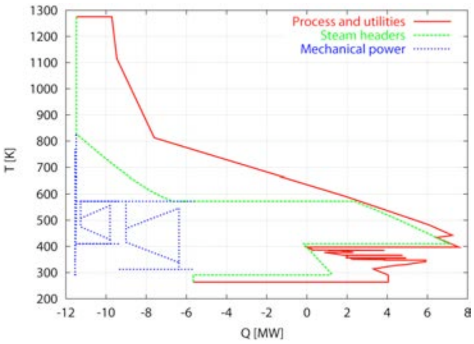
		steam cycle
Input	wood	100 %
Output	ethanol	32.3 %
	SNG	-
	electricity	17.1 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %
total efficiency		49.4 %

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

Site integration: process couplings
EtOH & SNG

Ethanol production from lignocellulosic biomass:





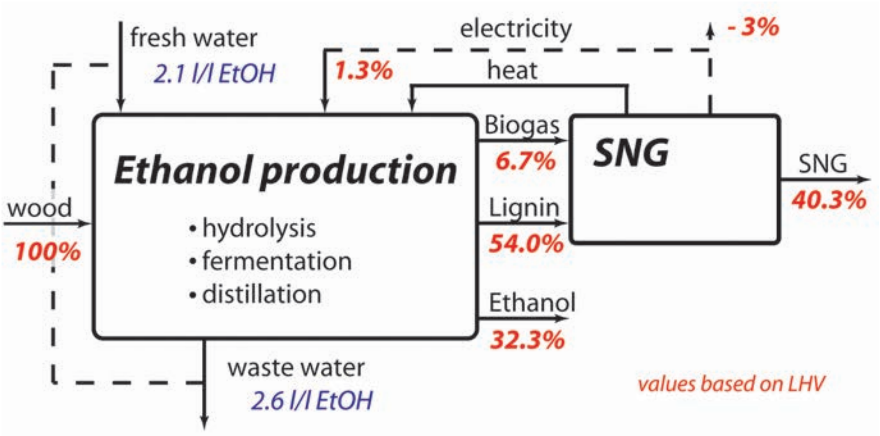
input: 58 $MW_{th,wood}$

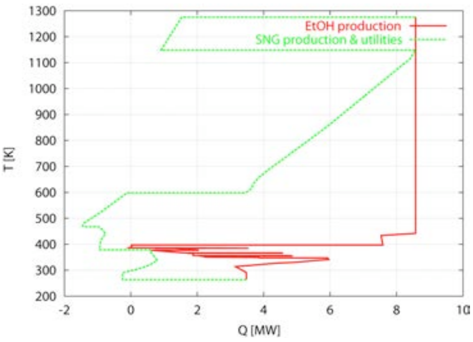
		steam cycle	IGCC
Input	wood	100 %	100 %
Output	ethanol	32.3 %	32.3 %
	SNG	-	-
	electricity	17.1 %	21.5 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %	70.0 %
total efficiency		49.4 %	53.8 %

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

Site integration: process couplings
EtOH & SNG

Ethanol production from lignocellulosic biomass:





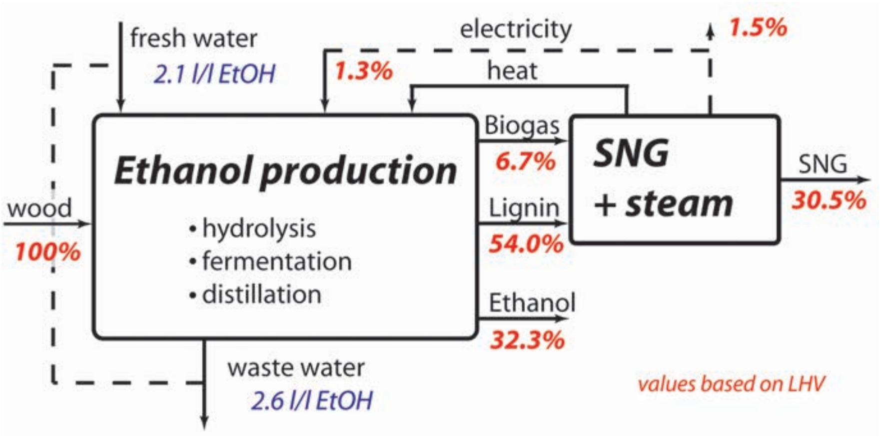
input: 58 $MW_{th,wood}$

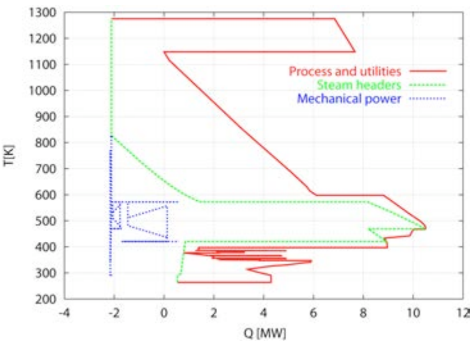
		steam cycle	IGCC	SNG
Input	wood	100 %	100 %	100 %
	ethanol	32.3 %	32.3 %	32.3 %
Output	SNG	-	-	40.3 %
	electricity	17.1 %	21.5 %	-3.0 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %	70.0 %	67.3 %
total efficiency		49.4 %	53.8 %	70.5 %

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

Site integration: process couplings
EtOH & SNG

Ethanol production from lignocellulosic biomass:





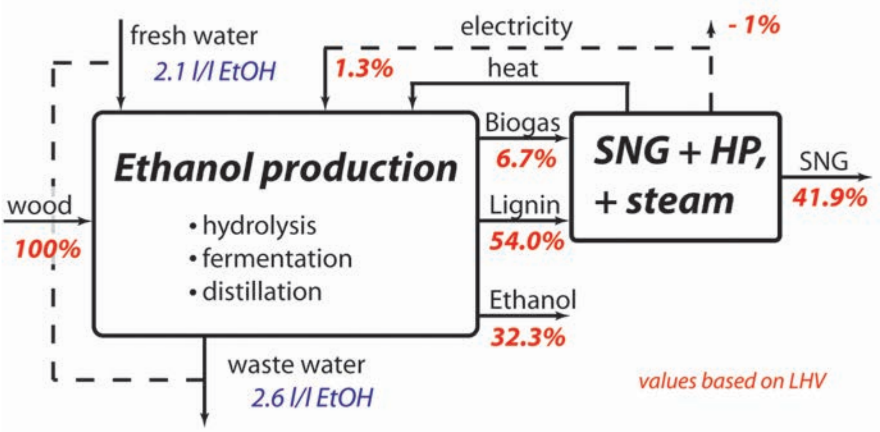
input: 58 $MW_{th,wood}$

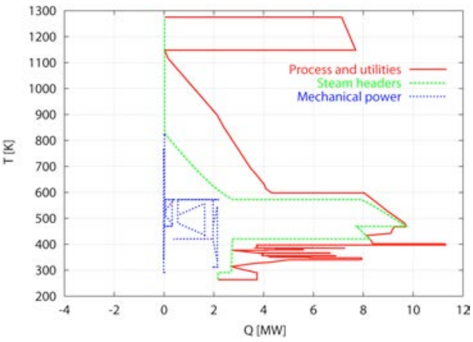
		steam cycle	IGCC	SNG	+ steam
Input	wood	100 %	100 %	100 %	100 %
	ethanol	32.3 %	32.3 %	32.3 %	32.2 %
Output	SNG	-	-	40.3 %	30.5 %
	electricity	17.1 %	21.5 %	-3.0 %	1.5 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %	70.0 %	67.3 %	65.3 %
total efficiency		49.4 %	53.8 %	70.5 %	64.2 %

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

Site integration: process couplings
EtOH & SNG

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 %

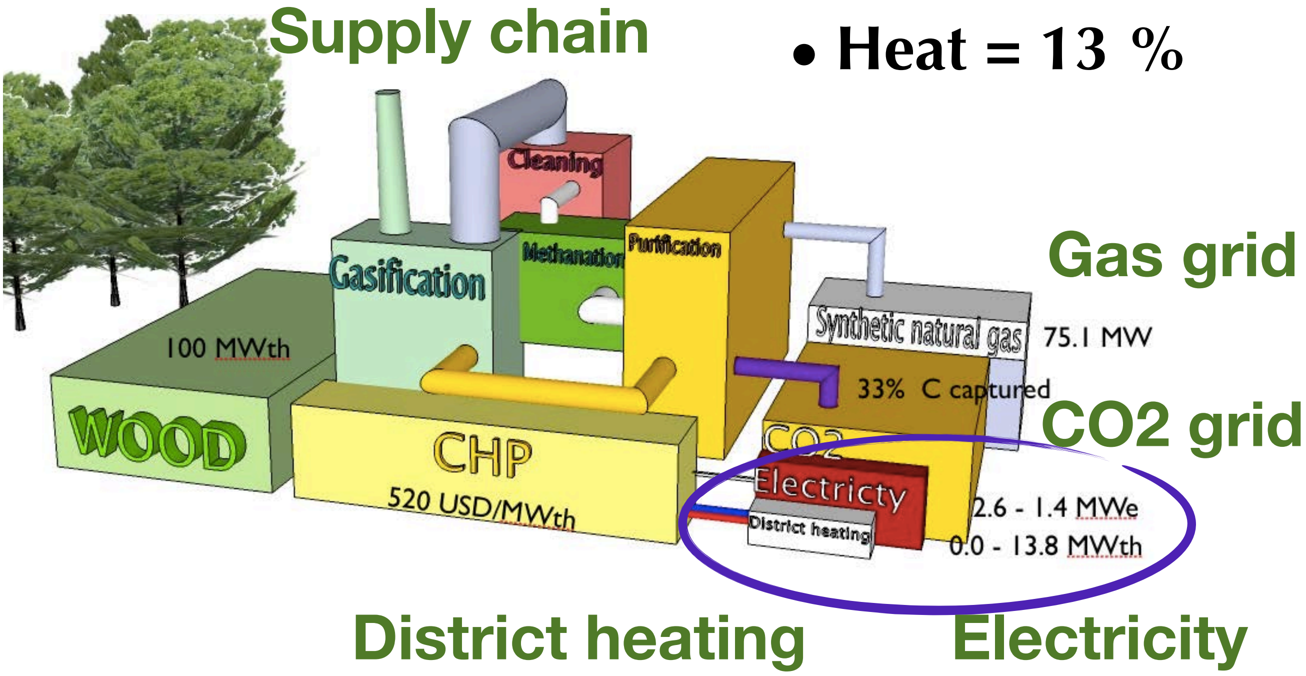
Energy balance for different process integration options (without seed train, non-optimised).

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

Large scale integration : multi-grids

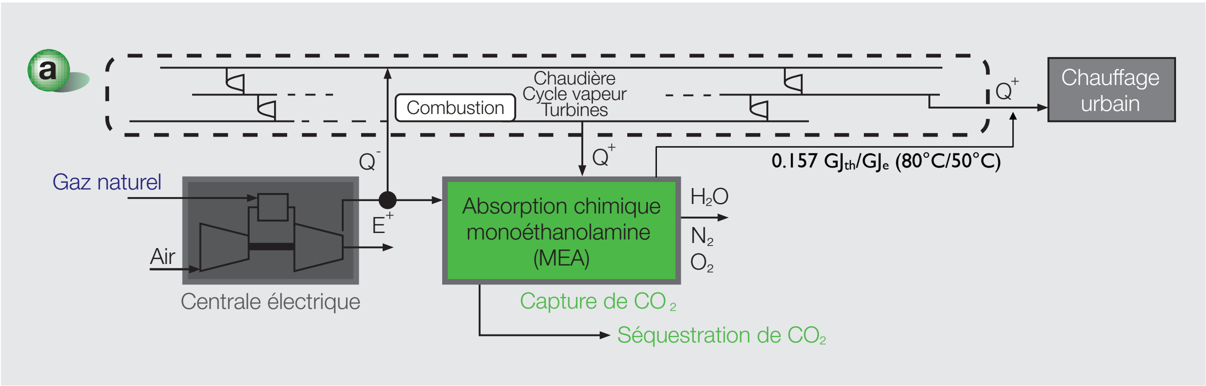
- **Resource productivity**

- **SNG = 75 %**
- **Elec = 2%**
- **Heat = 13 %**



CO2 capture

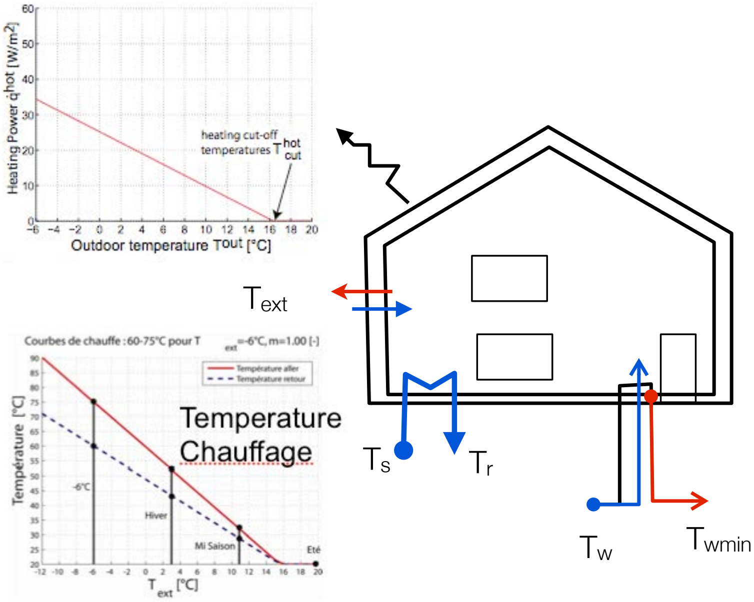
- District heating integration



300 MWe	NoCCS	CCS	CCS + DHC
Natural gas (MJ/MJe)	1.698	2.016	2.016
District heating (MW)	47 MW (50000 hab)		
NG for district (MJ/MJth)	0.174	0.174	0
Total	1.872	2.191	2.016
CO2 (kgCO2/GJe)	115.8	25.8	14.9

Process integration in buildings

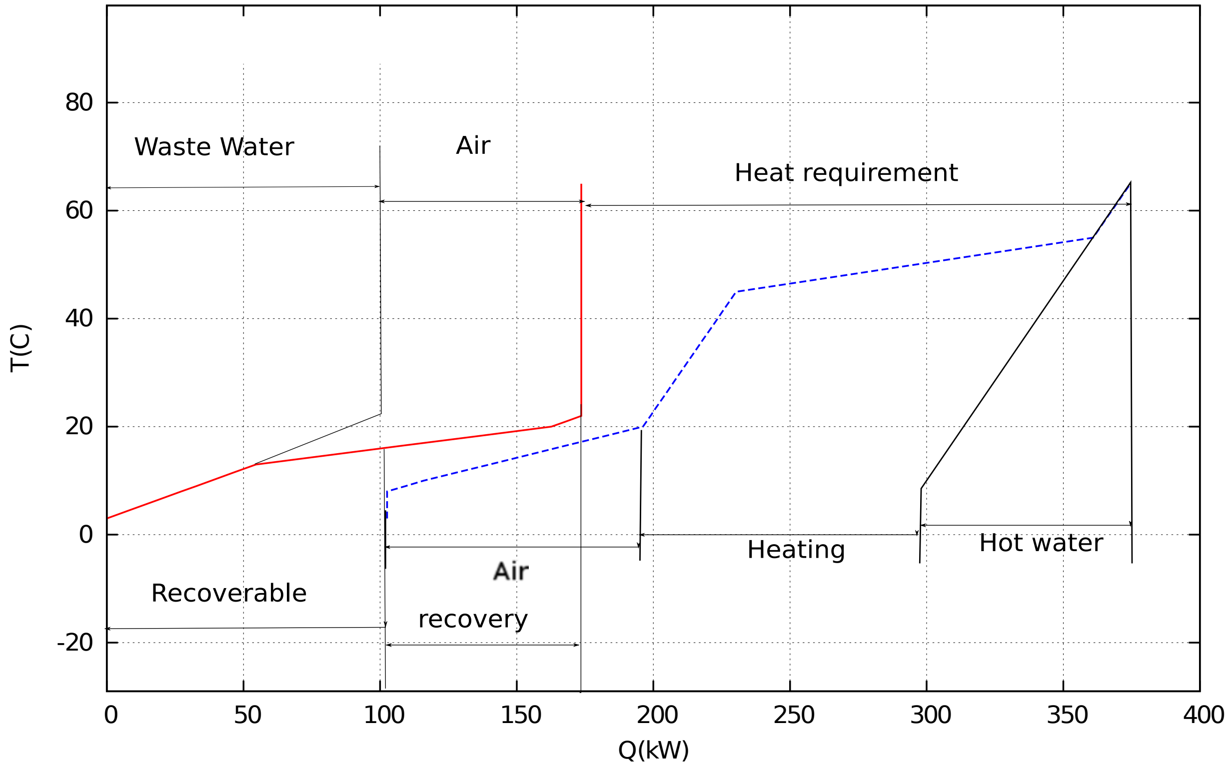
- **Definition of the energy needs**
  - Heating
  - Air renewal
  - Hot water
  - Waste Water
  - Air renewal



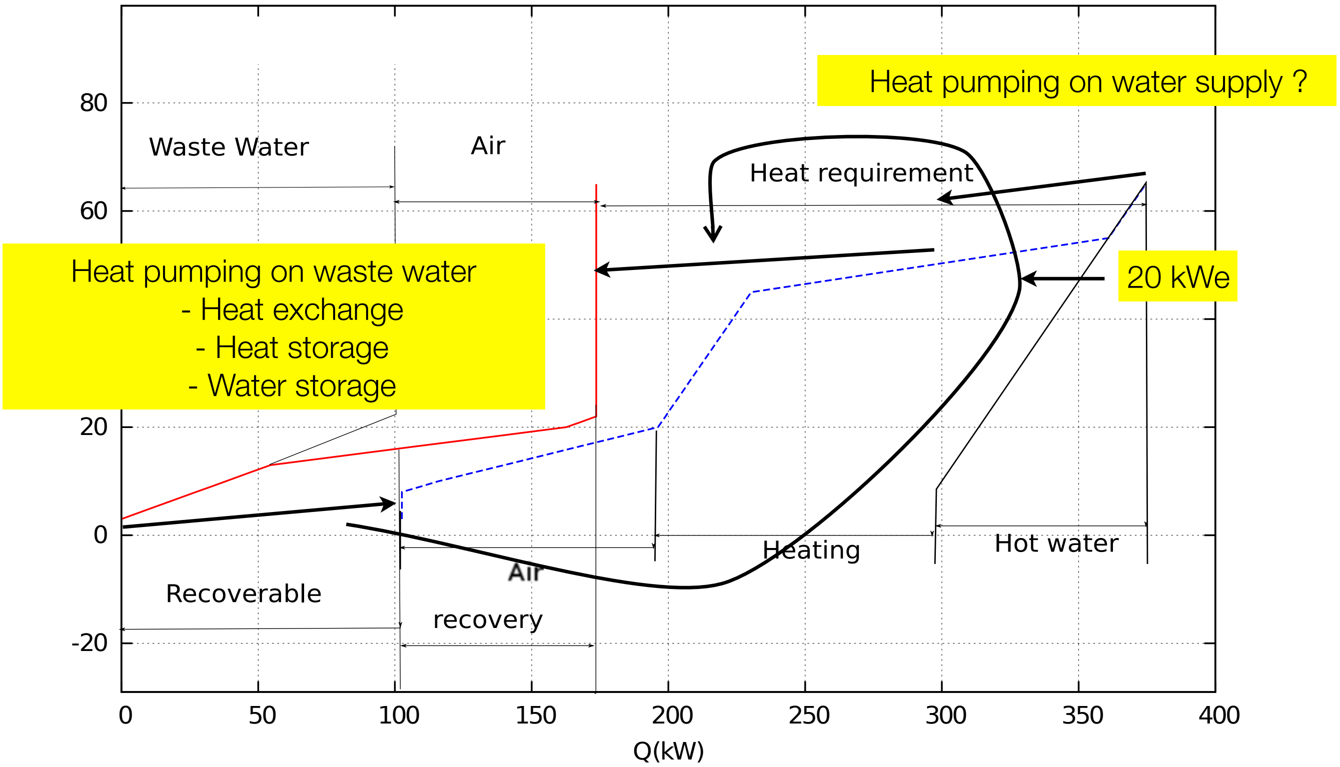
Do not forget Carnot (Exergy demand) :

* Heat with the lower temperature possible
* Cool with the highest possible temperature

Local heat recovery



Local Heat pumping on waste water



Heat pumping on water supply ?

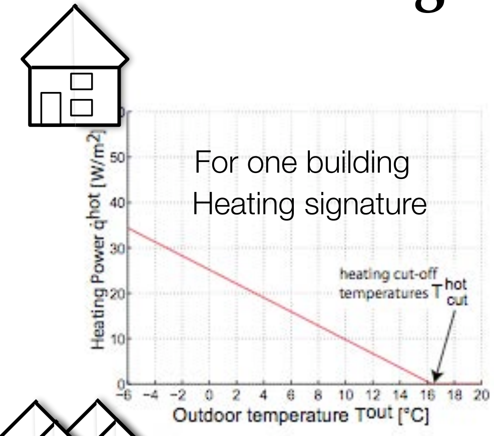
Heat pumping on waste water
- Heat exchange
- Heat storage
- Water storage

20 kWe

COP = 5 to 6

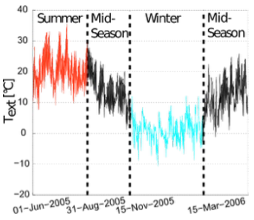
Define the demands of a district

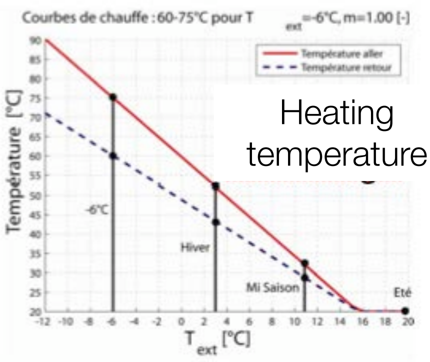
• Characterizing the services



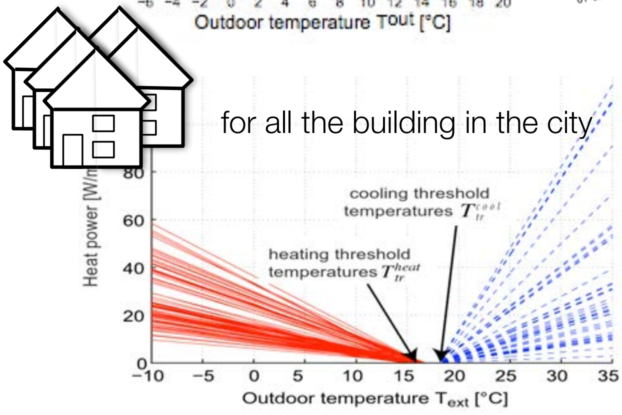
For one building
Heating signature

Seasonal temperature variation





Heating temperature



for all the building in the city

The urban system integration

- Multi Energy services
  - Electricity
  - Heating
  - Cooling
  - Hot water
  - Refrigeration
  - Industrial processes
- Agglomeration of demands
  - Composite curves ?
  - Heat-temperature diagrams
    - thermal distribution

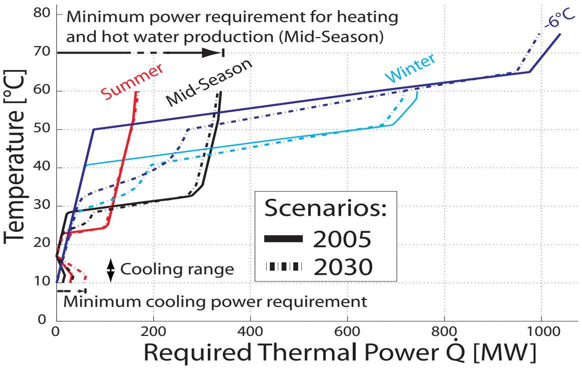
➡Seasonal profiles

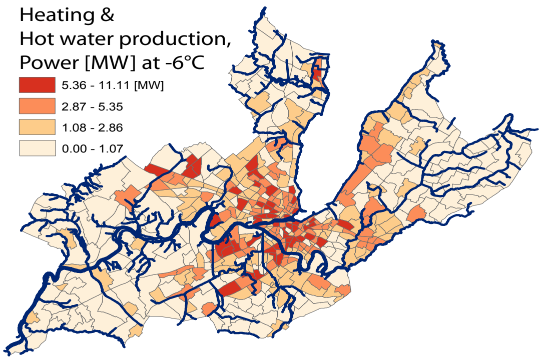
- ● stochastic !

➡Evolution scenarios

- ➡buildings stock
- ➡refurbishment

Composite curve of the Geneva canton

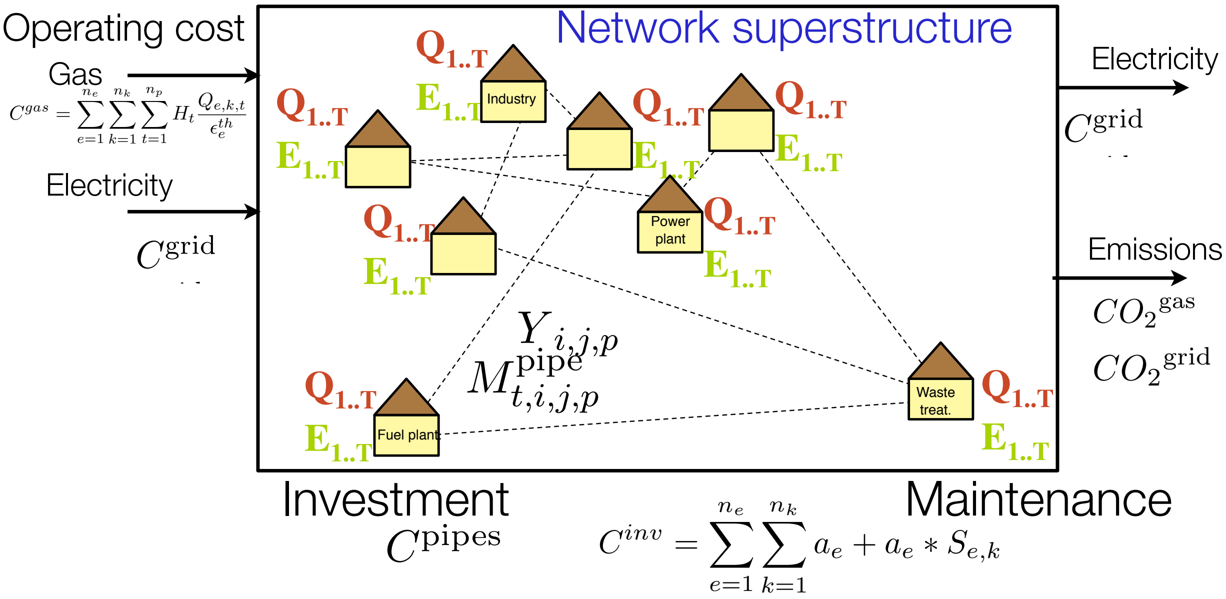




Girardin, et al.. "EnerGis: A Geographical Information Based System for the Evaluation of Integrated Energy Conversion Systems in Urban Areas." Energy 35, no. 2 (2010): 830–840.

Energy system design : problem definition

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 ?



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

C^{grid}

C^{grid}

$CO_2{}^{\mathrm{gas}}$

$CO_2{}^{\mathrm{grid}}$

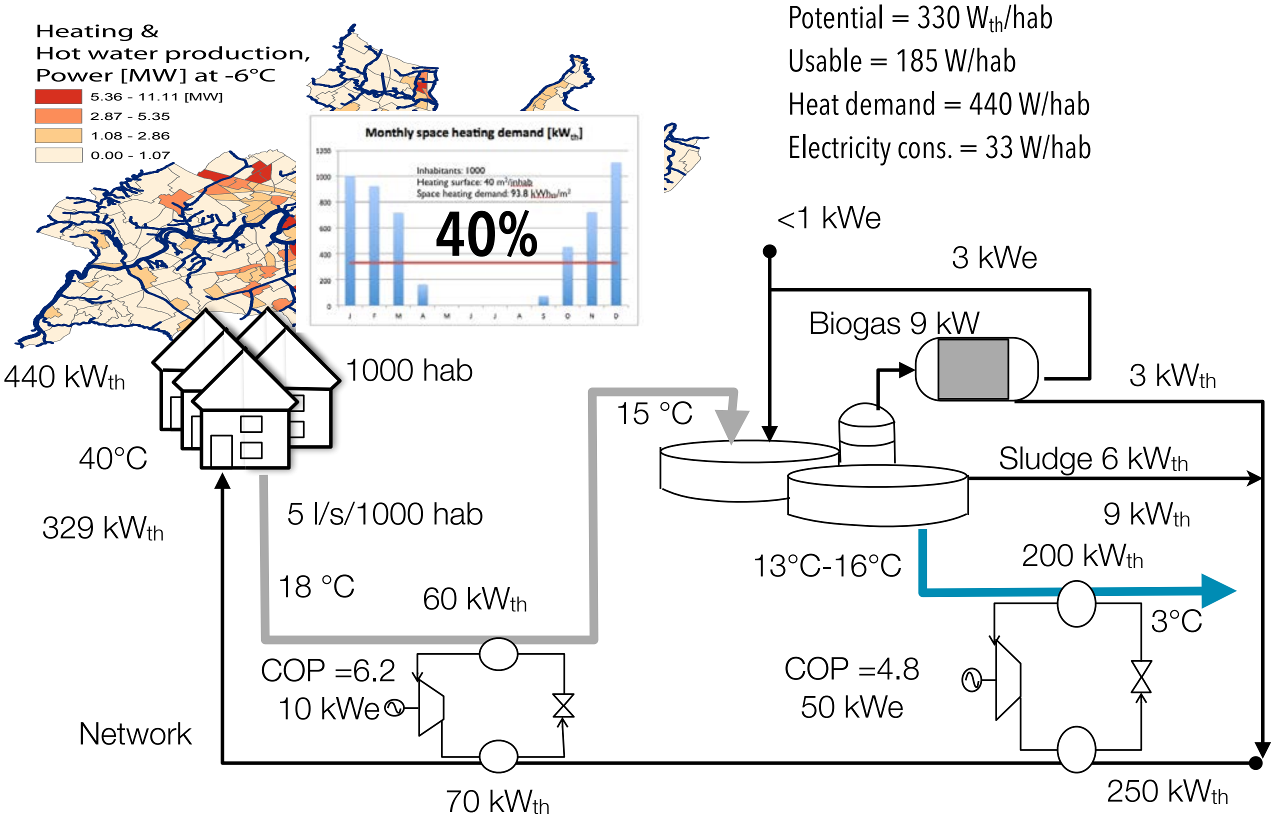
C^{pipes}

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

[5] Francois Marechal, Celine Weber, and Daniel Favrat. Multi-Objective Design and Optimisation of Urban Energy Systems, pages 39–81. Number ISBN: 978-3-527-31694-6. Wiley, 2008.

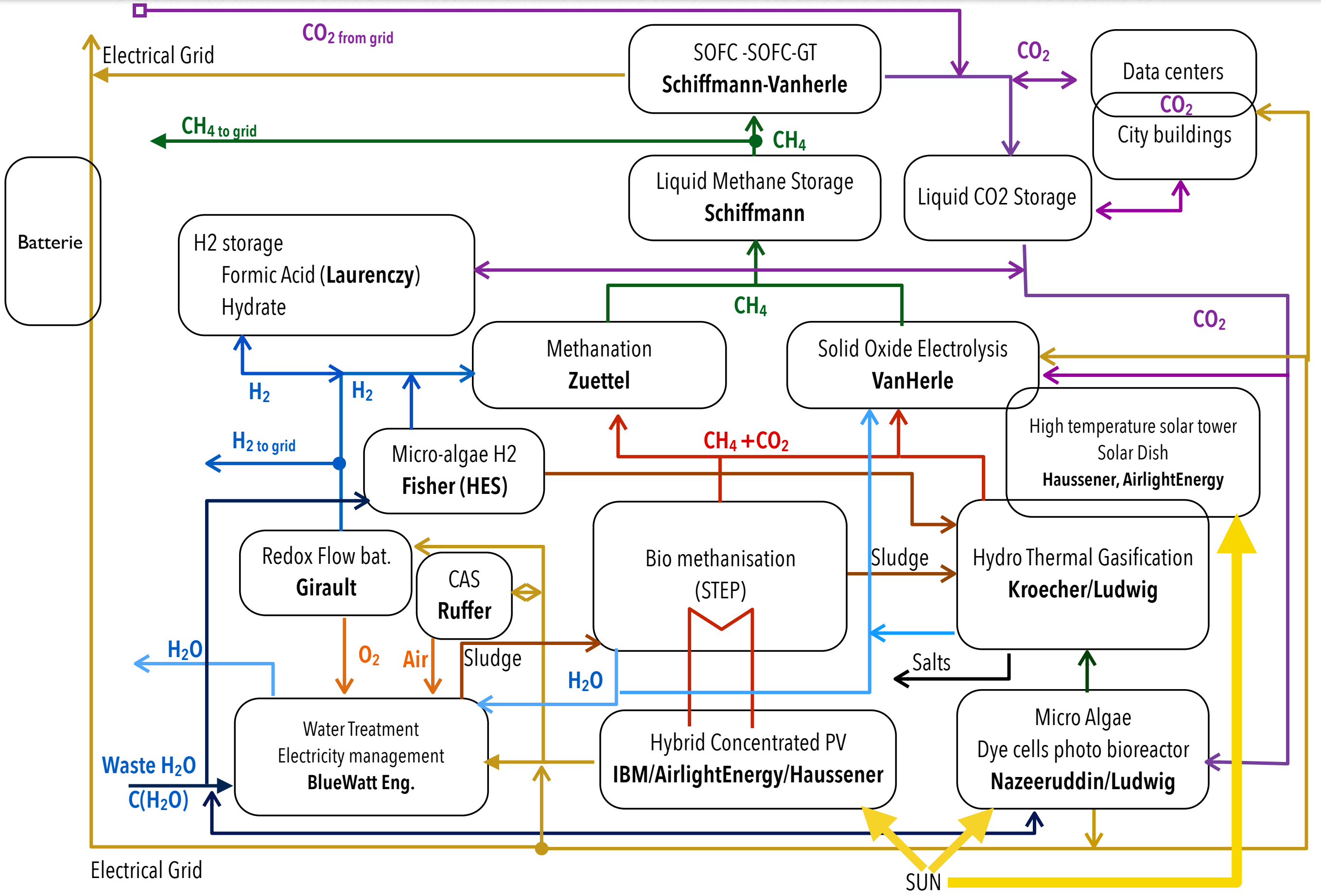
Access to local resources

Potential = 330 W_{th}/hab
Usable = 185 W/hab
Heat demand = 440 W/hab
Electricity cons. = 33 W/hab



Girardin et al., ENERGIS, A geographical information based system for the evaluation of integrated energy conversion systems in urban areas, Energy, 2010

Carbon valorisation of renewable energy source



Electrical Grid

CO_2 from grid

SOFC -SOFC-GT
Schiffmann-Vanherle

CO_2

Data centers

CO_2

City buildings

CH_4 to grid

CH_4

Batterie

Liquid Methane Storage
Schiffmann

Liquid CO2 Storage

H2 storage
Formic Acid (**Laurenczy**)
Hydrate

CH_4

CO_2

Methanisation
Zuettel

Solid Oxide Electrolysis
VanHerle

H_2

H_2

H_2 to grid

Micro-algae H2
Fisher (HES)

$CH_4 + CO_2$

High temperature solar tower
Solar Dish
Haussener, AirlightEnergy

Redox Flow bat.
Girault

CAS
Ruffer

Bio methanisation
(STEP)

Sludge

Hydro Thermal Gasification
Kroecher/Ludwig

H_2O

O_2

Air

Sludge

H_2O

Salts

Water Treatment
Electricity management
BlueWatt Eng.

Hybrid Concentrated PV
IBM/AirlightEnergy/Haussener

Micro Algae
Dye cells photo bioreactor
Nazeeruddin/Ludwig

Waste H_2O

$C(H_2O)$

Electrical Grid

SUN

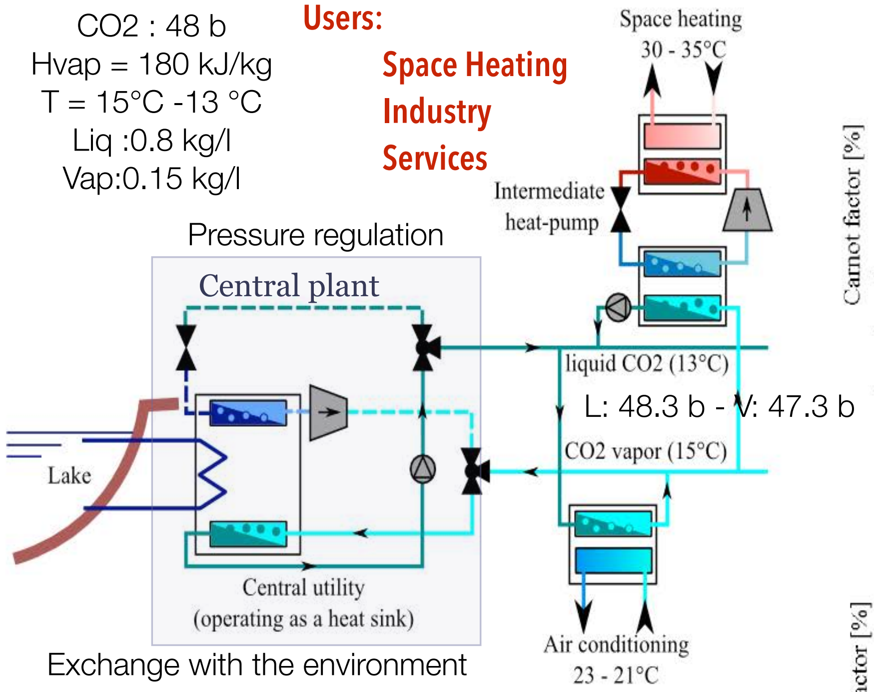
©Francois Marechal -IPESE-IGM-STI-EPFL 2014

CO2 District heating network for multiple sources

CO2 : 48 b
Hvap = 180 kJ/kg
T = 15°C -13 °C
Liq :0.8 kg/l
Vap:0.15 kg/l

Users:

Space Heating
Industry
Services



Space heating
30 - 35°C

Intermediate
heat-pump

Pressure regulation

Central plant

Lake

liquid CO2 (13°C)

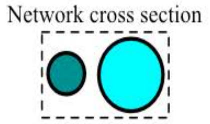
L: 48.3 b - V: 47.3 b

CO2 vapor (15°C)

Central utility
(operating as a heat sink)

Air conditioning
23 - 21°C

Exchange with the environment

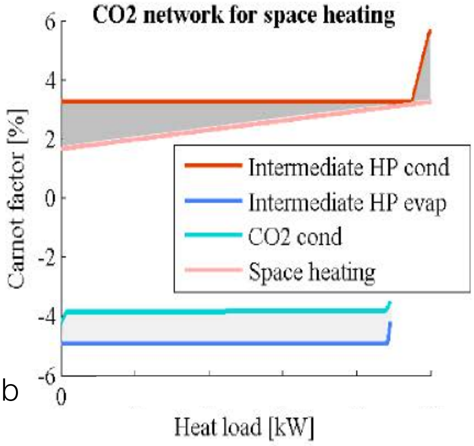


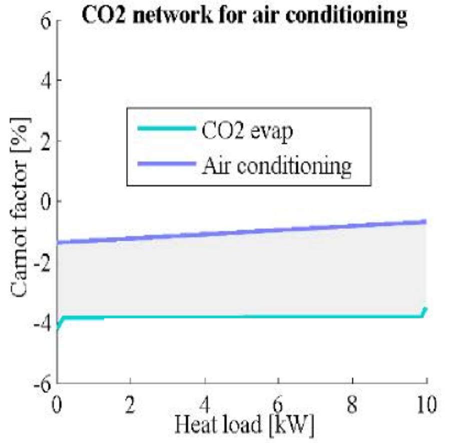
Network cross section

Cross section = Cross section water/4

Users:

Air Conditioning
Data centers
Refrigeration





©

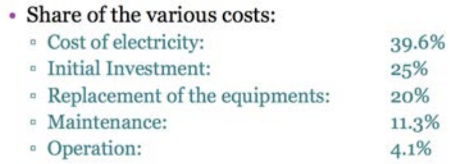
Advanced district heating systems for complex urban systems

Complex system with heating and cooling : (ERA) 687'800 m²

•Commercial:	23% inc. HVAC and refrigeration
•Offices:	60 % inc. data center
•Residential:	17%

Heating	**53.2 GWh**
Cooling	**49.4 GWh**

- The CO2 network integration : reduction of **84%** of the primary energy consumption if specific technologies are used
  - Profitability analysis : break-even in 5 years
- Combined with SOFC cogeneration : savings reach **88** %
- Combined with renovation : savings reach **92** % !



- **Share of the various costs:**

Cost of electricity:	39.6%
Initial Investment:	25%
Replacement of the equipments:	20%
Maintenance:	11.3%
Operation:	4.1%

Cost of services :

56 % related to equipment Investment !

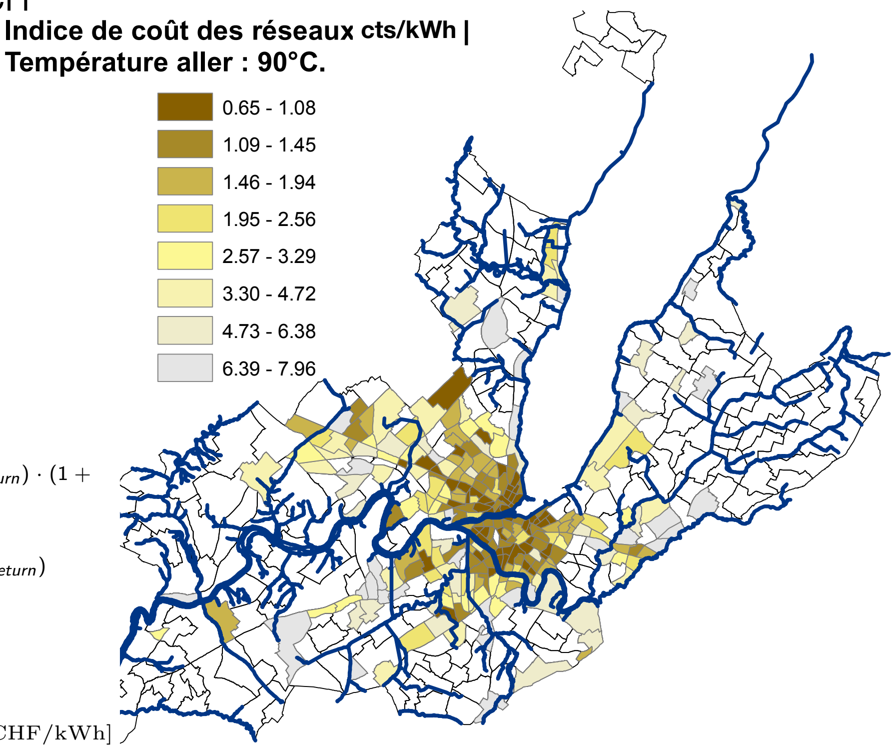
HENCHOZ S, FAVRAT D., WEBER C *Performance and profitability perspectives of a CO2 based district energy network in Geneva's city center.* DHC13, 13rd Int Symposium on District Heating and cooling, Copenhagen Sept 2012

Open question

- **Can we solve a problem ?**
  - 100000 buildings
  - 100000 + nodes => routing algorithm
  - Centralised and decentralised energy conversion technologies ?
  - How to estimate the profit
    - infrastructure investment : 60 years
    - daily and seasonal variation of the operation
    - decentralised and centralised units

District heat distribution cost : cts CHF/annual kWh

Clustering Approach



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

$$L_{DHN} = 2(N_b - 1)K\sqrt{\frac{A_h}{N_b}}$$

$$T^*_{supply} = T_{return} + (T_{supply} - T_{return}) \cdot (1 + f_{loss,ref}\frac{T_{supply} - T_{ground}}{T_{ref} - T_{ground}})$$

$$\dot{Q}_{DHN} = \dot{m}_{DHN}\, cp_{fluid}(T^*_{supply} - T_{return})$$

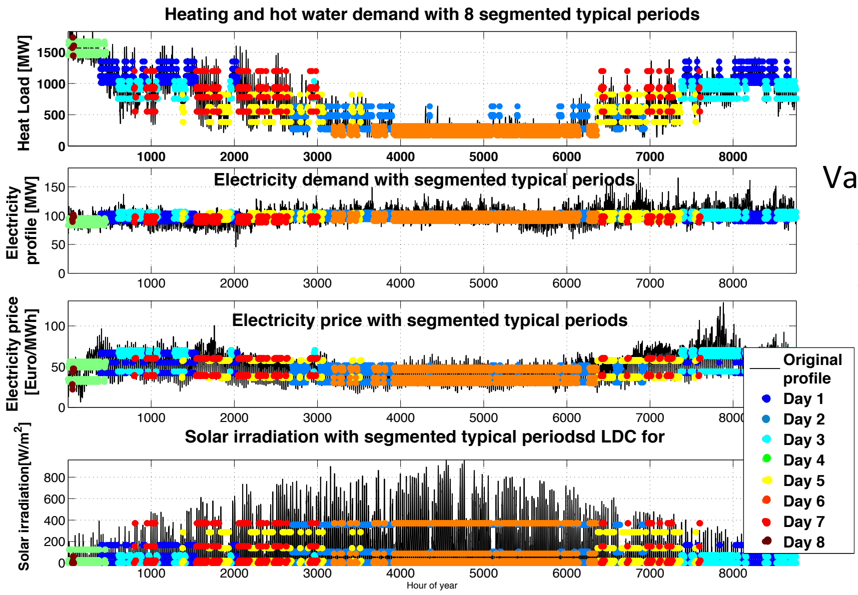
$$d_{DHN} = \sqrt{\frac{4\dot{m}_{DHN}}{\pi v_s \rho(T^*_{supply})}}$$

$$C_{DHN} = \frac{(c_1 d_{DHN} + c_2)L_{DHN}\frac{1}{\tau}}{\dot{Q}_{DHN}} \quad \text{[CHF/kWh]}$$

Girardin, Luc, François Marechal, Matthias Dubuis, Nicole Calame-Darbellay, and Daniel Favrat. “EnerGis: A Geographical Information Based System for the Evaluation of Integrated Energy Conversion Systems in Urban Areas.” *Energy* 35, no. 2 (February 2010): 830–840.

Evaluation of the operational cost

- **40 time steps : 7 days*5 sequence + 1 Extreme * 5 => instead of 8760 hours**
- **Probability of appearance (number of days)**
- **Using clustering techniques**



Validation is performed

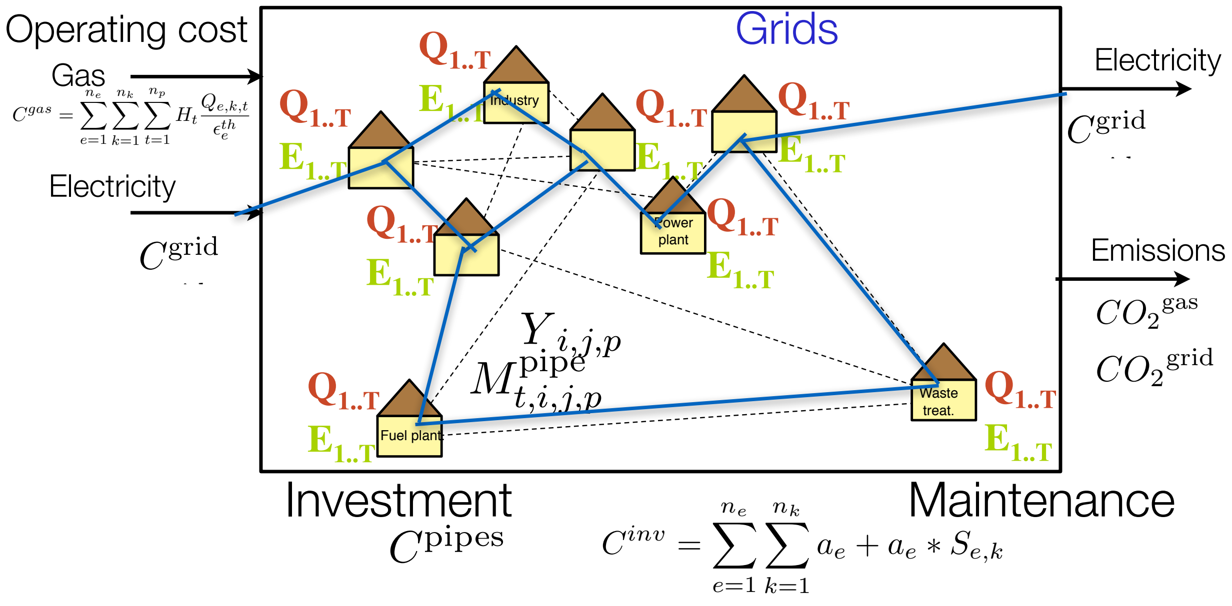
- 0.3-4.1% errors
- 40 times faster

Open Questions

- **Problem Size : Agglomeration methods ?**
  - Decomposition / meta models ?
  - Use Pareto-sets as models
  - mass and heat integration => services definition
- **Time scale problem**
  - When to invest ?
    - building stock evolution
    - Infrastructure development
      - *life time = 60 years*
      - *underground*
  - Operation
    - Daily - Seasonal storage
- **Stochasticity**
  - people
    - Behaviours
    - Customers
  - renewable
  - markets (Services/Energy)
- **Robust design methods**
- **Uncertainty management**
  - multi-stakeholders

Virtual power plant concept

What is the role of the district as a micro grid for the electricity supply ?



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}

Grids

$Y_{i,j,p}$

$M^{\mathrm{pipe}}_{t,i,j,p}$

Electricity

C^{grid}

Emissions

$CO_2{}^{\mathrm{gas}}$

$CO_2{}^{\mathrm{grid}}$

Investment

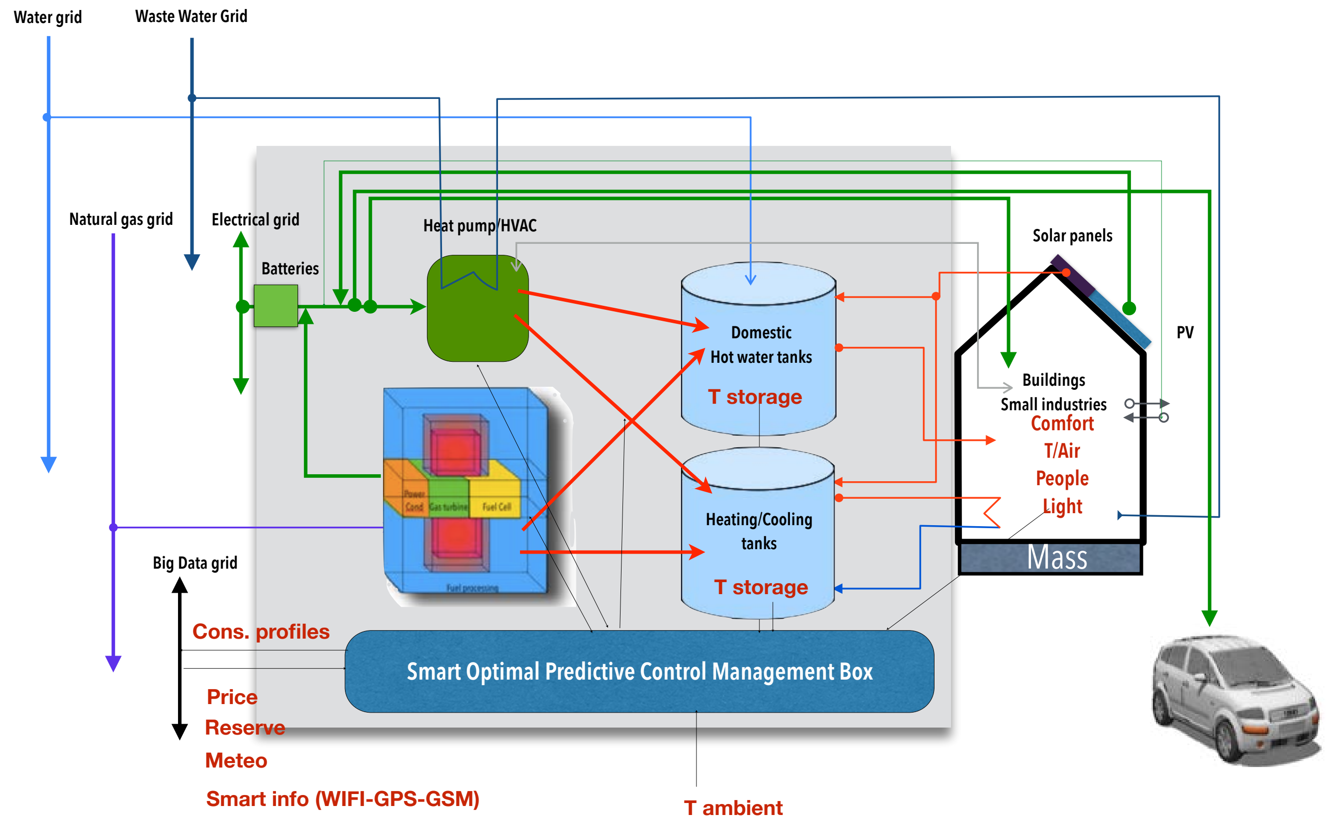
C^{pipes}

Maintenance

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

[5] Francois Marechal, Celine Weber, and Daniel Favrat. Multi-Objective Design and Optimisation of Urban Energy Systems, pages 39–81. Number ISBN: 978-3-527-31694-6. Wiley, 2008.

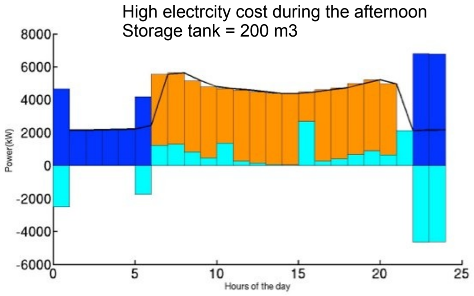
Virtual power plant Operation



Process integration : do not use batteries

CHP : 2000 kWe
Heat pump : 2000 kWe
Storage 200 m3

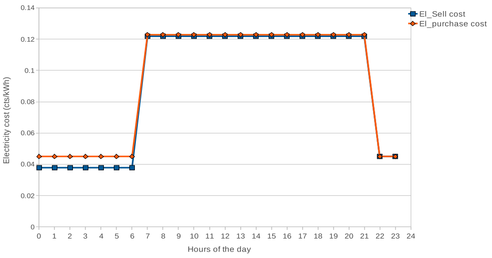
Demand mean heating power = 3000 kW

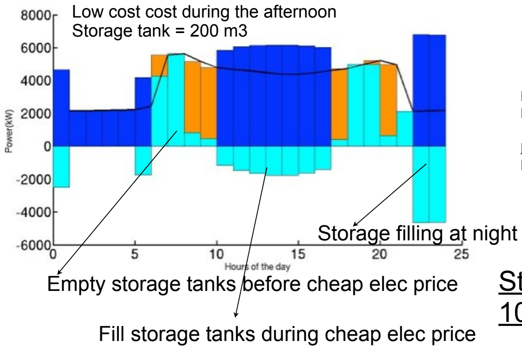


Heating : 72315 kWh
Electricity : 77897 kWhe

Electricity out : 5650 kWhe
Electricity bought : 62894 kWhe

Low price period
Electricity out : 4407 kWhe
Electricity in : 1269 kWhe
Balance : -3138 kWhe





Storage filling at night

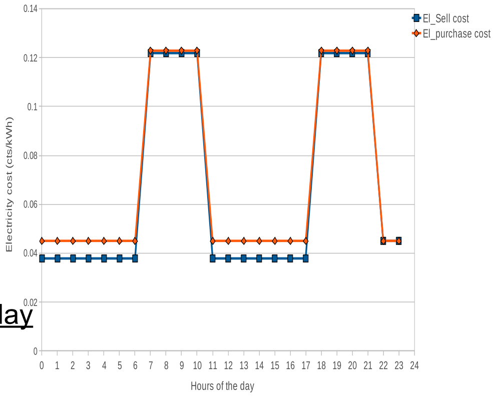
Empty storage tanks before cheap elec price

Fill storage tanks during cheap elec price

Electricity in : 99596 kWhe
Electricity out : 8710 kWhe

Low price period
Electricity in : 19345 kWhe

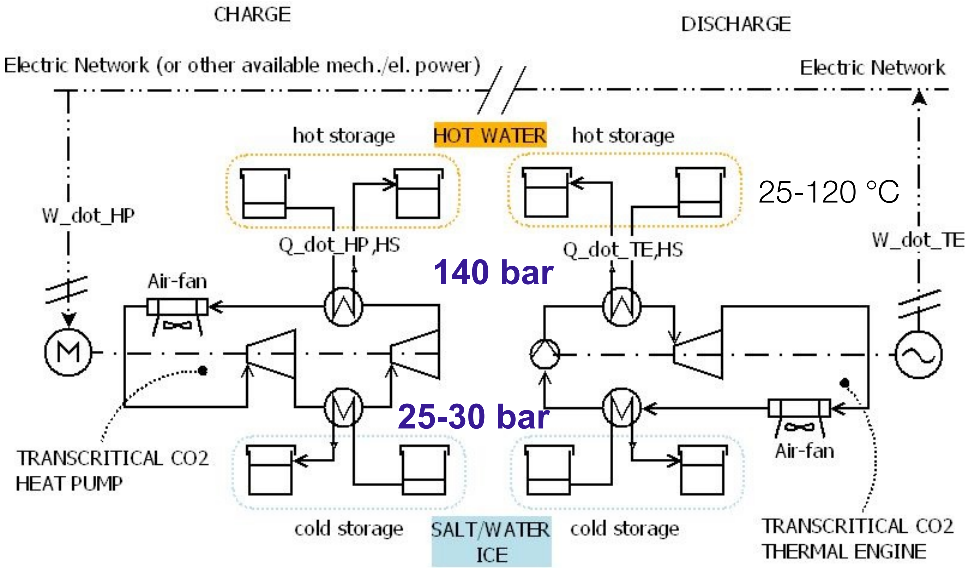
Storage : 22480 kWhe/day
10 hours of operation

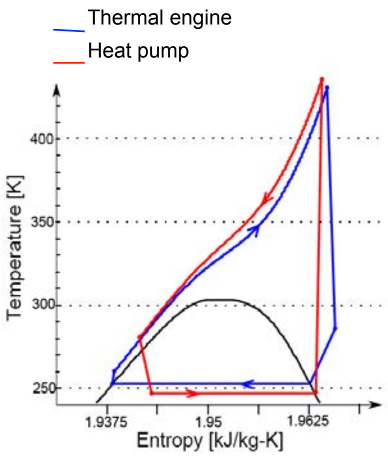


Electro Thermal Storage (ETES - ABB)

Round-trip eff.: 60%

Hot Water Storage
Transcritical CO2 cycles





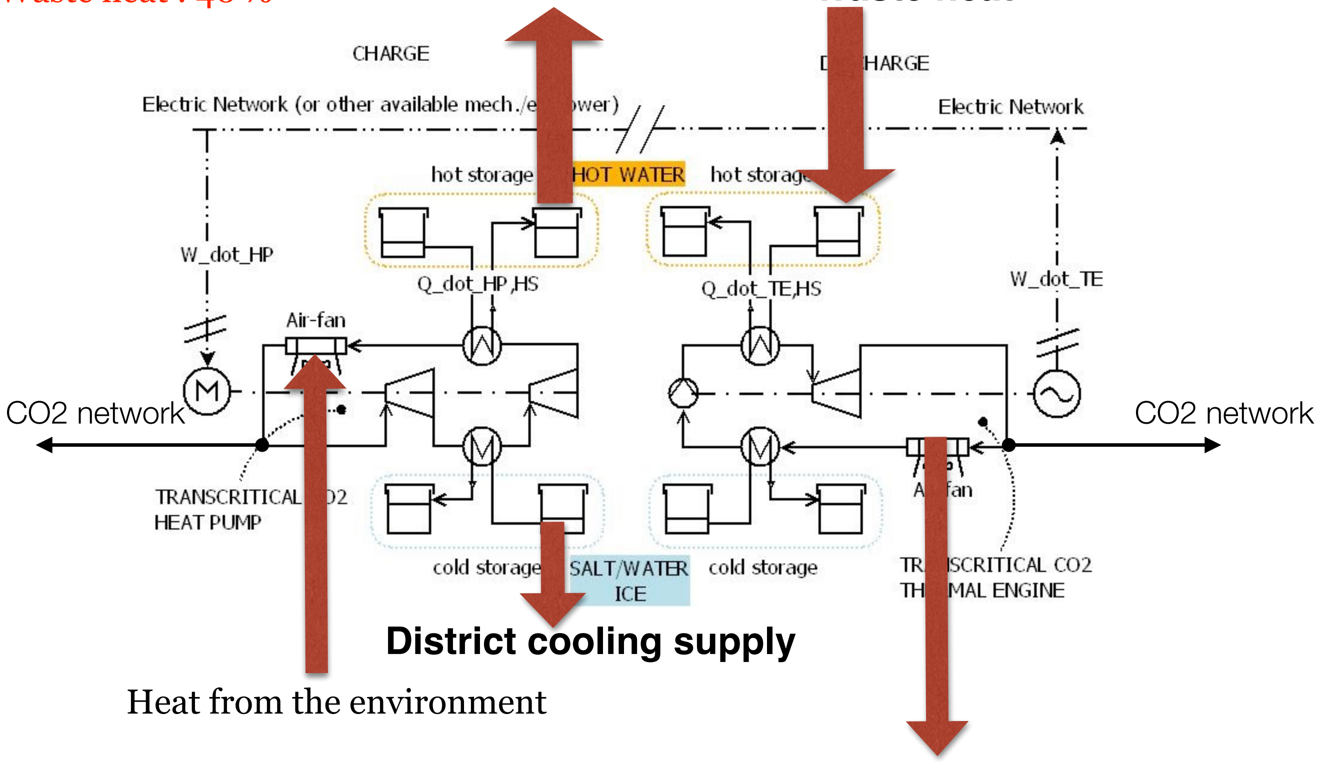
Morandin, Matteo, François Maréchal, Mehmet Mercangöz, and Florian Buchter. “Conceptual Design of a Thermo-Electrical Energy Storage System Based on Heat Integration of Thermodynamic Cycles – Part B: Alternative System Configurations.” Energy 45, no. 1 (September 2012): 386–396..

ETES & district heating/cooling

Round-trip eff.: 60%
Waste heat : 40 %

District heating supply

Solar Heat
Waste heat



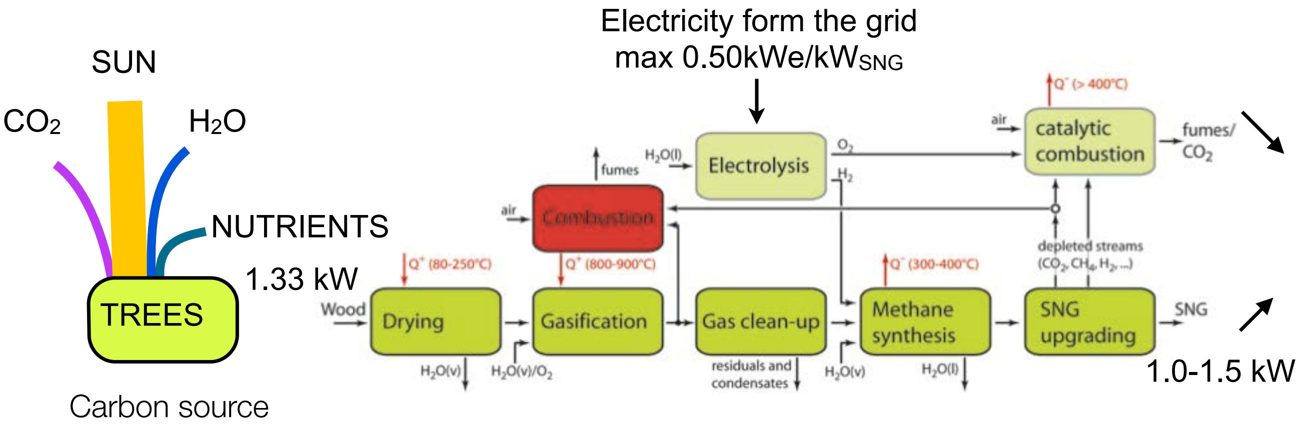
District cooling supply

Heat from the environment

Heat to the environment

Long term electricity storage by converting electricity to fuel

Power to gas concept



WOOD | Natural Gas | CO2 (pure)

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

$$+ 4\ H_2 \longrightarrow + CH_4 \quad - CO_2 \quad + 2\ H_2O$$

$$\Delta E^+ + 4H_2O \rightarrow + 4\ H_2,\ + 2\ O_2$$

Storage as transportation fuel

$$\eta_c = \frac{\Delta CH4^-_{LHV}}{\Delta E^+} = 85\%$$

Gassner, M., and F. Maréchal. *Energy* 33, no. 2 (2008) 189–198.

Round trip efficiency of electrcity storage

- **H2 electrolysis integrated in SNG process**
  - CO2 emissions are negative (wood carbon neutral, CO2 is captured)

$$\eta_c = \frac{\Delta CH4^-_{LHV}}{\Delta E^+} = 85\%$$

- **CH4 conversion NGCC (CO2 = 0 because C biogenic)**

$$\eta_d = \frac{E^-}{CH4^+_{LHV}} = 60\%$$

- **Roundtrip efficiency**

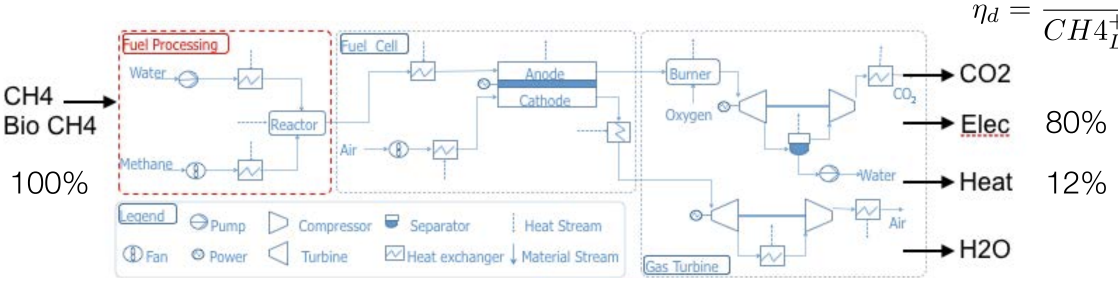
$$\eta = \frac{E^-}{E^+} = 50\%$$

- **Long term storage on the gas grid !**

If Electricity production efficiency increases

- Hybrid gas turbine SOFC combined cycle

$$\eta_d = \frac{E^-}{CH4^+_{LHV}} = 80\%$$



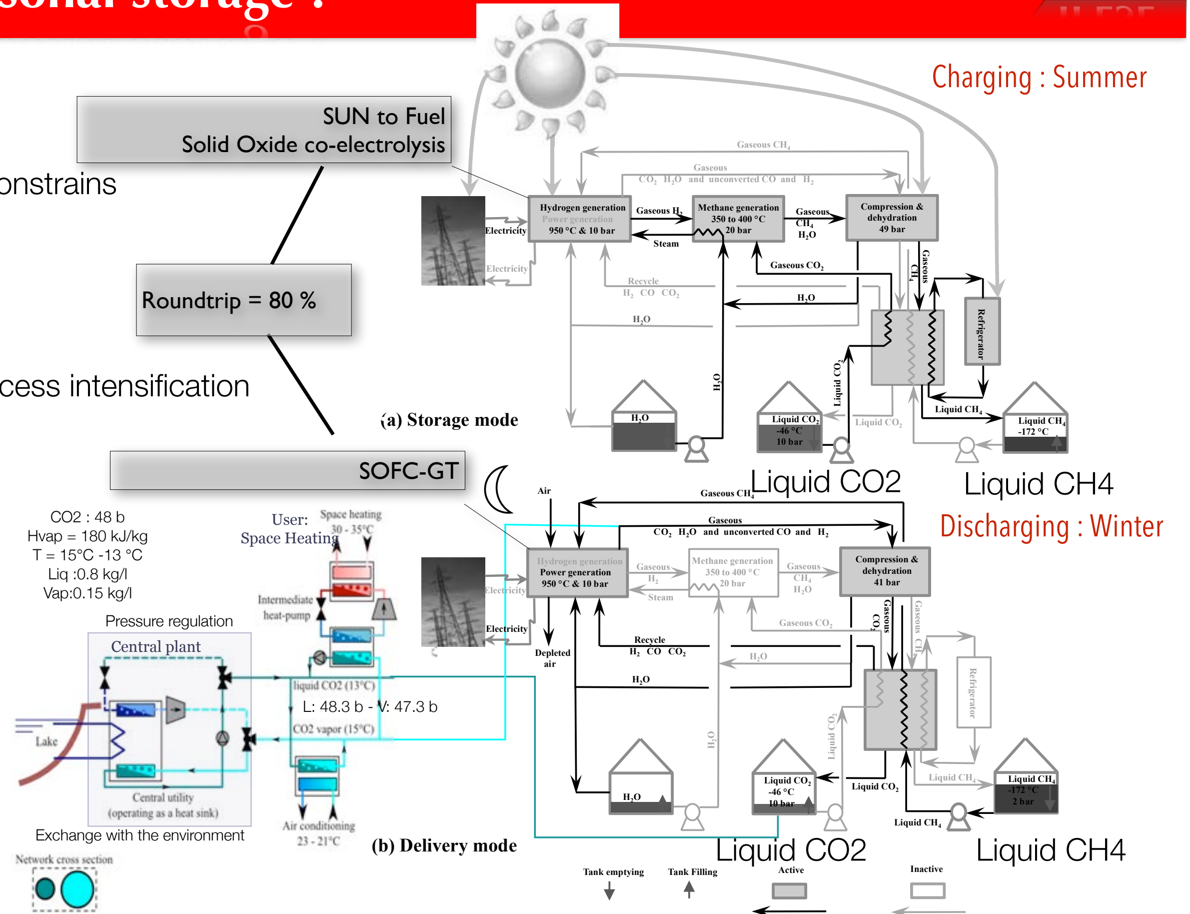
$$\eta = \frac{E^-}{E^+} = 68\%$$

A battery is 80%

- Round trip with long term storage on gas grid and decentralised production

---

Seasonal storage !



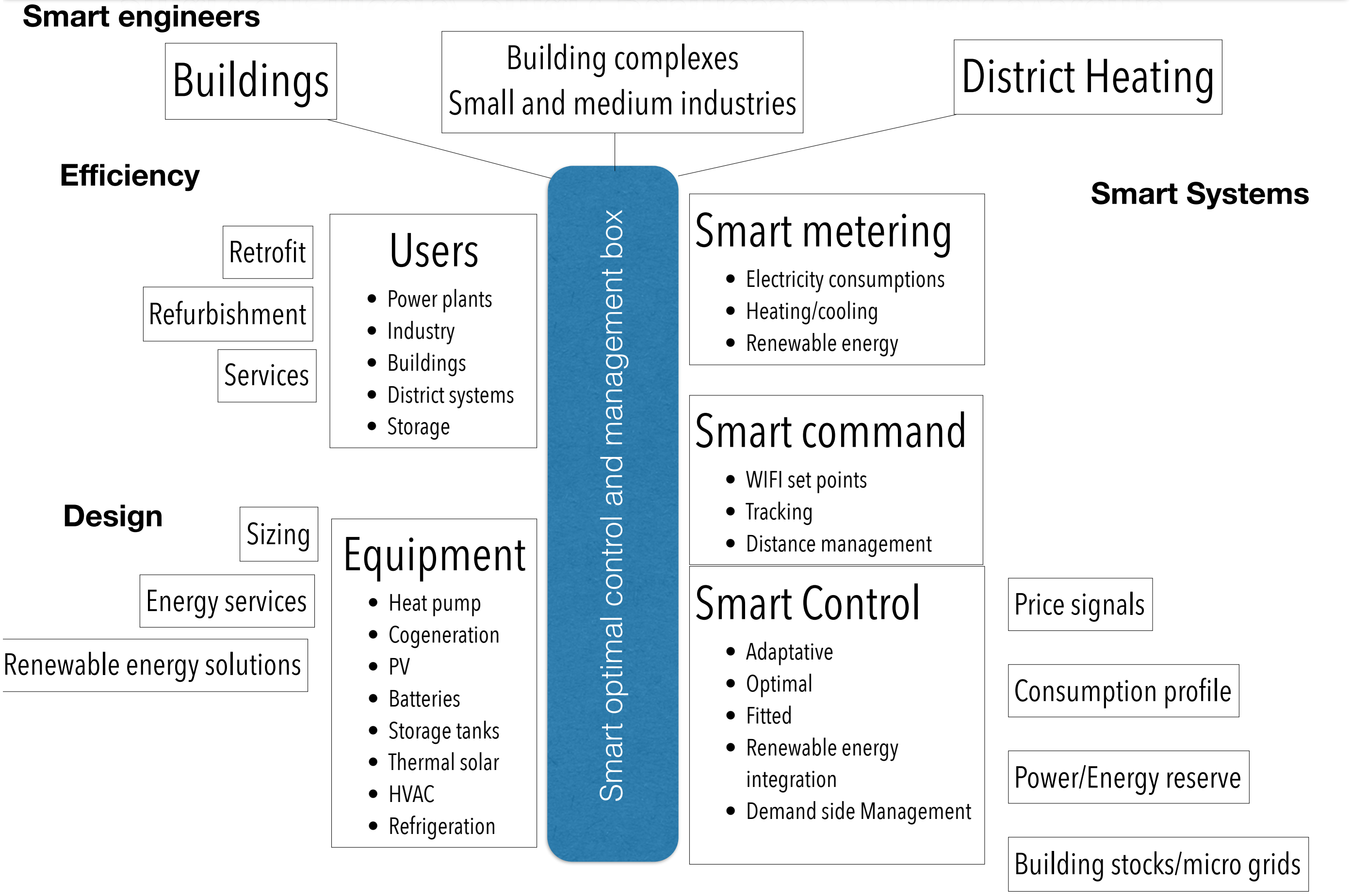
Using waste heat for heating/cooling purposes

Al–musleh et. al, Computer Aided Chemical Engineering, 2013.

Open questions : Energy storage

- **Simultaneous design**
  - Equipment & control
  - How to evaluate the profit ?
    - The system becomes a market player
- **System operation**
  - Predictive operation & control
    - Meteorological information
    - Presence
    - Functionalities (e.g. light, refrigeration, comfort)
    - Interconnection infrastructure
    - Flexibility/Robustness
    - Multi scale : 100 ms -> hours -> days -> Week -> Seasons
  - Identification of buffers
  - Networks of networks
    - Multi-levels grids (e.g. Voltage)
    - Internet of things
  - Big data integration
    - Machine learning for better predictions
  - Market integration

Smart engineers/ Smart Businesses / Smart systems



Smart engineers

Buildings

Building complexes
Small and medium industries

District Heating

Efficiency

Retrofit

Refurbishment

Services

Users
- Power plants
- Industry
- Buildings
- District systems
- Storage

Design

Sizing

Energy services

Renewable energy solutions

Equipment
- Heat pump
- Cogeneration
- PV
- Batteries
- Storage tanks
- Thermal solar
- HVAC
- Refrigeration

Smart optimal control and management box

Smart metering
- Electricity consumptions
- Heating/cooling
- Renewable energy

Smart command
- WIFI set points
- Tracking
- Distance management

Smart Control
- Adaptative
- Optimal
- Fitted
- Renewable energy integration
- Demand side Management

Smart Systems

Price signals

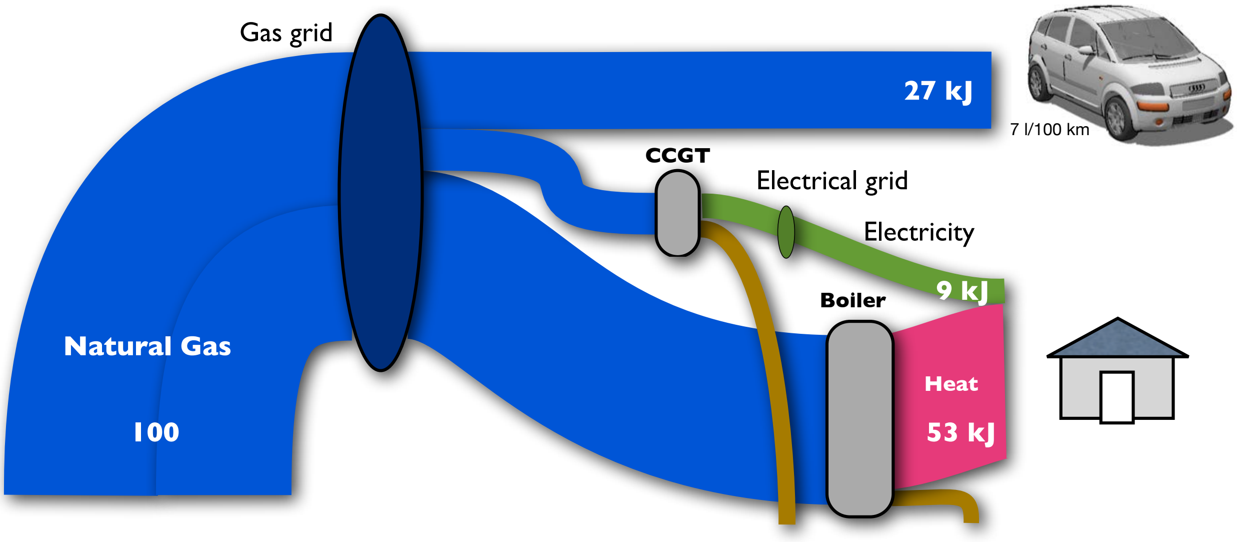
Consumption profile

Power/Energy reserve

Building stocks/micro grids

Energy transition for a household

Today's consumption : 100 kJ of Natural Gaz

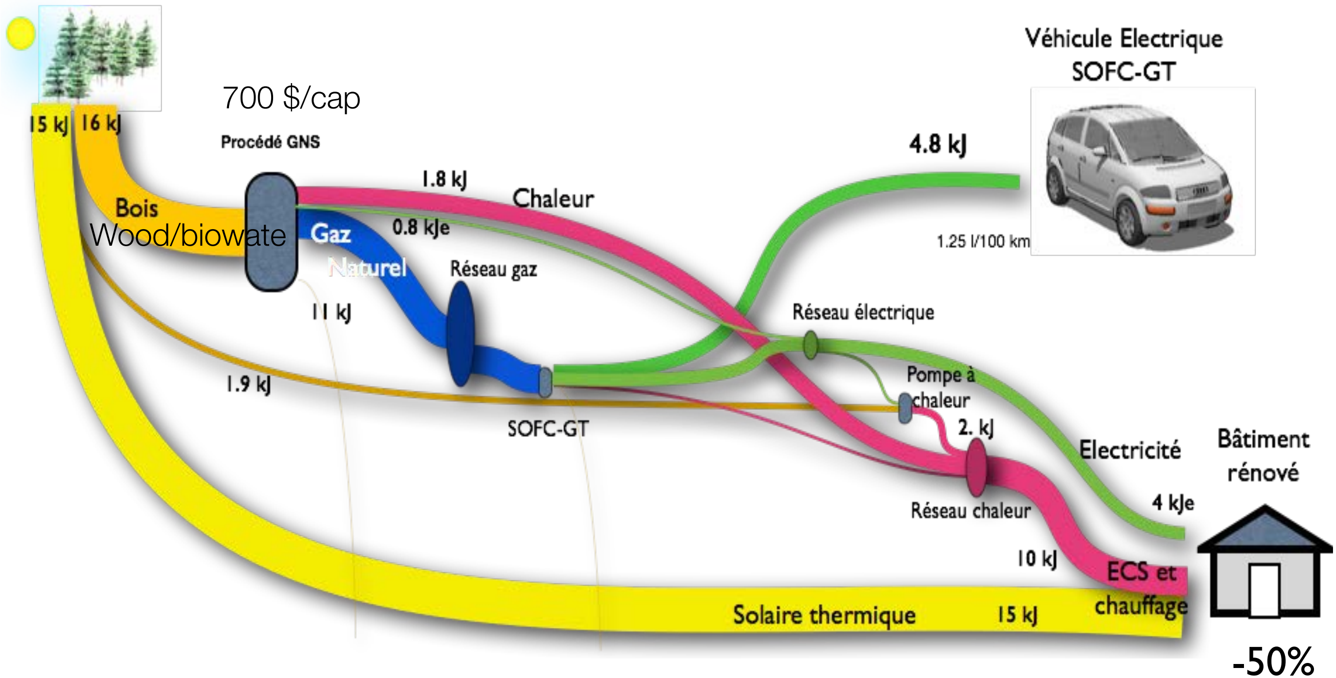


The energy system for a household

Tomorrow : Using wood and Renewable energy resources

Wood => Synthetic Natural Gas : 75%
Natural gas => Electricity (SOFC-GT): 80%
Electrical cars : 11 kWh/100 km

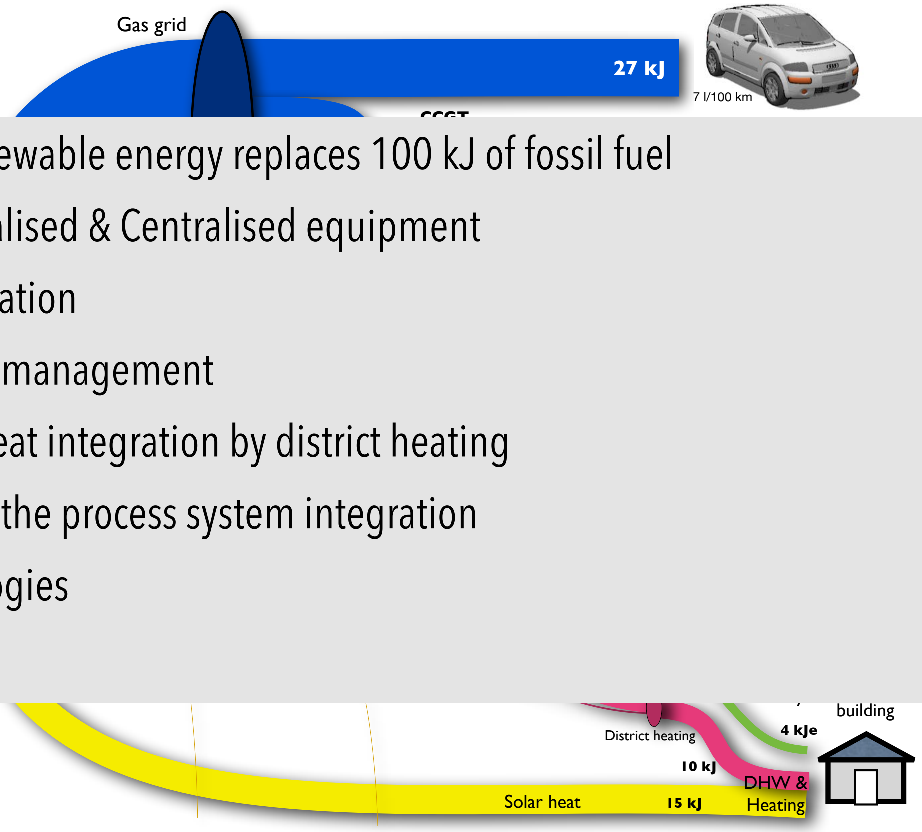
2 ha of sustainable forest/family



-50%

Sustainable energy system

The energy system for the household



- 31 kJ of renewable energy replaces 100 kJ of fossil fuel
  - Decentralised & Centralised equipment
  - Cogeneration
  - Optimal management
  - Waste heat integration by district heating
- Understand the process system integration
  - Technologies
  - Services

Energy transition needs smart process systems engineers

- **Integrate technologies**
  - Model the interactions by mass and heat integration
  - Use of Multi-objective optimisation to generate the list of solutions
- **Integrate services**
  - Multi-services
    - fuel/heat/electricity/storage/waste treatment
  - Optimal management
- **Integrate knowledge**
  - Reveals the inter-disciplinarity
- **Integrate the system**
  - Waste heat valorisation
  - System boundaries extension
- **Integrate the renewable energy resources**
  - Use of Biogenic carbon as an energy carrier/storage

Smart Energy transition needs

Smart Process system engineers !

Smart Process system engineers needs

Methods to solve complex problems

So that they are not complex anymore …