Process System Engineering and the energy transition

Smart engineers for smart systems

- Prof. François Marechal
- http://ipese.epfl.ch

ESI Seminar

Nov, 11, 2014

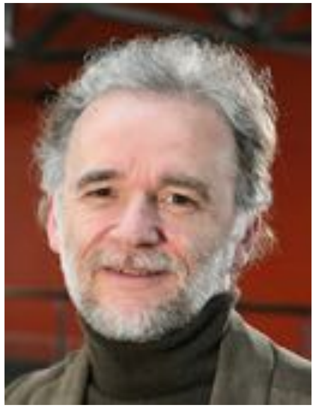
Industrial Process and Energy Systems Engineering
Institute of Mechanical Engineering
Sciences et Techniques de l'Ingénieur
Ecole Polytechnique Fédérale de Lausanne (EPFL)
Switzerland

Computer Aided methods for **Energy Systems Engineering**

Prof. Francois Marechal, PhD, Chem Eng.

Ecole Polytechnique Fédérale de Lausanne

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

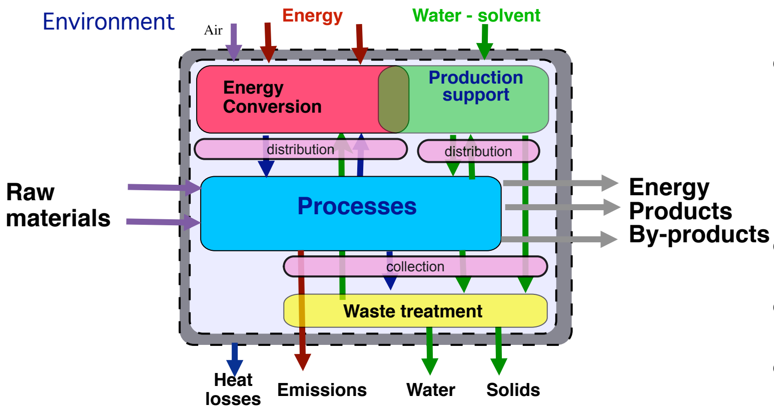
My scientific challenge :

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

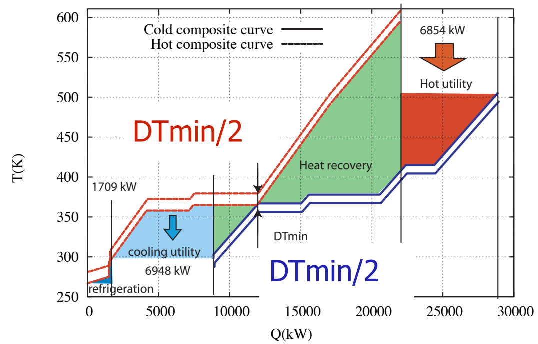
- **15 Researchers developing research in Computer aided energy systems engineering**
  - Thermo-economic-environomic modeling
  - Process and Energy Systems Integration
    - Modeling the system's interactions
    - Energy-Water-Waste
    - Renewable Energy Integration
  - Multi-objective optimisation 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

3 Domains of application

Energy and resource efficiency in industrial processes

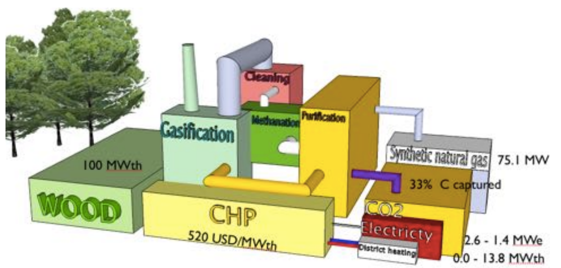


- Process integration
  - Pinch analysis
  - Exergy analysis
- Energy conversion
- Site Scale Integration
- Water & Waste

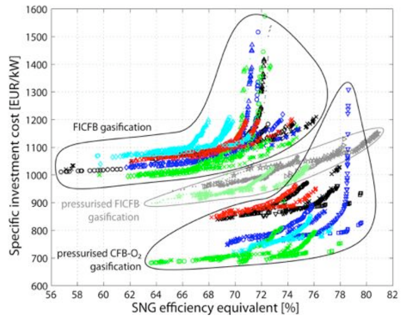


Process system design

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

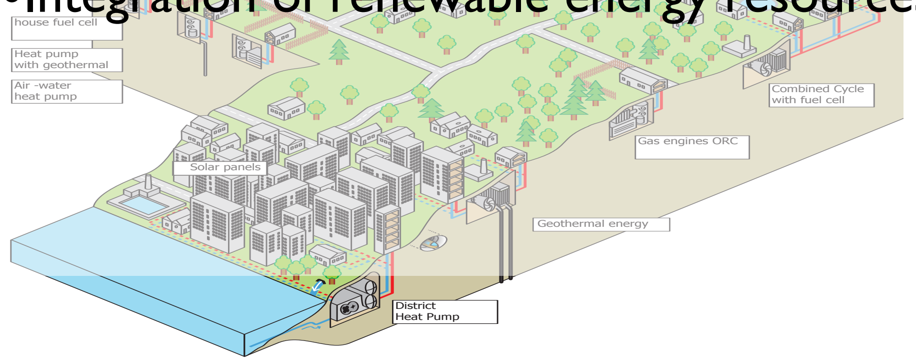


Thermo-economic Pareto front (cost vs efficiency):



Urban systems

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



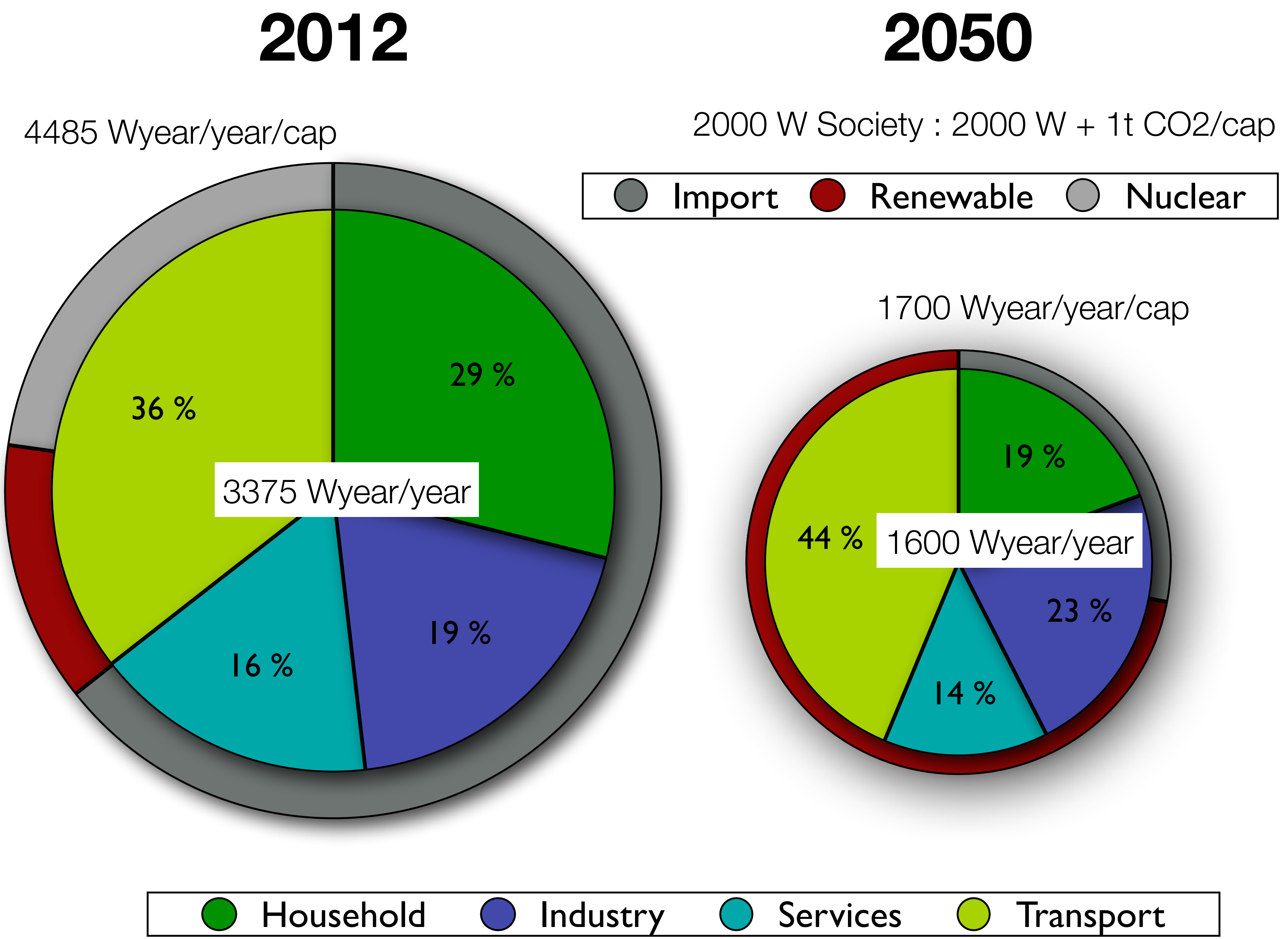
"System Engineering :
Treatment of Engineering Design as a decision making process"

Hazelrigg, 2012

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

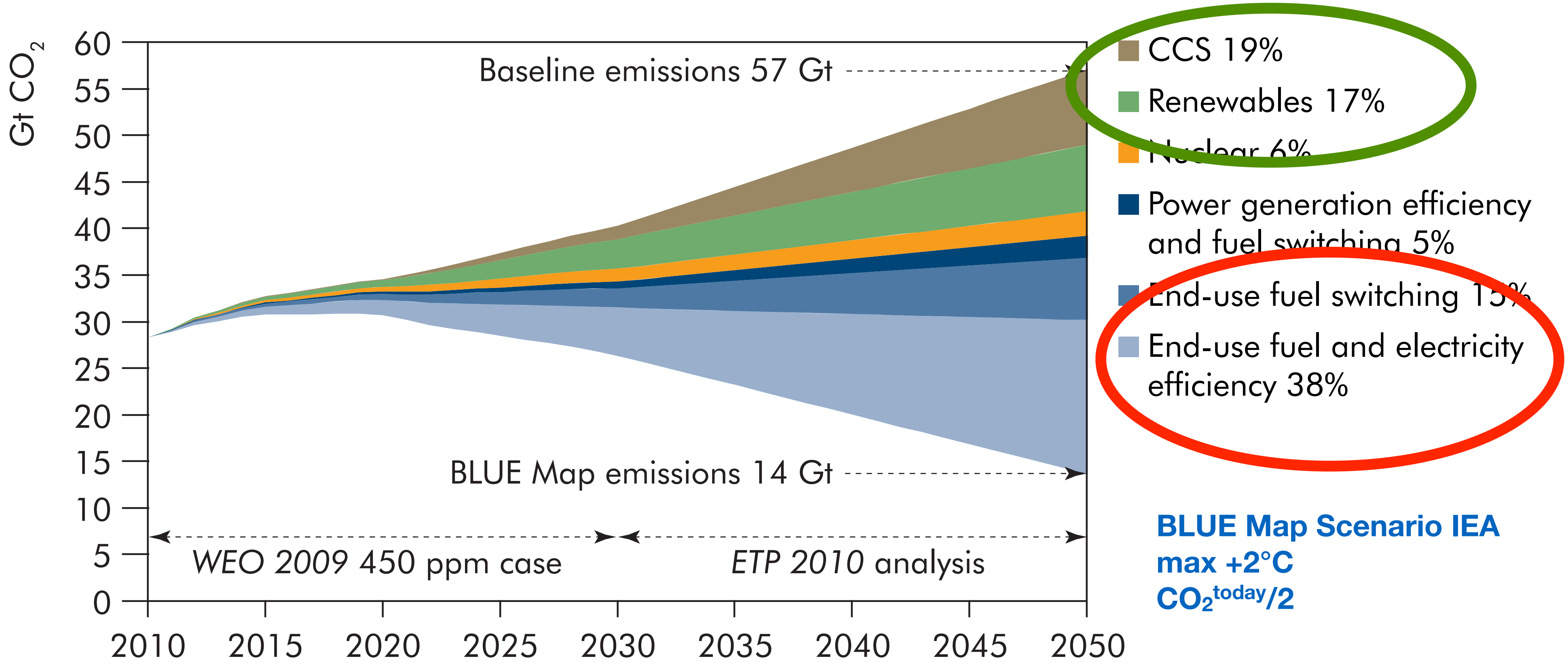
– Problem Statement
– Open Questions

Smart Engineers for Smart Systems ?


2012
2050
4485 Wyear/year/cap
2000 W Society : 2000 W + 1t CO2/cap
Import
Renewable
Nuclear
1700 Wyear/year/cap
36 %
29 %
3375 Wyear/year
19 %
16 %
19 %
44 %
1600 Wyear/year
23 %
14 %
Household
Industry
Services
Transport

The Energy Transition

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

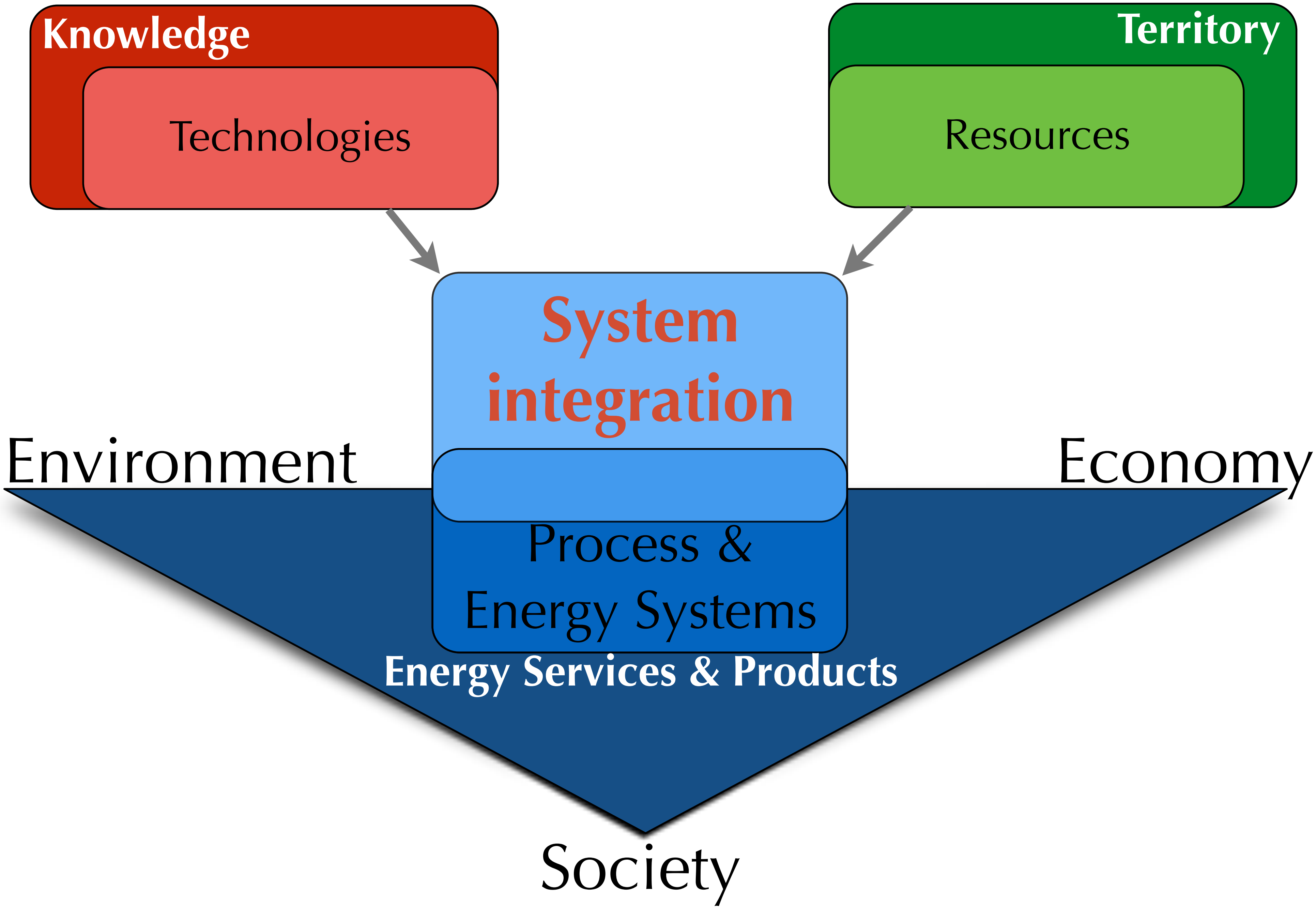


BLUE Map Scenario IEA
max +2°C
$CO_2^{today}/2$

- 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*

Sustainable Energy System design

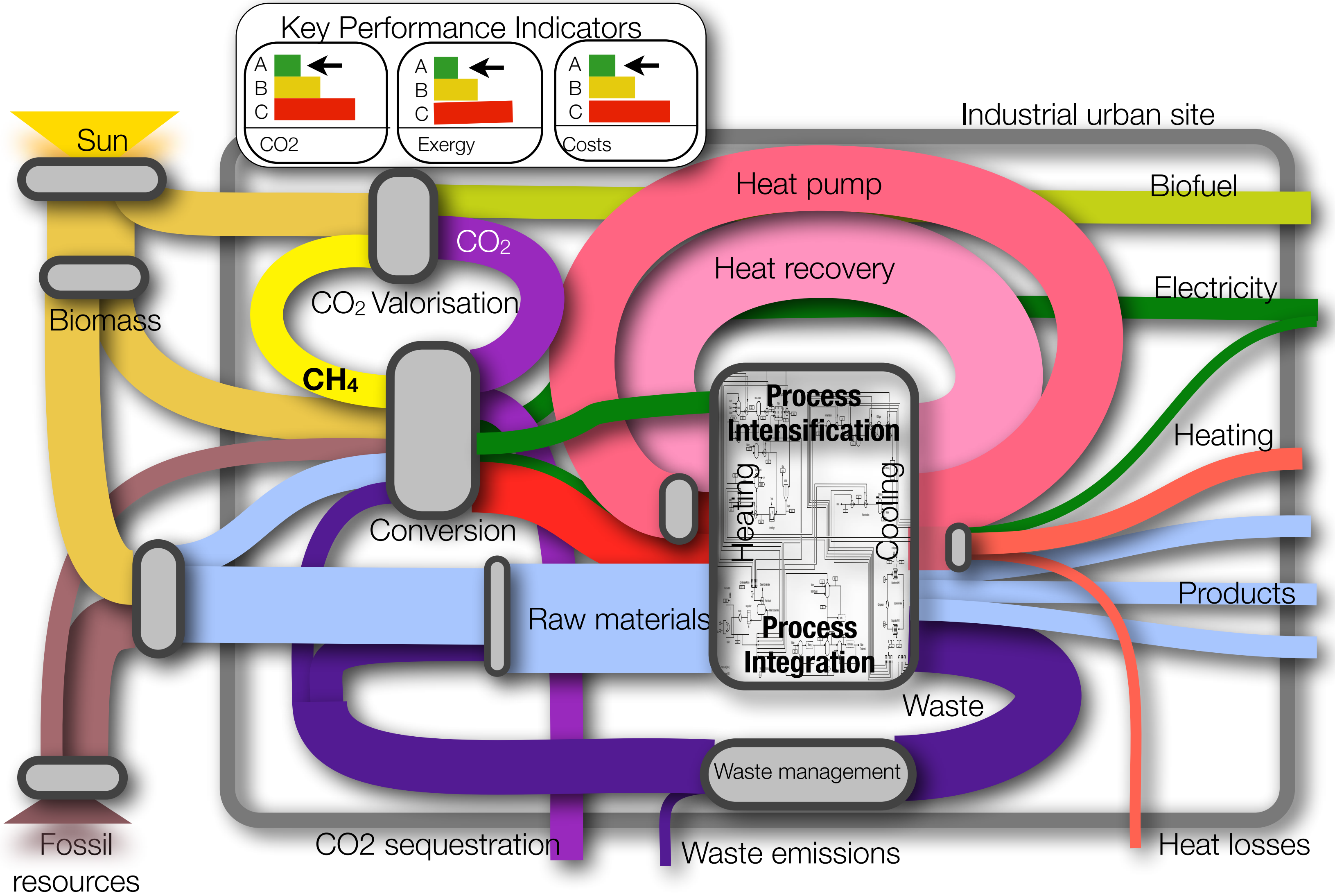


Energy Transition Actions

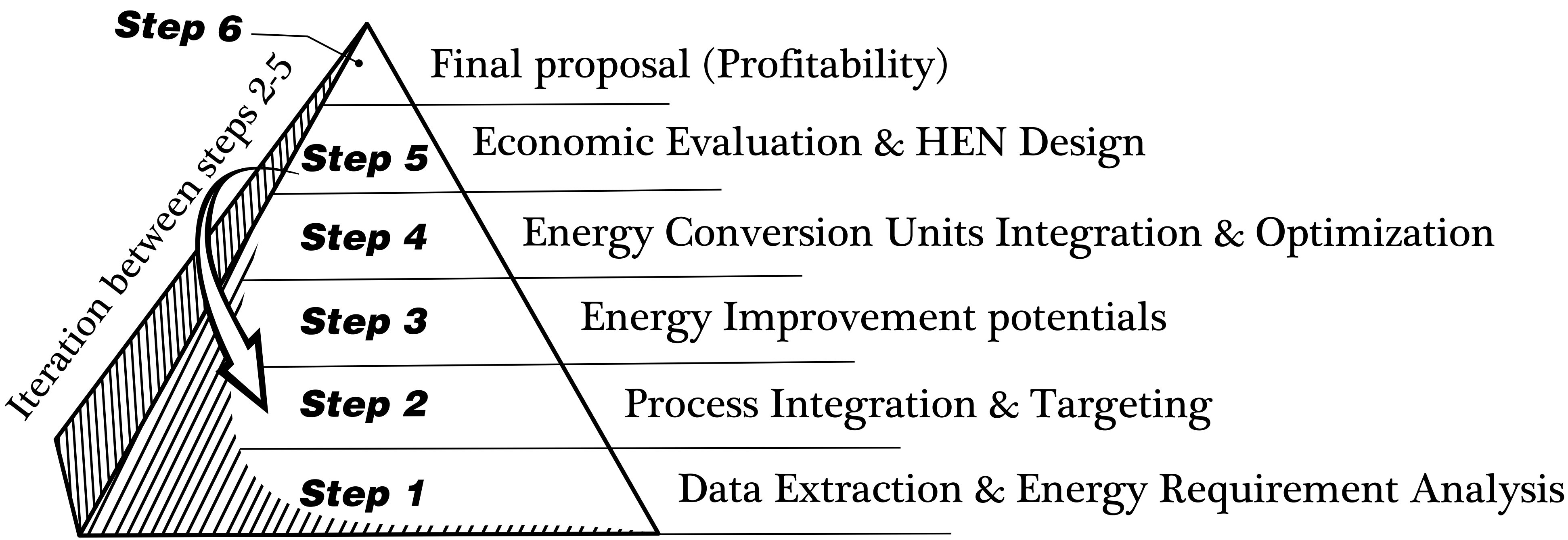
- **Actions**
  - **S**obriety => ask less for the same services
  - **E**fficiency => do more from the resources
  - **R**enewables => Integrate the endogenous resources
  - **I**ntegrate => Look for synergies
  - **E**quip => Invest Capital for equipments and infrastructure
  - **S**ystem => define the right system boundaries

Process system engineering

Selection, Integration, Sizing and optimal Operation in industrial system



- **A systematic implementing approach**

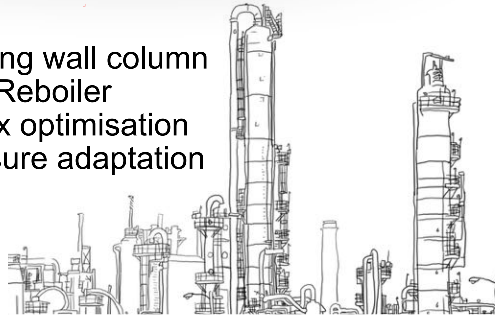


Pouransari, 2014

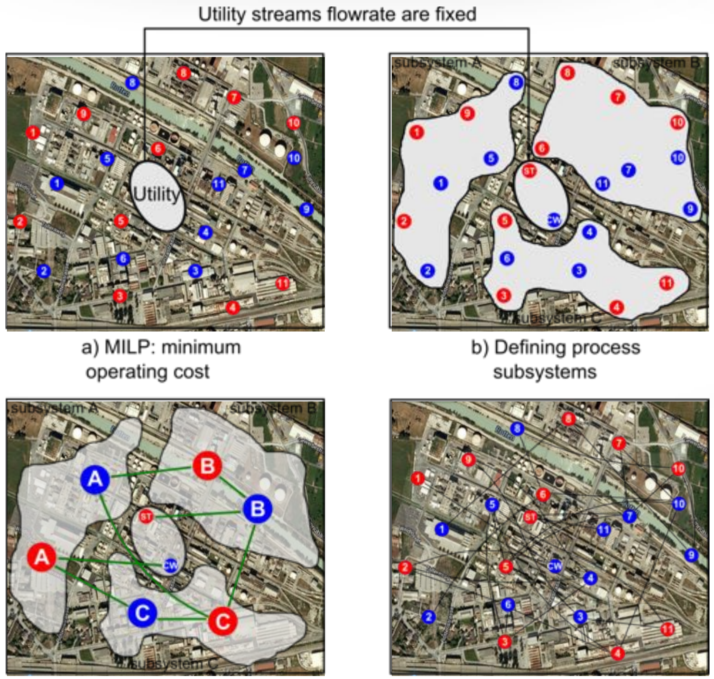
Large Scale Process Integration : in practice

Process operation

Dividing wall column
Side Reboiler
Reflux optimisation
Pressure adaptation



Site scale integration



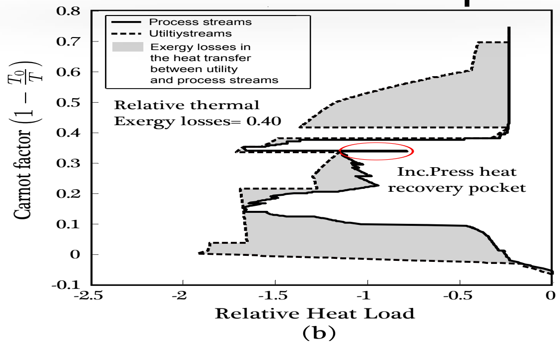
a) MILP: minimum operating cost

b) Defining process subsystems

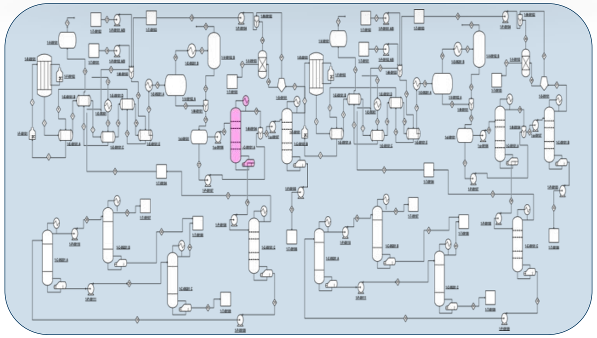
d) MILP: HLD between virtual and utility streams

i) Final solution, Heat recovery network

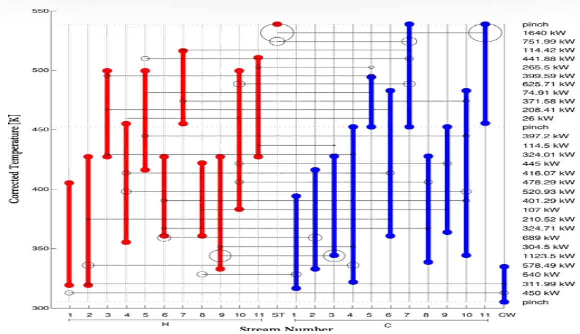
Combined heat and power



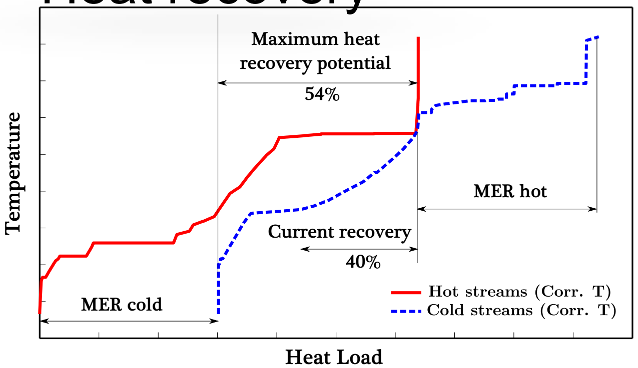
Process units integration



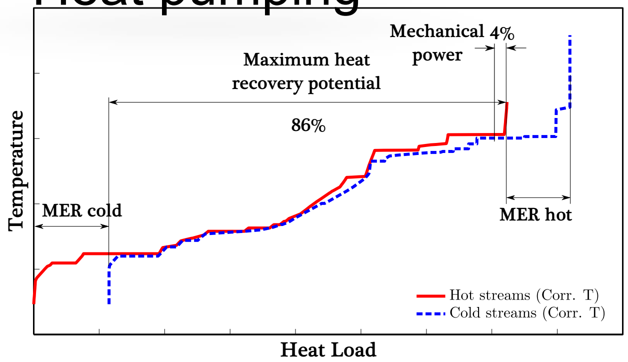
Heat exchanger network



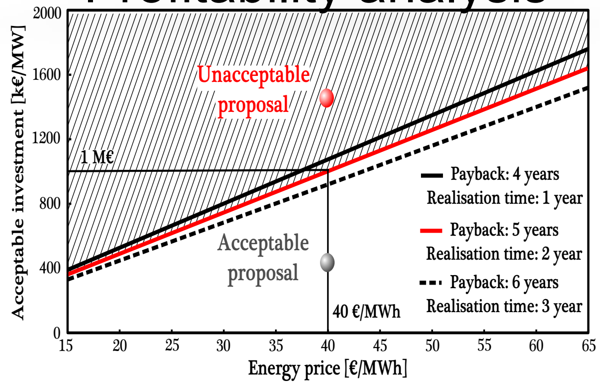
Heat recovery



Heat pumping



Profitability analysis

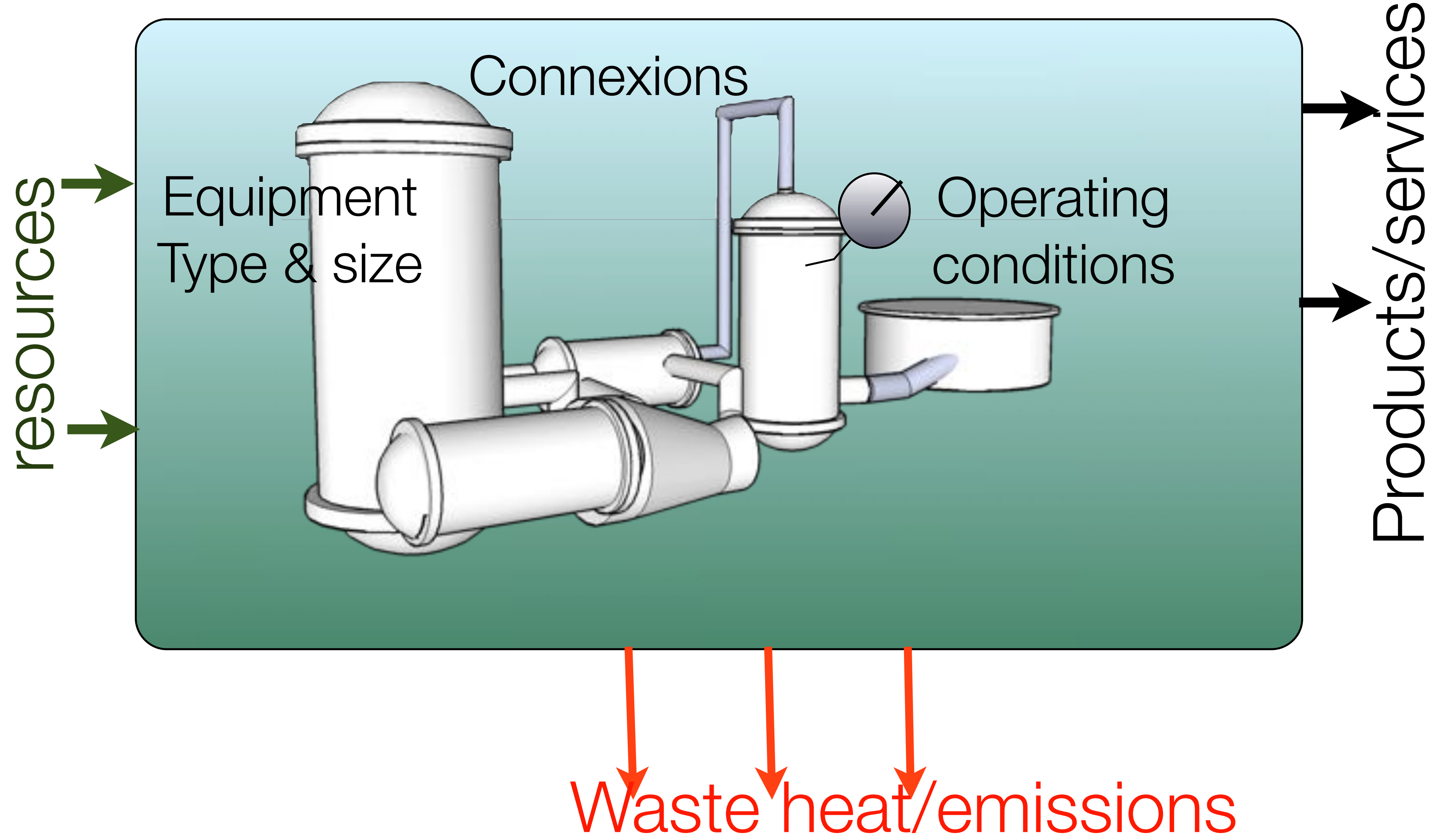


Total site integration : Open questions

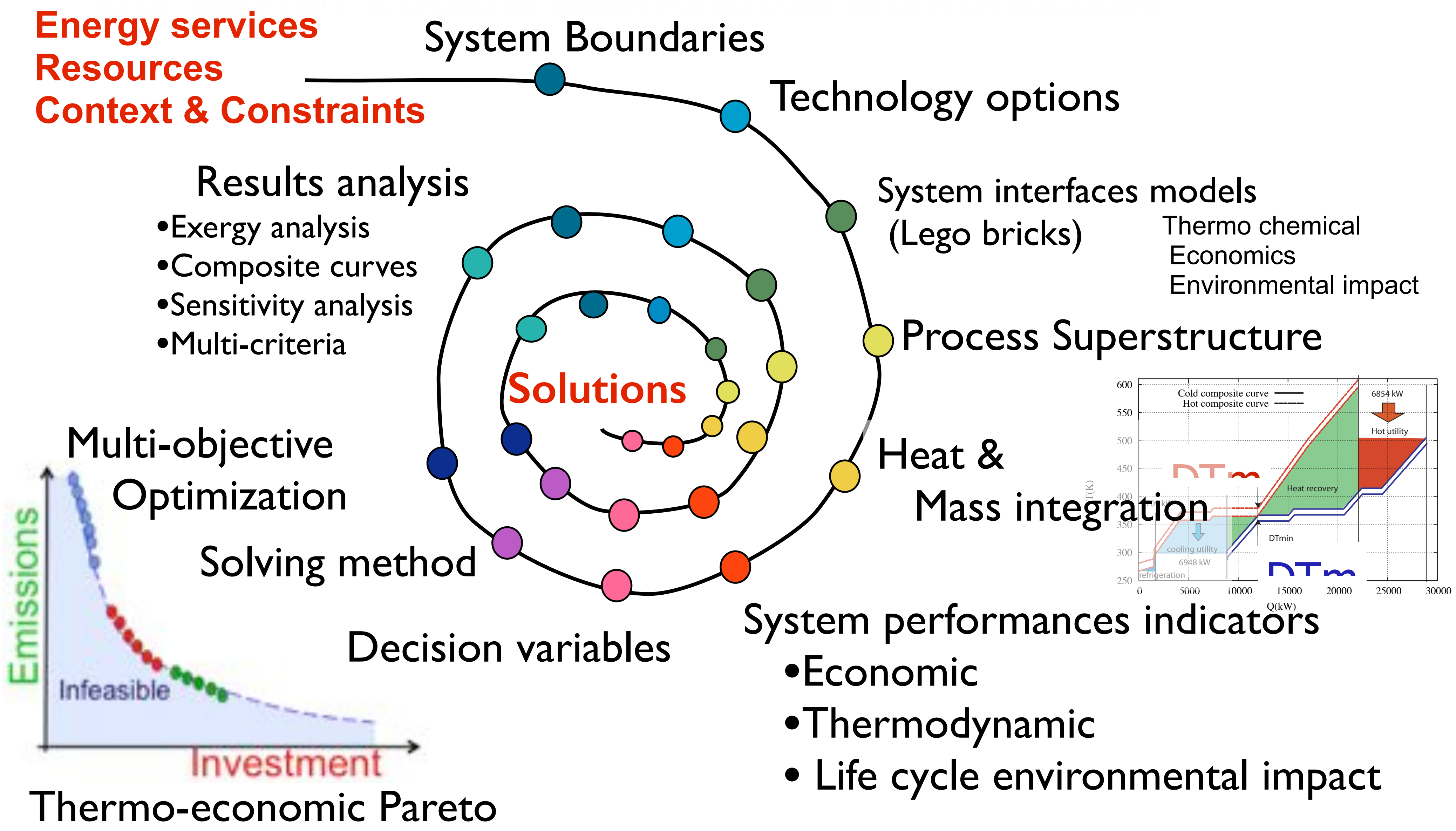
- **How to organise heat transfer between processes**
  - Third Party : ESCO ?
    - Process interfaces
      - *contract + confidentiality*
  - Restricted matches & HEN design
- **How to realise a holistic system design ?**
  - Energy conversion
    - Combined Heat - Cold and power production
    -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

Process system engineering

Selection, Integration, Sizing and optimal Operation in industrial system



The energy system engineering methodology



OSMOSE : Computer Aided Platform

IPESE

Grid computing

Decision support

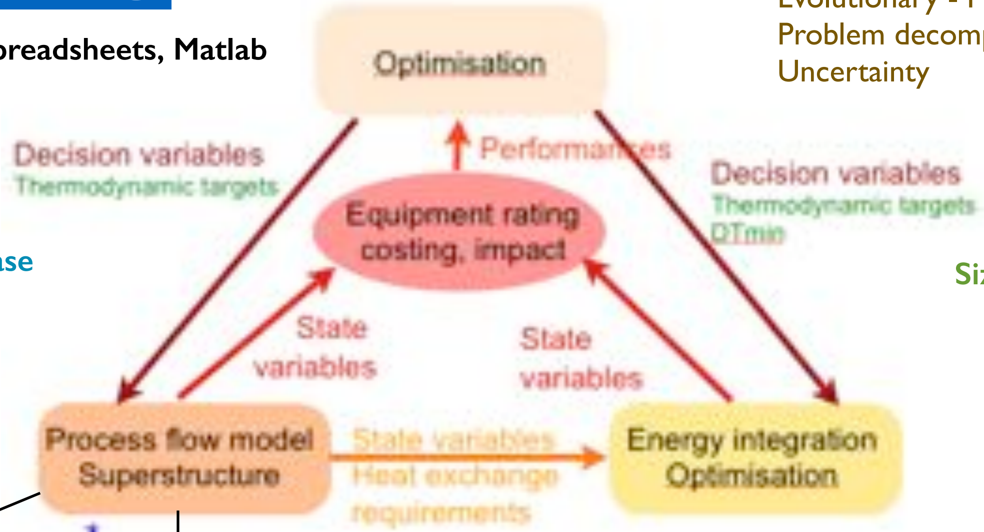
Multi-objective optimisation
- Evolutionary - Hybrid
- Problem decomposition
- Uncertainty

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

GUI interface
- •User interaction
- • Web interface + workflow organisation
- • Reporting

Modeling tools integration

Process synthesis of a fuel cell hybrid system

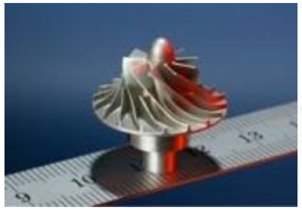
Equipment

Solid Oxide Fuel Cell

MER Jan Vanherle

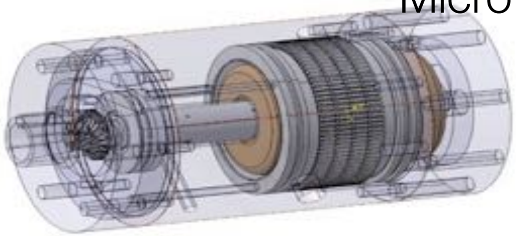
15 kWe

Prof. Favrat/Schiffmann



6 kWe

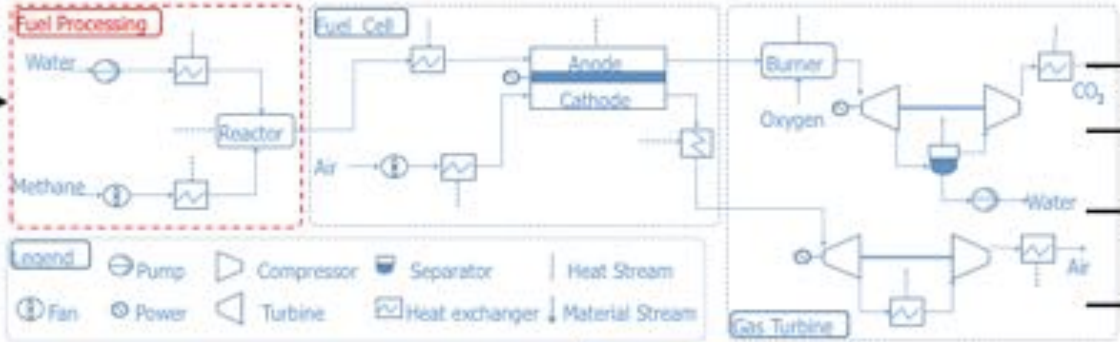
Micro Gas Turbine



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

Optimised operating conditions

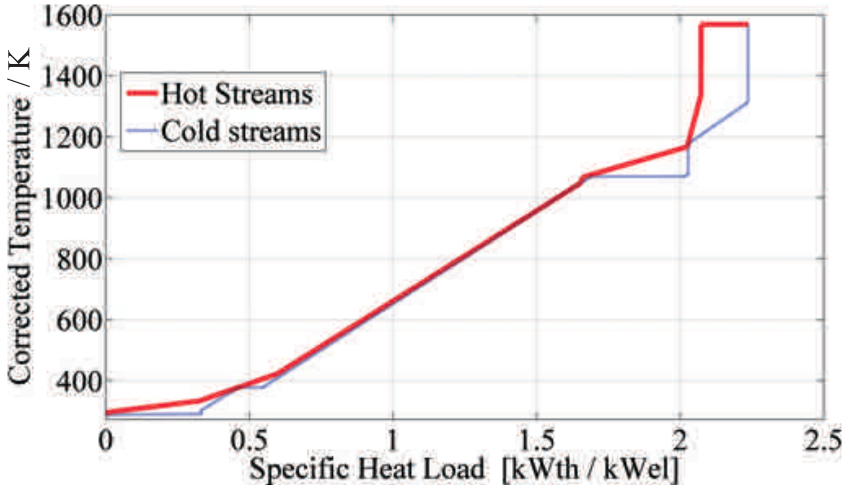


Fig. 7 HCox composite curves of optimal solution with π = 3 and max TIT = 1,573 K.

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

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

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

3D Design
3D Modeling
3D System control

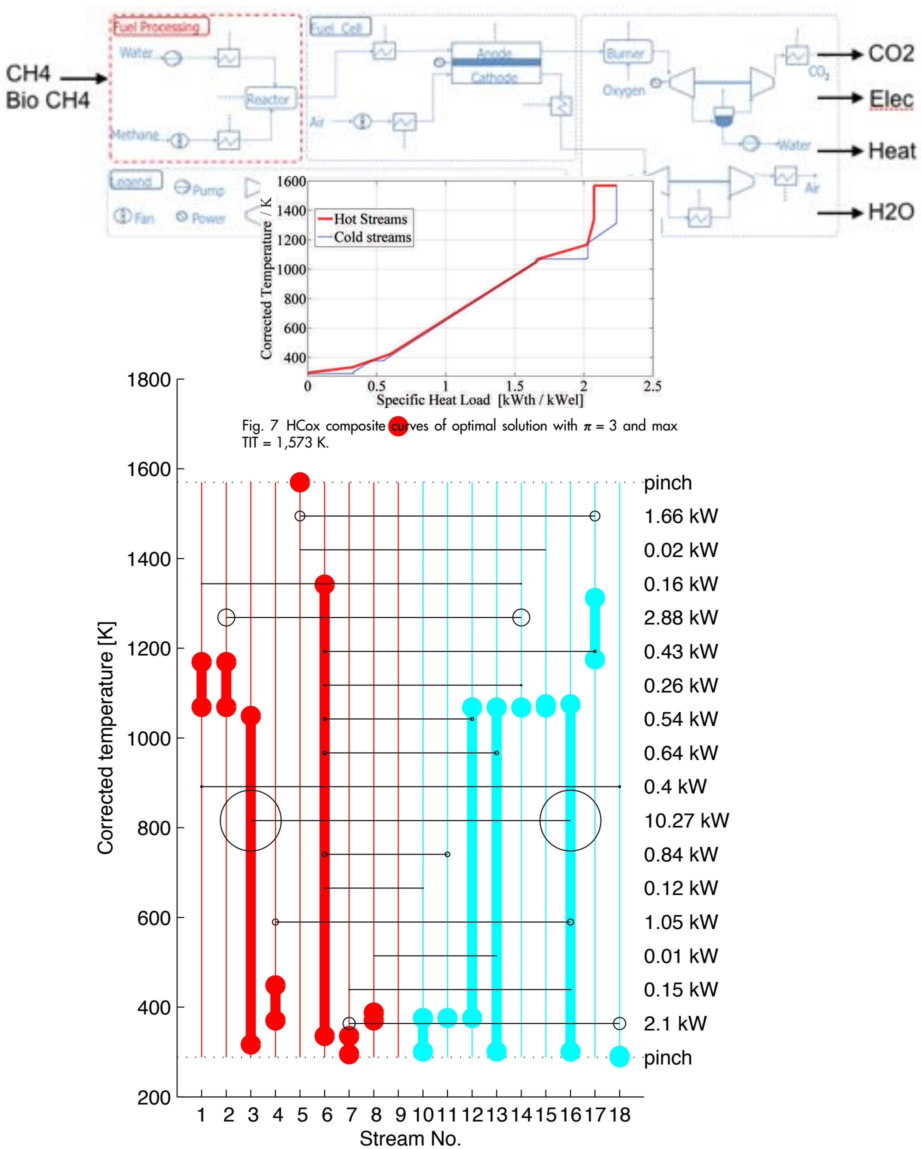
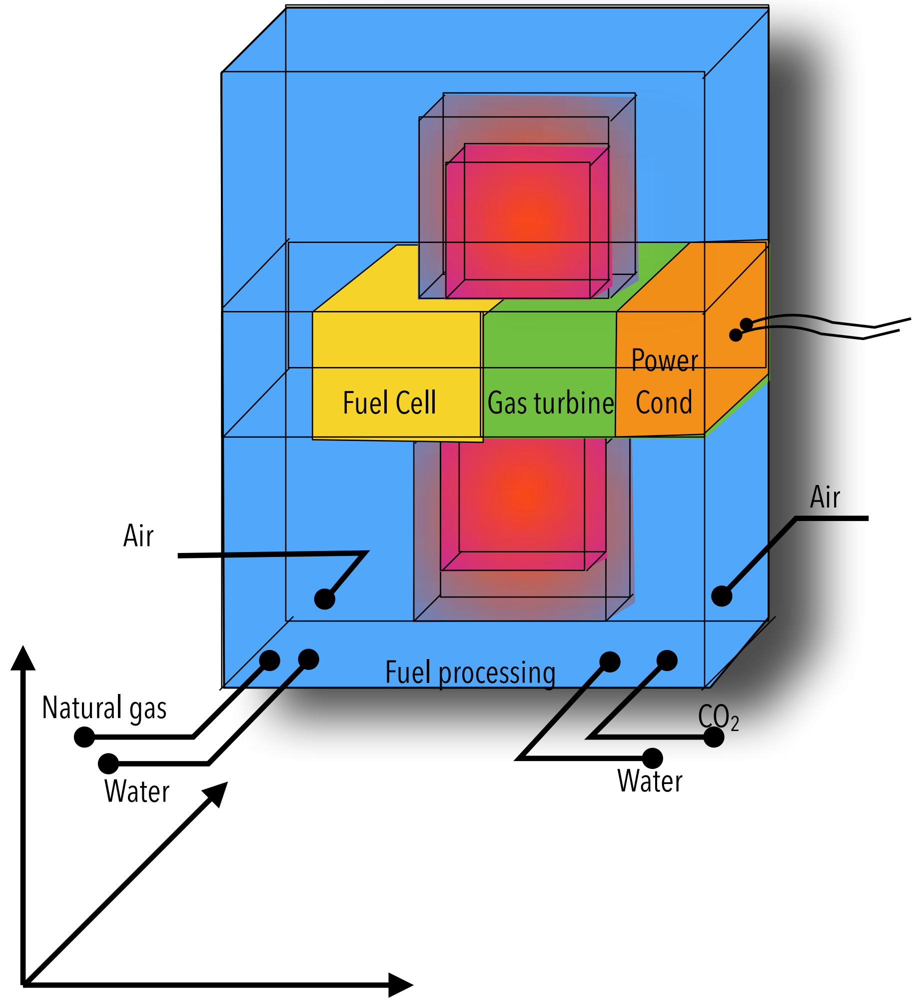


Fig. 7 HCox composite curves of optimal solution with $\pi = 3$ and max TIT = 1,573 K.

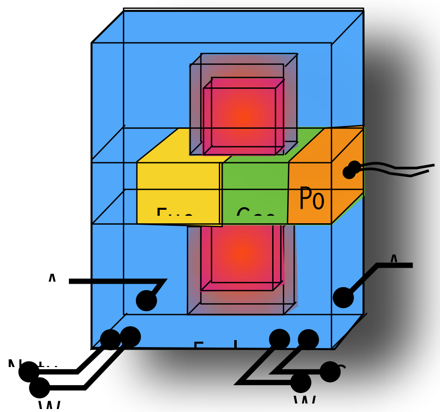


A paradigme for the energy system ?

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

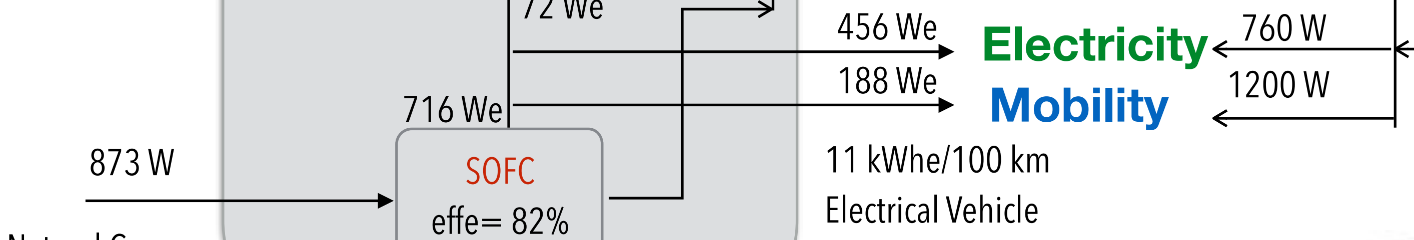
- **by ...**
  - 75000 units of 10 kWe / 80% elec
  - Distributed production
  - 13% heat for poly-generation (heating or cooling)
  - Cost scaling factor near 1

Motivation : for a typical Swiss household



90%

60%



70 kWh/100 km
Natural Gas Vehicle

Savings : 65 %

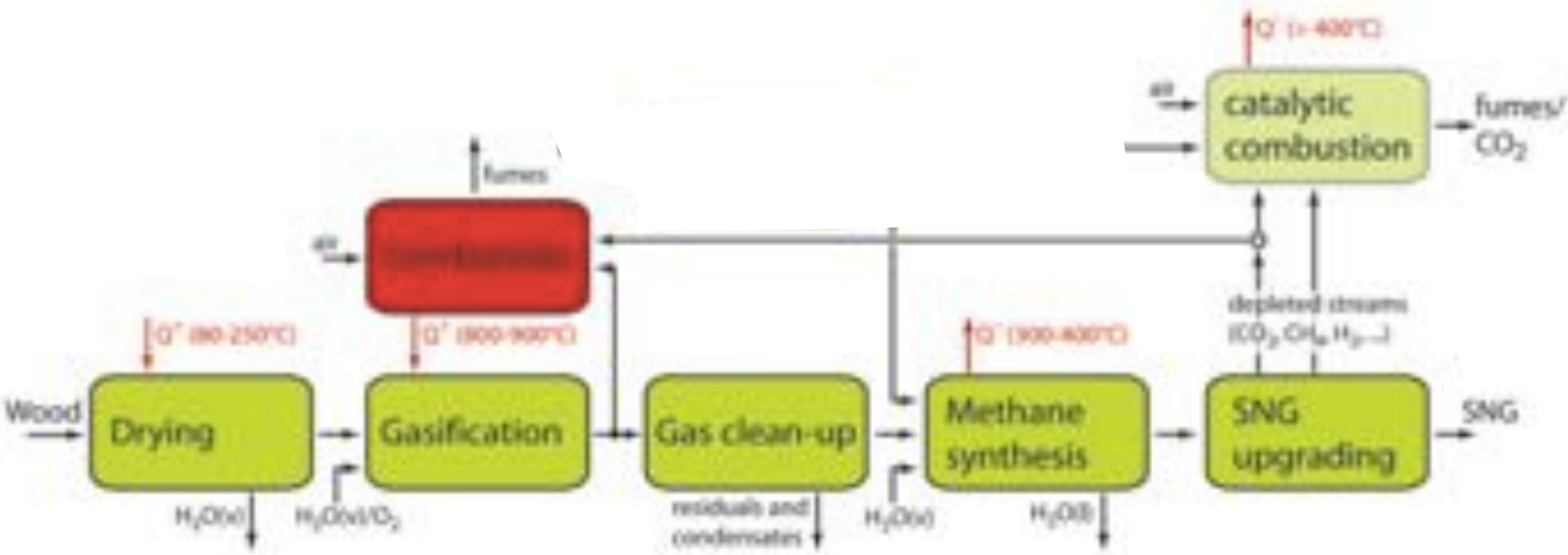
Factor 3, without changing the demand !

W means Wyear/year/cap

- **Smart engineers: Renewable energy integration**

Producing Natural gas from Wood

Renewable natural gas : Synthetic natural gas from biomass



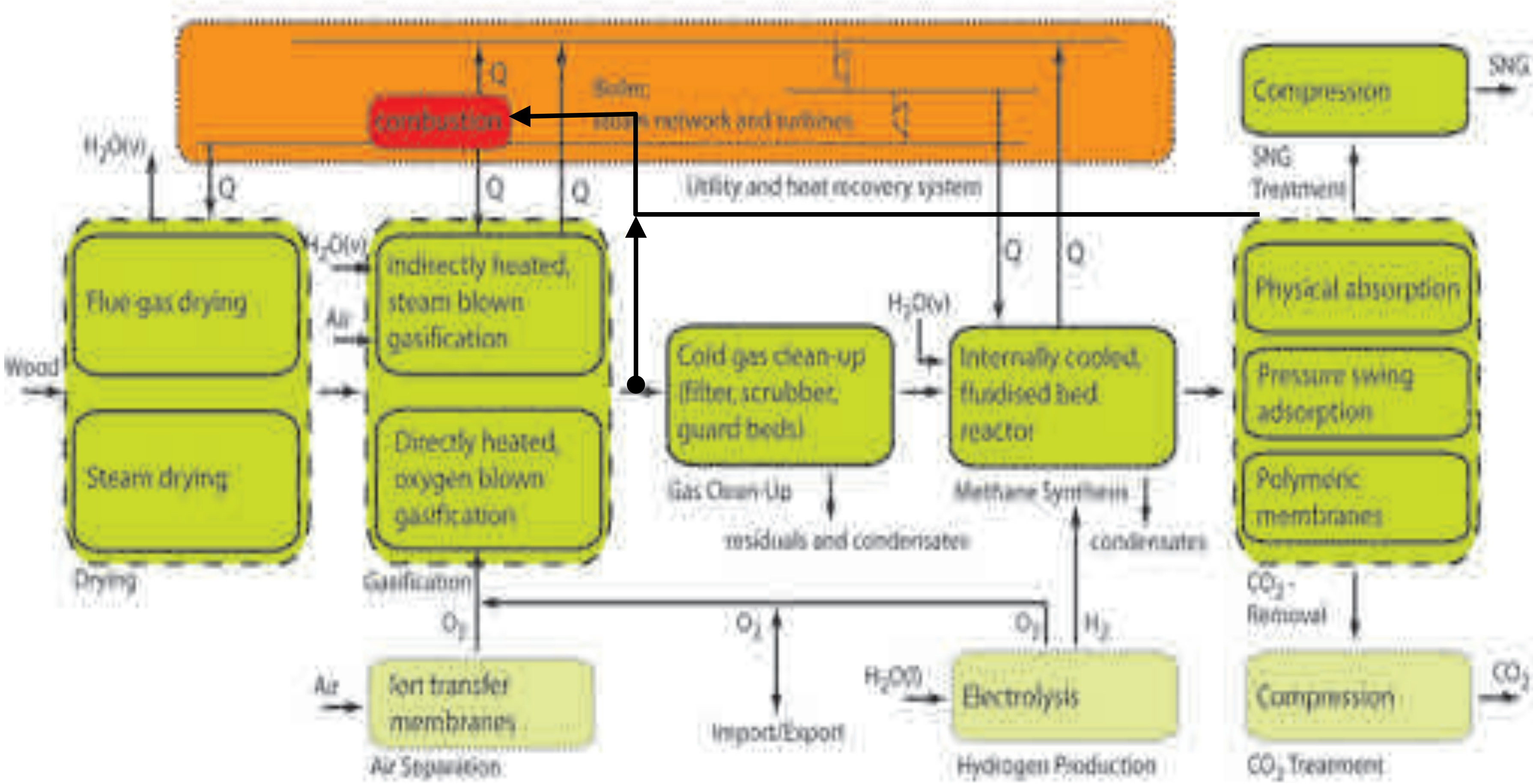
WOOD Natural Gas (SNG) CO2 (pure)

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

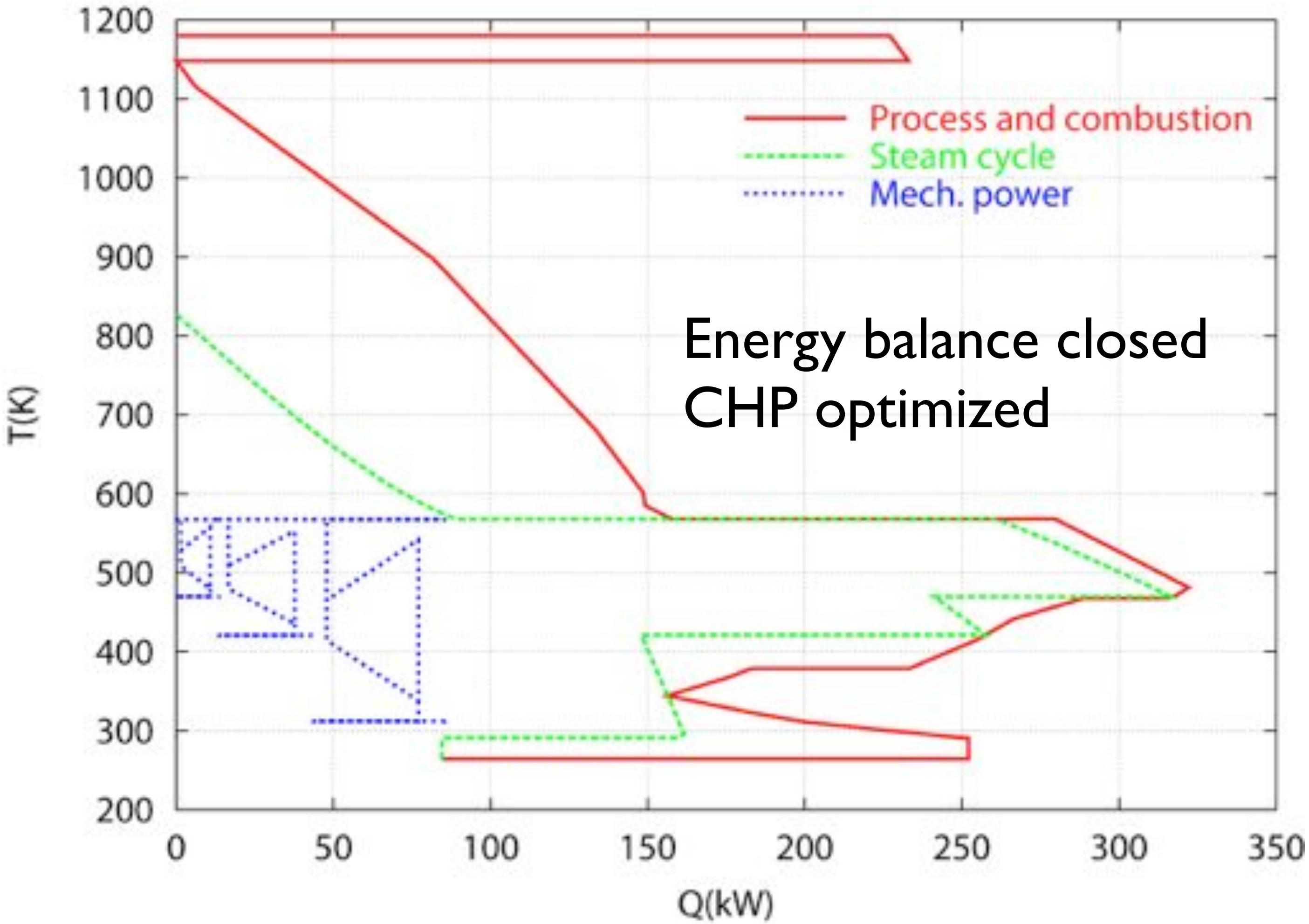
Gassner, M., and F. Maréchal. "Thermo-economic optimisation of the integration of electrolysis in synthetic natural gas production from wood." *Energy* 33, no. 2 (February 2008): 189-198.

Closing the energy balance

Integrating heat recovery technologies in the superstructure



- **The Heat Cascade is the HEN model**

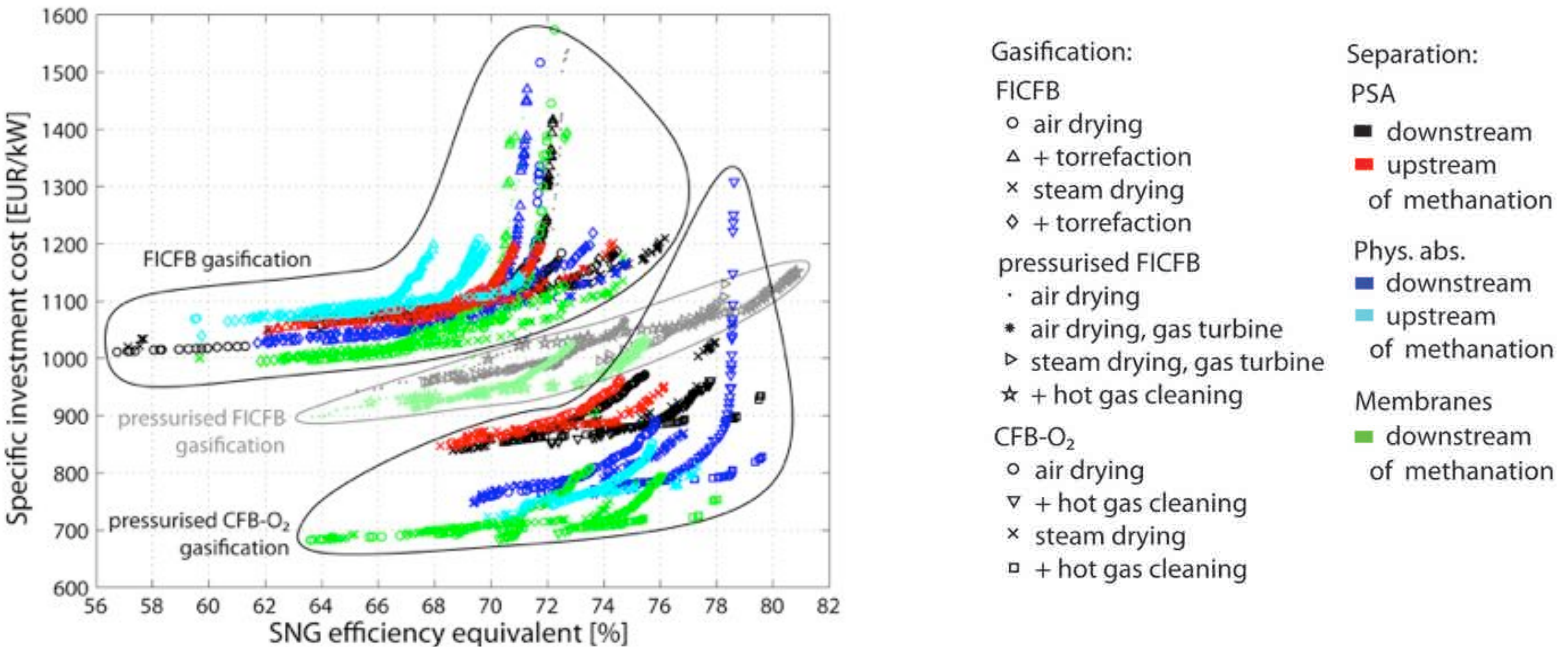


Energy balance closed
CHP optimized

Comparing options

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

Thermo-economic Pareto front (cost vs efficiency):

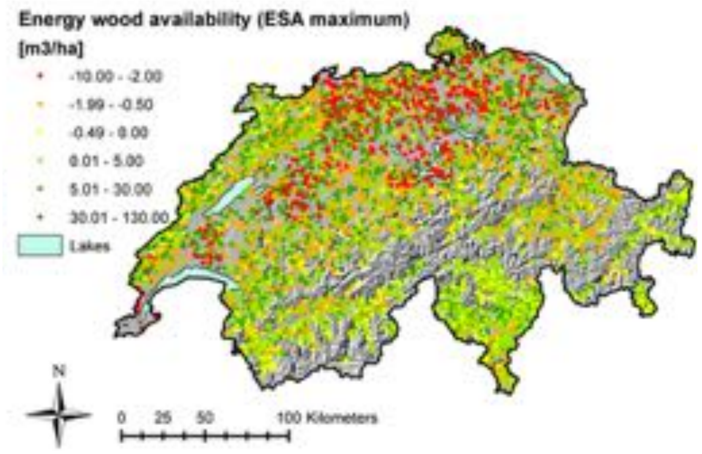


Note : 1.5 years of calculation time !

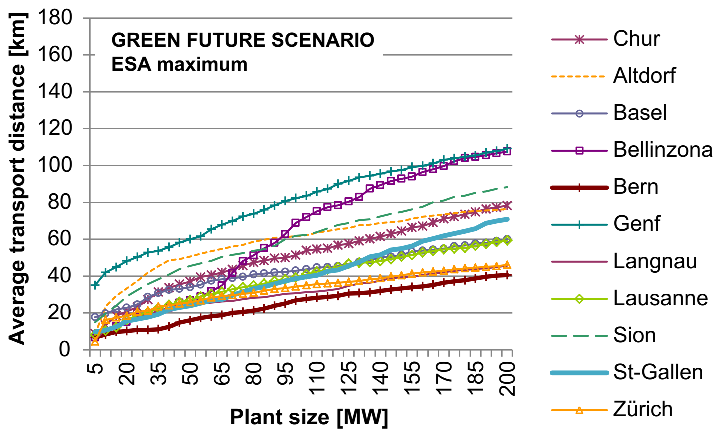
Gassner, Martin, and François Maréchal. *Energy & Environmental Science* 5, no. 2 (2012): 5768 – 5789.

Plant location

Area = 40 km2

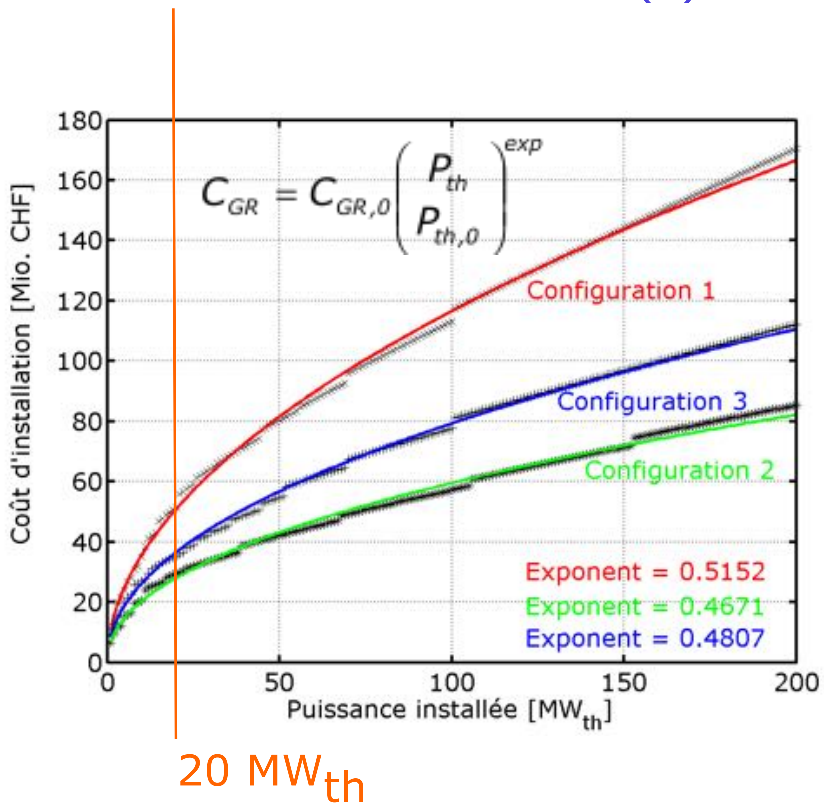


Transport = 10 % of the energy



Process Size => Investment

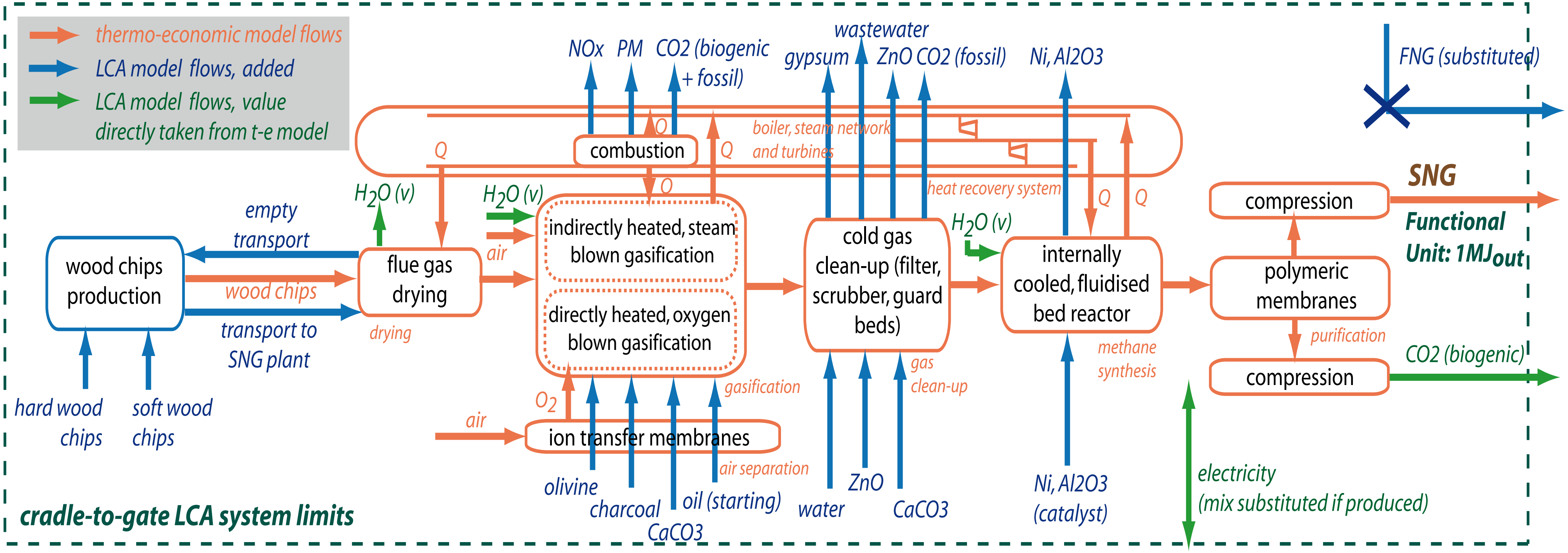
20 MW$_{th}$:
- 51.4 Mio. CHF (1)
- 29.5 Mio. CHF (2)
- 35.4 Mio. CHF (3)



Efficiency : 5000 Wyear/year/ha

Identification of Life Cycle Inventory elements

- **Process superstructure, extended with LCI**

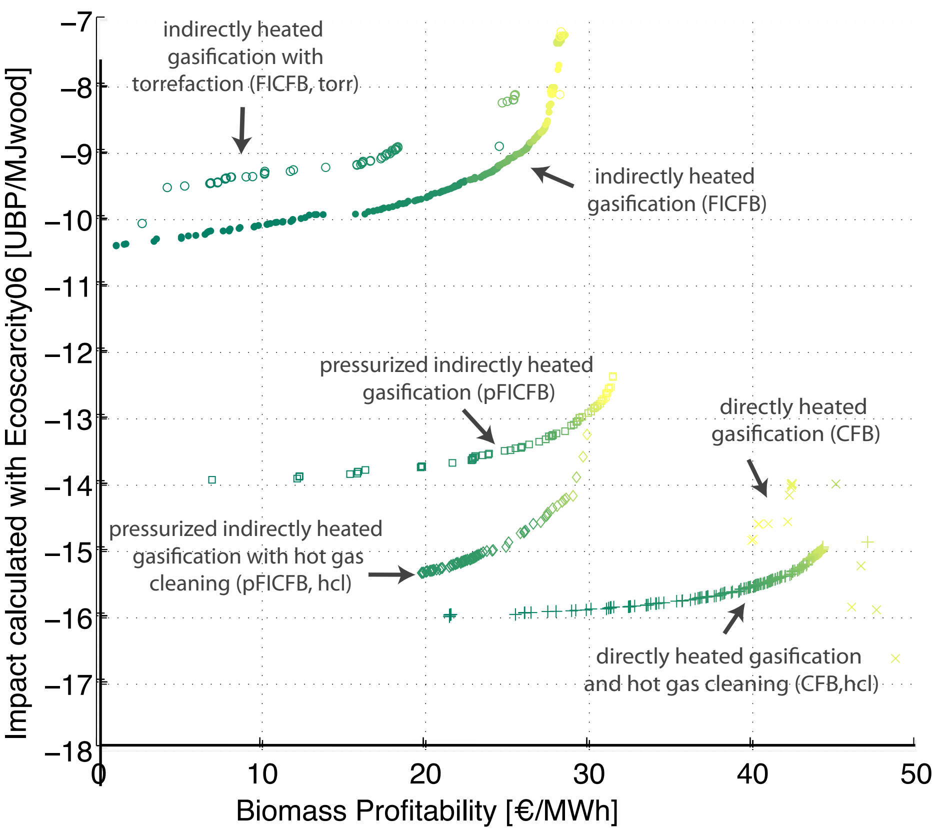


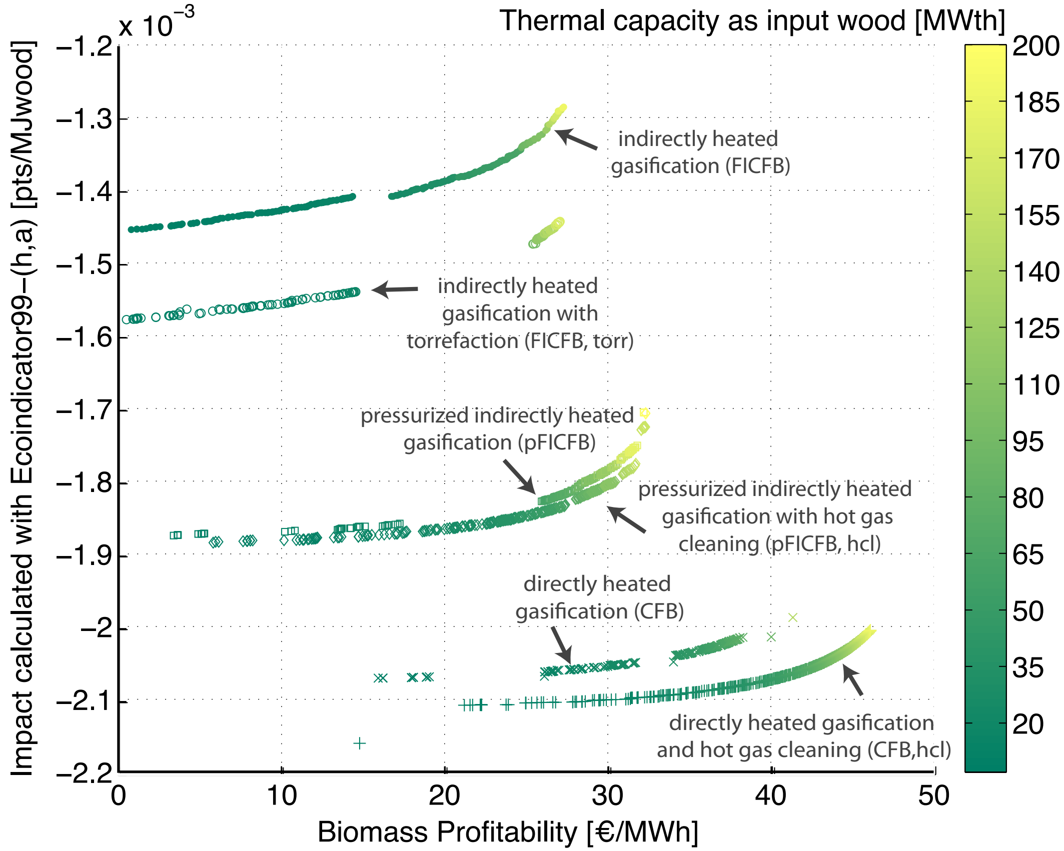
➡ **use of ecoinvent emission database (1) for each LCI element, to take into account off-site emissions**

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

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

• Optimal configurations





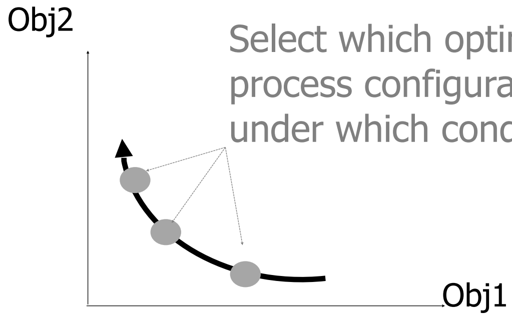
Land & supply chain are constraints

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

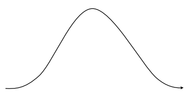
• Selecting the process in the Pareto set

Select which optimal process configuration under which conditions ?

Pareto optimal front for given economic scenario



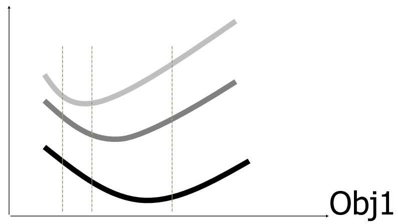
Economic parameters



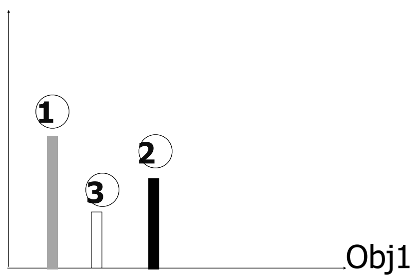
Distribution functions

Impact on decision criteria

Decision criteria



Ranking # of times in top 5



Solutions ranking based on probability
→Decision-making support

• Uncertainty of the economical conditions

– Economic assumptions probability distribution functions

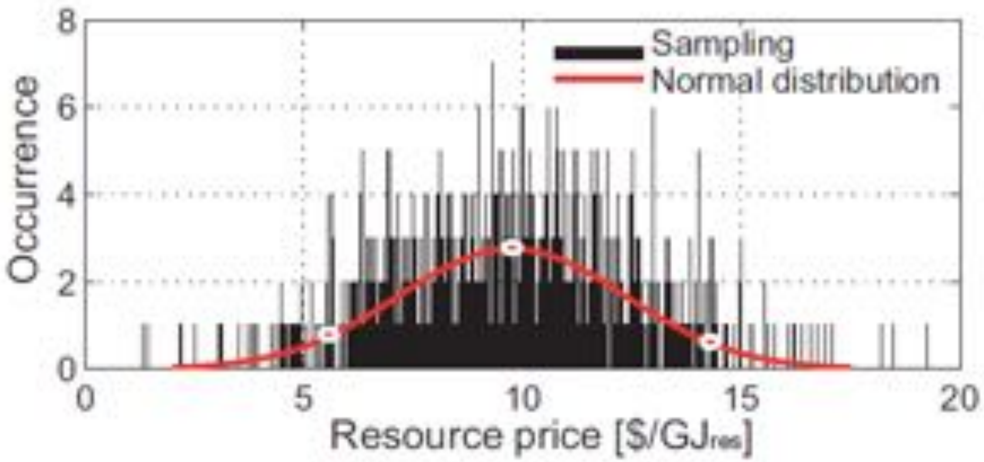
- Normal, uniform, beta distribution

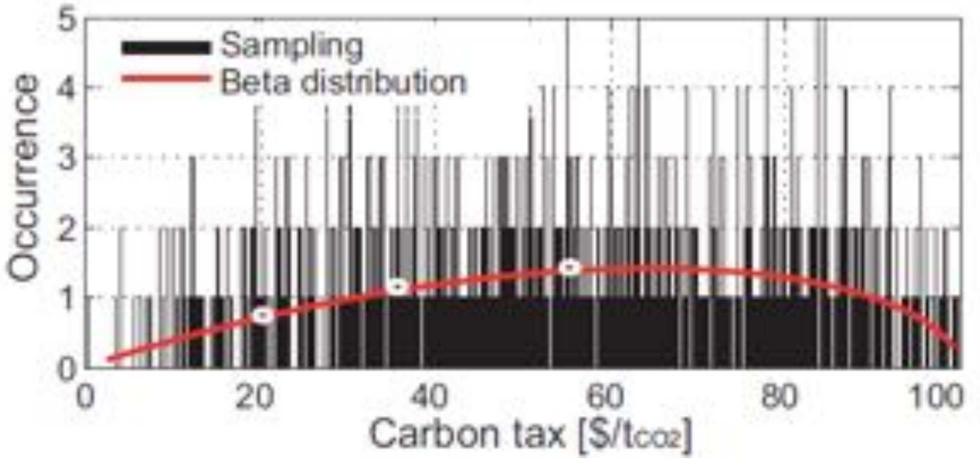
Scenario [IEA, EU, ZEP,...]	Base	Low	High
Resource price [$/GJ$_{res}$]	9.7	14.2	5.5
Carbon tax [$/t$_{CO2}$]	35	20	55
Yearly operation [h/y]	7500	4500	8200
Expected lifetime [y]	25	15	30
Interest rate [%]	6	4	8
Investment cost [%]	-30%	-	+30%

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

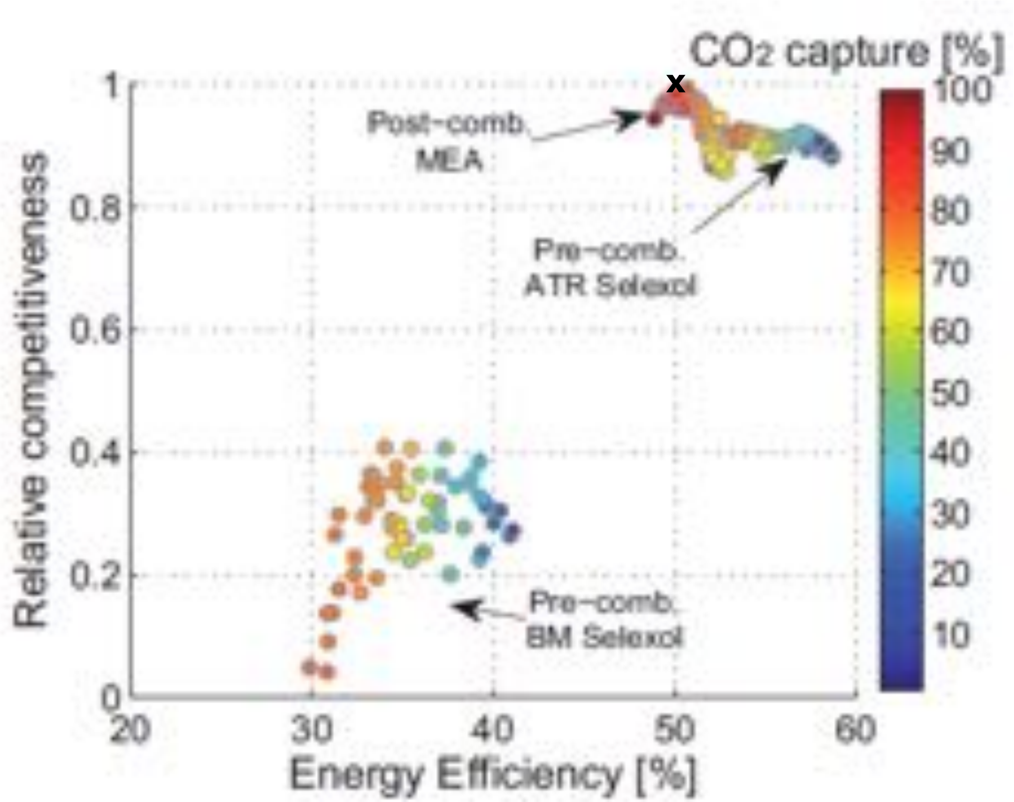
$$f(x) = \frac{1}{a-b}$$

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





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

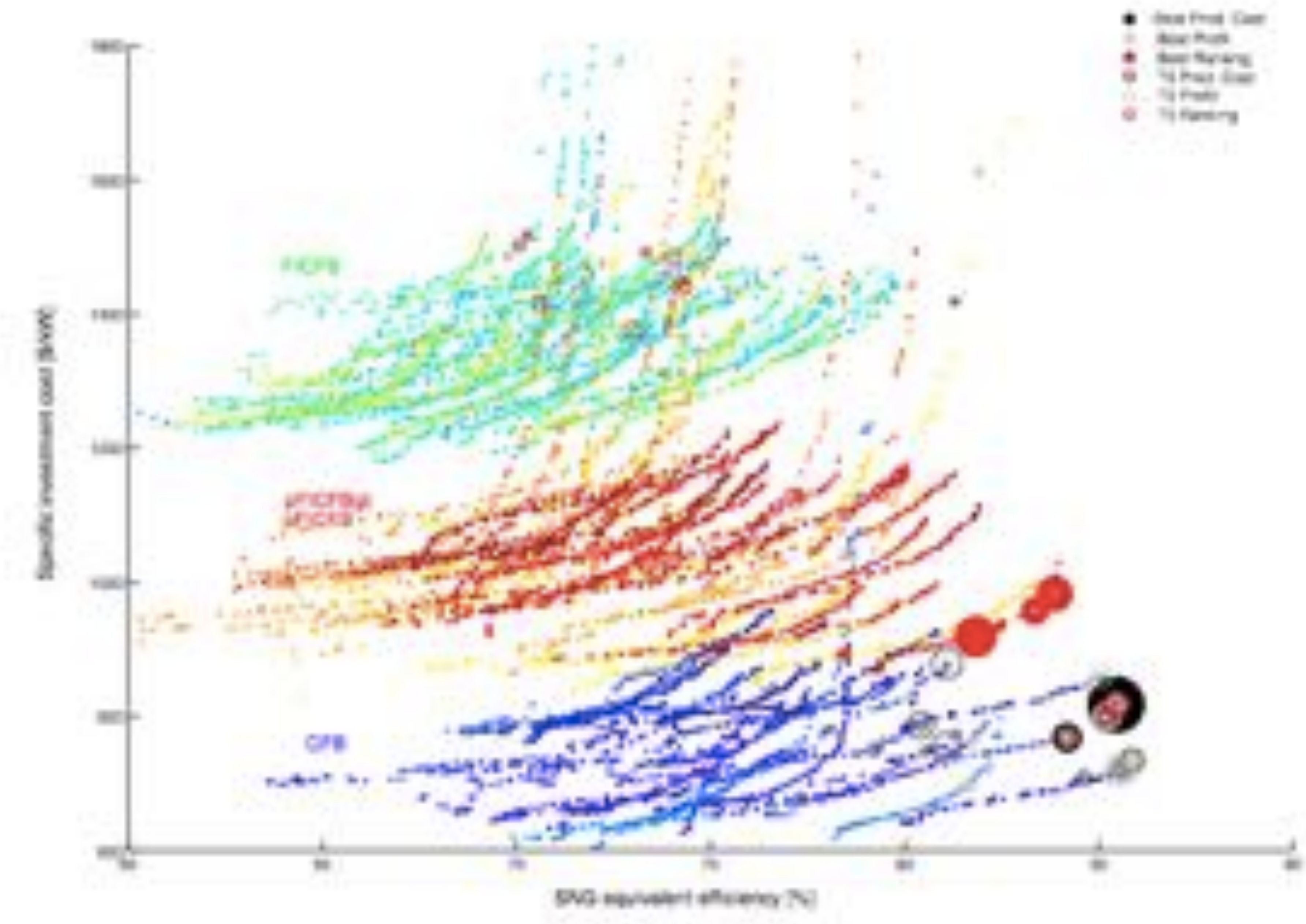


  - CO_2 capture is economically competitive for capture rates between 70 and 85%!

Laurence Tock, Thesis, 2013

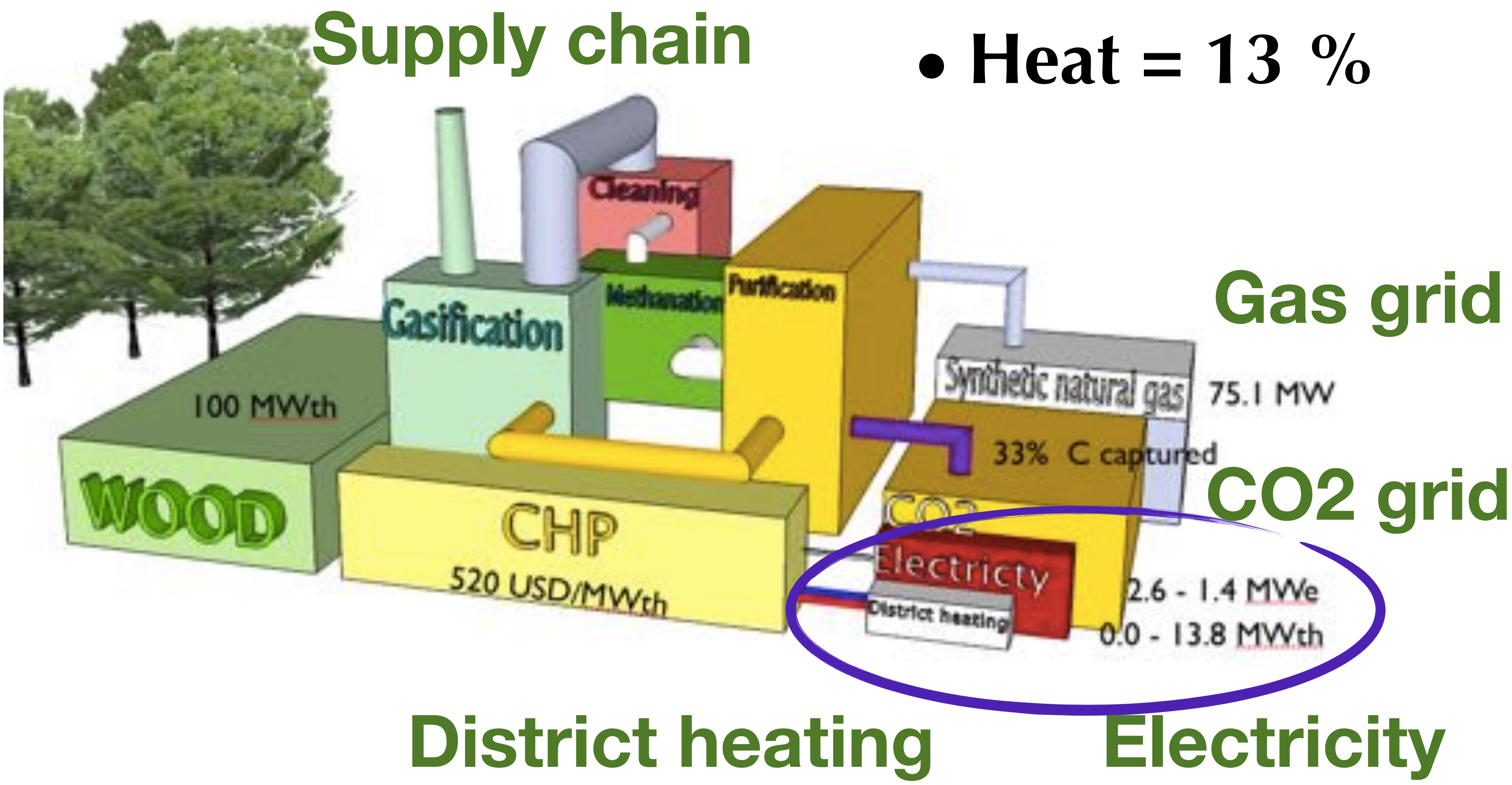
What is the best process design ?

Pareto optimal configurations => new process model for the energy system design



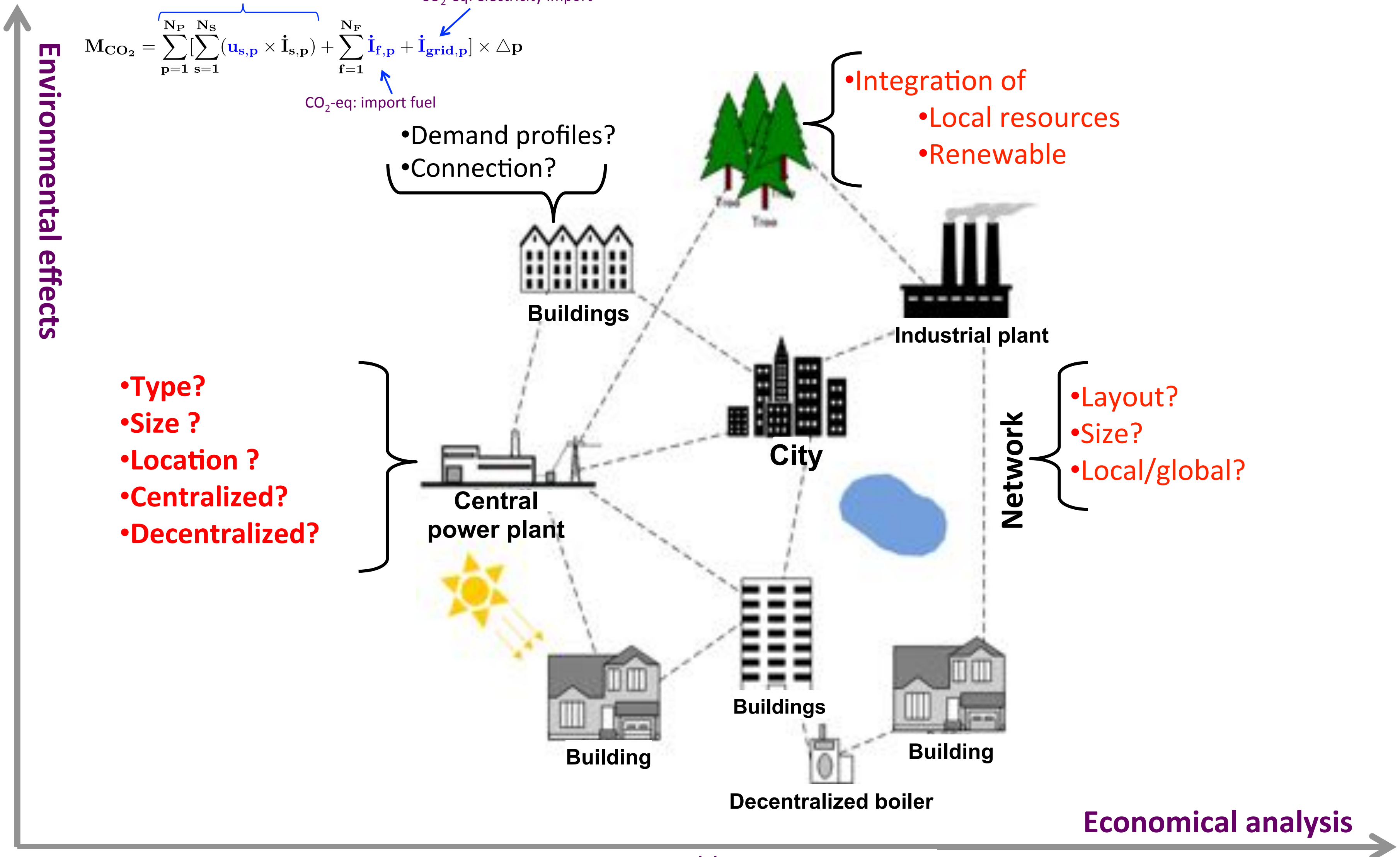
- Resource productivity

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



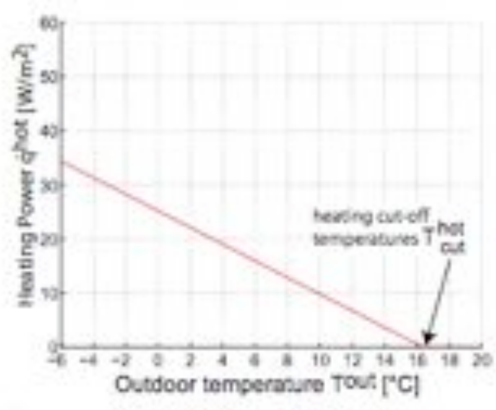
Smart Energy Systems : Problem statement

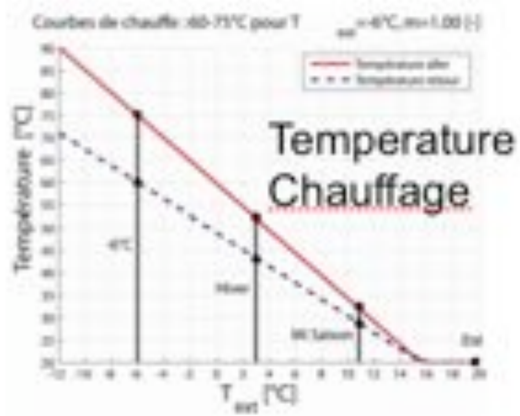
$$M_{CO_2} = \sum_{p=1}^{N_P}\Big[\overbrace{\sum_{s=1}^{N_S}(u_{s,p} \times \dot{i}_{s,p})}^{\text{CO}_2\text{-eq: subsystem } s} + \sum_{f=1}^{N_F} \underbrace{\dot{i}_{f,p}}_{\text{CO}_2\text{-eq: import fuel}} + \overbrace{\dot{i}_{grid,p}}^{\text{CO}_2\text{-eq: electricity import}}\Big] \times \Delta p$$

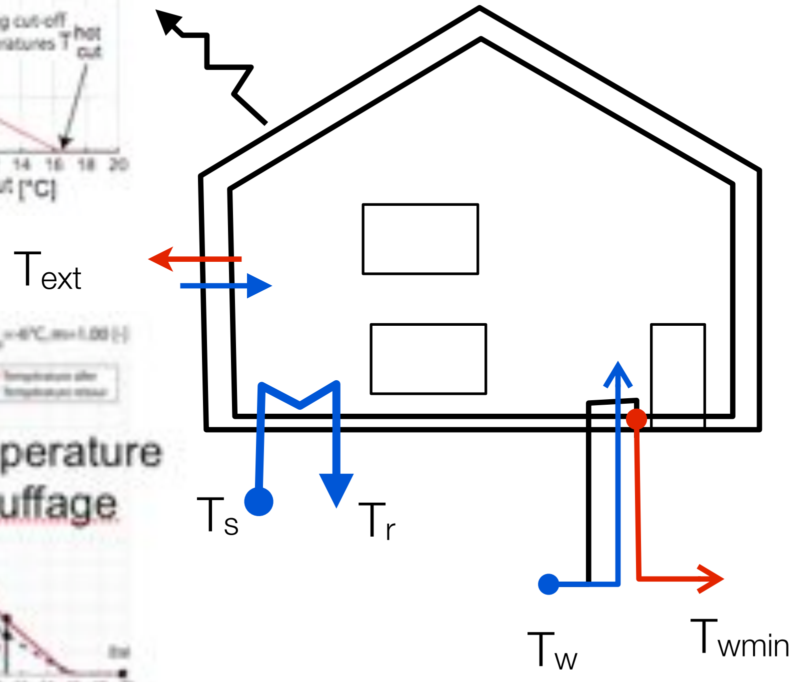


$$\mathrm{TAC} = \overbrace{\sum_{s=1}^{N_S}\sum_{p=1}^{N_P}(\dot{COV1}_{s,p} \times y_{s,p} + \dot{COV2}_{s,p} \times u_{s,p}) \times \Delta p}^{\text{Variable operating costs}} + \underbrace{\sum_{s=1}^{N_S}(COF1_s \times y_s + COF2_s \times u_s)}_{\text{Fixed operating costs}} + \underbrace{\sum_{s=1}^{N_S} CI_s \times \frac{i.(1+i)^{n_s}}{(1+i)^{n_s}-1}}_{\text{Annual investment costs}}$$

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





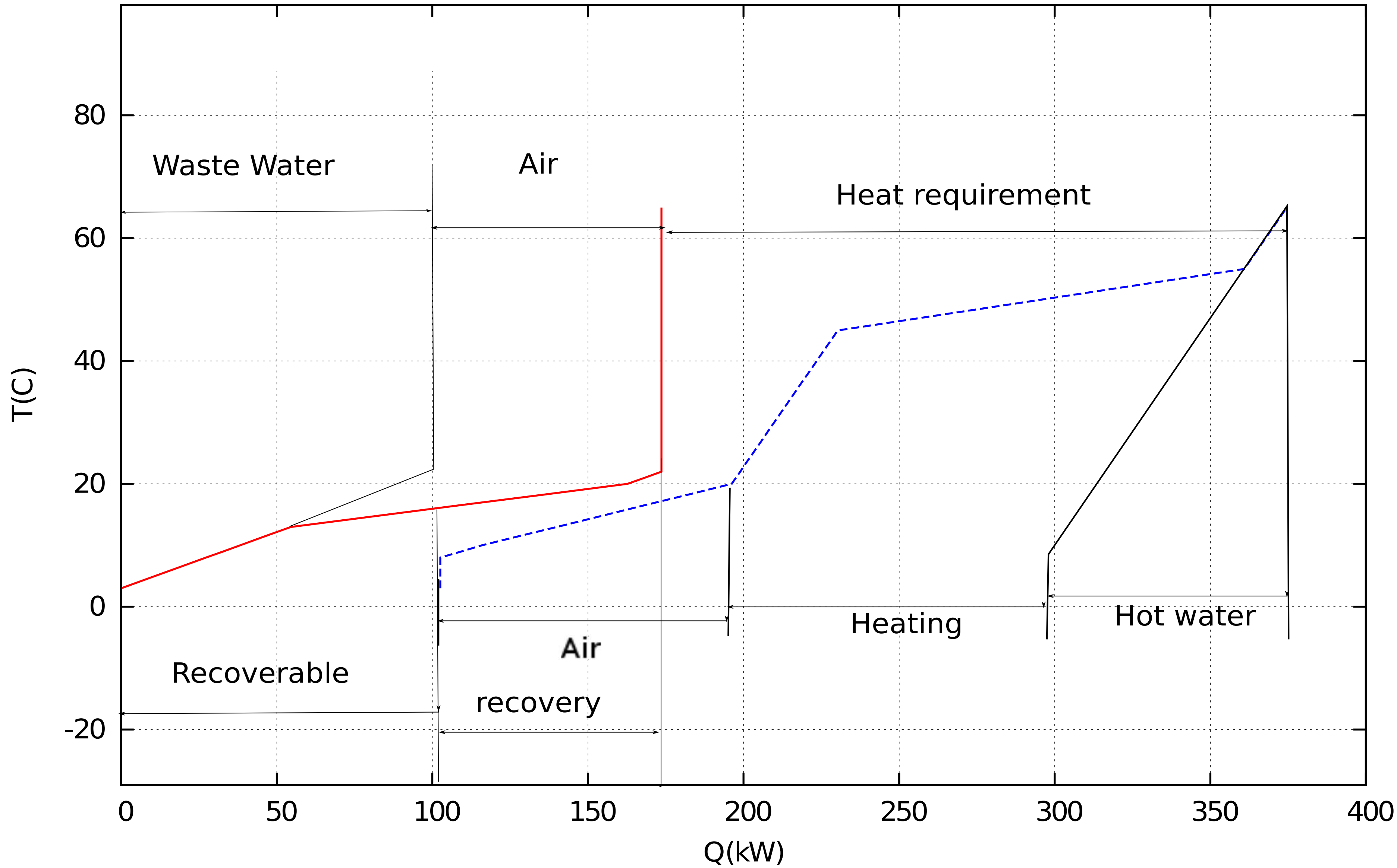


Do not forget Carnot (Exergy demand) :

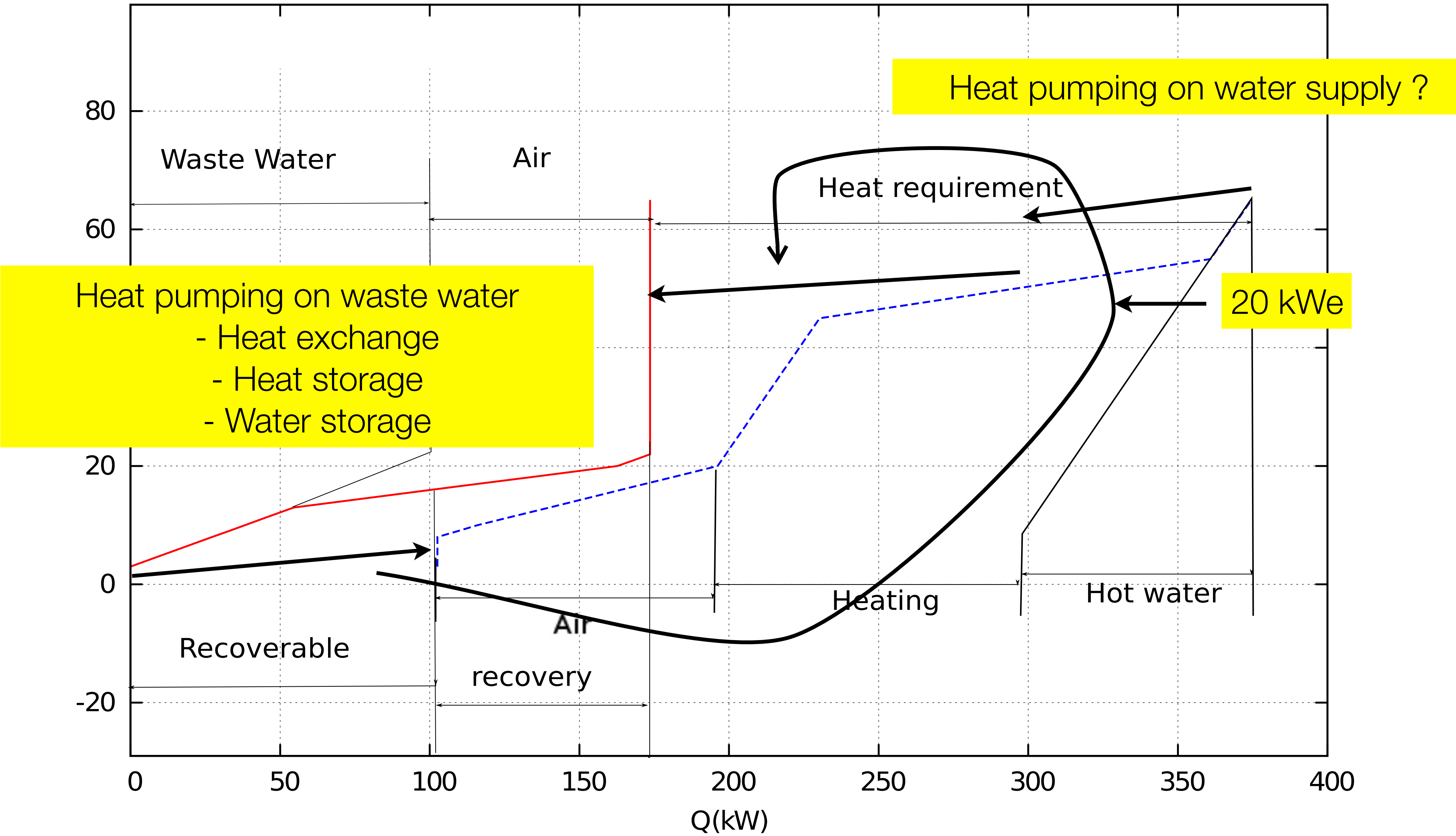
* Heat with the lower possible temperature

* Cool with the highest possible temperature

Local heat recovery



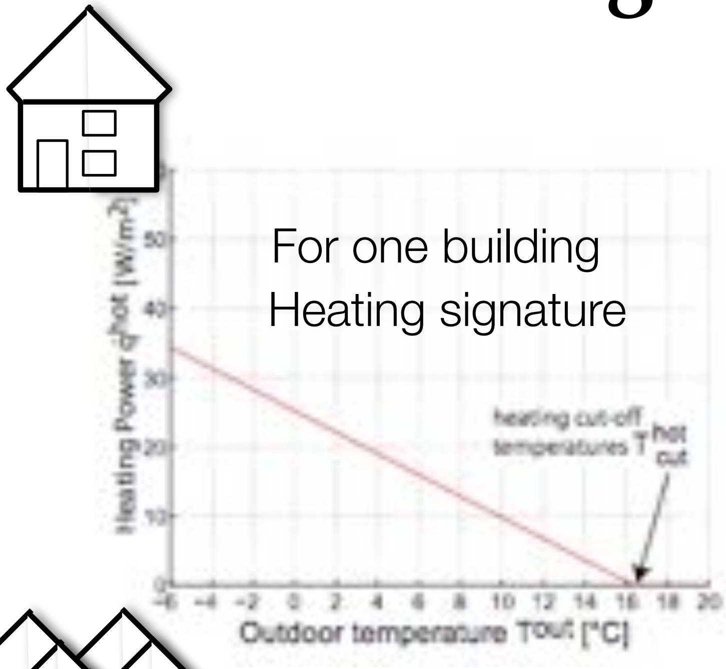
Local Heat pumping on waste water



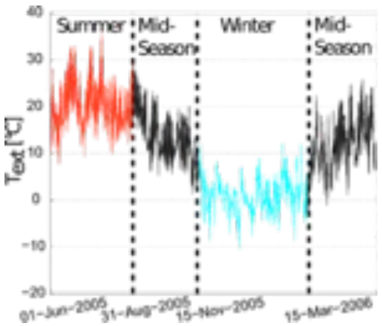
COP = 5 to 6

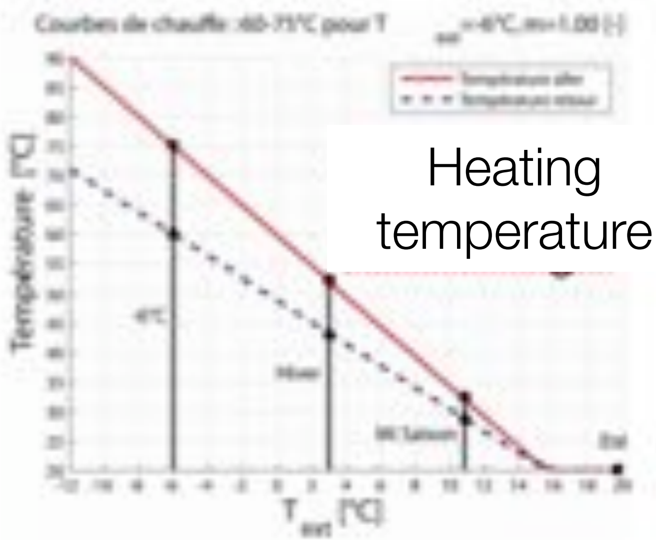
Define the demands of a district

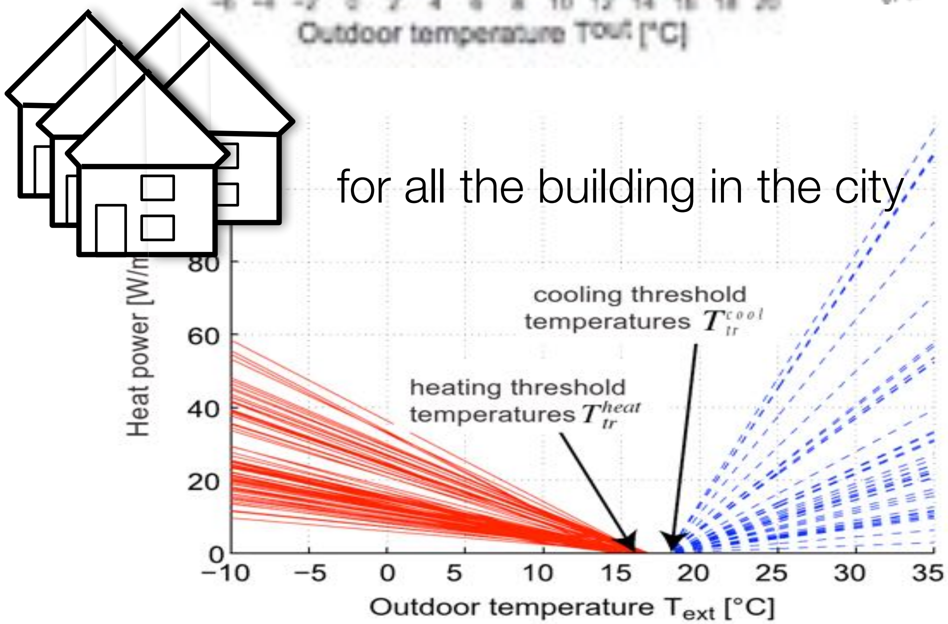
- **Characterizing the services**



Seasonal temperature variation

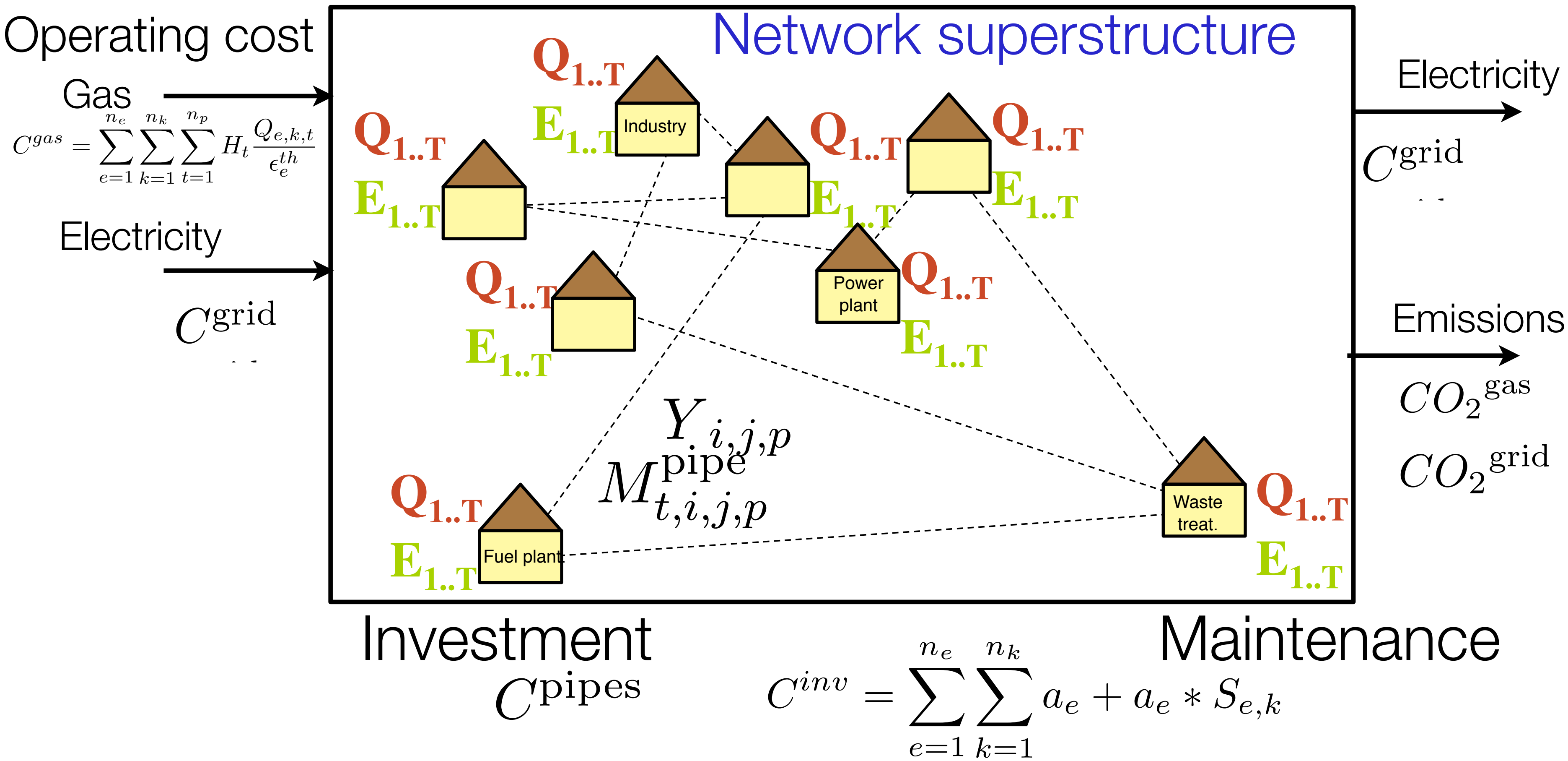






Energy system design : problem definition

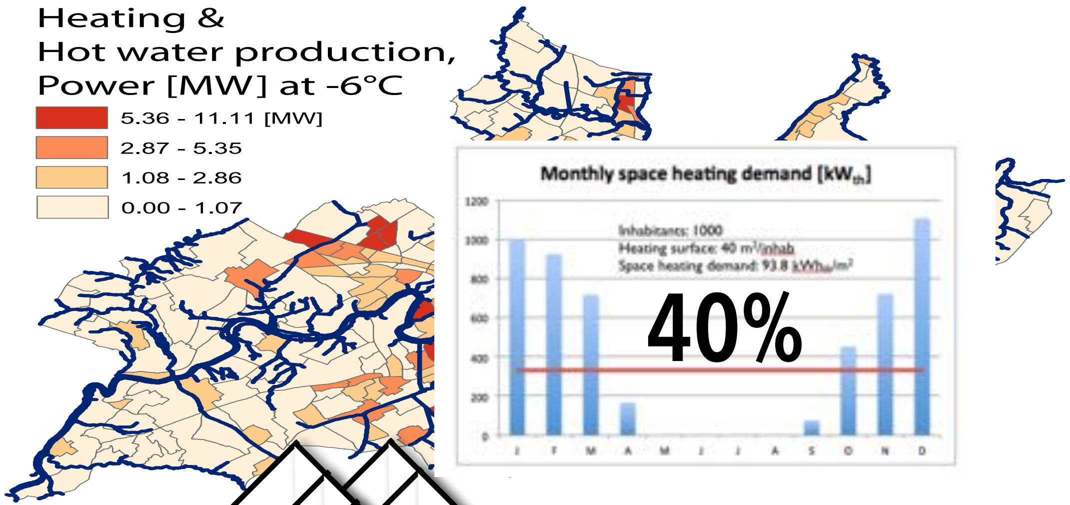
Given a set of energy conversion technologies :
- Where to locate the energy conversion technologies ?
- How to connect the buildings ?
- How to operate the energy conversion technologies ?

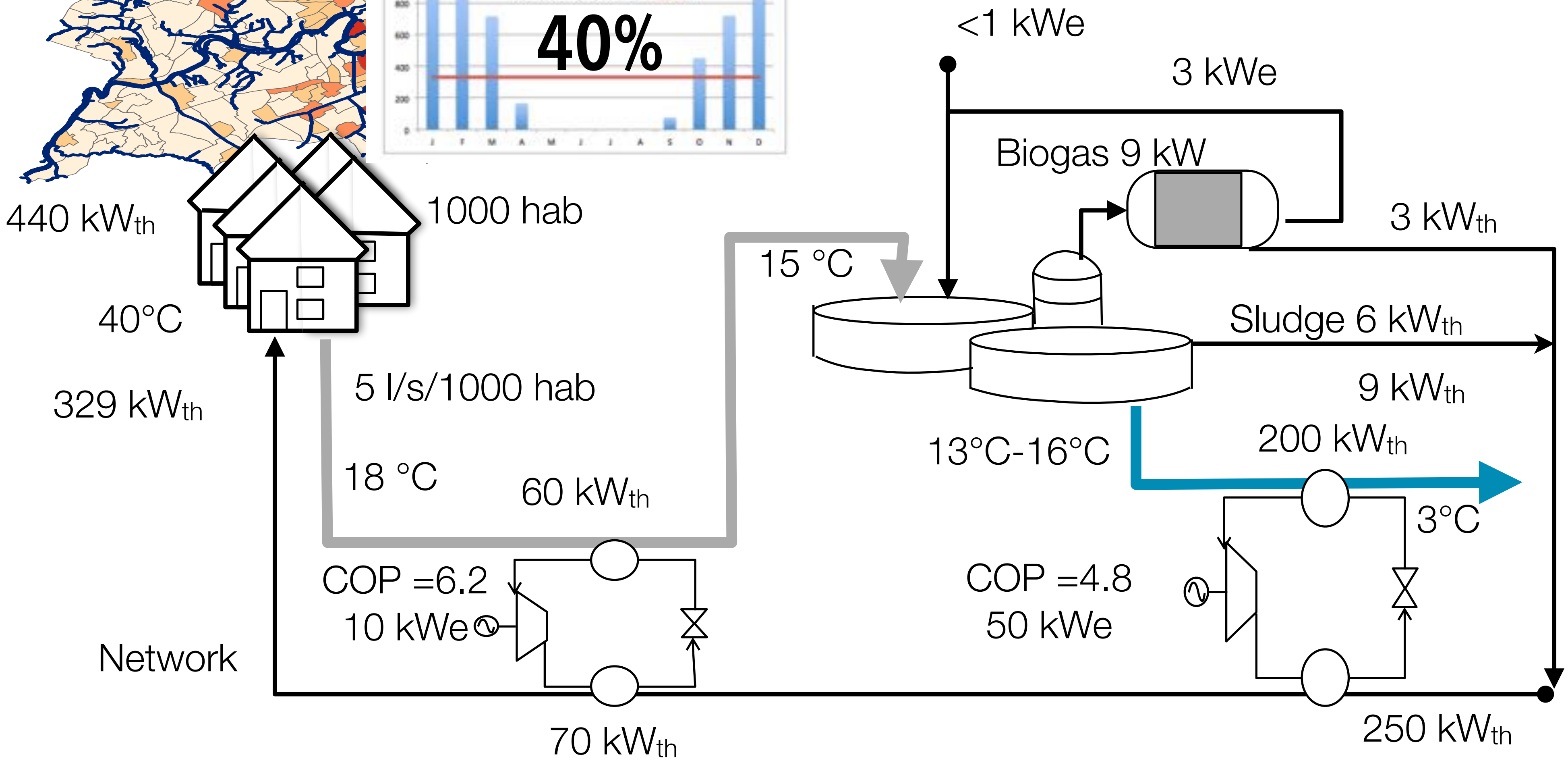


[5] Francois Marechal, Celine Weber, and Daniel Favrat. Multi-Objective Design and Optimisation of Urban Energy Systems, pages 39–81. Number ISBN: 978-3-527-31694-6. Wiley, 2008.

Access to local resources

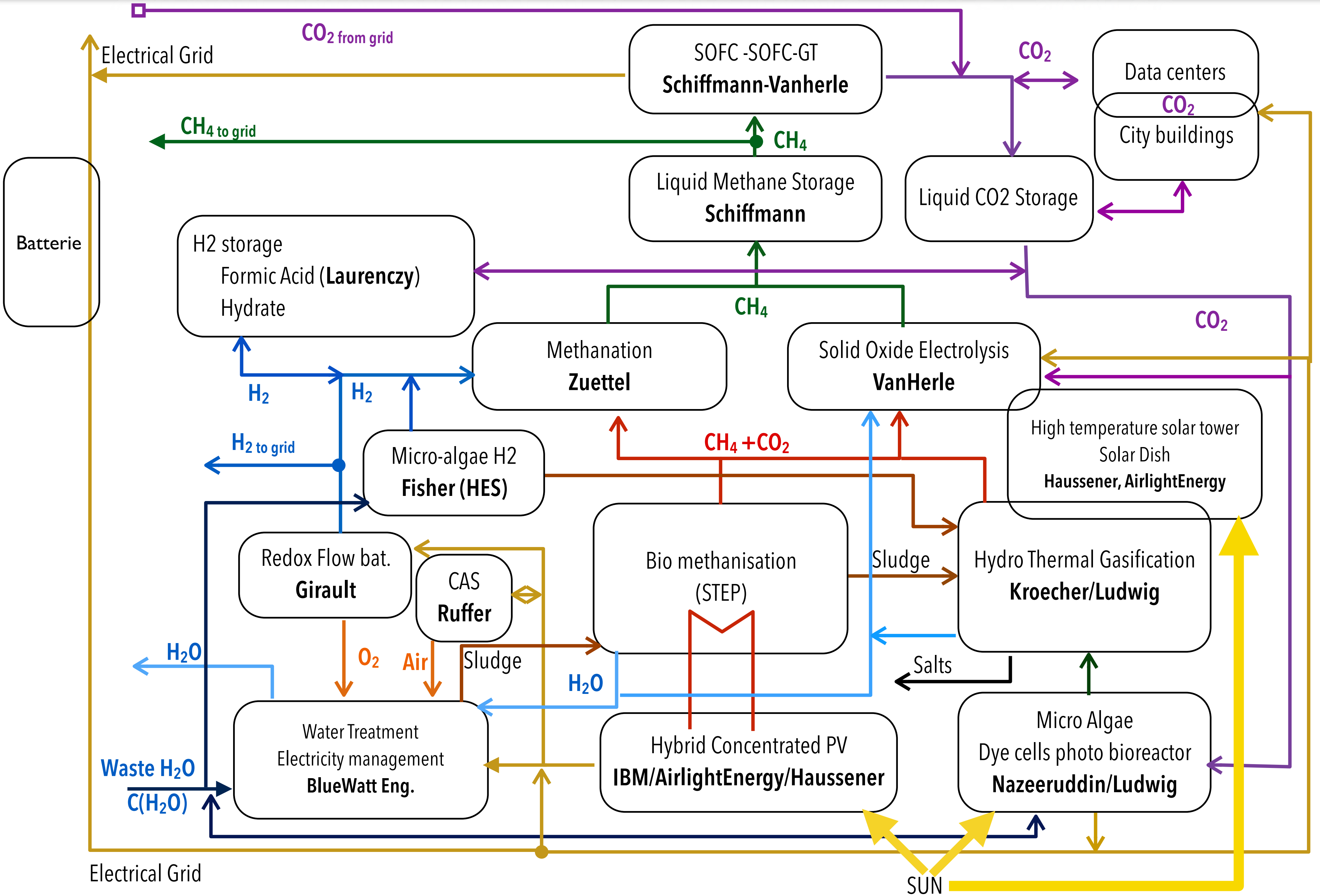
Potential = 330 W_{th}/hab
Usable = 185 W/hab
Heat demand = 440 W/hab
Electricity cons. = 33 W/hab





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 a renewable energy source



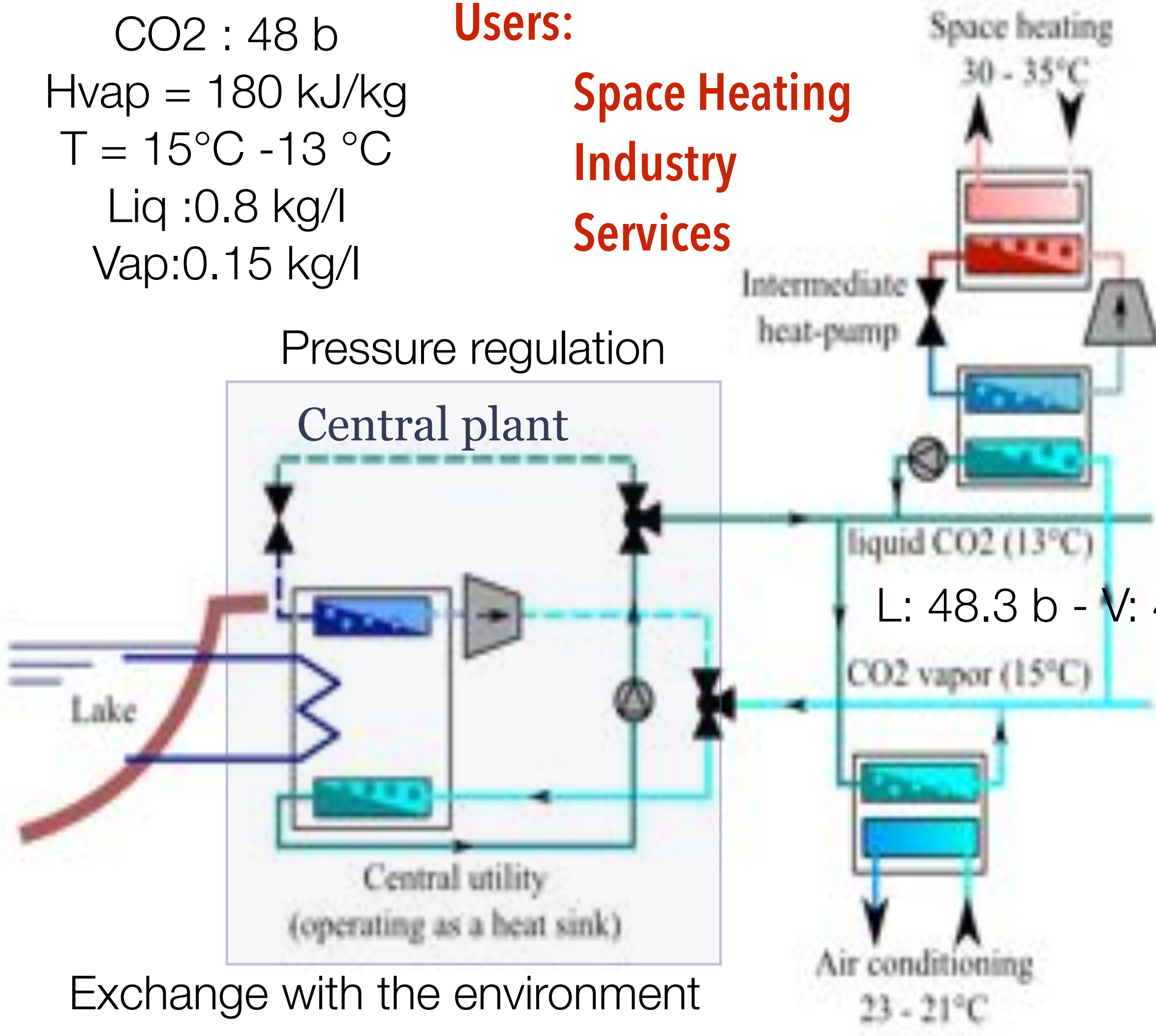
CO2 District heating network for multiple sources

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

Pressure regulation



L: 48.3 b - V: 47.3 b

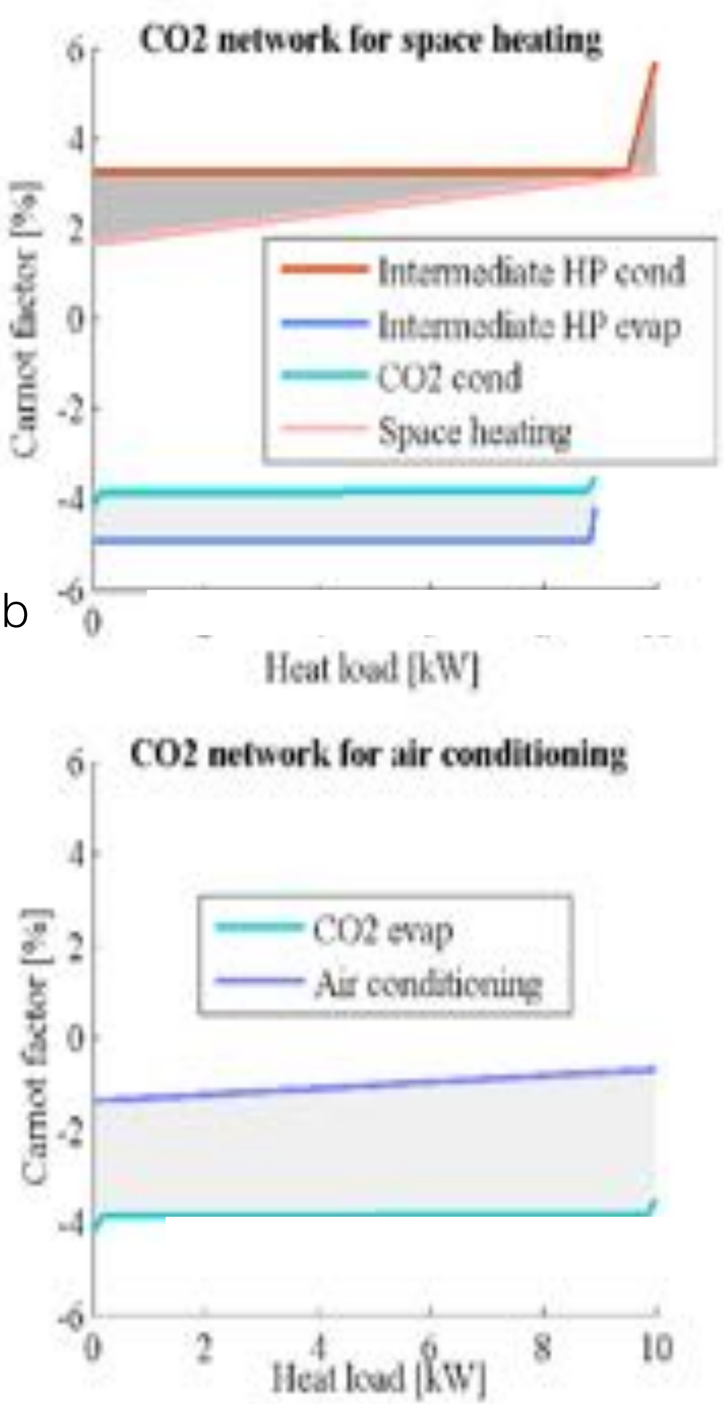
Exchange with the environment

Network cross section

Cross section = Cross section water/4

Users:

- Air Conditioning
- Data centers
- Refrigeration



Complex system with heating and cooling : (ERA) 687'800 m^2

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

Heating	**53.2 GWh/year**
Cooling	**49.4 GWh/year**

- 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

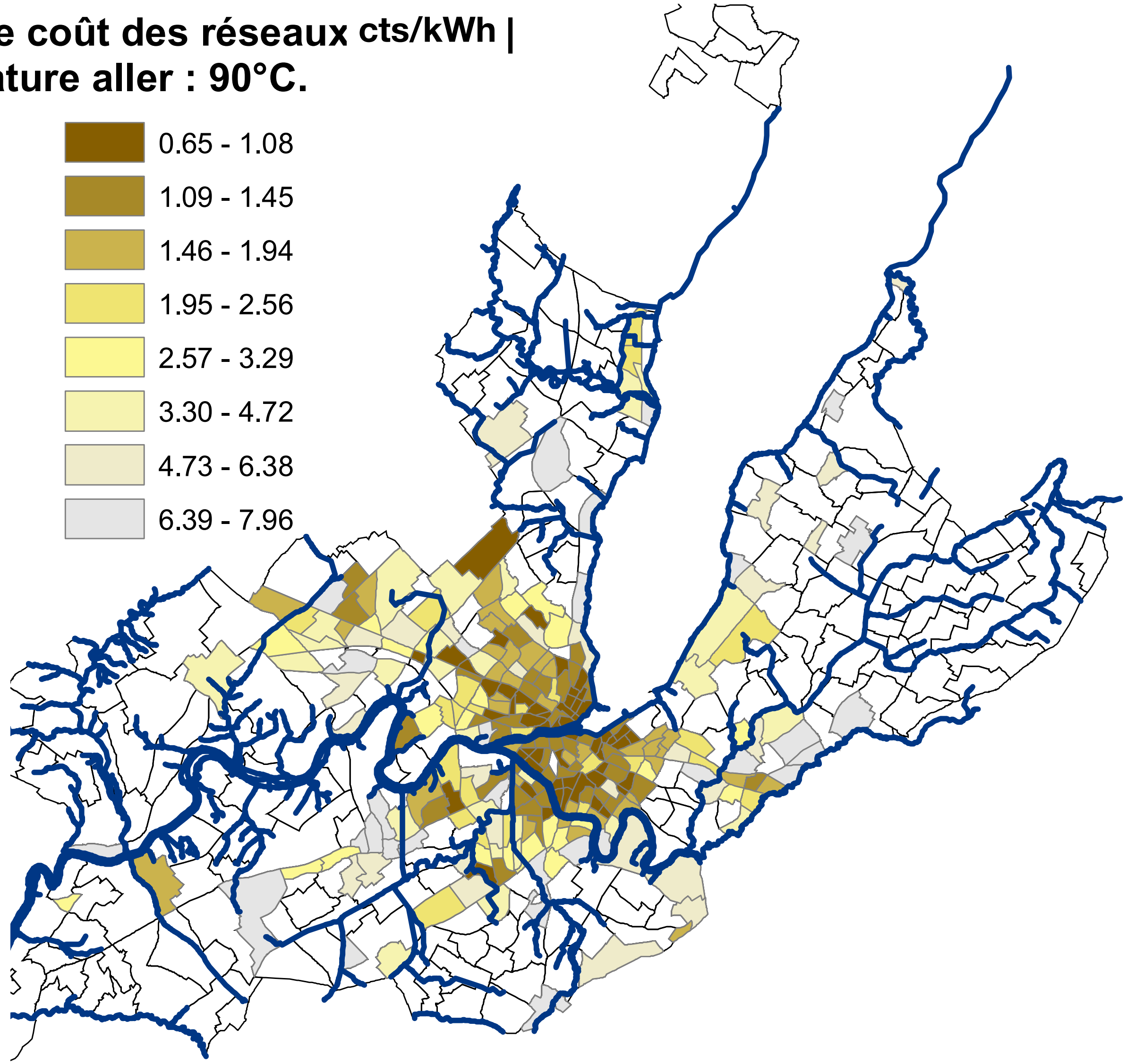
Open question

- **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

Indice de coût des réseaux cts/kWh | Température aller : 90°C.



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

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

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

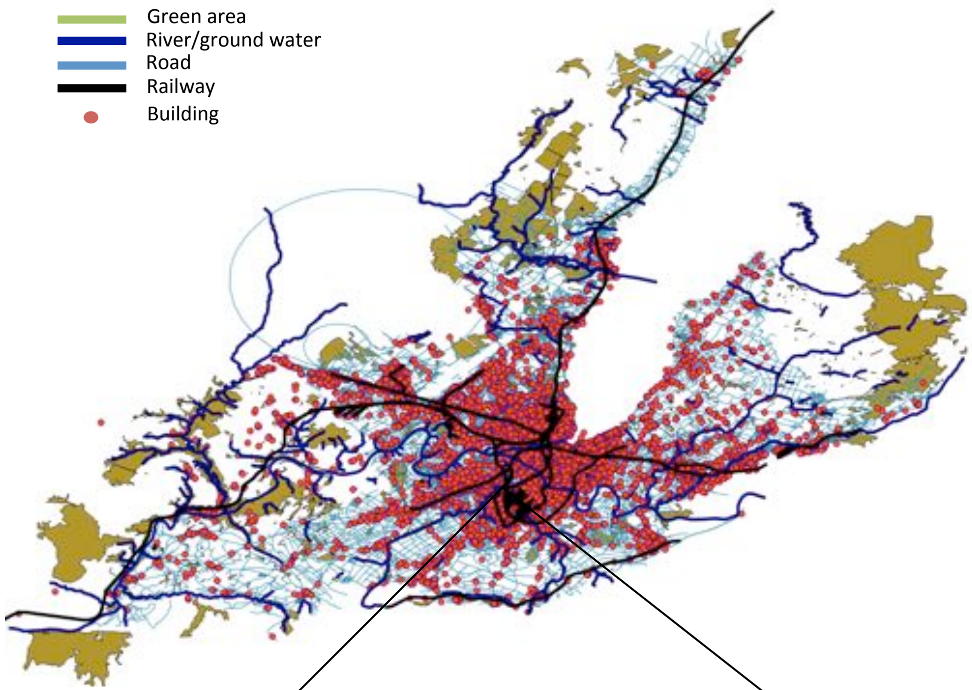
$$\dot{Q}_{DHN} = \dot{m}_{DHN} cp_{fluid}(T^*_{supply} - T_{return})$$

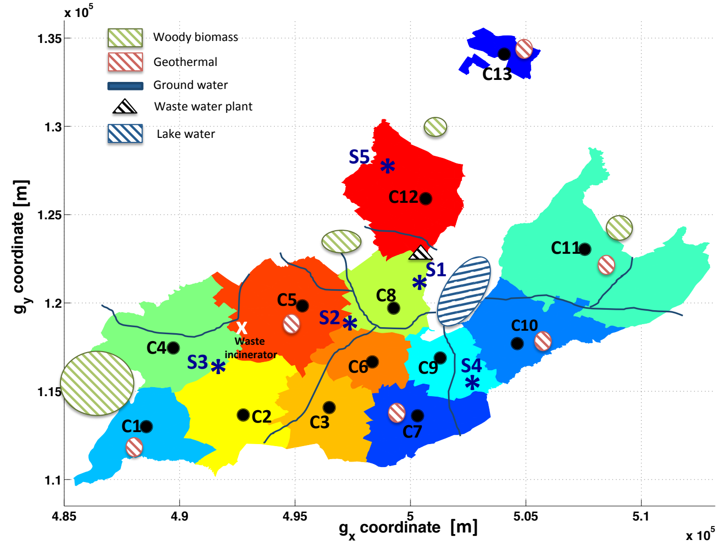
$$d_{DHN} = \sqrt{\frac{4\dot{m}_{DHN}}{\pi v_s \rho(T^*_{supply})}}$$

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

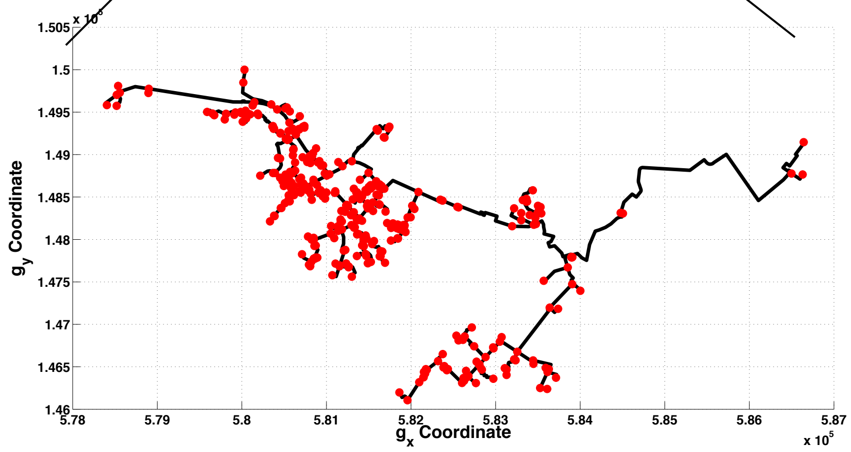
Girardin, Luc, François Marechal, Matthias Dubuis, Nicole Calame-Darbellay, and Daniel Favrat. “EnerGis: A Geographical Information Based System for the Evaluation of Integrated Energy Conversion Systems in Urban Areas.” *Energy* 35, no. 2 (February 2010): 830–840.

Clustering in sub-systems

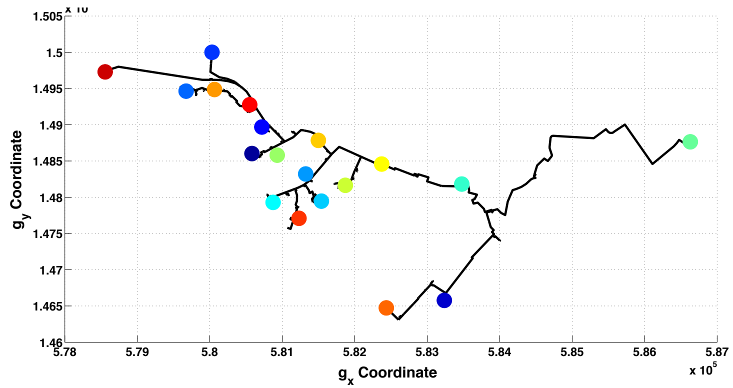




13 sub systems



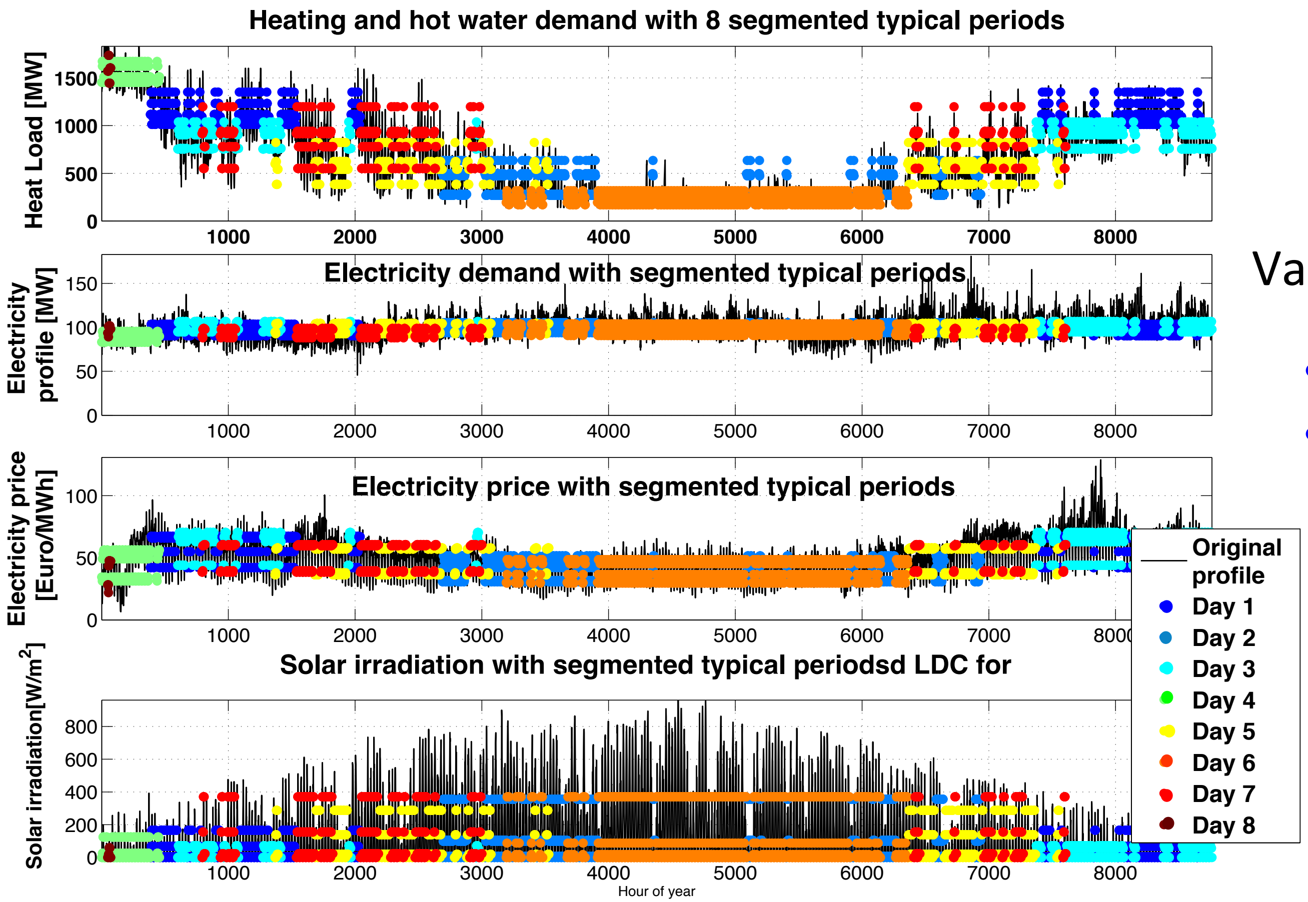
382 Buildings



19 sub networks

Clustering techniques for typical days

- 40 time steps : 7 days*5 time sequence + 1 Extreme * 5 time sequence
  => instead of 20*8760 hours
- Probability of appearance (number of days)
- Using clustering techniques

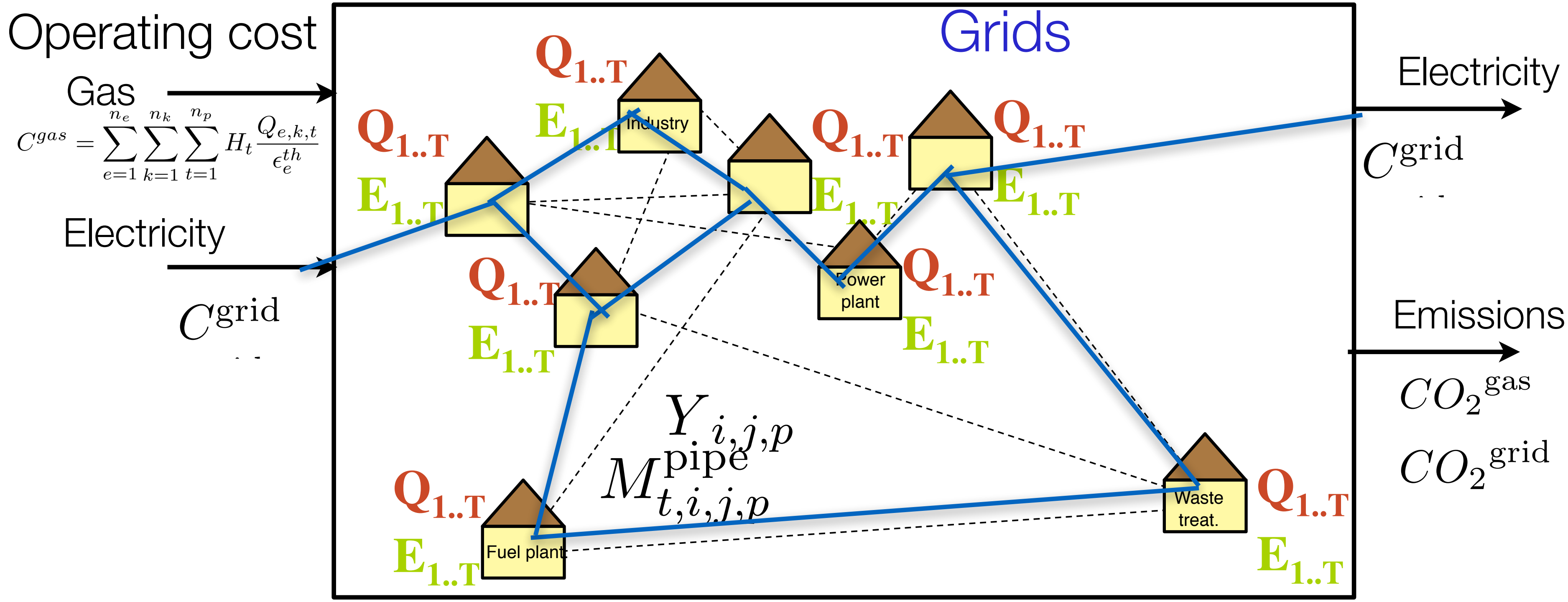


Validation is performed

- 0.3-4.1% errors
- 40 times faster

Virtual power plant concept

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



Investment

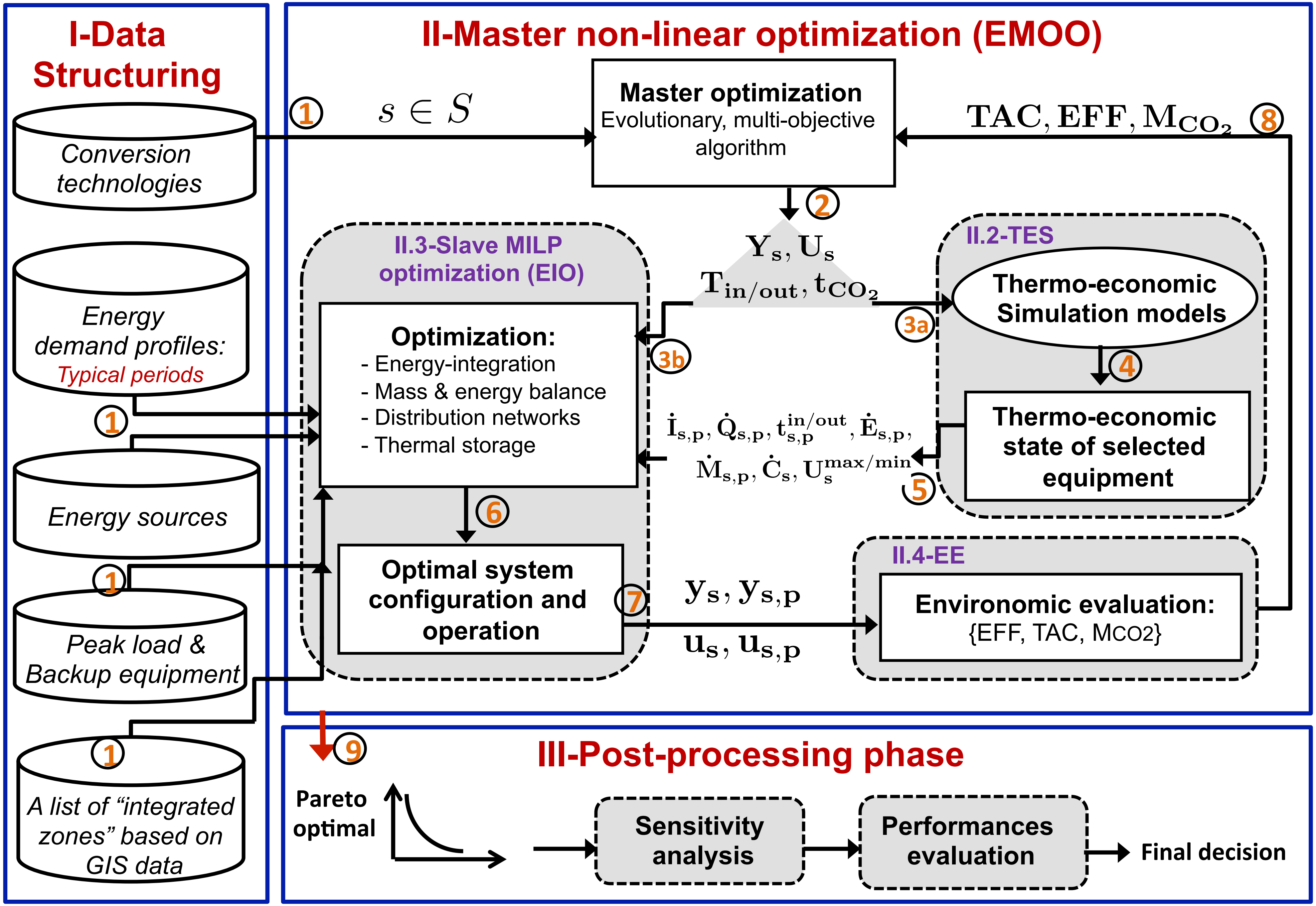
C^{pipes}

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.

Multi-objective optimisation algorithm



C. Weber, (2007), S. Fazlollahi (2014)

List of technology options in the data base

Resources

- Solar Irradiation
- Geothermal heat
- Natural gas
- Electricity import
- Woody biomass

Waste to be treated

- Municipal solid waste
- Waste-water
- Municipal Organic waste

Conversion Technologies

- Gas engine
- Waste-water treatment
- Gas turbine
- Gas boiler (centralized)
- Combined cycle
- Gas boiler (decentralized)
- Incinerator
- Steam cycle
- Heat pump
- Biomass boiler
- Biomethanation
- Biogas boiler
- Gasifier
- Biogas turbine
- Air dryer
- Biogas engine

Networks

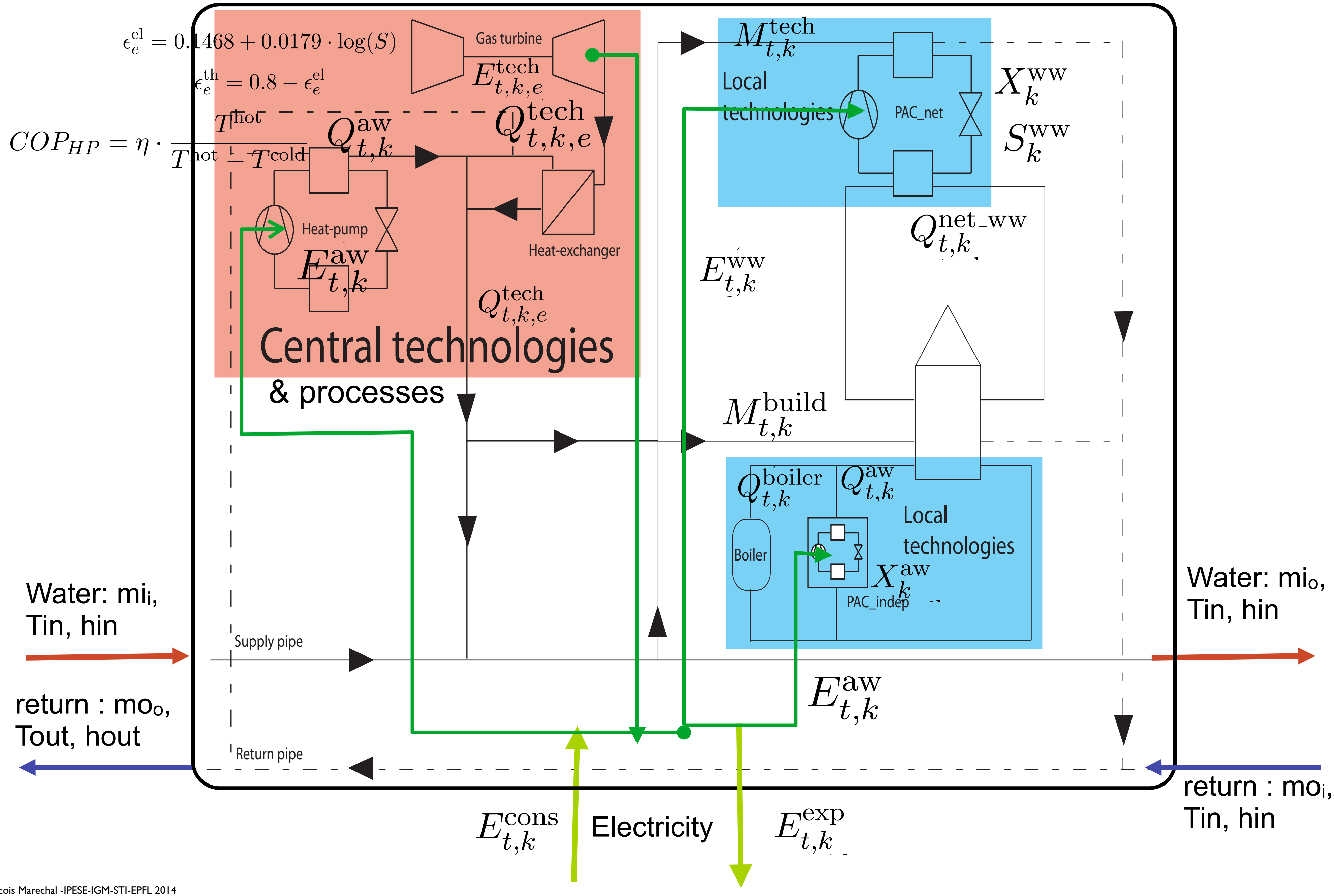
- Local district heating networks
- Global district heating networks

Services

Energy services

- Space heating
- Domestic hot water
- Electricity

Each node is a process with network connections



MILP process integration model @node k

IPESE

Technologies w, @node k period s and time t(s)

Demand @node k, period s and time t(s)

Heat echange by heat cascade model

Subject to : Heat cascade constraints

$$\sum_{w=1}^{n_w} f_w q_{w,r} + \sum_{s=1}^{n_s} Q_{s,r} + R_{r+1} - R_r = 0 \qquad \forall r = 1, \dots, n_r$$

Feasibility

$$R_r \geq 0 \qquad \forall r = 1, \dots, n_r; R_{n_r+1} = 0; R_1 = 0 \qquad E^+ \geq 0; E^- \geq 0$$

Electricity consumption

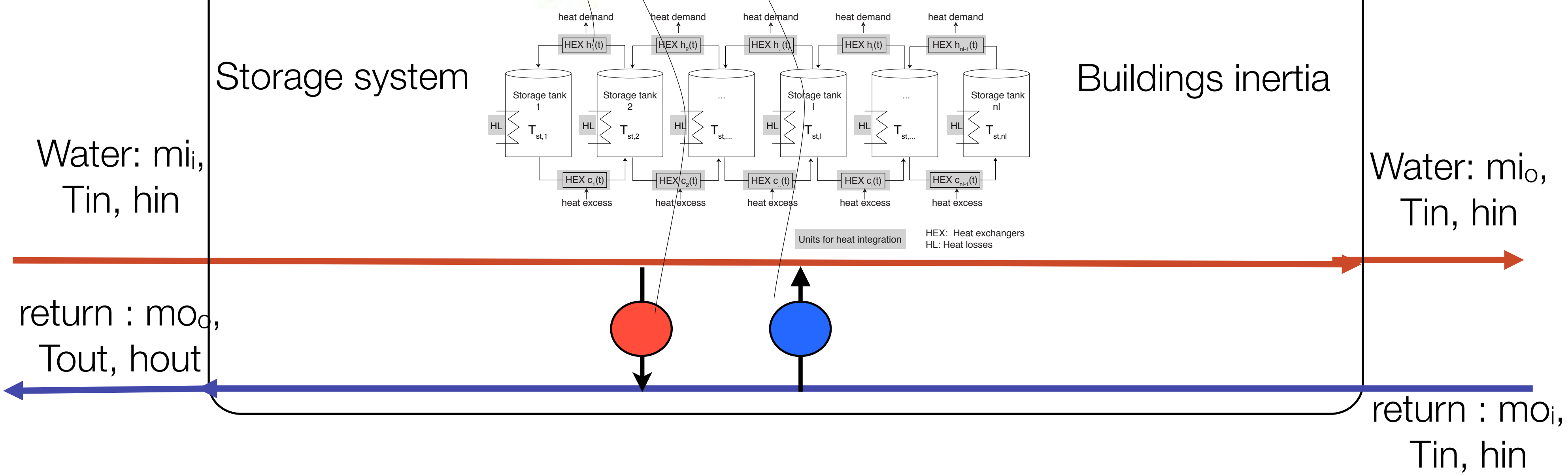
$$\sum_{w=1}^{n_w} f_w e_w + E^+ - E_c \geq 0$$

Electricity production

$$\sum_{w=1}^{n_w} f_w e_w + E^+ - E_c - E^- = 0$$

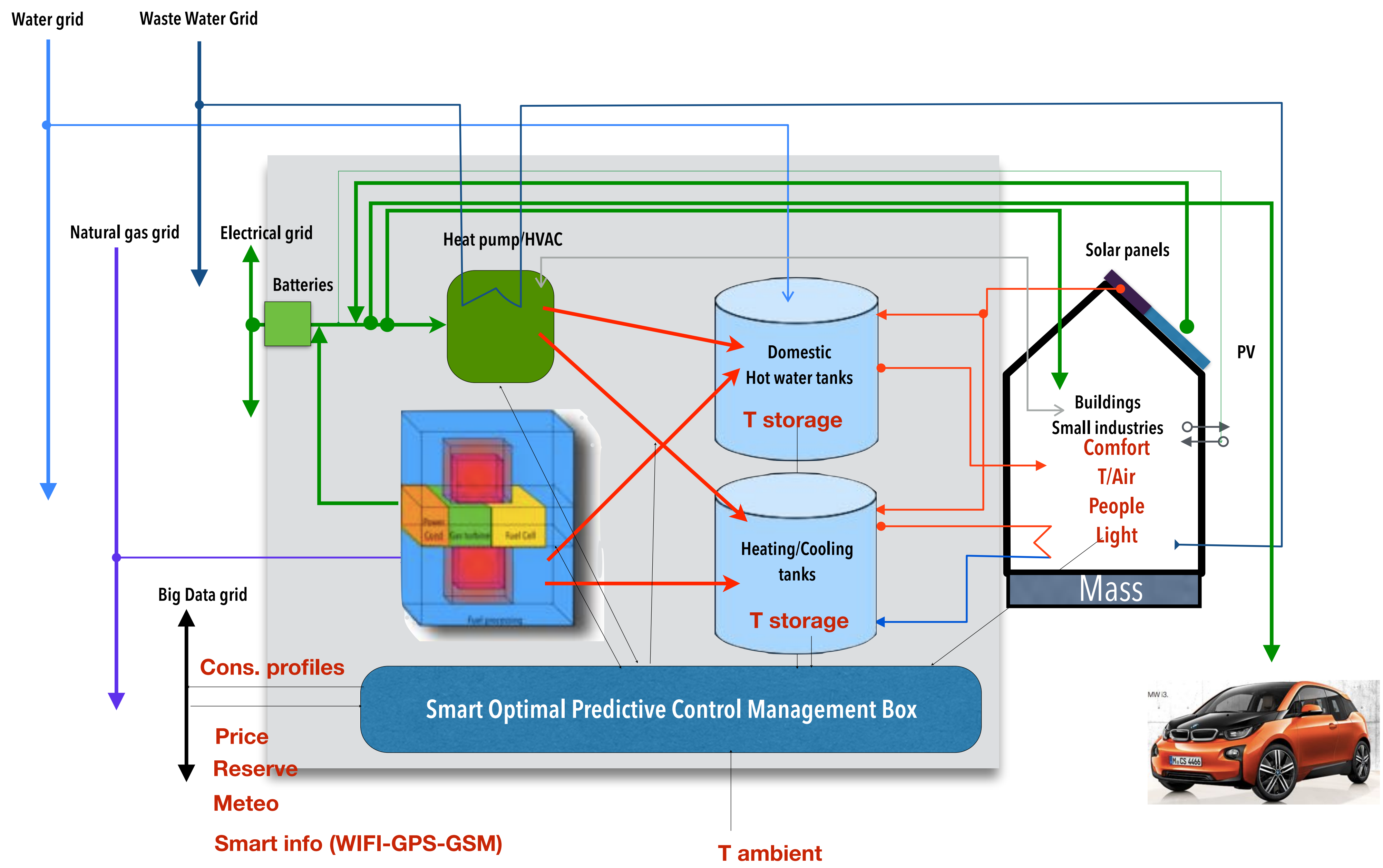
Energy conversion Technology selection

$$fmin_w y_w \leq f_w \leq fmax_w y_w \qquad y_w \in \{0,1\}$$

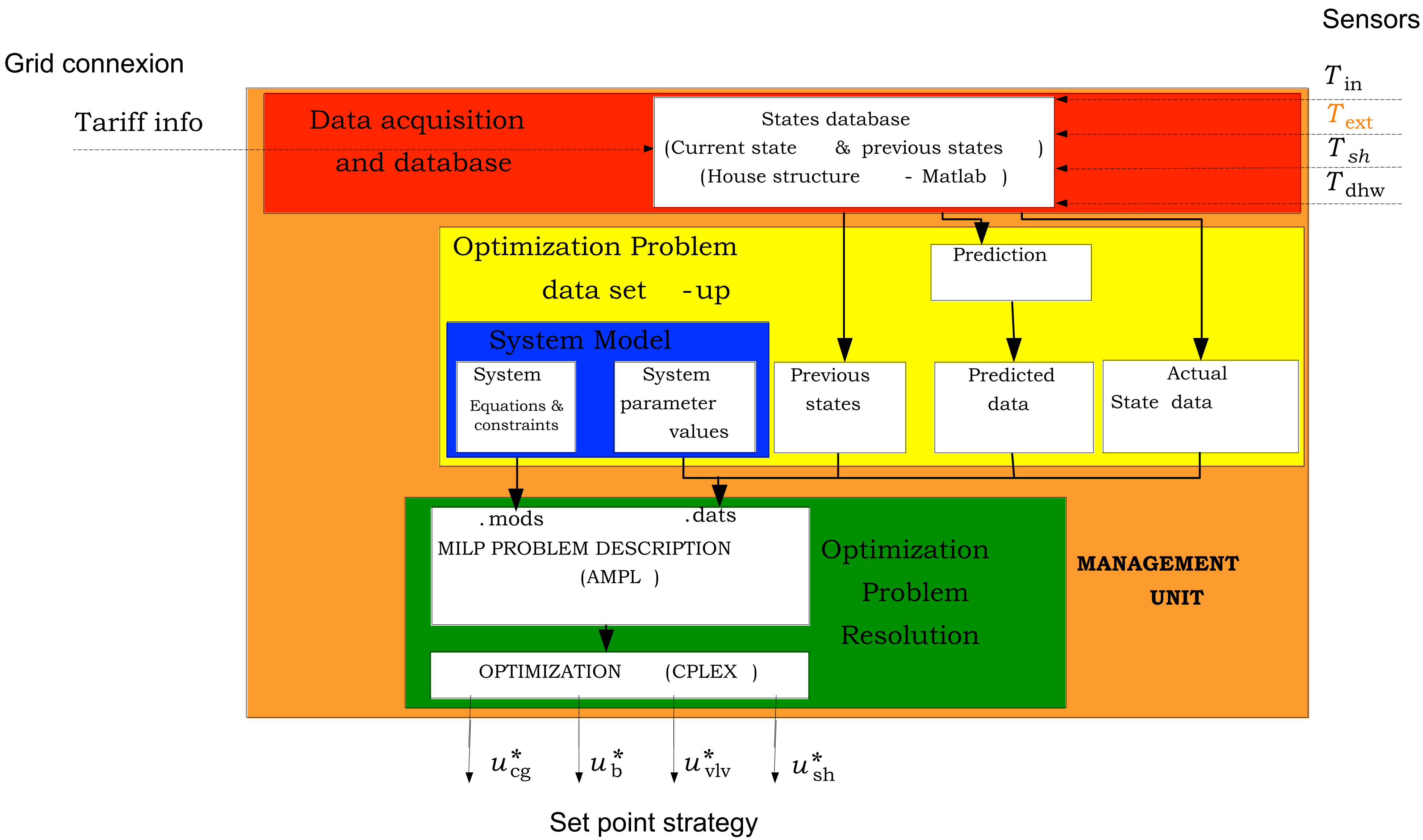


S. Fazlollahi, G. Becker and F. Maréchal. Multi-Objectives, Mul.-Period Optimization of district energy systems: II-Daily thermal storage, in Computers & Chemical Engineering, 2013a

Virtual power plant Operation



Smart predictive control management box



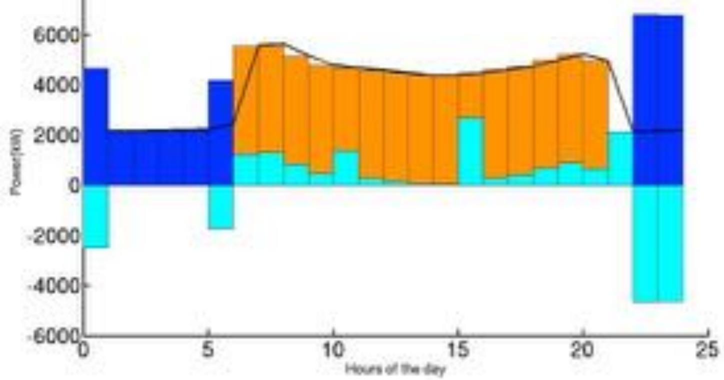
Collazos et al., Computers and Chemical Eng. 2009

Process integration : do not use batteries

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

Mean heating power = 3000 kW

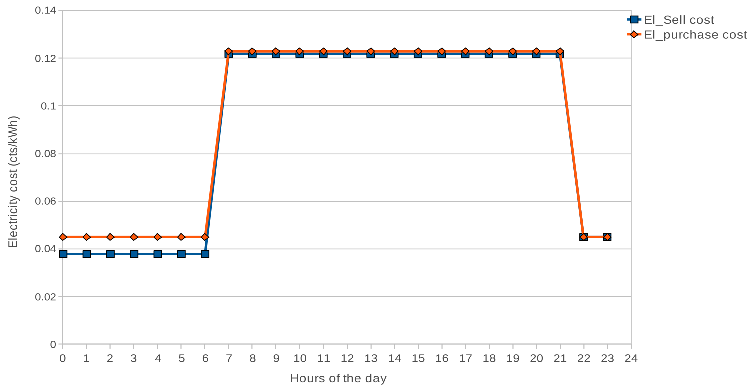
High electrcity cost during the afternoon
Storage tank = 200 m3



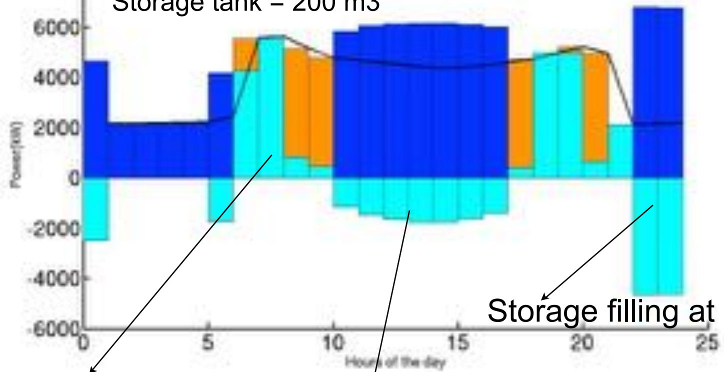
Heating : 72315 kWh
Electricity : 77897 kWhe

Electricity out : 5650 kWhe
Electricity bought : 62894 kWhe

<u>Low price period</u>
Electricity out : 4407 kWhe
Electricity in : 1269 kWhe
Balance : -3138 kWhe



Low cost cost during the afternoon
Storage tank = 200 m3



Storage filling at night

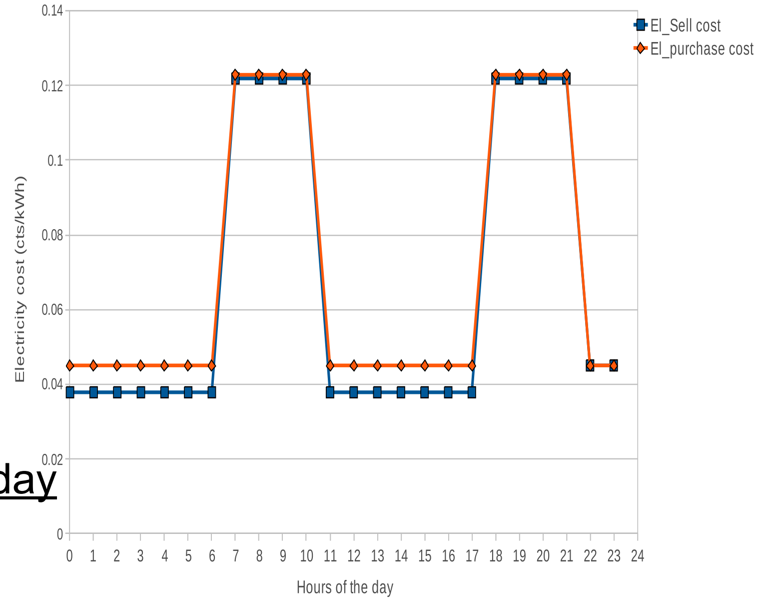
Empty storage tanks before cheap elec price

Fill storage tanks during cheap elec price

Electricity in : 99596 kWhe
Electricity out : 8710 kWhe

<u>Low price period</u>
Electricity in : 19345 kWhe

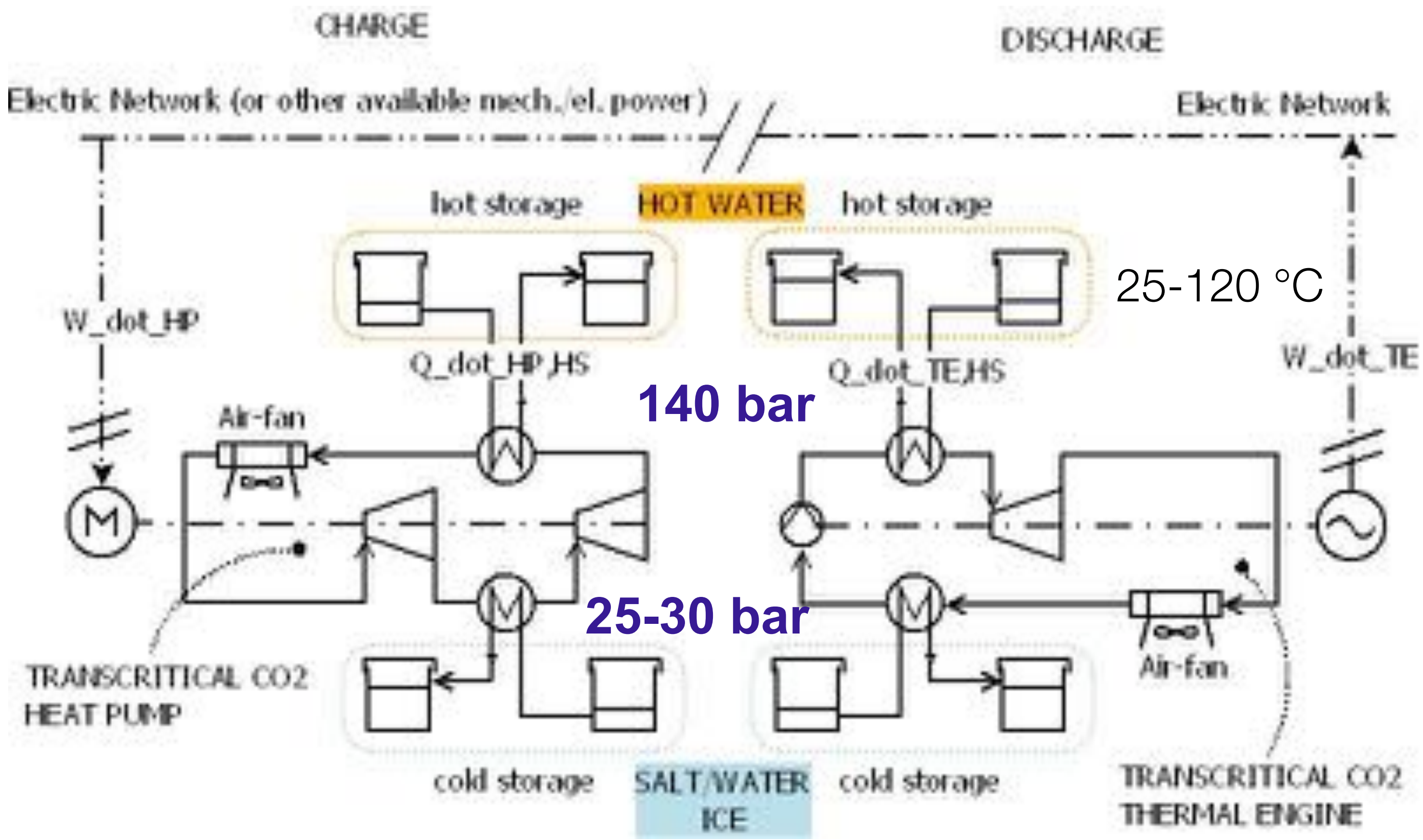
<u>Storage : 22480 kWhe/day</u>
<u>10 hours of operation</u>

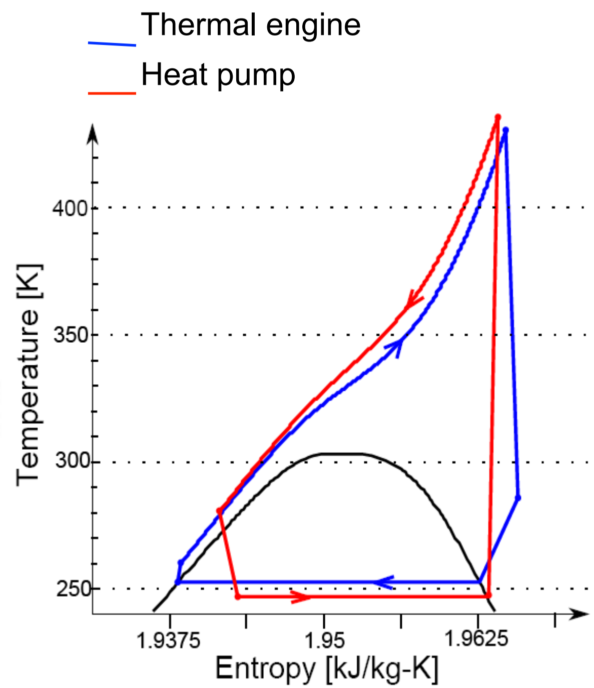


Electro Thermal Storage (ETES - ABB)

Round-trip eff.: 60%

Hot Water Storage
Transcritical CO_2 cycles

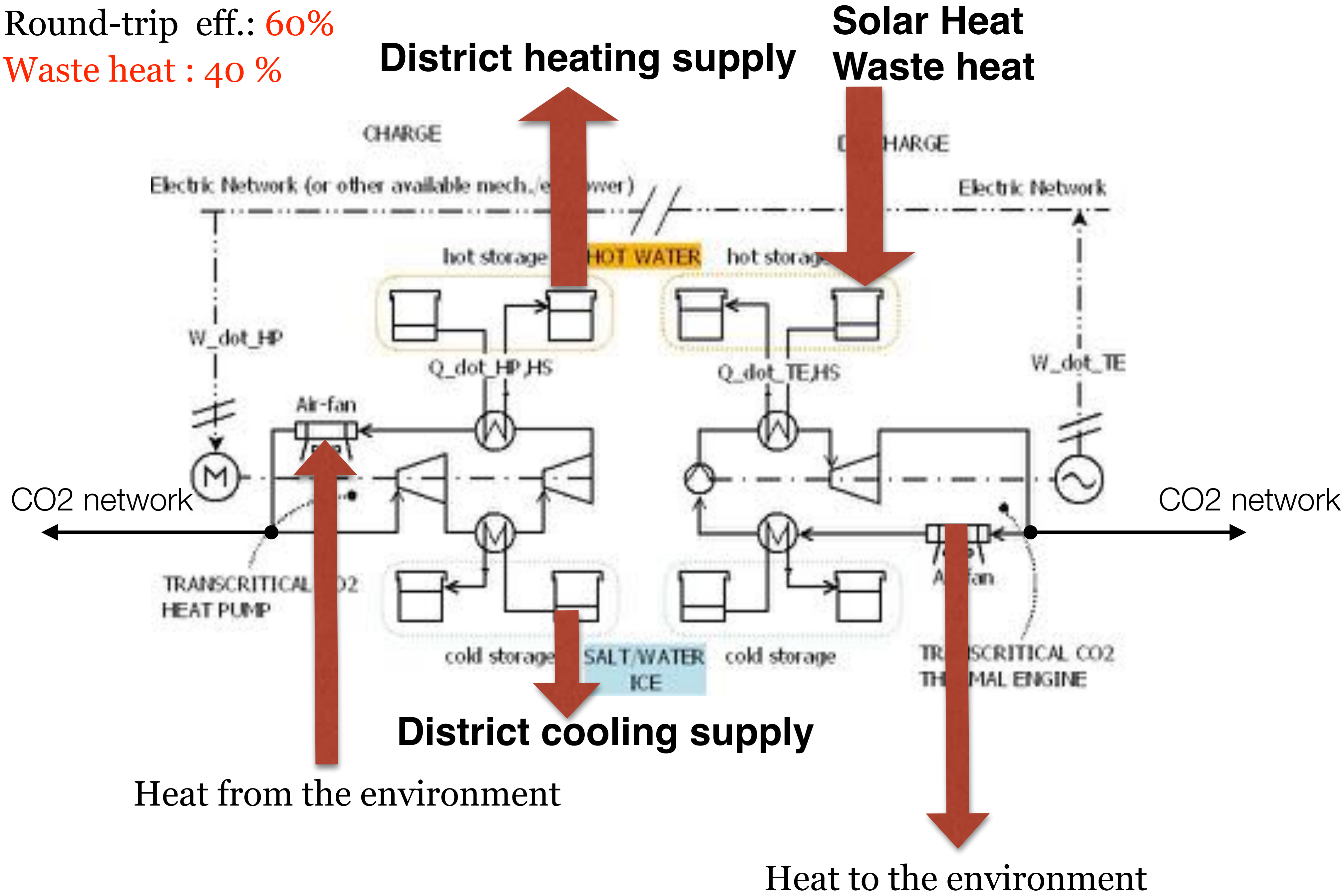




Morandin, Matteo, François Maréchal, Mehmet Mercangöz, and Florian Buchter. "Conceptual Design of a Thermo-Electrical Energy Storage System Based on Heat Integration of Thermodynamic Cycles – Part B: Alternative System Configurations." Energy 45, no. 1 (September 2012): 386–396..

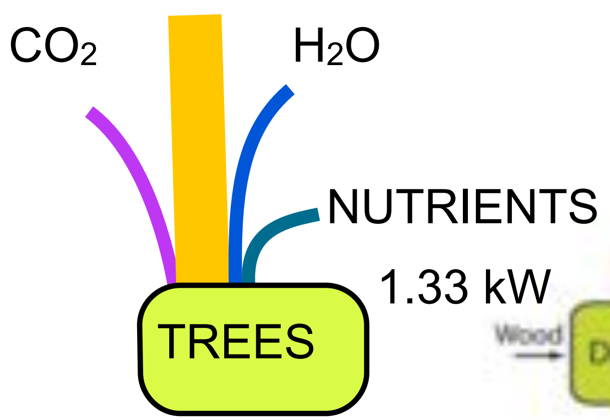
ETES & district heating/cooling

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



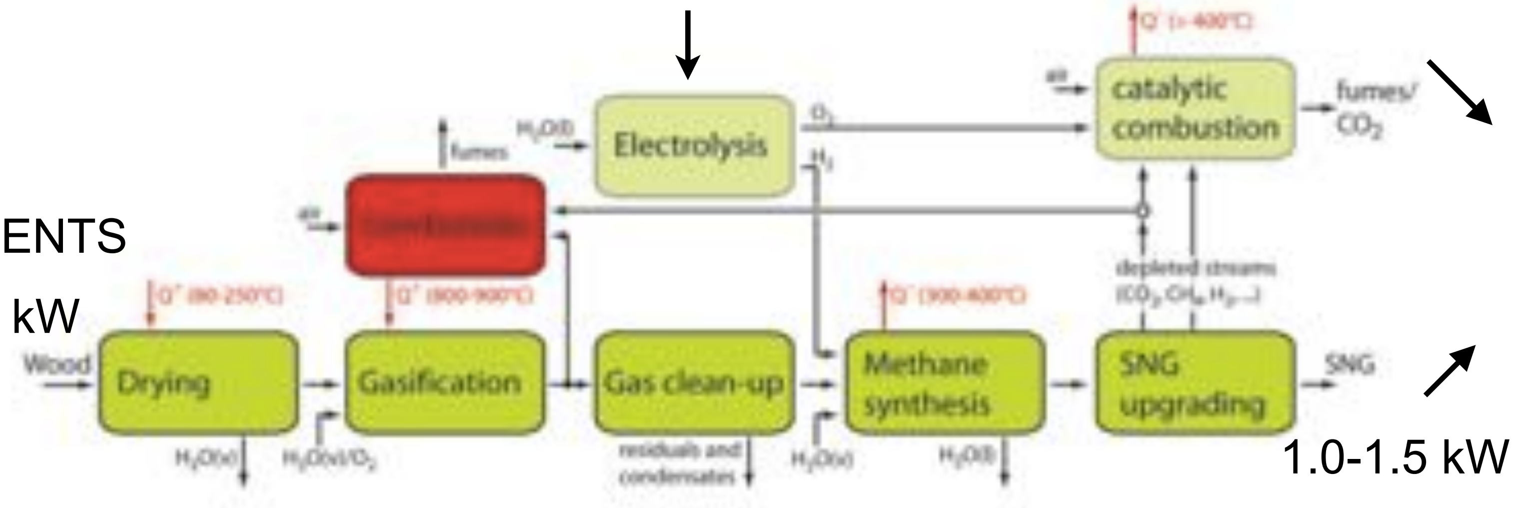
Long term electricity storage by converting electricity to fuel

Power to gas concept



Carbon source

Electricity form the grid
max 0.50kWe/kW_{SNG}



WOOD		Natural Gas	CO2 (pure)

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

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

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

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**

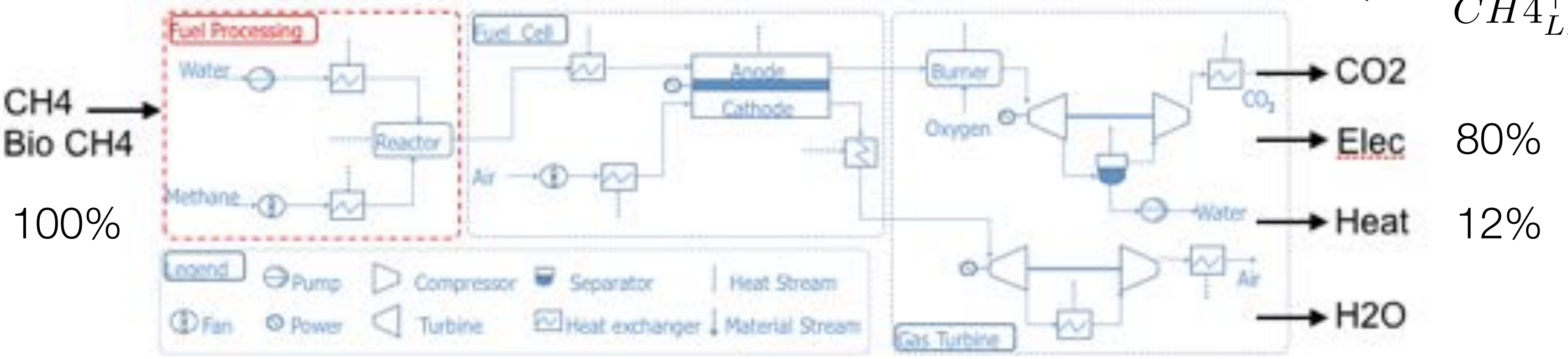
$$\eta = \frac{E^{-}}{E^{+}} = 50\%$$

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

If Electricity production efficiency increases

- **Hybrid gas turbine SOFC combined cycle**

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



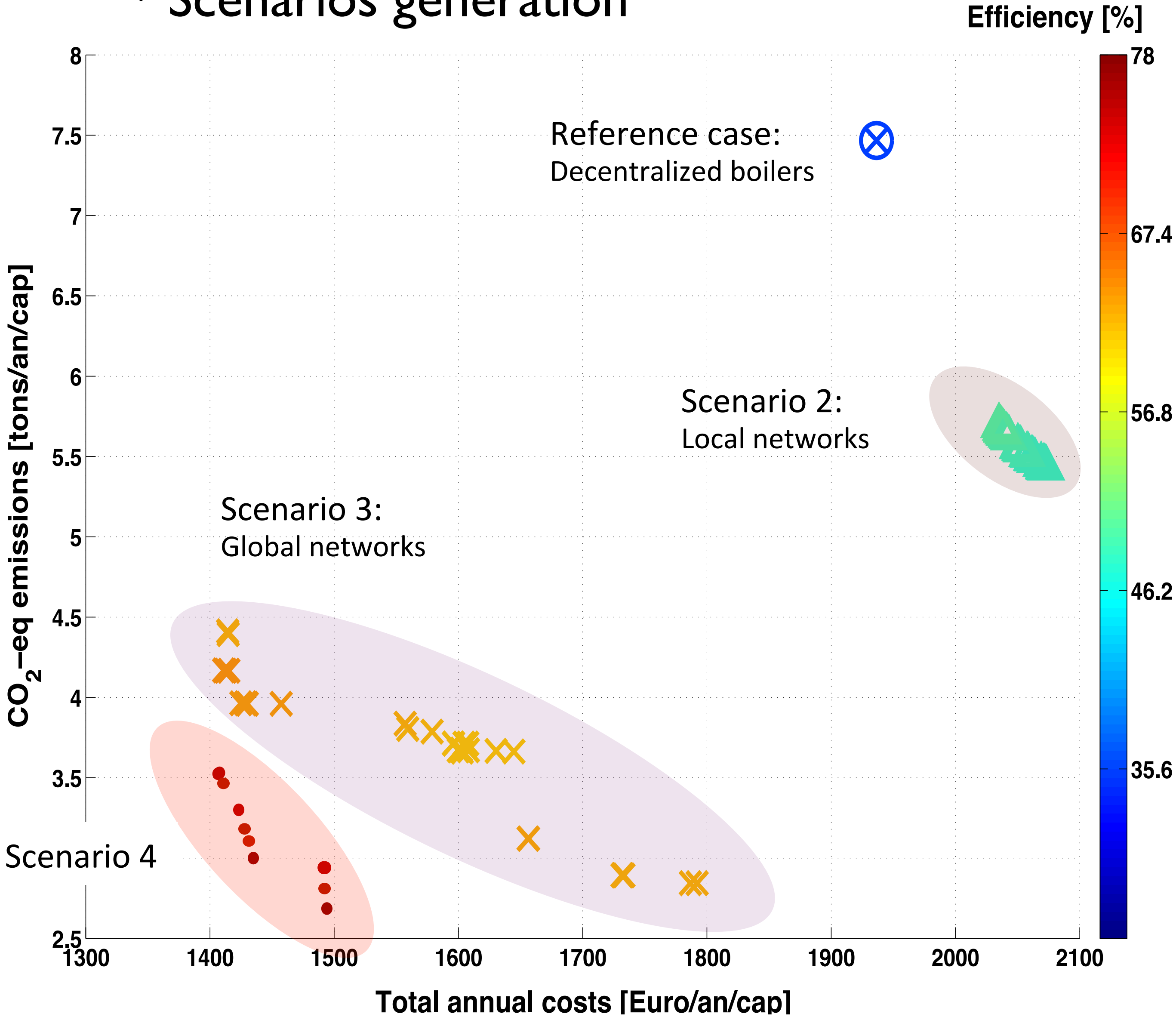
$$\eta = \frac{E^-}{E^+} = 68\%$$

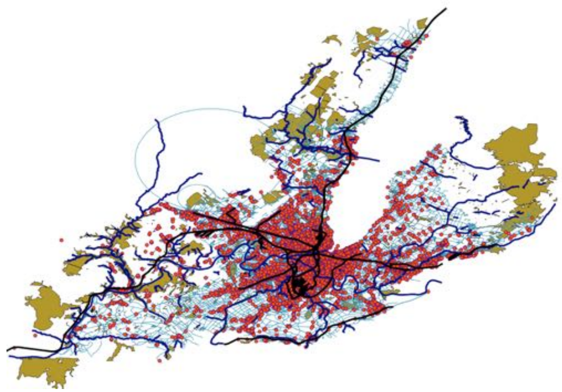
A battery is 80%

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

Multi-objective optimisation : application to a canton

* 3 Objectives optimisation
* Scenarios generation





450,000 Population

246 km²

60,000 buildings

4637 GWh/year space heating

954 GWh/year hot water

870 GWh/year electricity

Integrating Renewable energy : Seasonal storage !

IPESE

SUN to Fuel
Solid Oxide co-electrolysis

Land m2 constrains

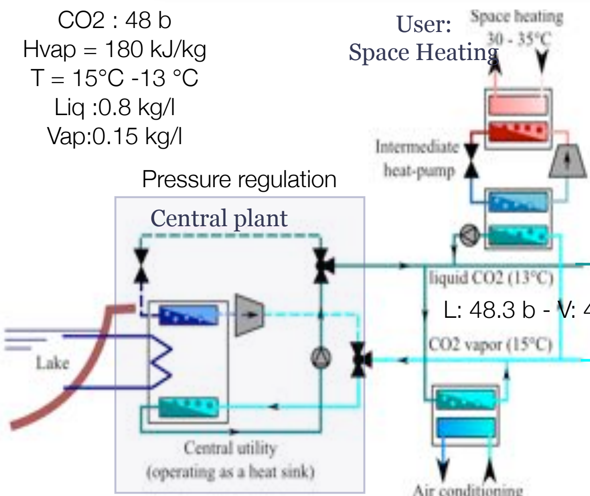
Roundtrip = 55 %

Grids & process intensification

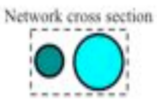
SOFC-GT

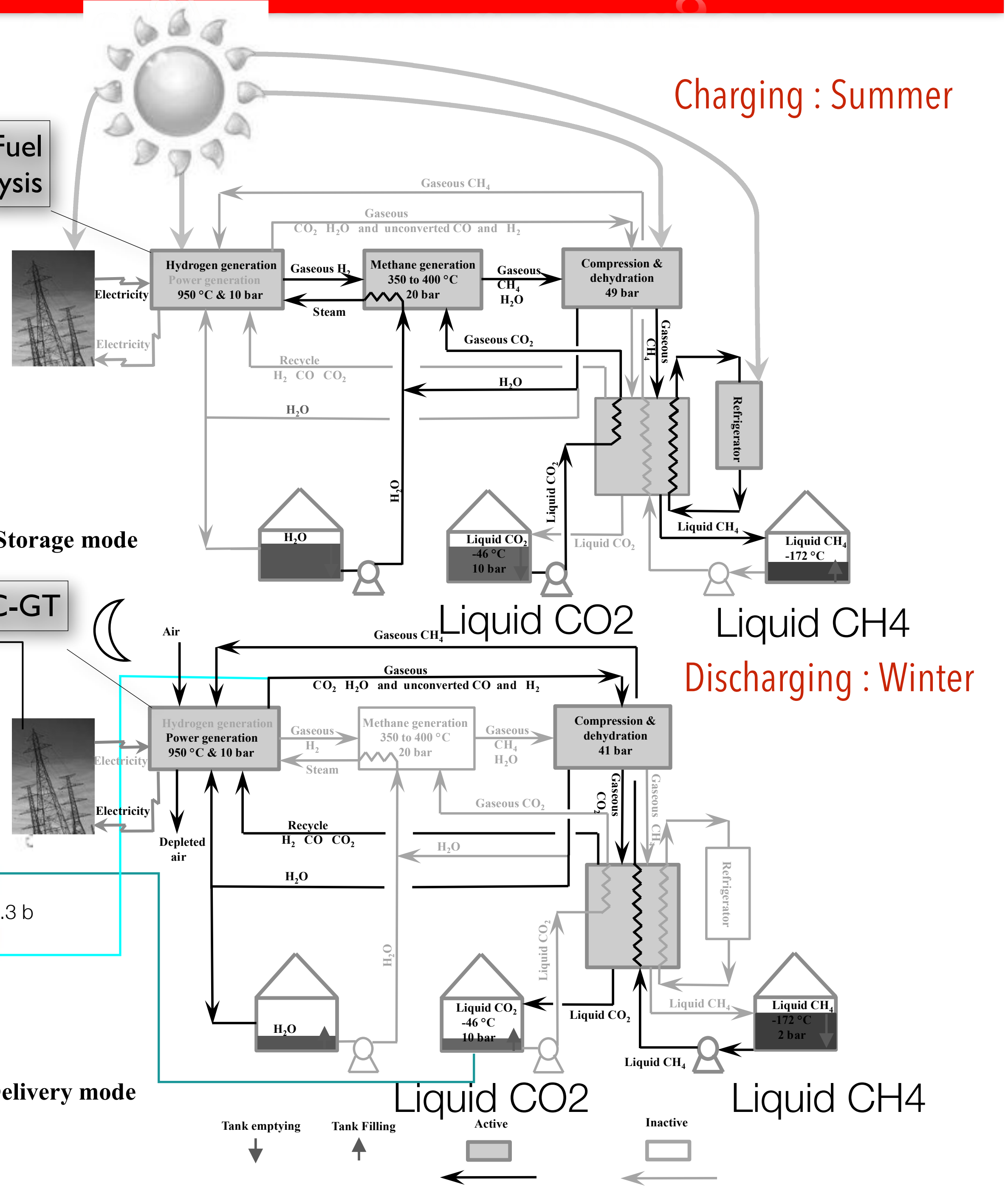
CO2 : 48 b
Hvap = 180 kJ/kg
T = 15°C -13 °C
Liq :0.8 kg/l
Vap:0.15 kg/l

Pressure regulation



Exchange with the environment





Using waste heat for heating/cooling purposes

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

Power train optimisation

Collaboration with PSA

Component set

- ICE -> Drive
- Fuel cell
- Batteries
- El Motor
- Pneumatic storage
- Transmission line
- HVAC
- Energy conversion

=> Size & Weight & Cost

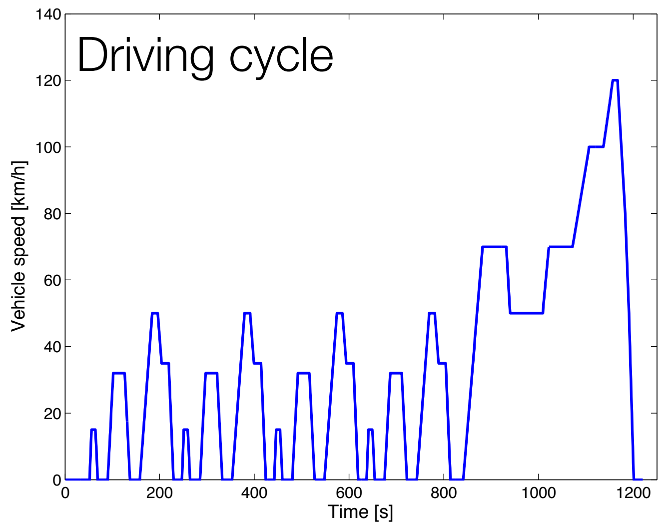
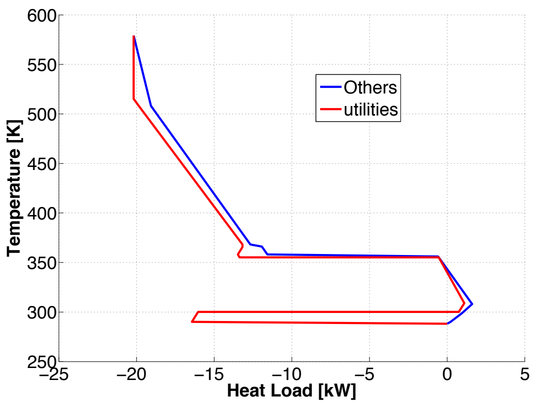


Figure 6.2 New European Driving Cycle.

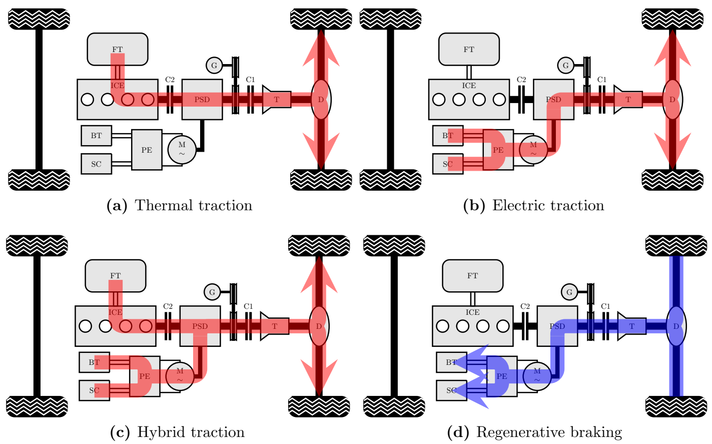
Waste Heat Recovery

* ORC integration



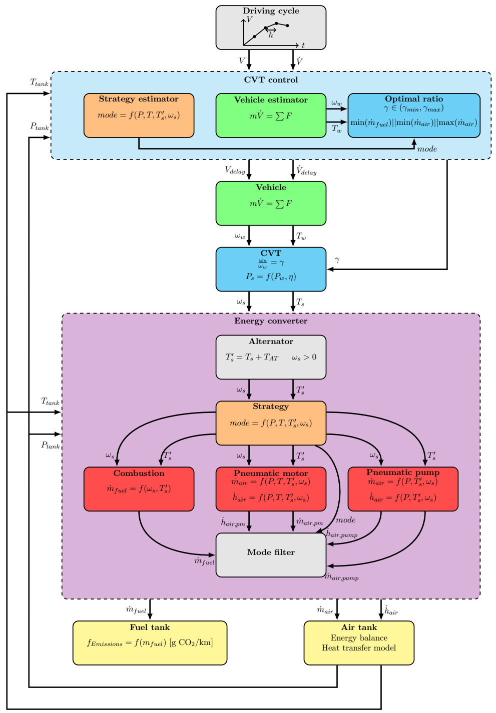
(a) Operating point: 2000 RPM and 2.2 bars.

Operation strategy



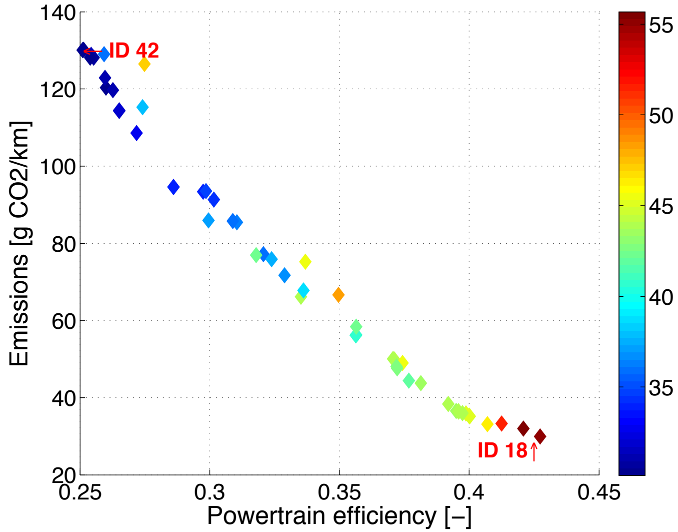
(a) Thermal traction (b) Electric traction

(c) Hybrid traction (d) Regenerative braking

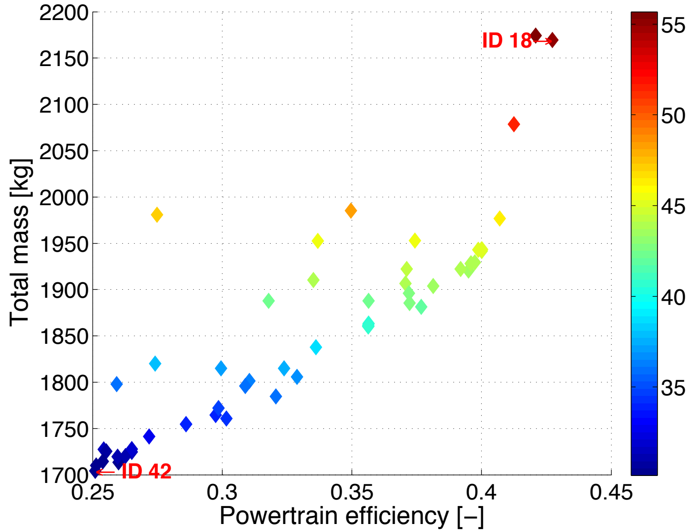


Power train Multi-objective Optimisation

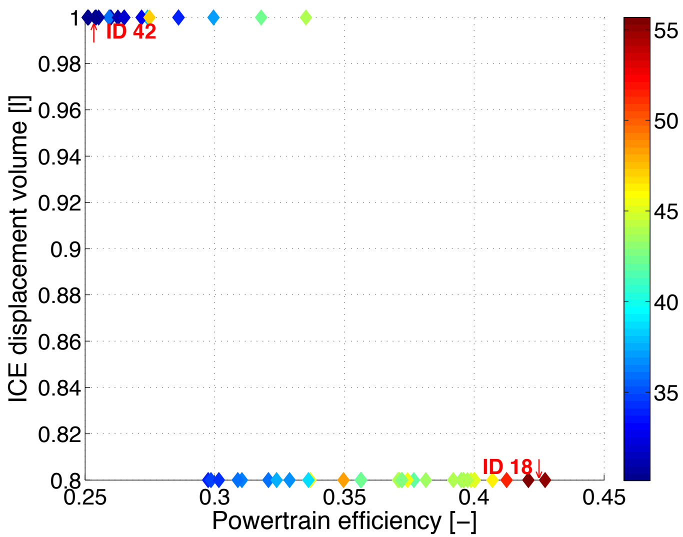
- **Decision variables**
  - Component sizes
  - Control strategies
- **Evaluation**
  - Driving cycles
  - Seasons



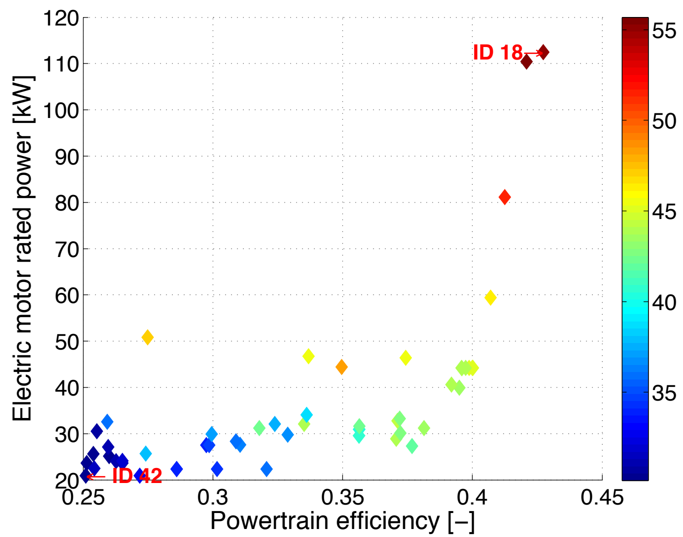
(a) Fuel emissions.



(b) Total mass.



(c) ICE displacement volume.



(d) Electric motor rated power.

Smart engineers/ Smart Businesses / Smart systems

Smart engineers

Buildings

Building complexes
Small and medium industries

District Heating

Smart optimal control and management box

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 Systems

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

Price signals

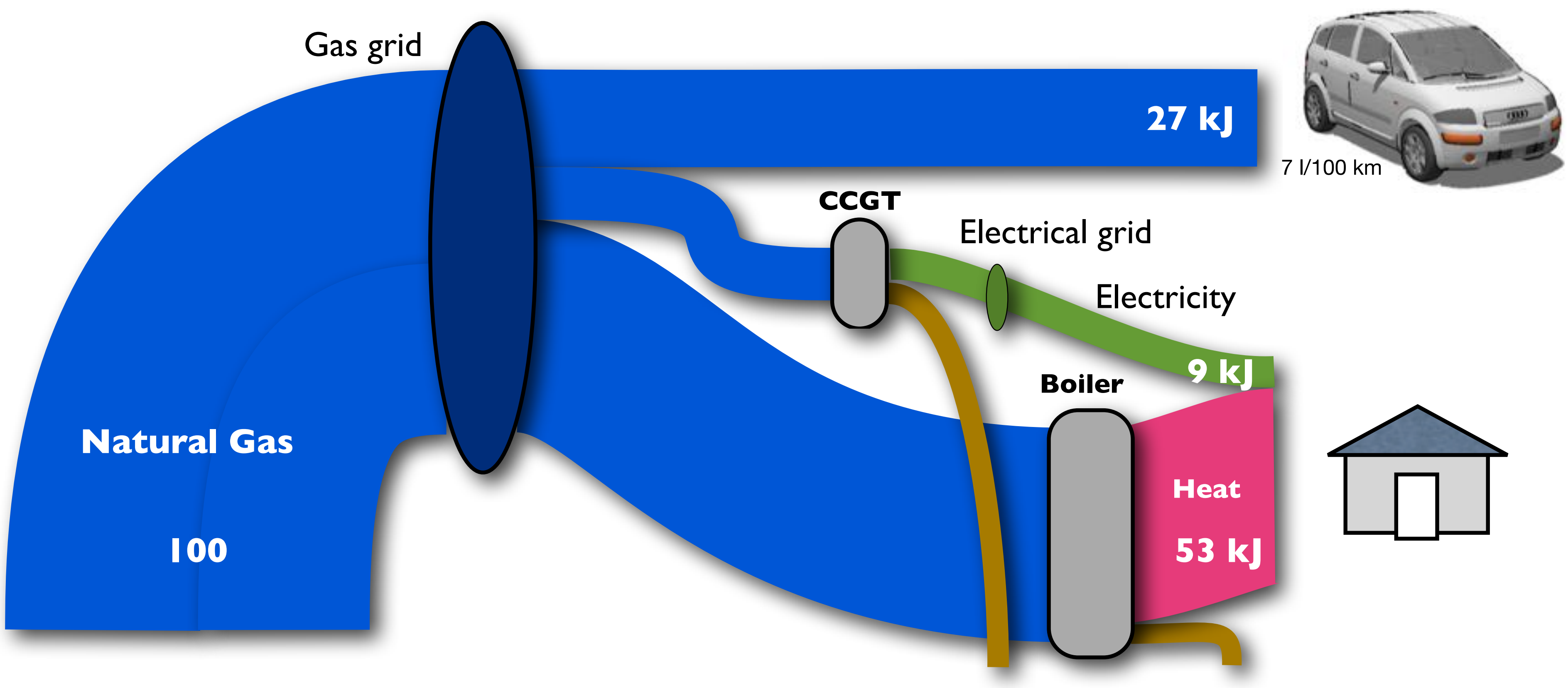
Consumption profile

Power/Energy reserve

Building stocks/micro grids

Energy transition for a household

Today's consumption : 100 kJ of Natural Gaz

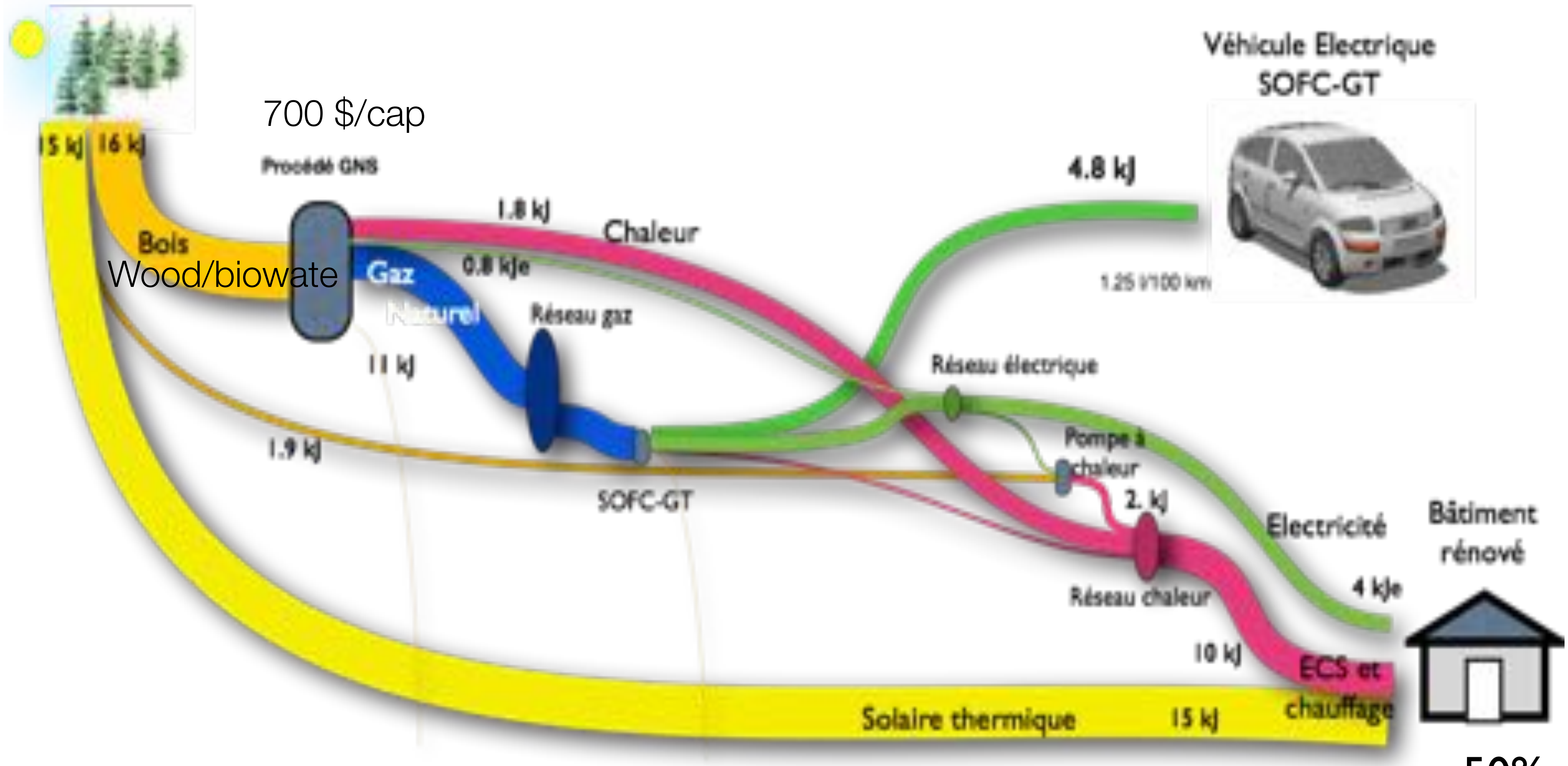


The energy system for a household

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%

One more 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 …