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Optimisation models for urban system design

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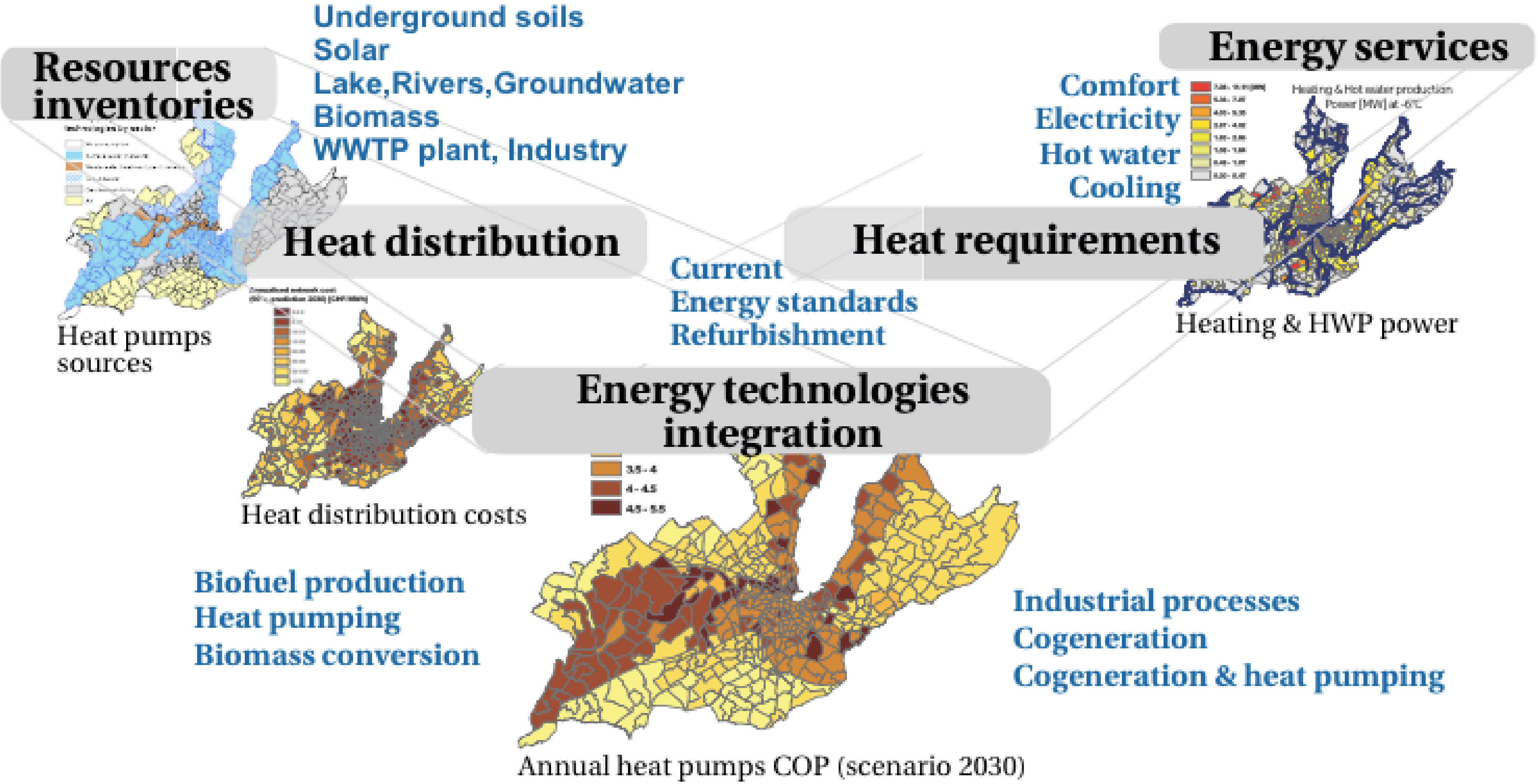
Content

- **Energy system analysis**
  - defining the requirement
- **Energy system integration**
  - Energy conversion
  - Networks
- **Multi objective thermo-economic & environomic optimisation**
  - Models
  - Optimisation strategy
  - Optimisation tricks
- **System boundaries**
- **Conclusions**

A multi dimension approach



Resources inventories

Underground soils
Solar
Lake,Rivers,Groundwater
Biomass
WWTP plant, Industry

Heat pumps sources

Heat distribution

Heat distribution costs

Energy services

Comfort
Electricity
Hot water
Cooling

Heat requirements

Current
Energy standards
Refurbishment

Heating & HWP power

Energy technologies integration

Biofuel production
Heat pumping
Biomass conversion

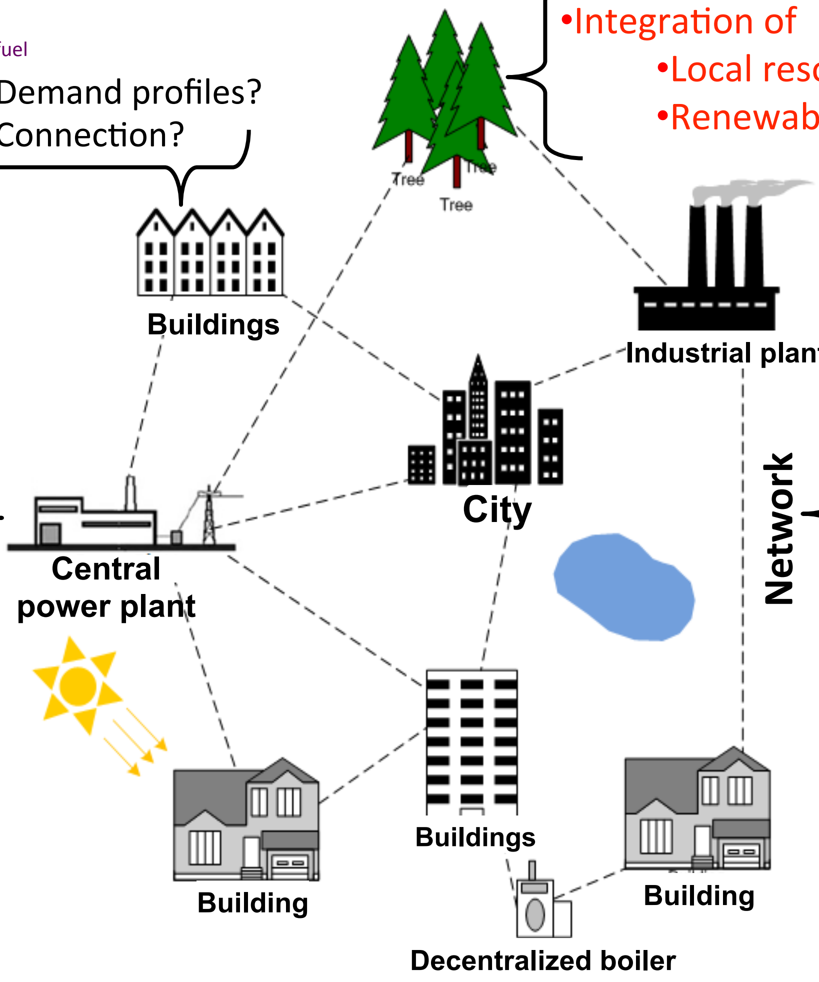
Industrial processes
Cogeneration
Cogeneration & heat pumping

Annual heat pumps COP (scenario 2030)

Problem statement

Environmental effects

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



- Demand profiles?
- Connection?

- Integration of
  - Local resources
  - Renewable

- Type?
- Size ?
- Location ?
- Centralized?
- Decentralized?

Network
- Layout?
- Size?
- Local/global?

Economical analysis

$$\mathrm{TAC} = \overbrace{\sum_{s=1}^{N_S}\sum_{p=1}^{N_P}(\mathbf{C\dot{O}V1_{s,p}} \times \mathbf{y_{s,p}} + \mathbf{C\dot{O}V2_{s,p}} \times \mathbf{u_{s,p}}) \times \triangle p}^{\text{Variable operating costs}} + \underbrace{\sum_{s=1}^{N_S}(\mathbf{COF1_s} \times \mathbf{y_s} + \mathbf{COF2_s} \times \mathbf{u_s})}_{\text{Fixed operating costs}} + \underbrace{\sum_{s=1}^{N_S} \mathbf{CI_s} \times \frac{\mathbf{i}.(1+\mathbf{i})^{n_s}}{(1+\mathbf{i})^{n_s} - 1}}_{\text{Annual investment costs}}$$

Multi scale approach

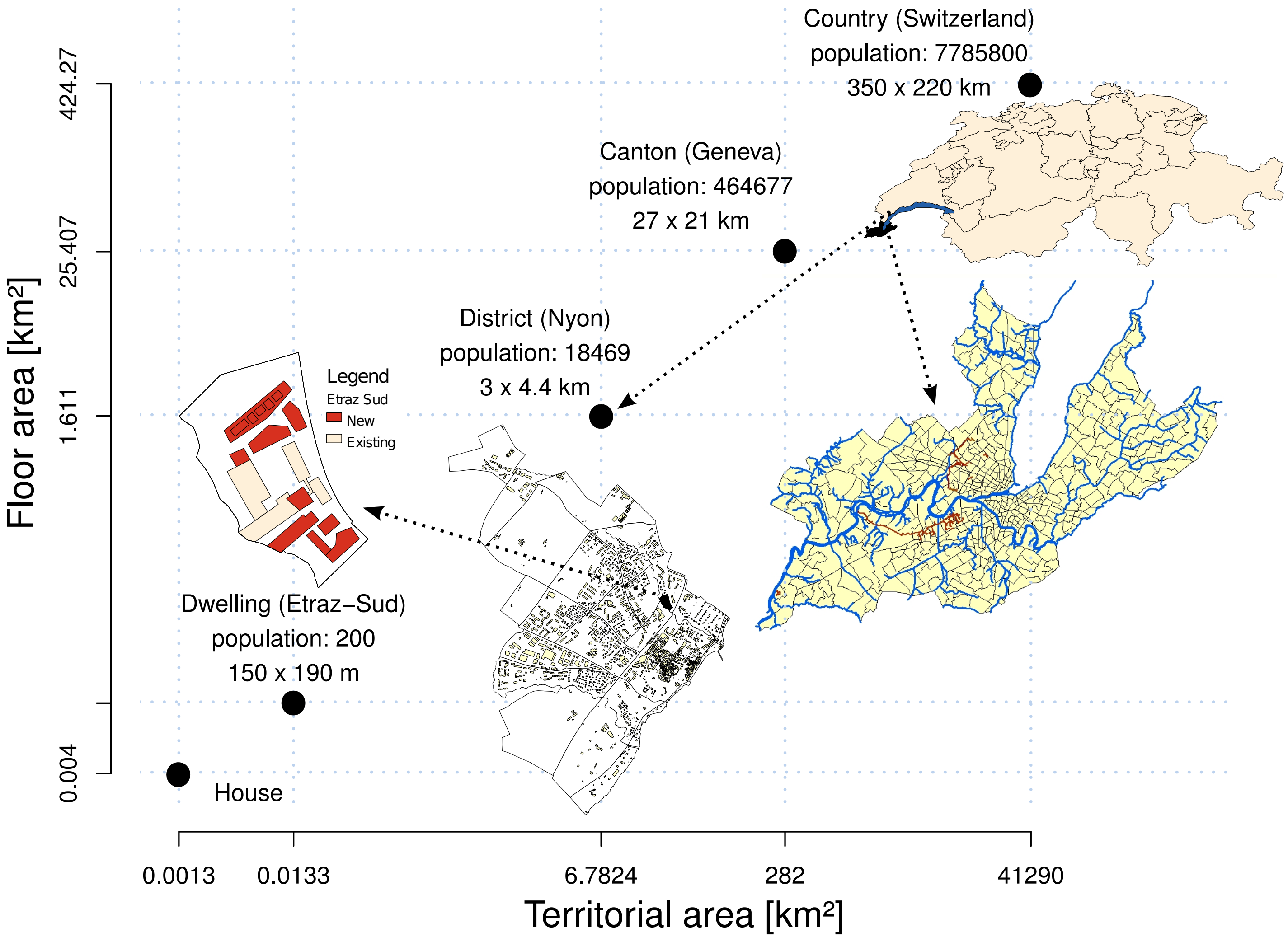
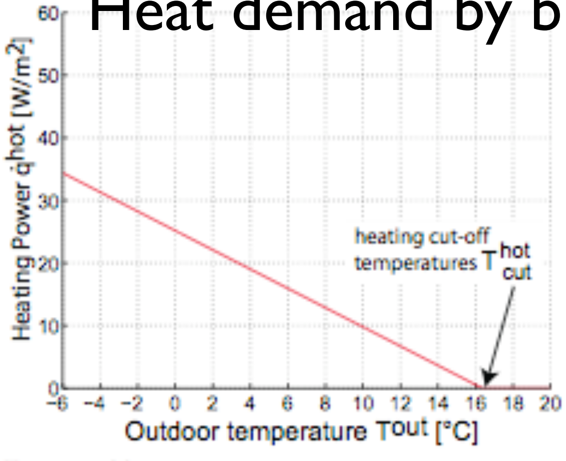


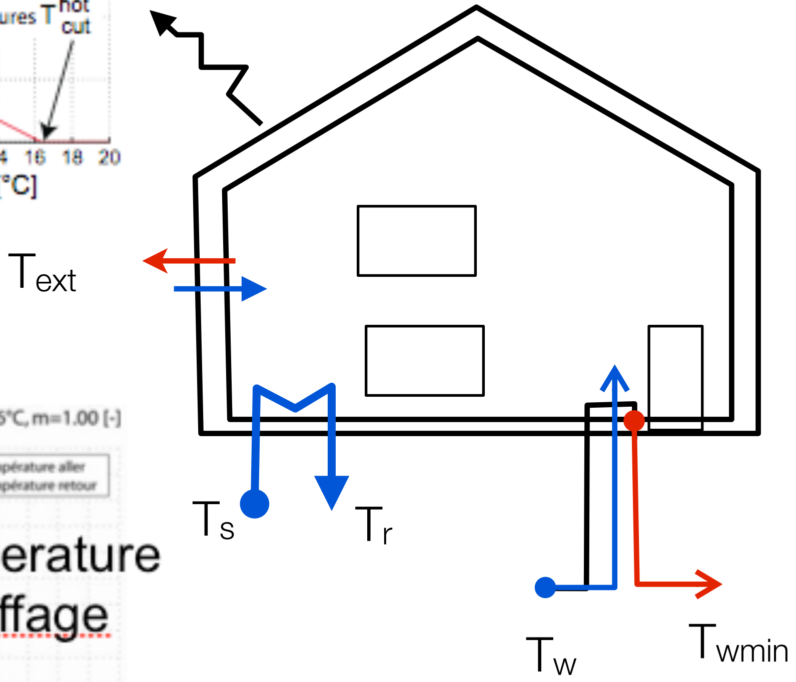
Figure 1.15: Log-log plot of the magnitude of the spatial scale to deal with in urban studies.

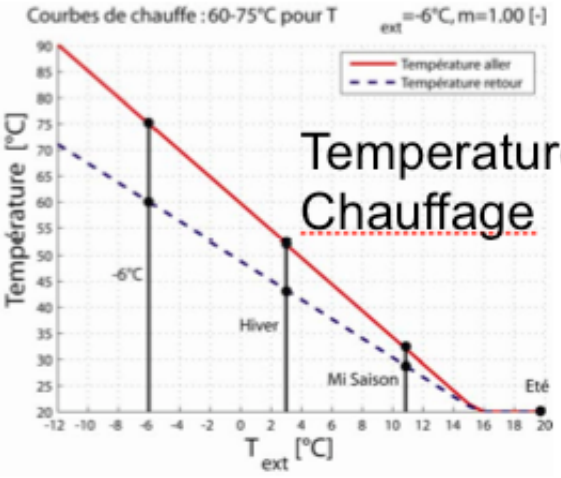
A Building as an industrial process

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

Heat demand by building simulation models

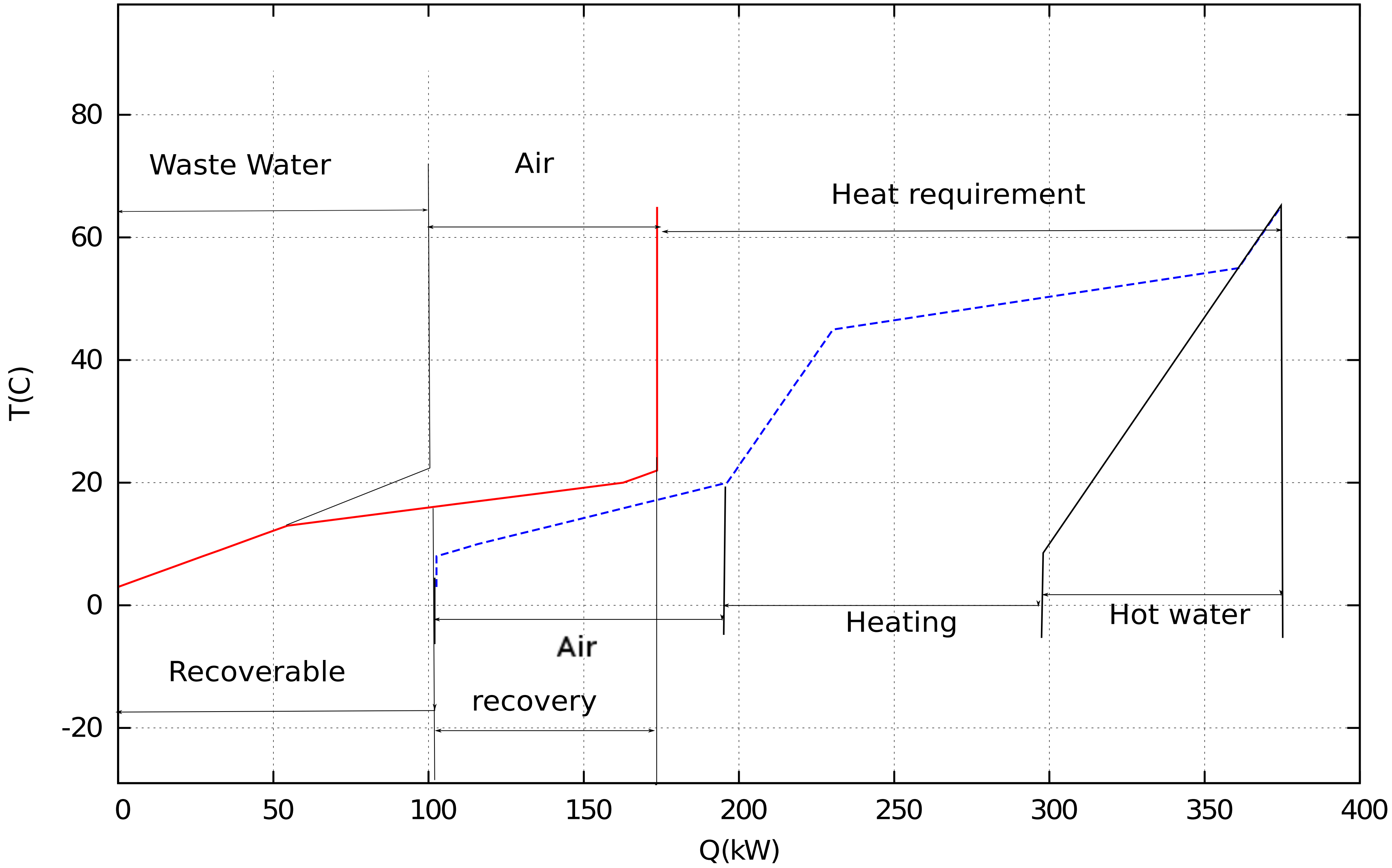






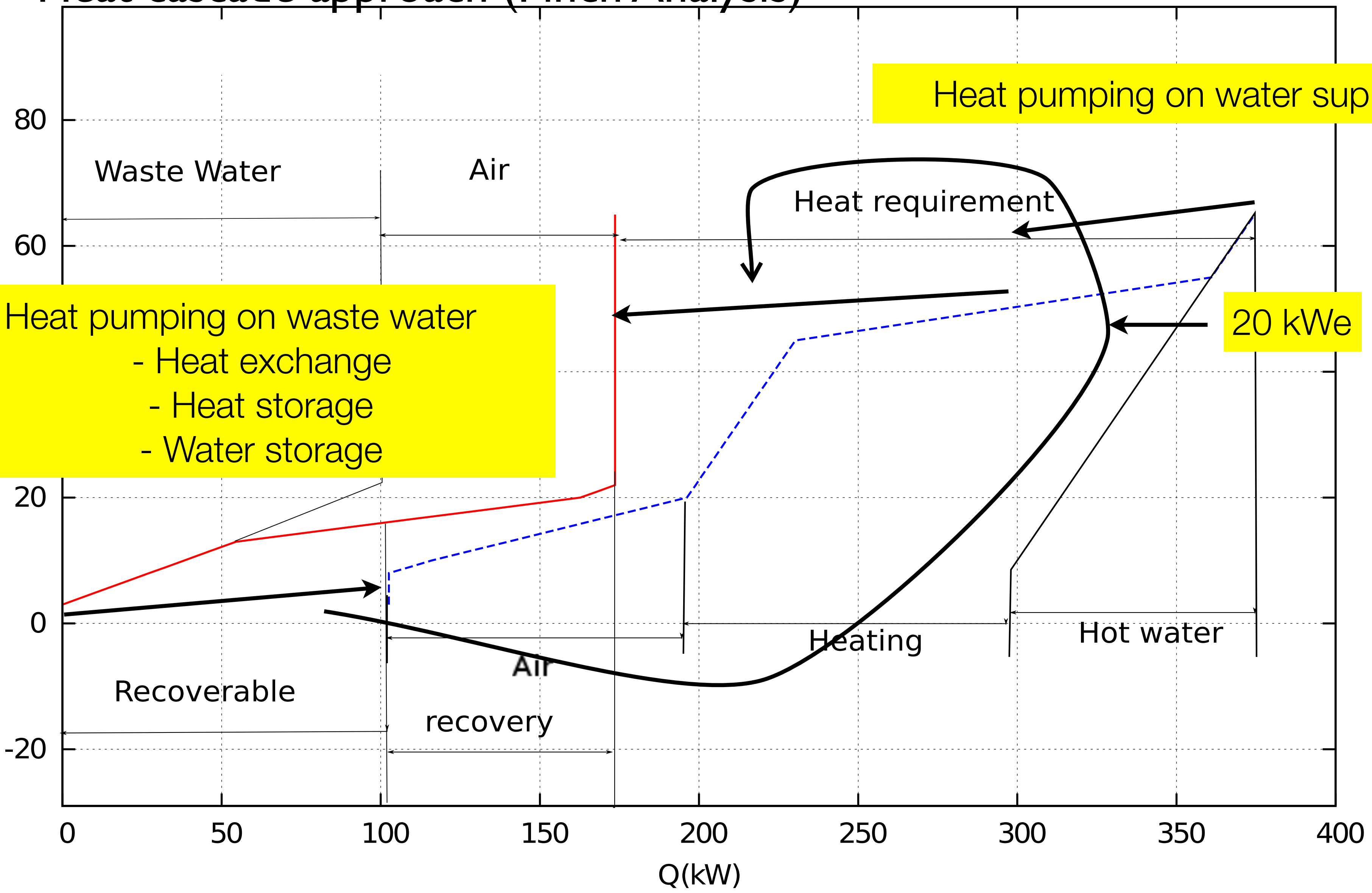
Temperature Chauffage

Local heat recovery



Heat recovery and reuse in a building

Heat cascade approach (Pinch Analysis)



Heat pumping on water supply ?

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

20 kWe

COP = 5 to 6

Conversion system

- **Electrical (?)**
- **Boilers (90% Nom eff., 80-85 % annual)**
  - Fuel Oil
  - Natural gas
  - Biomass
- **Cogeneration**
  - Decentralised => engines, fuel cells
  - Centralised => Waste incineration, NGCC Biomass + ORC or Steam
- **Heat pumps**
  - Air, Water, Geothermal,Waste heat
- **Solar technologies**
  - Heat and electricity

MILP formulation

$$\min_{R_r, y_w, f_w, E^+, E^-} \left(\sum_{w=1}^{n_w} C2_w f_w + C_{el^+}E^+ - C_{el^-}E^-\right) * t$$

Operating cost

$$+ \sum_{w=1}^{n_w} C1_w y_w + \frac{1}{\tau}\left(\sum_{w=1}^{n_w} (CI1_w y_w + CI2_w f_w)\right)$$

Fixed maintenance

Investment

Subject to : Heat cascade constraints

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

Feasibility

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

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

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

Logical relations

At least 1 of 4	$\sum_{i=1}^{4} y_i \geq 1$
At most 1 of 4	$\sum_{i=1}^{4} y_i \leq 1$
y1 or y2	$y_1 + y_2 = 1$
if y1 then y2	$y_2 \geq y_1$
if y1 then not y2	$y_b \leq (1 - y_a)$

Targeting the optimal integration : model

- MILP formulation

Gas turbine g : hot stream from T_{OT} to T_{stack}

$$Q_g^{gt} = f_g * \dot{m}_g * cpf_g * (TOT_g - Tstack_g)$$

unknown

$$f_g^{min} * y_g \leq f_g \leq y_g * f_g^{max}$$

Fuel

$$\sum_{c=1}^{n_{cgt}} f_c^g * LHV_c - \sum_{g=1}^{n_g} y_g * FCI_g + f_g * FCP_g = 0$$

Electricity

$$W_{gt} - \sum_{g=1}^{n_g} y_g * WI_g + f_g * WP_g = 0$$

Part load efficiency

Operating cost

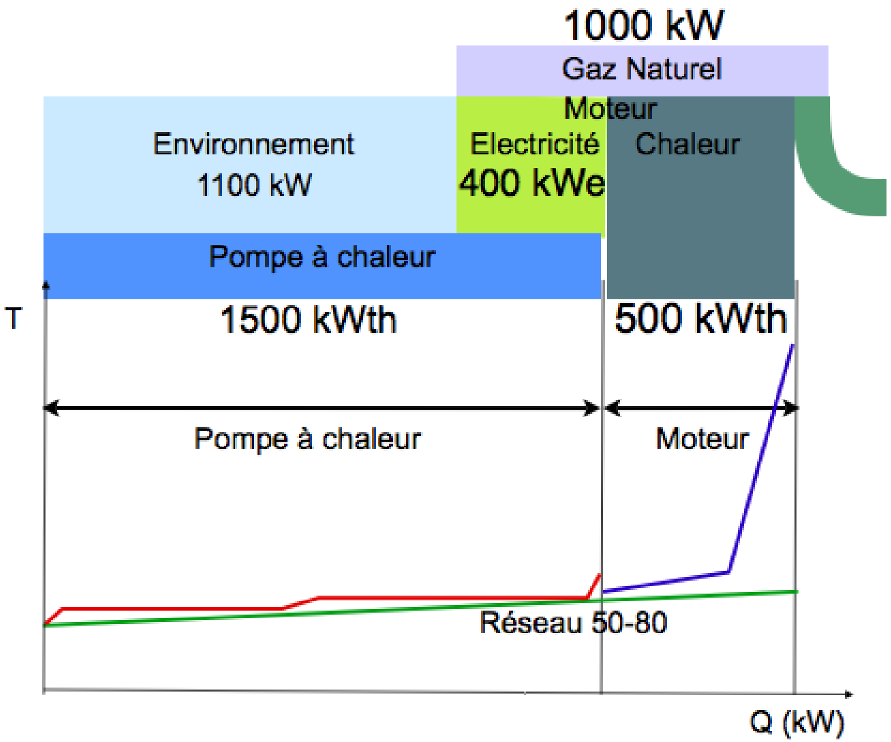
$$\sum_{g=1}^{n_g} (y_g * OCI_g + f_g * OCP_g) - OC_{gt} = 0$$

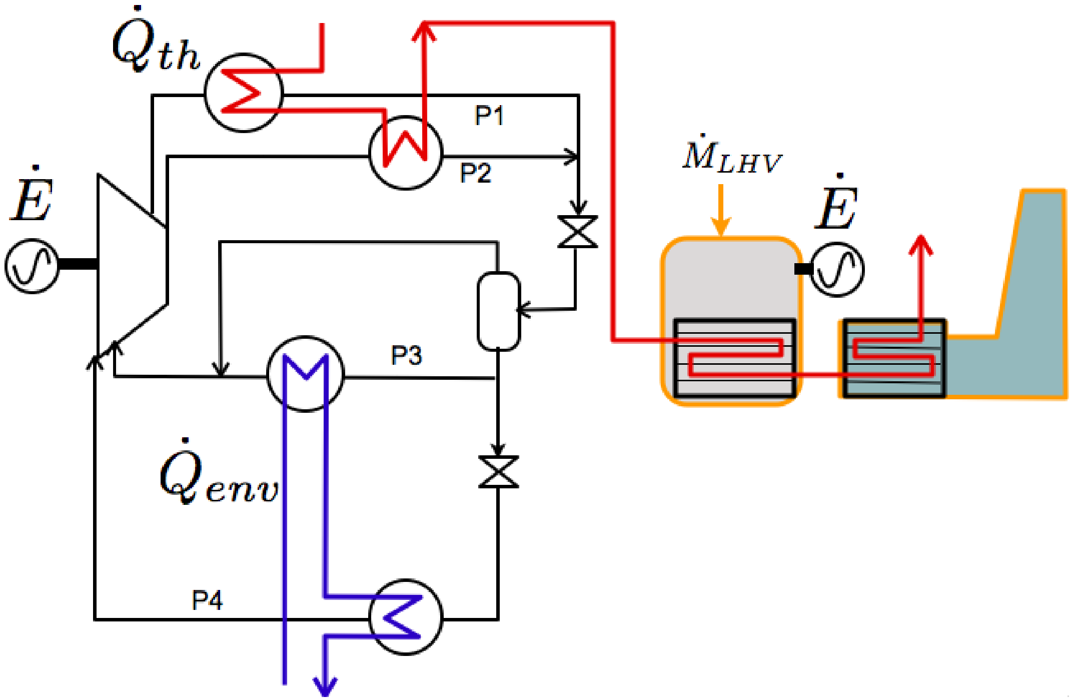
Investments

$$\sum_{g=1}^{n_g} y_g * ICI_g - IC_{gt} = 0$$

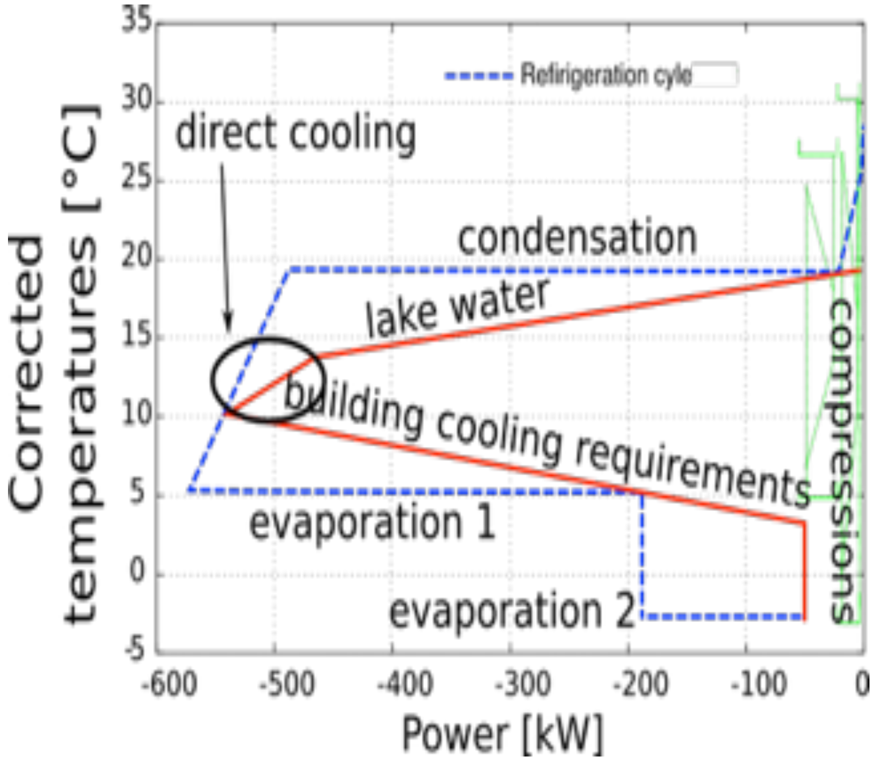
Integrated systems

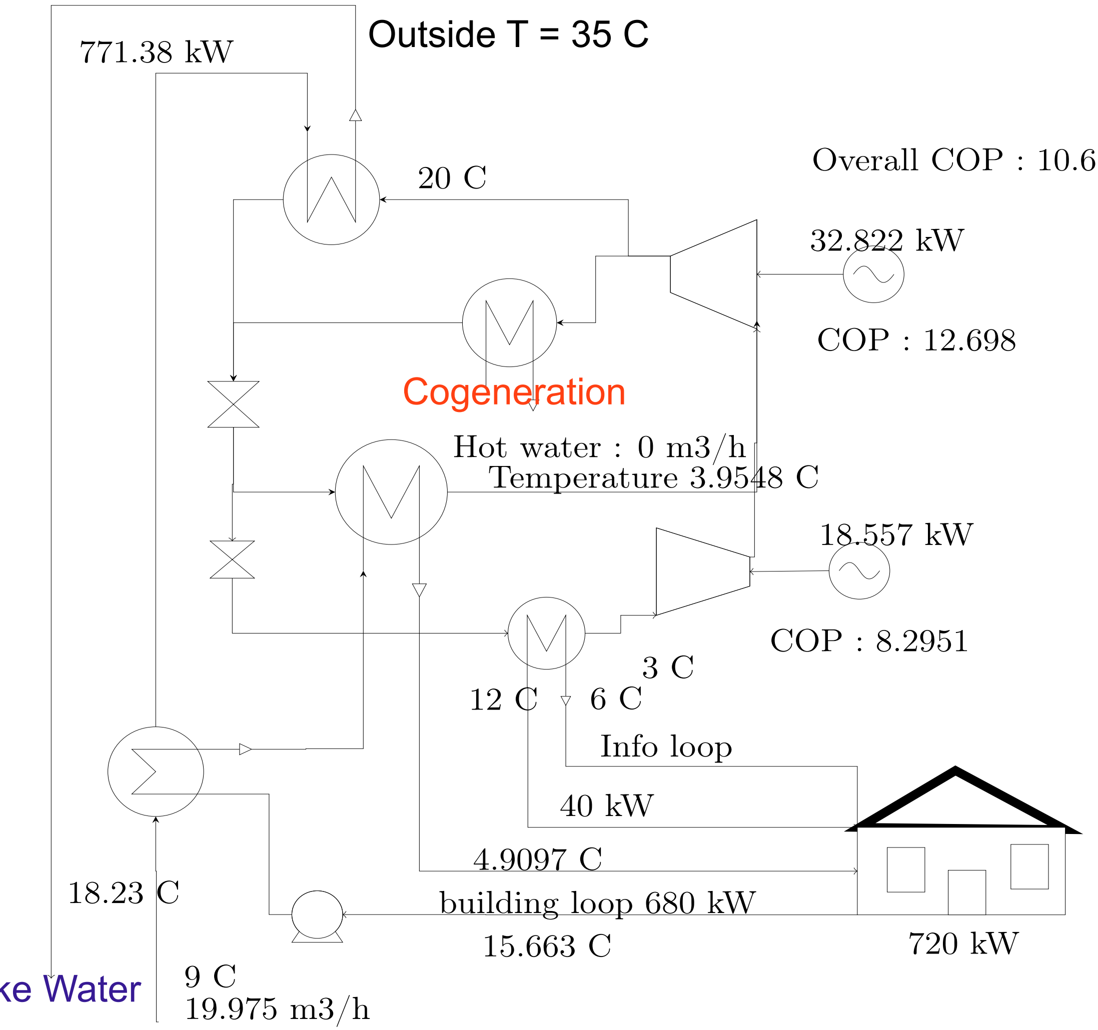
- **Integrating several energy conversion systems**
  - Higher complexity - higher efficiency - higher investment
  - flexible operation





Local integration data center integration





Generating order list of Integer Sets Solutions

- **Integer cut constraint**
  - assuming that we know already k solutions
  - problem k + 1 is defined by adding to the previous MILP problem the integer cut constraint

$$Problem^{k+1}:$$

$$Problem^{k}$$

$$\sum_{i=1}^{n_y}(2y_i^k - 1) * y_i \leq \sum_{i=1}^{n_y} y_i^k$$

where y_i^k value of y_i in solution of problem k

MILP optimization

- **Linear programming**
  - optimum defined by constraints
    - max/min
    - Pinch points
  - Cost may create strange results
    - if electricity is cheaper than the fuel, a heat pump becomes an electrical heater
  - Integer variables for technology selection
    - Can be used to select among options
- **Heat balance constraints**
  - if the hot and cold utility have not the appropriate levels no solution is found
  - max flows may prevent to close the balance
  - max flows may prevent convergence

$$y_i \cdot f_{min} \leq f \leq y_i \cdot f_{max}$$

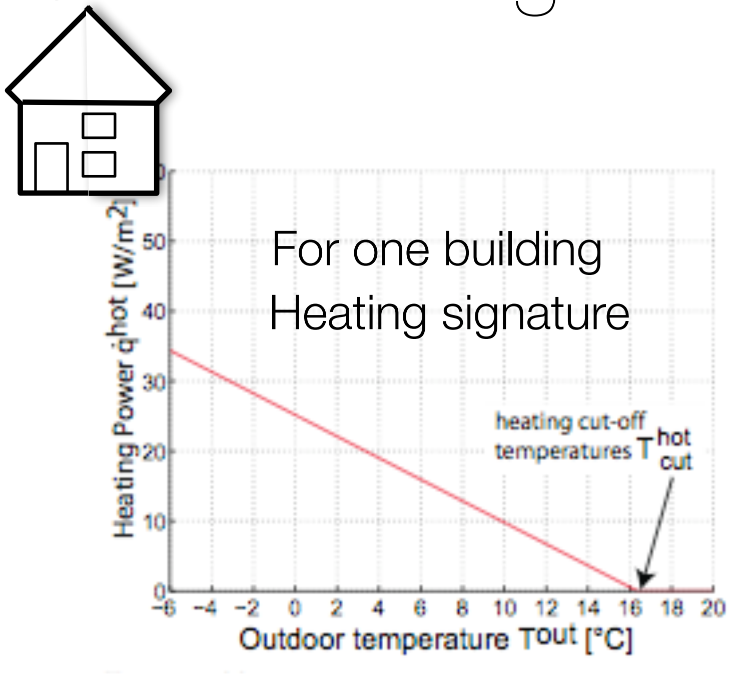
$$1. \leq 0.000001 \cdot 1'000'000$$

$$\text{is } y_i = 0.000001 =? \ 0 \text{ or } 1$$

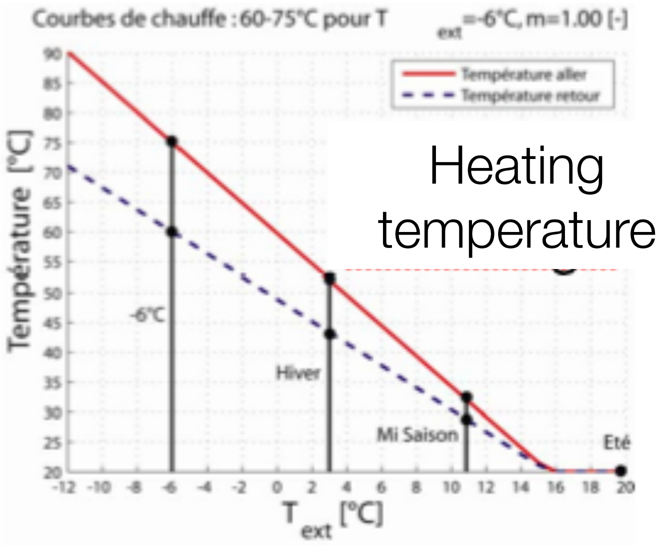
- **Additional constraints**
  - have to be satisfied
- **Need to analyze solutions**

Changing the scale

- Characterizing the services

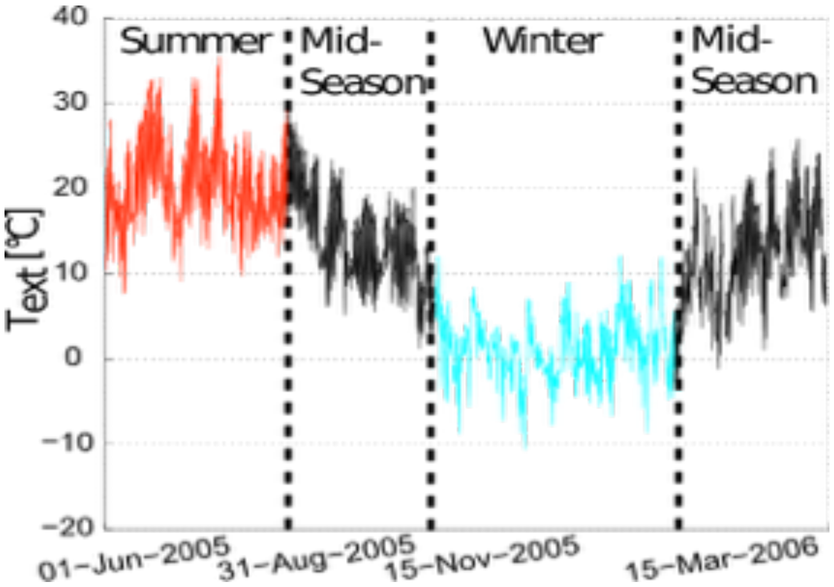


For one building
Heating signature



Heating temperature

Seasonal temperature variation



Source de données

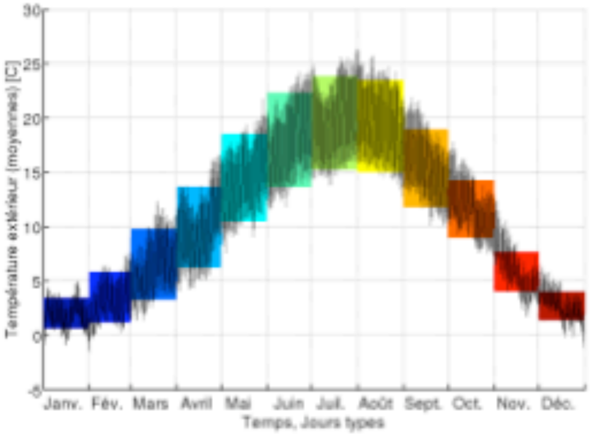
Données géolocalisées

1. Offices statistiques
   - RegBL (OFS),
   - RCB (OIT)

Symbole	Description	Bâtiments d'habitation	Bâtiments mixte avec habitation
EGID	Id. fédéral de bâtiment	indispensable	indispensable
GBAUP	Période de construction	obligatoire	obligatoire
GHEIZ	Système de chauffage	obligatoire	obligatoire
GENHZ	Agents énergétiques pour chauffage	obligatoire	obligatoire
GWWV	Installation de fourniture d'eau chaude	obligatoire	obligatoire
GENWW	Agents énergétiques pour l'eau chaude	obligatoire	obligatoire
GKAT	Catégorie de bâtiment	obligatoire	obligatoire
GASTW	Nombre de niveaux	obligatoire	obligatoire
GKLAS	Classe de bâtiment	obligatoire	facultatif
GAREA	Surface du bâtiment	facultatif	facultatif
GRENP	Période de rénovation	facultatif	facultatif
STRNAMK	Désignation abrégée de la rue	facultatif	facultatif
DEINR	N° d'entrée du bâtiment	facultatif	facultatif

2. Données cartographiques
   - Swisstopo,
   - Cadastres

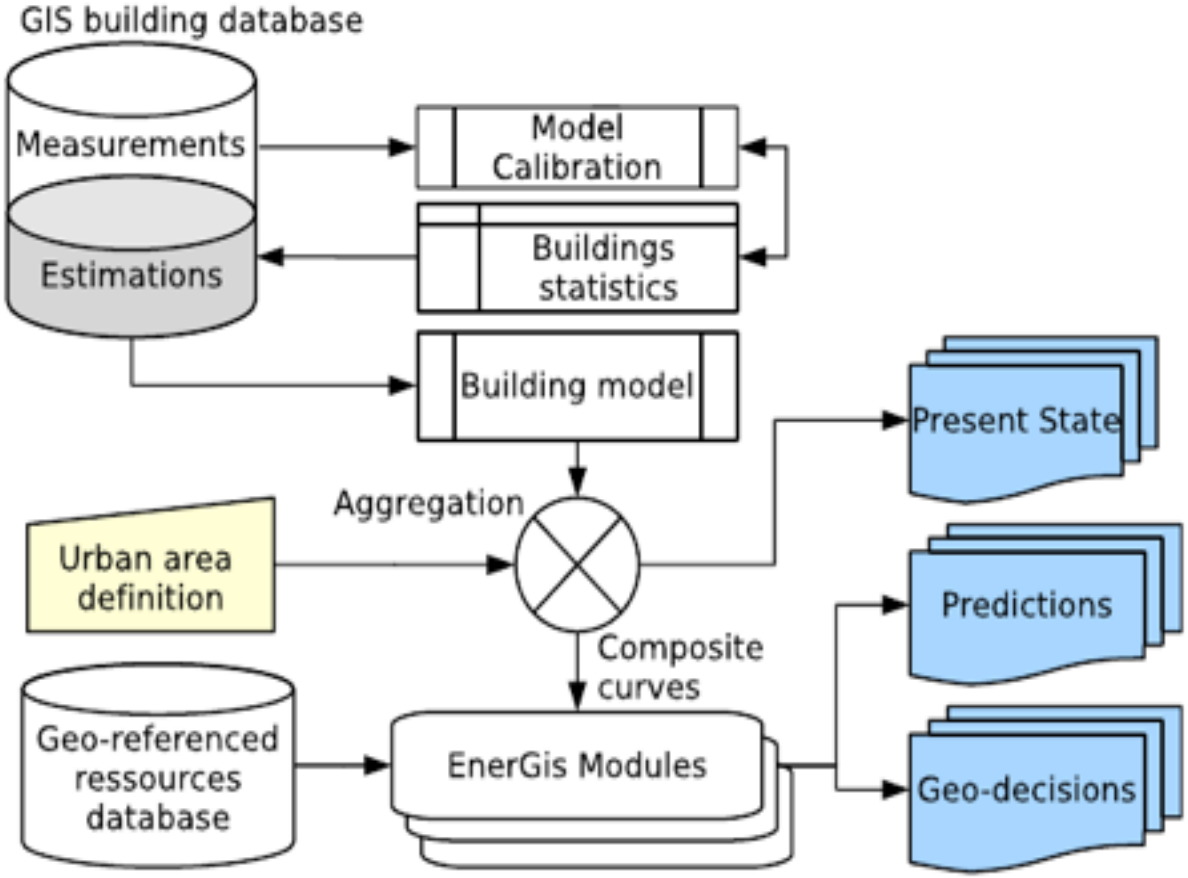
3. Données météorologiques
   - MeteoSwiss



Methodology : overview

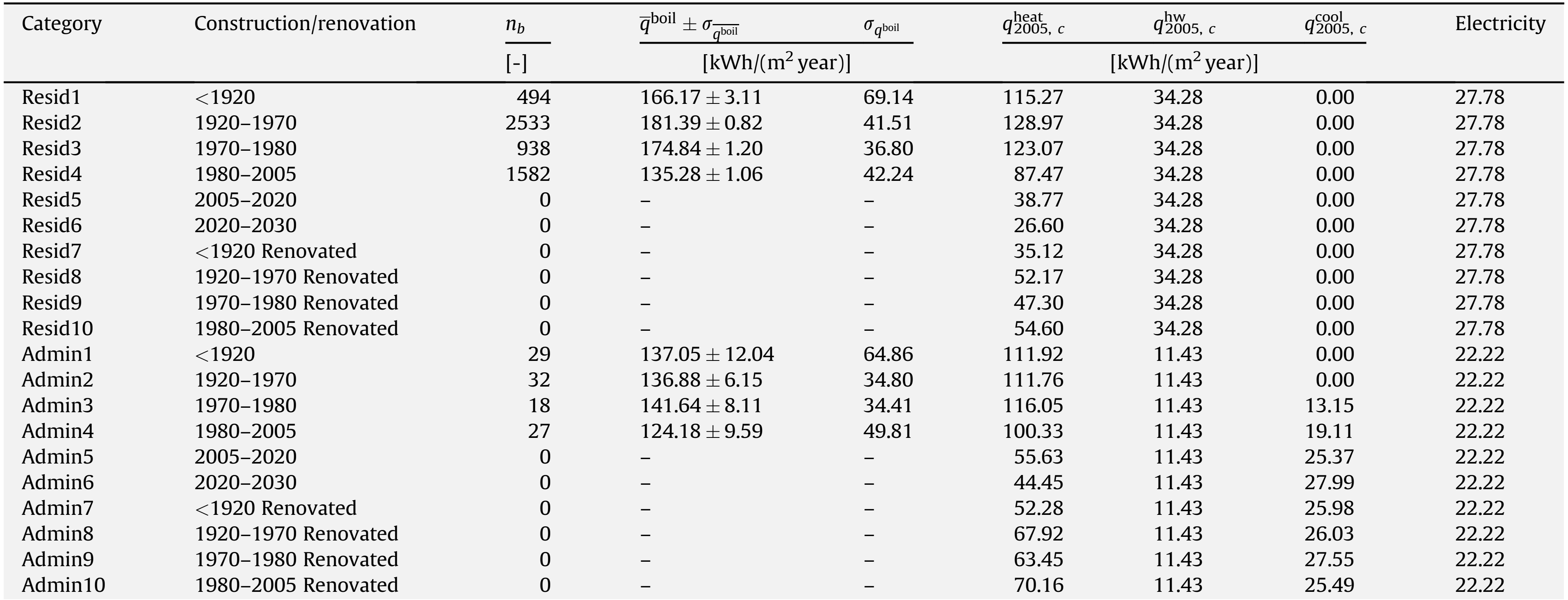
A geographical information based system for the evaluation of integrated energy conversion systems in urban areas

- GIS Database creation
- Database validation
- Simulation
- Energy integration
- Evaluation



Source : Girardin L, et al., EnerGis: A geographical information based system for the evaluation of integrated energy,
Energy (2009), doi:10.1016/j.energy.2009.08.018

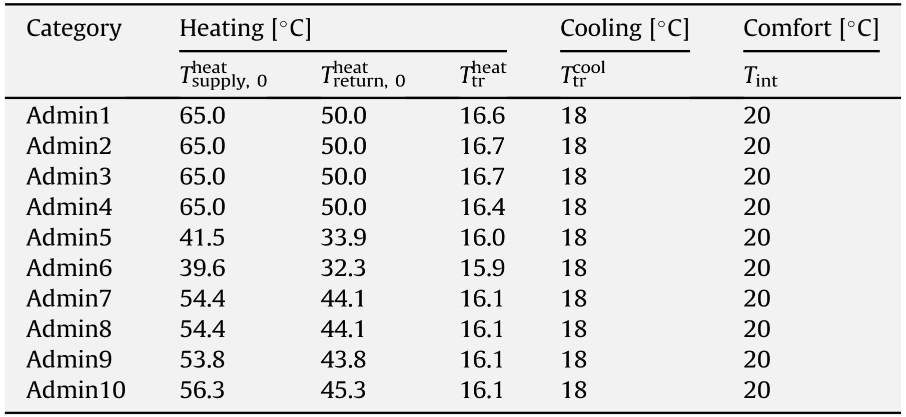
Table 1
Annual energy requirements.



Category	Construction/renovation	n_b	$\overline{q}^{boil} \pm \sigma_{\overline{q}^{boil}}$	$\sigma_{q^{boil}}$	$q^{heat}_{2005,\,c}$	$q^{hw}_{2005,\,c}$	$q^{cool}_{2005,\,c}$	Electricity
		[-]	[kWh/(m^2 year)]		[kWh/(m^2 year)]			
Resid1	<1920	494	166.17 ± 3.11	69.14	115.27	34.28	0.00	27.78
Resid2	1920–1970	2533	181.39 ± 0.82	41.51	128.97	34.28	0.00	27.78
Resid3	1970–1980	938	174.84 ± 1.20	36.80	123.07	34.28	0.00	27.78
Resid4	1980–2005	1582	135.28 ± 1.06	42.24	87.47	34.28	0.00	27.78
Resid5	2005–2020	0	–	–	38.77	34.28	0.00	27.78
Resid6	2020–2030	0	–	–	26.60	34.28	0.00	27.78
Resid7	<1920 Renovated	0	–	–	35.12	34.28	0.00	27.78
Resid8	1920–1970 Renovated	0	–	–	52.17	34.28	0.00	27.78
Resid9	1970–1980 Renovated	0	–	–	47.30	34.28	0.00	27.78
Resid10	1980–2005 Renovated	0	–	–	54.60	34.28	0.00	27.78
Admin1	<1920	29	137.05 ± 12.04	64.86	111.92	11.43	0.00	22.22
Admin2	1920–1970	32	136.88 ± 6.15	34.80	111.76	11.43	0.00	22.22
Admin3	1970–1980	18	141.64 ± 8.11	34.41	116.05	11.43	13.15	22.22
Admin4	1980–2005	27	124.18 ± 9.59	49.81	100.33	11.43	19.11	22.22
Admin5	2005–2020	0	–	–	55.63	11.43	25.37	22.22
Admin6	2020–2030	0	–	–	44.45	11.43	27.99	22.22
Admin7	<1920 Renovated	0	–	–	52.28	11.43	25.98	22.22
Admin8	1920–1970 Renovated	0	–	–	67.92	11.43	26.03	22.22
Admin9	1970–1980 Renovated	0	–	–	63.45	11.43	27.55	22.22
Admin10	1980–2005 Renovated	0	–	–	70.16	11.43	25.49	22.22

- **cont.... 80 types**

Table 2
Design temperature of the domestic hydronic system.



Category	Heating [°C]			Cooling [°C]	Comfort [°C]
	$T^{heat}_{supply,\,0}$	$T^{heat}_{return,\,0}$	T^{heat}_{tr}	T^{cool}_{tr}	T_{int}
Admin1	65.0	50.0	16.6	18	20
Admin2	65.0	50.0	16.7	18	20
Admin3	65.0	50.0	16.7	18	20
Admin4	65.0	50.0	16.4	18	20
Admin5	41.5	33.9	16.0	18	20
Admin6	39.6	32.3	15.9	18	20
Admin7	54.4	44.1	16.1	18	20
Admin8	54.4	44.1	16.1	18	20
Admin9	53.8	43.8	16.1	18	20
Admin10	56.3	45.3	16.1	18	20

L. Girardin et al. / Energy 35 (2010) 830–840

Building stock characterisation

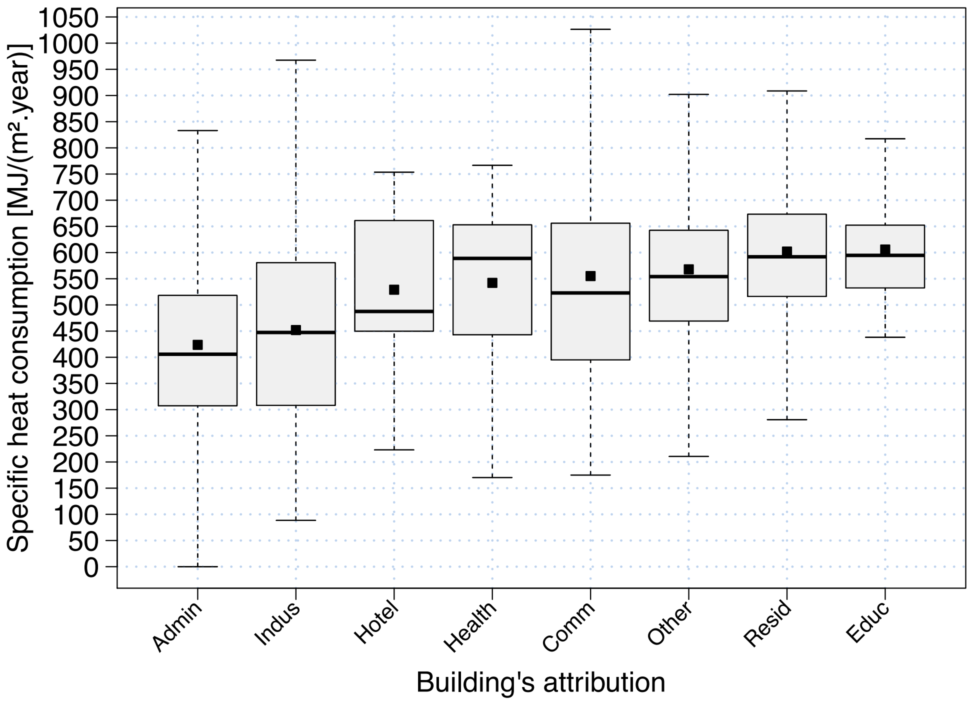
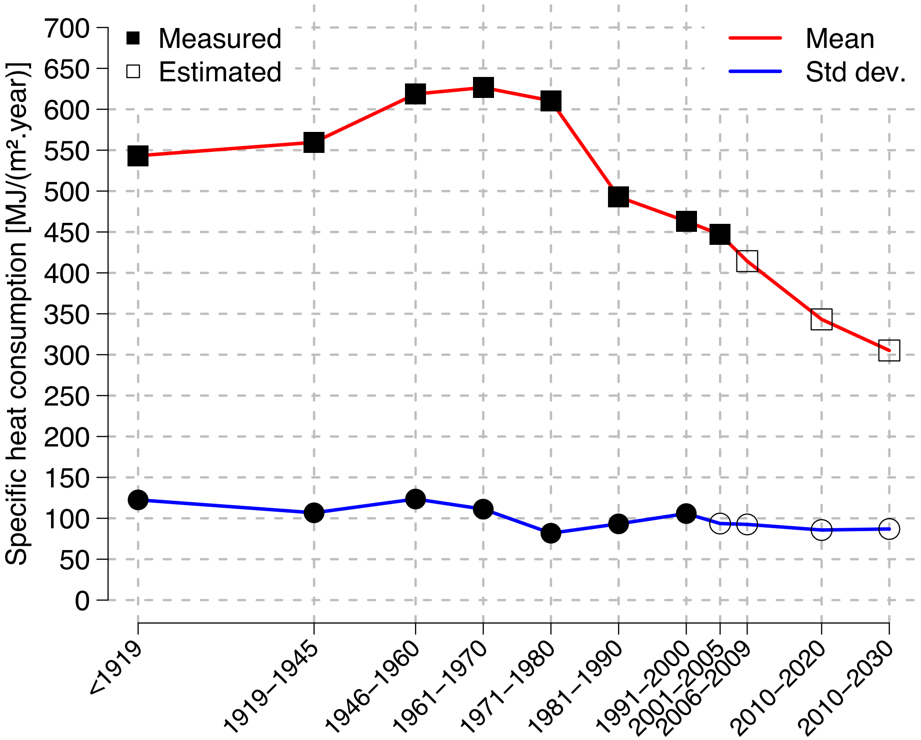
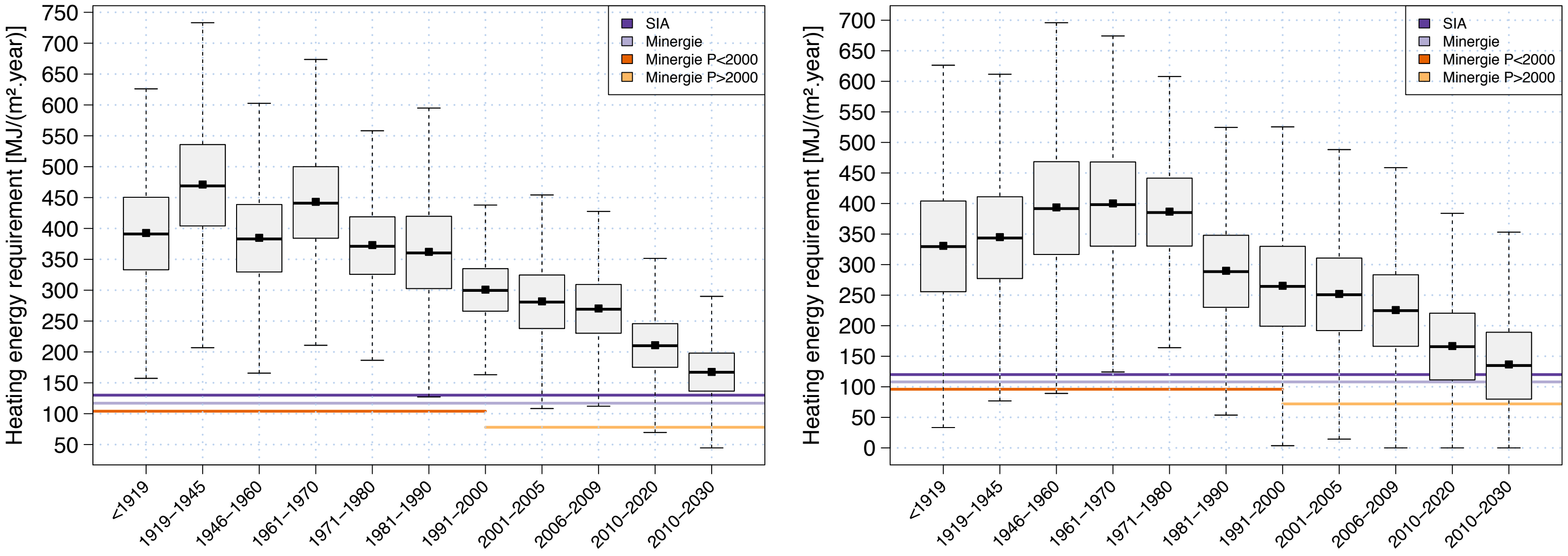


Figure 2.14: Annual heat-energy final consumption per building type.



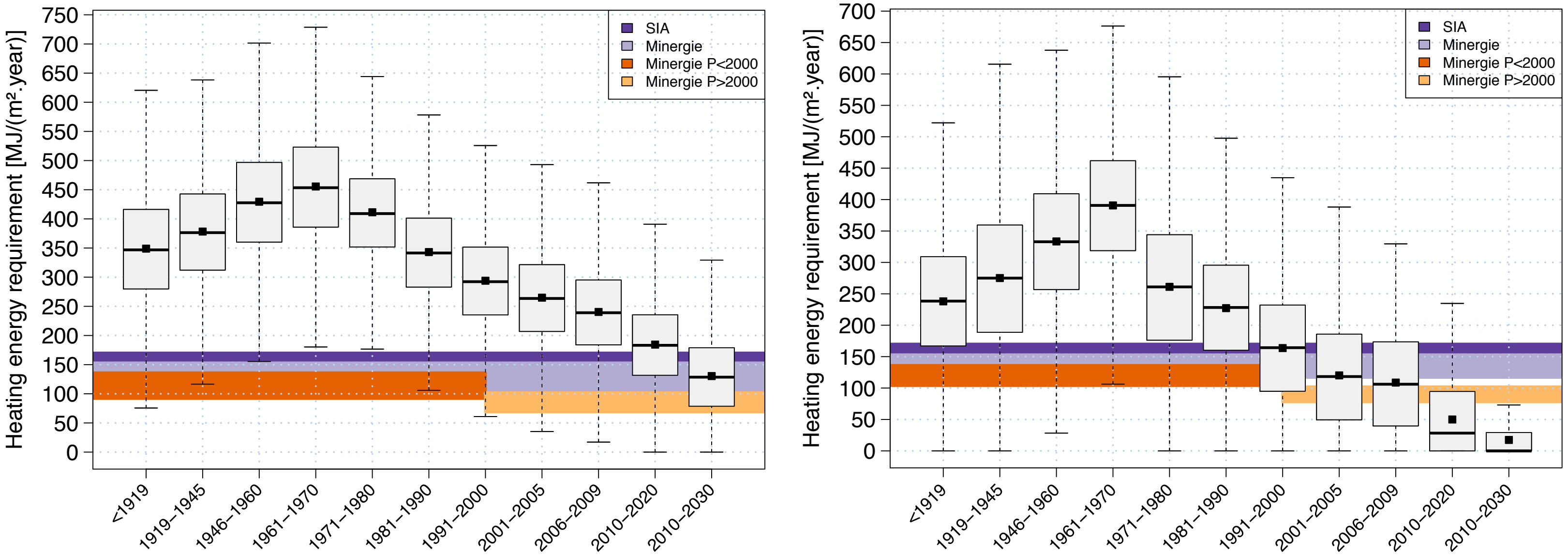
2.15.2: Building with several households (ResidCollective)

Building stock and norms



2.16.1: Individual homes

2.16.2: Building with several households



2.16.3: Building partially used for habitation

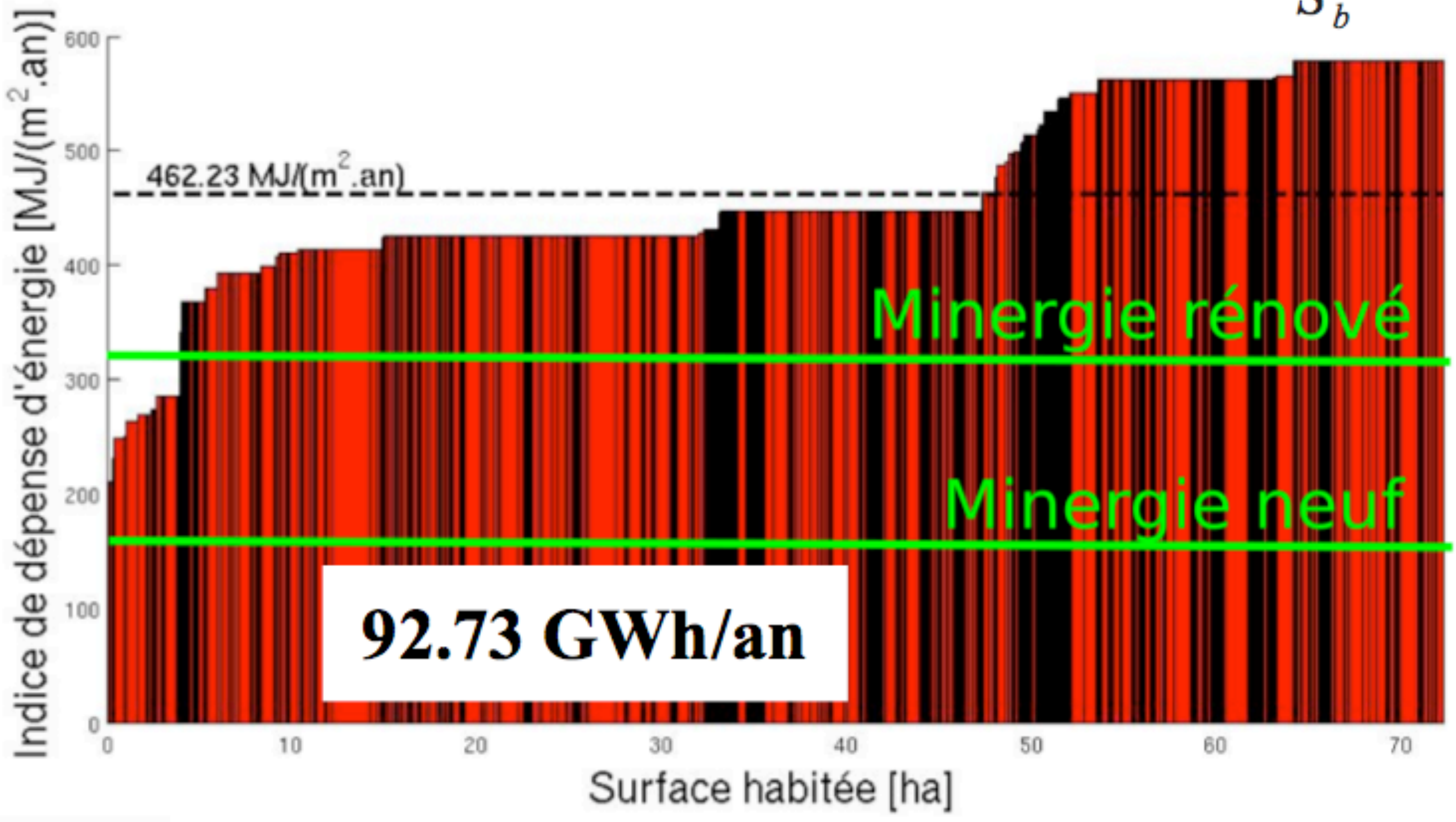
2.16.4: Housing with other end-use

Figure 2.16: Specific Heating requirement for the official categorization of Switzerland's households.

Effect of the refurbishment

Calculs d'indices de dépense

$$\dot{q}_b^c = \frac{\left(Q_b^{c,hs} + Q_b^{c,hw}\right)}{S_b}$$



Where to act ?

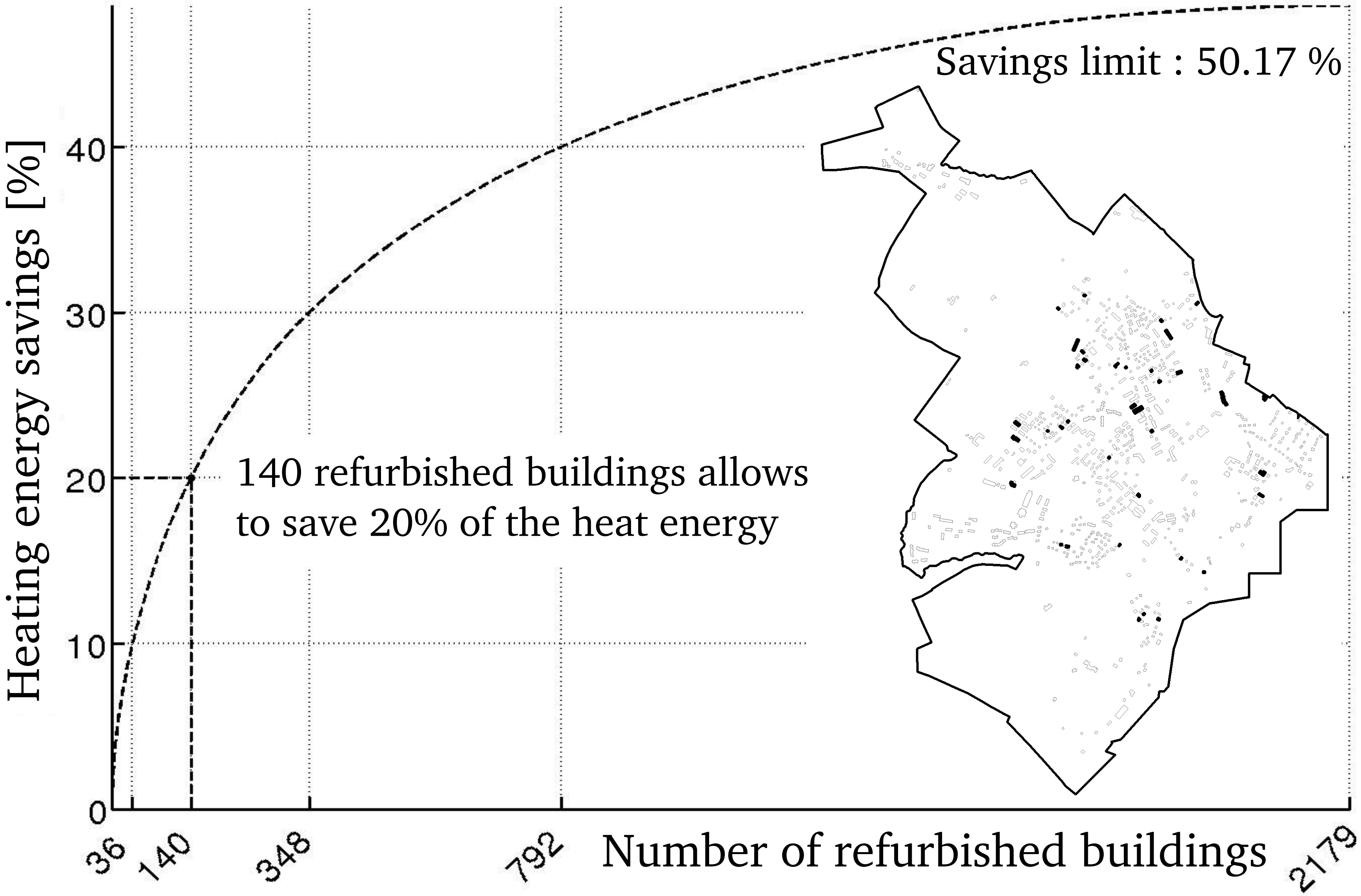


Figure 2.25: Evolutionary curve of the potential of building's improvement actions.

What is the effect of refurbishment

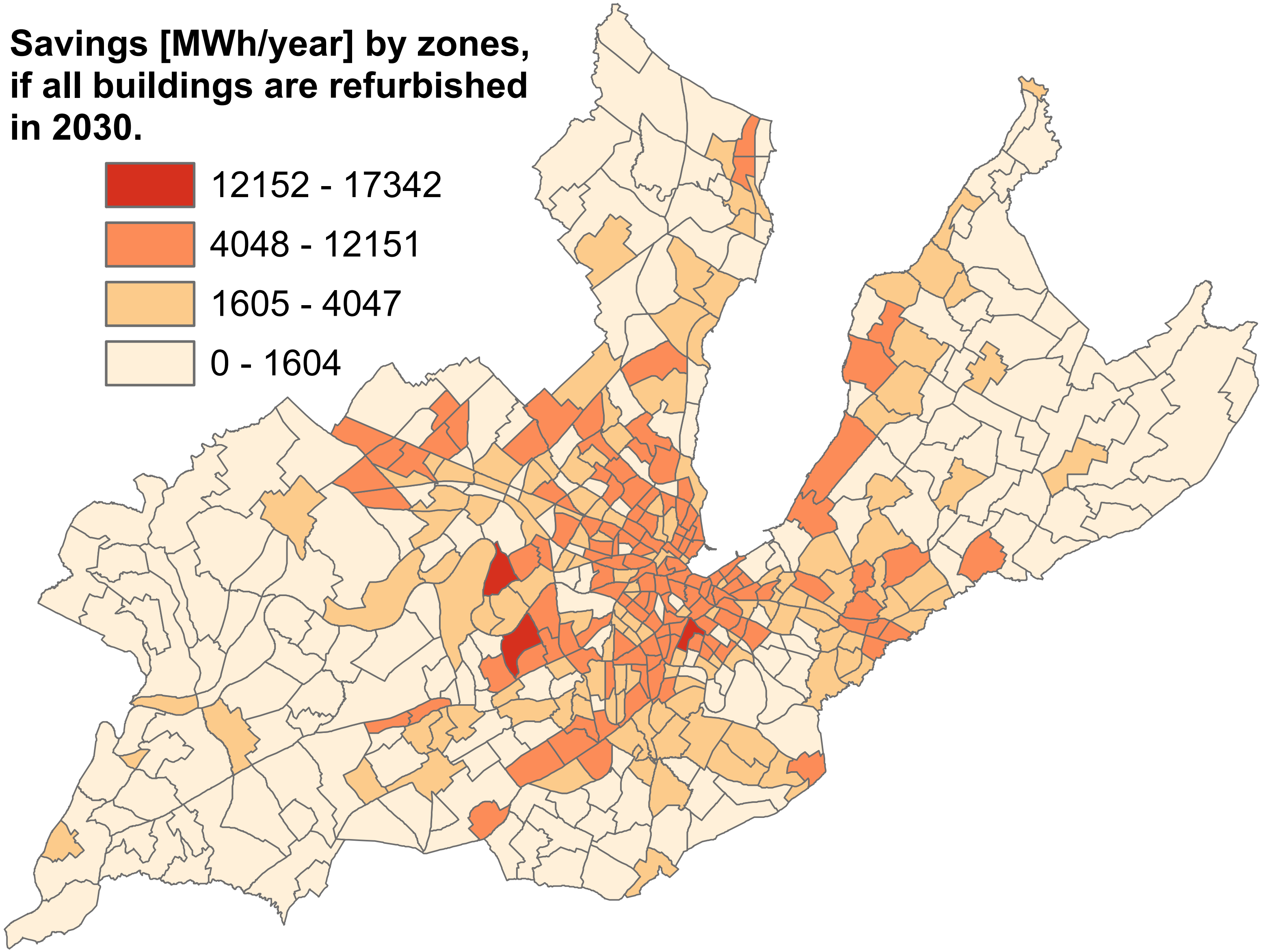
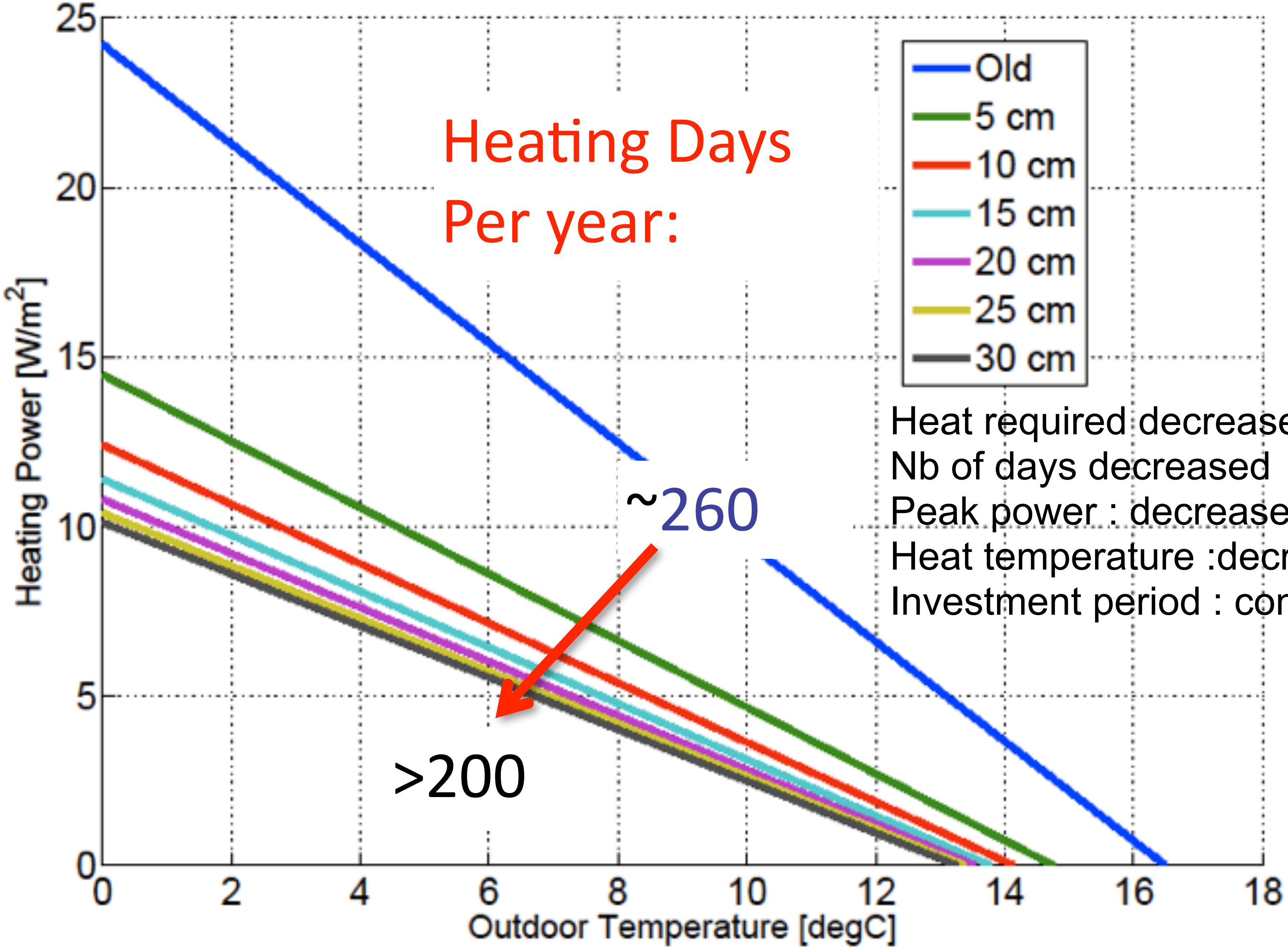


Fig. 8. Savings by zones at the horizon 2030 if all buildings build before 2005 are refurbished.

Building renovation



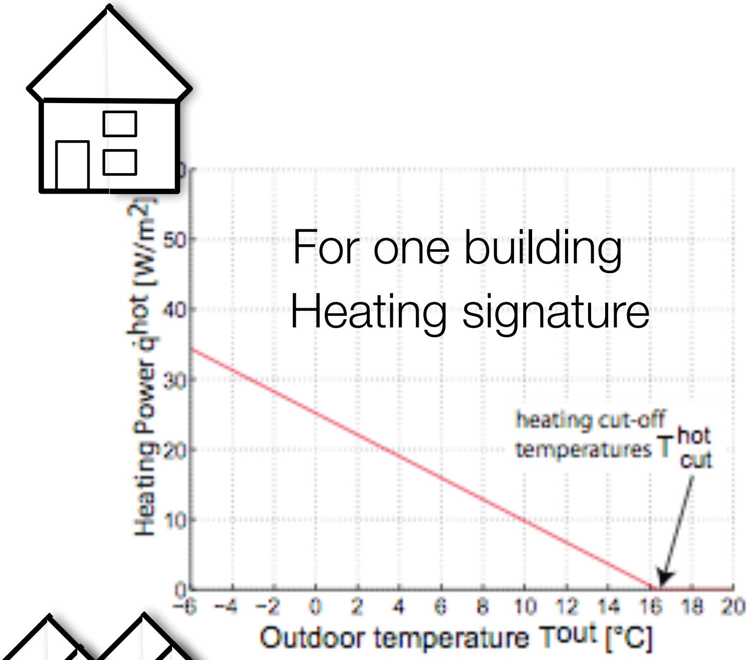
Heating Days
Per year:

~260

>200

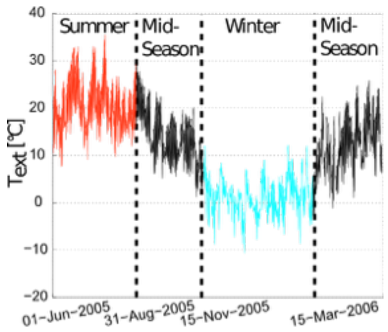
Heat required decreased
Nb of days decreased
Peak power : decreased
Heat temperature :decreased
Investment period : constant !

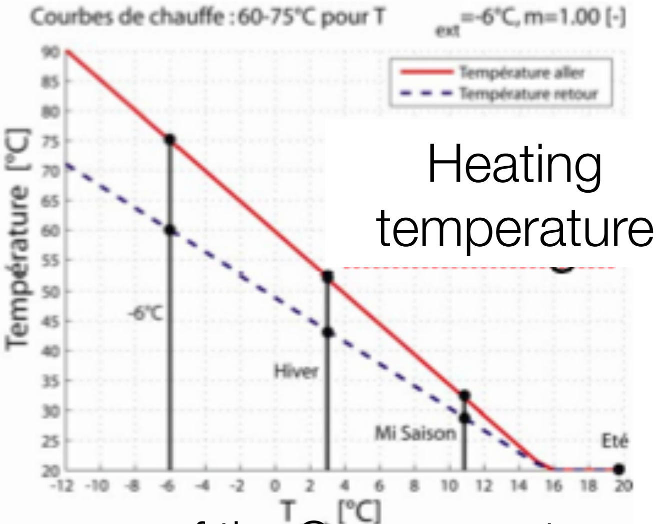
System integration



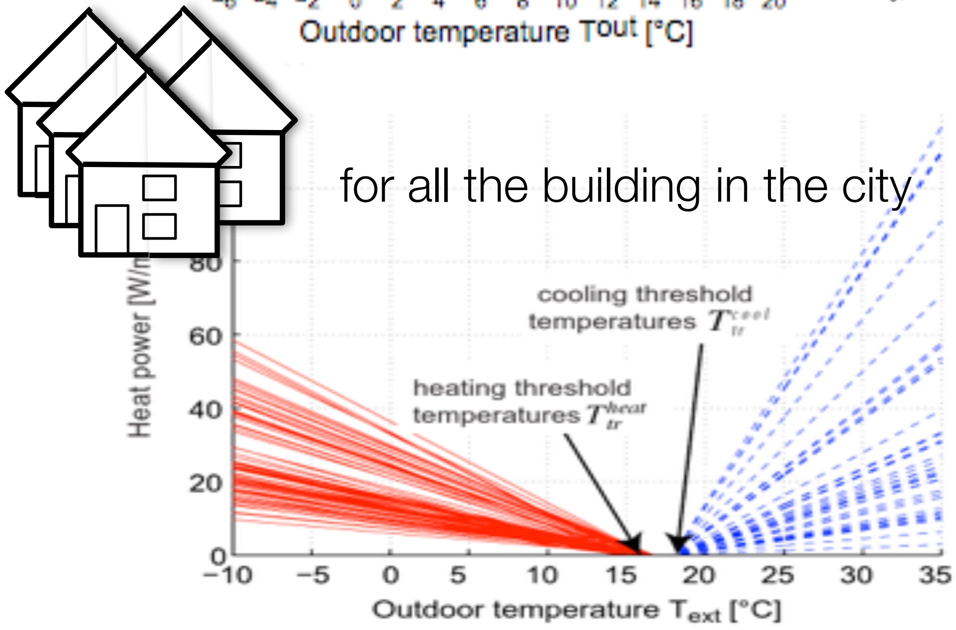
For one building
Heating signature

Seasonal temperature variation



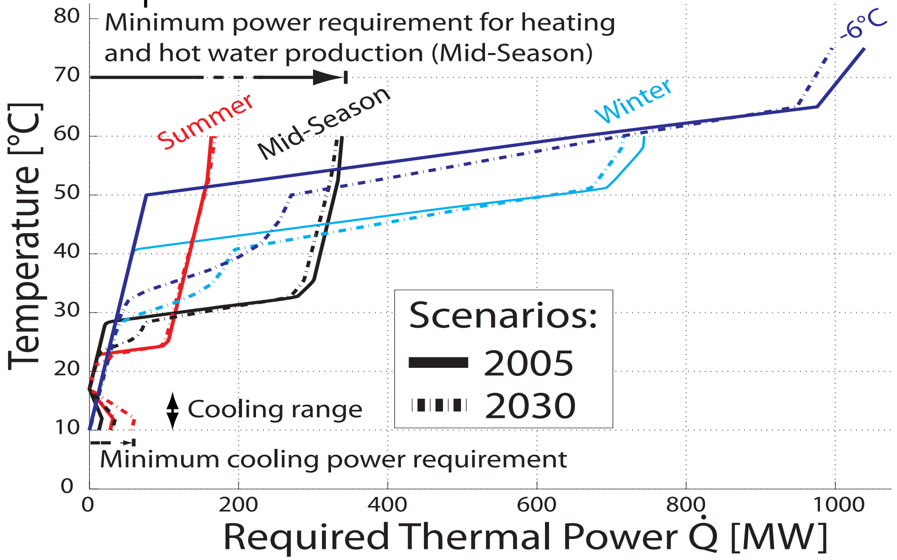


Heating temperature



for all the building in the city

Composite curve of the Geneva canton



Integrating the demand : the whole canton

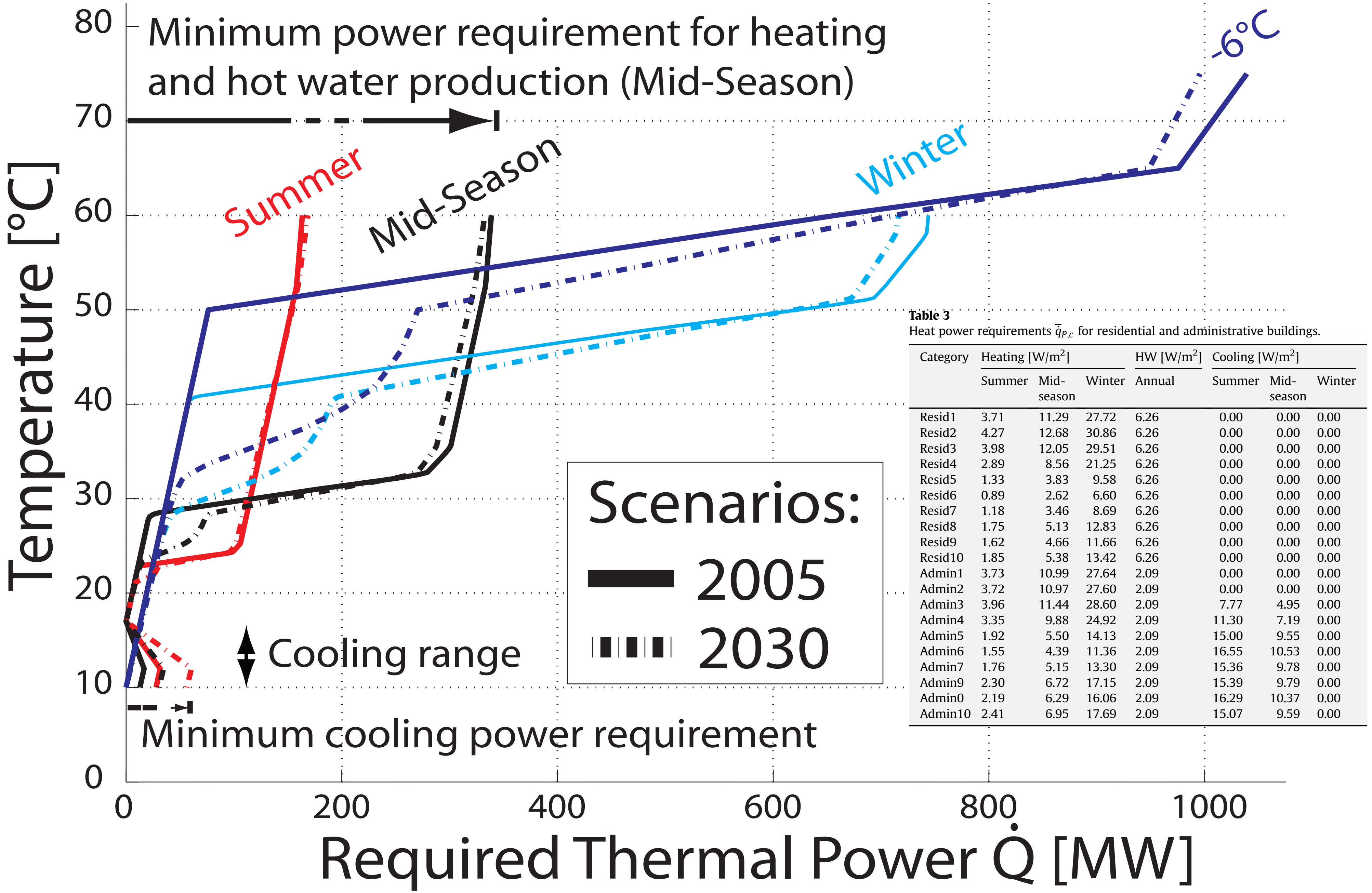
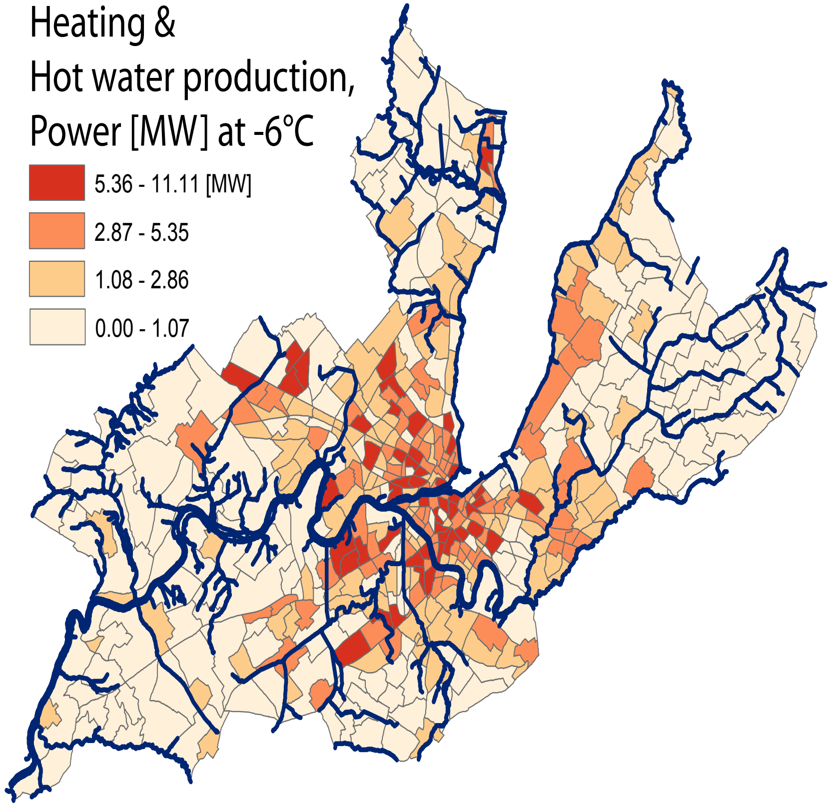


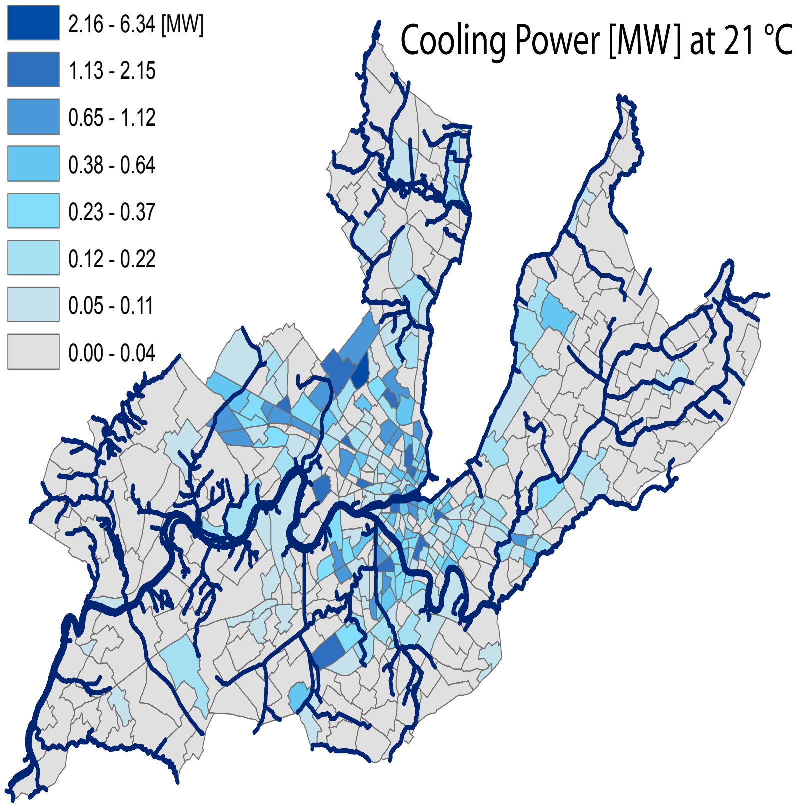
Table 3
Heat power requirements $\bar{\dot{q}}_{P,c}$ for residential and administrative buildings.

Category	Heating [W/m²]			HW [W/m²]	Cooling [W/m²]		
	Summer	Mid-season	Winter	Annual	Summer	Mid-season	Winter
Resid1	3.71	11.29	27.72	6.26	0.00	0.00	0.00
Resid2	4.27	12.68	30.86	6.26	0.00	0.00	0.00
Resid3	3.98	12.05	29.51	6.26	0.00	0.00	0.00
Resid4	2.89	8.56	21.25	6.26	0.00	0.00	0.00
Resid5	1.33	3.83	9.58	6.26	0.00	0.00	0.00
Resid6	0.89	2.62	6.60	6.26	0.00	0.00	0.00
Resid7	1.18	3.46	8.69	6.26	0.00	0.00	0.00
Resid8	1.75	5.13	12.83	6.26	0.00	0.00	0.00
Resid9	1.62	4.66	11.66	6.26	0.00	0.00	0.00
Resid10	1.85	5.38	13.42	6.26	0.00	0.00	0.00
Admin1	3.73	10.99	27.64	2.09	0.00	0.00	0.00
Admin2	3.72	10.97	27.60	2.09	0.00	0.00	0.00
Admin3	3.96	11.44	28.60	2.09	7.77	4.95	0.00
Admin4	3.35	9.88	24.92	2.09	11.30	7.19	0.00
Admin5	1.92	5.50	14.13	2.09	15.00	9.55	0.00
Admin6	1.55	4.39	11.36	2.09	16.55	10.53	0.00
Admin7	1.76	5.15	13.30	2.09	15.36	9.78	0.00
Admin9	2.30	6.72	17.15	2.09	15.39	9.79	0.00
Admin0	2.19	6.29	16.06	2.09	16.29	10.37	0.00
Admin10	2.41	6.95	17.69	2.09	15.07	9.59	0.00

ENERGIS : urban energy integration

- **ENERGIS**
  - Energy services georeferenced





Reference: Girardin et al., A geographical information based system for the evaluation of integrated energy conversion systems in urban areas, ECOS 2008

The urban system integration

- Multi Energy services
  - Electricity
  - Heating
  - Cooling
  - Hot water
  - Refrigeration
  - Industrial processes
- Heat integration
  - Composite curves
  - Heat-temperature diagrams
    - thermal distribution

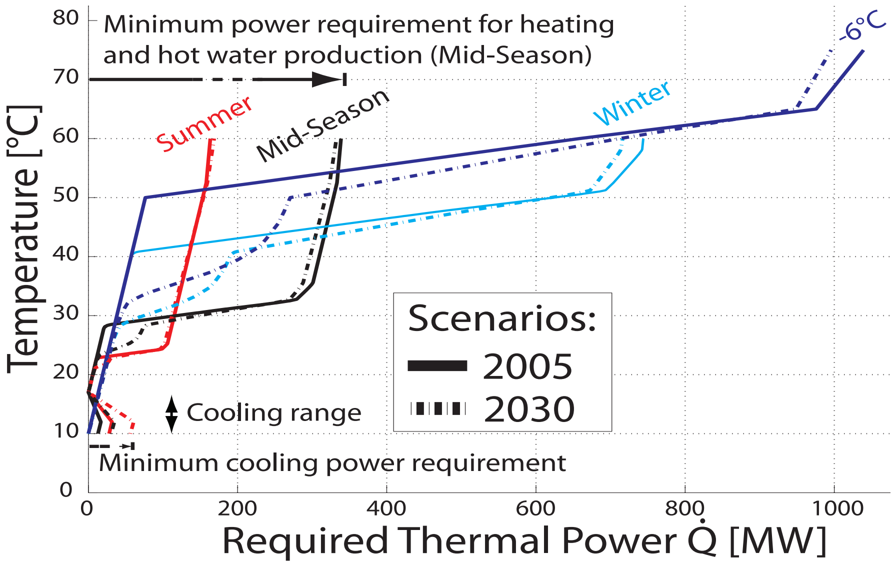
➡Seasonal profiles

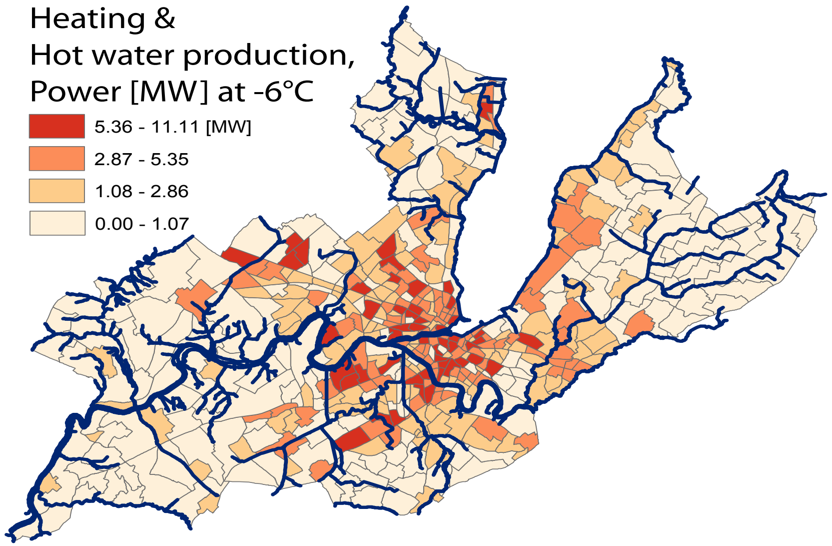
- ● stochastic !

➡Evolution scenarios

- ➡buildings stock
- ➡refurbishment

Composite curve of the Geneva canton





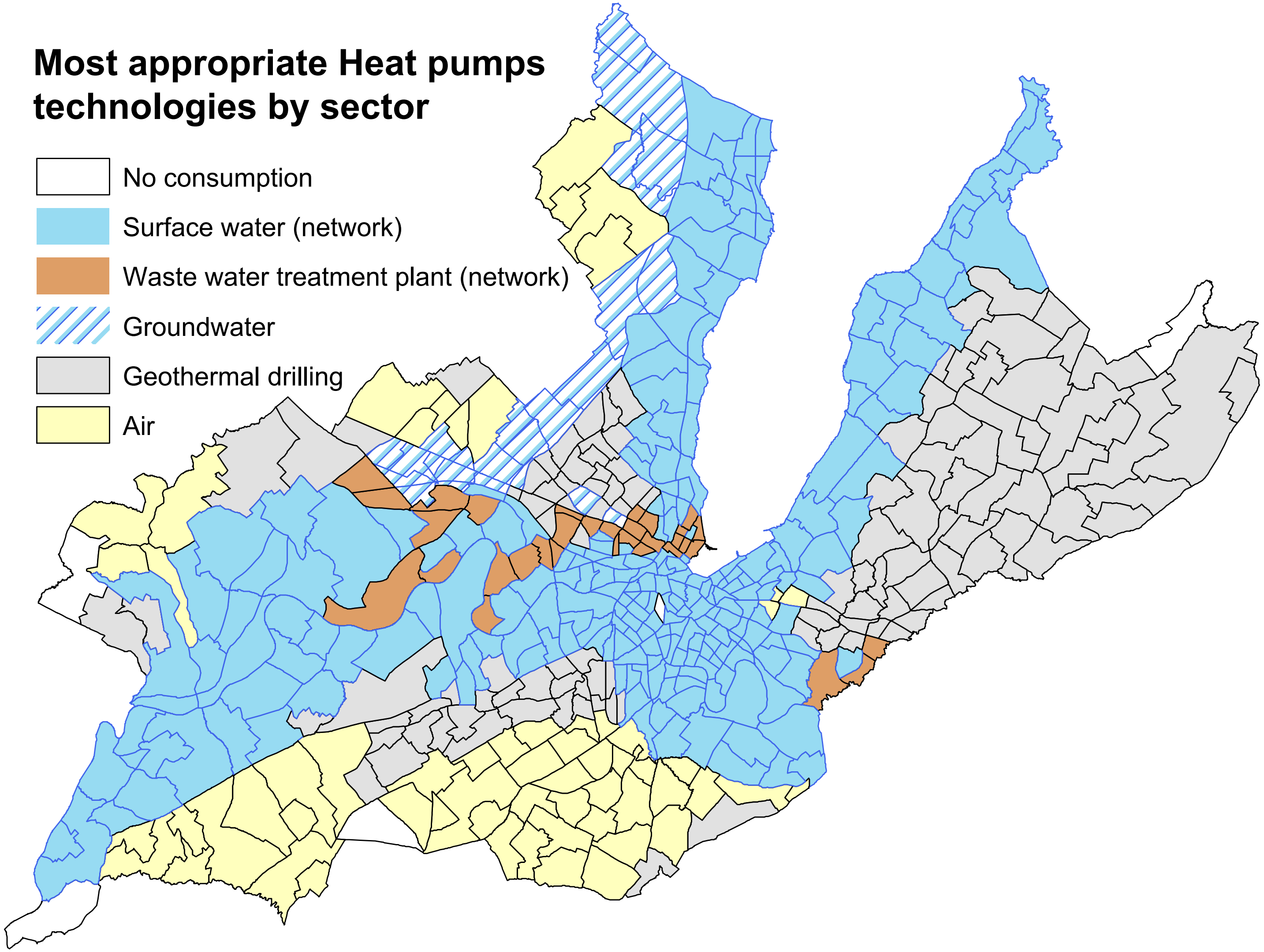
Girardin, et al.. "EnerGis: A Geographical Information Based System for the Evaluation of Integrated Energy Conversion Systems in Urban Areas." Energy 35, no. 2 (2010): 830–840.

Heat pumps and local renewable resources

Local resources

- Air
- Geothermal
- Surface water (lake -river)
- Waste water
- Industry waste heat

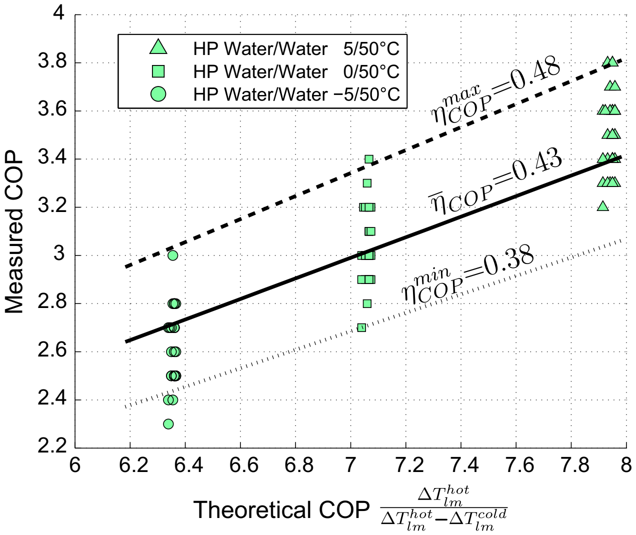
Resources localisation



Most appropriate Heat pumps technologies by sector

Table 4
Theorical COP efficiency factors.

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



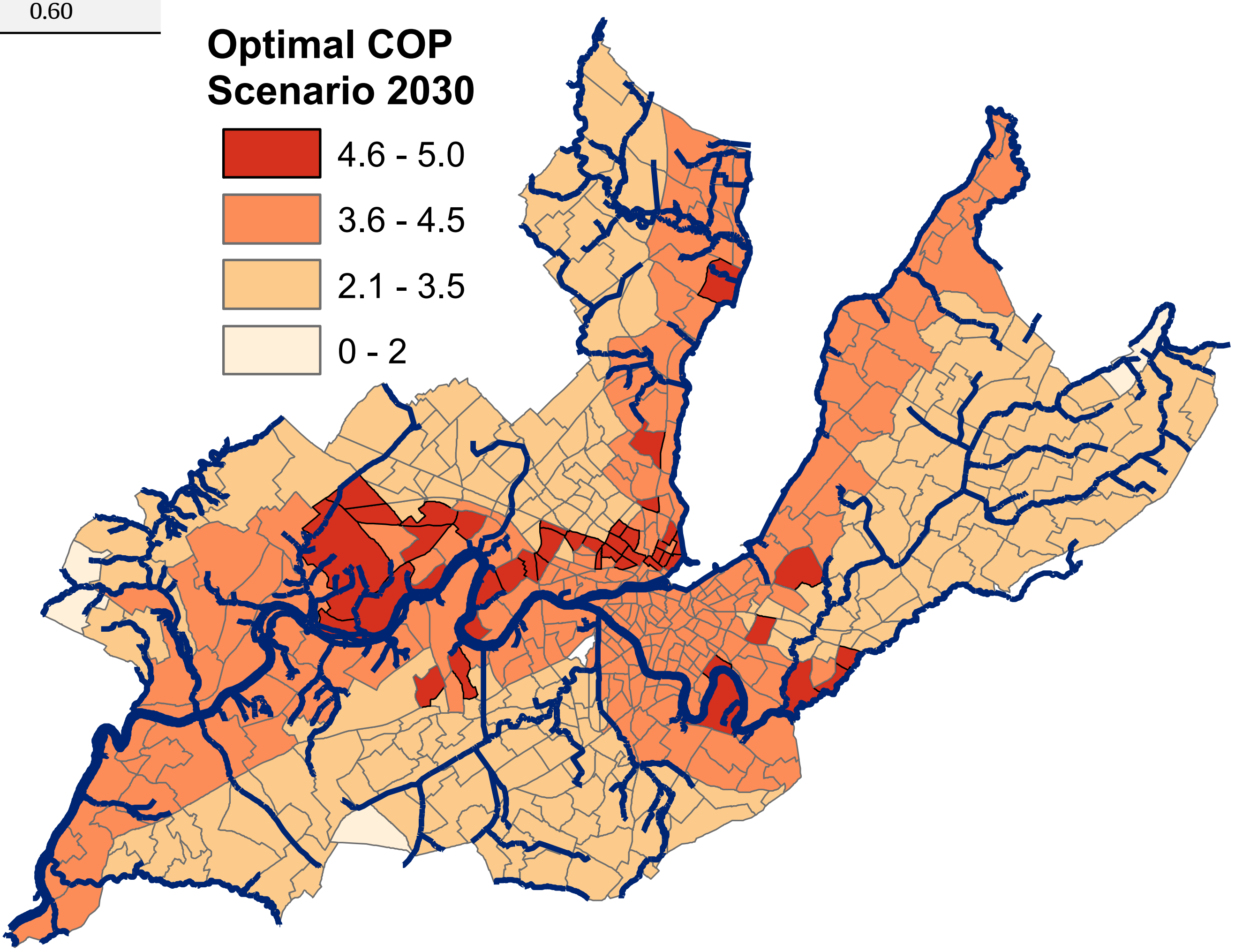
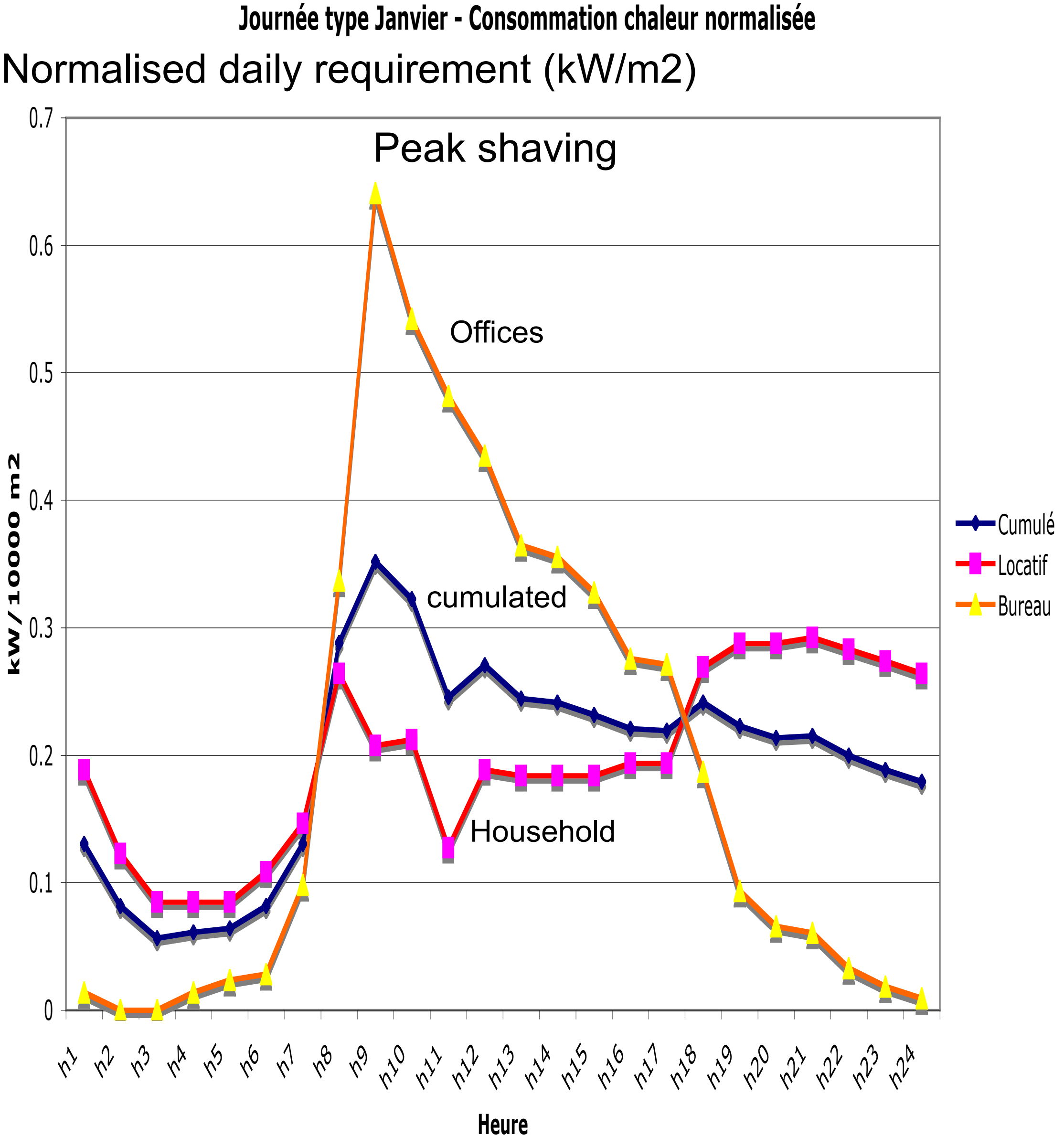


Fig. 13. COP map considering the available resources for heat pumping in 2030.

District heating : infrastructure development

Heat Loss = 8% @ 100 °C
(depends on temperature)


Journée type Janvier - Consommation chaleur normalisée

Normalised daily requirement (kW/m2)

Peak shaving

Interest of district heating systems

- **Size (mutualisation)**
  - efficiency
  - cost
- **Higher technicity**
- **Energy services companies**
- **Access to local Resources**
  - Water
  - Biomass
  - Geothermal
- **Optimal Management**
  - Peak shaving
  - Market

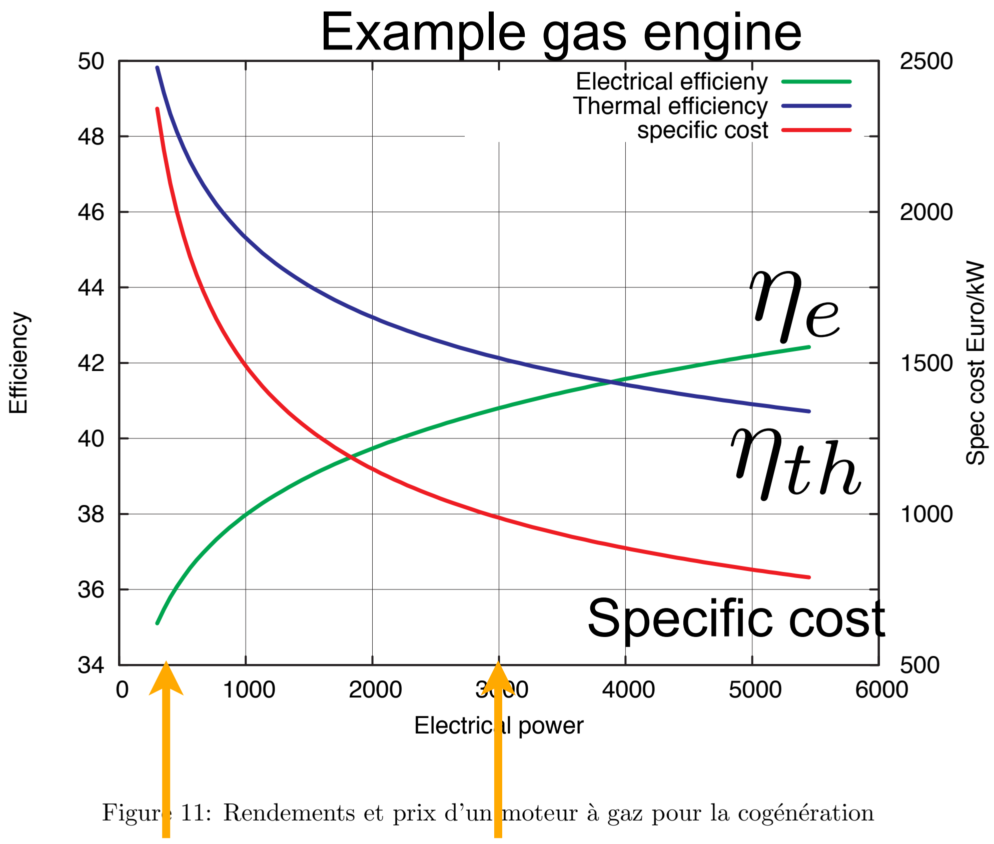
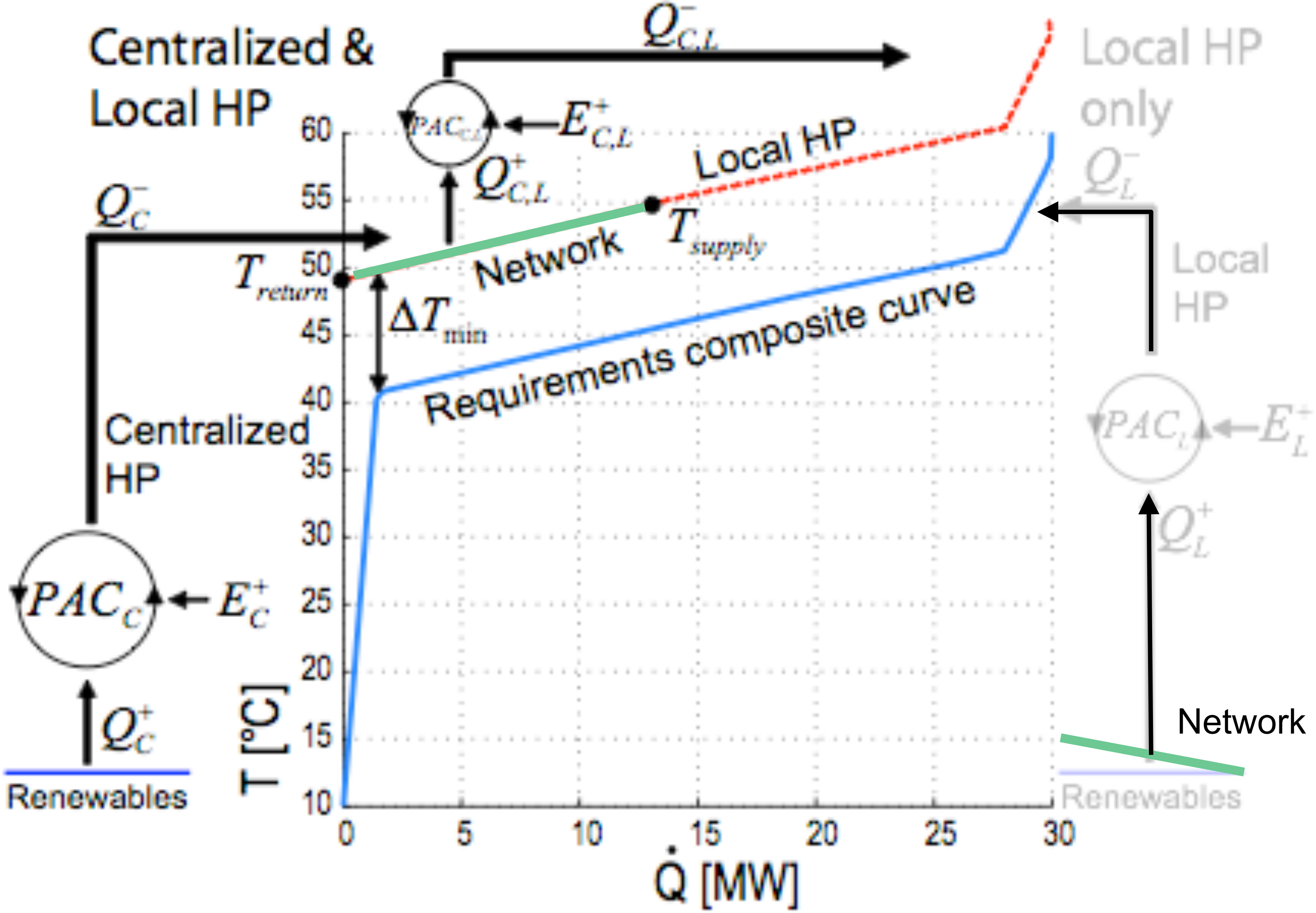


Figure 11: Rendements et prix d'un moteur à gaz pour la cogénération

Building

District heating

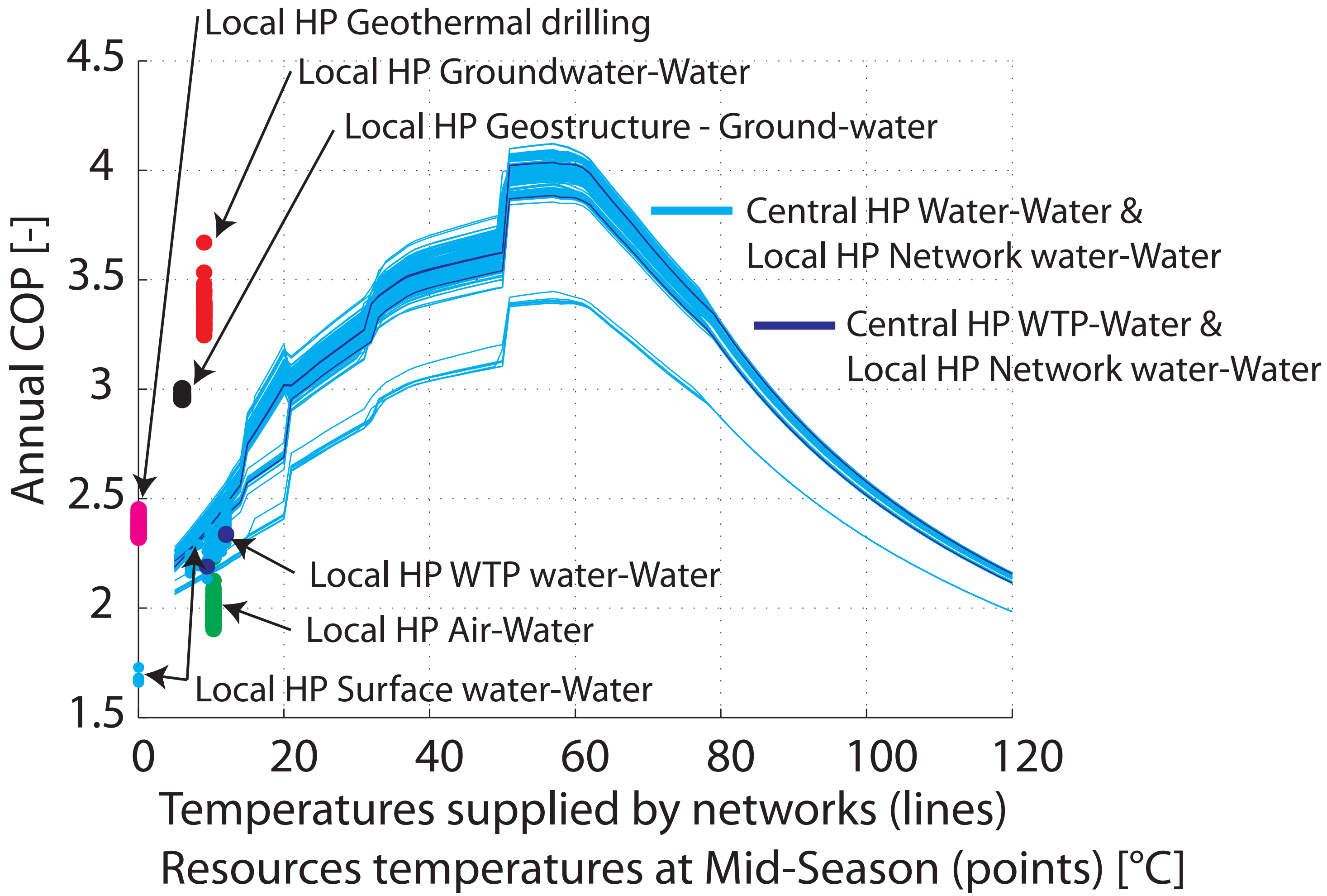
District heating



What is the temperature of the network

Temeprature of the heat distribution

Heat pump integration



Heat distribution cost : cts CHF/annual kWh

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

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

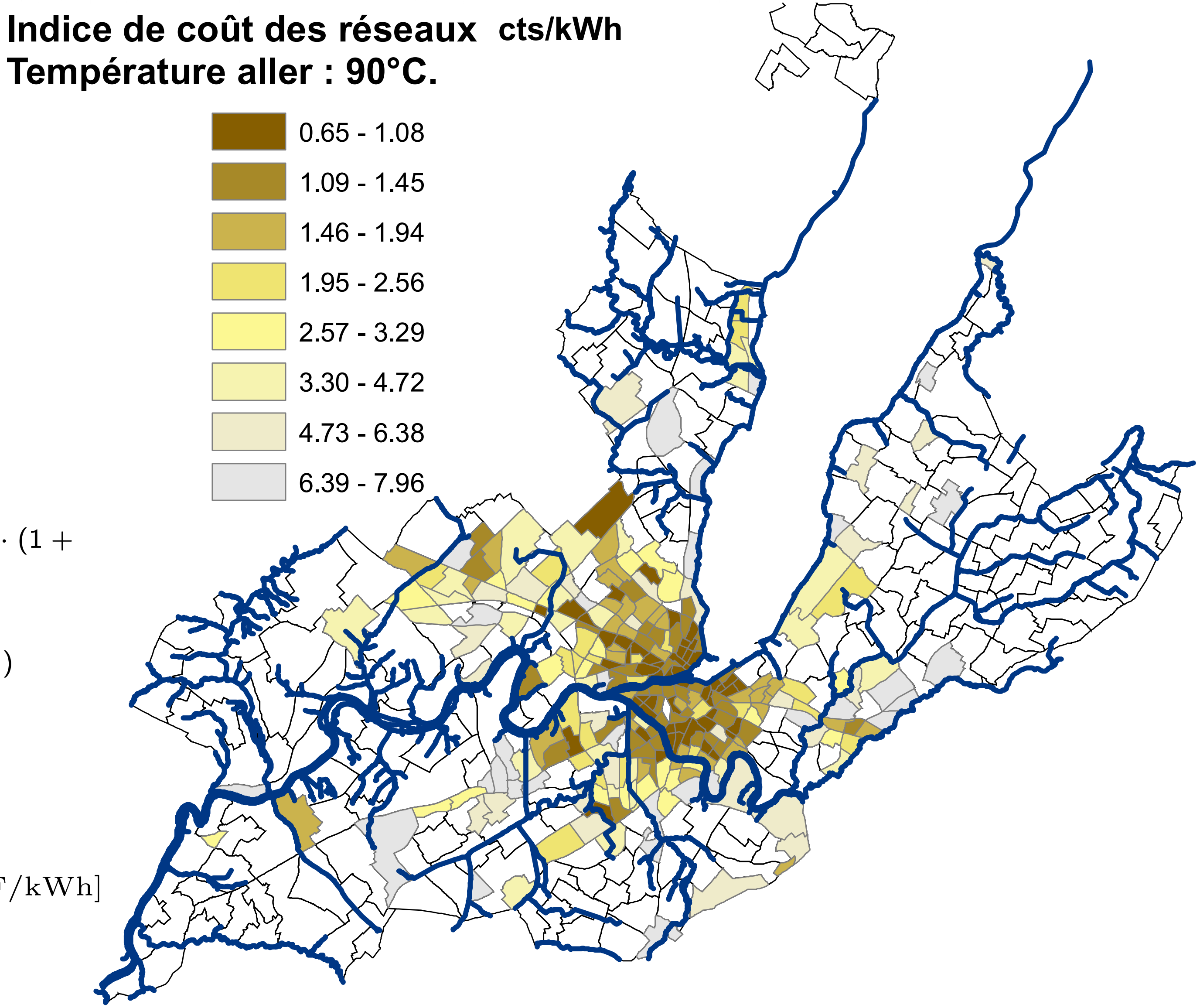
$$T^*_{supply} = T_{return} + (T_{supply} - T_{return}) \cdot (1 + f_{loss,ref}\frac{T_{supply} - T_{ground}}{T_{ref} - T_{ground}})$$

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

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

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

$c_1 = 7047\ CHF/m^2$ $\qquad$ $c_2 = 752.8\ CHF/m$



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

Table 4.1: Typical cost of network pipes, for diameters between 25mm and 300mm.

Parameters	values											
pipe diameter $[mm]$	25	32	40	50	65	80	100	125	150	200	250	300
pipe cost $[CHF/m]$	950	950	1000	1200	1250	1350	1470	1600	1750	2000	2500	3000

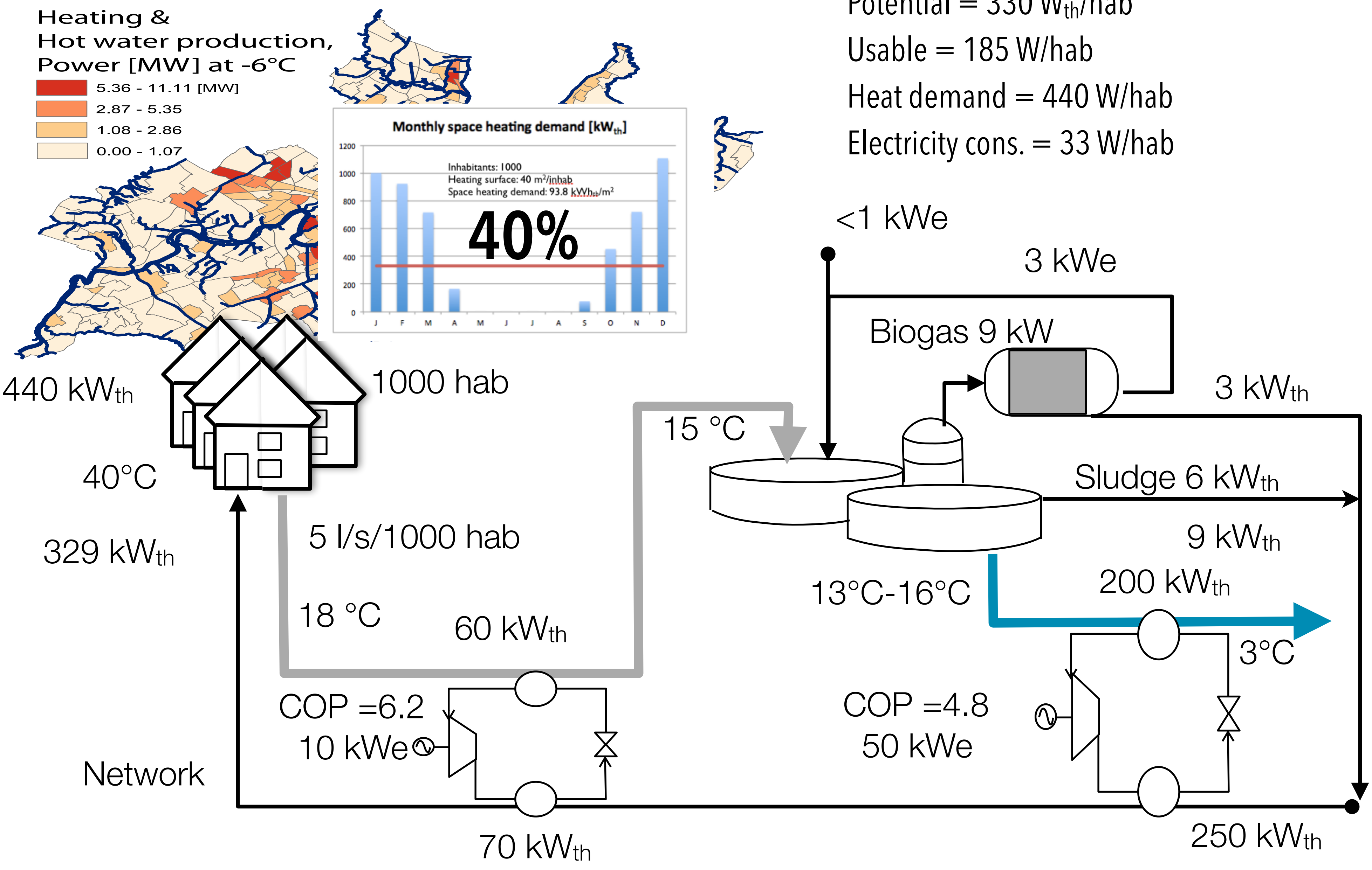
Waste water reuse District Heating Perspective

Potential = 330 W$_{th}$/hab

Usable = 185 W/hab

Heat demand = 440 W/hab

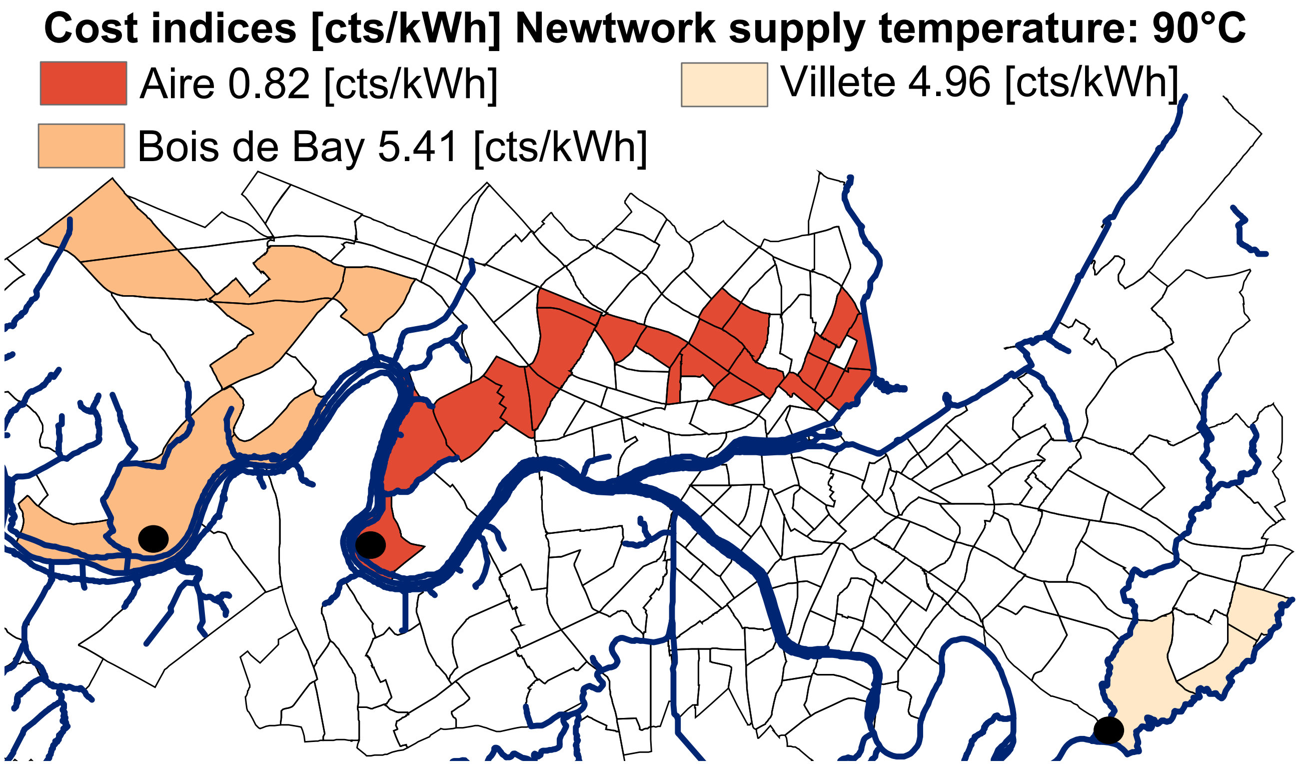
Electricity cons. = 33 W/hab



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

Matching resources and demands

- Define the influence zone of a limited resource
  - e.g. waste water treatment plant
- Calculate the heat distribution cost



- Covered area
- Temperature level
- Heat load density
- Future demand
- Efficiency

Reference: Girardin et al., A geographical information based system for the evaluation of integrated energy conversion systems in urban areas, ECOS 2008

Producing Electricity & CO2 compensation

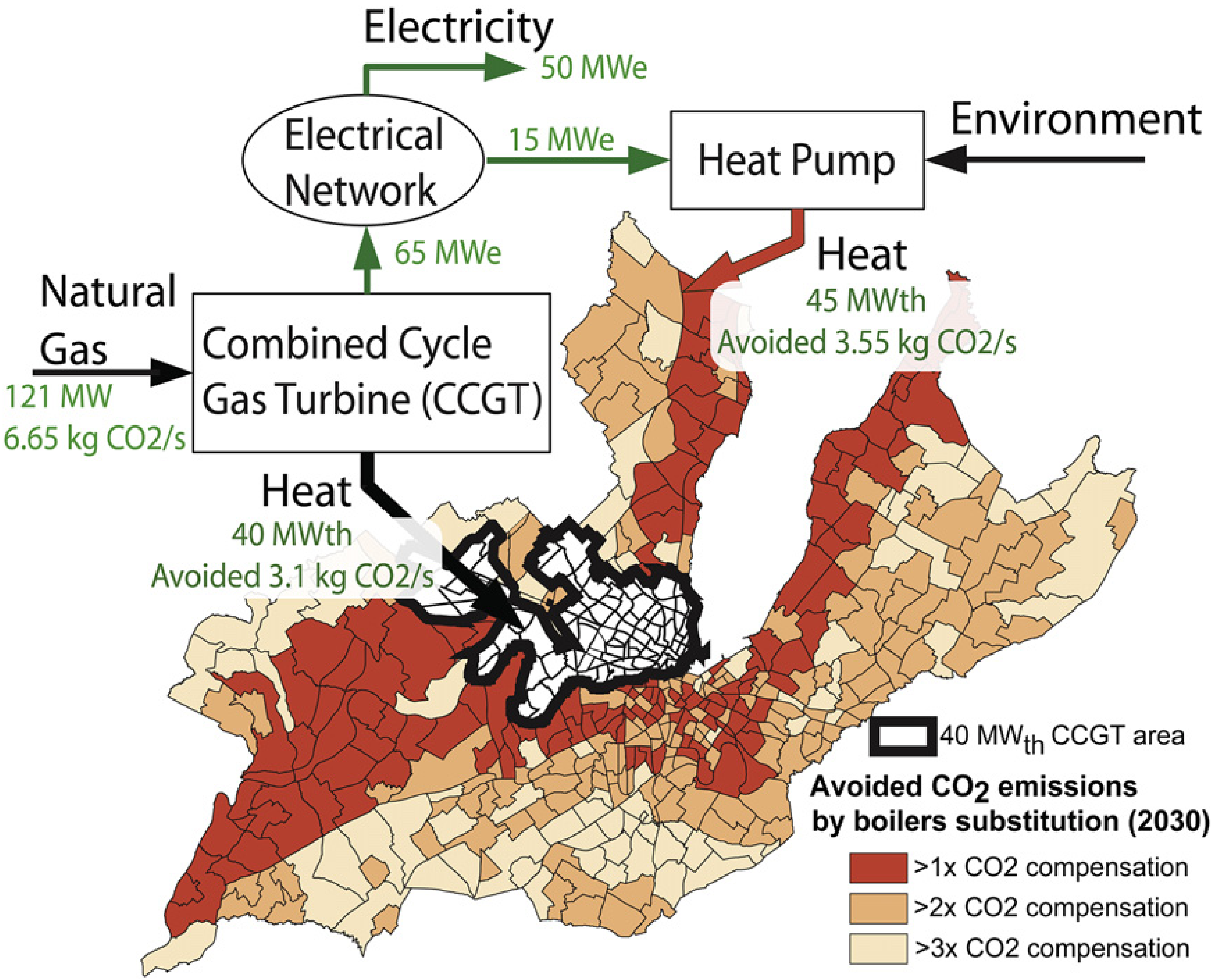
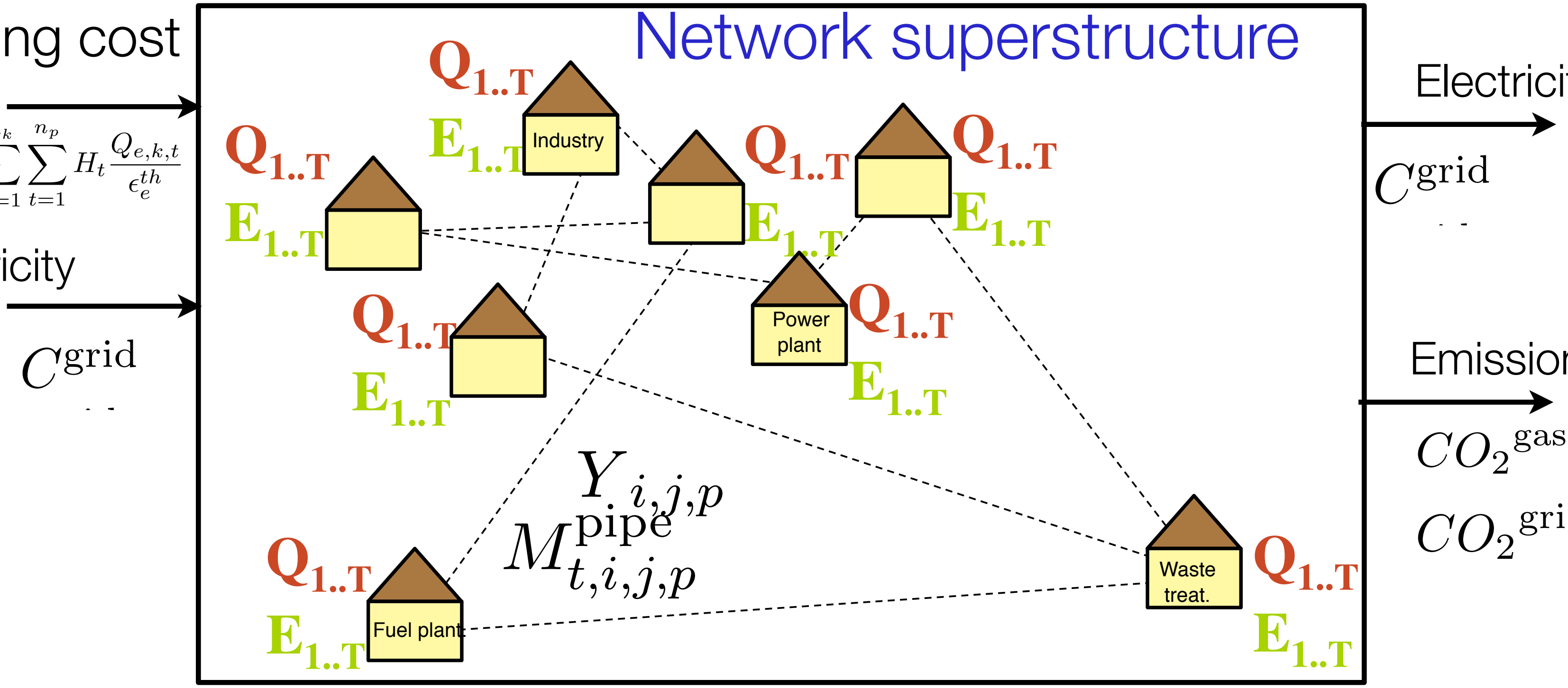


Fig. 15. Combined heat pumping and combined cycle option in the district.

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 ?



Operating cost

Gas

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

Electricity

C^{grid}

Electricity

C^{grid}

Emissions

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

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

Investment

C^{pipes}

Maintenance

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

[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.

Superstructure slave optimization model

$$\min \sum_{s} \mathrm{OPEX}(\overbrace{y_s, y_{s,p}}^{\text{On/off states}}, \underbrace{u_s, u_{s,p}}_{\text{Op. utilization levels}}) + \sum_{p=1}^{N_P} (\underset{\text{Total impacts}}{i_p} \times \overset{\text{CO}_2\text{-eq tax}}{t_{CO_2}} \times \triangle p)$$

Layers

Local balancing layers(L_{bl})

Power / material streams $\longrightarrow$

$\dot{E}^{+/-}_{g,L_{bl},s_e,p}$ $\dot{M}^{+/-}_{g,L_{bl},s_f,p}$

Global balancing layers (L_{bg})

Power / material streams $\longrightarrow$

$\dot{E}^{+/-}_{g,L_{bg},s_e,p}$ $\dot{M}^{+/-}_{g,L_{bg},s_f,p}$

- ❖ *Transportation*
- ✓ *Material flows*
- ✓ *Trade-off between transportation systems*

Heat cascading layer (L_h)

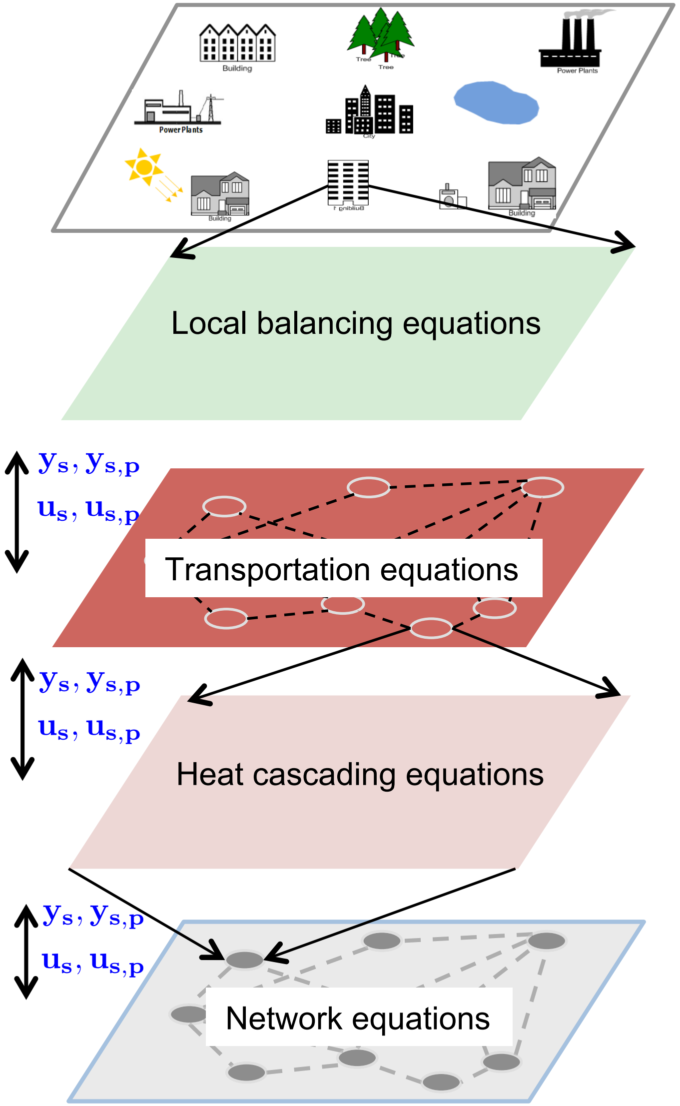
Hot & cols streams $\longrightarrow$

$\dot{Q}^{+/-}_{g,L_h,s_{j/i},p}$

- ✓ *Heat cascade restriction*

❖ *Distribution network*

- ✓ *Layout (GIS)*
- ✓ *Operating schedule*
- ✓ *Fluid type*
- ✓ *Heat flows*



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

Networks

- Local district heating networks
- Global district heating networks

Services

Energy services

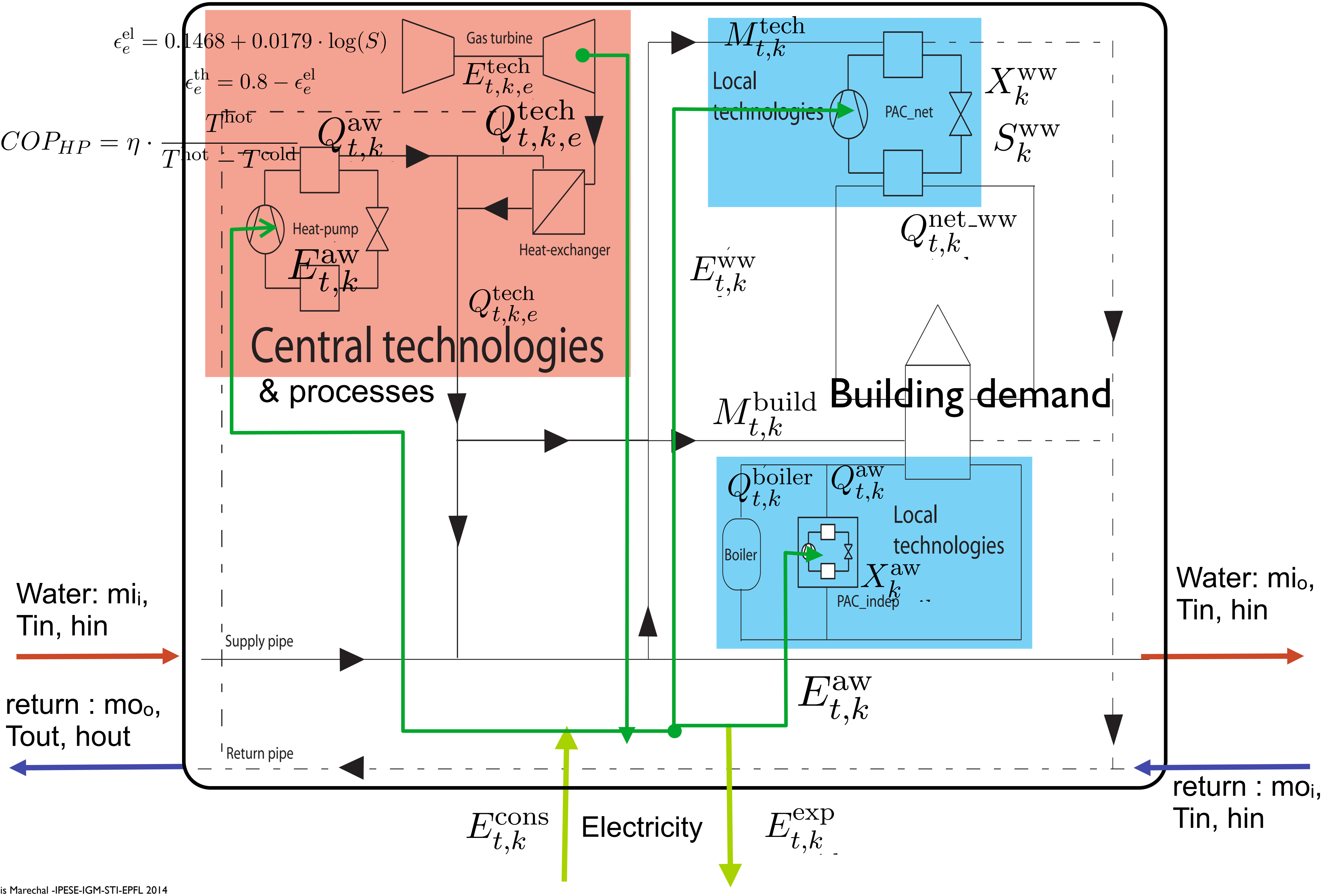
- Space heating
- Domestic hot water
- Electricity

Each node is a process with network connections

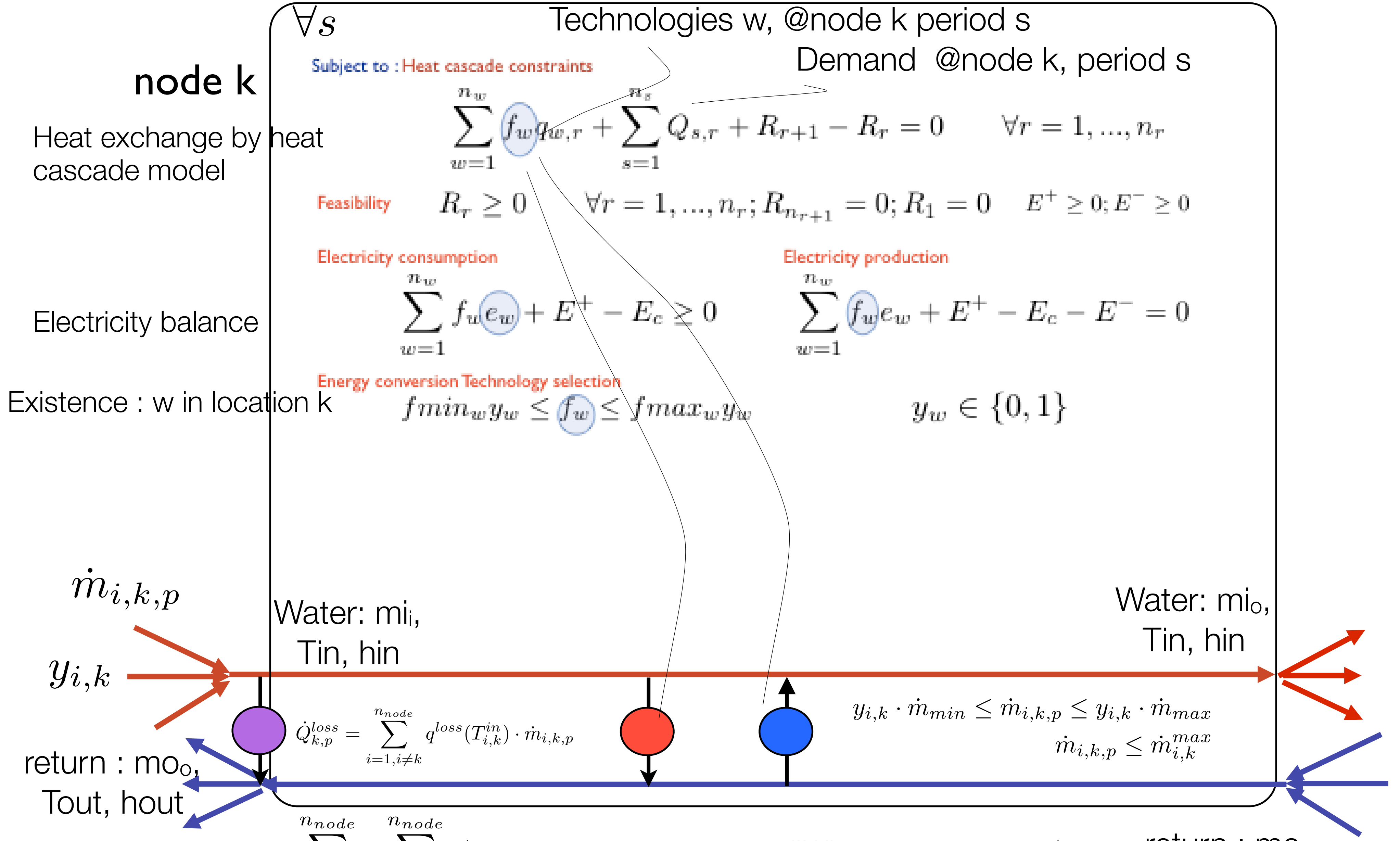
$$\epsilon_e^{el} = 0.1468 + 0.0179 \cdot \log(S)$$

$$\epsilon_e^{th} = 0.8 - \epsilon_e^{el}$$

$$COP_{HP} = \eta \cdot \frac{T^{hot}}{T^{hot} - T^{cold}}$$



Heat storage model



$\forall s$

Technologies w, @node k period s

Demand @node k, period s

node k

Heat exchange by heat cascade model

Subject to : Heat cascade constraints

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

Feasibility

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

Electricity balance

Electricity consumption

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

Electricity production

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

Existence : w in location k

Energy conversion Technology selection

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

$\dot{m}_{i,k,p}$

$y_{i,k}$

Water: mi_i, Tin, hin

Water: mi_o, Tin, hin

$$\dot{Q}^{loss}_{k,p} = \sum_{i=1, i \neq k}^{n_{node}} q^{loss}(T^{in}_{i,k}) \cdot \dot{m}_{i,k,p}$$

$$y_{i,k} \cdot \dot{m}_{min} \leq \dot{m}_{i,k,p} \leq y_{i,k} \cdot \dot{m}_{max}$$

$$\dot{m}_{i,k,p} \leq \dot{m}^{max}_{i,k}$$

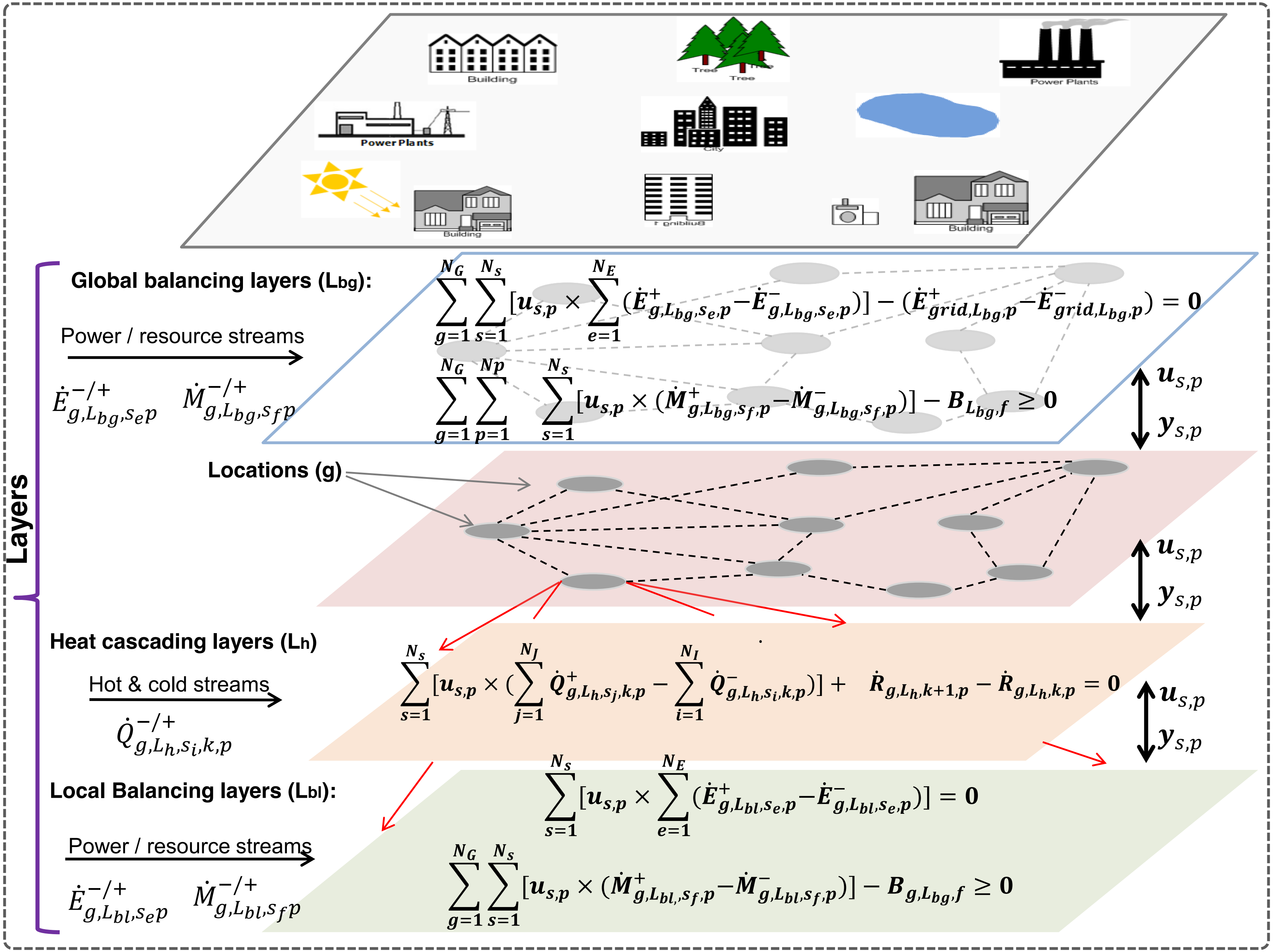
return : mo_o, Tout, hout

return : mo_i, Tin, hin

$$Cost_{pipe} = \sum_{i=1, i \neq k}^{n_{node}} \sum_{k=1, k \neq i}^{n_{node}} (y_{i,k} \cdot cf_{pipe} \cdot length_{i,k} + \dot{m}^{max}_{i,k} \cdot cd_{pipe} \cdot length_{i,k})$$

$$\dot{E}_{pump,i,k,p} = y_{i,k} \cdot e^0_{pipe} \cdot length_{i,k} + \dot{m}_{i,k,p} \cdot e^1_{pipe,i,k}$$

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



Layers

Global balancing layers (Lbg):

Power / resource streams

$\dot{E}^{-/+}_{g,L_{bg},s_e p}$ $\dot{M}^{-/+}_{g,L_{bg},s_f p}$

$$\sum_{g=1}^{N_G}\sum_{s=1}^{N_s}[u_{s,p}\times\sum_{e=1}^{N_E}(\dot{E}^{+}_{g,L_{bg},s_e,p}-\dot{E}^{-}_{g,L_{bg},s_e,p})]-(\dot{E}^{+}_{grid,L_{bg},p}-\dot{E}^{-}_{grid,L_{bg},p})=0$$

$$\sum_{g=1}^{N_G}\sum_{p=1}^{Np}\sum_{s=1}^{N_s}[u_{s,p}\times(\dot{M}^{+}_{g,L_{bg},s_f,p}-\dot{M}^{-}_{g,L_{bg},s_f,p})]-B_{L_{bg},f}\geq 0$$

$u_{s,p}$ $y_{s,p}$

Locations (g)

$u_{s,p}$ $y_{s,p}$

Heat cascading layers (Lh)

Hot & cold streams

$\dot{Q}^{-/+}_{g,L_h,s_i,k,p}$

$$\sum_{s=1}^{N_s}[u_{s,p}\times(\sum_{j=1}^{N_J}\dot{Q}^{+}_{g,L_h,s_j,k,p}-\sum_{i=1}^{N_I}\dot{Q}^{-}_{g,L_h,s_i,k,p})]+\dot{R}_{g,L_h,k+1,p}-\dot{R}_{g,L_h,k,p}=0$$

$u_{s,p}$ $y_{s,p}$

Local Balancing layers (Lbl):

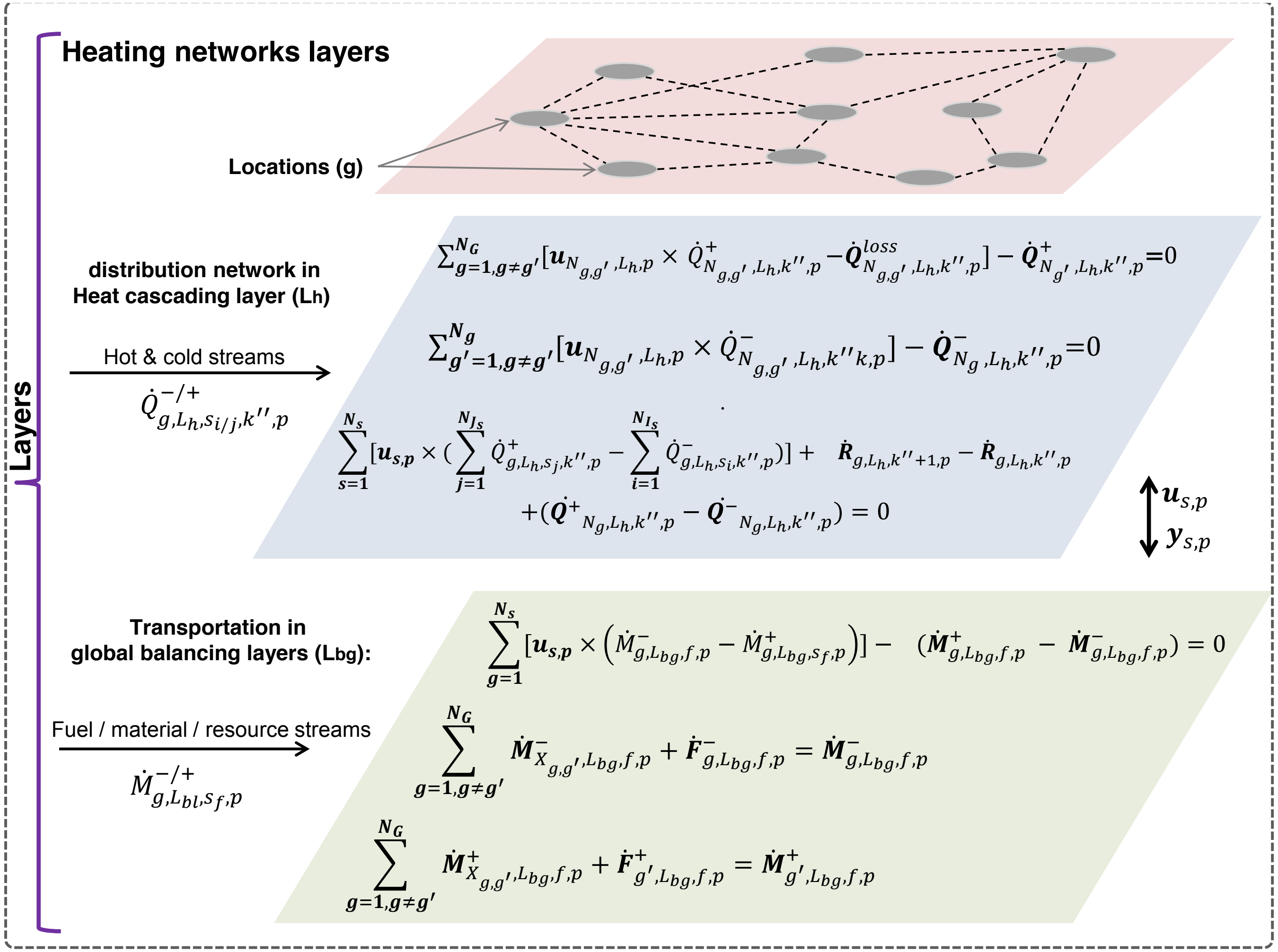
Power / resource streams

$\dot{E}^{-/+}_{g,L_{bl},s_e p}$ $\dot{M}^{-/+}_{g,L_{bl},s_f p}$

$$\sum_{s=1}^{N_s}[u_{s,p}\times\sum_{e=1}^{N_E}(\dot{E}^{+}_{g,L_{bl},s_e,p}-\dot{E}^{-}_{g,L_{bl},s_e,p})]=0$$

$$\sum_{g=1}^{N_G}\sum_{s=1}^{N_s}[u_{s,p}\times(\dot{M}^{+}_{g,L_{bl,},s_f,p}-\dot{M}^{-}_{g,L_{bl},s_f,p})]-B_{g,L_{bg},f}\geq 0$$

District heating supestructure



Heating networks layers

distribution network in Heat cascading layer (Lh)

Hot & cold streams

$\dot{Q}^{-/+}_{g,L_h,s_{i/j},k'',p}$

$$\sum_{g=1,g\neq g'}^{N_G}[u_{N_{g,g'},L_h,p} \times \dot{Q}^{+}_{N_{g,g'},L_h,k'',p} - \dot{Q}^{loss}_{N_{g,g'},L_h,k'',p}] - \dot{Q}^{+}_{N_{g'},L_h,k'',p} = 0$$

$$\sum_{g'=1,g\neq g'}^{N_g}[u_{N_{g,g'},L_h,p} \times \dot{Q}^{-}_{N_{g,g'},L_h,k''k,p}] - \dot{Q}^{-}_{N_g,L_h,k'',p} = 0$$

$$\sum_{s=1}^{N_s}[u_{s,p} \times (\sum_{j=1}^{N_{J_s}} \dot{Q}^{+}_{g,L_h,s_j,k'',p} - \sum_{i=1}^{N_{I_s}} \dot{Q}^{-}_{g,L_h,s_i,k'',p})] + \dot{R}_{g,L_h,k''+1,p} - \dot{R}_{g,L_h,k'',p} + (\dot{Q}^{+}{}_{N_g,L_h,k'',p} - \dot{Q}^{-}{}_{N_g,L_h,k'',p}) = 0$$

$u_{s,p}$ ↕ $y_{s,p}$

Transportation in global balancing layers (Lbg):

Fuel / material / resource streams

$\dot{M}^{-/+}_{g,L_{bl},s_f,p}$

$$\sum_{g=1}^{N_s}[u_{s,p} \times \left(\dot{M}^{-}_{g,L_{bg},f,p} - \dot{M}^{+}_{g,L_{bg},s_f,p}\right)] - (\dot{M}^{+}_{g,L_{bg},f,p} - \dot{M}^{-}_{g,L_{bg},f,p}) = 0$$

$$\sum_{g=1,g\neq g'}^{N_G} \dot{M}^{-}_{X_{g,g'},L_{bg},f,p} + \dot{F}^{-}_{g,L_{bg},f,p} = \dot{M}^{-}_{g,L_{bg},f,p}$$

$$\sum_{g=1,g\neq g'}^{N_G} \dot{M}^{+}_{X_{g,g'},L_{bg},f,p} + \dot{F}^{+}_{g',L_{bg},f,p} = \dot{M}^{+}_{g',L_{bg},f,p}$$

Routing algorithm

Virtua power plant

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

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

Subject to : Heat cascade constraints

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

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

Electricity consumption

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

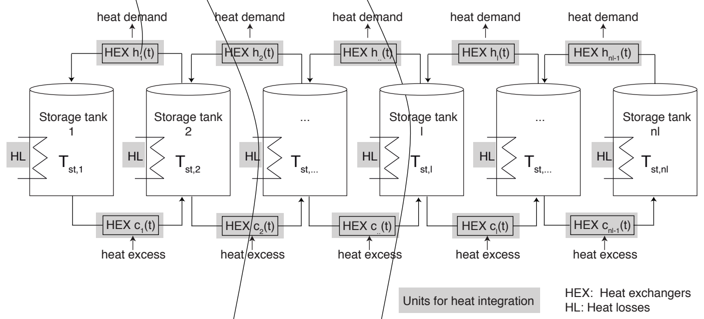
Electricity production

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

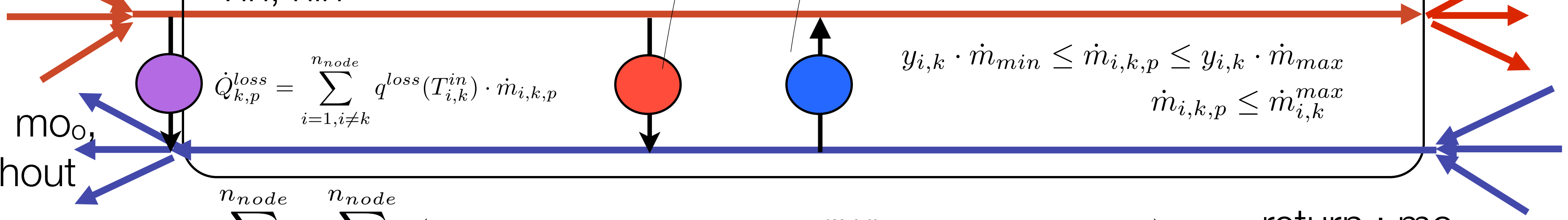
Energy conversion Technology selection

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

Storage system



Buildings inertia
Batteries



$\dot{m}_{i,k,p}$

$y_{i,k}$

Water: mi_i,
Tin, hin

Water: mi_o,
Tin, hin

return : mo_o,
Tout, hout

$$\dot{Q}^{loss}_{k,p} = \sum_{i=1, i \neq k}^{n_{node}} q^{loss}(T^{in}_{i,k}) \cdot \dot{m}_{i,k,p}$$

$$y_{i,k} \cdot \dot{m}_{min} \leq \dot{m}_{i,k,p} \leq y_{i,k} \cdot \dot{m}_{max}$$

$$\dot{m}_{i,k,p} \leq \dot{m}^{max}_{i,k}$$

return : mo_i,
Tin, hin

$$Cost_{pipe} = \sum_{i=1, i \neq k}^{n_{node}} \sum_{k=1, k \neq i}^{n_{node}} (y_{i,k} \cdot cf_{pipe} \cdot length_{i,k} + \dot{m}^{max}_{i,k} \cdot cd_{pipe} \cdot length_{i,k})$$

$$\dot{E}_{pump,i,k,p} = y_{i,k} \cdot e^0_{pipe} \cdot length_{i,k} + \dot{m}_{i,k,p} \cdot e^1_{pipe,i,k}$$

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

Storage tank model

Storage tank Model

$$\sum_{t=1}^{nt}(cf_{hs}\cdot d_{p,t}\sum_{l=1}^{nl}(\sum_{h_l=1}^{ns_{h,l}}\boldsymbol{f_{u,p,t}}\dot{M}_{h,l,u,p,t}-\sum_{c_l=1}^{ns_{c,l}}\boldsymbol{f_{u,p,t}}\dot{M}_{c,l,u,p,t}))=0 \tag{13}$$

$$\begin{aligned}\boldsymbol{M_{l,p,t}}=\boldsymbol{M_{0,l}}+\sum_{t=1}^{t}(cf_{hs}\cdot d_{p,t}\sum_{l=1}^{nl}(\sum_{h_l=1}^{ns_{h,l}}\boldsymbol{f_{u,p,t}}\dot{M}_{h,l,u,p,t}-\sum_{c_l=1}^{ns_{c,l}}\boldsymbol{f_{u,p,t}}\dot{M}_{c,l,u,p,t}))\\ \forall l=1...,nl\quad\forall t=1...,nt\end{aligned} \tag{14}$$

$$\boldsymbol{M_{l,p,t}}>0\qquad\boldsymbol{M_{0,l}}>0\qquad\forall l=1...,nl\quad\forall t=1...,nt \tag{15}$$

$$\sum_{l=1}^{nl}\boldsymbol{M_{l,t}}<M_{tot}\qquad\sum_{l=1}^{nl}\boldsymbol{M_{0,l}}<M_{tot}\qquad\forall l=1...,nl\quad\forall t=1...,nt \tag{16}$$

$$\begin{aligned}\boldsymbol{M_{0,l}}+\sum_{t=1}^{t}(cf_{hs}\cdot d_{p,t}\sum_{l=1}^{nl}(\sum_{h_l=1}^{ns_{h,l}}\boldsymbol{f_{u,t}}\dot{M}_{h,l,u,p,t}))\\ -\sum_{t=1}^{t-1}(cf_{hs}\cdot d_{p,t}\sum_{l=1}^{nl}(\sum_{h_l=1}^{ns_{c,l}}\boldsymbol{f_{u,p,t}}\dot{M}_{c,l,u,p,t}))-\boldsymbol{M_{l,p,t}}\geq 0\quad\forall l=1...,nl\quad\forall t=1...,nt\end{aligned} \tag{17}$$

$$\dot{Q}_{c,l}=\boldsymbol{f_{u,p,t}}\cdot\dot{M}_{c,l,u,p,t}\cdot c_p\cdot(T_{st,l+1}-T_{st,l}) \tag{18}$$

$$\dot{Q}_{h,l}=\boldsymbol{f_{u,p,t}}\cdot\dot{M}_{h,l,u,p,t}\cdot c_p\cdot(T_{st,l}-T_{st,l+1}) \tag{19}$$

Heat losses in storage tanks

$$\dot{Q}_{hl,l,p,t}=k_{hl}\cdot\frac{f_{hl}\cdot 4\cdot M_{l,p,t}}{\rho\cdot d}\cdot(T_{st,l}-T_a)\qquad\forall l=1...,nl\quad\forall t=1...,nt \tag{20}$$

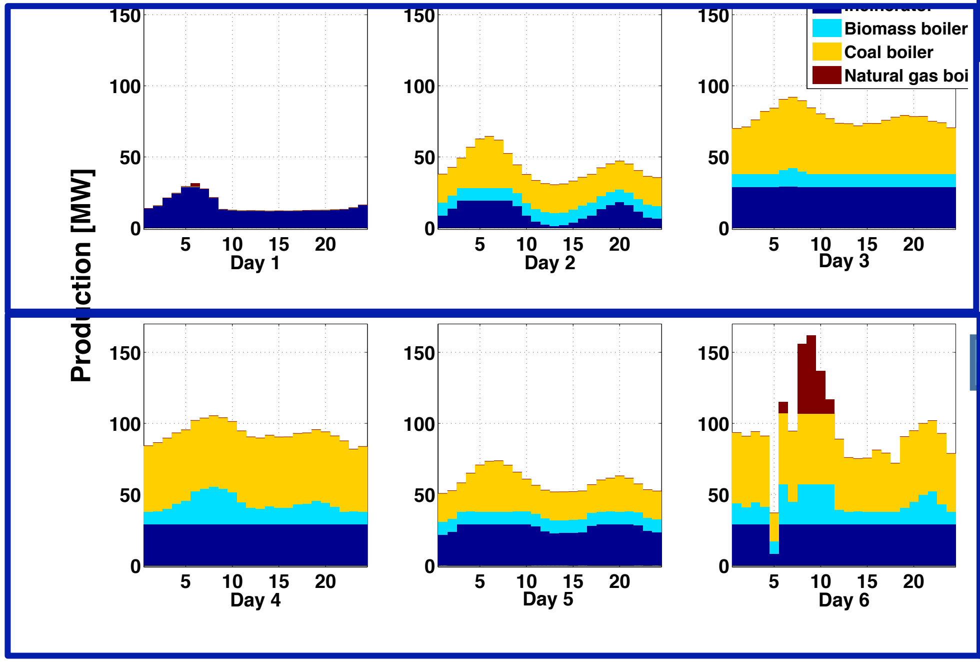
with $A=\pi\cdot d\cdot h, V=\pi\cdot\frac{d^2}{4}\cdot h$

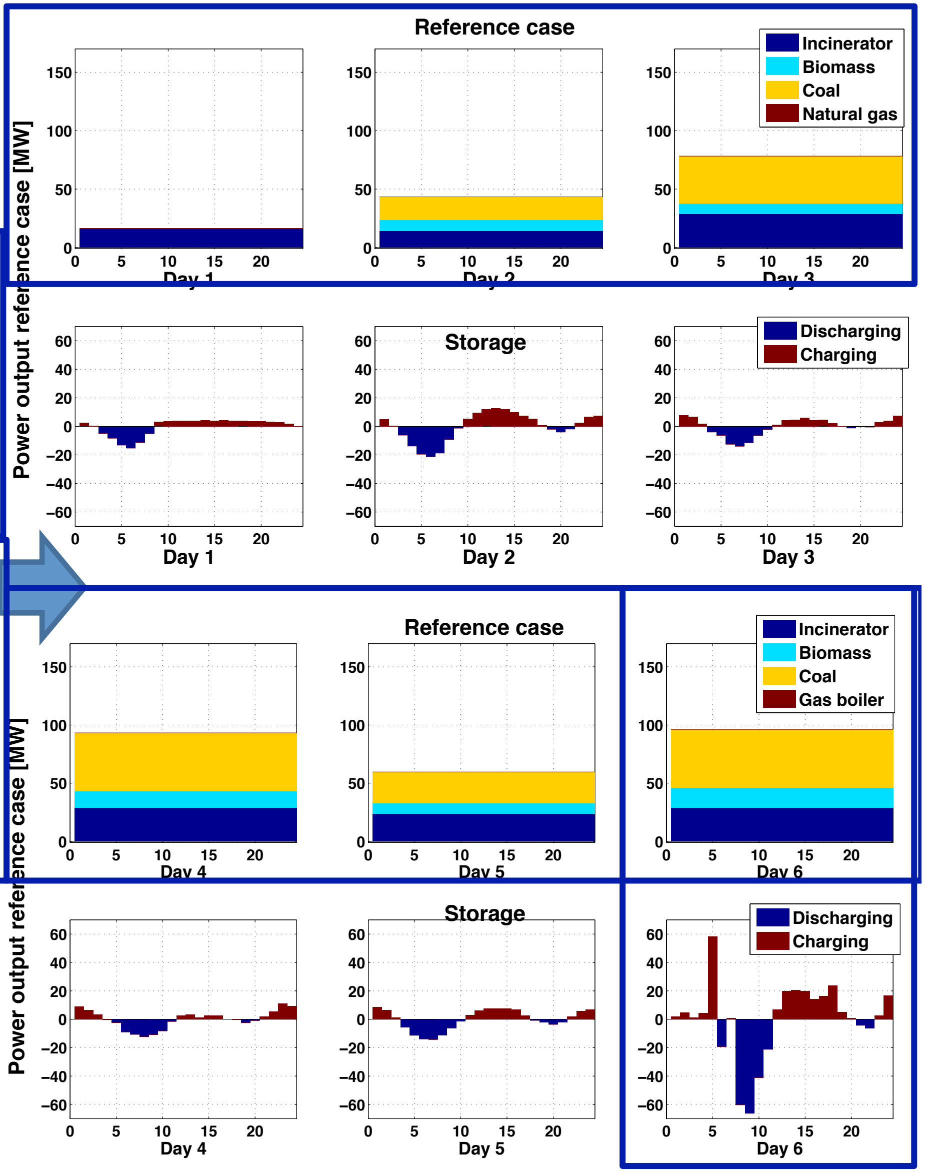
Variables

cy_p	number of cycles of period p
$d_{p,t}$	operating time of time slice t in period p
$c^+_{el,p,t}$	electricity purchase costfor time slice t in period p
$c^-_{el,p,t}$	Electrcity selling price for time slice t in period p.
$c^+_{f,p,t}$	is the fuel price for time slice t in period p.
$E^+_{f,u,p,t}$	nominal energy delivered to unit u for time slice t in period p
$\dot{E}_{el,u,p,t}$	nominal electricity demand$^{(+)}$ or excess$^{(-)}$ of unit u for time slice t in period p.
c_u	is the nominal operating cost per hour of unit u (excluding the fuel and electricity costs).
$\boldsymbol{f_{u,p,t}}$	multiplication factor of unit u for time slice t in period p
$\boldsymbol{y_{u,p,t}}$	use of unit u in time slice t in period p.
$\dot{Q}_{h,s,k,u,p,t}$	nominal heat load of hot stream h in sub-system s and temperature interval k, belonging to unit u and in time slice t.
$\boldsymbol{\dot{Q}^-_{hts(s),s,k,p,t}}$	Heat supplied to the heat transfer fluid in the temperature interval k and in time slice t)
$\boldsymbol{\dot{R}_{s,k,p,t}}$	cascaded heat to the lower temperature interval k in sub-system s.
cf_{hs}	unit conversion factor
$\dot{M}_{h,l,u,p,t}$	nominal flow-rates of the hot stream of storage tank
$\dot{M}_{c,l,u,p,t}$	nominal flowrate of the cold stream respectively in time slice t.
$\boldsymbol{M_{0,l}}$	initial water content of tank l.

comparison between storage and not inthe central plant

	Total heat demand	Incinerator (OM)	Biomass boiler	Coal boiler	Peak gas boiler
[GWh]	300	180	48.7	156	0.6





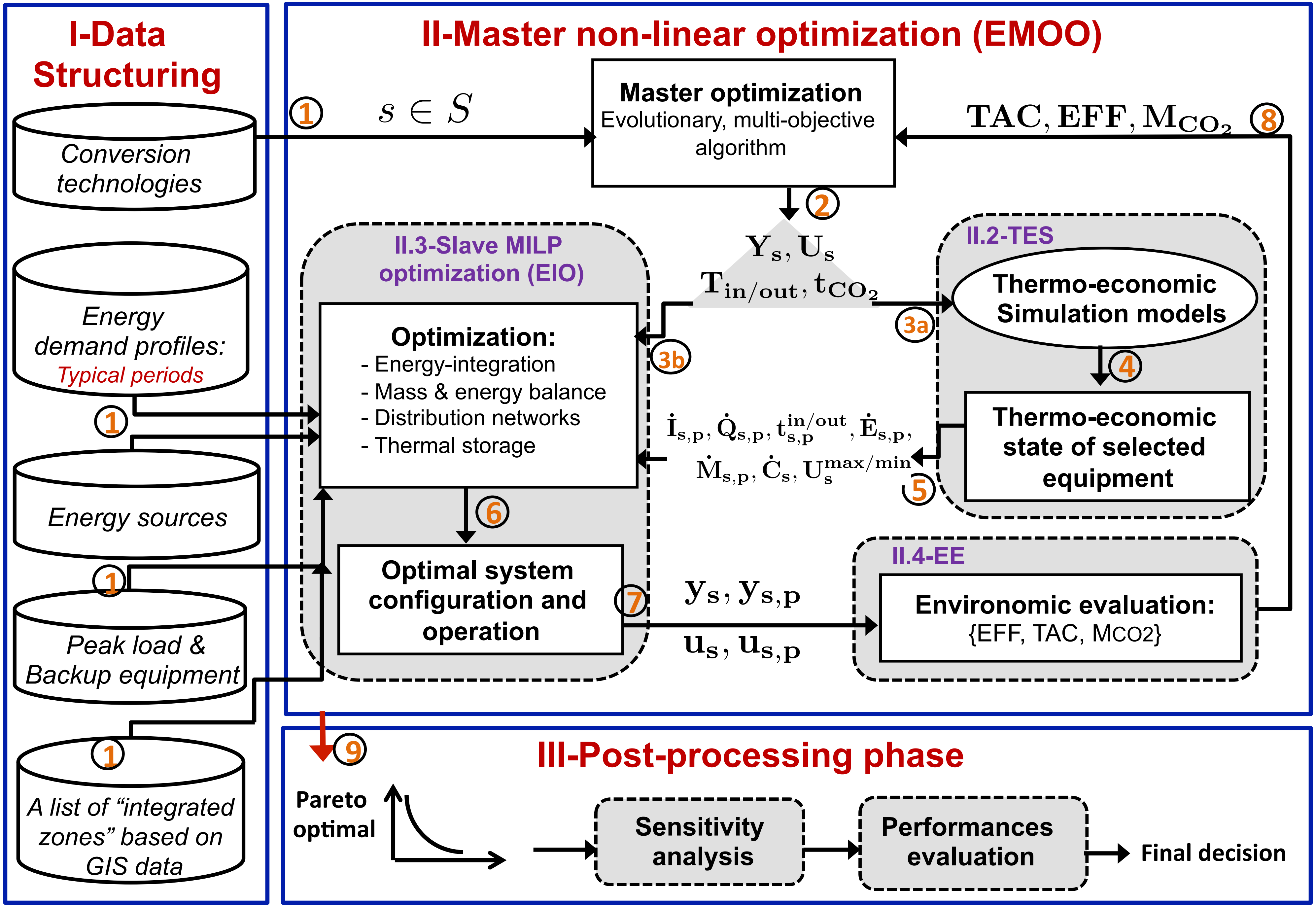
Heat cost: 51 [€/MWh]
CO_2: 197 [kg/MWh]

Heat cost: 46 [€/MWh]
CO_2: 197 [kg/MWh]

10%
Marginal inv. costs

300 [€/m^3/year]

The overall algorithm



I-Data Structuring

① *Conversion technologies*

Energy demand profiles:
Typical periods

① *Energy sources*

① *Peak load & Backup equipment*

① *A list of "integrated zones" based on GIS data*

II-Master non-linear optimization (EMOO)

① $s \in S$

Master optimization
Evolutionary, multi-objective algorithm

$\mathrm{TAC}, \mathrm{EFF}, \mathrm{M_{CO_2}}$ ⑧

② $\mathrm{Y_s}, \mathrm{U_s}$
$\mathrm{T_{in/out}}, \mathrm{t_{CO_2}}$

(3a) (3b)

II.3-Slave MILP optimization (EIO)

Optimization:
- Energy-integration
- Mass & energy balance
- Distribution networks
- Thermal storage

⑥

Optimal system configuration and operation ⑦

II.2-TES

Thermo-economic Simulation models

④

Thermo-economic state of selected equipment

$\dot{\mathrm{I}}_{\mathrm{s,p}}, \dot{\mathrm{Q}}_{\mathrm{s,p}}, \mathrm{t_{s,p}^{in/out}}, \dot{\mathrm{E}}_{\mathrm{s,p}}, \dot{\mathrm{M}}_{\mathrm{s,p}}, \dot{\mathrm{C}}_{\mathrm{s}}, \mathrm{U_s^{max/min}}$ ⑤

$\mathrm{y_s}, \mathrm{y_{s,p}}$
$\mathrm{u_s}, \mathrm{u_{s,p}}$

II.4-EE

Environomic evaluation:
{EFF, TAC, MCO2}

III-Post-processing phase

⑨

Pareto optimal

Sensitivity analysis

Performances evaluation

Final decision

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

Estimating investment cost based on reference data

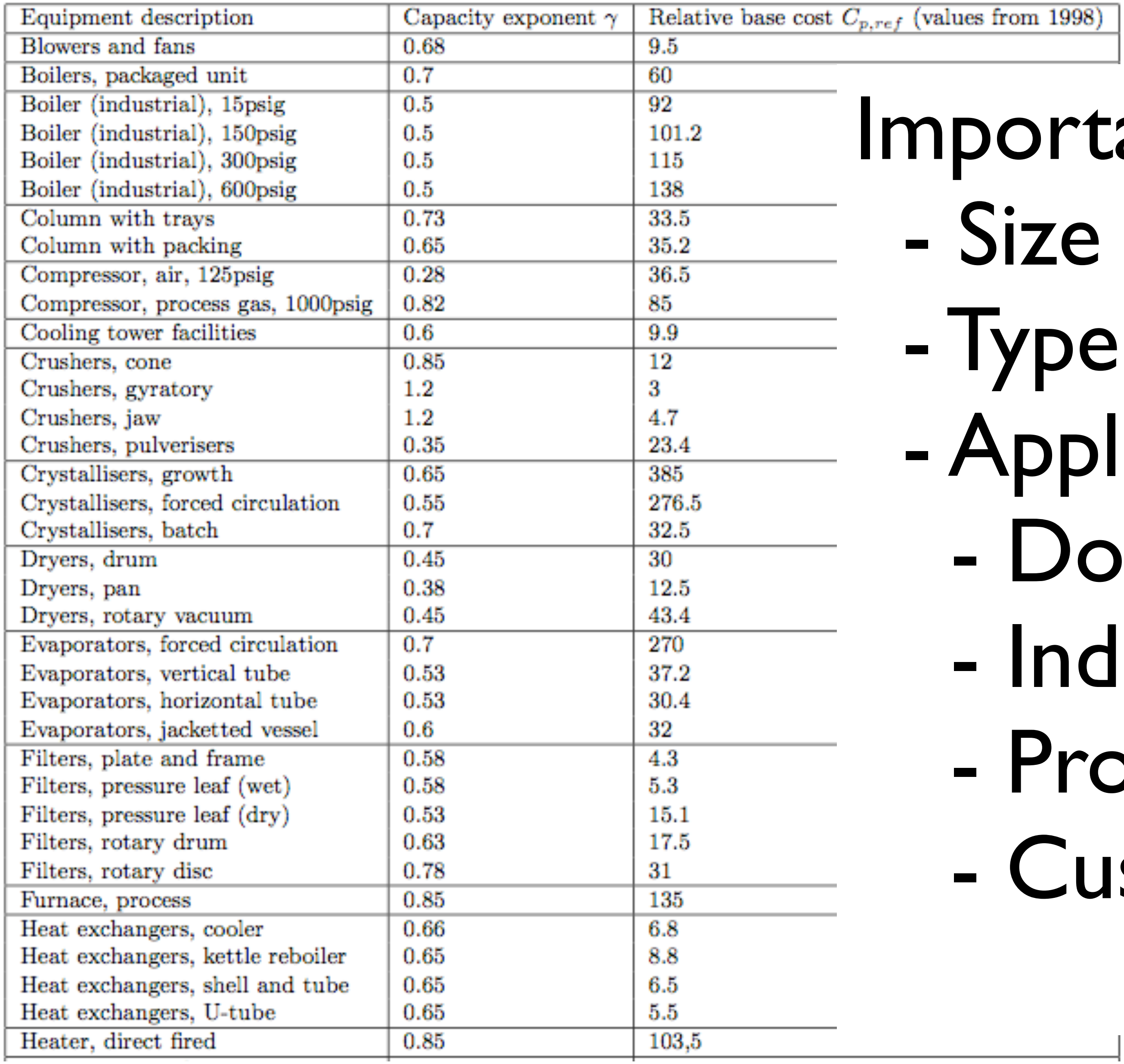
$$C_p = C_{p,ref} \cdot \left(\frac{A}{A_{ref}}\right)^{\gamma} \cdot \frac{I_t}{I_{t,ref}}$$

$C_{p,ref}$	purchase cost of the reference case
A	equipment attribute
A_{ref}	equipment reference attribute
γ	capacity exponent
$I_{t,ref}$	cost index for the reference year
I_t	cost index for the actual year

– Index :

- Marshall & Swift Equipment Cost Index
- CEPCI : Chemical Engineering Plant Cost Index

Example of data

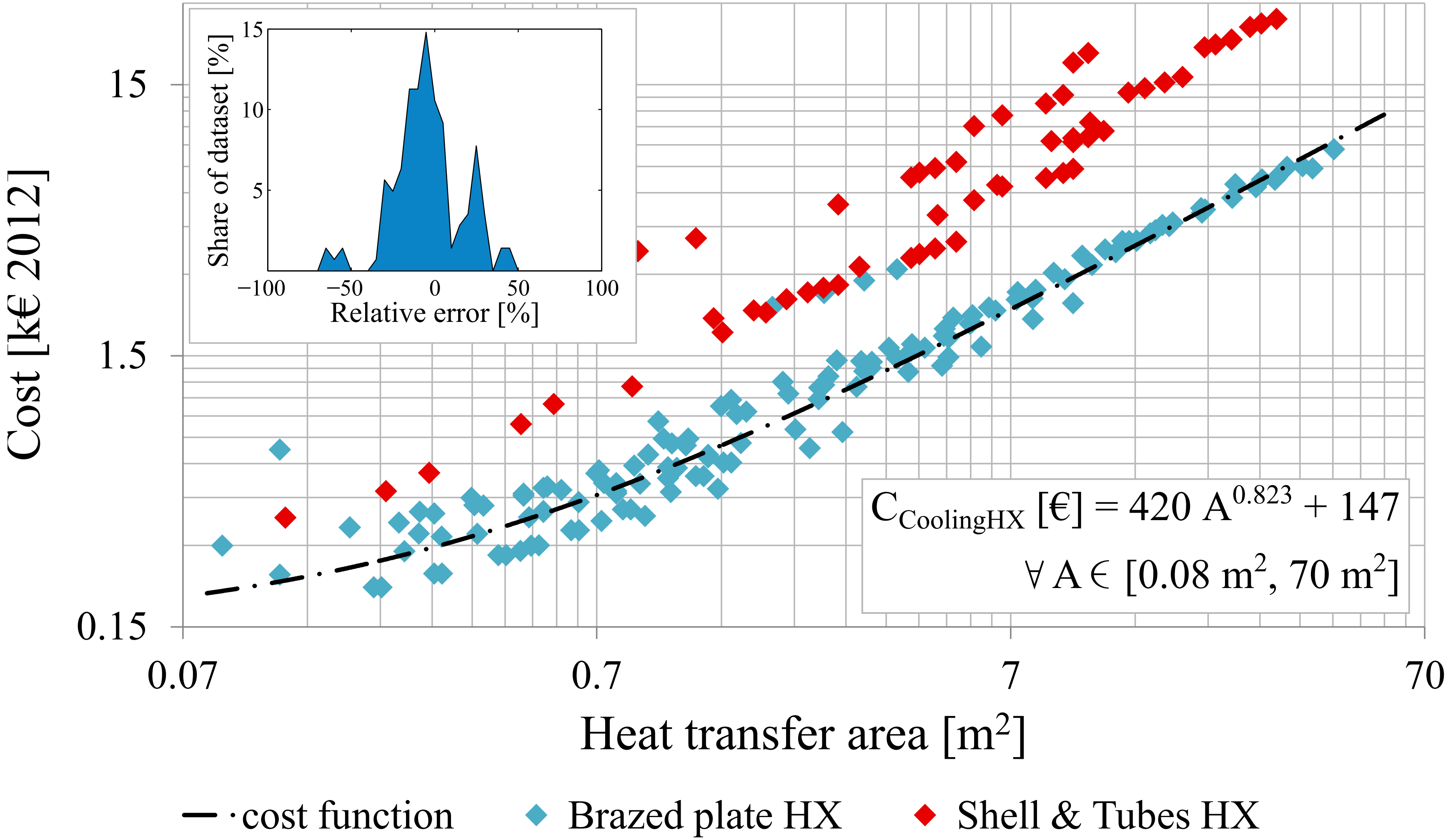


Equipment description	Capacity exponent γ	Relative base cost $C_{p,ref}$ (values from 1998)
Blowers and fans	0.68	9.5
Boilers, packaged unit	0.7	60
Boiler (industrial), 15psig	0.5	92
Boiler (industrial), 150psig	0.5	101.2
Boiler (industrial), 300psig	0.5	115
Boiler (industrial), 600psig	0.5	138
Column with trays	0.73	33.5
Column with packing	0.65	35.2
Compressor, air, 125psig	0.28	36.5
Compressor, process gas, 1000psig	0.82	85
Cooling tower facilities	0.6	9.9
Crushers, cone	0.85	12
Crushers, gyratory	1.2	3
Crushers, jaw	1.2	4.7
Crushers, pulverisers	0.35	23.4
Crystallisers, growth	0.65	385
Crystallisers, forced circulation	0.55	276.5
Crystallisers, batch	0.7	32.5
Dryers, drum	0.45	30
Dryers, pan	0.38	12.5
Dryers, rotary vacuum	0.45	43.4
Evaporators, forced circulation	0.7	270
Evaporators, vertical tube	0.53	37.2
Evaporators, horizontal tube	0.53	30.4
Evaporators, jacketted vessel	0.6	32
Filters, plate and frame	0.58	4.3
Filters, pressure leaf (wet)	0.58	5.3
Filters, pressure leaf (dry)	0.53	15.1
Filters, rotary drum	0.63	17.5
Filters, rotary disc	0.78	31
Furnace, process	0.85	135
Heat exchangers, cooler	0.66	6.8
Heat exchangers, kettle reboiler	0.65	8.8
Heat exchangers, shell and tube	0.65	6.5
Heat exchangers, U-tube	0.65	5.5
Heater, direct fired	0.85	103,5

Importance of
- Size range
- Type of materials
- Application area
  - Domestic
  - Industry
  - Production
  - Custom made

Observing the market

Cost of heat exchangers

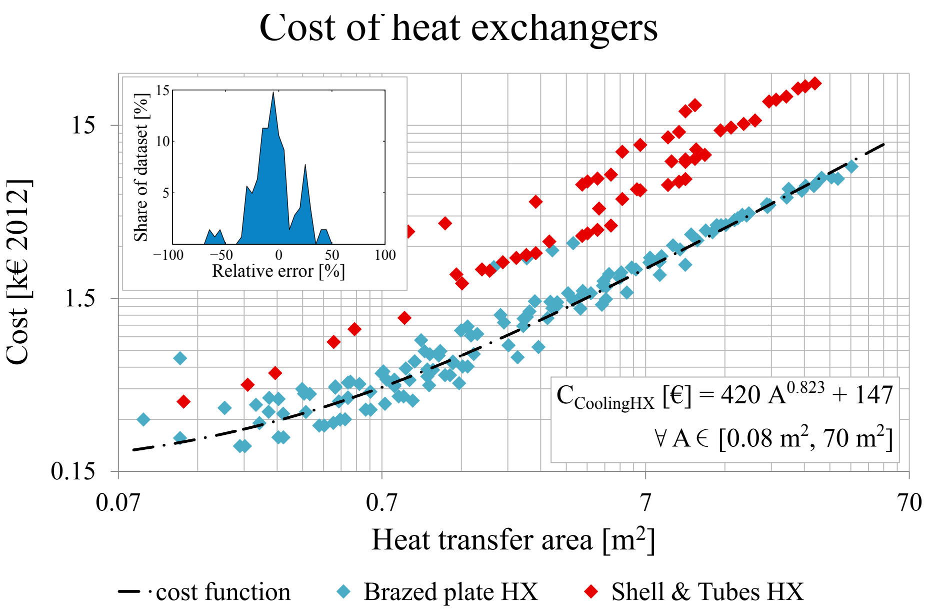


$$C_{\text{CoolingHX}}\ [€] = 420\ A^{0.823} + 147$$

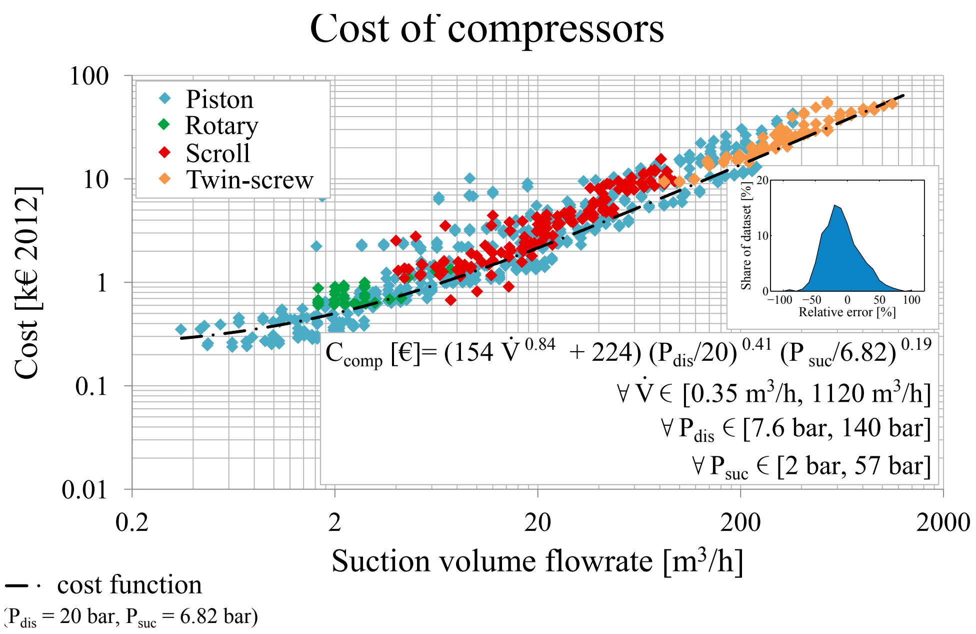
$$\forall A \in [0.08\ \text{m}^2, 70\ \text{m}^2]$$

Thesis Henchoz, 2015, Heat exchanger cost for CO2 network

Validity for the different types of technologies

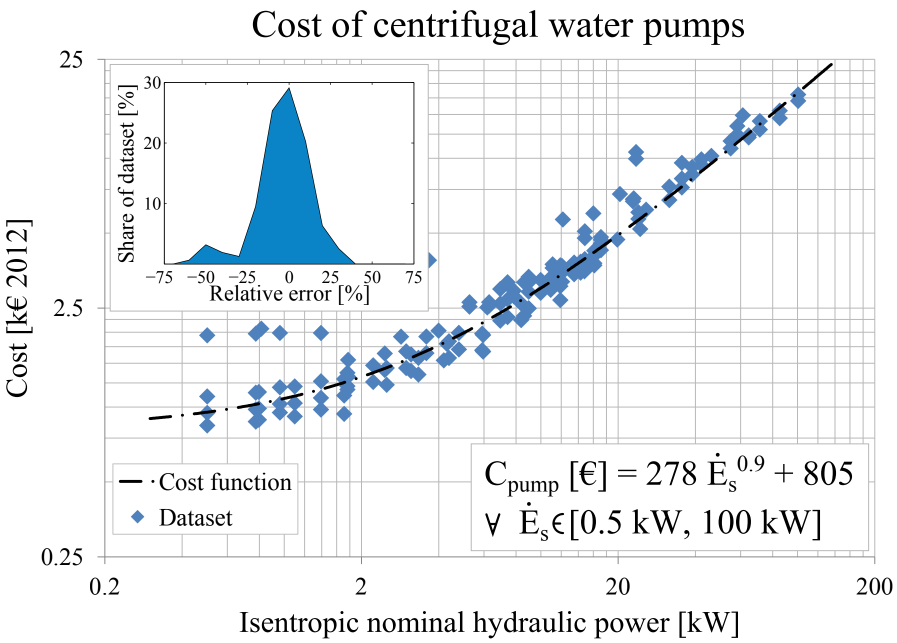

Cost of heat exchangers

$$C_{CoolingHX}\ [€] = 420\ A^{0.823} + 147$$
$$\forall\ A \in [0.08\ m^2, 70\ m^2]$$


Cost of compressors

$$C_{comp}\ [€] = (154\ \dot{V}^{0.84} + 224)\ (P_{dis}/20)^{0.41}\ (P_{suc}/6.82)^{0.19}$$
$$\forall\ \dot{V} \in [0.35\ m^3/h, 1120\ m^3/h]$$
$$\forall\ P_{dis} \in [7.6\ bar, 140\ bar]$$
$$\forall\ P_{suc} \in [2\ bar, 57\ bar]$$

(P_{dis} = 20 bar, P_{suc} = 6.82 bar)


Cost of centrifugal water pumps

$$C_{pump}\ [€] = 278\ \dot{E}_s^{0.9} + 805$$
$$\forall\ \dot{E}_s \in [0.5\ kW, 100\ kW]$$

OSMOSE : Computer Aided Platform

Grid computing

Decision support

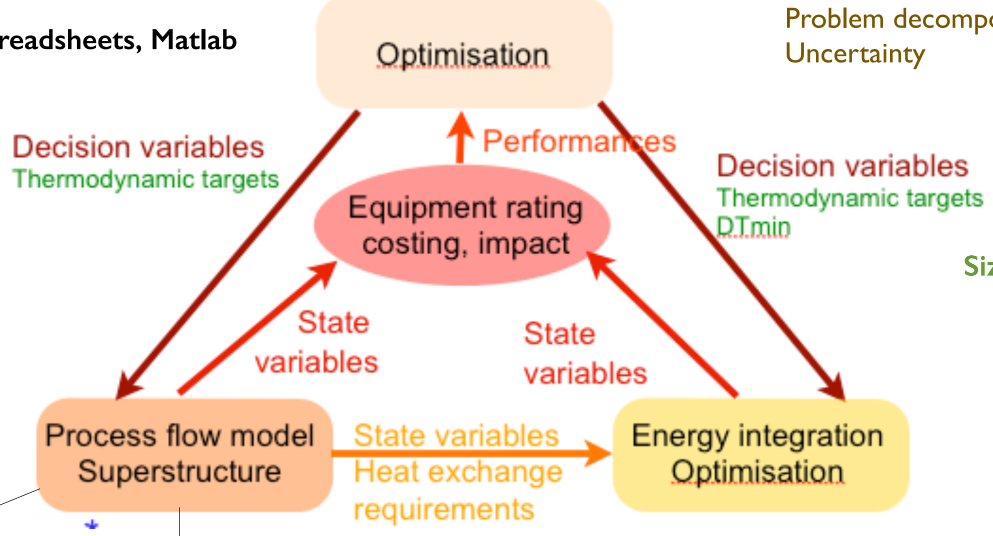
Multi-objective optimisation
- Evolutionary - Hybrid
- Problem decomposition
- Uncertainty

Data Structuring

GIS data base
- Industrial ecology
- Urban systems

GUI : Spreadsheets, Matlab

Technology models data base
- Energy conversion
- Sharing knowledge



Optimisation

Decision variables
Thermodynamic targets

Performances

Decision variables
Thermodynamic targets
DTmin

Equipment rating
costing, impact

State
variables

State
variables

Process flow model
Superstructure

State variables
Heat exchange
requirements

Energy integration
Optimisation

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 ?

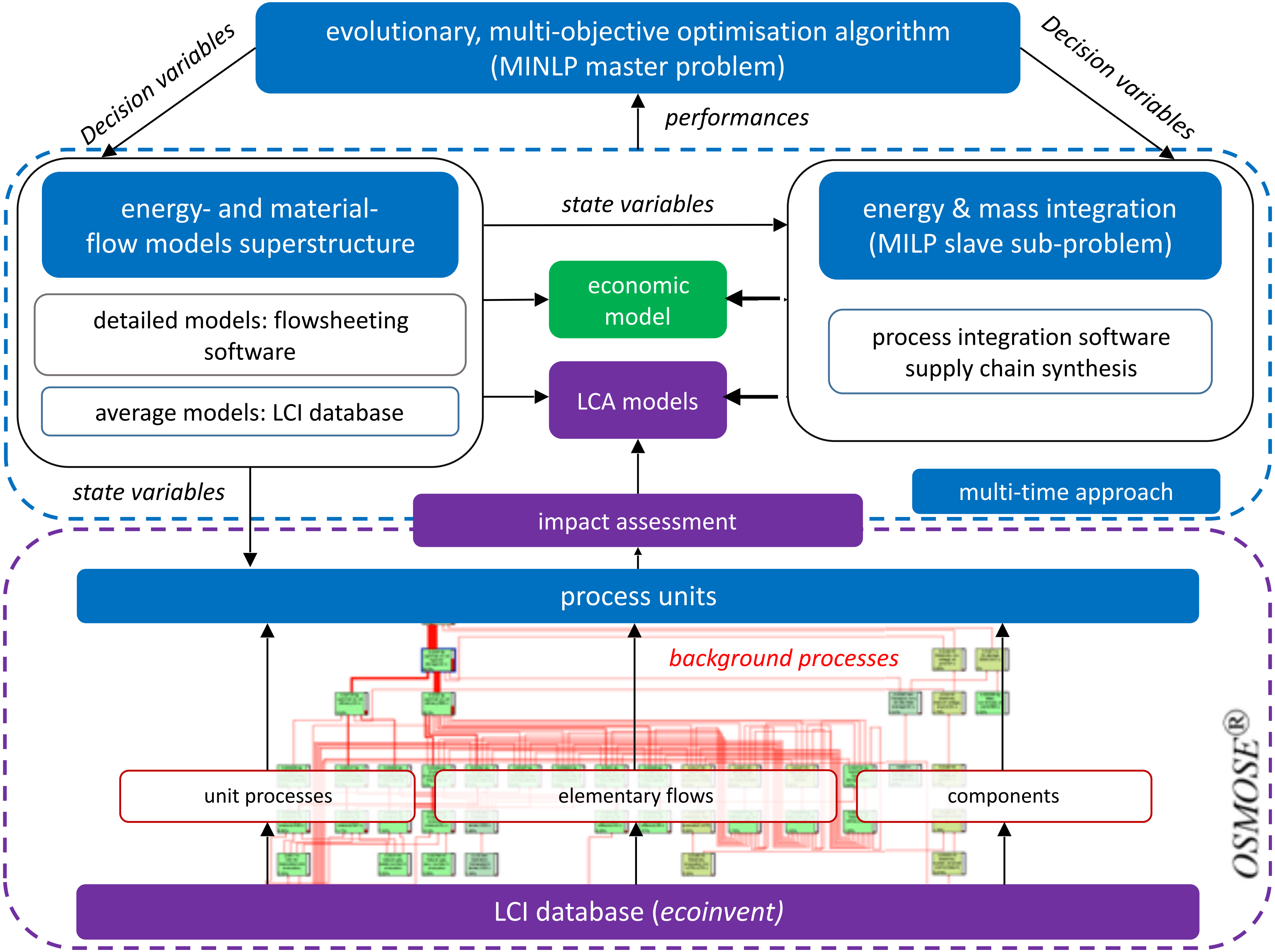
Energy technology data base
- •Data/models interfaces
- •Simulation
- •Process integration interface
- •Costing/LCIA performances
- •Reporting/documentation
- •Certified dev procedure

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

Process integration

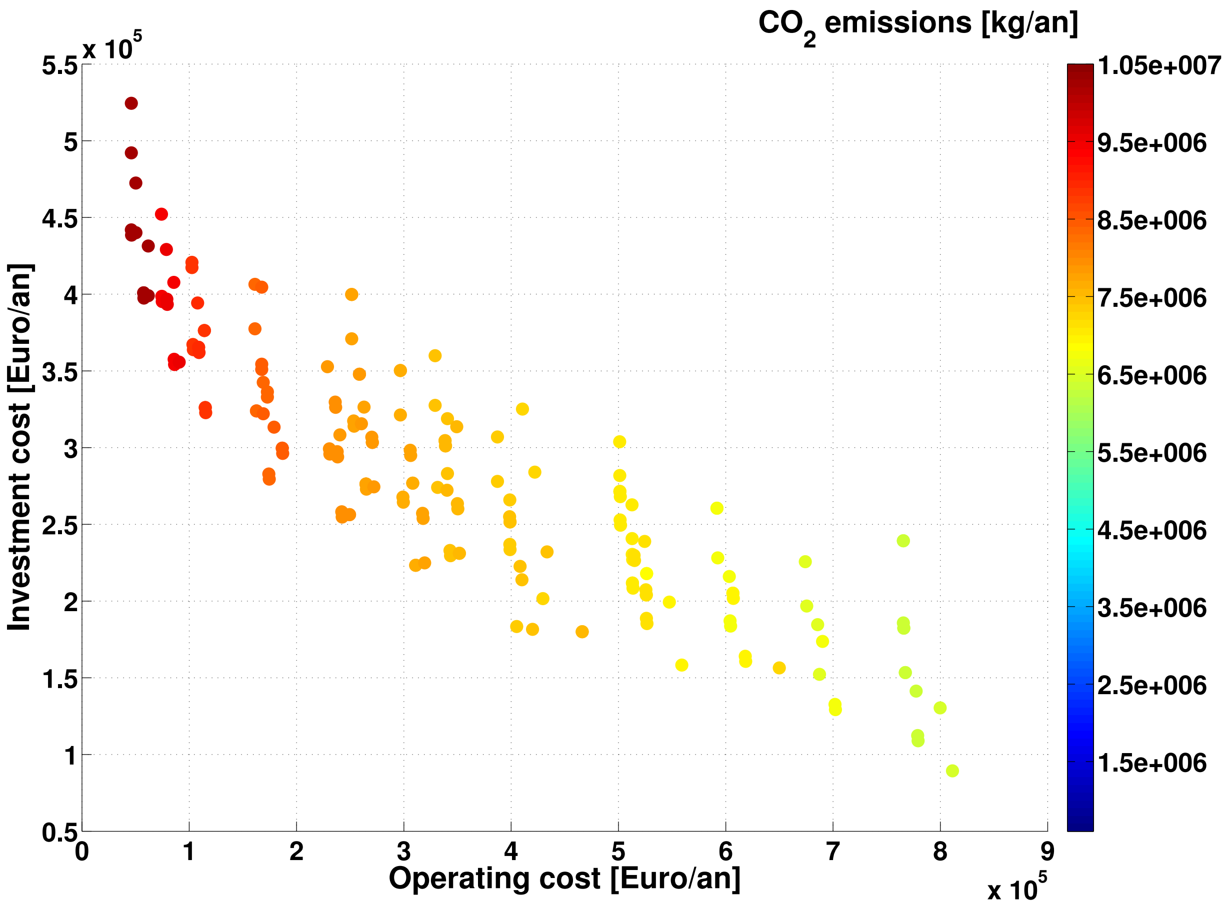
Modeling tools integration

Environmental model

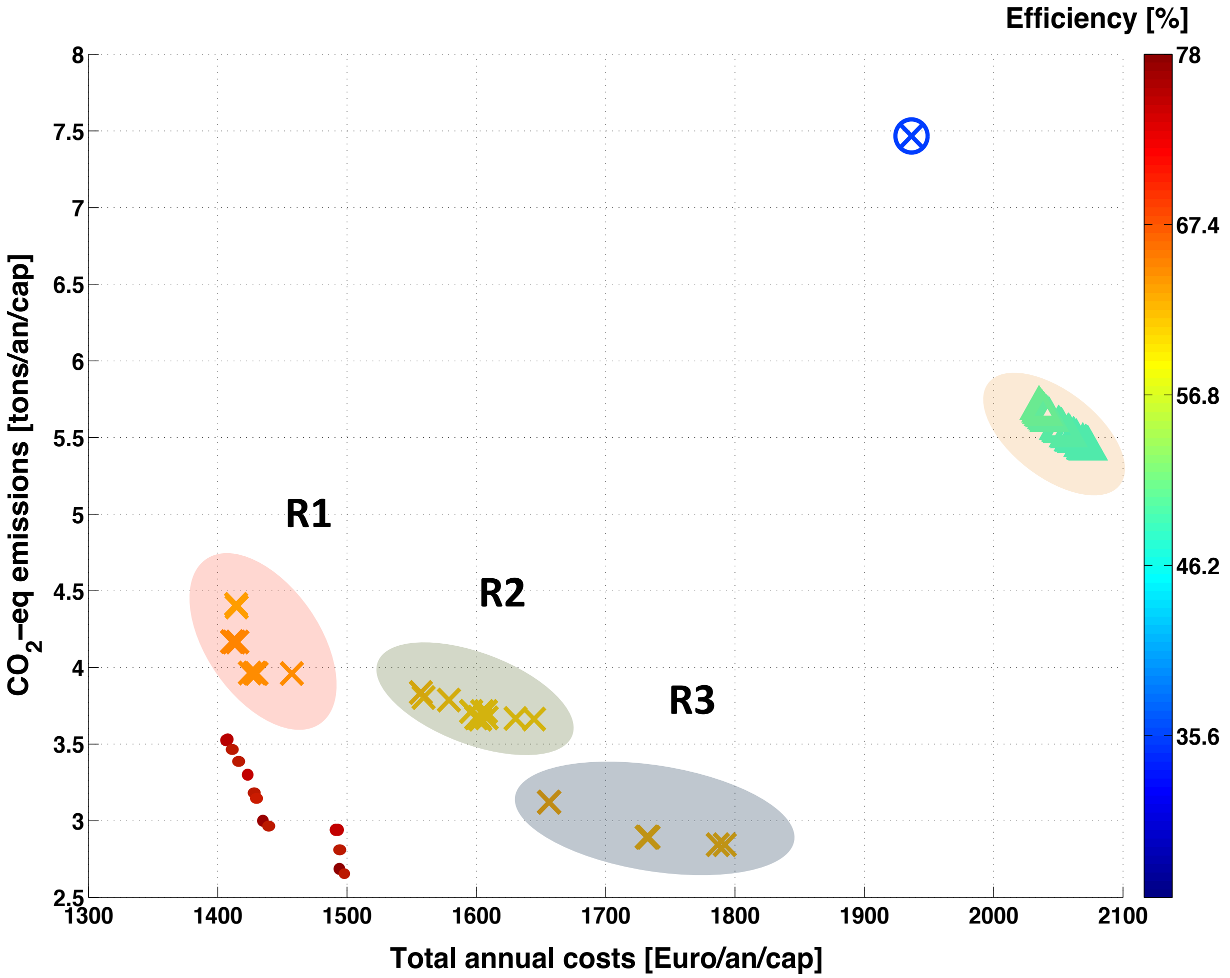


Multi-objective optimisation

Thermo-economic/environomic Pareto

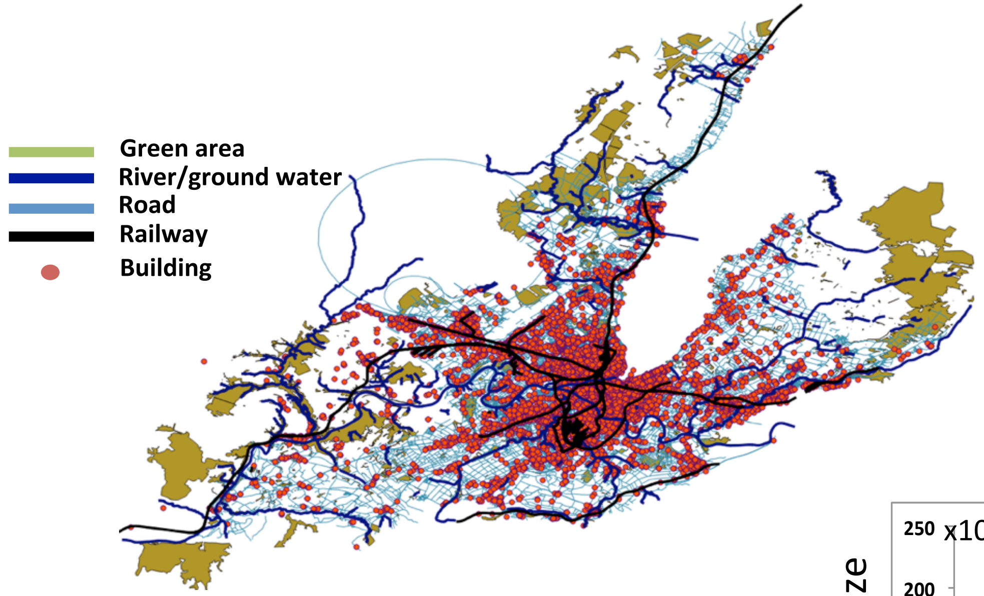


Identify clusters of solutions



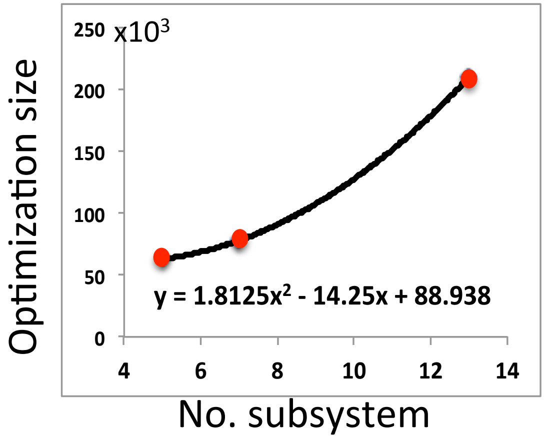
The difficulty of the urban size

A list of "integrated zones" based on GIS data



60,000 buildings

No. buildings	5	7	13	470
Constraints (x10^3)	63	88	210	9000
Variables (x10^3)	190	260	575	27000
Binary variables (x10^3)	3	4	9	40



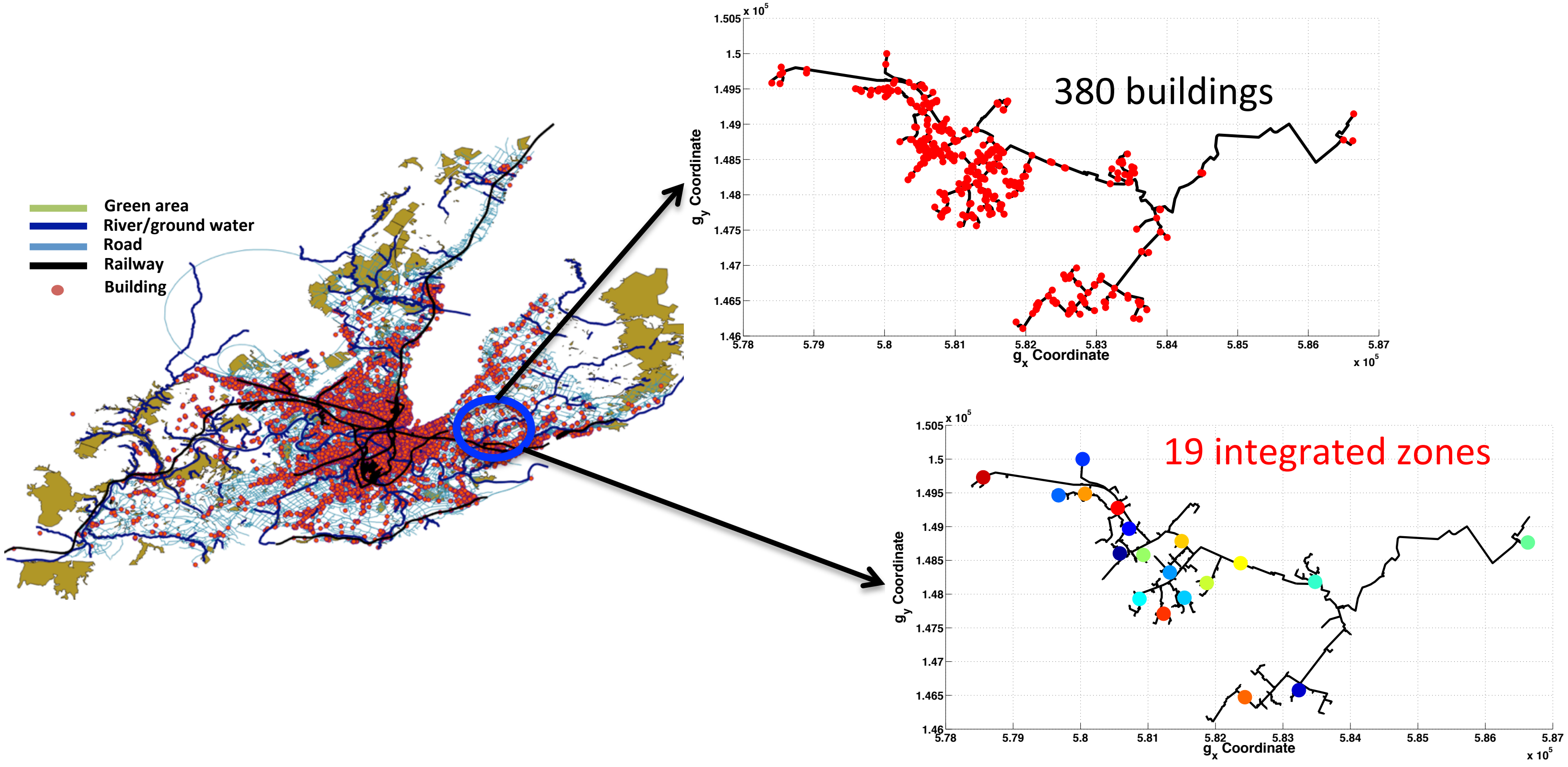
$y = 1.8125x^2 - 14.25x + 88.938$

How we can reduce the optimization size and computational load considering the number of subsystems?

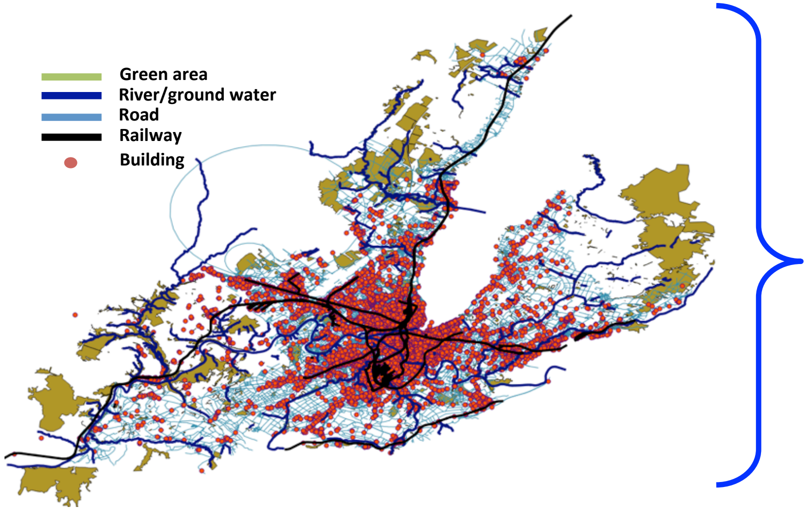
GIS Clustering

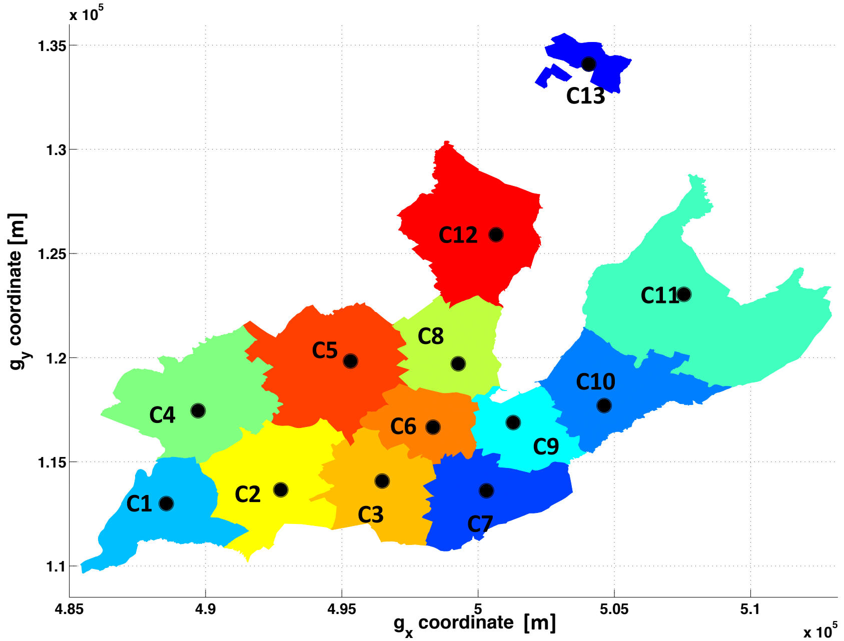
Cluster the city into limited number of "integrated zones"!

- The integrated zone is an area where resources, energy conversion technologies, and buildings are aggregated



GIS clustering





Subsystems	60,000 buildings	13 integrated zones
Constraints (x10^3)	6,480,000	210

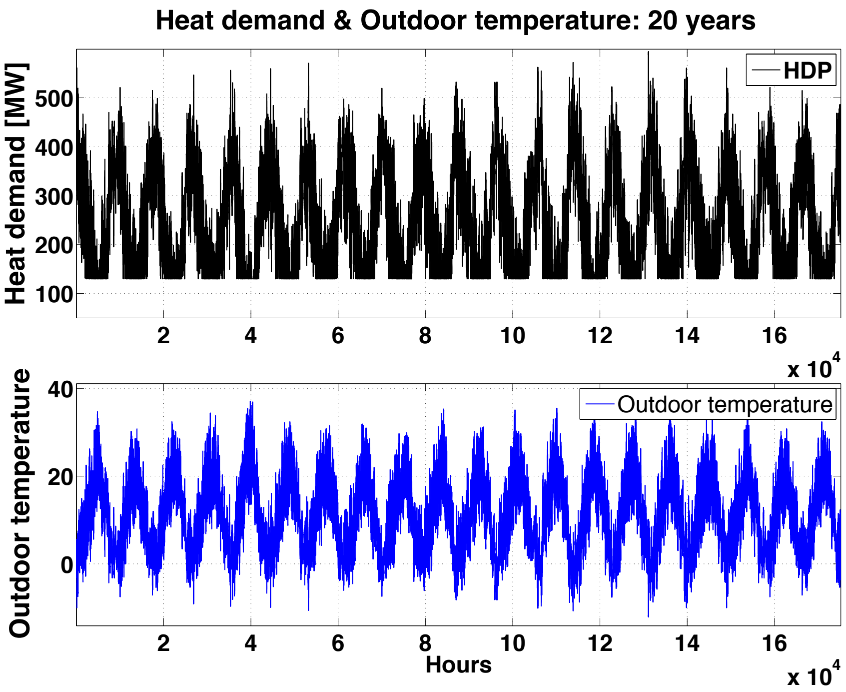
Each building has a probability of being connected to the grid

Reduce the optimization size significantly

Evaluation of the operational cost

20 x 8760 hours

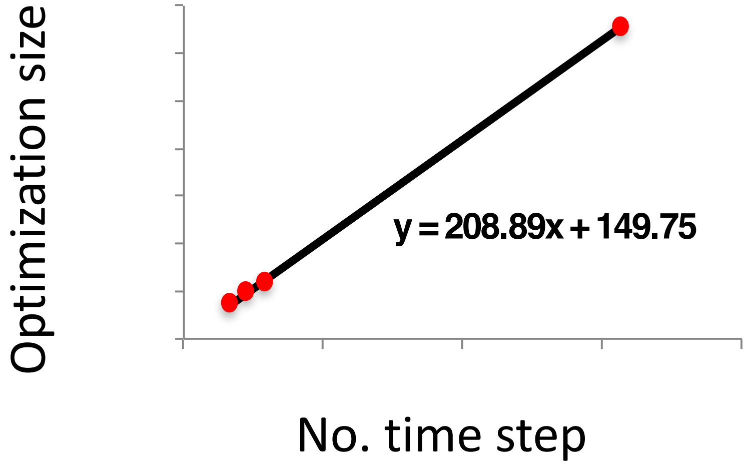
175’200 hours



MILP problem size

How we can reduce the optimization size (variables & constraints) and computational load?

No. time steps	35	312	8760
Constraints	***7400***	***65000***	***1830000***
Variables	6200	54000	1520000
Binary variables	***400***	***3700***	***104000***
Resolution Time [s]	23	85	2700

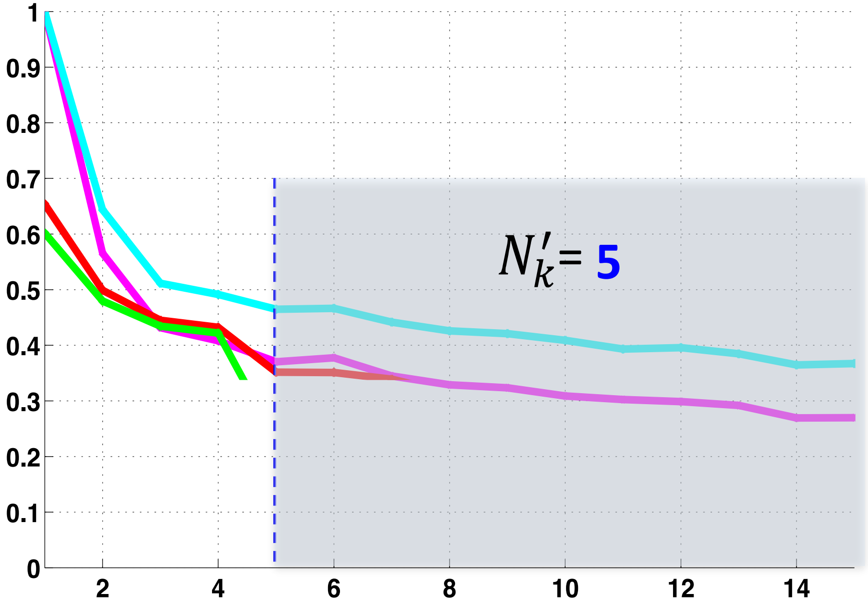


While achieving accurate representation of data!

I-Data structuring: Typical periods selection method

⑤ raw the Pareto frontier of each performance indicator and select N_k', the minimum accepted number of clusters

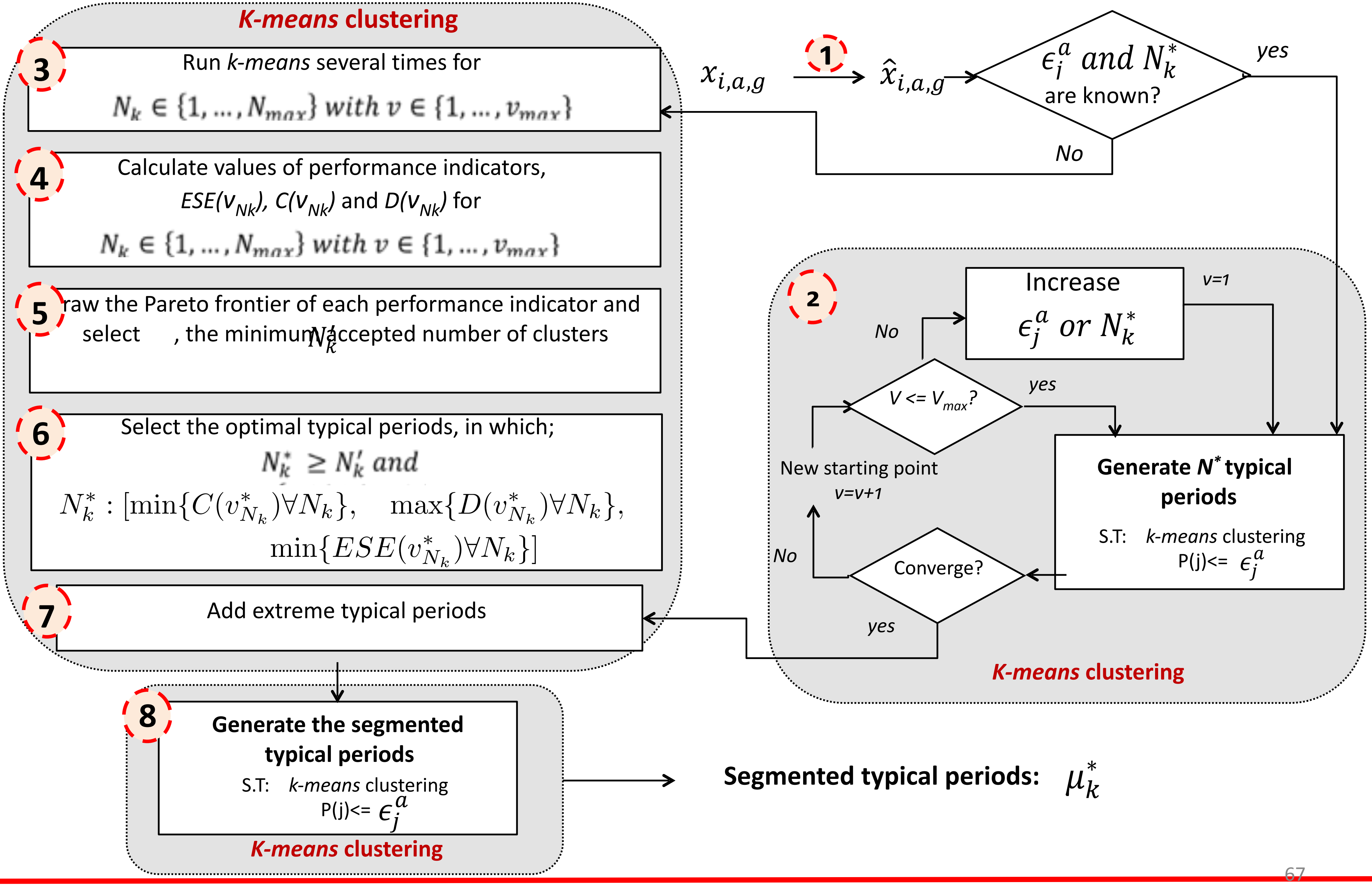
N_k': the indicators’ improvement on the Pareto frontier from N_k' to $N_k'+1$ is not significant



At least we need 5 clusters

Normalized Pareto frontiers of performance indicators for each type of attributes

I-Data structuring: Typical periods selection method



K-means clustering

3 Run *k-means* several times for

$N_k \in \{1, \dots, N_{max}\}$ with $v \in \{1, \dots, v_{max}\}$

4 Calculate values of performance indicators, *ESE*(v_{Nk}), *C*(v_{Nk}) and *D*(v_{Nk}) for

$N_k \in \{1, \dots, N_{max}\}$ with $v \in \{1, \dots, v_{max}\}$

5 raw the Pareto frontier of each performance indicator and select N'_k, the minimum accepted number of clusters

6 Select the optimal typical periods, in which;

$$N^*_k \geq N'_k \text{ and}$$

$$N^*_k : [\min\{C(v^*_{N_k})\forall N_k\}, \quad \max\{D(v^*_{N_k})\forall N_k\}, \min\{ESE(v^*_{N_k})\forall N_k\}]$$

7 Add extreme typical periods

$x_{i,a,g}$ ① $\hat{x}_{i,a,g}$

ϵ^a_j and N^*_k are known?

yes

No

2 Increase ϵ^a_j or N^*_k

v=1

No

$V <= V_{max}$?

yes

New starting point

v=v+1

Generate N^* typical periods

S.T: *k-means* clustering

P(j)<= ϵ^a_j

No

Converge?

yes

K-means clustering

8 **Generate the segmented typical periods**

S.T: *k-means* clustering

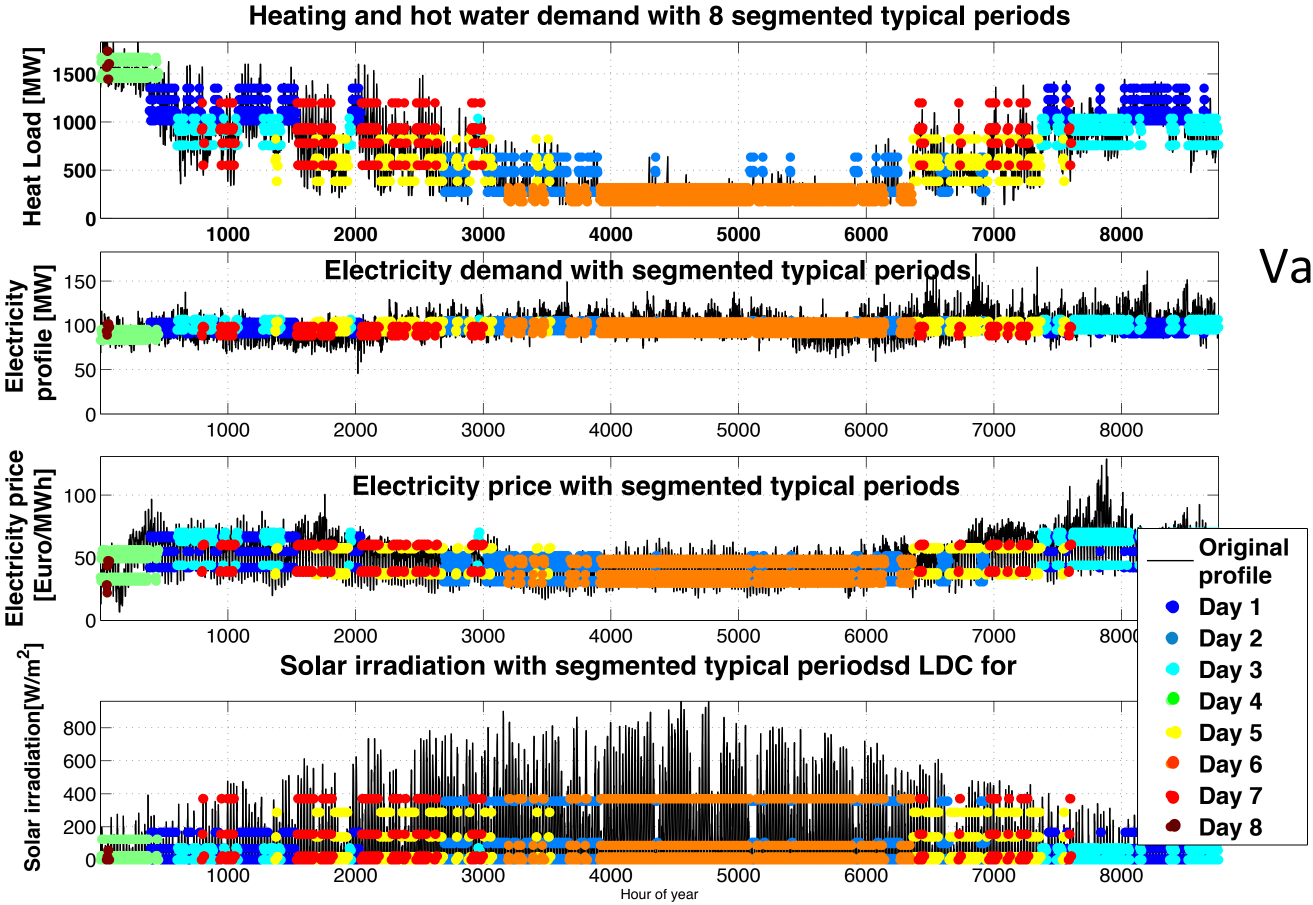
P(j)<= ϵ^a_j

K-means clustering

Segmented typical periods: μ^*_k

Typical days definition

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



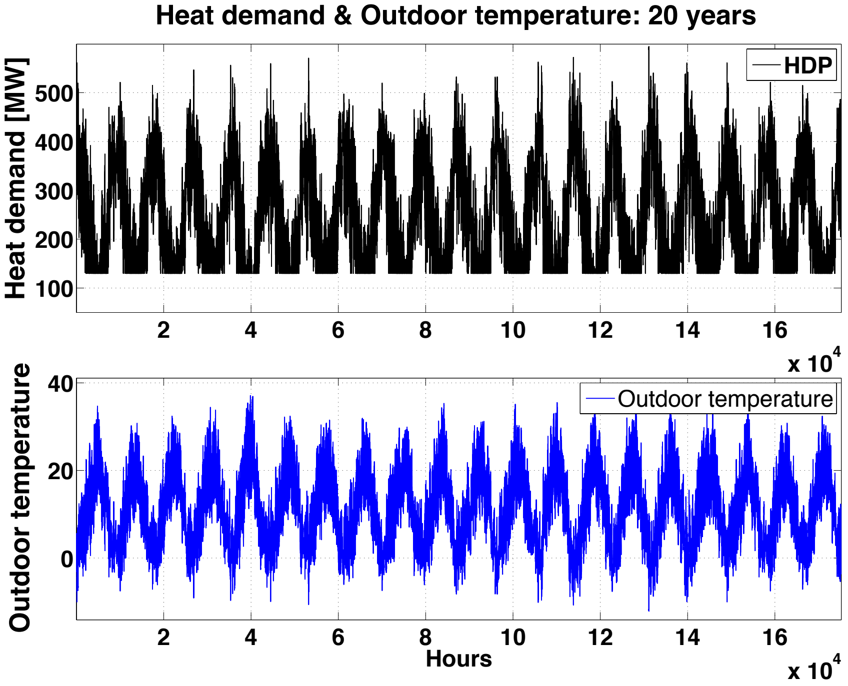
Validation is performed

- 0.3-4.1% errors
- 40 times faster

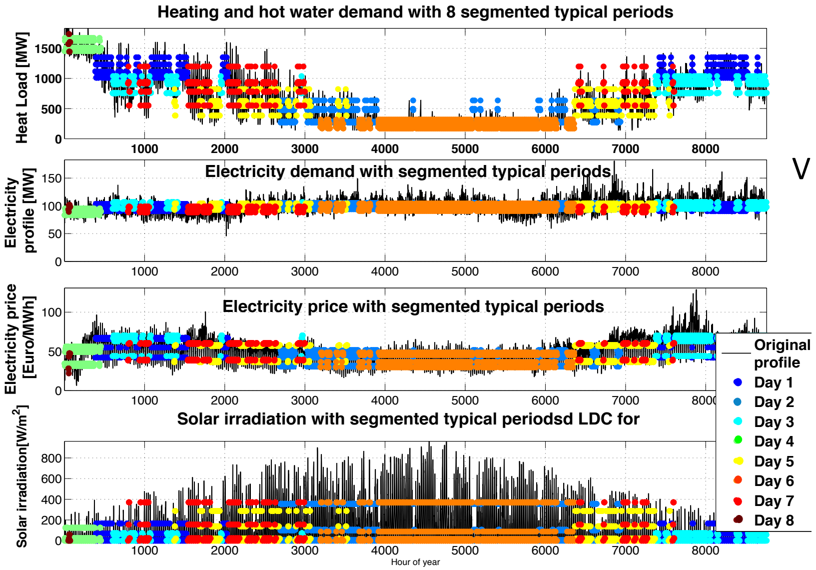
Evaluation of the operational cost

20 x 8760 hours

175200 hours



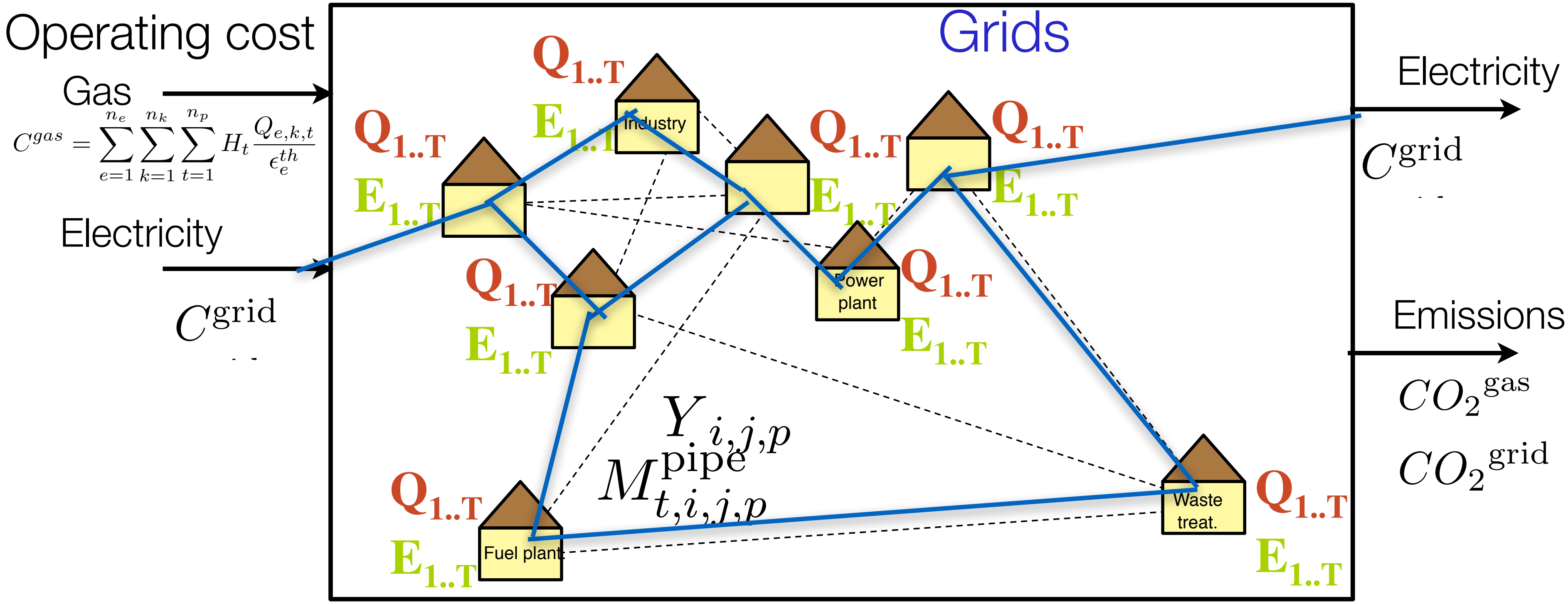
Clustering techniques



- **40 time steps :**
    - **7 days*5 sequence + 1 Extreme * 5**
- **Probability of appearance**
    - **=>number of days**
- **Robustness**

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}

Electricity

C^{grid}

Emissions

${CO_2}^{gas}$

${CO_2}^{grid}$

Investment

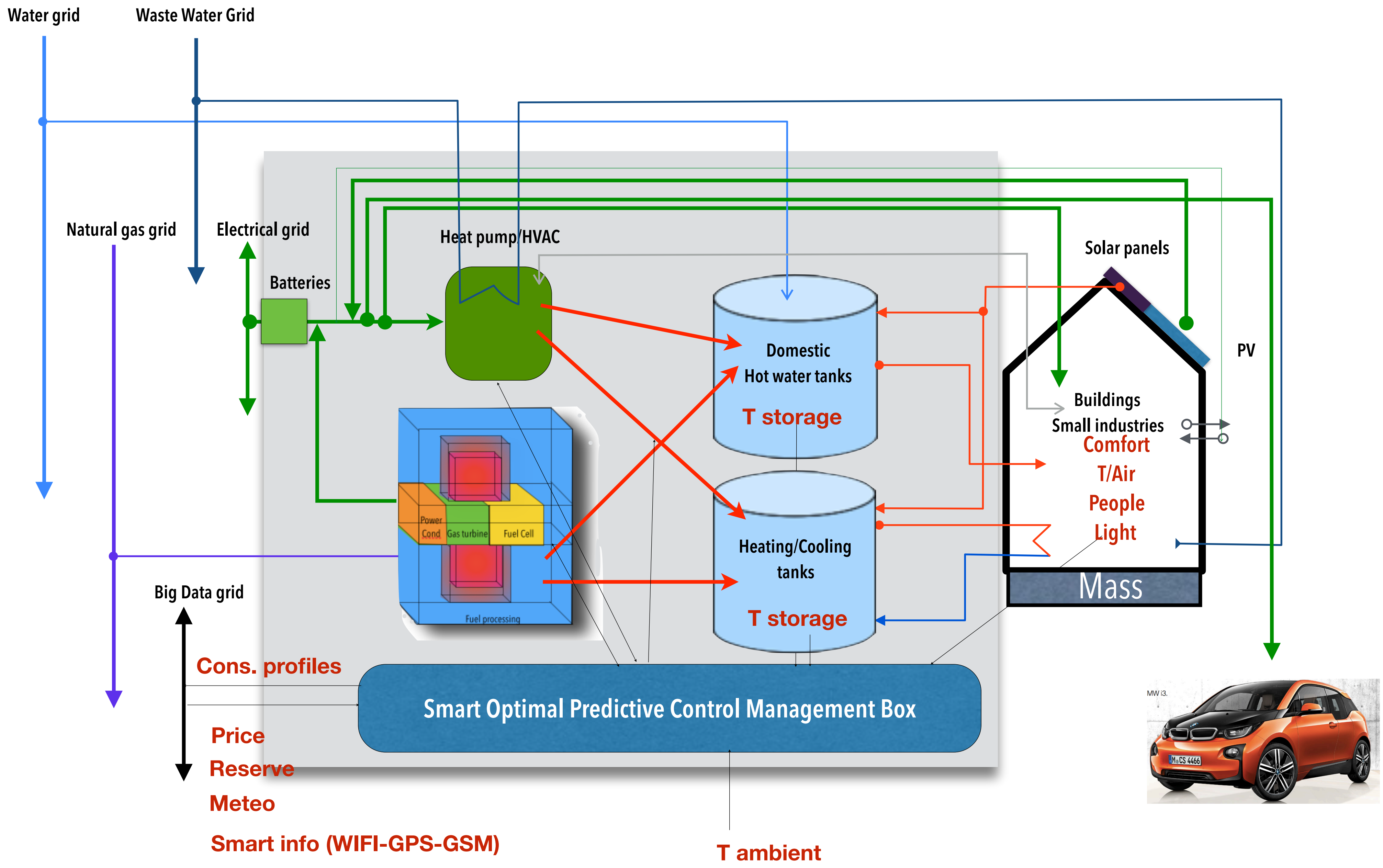
C^{pipes}

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



Water grid

Waste Water Grid

Natural gas grid

Electrical grid

Batteries

Heat pump/HVAC

Solar panels

PV

Domestic
Hot water tanks

T storage

Buildings
Small industries

Comfort

T/Air

People

Light

Mass

Heating/Cooling
tanks

T storage

Big Data grid

Cons. profiles

Smart Optimal Predictive Control Management Box

Price

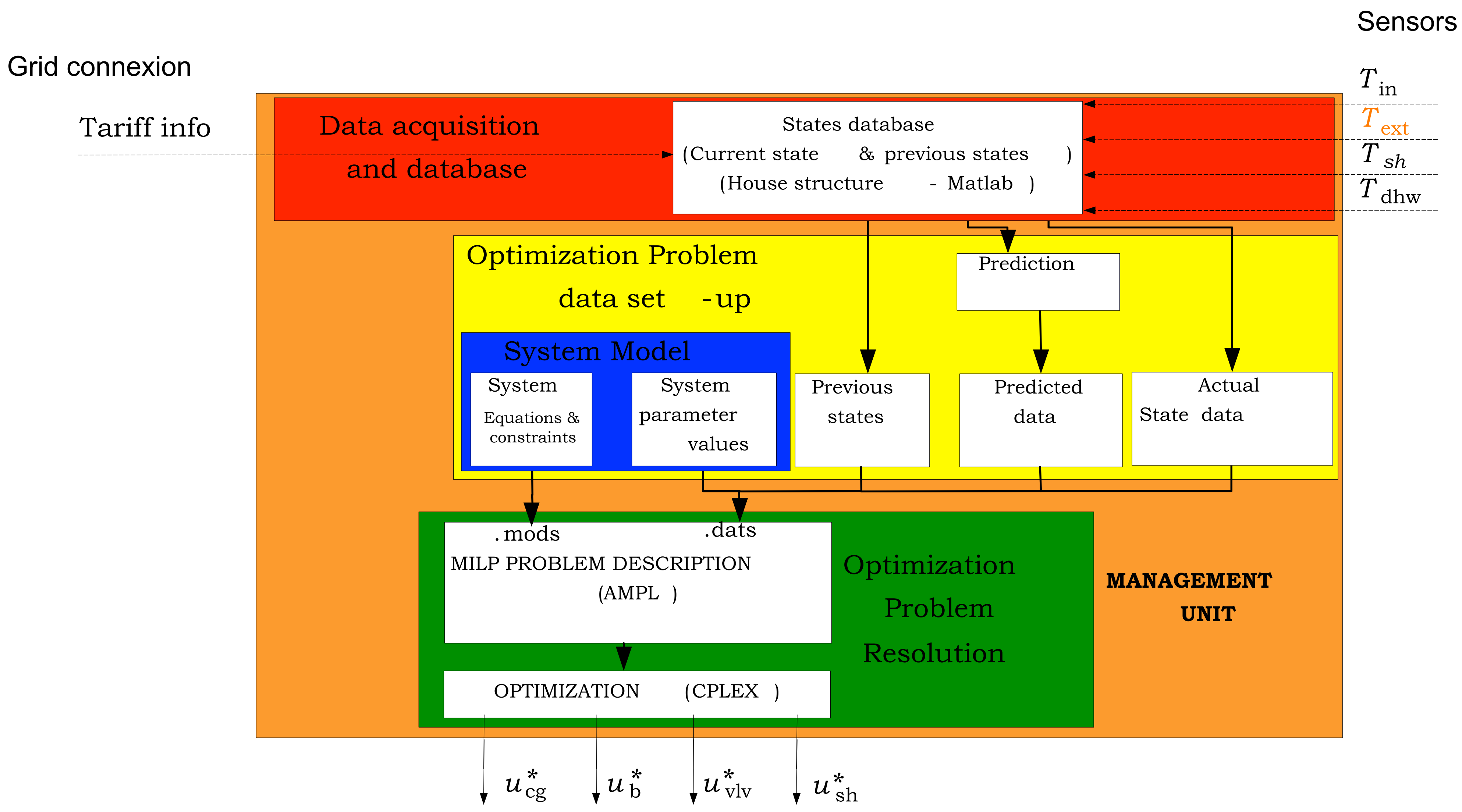
Reserve

Meteo

Smart info (WIFI-GPS-GSM)

T ambient

Smart predictive control management box



Grid connexion

Tariff info

Sensors

T_{in}

T_{ext}

T_{sh}

T_{dhw}

Data acquisition and database

States database
(Current state & previous states)
(House structure - Matlab)

Optimization Problem data set -up

Prediction

System Model

System Equations & constraints

System parameter values

Previous states

Predicted data

Actual State data

.mods

.dats

MILP PROBLEM DESCRIPTION (AMPL)

OPTIMIZATION (CPLEX)

Optimization Problem Resolution

MANAGEMENT UNIT

u^*_{cg} u^*_{b} u^*_{vlv} u^*_{sh}

Set point strategy

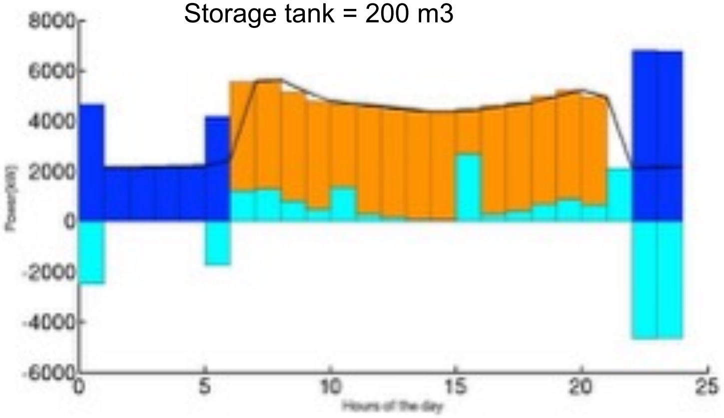
Collazos et al., Computers and Chemical Eng. 2009

Demonstration of the "storage" capacity

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

Demand mean heating power = 3000 kW

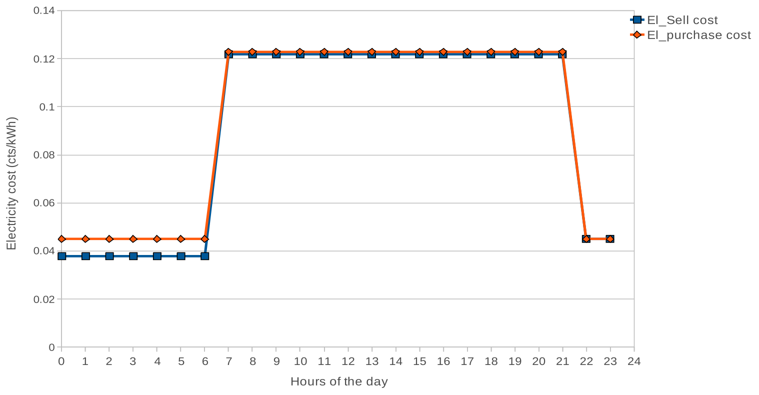
High electrcity cost during the afternoon
Storage tank = 200 m3



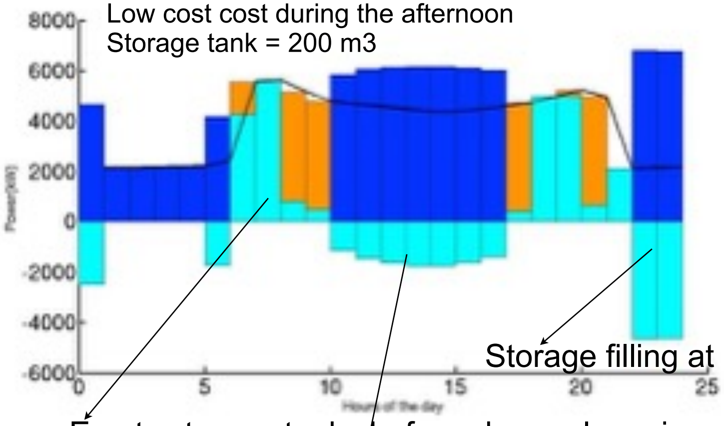
Heating : 72315 kWh
Electricity : 77897 kWhe

Electricity out : 5650 kWhe
Electricity bought : 62894 kWhe

Low price period
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

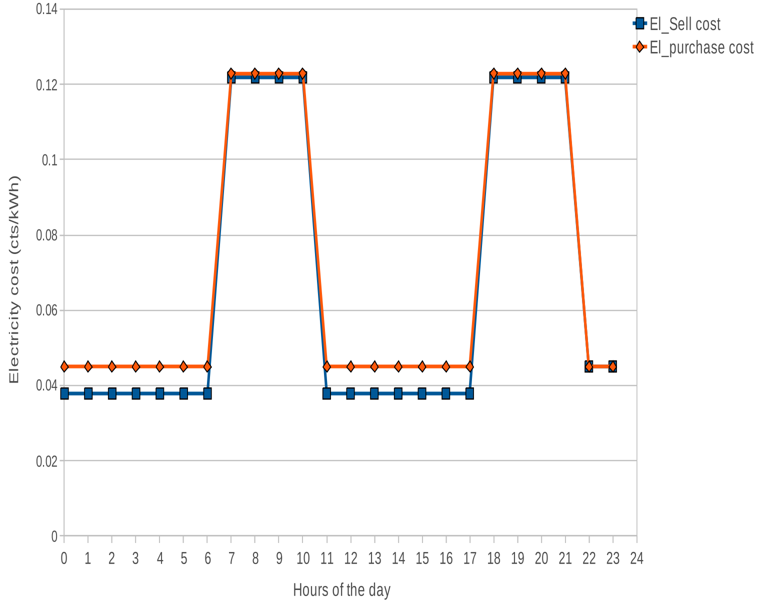
Empty storage tanks before cheap elec price

Fill storage tanks during cheap elec price

Electricity in : 99596 kWhe
Electricity out : 8710 kWhe

Low price period
Electricity in : 19345 kWhe

Storage : 22480 kWhe



Storage capacity

- Cogen system
  - Storage : 10.5 kWhe/day (E-E without Storage)
  - Round trip efficiency of cogen
    - 10.5kWh/ 13.2 kWh (E + DLHV) = 0.80
- Heat pump system
  - 5.3 kWhe/day
  - Round trip efficiency = 5.3kWh/6.3kWh = 0.85
- HP + Cogen
  - 12.1 kWhe/day
  - Roundtrip = 12.1kWh/15kWh = 0.81

Day of the year = February 25
Useable floor area of house = 188.8 m2
Heat Requirement of the day=71.3 kWh

Size of the thermal storage tank: 0.6 cubic metres
Size of the heat pump = 3kWth
Size of the cogeneration engine = 2.25kWe

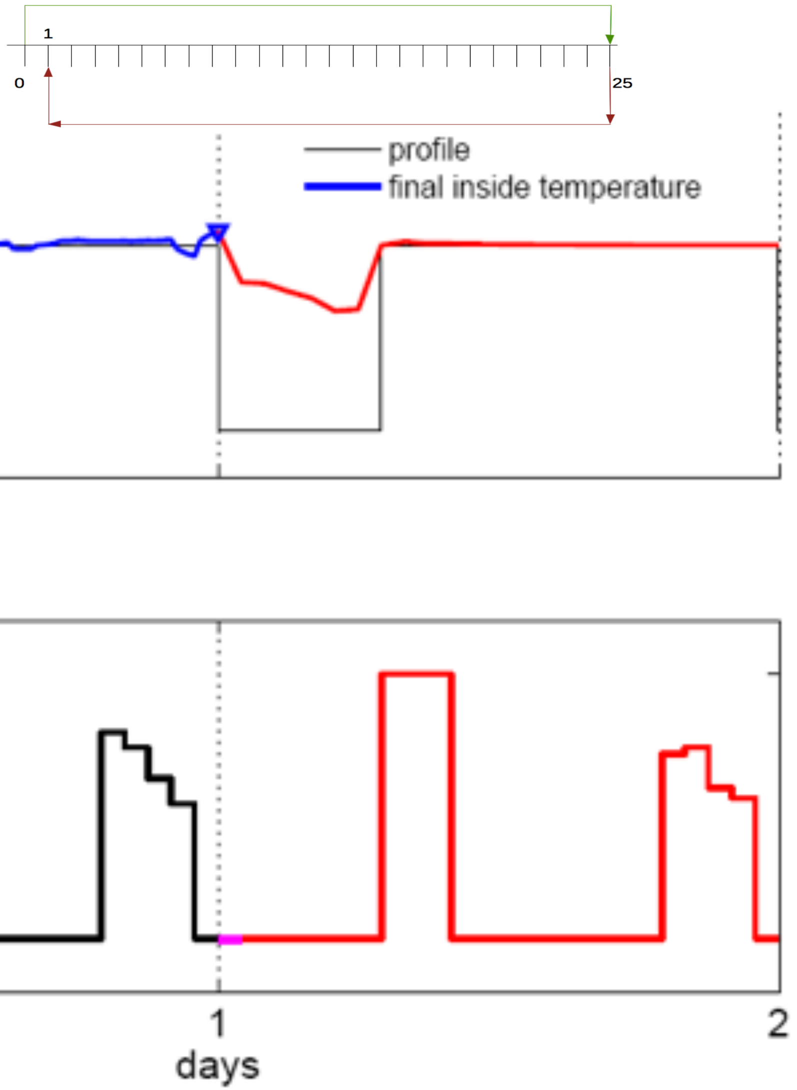
Smart building : Integration of PV system

- Requirement
  - Electricity : 3.03 MWh_e/year
  - Heating : 17.6 MWh_{th}/year
  - Hot water : 3.4 MWh_{th}/year
  - Heat pump size : 5 kWe / COP = 3.11
- PV system : 50 m^2
  - 7.5 MWh_e/year
  - Self consumption : 4.8 MWh_e/year (63%)
- Optimal battery and heat storage tanks
  - Battery : 0.01 m3 (3 kWh_e)
  - Tanks : 1 m3 (25 kWh_{th})
- Model predictive control

+ 17 % of self consumption

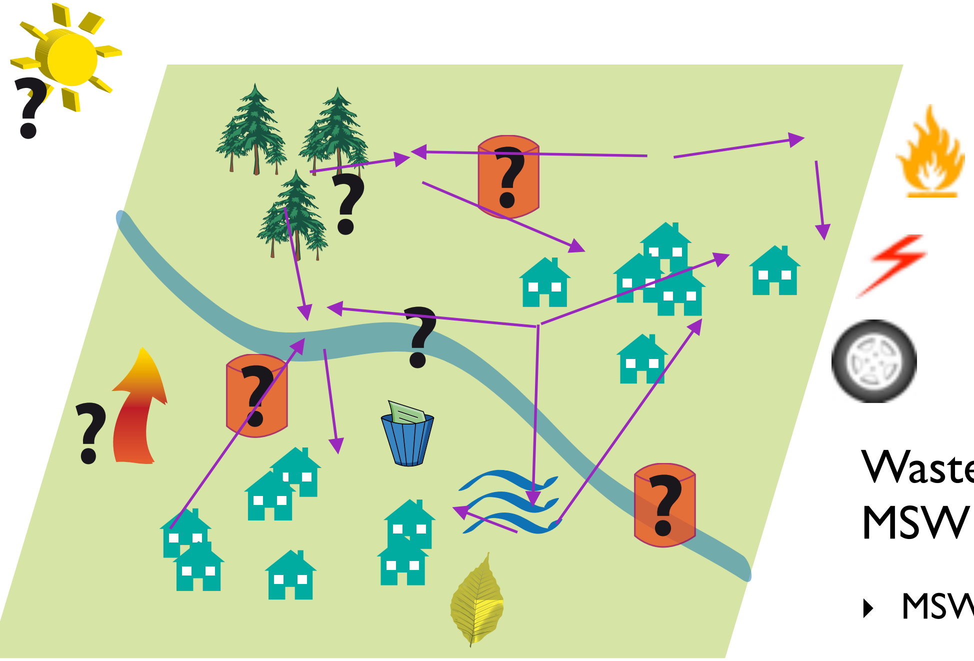
Predictive Controller

- **Predictive Control Algorithm : Moving horizon => simulation models have to integrate the control system**
  - hour 1 : set-point control + 24 h Cyclic : strategy



Extending the system boundaries

- **40‘000 inhabitants city in Switzerland (La Chaux-de-Fonds, 1000m alt.)**



Energy services to be supplied:

- Heat using existing district heating network (seasonal variation in T and load): **3357 $\mathrm{kWh_{th}}$/yr/cap**
- Electricity (seasonal variation): **8689 $\mathrm{kWh_{e}}$/yr/cap**
- Mobility: **11392 pkm/yr/cap**

Waste to be treated (existing facilities for MSW and WWTP):

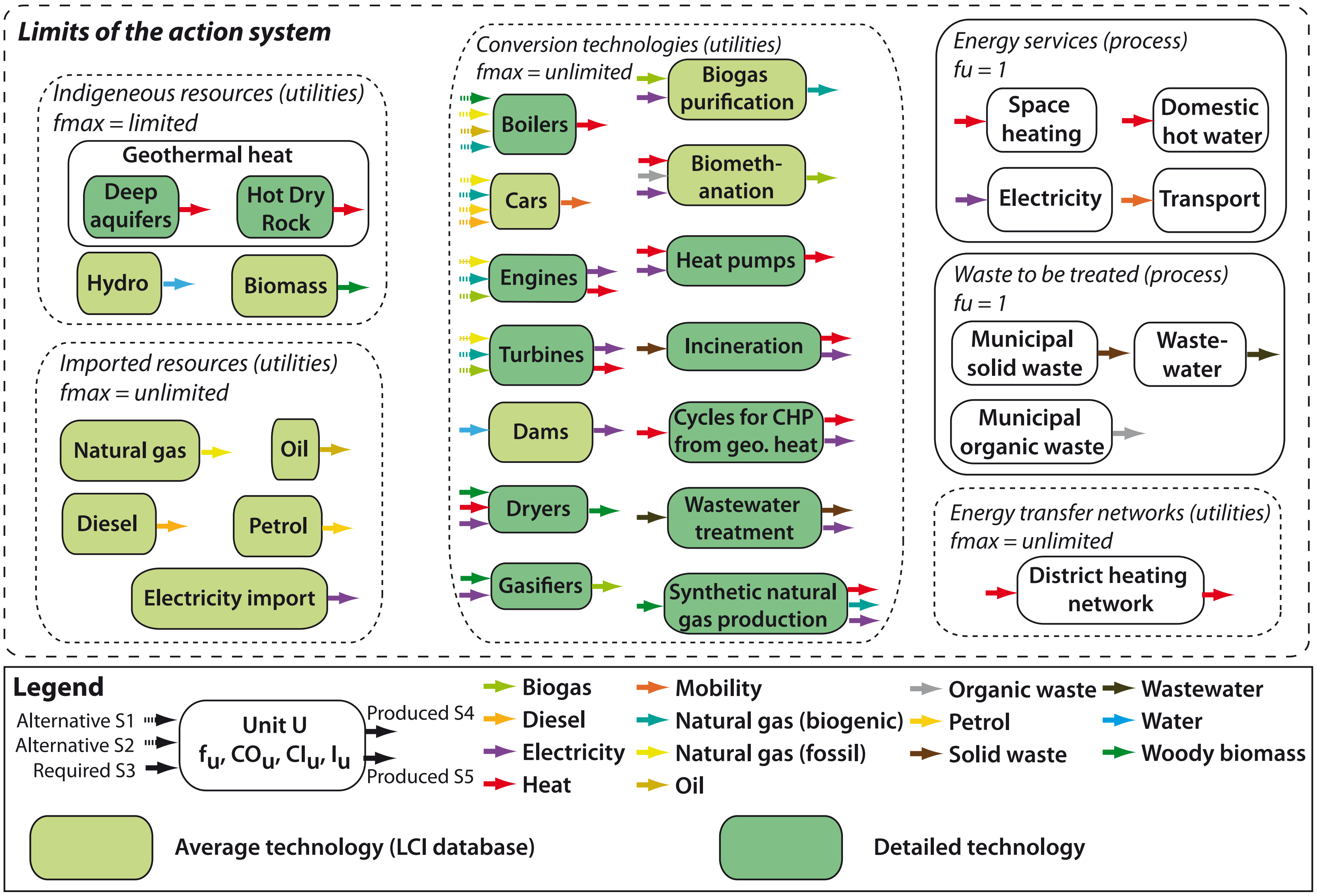
- MSW: **1375 kg/yr/cap**
- Wastewater: **300 m3/yr/cap**
- Biowaste: **87.5 kg/yr/cap**

Available endogenous resources:

- Woody biomass: 18’900 $\mathrm{MWh_{th}}$/yr
- Geothermal: 9496 $\mathrm{MWh_{th}}$/yr
- Sun (seasonal variation in T and load): 10‘328 $\mathrm{MWh_{th}}$/yr
- Hydro (existing dams): 187‘850 $\mathrm{MWh_{e}}$/yr

- Which resources with which technologies for which services?
  - Min. Costs and CO2 emissions

Ecodesign of a urban system



Limits of the action system

Indigeneous resources (utilities)
fmax = limited
Geothermal heat
Deep aquifers
Hot Dry Rock
Hydro
Biomass

Imported resources (utilities)
fmax = unlimited
Natural gas
Oil
Diesel
Petrol
Electricity import

Conversion technologies (utilities)
fmax = unlimited
Boilers
Cars
Engines
Turbines
Dams
Dryers
Gasifiers
Biogas purification
Biometh-anation
Heat pumps
Incineration
Cycles for CHP from geo. heat
Wastewater treatment
Synthetic natural gas production

Energy services (process)
fu = 1
Space heating
Domestic hot water
Electricity
Transport

Waste to be treated (process)
fu = 1
Municipal solid waste
Waste-water
Municipal organic waste

Energy transfer networks (utilities)
fmax = unlimited
District heating network

Legend

Alternative S1
Alternative S2
Required S3
Unit U
f_u, CO_u, CI_u, I_u
Produced S4
Produced S5

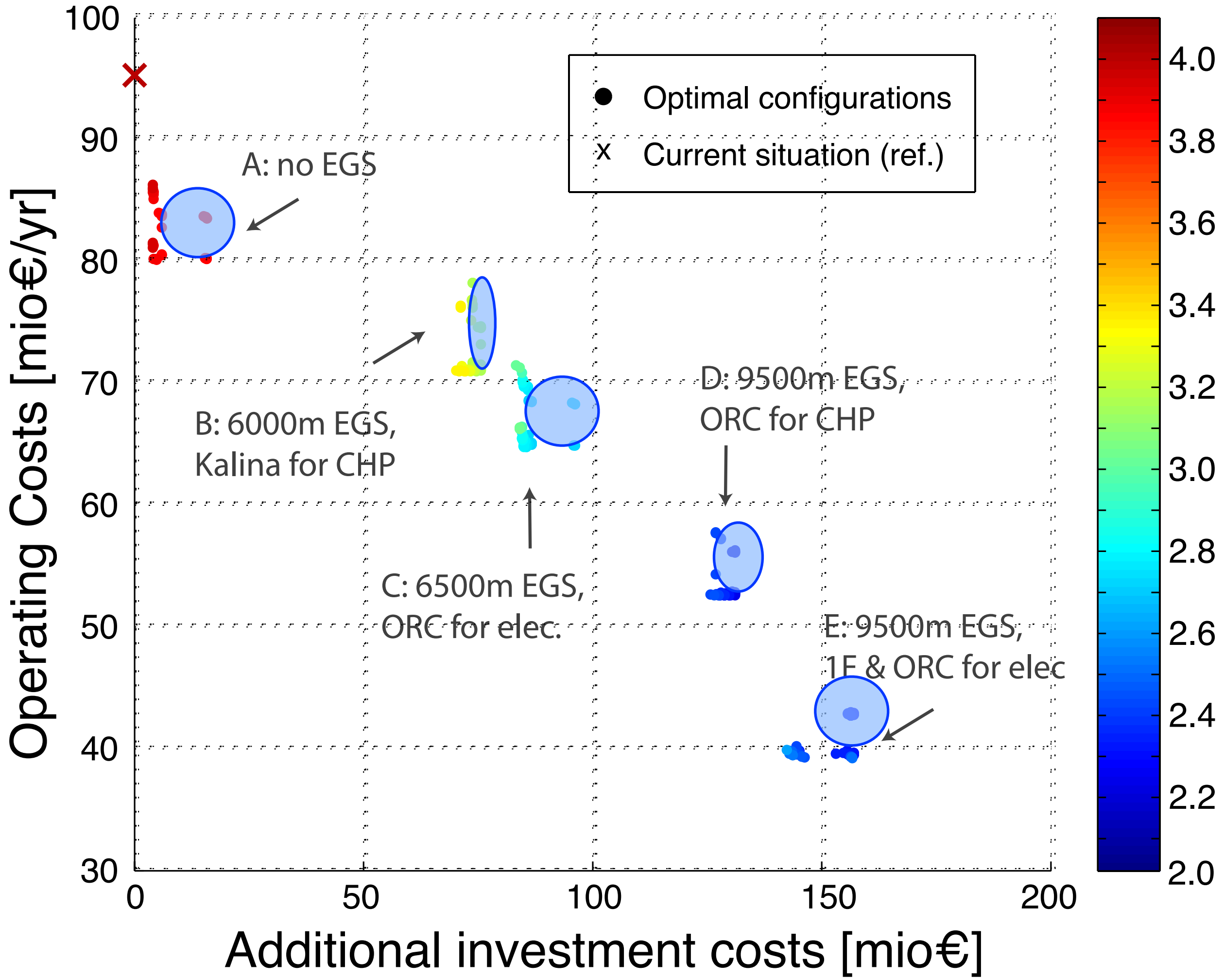
Biogas
Diesel
Electricity
Heat
Mobility
Natural gas (biogenic)
Natural gas (fossil)
Oil
Organic waste
Petrol
Solid waste
Wastewater
Water
Woody biomass

Average technology (LCI database)
Detailed technology

Supply the energy services of a region

- *min. investment*
- *min. operating costs*
- *min. CO2-eq. emissions*

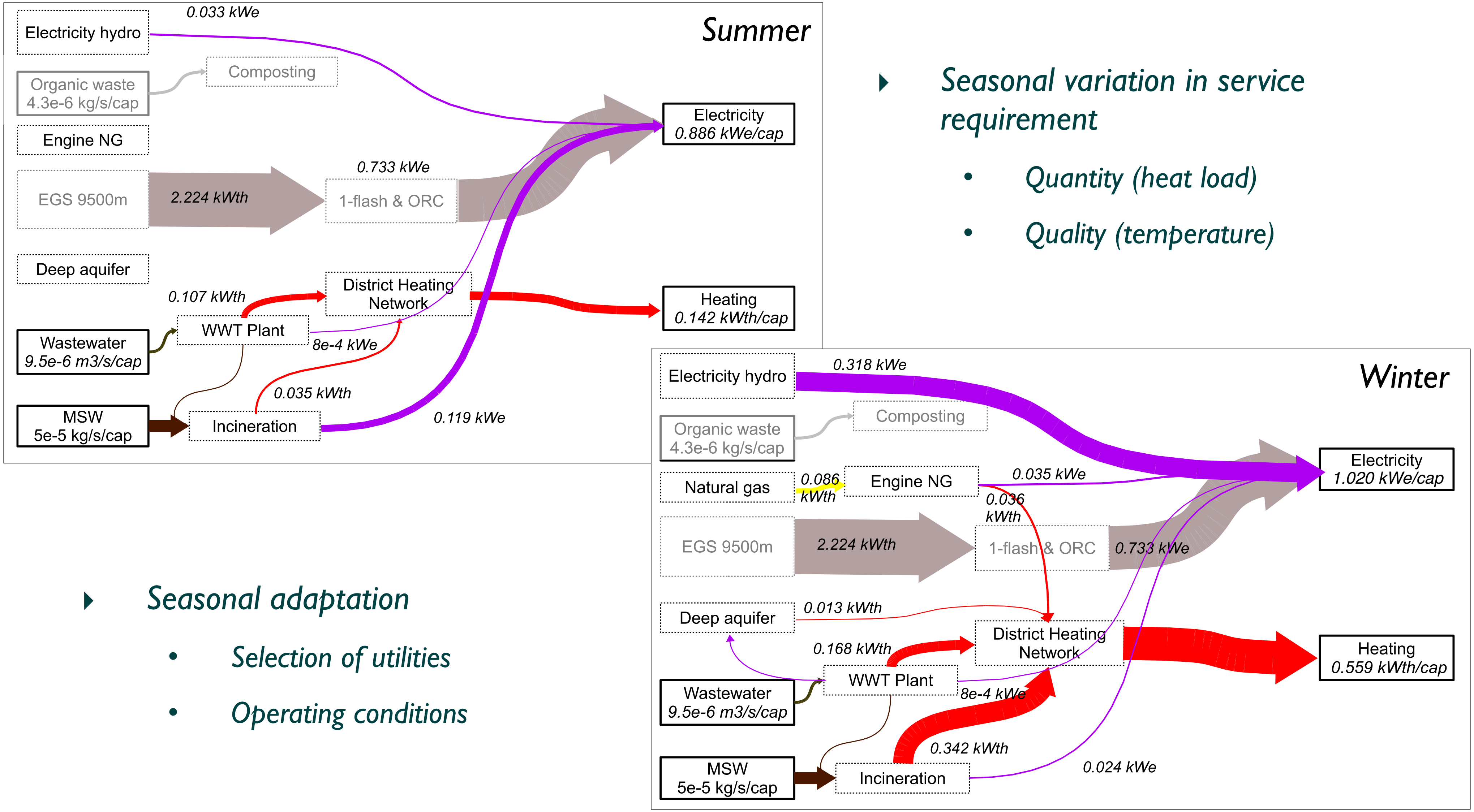
Multi-objective optimization results



- Trade-off between 3 objectives
- In each cluster, panel of “environomic“ solutions
  - not considered if pure economic optimization
  - Biomass & biowaste conversion
- *economic*: 39.5% max impact reduction
- *environomic*: 44.8% max impact reduction

Seasonal operation (independent multi-period)

- Example of summer and winter system operation

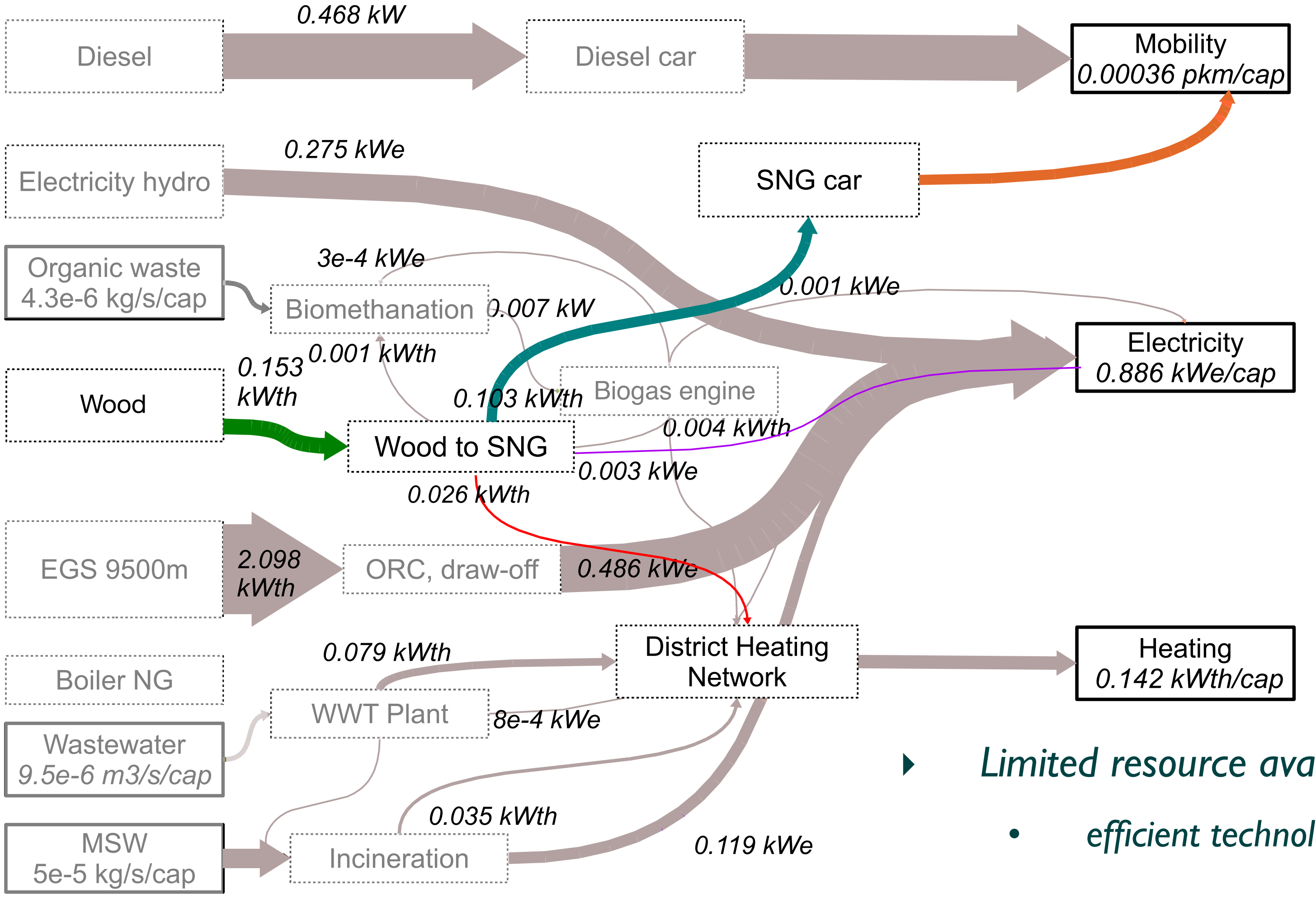


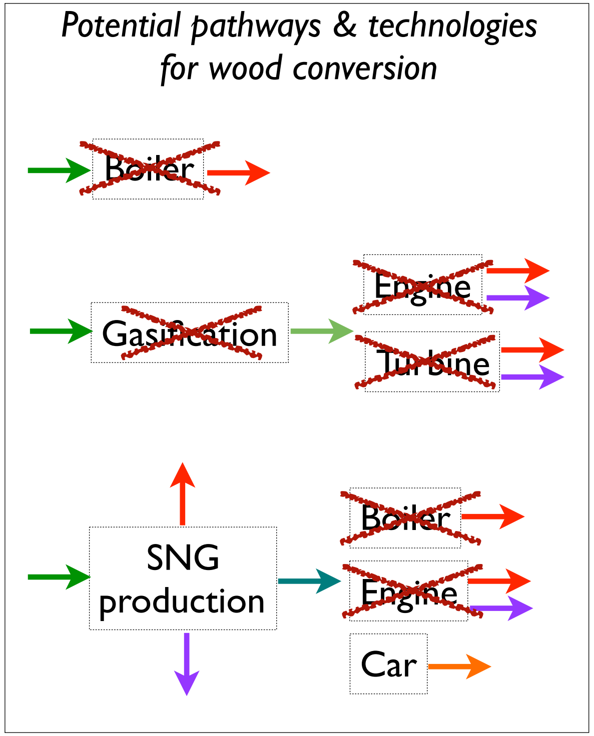
- *Seasonal variation in service requirement*
  - *Quantity (heat load)*
  - *Quality (temperature)*

- *Seasonal adaptation*
  - *Selection of utilities*
  - *Operating conditions*

Optimal pathways and technology selection

- Example of wood in environomic configurations

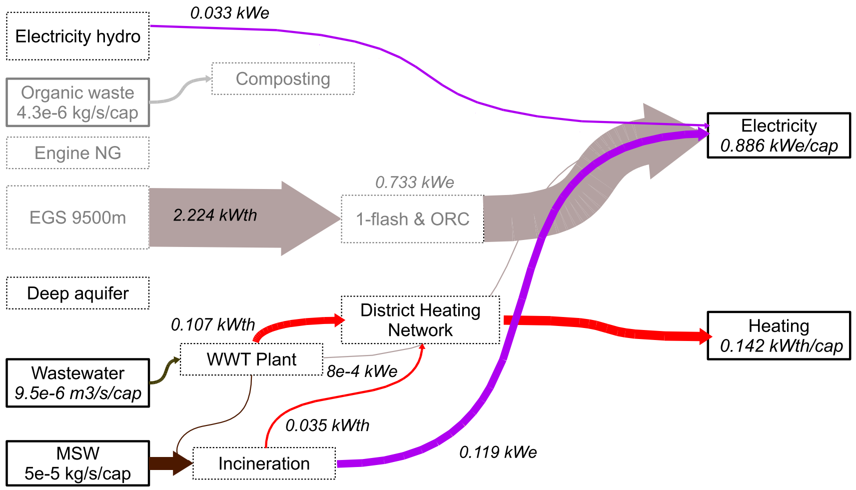




- *Limited resource availability*
    - *efficient technologies*
- *Alternatives for producing services (e.g. transport)*

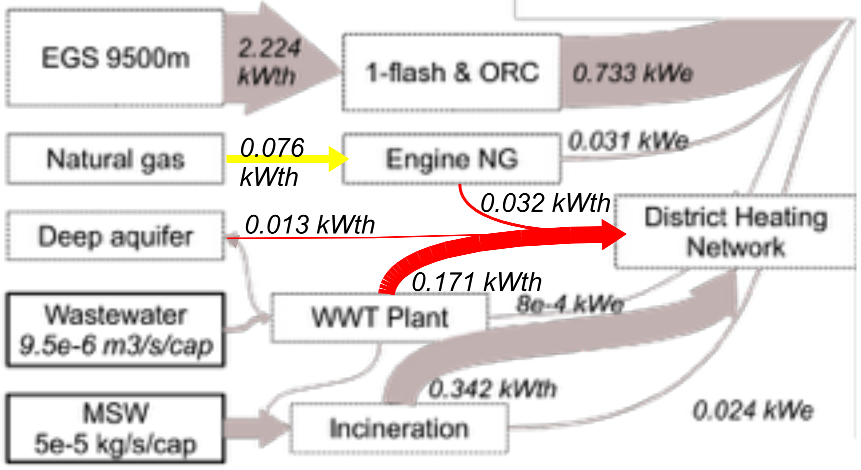
Competitions and synergies

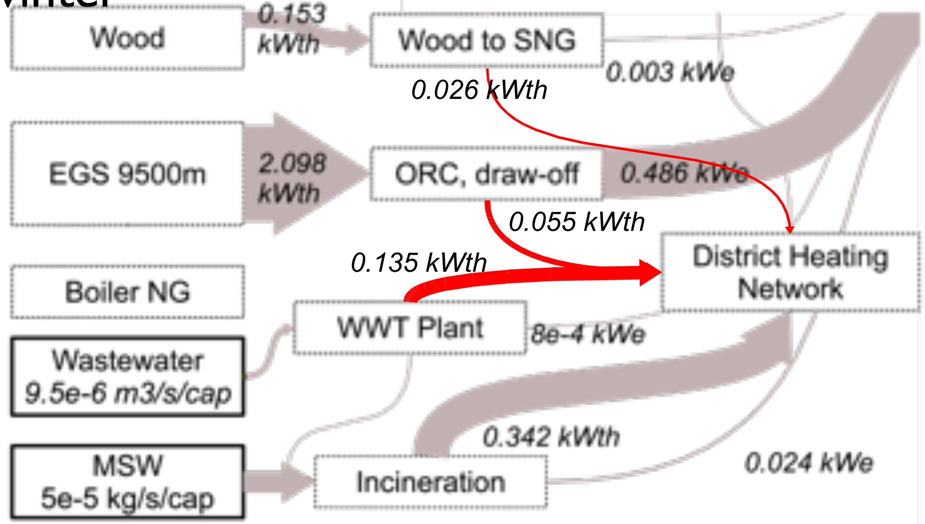
- Example of interaction between MSWI and WWTP in summer



- *Usage of waste heat from WWTP*
  - *reduces supplementary requirement*
- *More electricity available from MSWI*
  - *reduces import*

- Example of supplementary heat requirement in winter



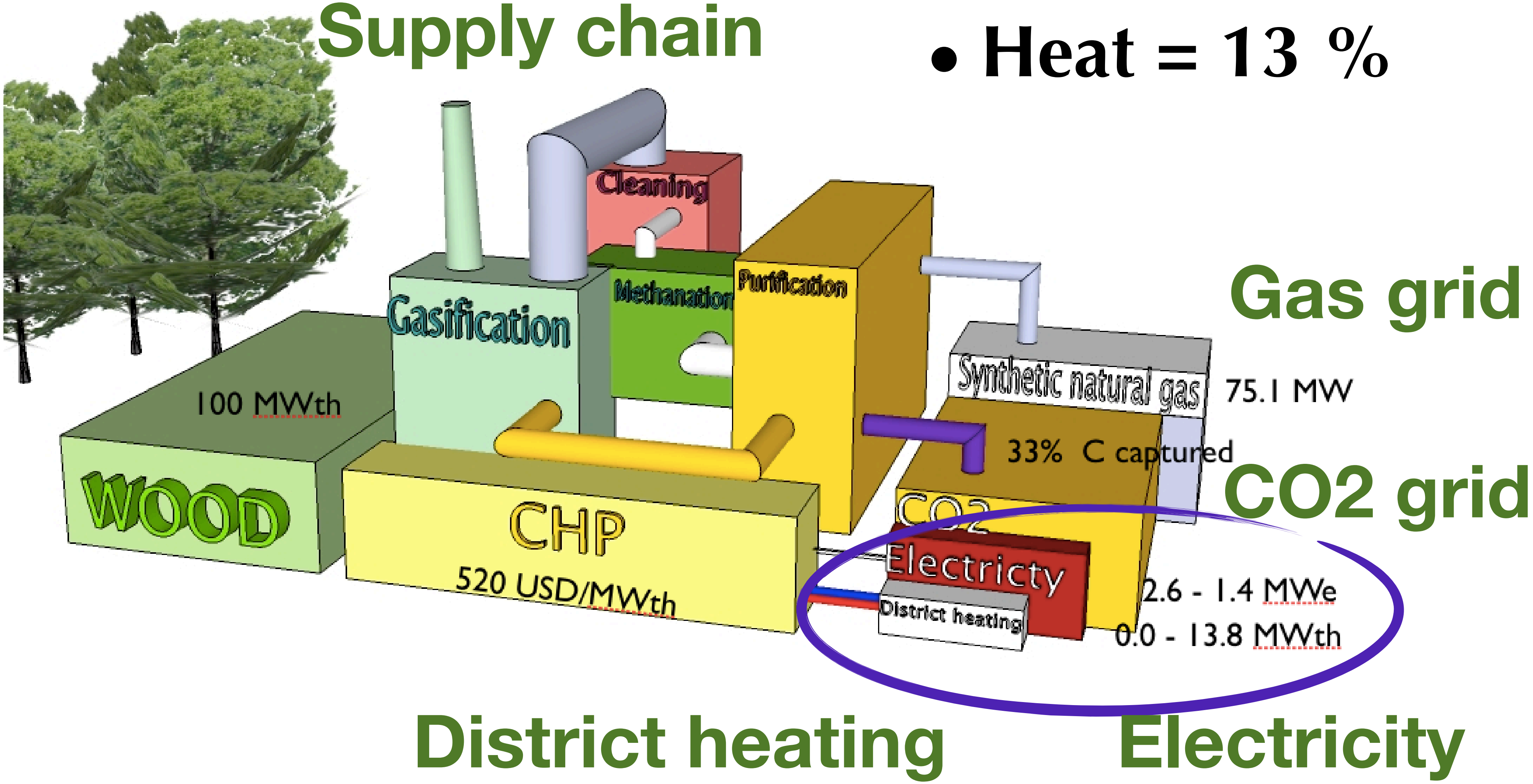


- *Deep aquifer competing with EGS for CHP & Wood to SNG conversion*

Large scale integration : multi-grids

- Resource productivity

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



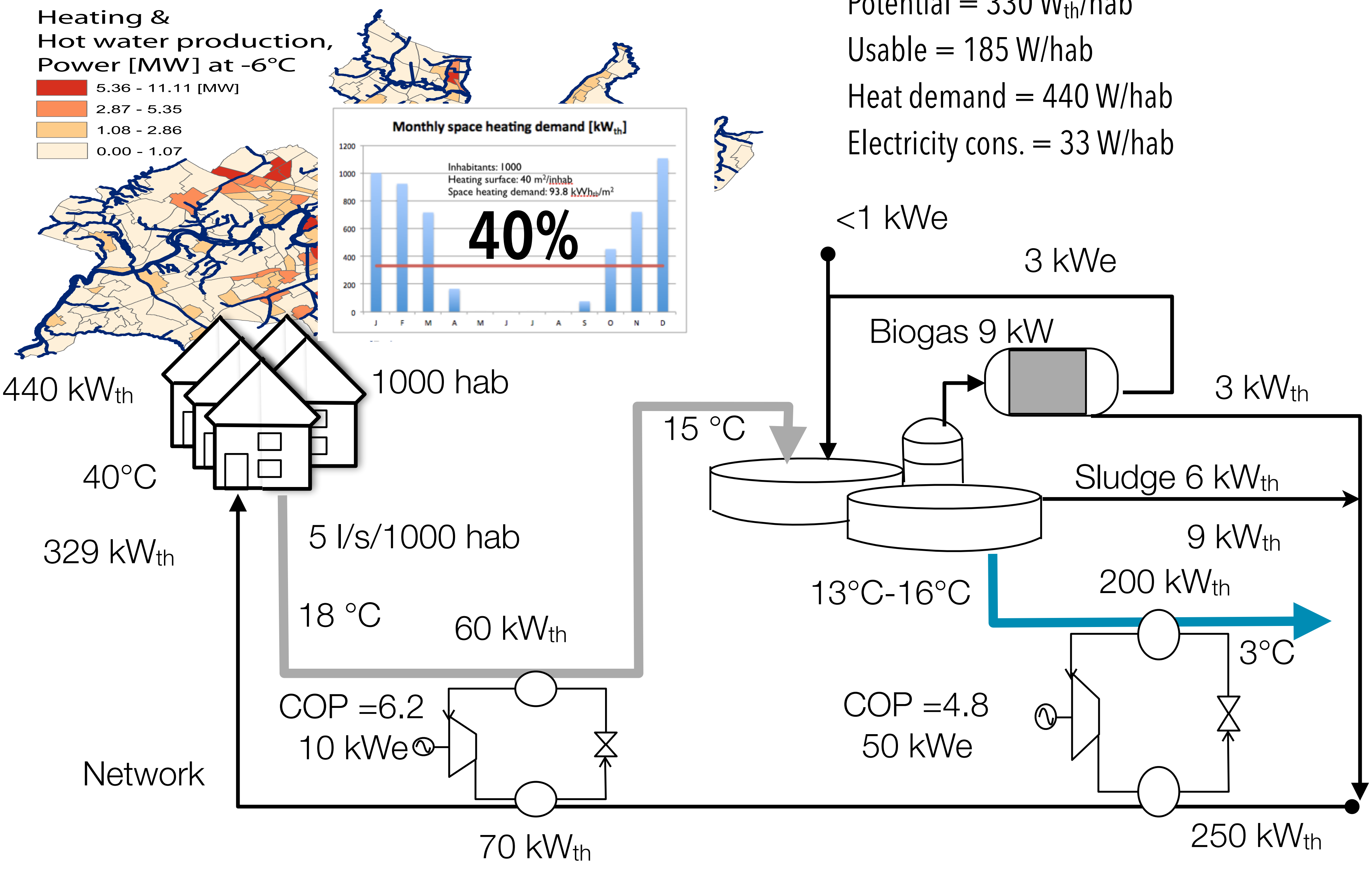
Access to local resources

Potential = 330 W_{th}/hab

Usable = 185 W/hab

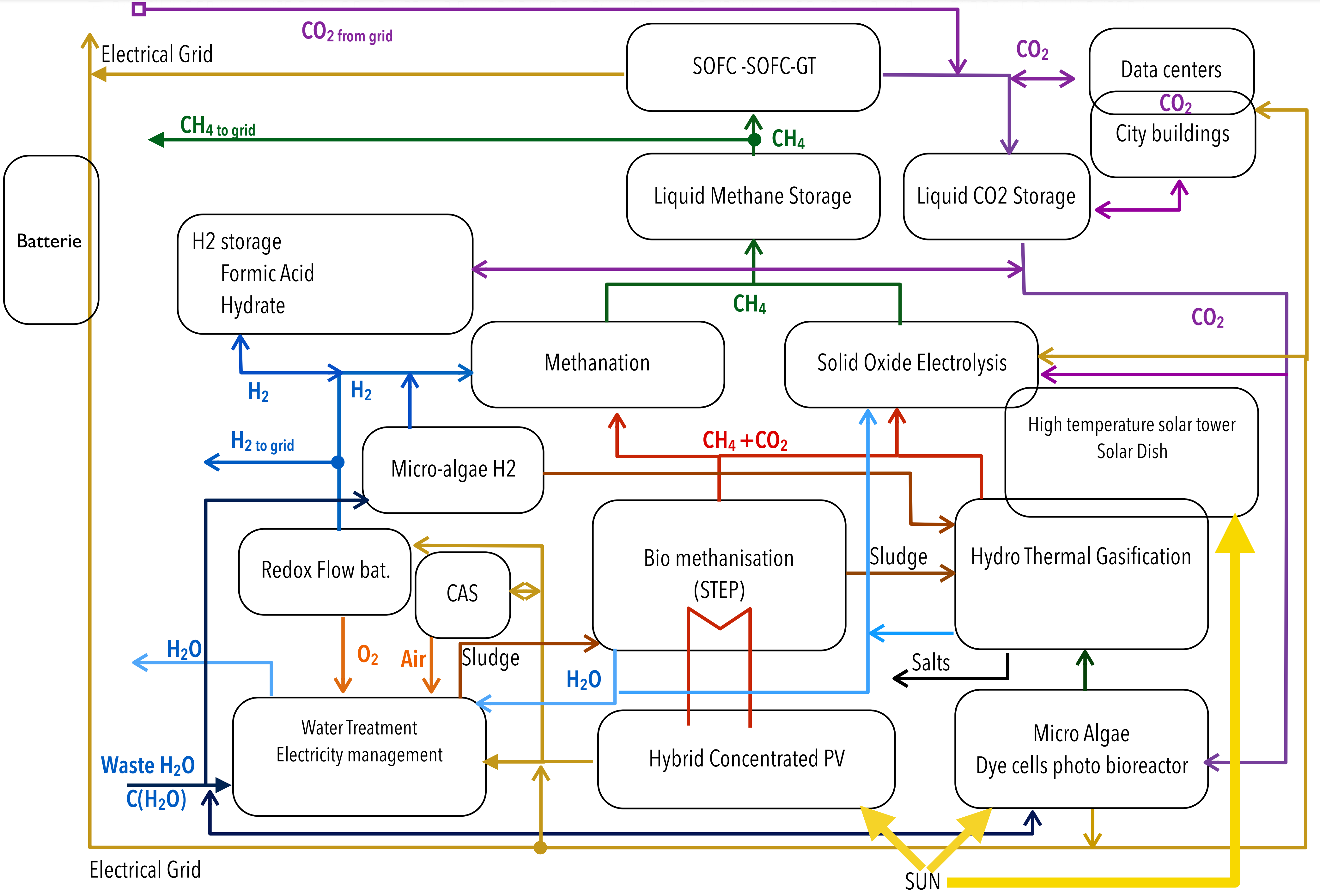
Heat demand = 440 W/hab

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

Biogenic carbon valorisation at the waste water treatment plant



CO_2 from grid

Electrical Grid

SOFC -SOFC-GT

CO_2

Data centers

CO_2

City buildings

CH_4 to grid

CH_4

Liquid Methane Storage

Liquid CO2 Storage

Batterie

H2 storage
Formic Acid
Hydrate

CH_4

CO_2

Methanation

Solid Oxide Electrolysis

H_2

H_2

High temperature solar tower
Solar Dish

H_2 to grid

Micro-algae H2

$CH_4 + CO_2$

Redox Flow bat.

CAS

Bio methanisation
(STEP)

Sludge

Hydro Thermal Gasification

H_2O

O_2

Air

Sludge

H_2O

Salts

Water Treatment
Electricity management

Hybrid Concentrated PV

Micro Algae
Dye cells photo bioreactor

Waste H_2O

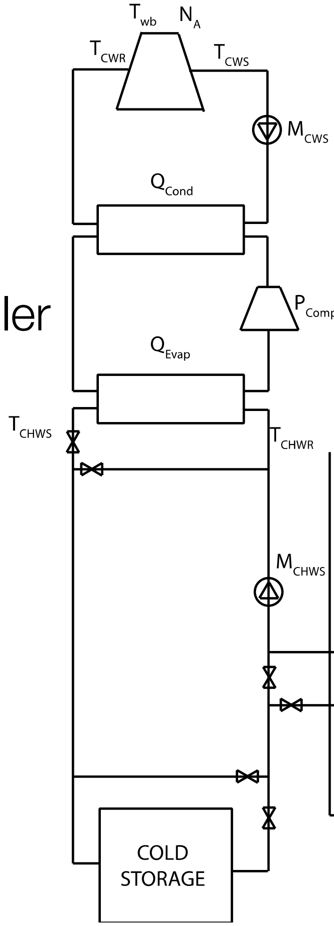
$C(H_2O)$

Electrical Grid

SUN

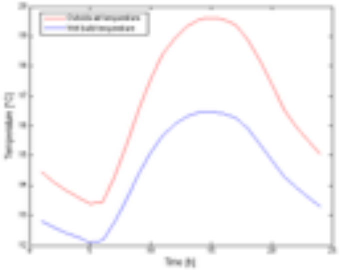
Other services : Data center integration

- Air flow management
- Chiller
- Ice Cold storage
- Heat source for the district



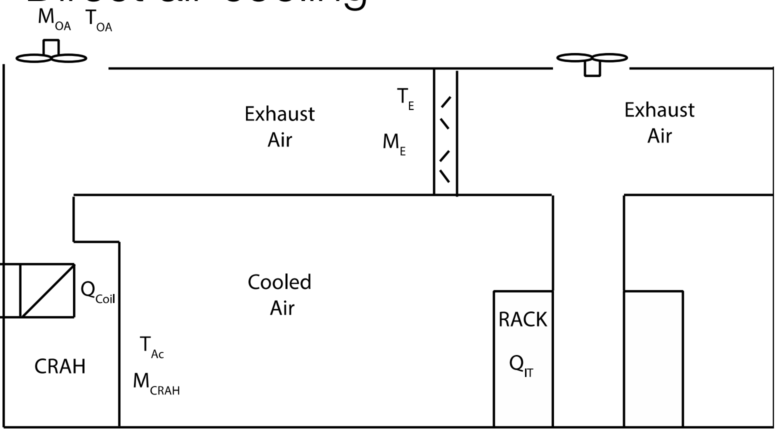
Cooling tower

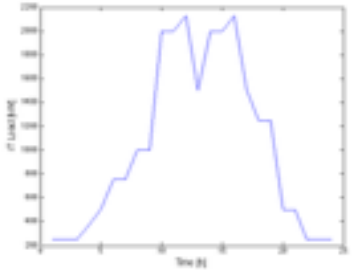
Chiller



Ambient T

Direct air cooling



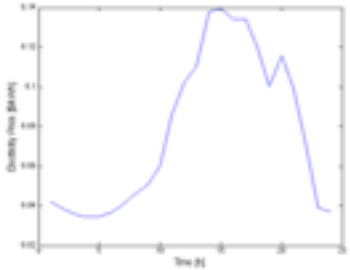


Electricity price

Ice Storage

Server Operation

Operation temperature



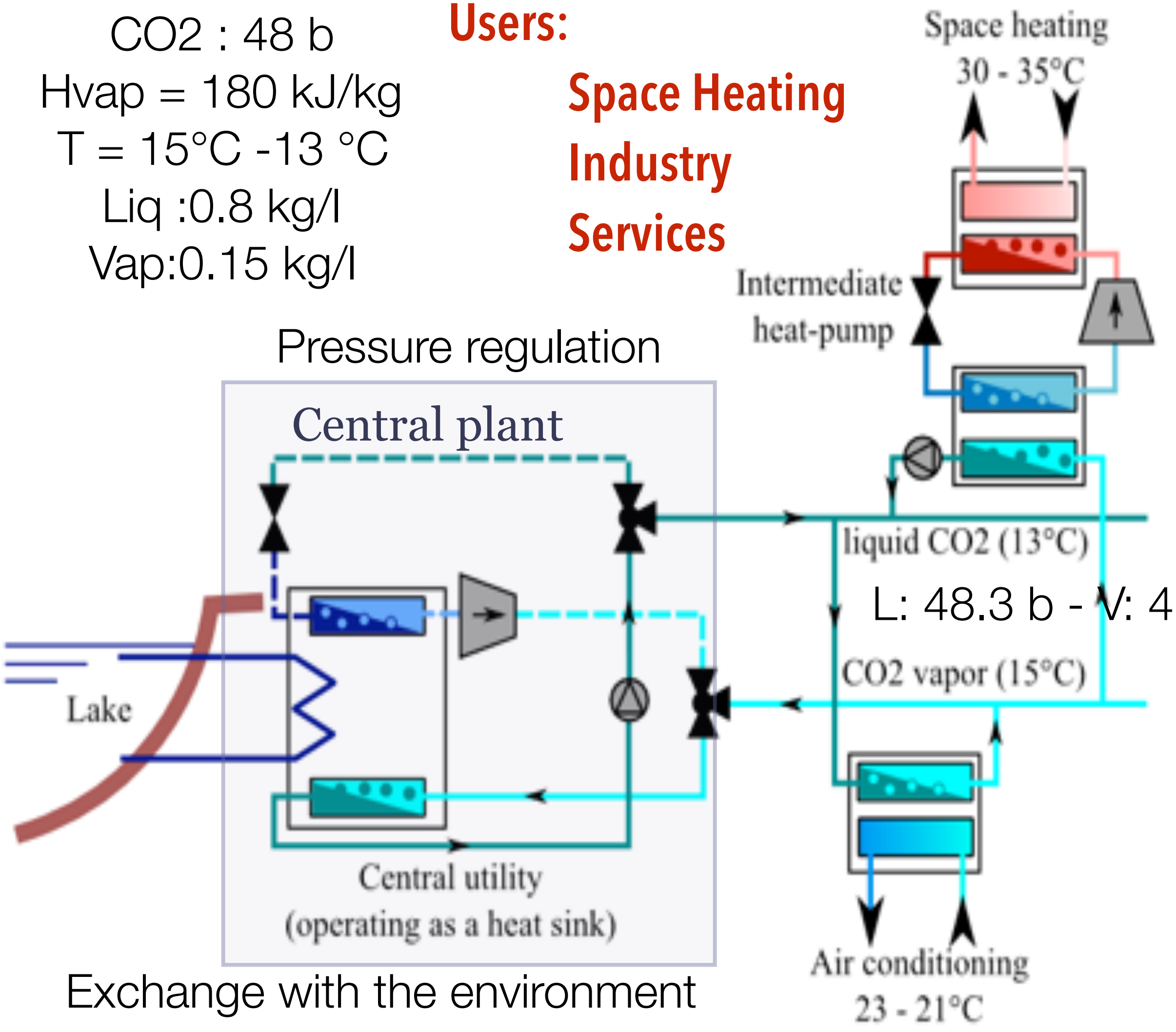
CO2 District heating network for multiple sources

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

Users:

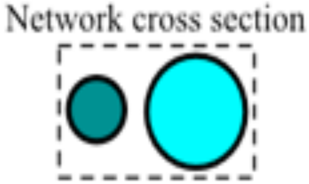
- **Space Heating**
- **Industry**
- **Services**

Pressure regulation



L: 48.3 b - V: 47.3 b

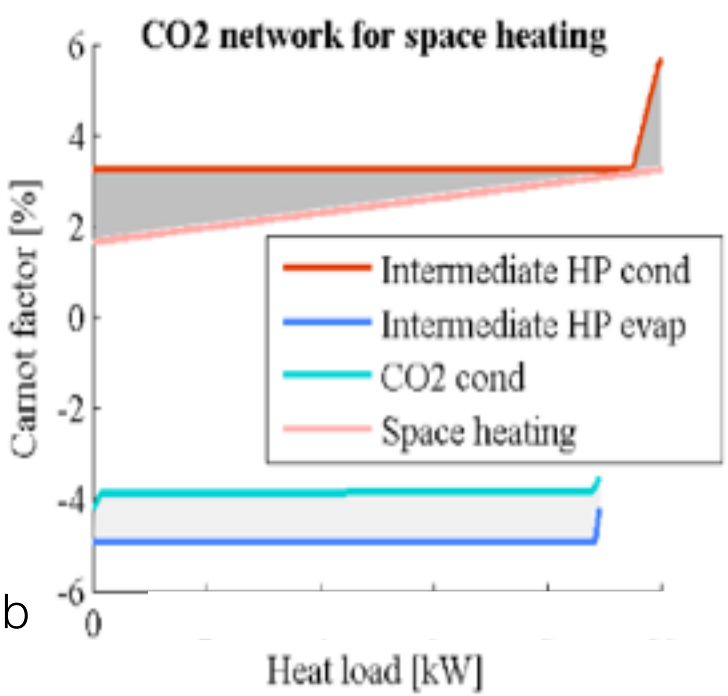
Exchange with the environment

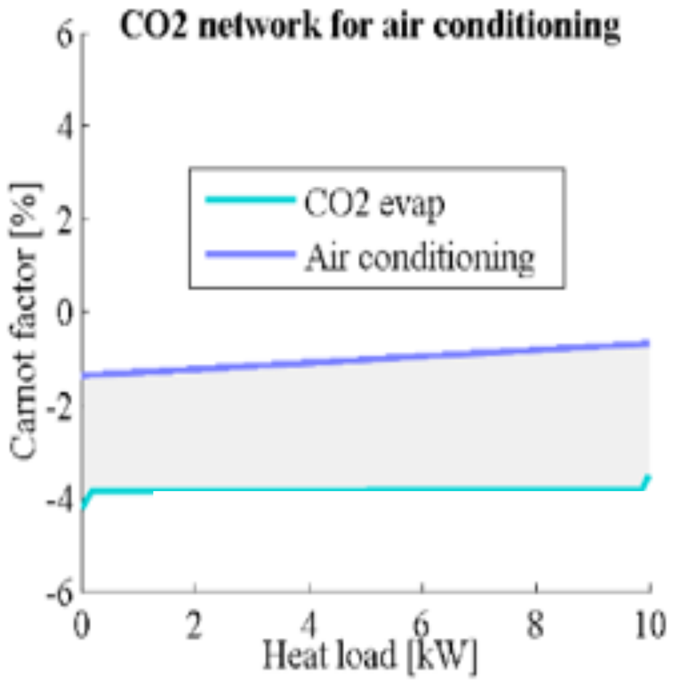


Cross section = Cross section water/4

Users:

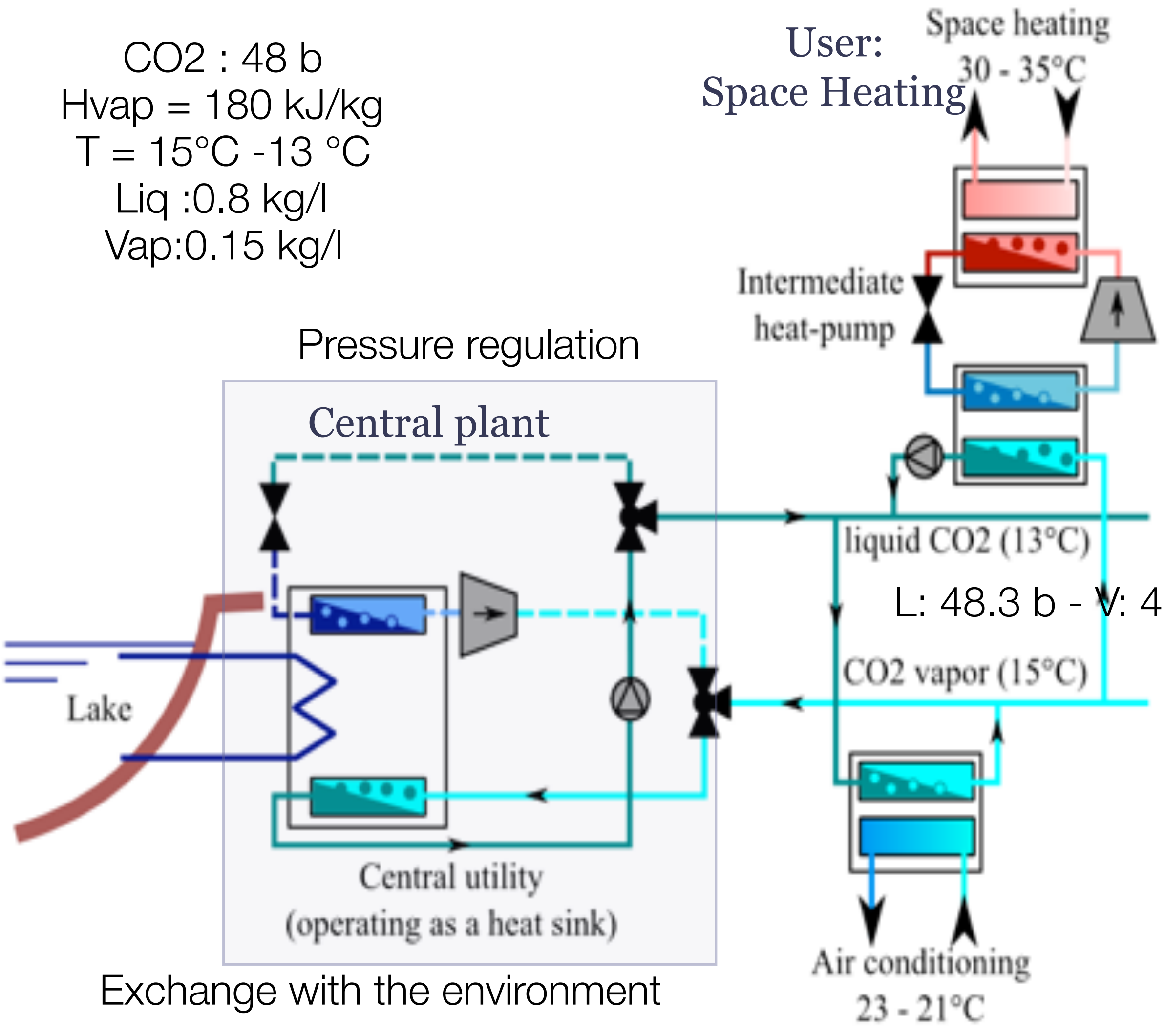
- **Air Conditioning**
- **Data centers**
- **Refrigeration**





CO2 District heating/cooling network

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



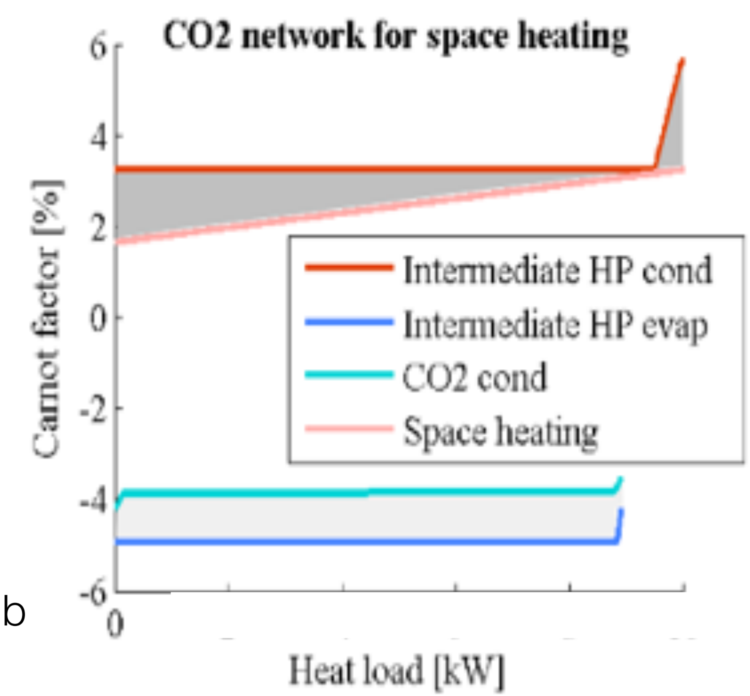
User:
Space Heating

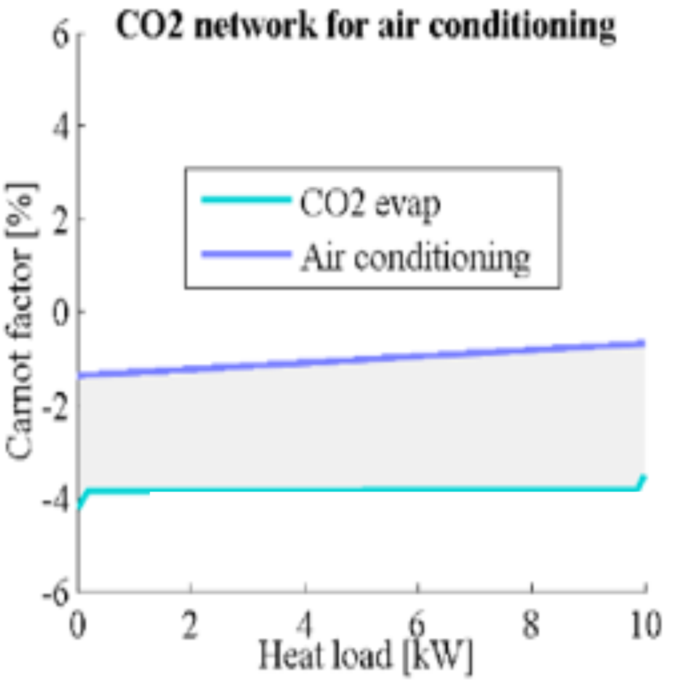
Pressure regulation

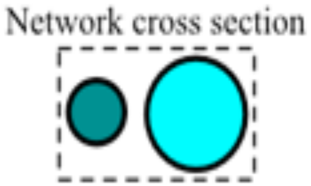
L: 48.3 b - V: 47.3 b

Exchange with the environment

User:
Air Conditioning



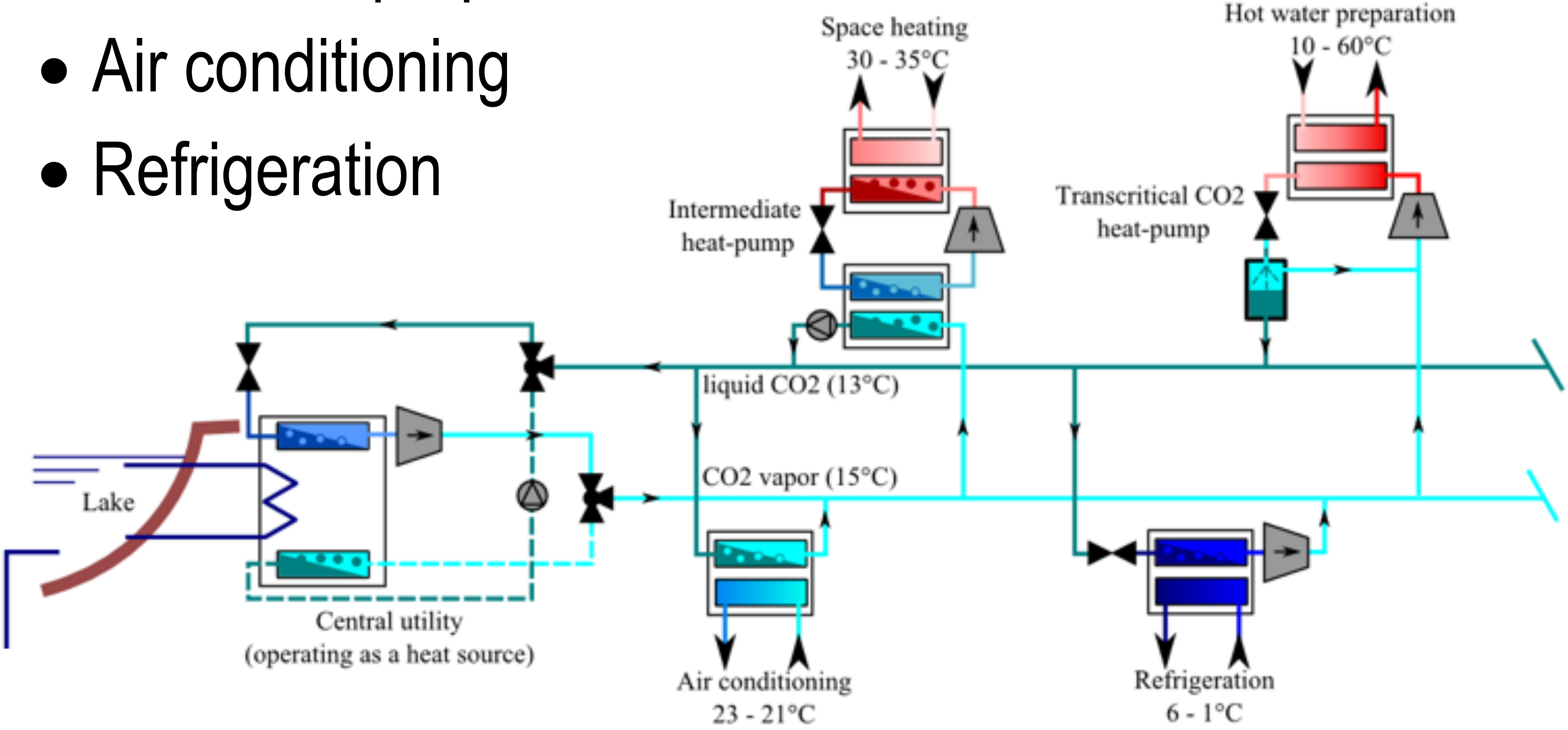




Cross section = Cross section water/4

Advanced CO2 based district energy networks

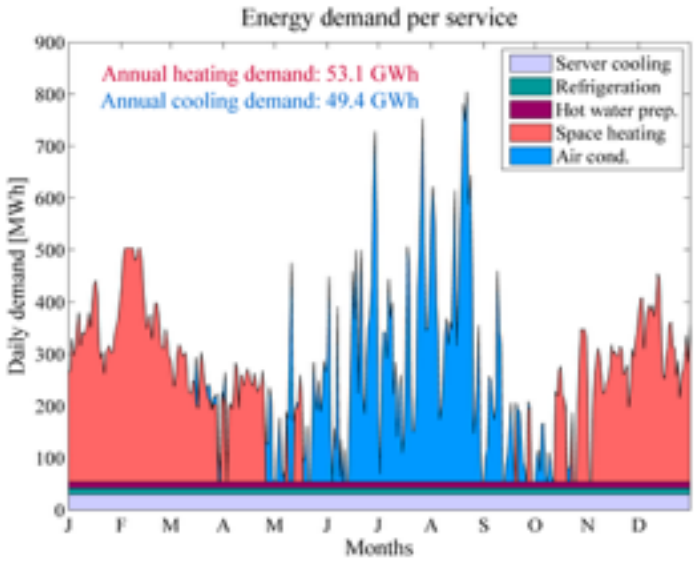
- Space Heating
- Hot water preparation
- Air conditioning
- Refrigeration

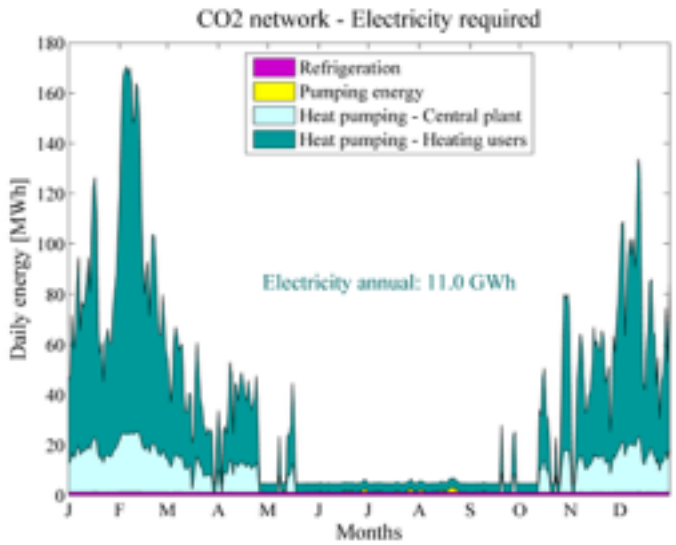


Advanced district heating/cooling systems for urban systems

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

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

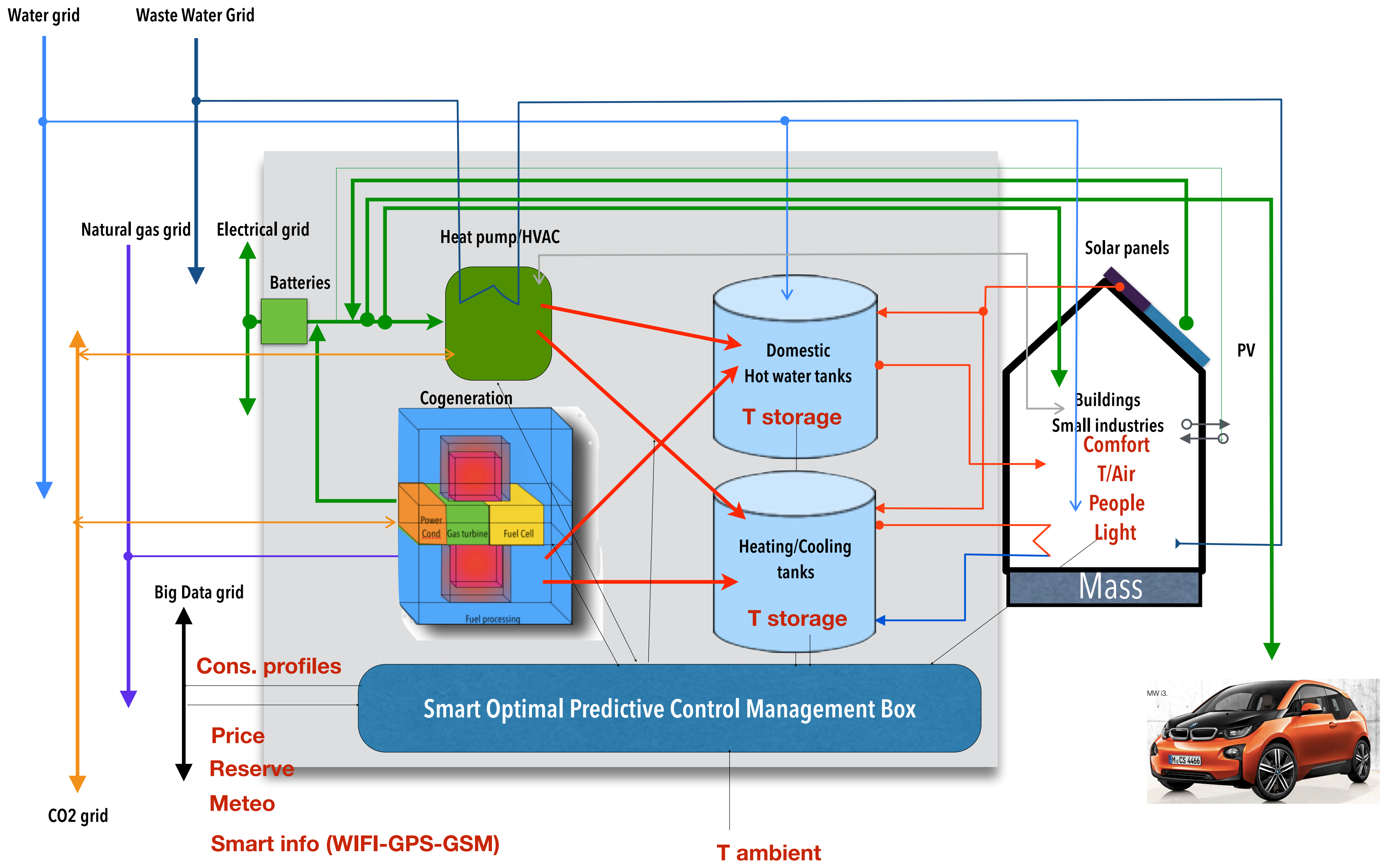




- Present situation
  - Oil : 57 GWh/year
  - Electricity : 10.5 GWh/year
- CO2 network integration
  - Electricity consumption : 11 GWh/year
    - User heat pumps : 7.7 GWh/year
    - Central Heat pump : 2.7 GWh/year
    - Refrigeration : 0.5 GWh/year
    - Pumps : 0.2 GWh/year
- Comparison
  - Reduction by **84%** of the primary energy consumption
  - Profitability analysis : break-even in 5 years
  - 56 % of the energy services cost is investment (certain)
  - 0.07 cts/kWh of services

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

Smart Household System Integrated



Water grid

Waste Water Grid

Natural gas grid

Electrical grid

Batteries

Heat pump/HVAC

Solar panels

PV

Domestic
Hot water tanks
T storage

Cogeneration

Power Cond

Gas turbine

Fuel Cell

Fuel processing

Buildings
Small industries

Comfort
T/Air
People
Light

Mass

Heating/Cooling
tanks
T storage

Big Data grid

Cons. profiles

Smart Optimal Predictive Control Management Box

Price
Reserve
Meteo

CO2 grid

Smart info (WIFI-GPS-GSM)

T ambient

Virtua power plant

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

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

Subject to : Heat cascade constraints

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

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

Electricity consumption

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

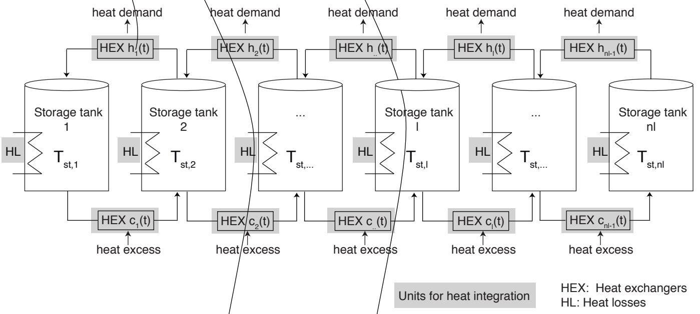
Electricity production

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

Energy conversion Technology selection

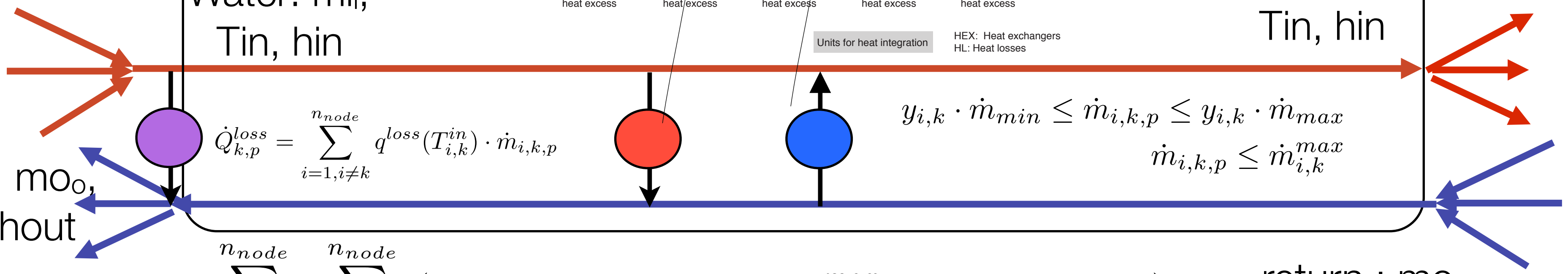
$$fmin_w y_w \leq f_w \leq fmax_w y_w \qquad y_w \in \{0, 1\}$$

Storage system



HEX: Heat exchangers
HL: Heat losses

Buildings inertia
Batteries



Water: mi$_i$,
Tin, hin

Water: mi$_o$,
Tin, hin

return : mo$_o$,
Tout, hout

return : mo$_i$,
Tin, hin

$$\dot{Q}^{loss}_{k,p} = \sum_{i=1, i\neq k}^{n_{node}} q^{loss}(T^{in}_{i,k}) \cdot \dot{m}_{i,k,p}$$

$$y_{i,k} \cdot \dot{m}_{min} \leq \dot{m}_{i,k,p} \leq y_{i,k} \cdot \dot{m}_{max}$$

$$\dot{m}_{i,k,p} \leq \dot{m}^{max}_{i,k}$$

$$Cost_{pipe} = \sum_{i=1, i\neq k}^{n_{node}} \sum_{k=1, k\neq i}^{n_{node}} (y_{i,k} \cdot cf_{pipe} \cdot length_{i,k} + \dot{m}^{max}_{i,k} \cdot cd_{pipe} \cdot length_{i,k})$$

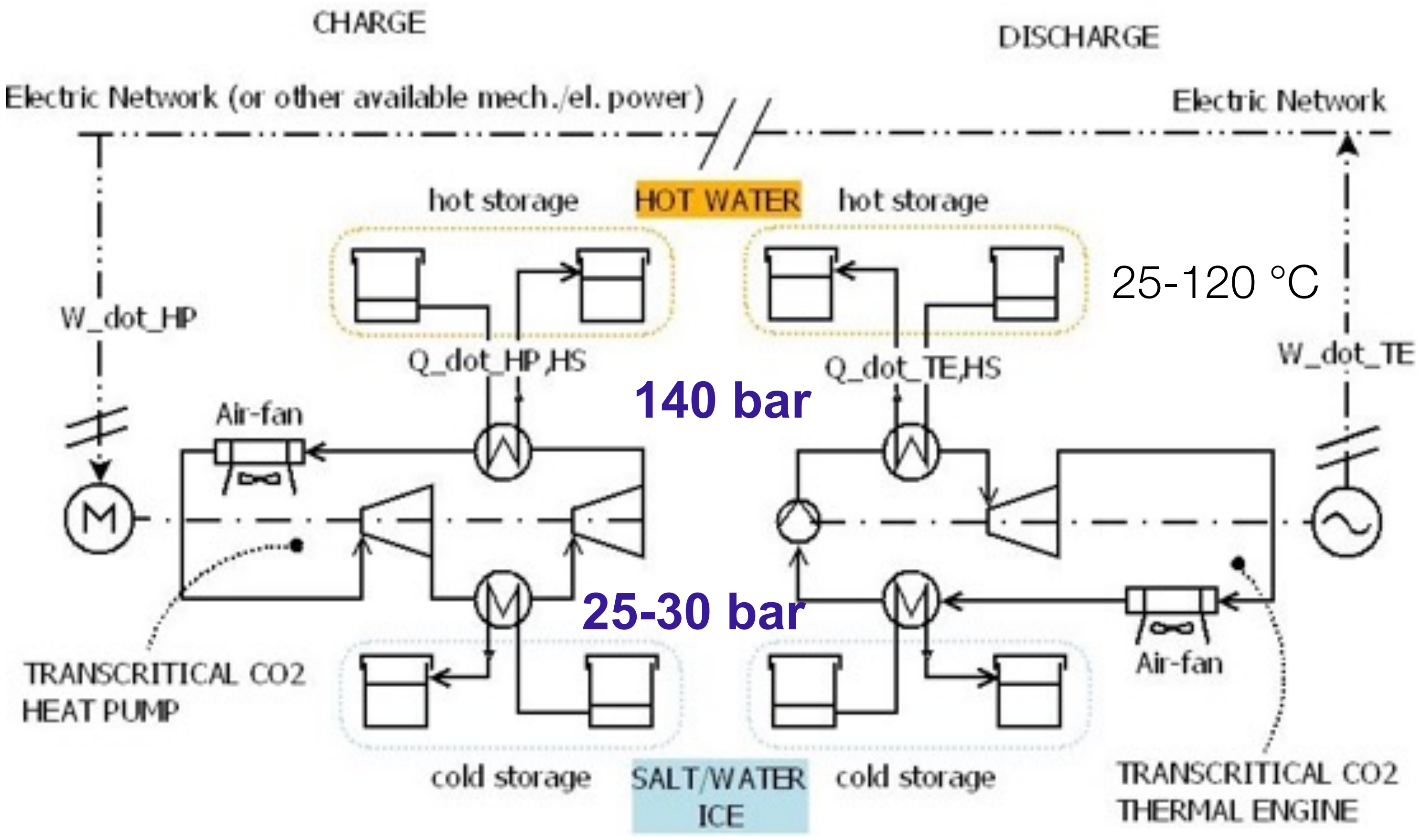
$$\dot{E}_{pump,i,k,p} = y_{i,k} \cdot e^0_{pipe} \cdot length_{i,k} + \dot{m}_{i,k,p} \cdot e^1_{pipe,i,k}$$

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

Electro Thermal Storage (ETES - ABB) (daily)

Round-trip eff.: 60%

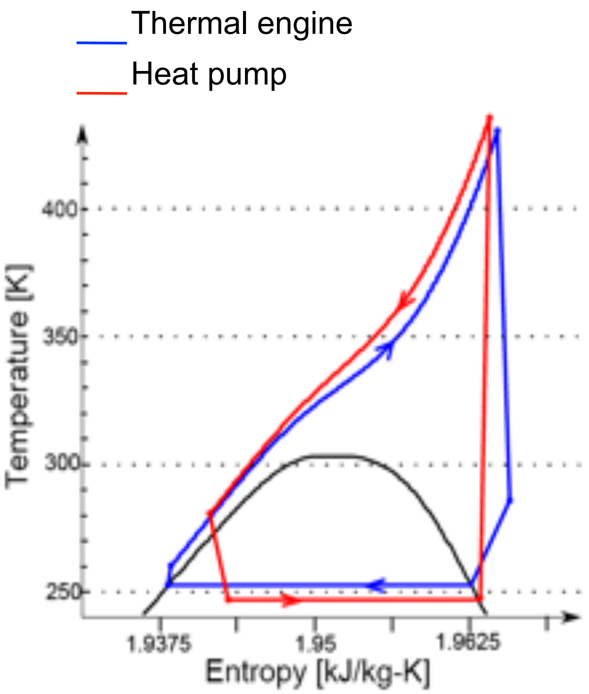
Hot Water Storage
Transcritical CO_2 cycles



25-120 °C

140 bar

25-30 bar

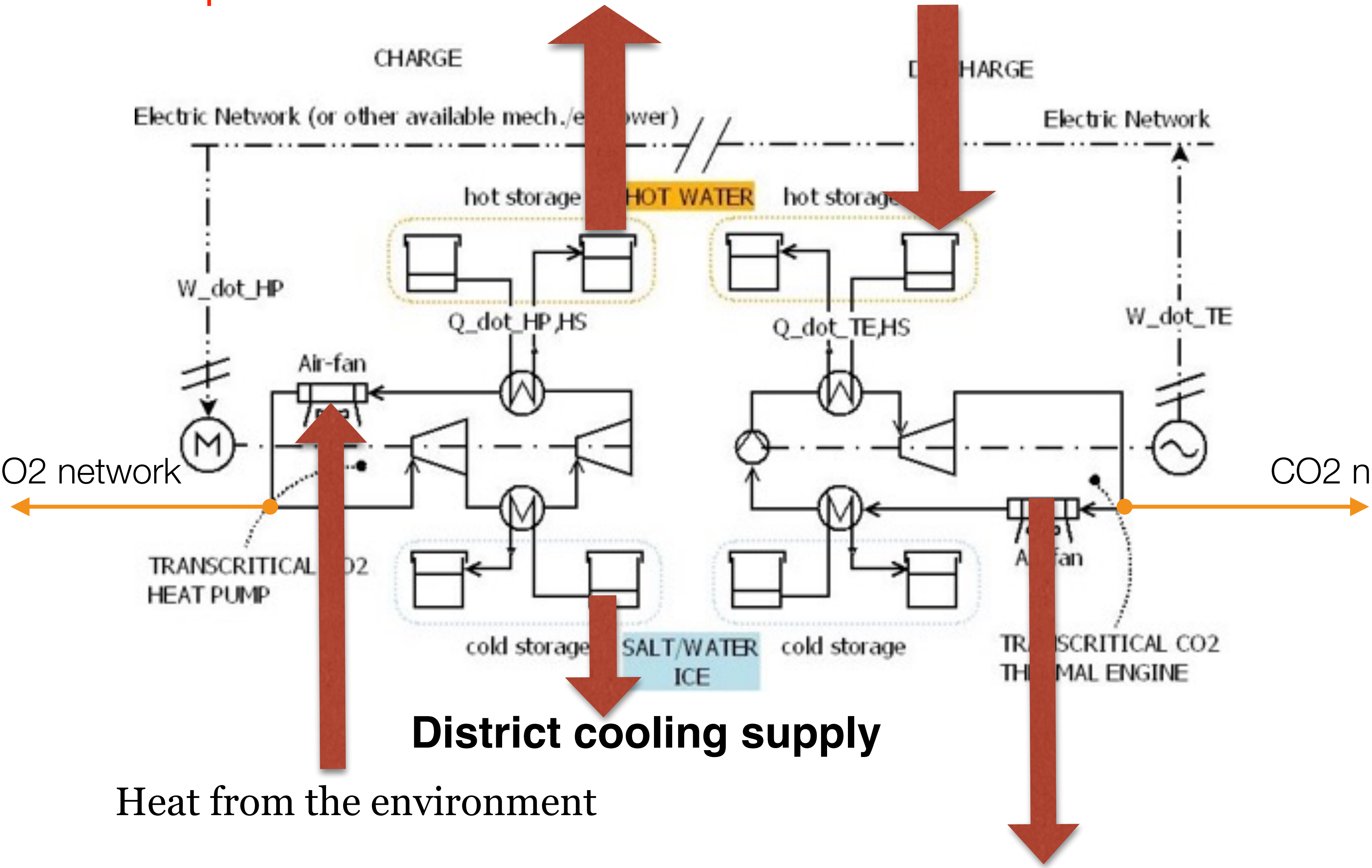


Morandin, Matteo, François Maréchal, Mehmet Mercangöz, and Florian Buchter. “Conceptual Design of a Thermo-Electrical Energy Storage System Based on Heat Integration of Thermodynamic Cycles – Part B: Alternative System Configurations.” Energy 45, no. 1 (September 2012): 386–396..

ETES & district heating/cooling (daily)

Round-trip eff.: 60%

Waste heat : 40 %



District heating supply

Solar Heat
Waste heat

CO2 network

CO2 network

District cooling supply

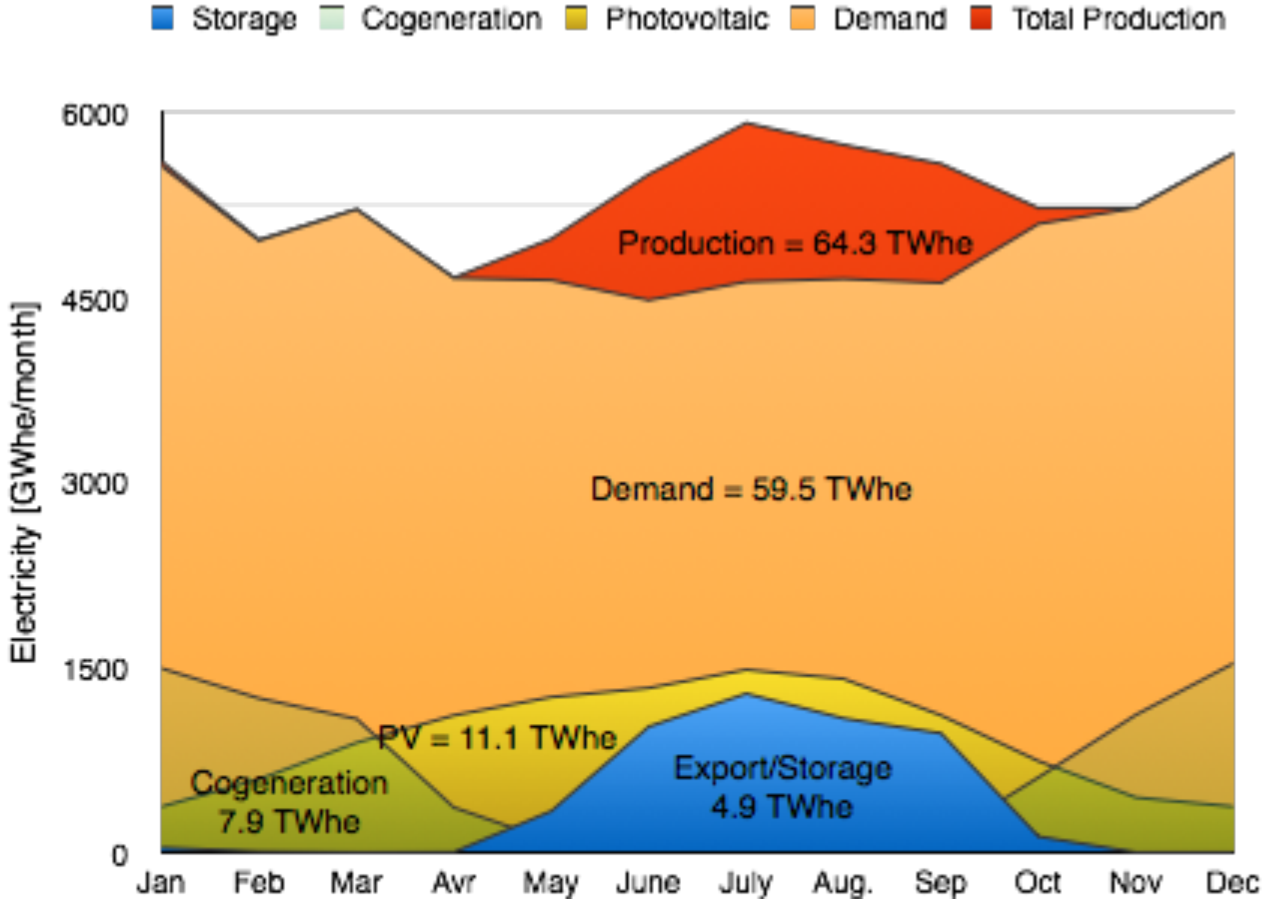
Heat from the environment

Heat to the environment

Producing Electricity using renewables

- Who is going to use the extra amount in the Summer ?

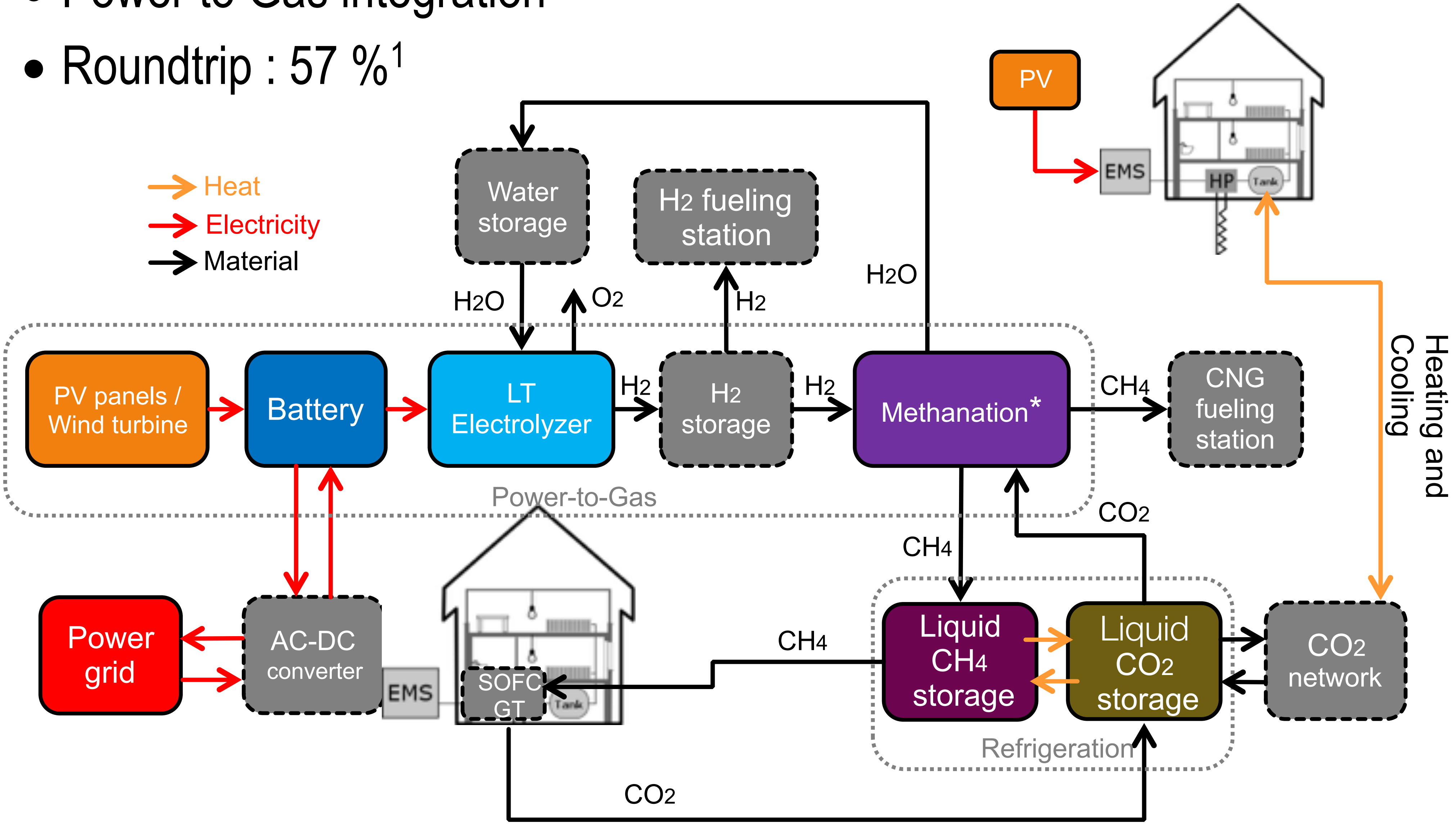
Scenario 2050 : OFEN / Low



http://www.energyscope.ch

Long term electricty storage

- Power to Gas integration
- Roundtrip : 57 %[1]



Heat

Electricity

Material

Water storage

H_2 fueling station

PV

EMS

HP

Tank

H_2O

O_2

H_2

H_2O

PV panels / Wind turbine

Battery

LT Electrolyzer

H_2

H_2 storage

H_2

Methanation*

CH_4

CNG fueling station

Heating and Cooling

Power-to-Gas

CO_2

CH_4

Power grid

AC-DC converter

EMS

SOFC GT

Tank

CH_4

Liquid CH_4 storage

Liquid CO_2 storage

CO_2 network

Refrigeration

CO_2

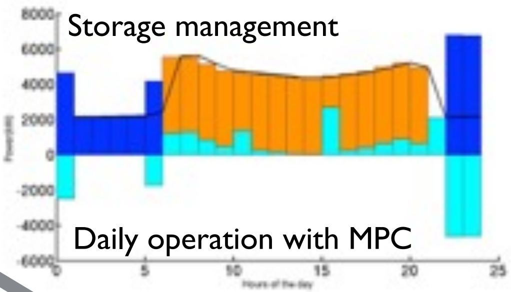
* $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ + heat

[1] Easa I. Al-musleh, Dharik S. Mallapragada, and Rakesh Agrawal. Continuous power supply from a baseload renewable power plant. Applied Energy, 122:83–93, 2014.

Autonomuous District

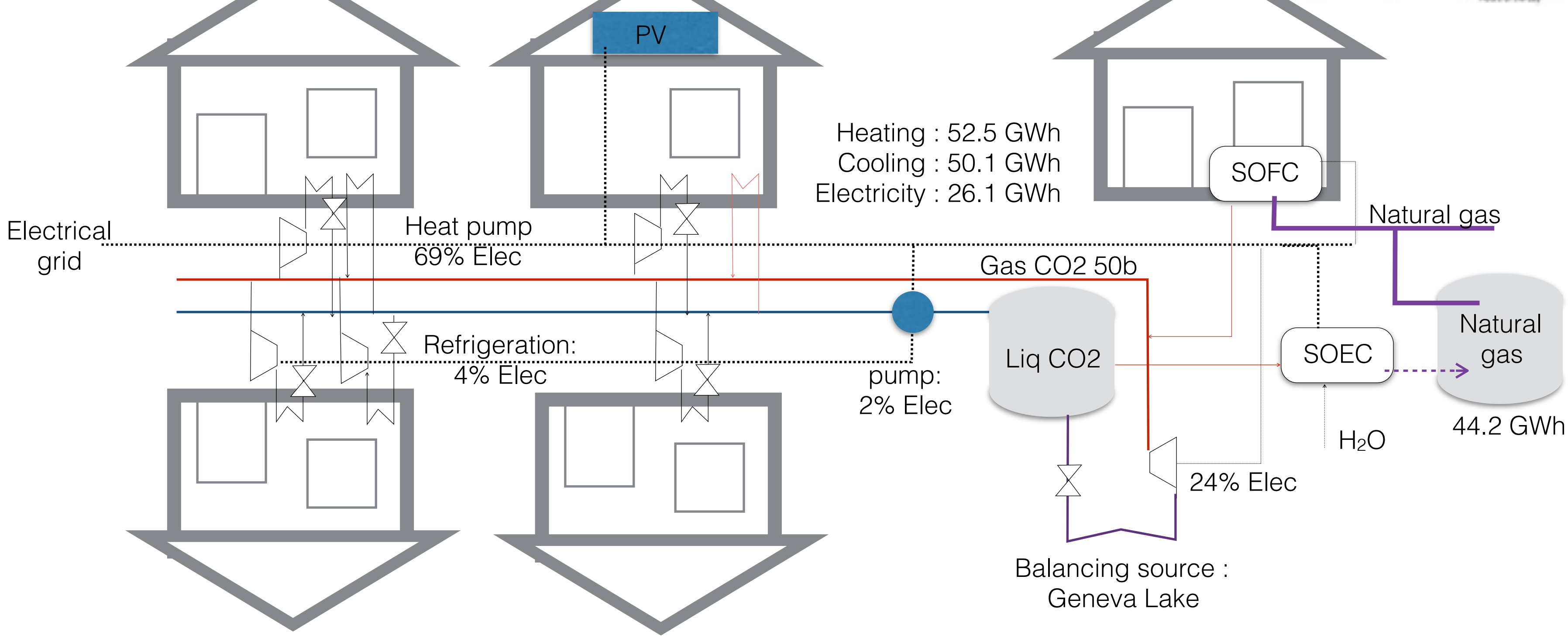
Complex system with heating and cooling : (ERA) 687'800 m^2

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


Storage management

Daily operation with MPC

Renewable Electricity : 66.5 GWh
PV Panel area : 0.8 m2/ m2 heated



Heating : 52.5 GWh
Cooling : 50.1 GWh
Electricity : 26.1 GWh

Electrical grid

Heat pump
69% Elec

Refrigeration:
4% Elec

pump:
2% Elec

Gas CO2 50b

Liq CO2

SOFC

Natural gas

SOEC

Natural gas

H_2O

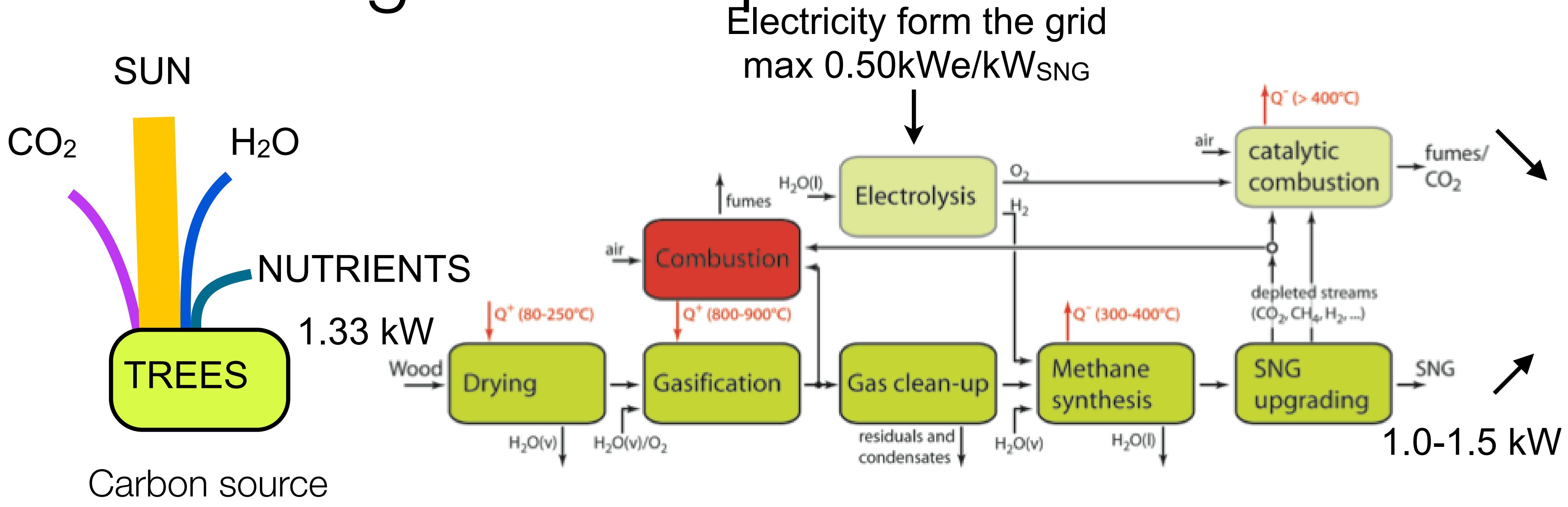
44.2 GWh

24% Elec

Balancing source :
Geneva Lake

- The CO2 network integration : reduction by **84%** of the primary energy consumption
- Combined with SOFC cogeneration : savings reach **88** %
- Combined with renovation : savings reach **92** % !

Power to gas concept



Electricity form the grid
max 0.50kWe/kWSNG

SUN

CO_2

H_2O

NUTRIENTS

TREES

1.33 kW

Carbon source

1.0-1.5 kW

WOOD — Natural Gas — CO2 (pure)

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

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

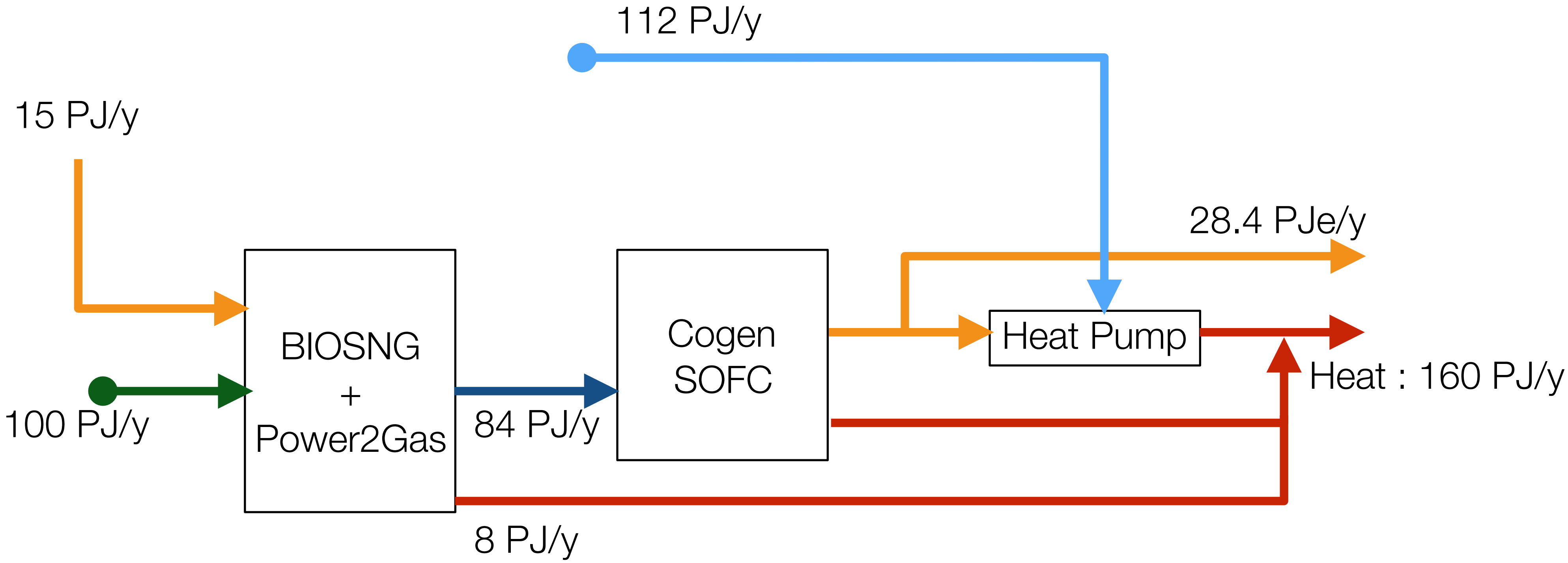
$$\Delta E^+ + 4H_2O \rightarrow +\ 4\ H_2 \quad +\ 2\ O_2$$

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.

Biomass as a resource



Swiss Energy Scope : Total Heat demand 2050 : 160 PJ/y

No more wood available for Heating

Heat →
Electricity →
Natural Gas →
Biomass →
Env. →

Conclusions & Perspective

- **Data Structuring**
  - Geographic clustering => Out layers
  - Typical days structuring => Extreme days
- **Superstructure modelling**
  - Building models for typical days
  - Energy conversion technologies
  - Storage tanks
  - Material flows integration
  - Heat/cold distribution networks
  - Heat cascade models
- **Master-Slave decomposition optimisation**
  - Multi-objective optimisation techniques => improved DFO algorithms
  - MILP models => Superstructure + piece wize linearisation strategies
    - Operation strategy
    - Interconnections models
- **Uncertainty & Risk**
  - Uncertainty analysis
  - Stochastic optimisation
  - Robust Optimisation

Thanks to my co-workers

- **Jakob Rager, Samira Fazlollahi, Nils Schüler, Leandro Salgueiro, Stefano Moret, Alexandre Bertrand, Jean Loup Robineau**
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    - Dubuis, Matthias. “Energy System Design under Uncertainty.” EPFL, 2012.
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