
Optimisation models for district energy system design

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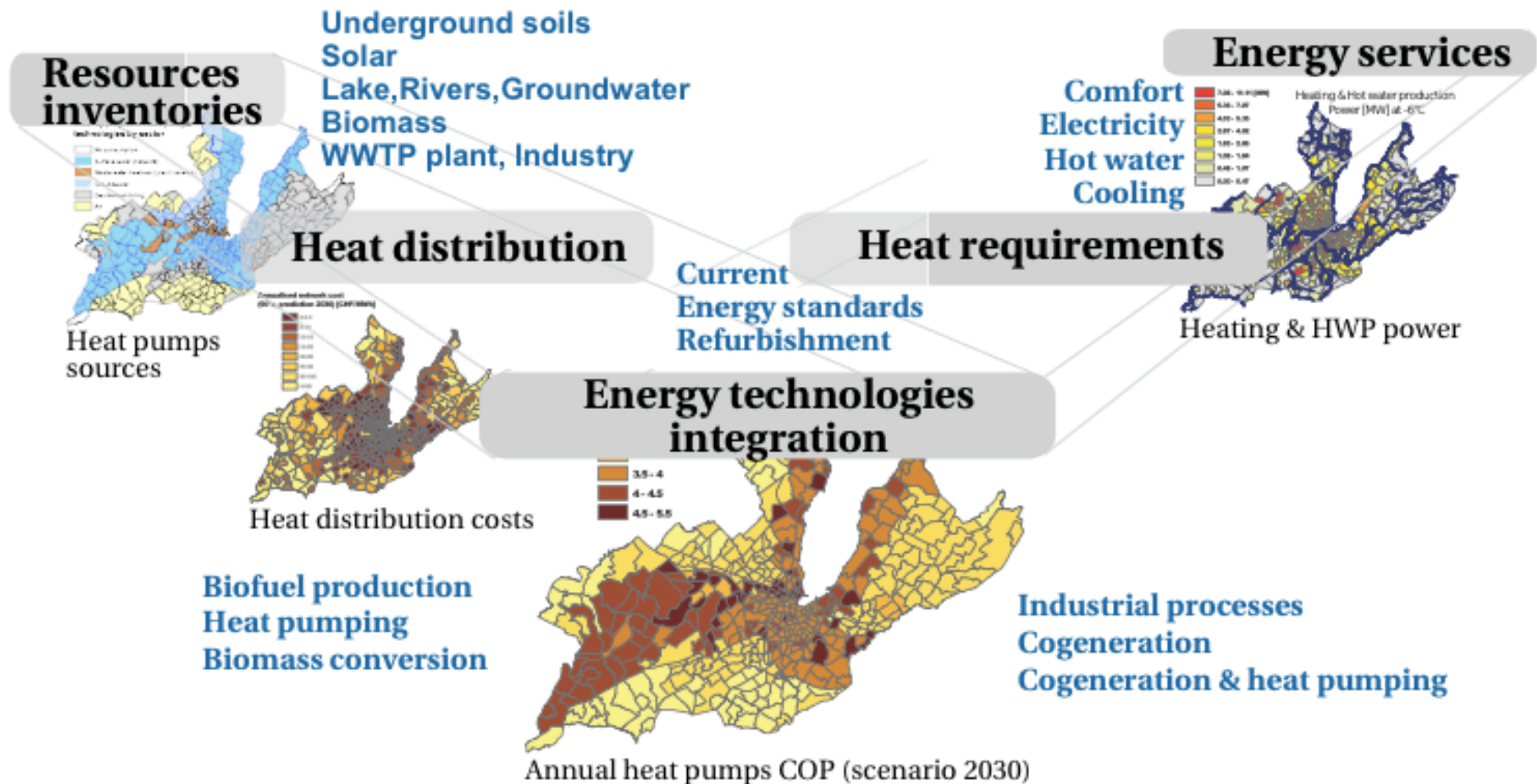
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<http://ipese.epfl.ch>

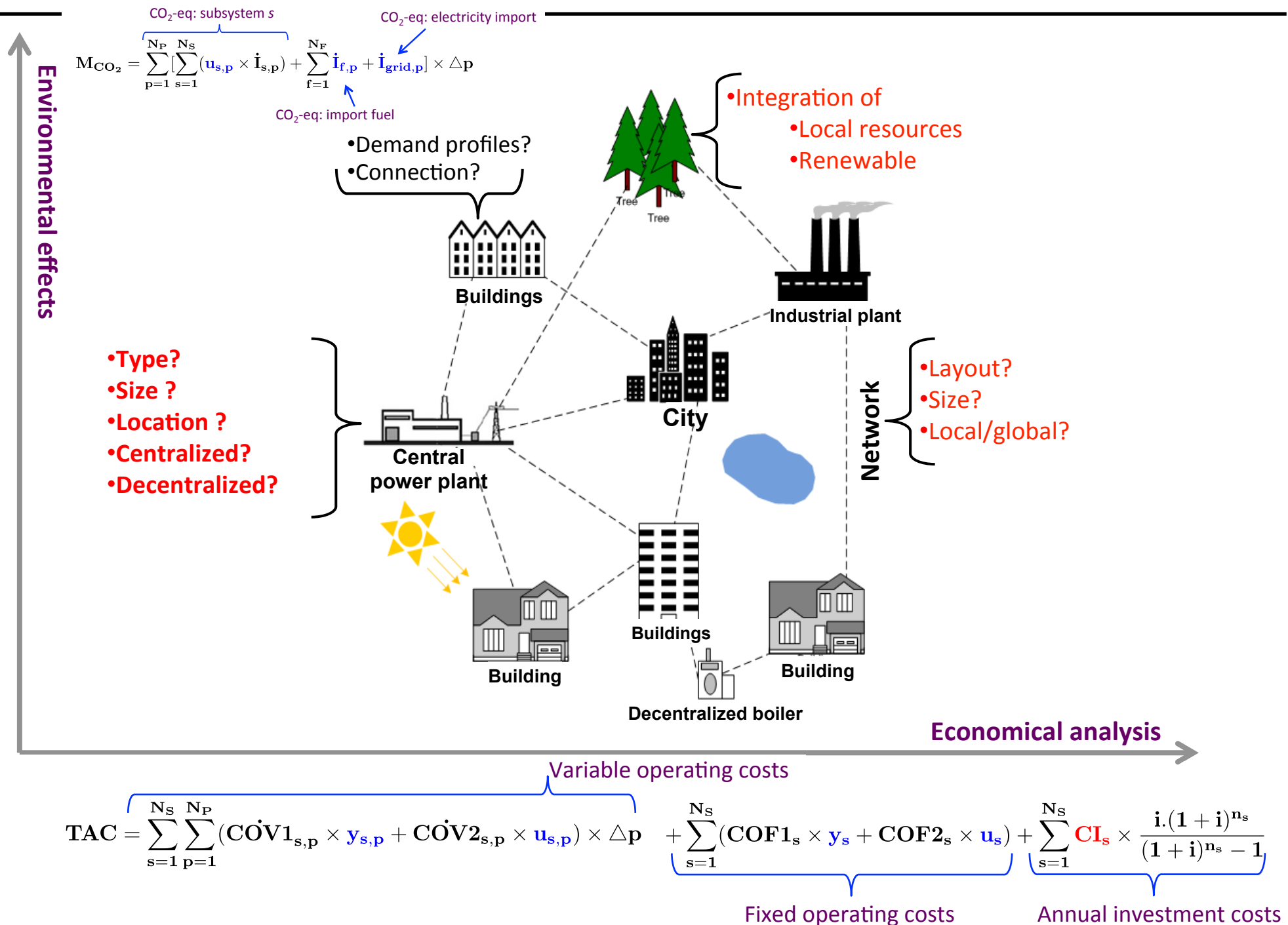
Content

- Energy system models
- Energy system integration
 - Defining the requirement & Resources
 - Energy conversion
 - Networks integration
- Multi objective environomic optimisation
 - Problem statement
 - Optimisation strategy
 - Optimisation tricks
- Conclusions

A multi dimension approach



Problem statement



Multi scale approach

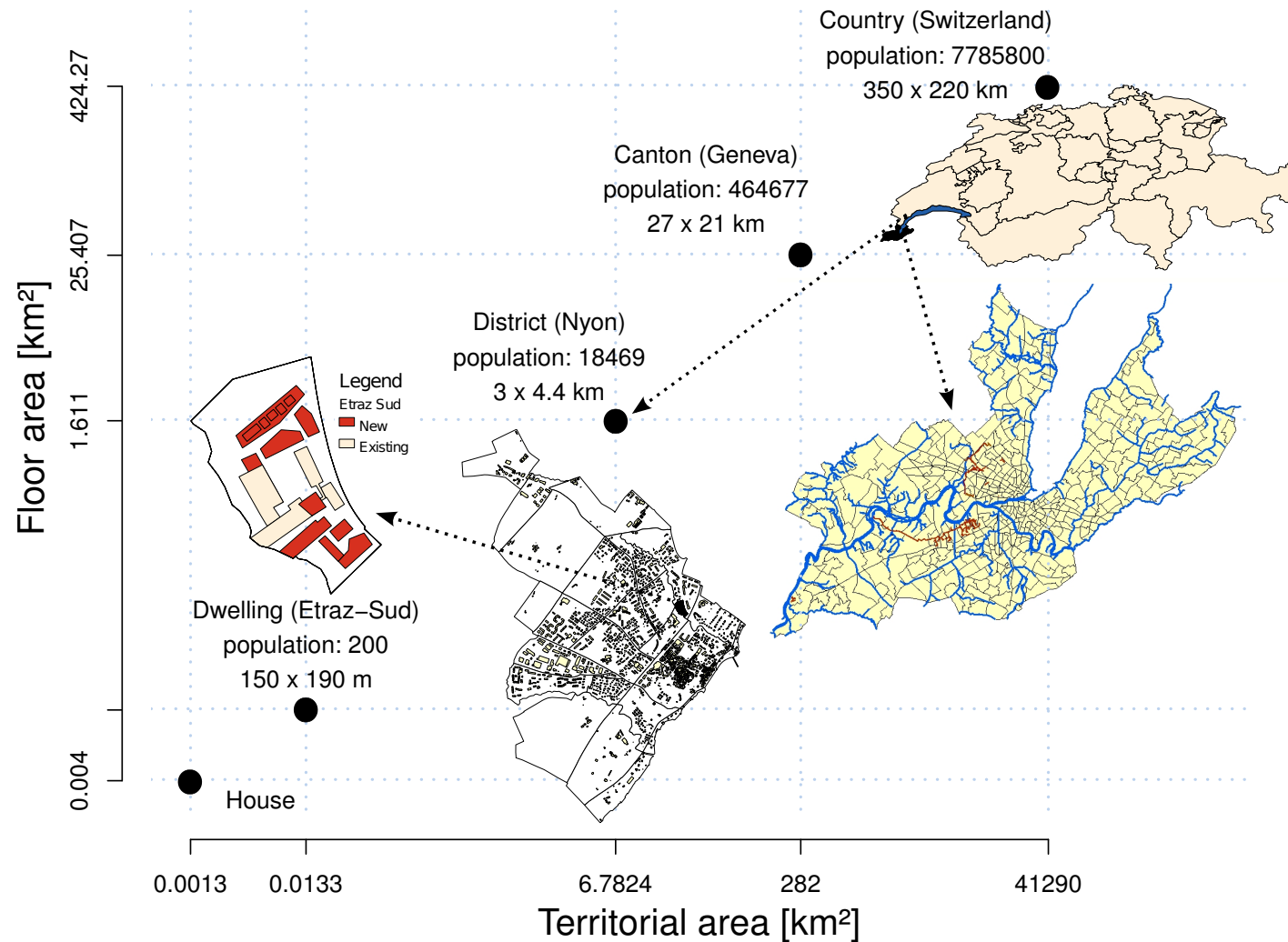


Figure 1.15: Log-log plot of the magnitude of the spatial scale to deal with in urban studies.

Energy system design : Industrial Ecology Concepts

- For a given city : select the optimal energy system
 - Integration of processes in the urban system

40'000 inhabitants city in Switzerland (1000m alt.)



Energy services to be supplied:

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

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

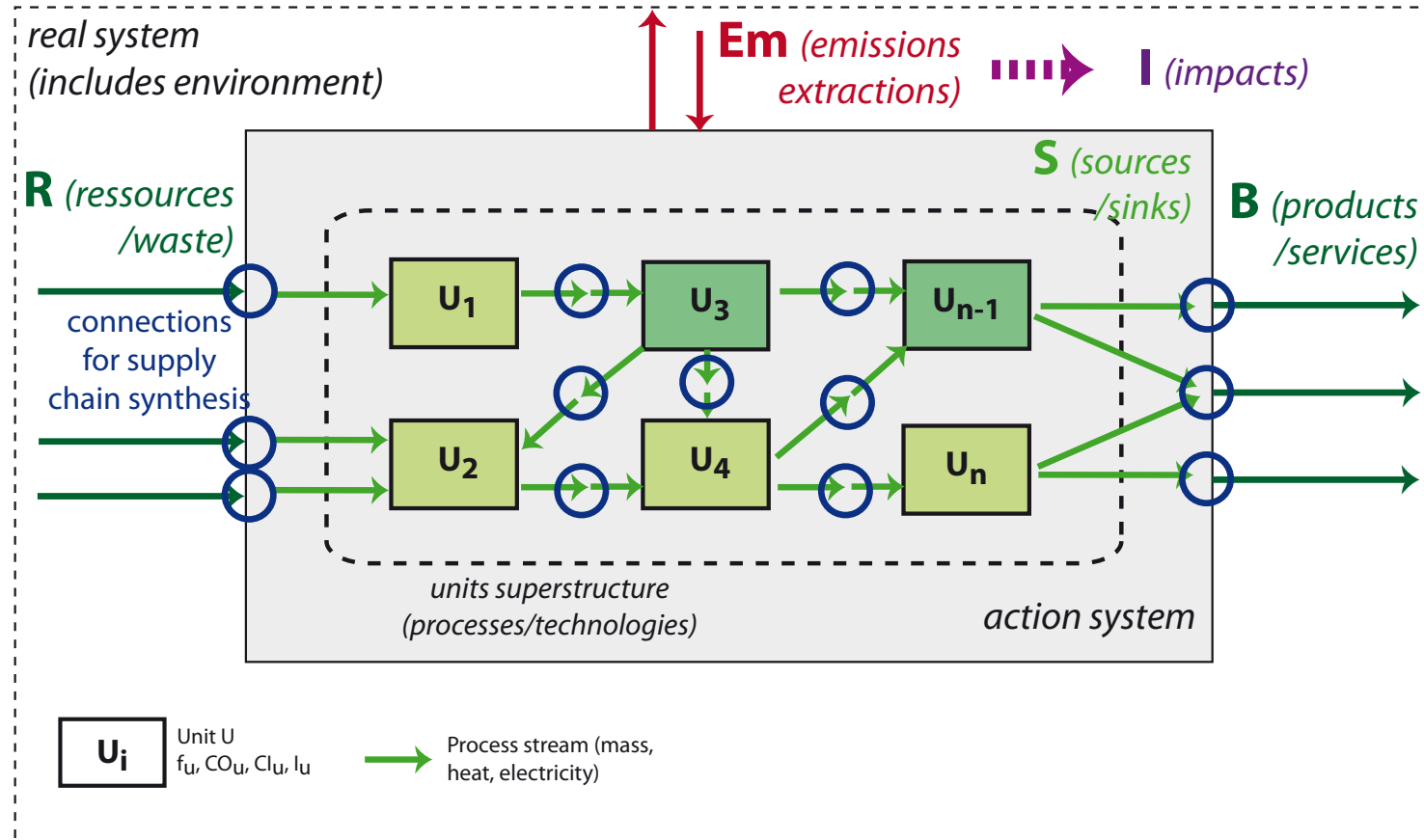
- ▶ MSW: **1375 kg/yr/cap**
- ▶ Wastewater: **300 m³/yr/cap**
- ▶ Biowaste: **87.5 kg/yr/cap**

Available endogenous resources:

- ▶ Woody biomass: 18'900 MWh_{th}/yr
- ▶ Geothermal: 9496 MWh_{th}/yr
- ▶ Sun (seasonal variation in T and load): 10'328 MWh_{th}/yr
- ▶ Hydro (existing dams): 187'850 MWh_e/yr

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

Superstructure generation and supply chain synthesis



Heat balance

► Heat cascade

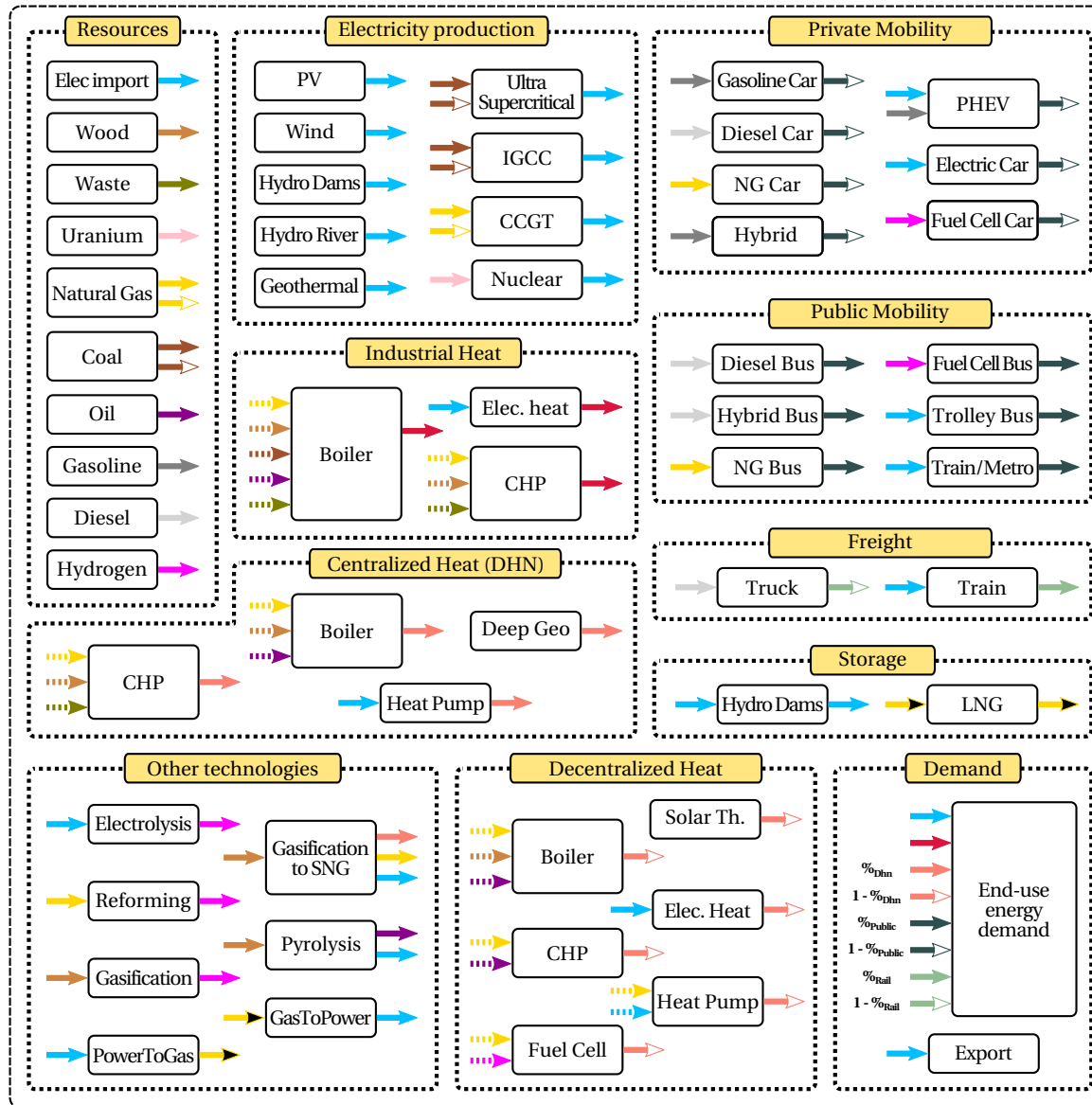
Mass balance

► Mass balance for each source/sink

Environmental impact

► Choose the supply chain

Input-output models for Swiss Energy System in energyscope.ch



Legend

Electricity [GW]	Natural Gas [GW]	Public Mobility [Mpkkm/h]	Heat Low T DHN [GW]
Uranium [GW]	NG (CCS) [GW]	Private Mobility [Mpkkm/h]	Heat Low T Decen [GW]
Oil [GW]	LNG [GW]	Freight Rail [Mtkm/h]	Heat High T [GW]
Diesel [GW]	Coal [GW]	Freight Road [Mtkm/h]	
Gasoline [GW]	Coal (CCS) [GW]	Waste [GW]	
	Hydrogen [GW]	Wood [GW]	

Inputs →
 Optional Inputs →
 Outputs →

Moret et al., Applied Energy, 2017

Linear programming multi period model

$$\min C_{\text{tot}} = \sum_{j \in \text{TECH}} (\tau(j) C_{\text{inv}}(j) + C_{\text{maint}}(j)) + \sum_{i \in \text{RES}} C_{\text{op}}(i) \quad (1.1)$$

$$\text{s.t. } \tau(j) = \frac{i_{\text{rate}}(i_{\text{rate}} + 1)^{n(j)}}{(i_{\text{rate}} + 1)^{n(j)} - 1} \quad \forall j \in \text{TECH} \quad (1.2)$$

$$C_{\text{inv}}(j) = c_{\text{inv}}(j) F(j) \quad \forall j \in \text{TECH} \quad (1.3)$$

$$C_{\text{maint}}(j) = c_{\text{maint}}(j) F(j) \quad \forall j \in \text{TECH} \quad (1.4)$$

$$\text{GWP}_{\text{constr}}(j) = \text{gwp}_{\text{constr}}(j) F(j) \quad \forall j \in \text{TECH} \quad (1.5)$$

$$f_{\text{min}}(j) \leq F(j) \leq f_{\text{max}}(j) \quad \forall j \in \text{TECH} \quad (1.6)$$

$$N(j) f_{\text{ref}}(j) = F(j) \quad \forall j \in \text{TECH} \quad (1.7)$$

$$F_t(j, t) \leq F(j) c_{p,t}(j, t) \quad \forall j \in \text{TECH}, \forall t \in T \quad (1.8)$$

$$\sum_{t \in T} F_t(j, t) t_{\text{op}}(t) \leq F(j) c_p(j) \sum_{t \in T} t_{\text{op}}(t) \quad \forall j \in \text{TECH} \quad (1.9)$$

$$C_{\text{op}}(i) = \sum_{t \in T} c_{\text{op}}(i, t) F_t(i, t) t_{\text{op}}(t) \quad \forall i \in \text{RES} \quad (1.10)$$

$$\text{GWP}_{\text{op}}(i) = \sum_{t \in T} \text{gwp}_{\text{op}}(i, t) F_t(i, t) t_{\text{op}}(t) \quad \forall i \in \text{RES} \quad (1.11)$$

$$\sum_{t \in T} F_t(i, t) t_{\text{op}}(t) \leq \text{avail}(i) \quad \forall i \in \text{RES} \quad (1.12)$$

$$\sum_{i \in \text{RES} \cup \text{TECH} \setminus \text{STO}} f(i, l) F_t(i, t) + \sum_{j \in \text{STO}} (\text{Sto}_{\text{out}}(j, l, t) - \text{Sto}_{\text{in}}(j, l, t)) - \text{EndUses}(l, t) = 0 \quad \forall l \in L, \forall t \in T \quad (1.13)$$

$$F_t(j, t) = F_t(j, t-1) + t_{\text{op}}(t) \cdot \left(\sum_{l \in L | \eta_{\text{sto}, \text{in}}(j, l) > 0} \text{Sto}_{\text{in}}(j, l, t) \eta_{\text{sto}, \text{in}}(j, l) - \sum_{l \in L | \eta_{\text{sto}, \text{out}}(j, l) > 0} \text{Sto}_{\text{out}}(j, l, t) / \eta_{\text{sto}, \text{out}}(j, l) \right) \quad \forall j \in \text{STO}, \forall t \in T \quad (1.14)$$

$$\text{Sto}_{\text{in}}(j, l, t) (\lceil \eta_{\text{sto}, \text{in}}(j, l) \rceil - 1) = 0 \quad \forall j \in \text{STO}, \forall l \in L, \forall t \in T \quad (1.15)$$

$$\text{Sto}_{\text{out}}(j, l, t) (\lceil \eta_{\text{sto}, \text{out}}(j, l) \rceil - 1) = 0 \quad \forall j \in \text{STO}, \forall l \in L, \forall t \in T \quad (1.16)$$

$$\left\lceil \sum_{l \in L | \eta_{\text{sto}, \text{in}}(j, l) > 0} \text{Sto}_{\text{in}}(j, l, t) / m(j, l, t) \right\rceil + \left\lceil \sum_{l \in L | \eta_{\text{sto}, \text{out}}(j, l) > 0} \text{Sto}_{\text{out}}(j, l, t) / m(j, l, t) \right\rceil \quad \forall j \in \text{STO}, \forall t \in T \quad (1.17)$$

$$\text{Loss}(eut, t) = \left(\sum_{i \in \text{RES} \cup \text{TECH} \setminus \text{STO} | f(j, k) > 0} f(j, k) F_t(j, t) \right) \%_{\text{loss}}(eut) \quad \forall eut \in \text{EUT}, \forall t \in T \quad (1.18)$$

$$F_t(j, t) + F_t(k, t) Y_{\text{Solar}}(j) \geq \frac{\text{EndUses}(\text{HeatLowTDHN}, t) + \text{EndUses}(\text{HeatLowTDec}, t)}{\text{endUsesInput}(\text{HeatLowTSH}) + \text{endUsesInput}(\text{HeatLowTHW})} \sum_{t \in T} F_t(j, t) t_{\text{op}}(t) \quad k = \text{DecSolar}, \forall j \in \text{TECH OF EUT}(\text{HeatLowTDec}) \setminus \{k\}, \forall t \in T \quad (1.19)$$

$$\sum_{j \in \text{TECH}} Y_{\text{Solar}}(j) \leq 1 \quad (1.20)$$

MILP model

$$\sum_{j' \in \text{TECH OF EUT}(eut)} f_{\min, \%}(j) \sum_{t \in T} \mathbf{F}_t(j', t) t_{op}(t) \leq \sum_{t \in T} \mathbf{F}_t(j, t) t_{op}(t) \leq \sum_{j' \in \text{TECH OF EUT}(eut)} f_{\max, \%}(j) \sum_{t \in T} \mathbf{F}_t(j', t) t_{op}(t) \quad \forall eut \in EUT, \forall j \in \text{TECH OF EUT}(eut) \quad (1.22)$$

$$\mathbf{F}_t(j, t) \sum_{t \in T} t_{op}(t) \geq \sum_{t \in T} \mathbf{F}_t(j, t) t_{op}(t) \quad \forall j \in \text{TECH OF EUC}(\text{MobPass}) \cup \text{TECH OF EUC}(\text{MobFreight}), \forall t \in T \quad (1.23)$$

$$\mathbf{F}(\text{StoHydro}) \leq f_{\max}(\text{StoHydro}) \frac{\mathbf{F}(\text{NewHydroDam}) - f_{\min}(\text{NewHydroDam})}{f_{\max}(\text{NewHydroDam}) - f_{\min}(\text{NewHydroDam})} \quad (1.24)$$

$$\mathbf{Sto}_{\text{in}}(\text{StoHydro}, \text{Elec}, t) \leq \mathbf{F}_t(\text{HydroDam}, t) + \mathbf{F}_t(\text{NewHydroDam}, t) \quad \forall t \in T \quad (1.25)$$

$$\mathbf{F}(\text{DHN}) \geq \sum_{j \in \text{TECH OF EUT}(\text{HeatLowTDHN})} \mathbf{F}(j) \quad (1.26)$$

$$\sum_{j \in \text{TECH OF EUT}(\text{HeatLowTDHN})} \mathbf{F}(j) \geq \%_{\text{Peak}_{\text{DHN}}} \max_{t \in T} \{\mathbf{EndUses}(\text{HeatLowTDHN}, t)\} \quad (1.27)$$

$$\mathbf{F}(\text{Grid}) \geq \frac{9400}{c_{\text{inv}}(\text{Grid})} \frac{\mathbf{F}(\text{Wind}) + \mathbf{F}(\text{PV})}{f_{\max}(\text{Wind}) + f_{\max}(\text{PV})} \quad (1.28)$$

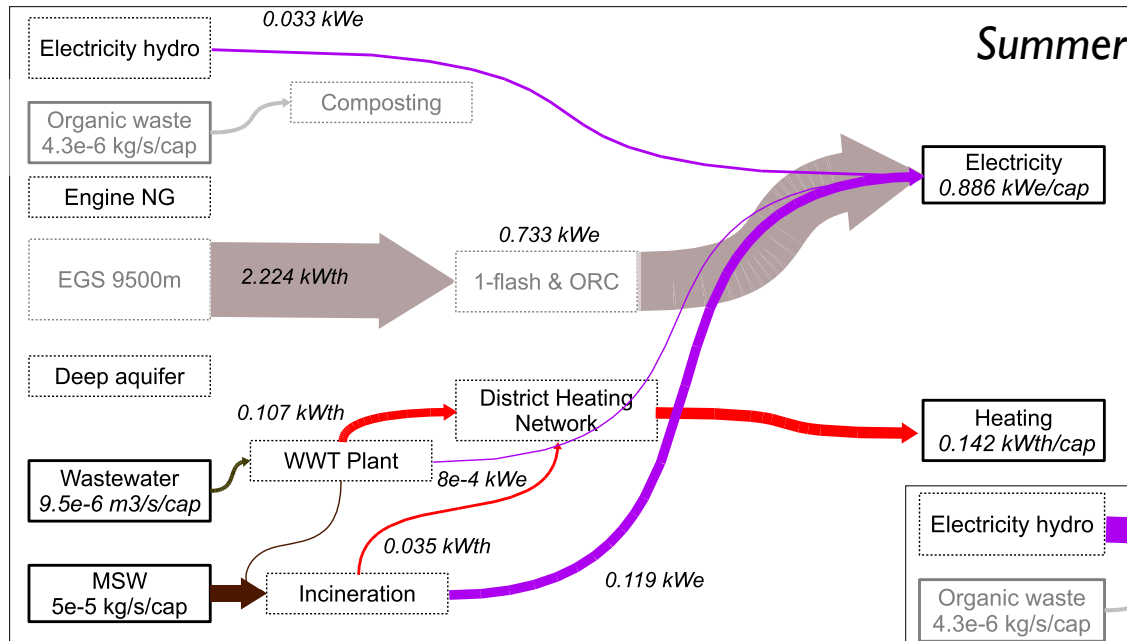
$$\mathbf{F}(\text{PowerToGas}) = \max\{\mathbf{F}(\text{PowerToGas}), \mathbf{F}(\text{GasToPower})\} \quad (1.29)$$

MILP model

Parameter	Units	Description
$endUses_{year}(eui, s)$	[GWh/y] ^a	Annual end-uses in energy services per sector
$endUsesInput(eui)$	[GWh/y] ^a	Total annual end-uses in energy services
$\tau(tech)$	[-]	Investment cost annualization factor
i_{rate}	[-]	Real discount rate
$\%_{public,min}, \%_{public,max}$	[-]	Upper and lower limit to $\%_{Public}$
$\%_{rail,min}, \%_{rail,max}$	[-]	Upper and lower limit to $\%_{Rail}$
$\%_{dhn,min}, \%_{dhn,max}$	[-]	Upper and lower limit to $\%_{Dhn}$
$t_{op}(t)$	[h]	Time periods duration
$\%_{lighting}(t)$	[-]	Yearly share (adding up to 1) of lighting end-uses
$\%_{sh}(t)$	[-]	Yearly share (adding up to 1) of SH end-uses
$f(res \cup tech \setminus sto, l)$	[GW] ^b	Input from (< 0) or output to (> 0) layers. $f(i, j) = 1$ if j is main output layer for technology/resource i
$f_{ref}(tech)$	[GW] ^{bc}	Reference size with respect to main output
$c_{inv}(tech)$	[MCHF/GW] ^{bc}	Technology specific investment cost
$c_{maint}(tech)$	[MCHF/GW/y] ^{bc}	Technology specific yearly O&M cost
$gwp_{constr}(tech)$	[ktCO ₂ -eq./GW] ^{bc}	Technology construction specific GHG emissions
$n(tech)$	[y]	Technology lifetime
$f_{min}, f_{max}(tech)$	[GW] ^{bc}	Min./max. installed size of the technology
$f_{min,\%}, f_{max,\%}(tech)$	[-]	Min./max. relative share of a technology in a layer
$avail(res)$	[GWh/y]	Resource yearly total availability
$c_{p,t}(tech, t)$	[-]	Period capacity factor (default 1)
$c_p(tech)$	[-]	Yearly capacity factor
$c_{op}(res, t)$	[MCHF/GWh]	Specific cost of resources
$gwp_{op}(res)$	[ktCO ₂ -eq./GWh]	Specific GHG emissions of resources
$\eta_{sto,in}, \eta_{sto,out}(sto, l)$	[-]	Efficiency [0; 1] of storage input from/output to layer. Set to 0 if storage not related to layer.
$\%_{loss}(eut)$	[-]	Losses [0; 1] in the networks (grid and DHN)
$\%_{Peak_{DHN}}$	[-]	Ratio peak/max. average DHN heat demand

Seasonal operation (independent multi-period)

- Example of summer and winter system operation

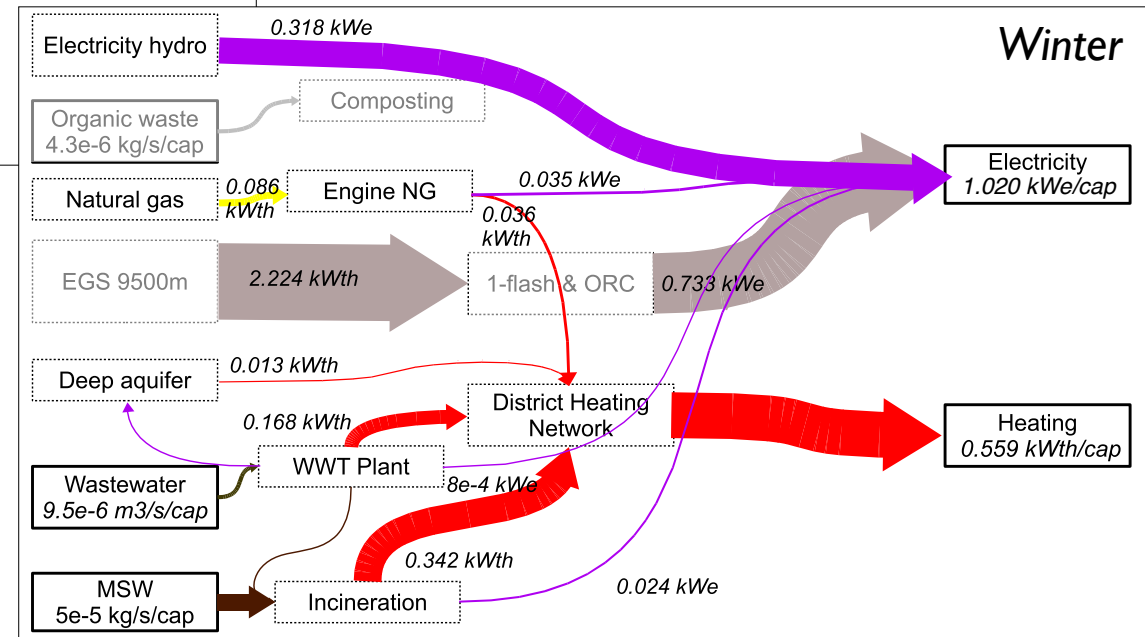


- Seasonal variation in service requirement

- Quantity (heat load)
- Quality (temperature)

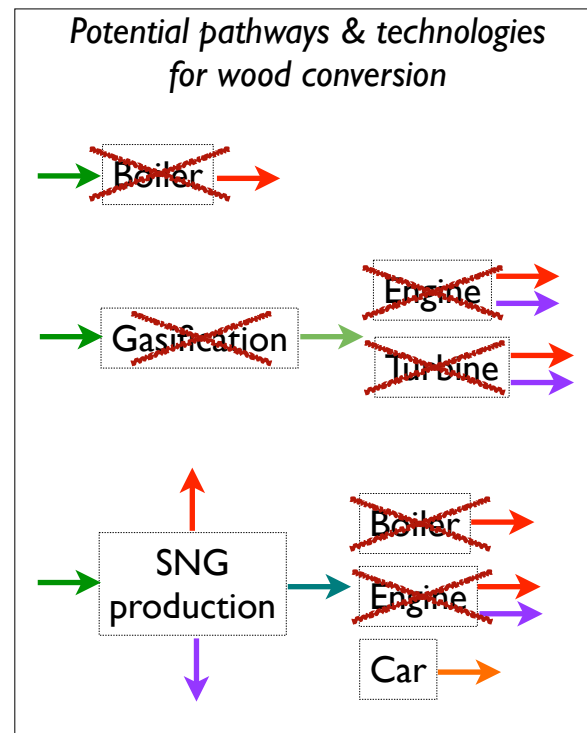
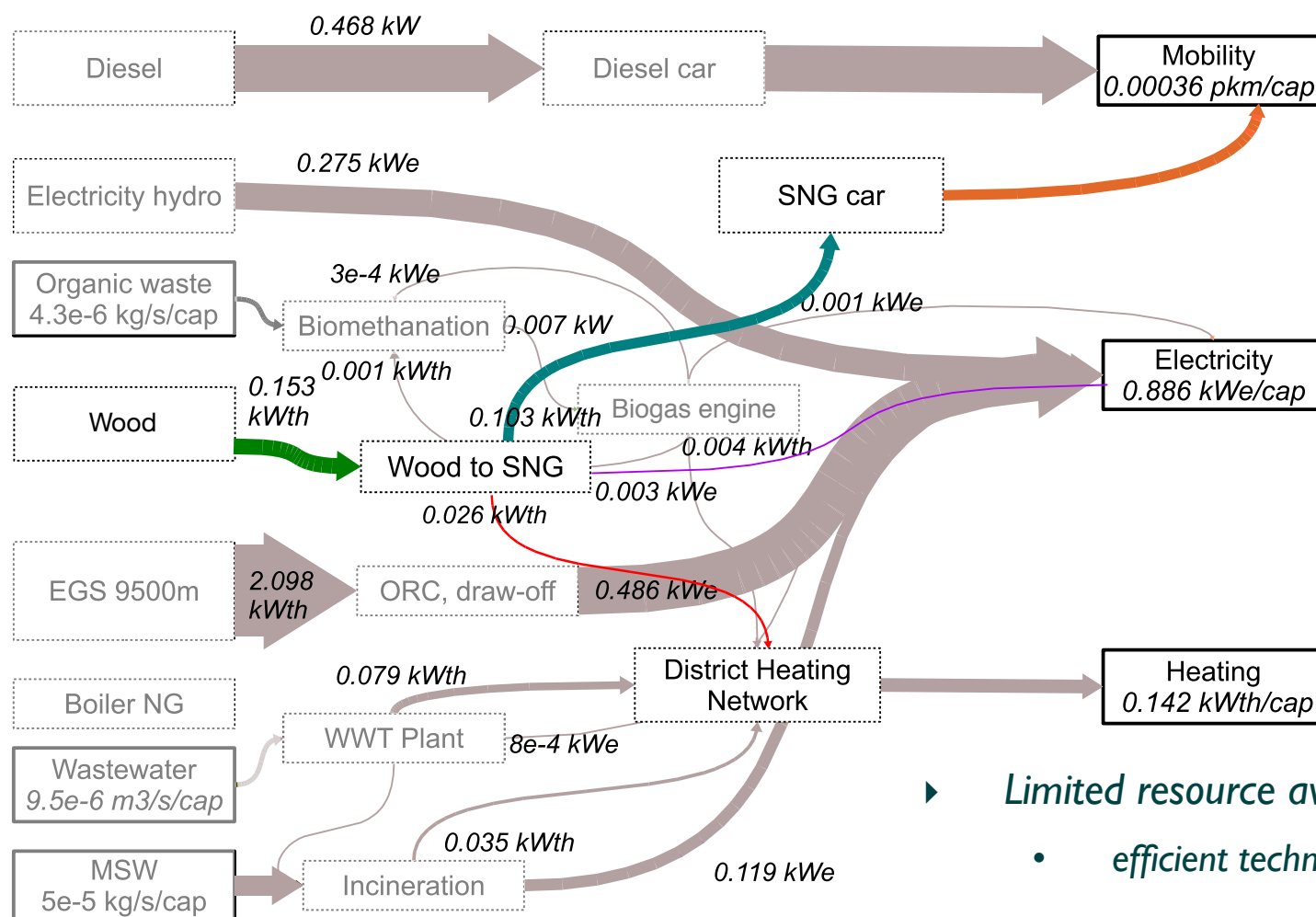
- Seasonal adaptation

- Selection of utilities
- Operating conditions



Optimal pathways and technology selection

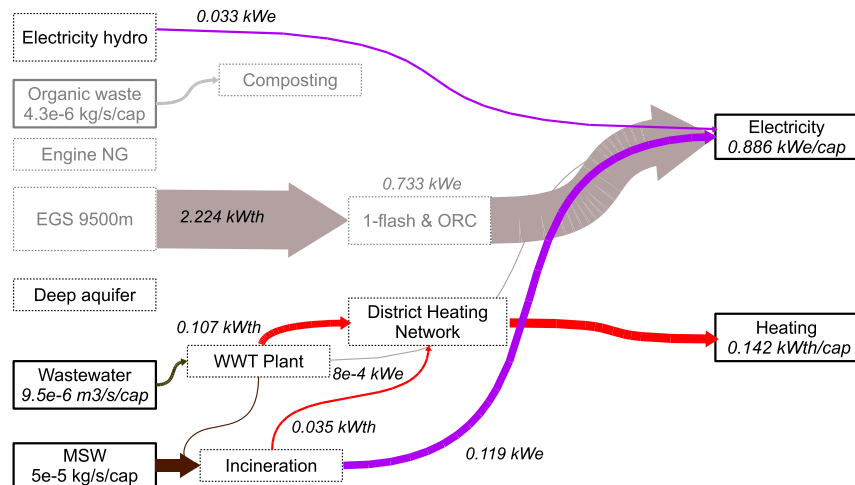
- Example of wood in environomic configurations



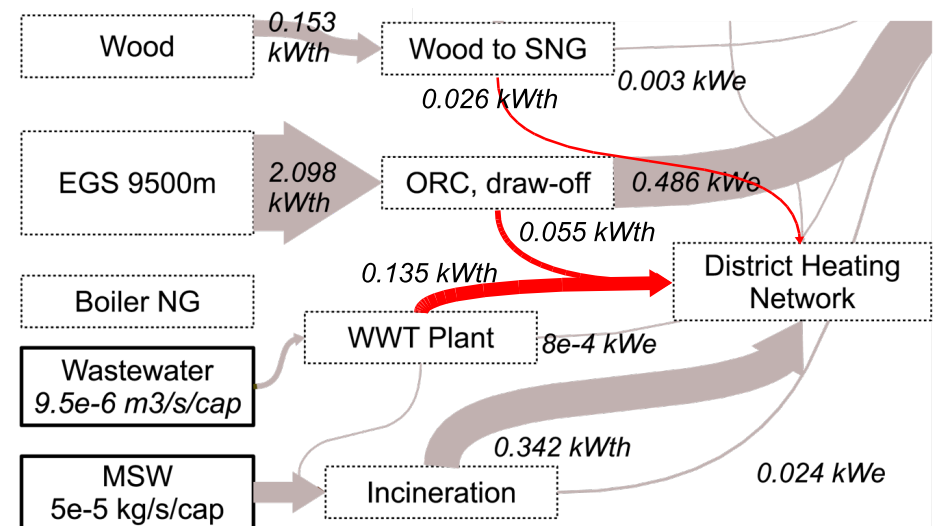
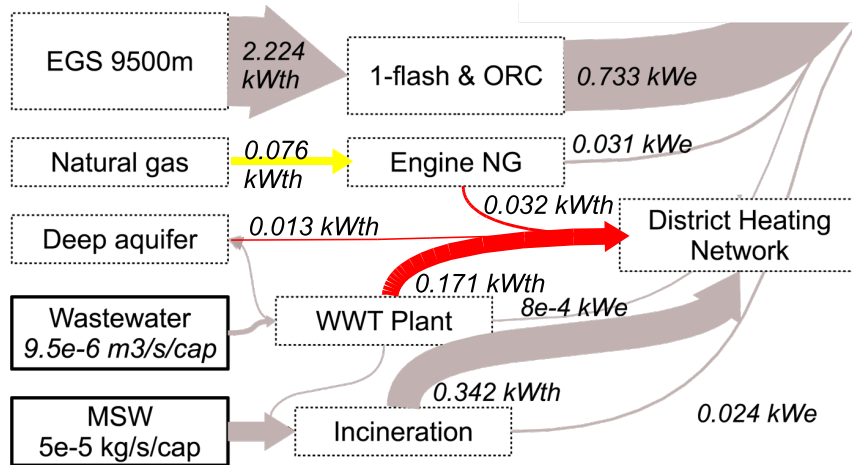
- ▶ *Limited resource availability*
 - *efficient technologies*
- ▶ *Alternatives for producing services (e.g. transport)*

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



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

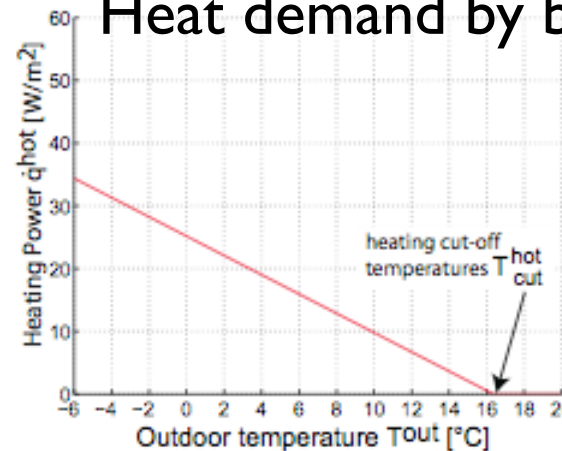
In more detail ...

Defining the requirement of a building

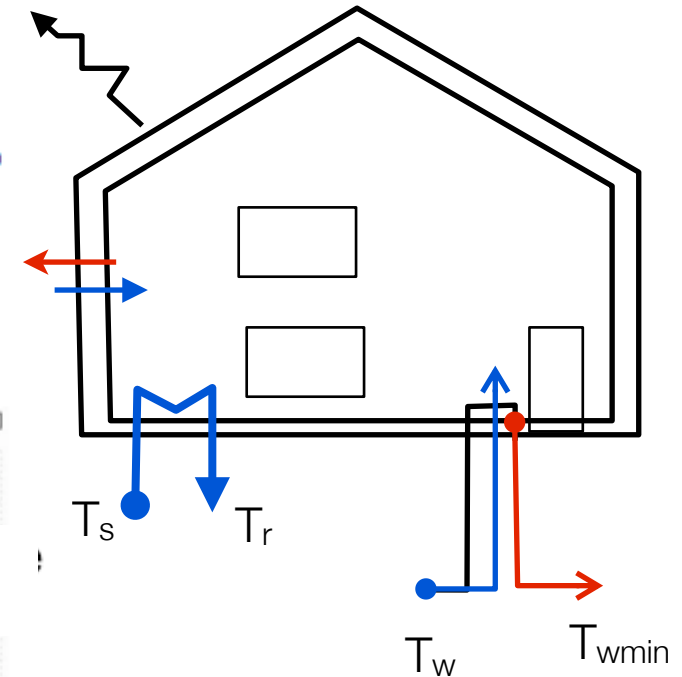
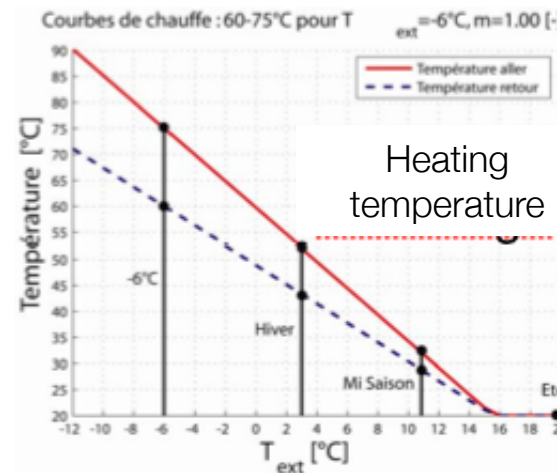
- Definition of the energy requirement

- Heating
- Air renewal
- Hot water
- Waste Water
- Air renewal

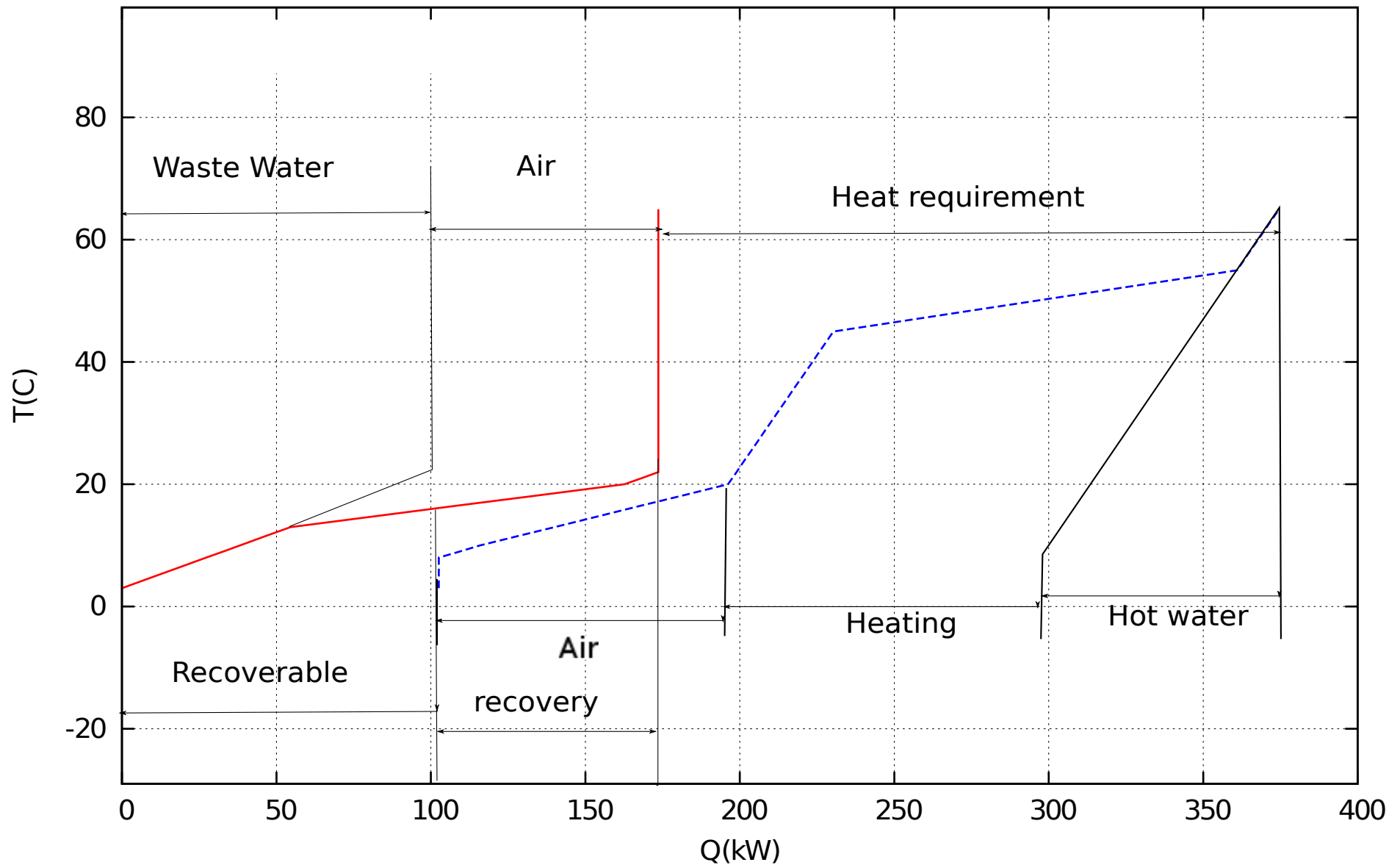
Heat demand by building simulation models



T_{ext}

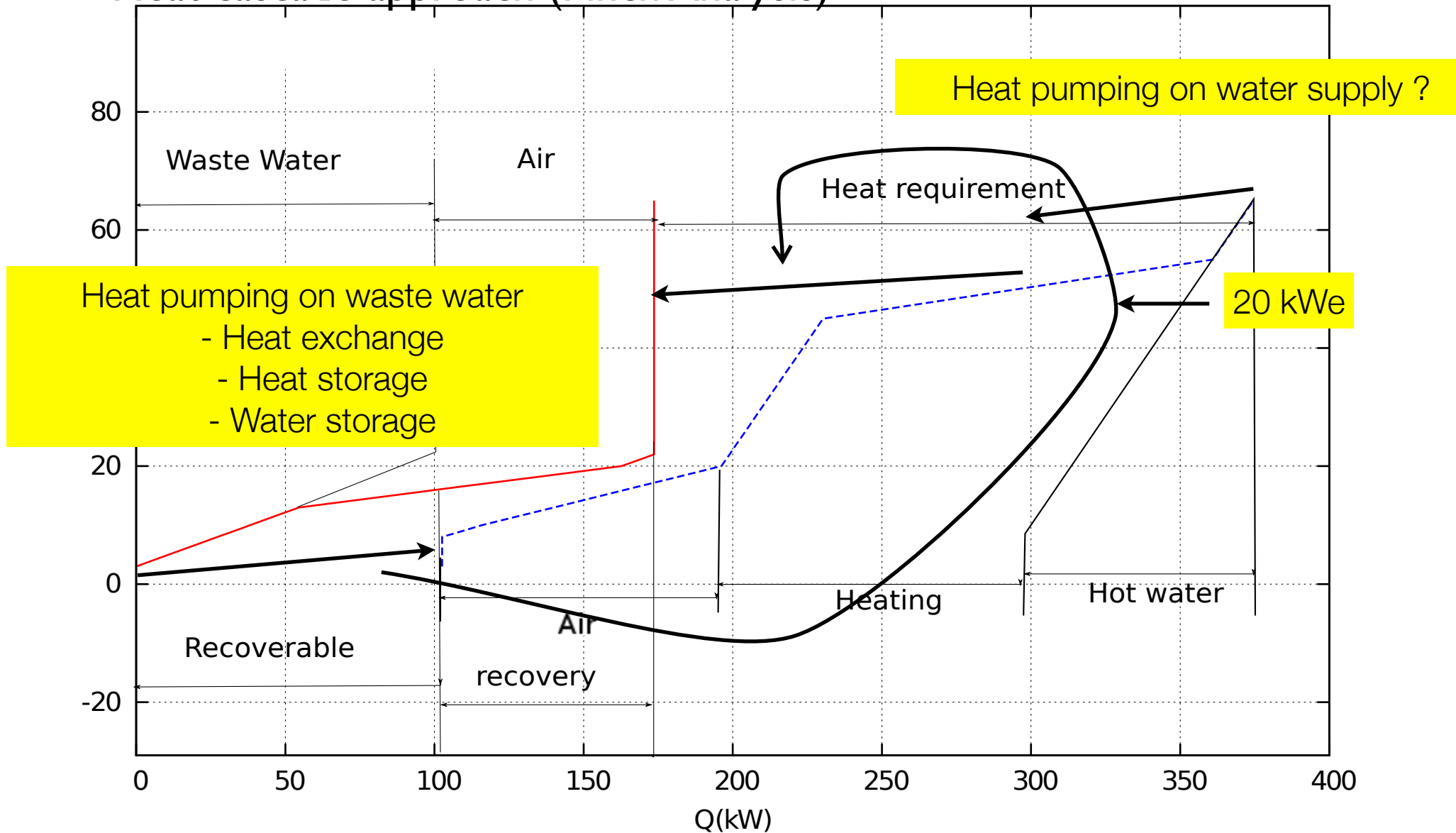


Local heat recovery



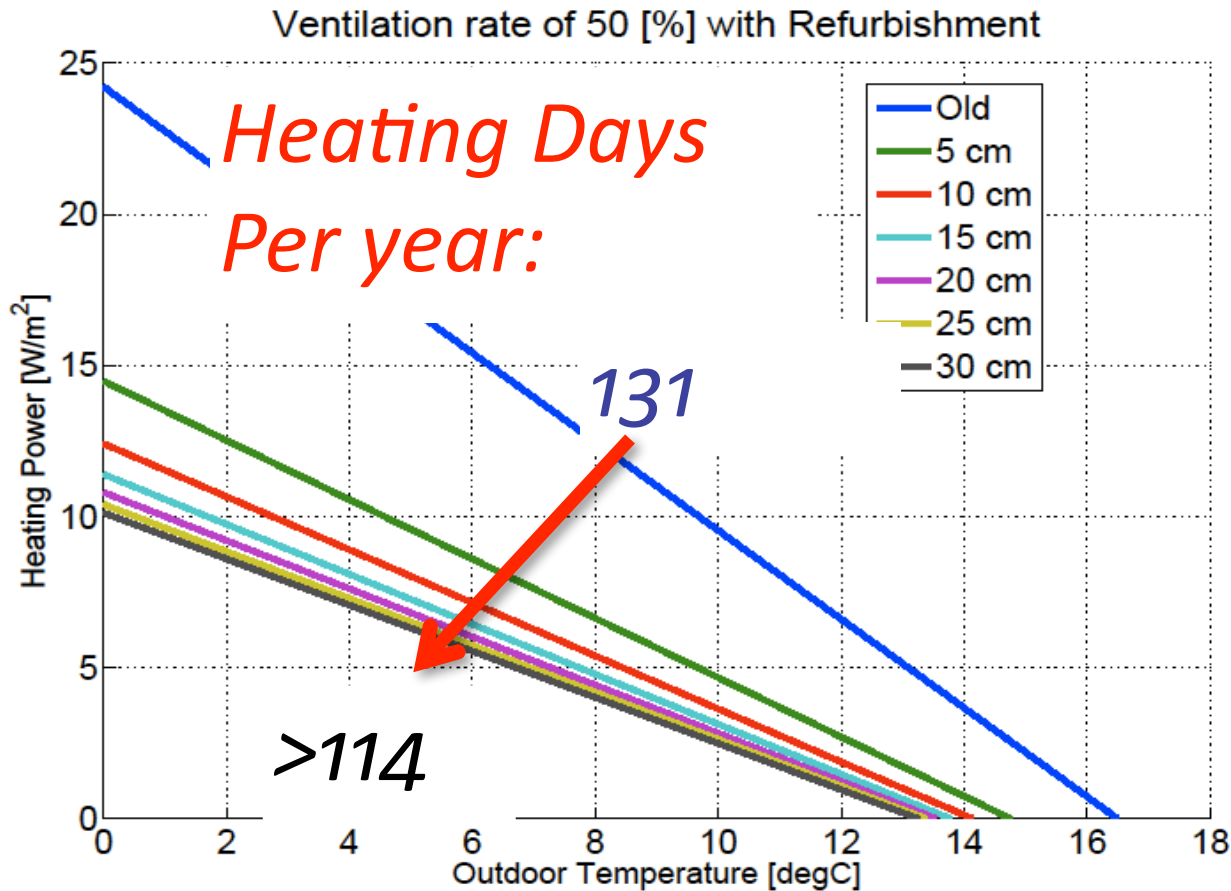
Heat recovery and reuse in a building

Heat cascade approach (Pinch Analysis)

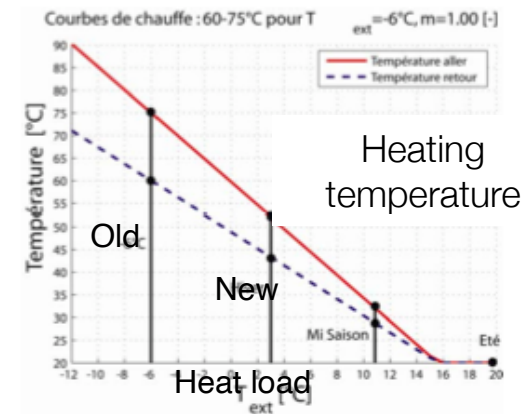


COP = 5 to 6

Building renovation



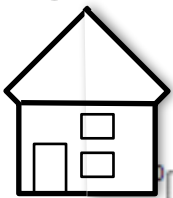
Heat required : - 60%
 Nb of days : - 16%
 Peak power : - 37 %
 Heating temperature :
 COP : + 10%
 Investment period : constant !



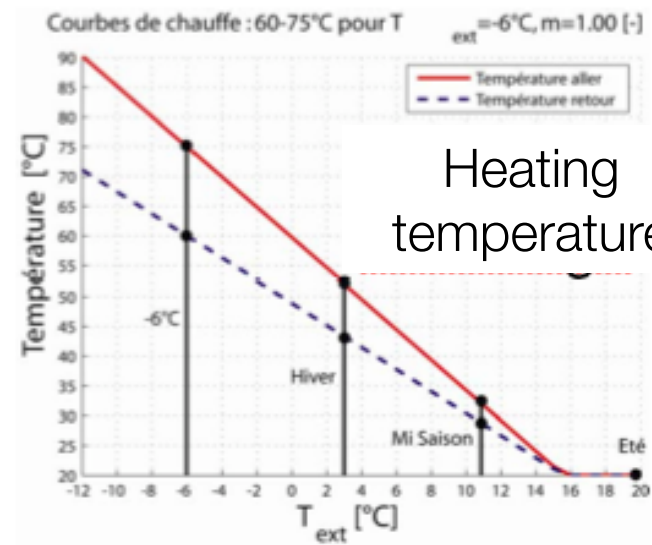
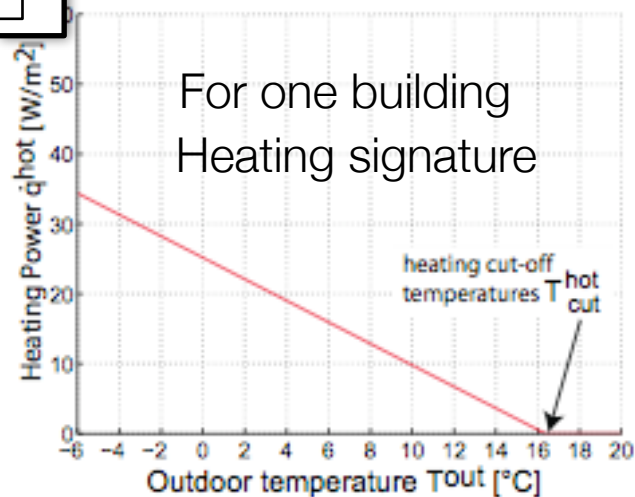
Appartment block Geneva with air heat pump renovated

Changing the scale

- Characterizing the services

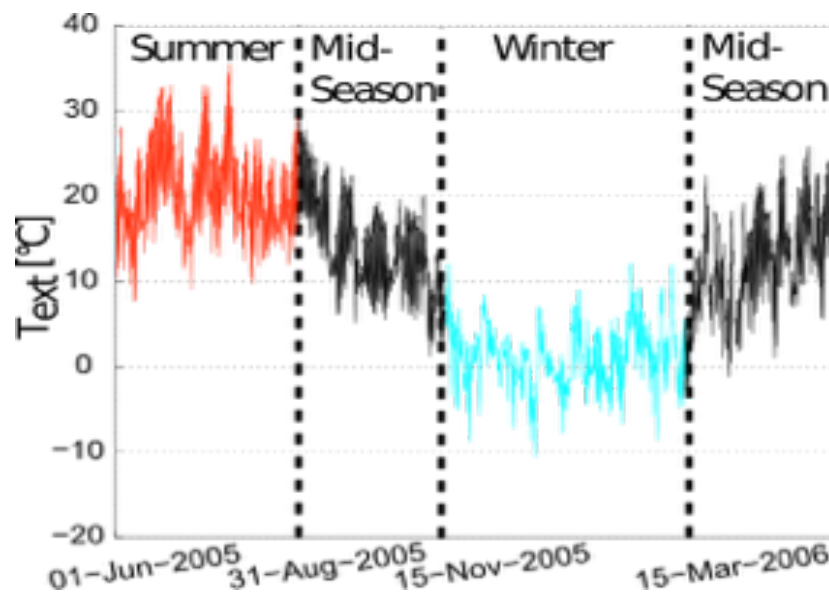


For one building
Heating signature

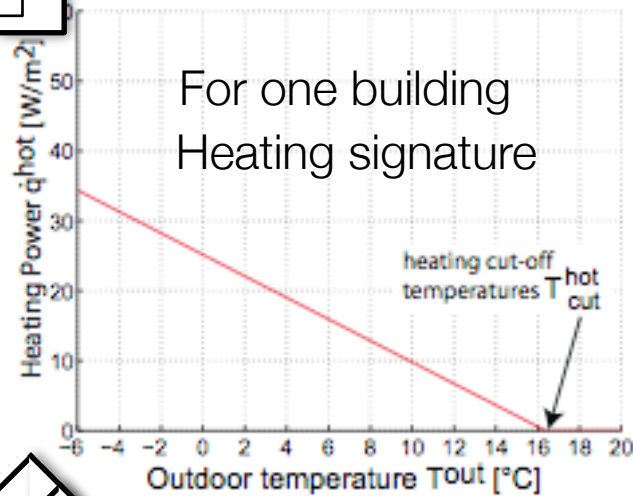
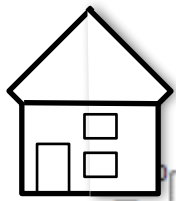


Heating
temperature

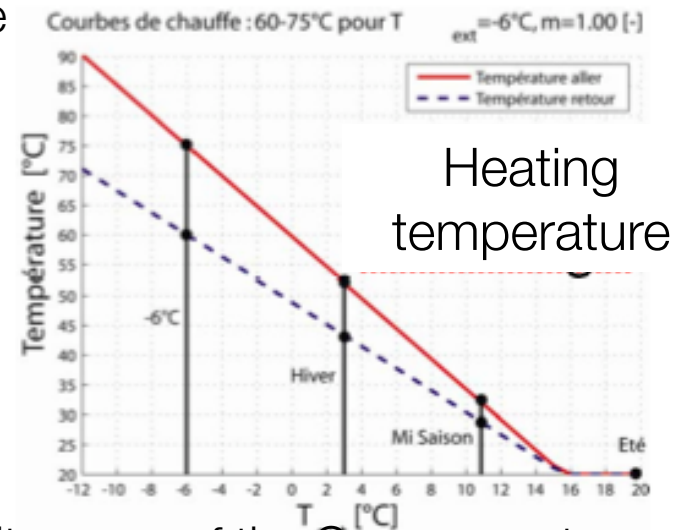
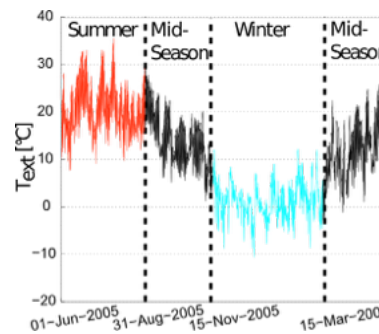
Seasonal temperature
variation



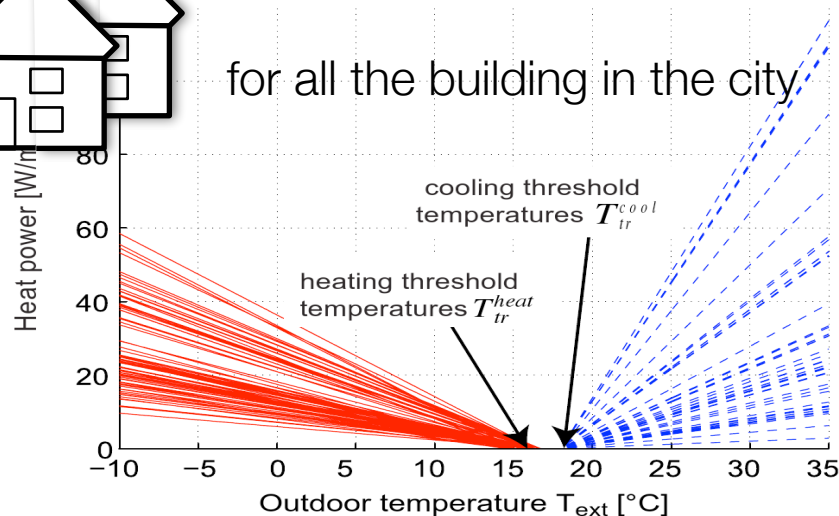
System integration



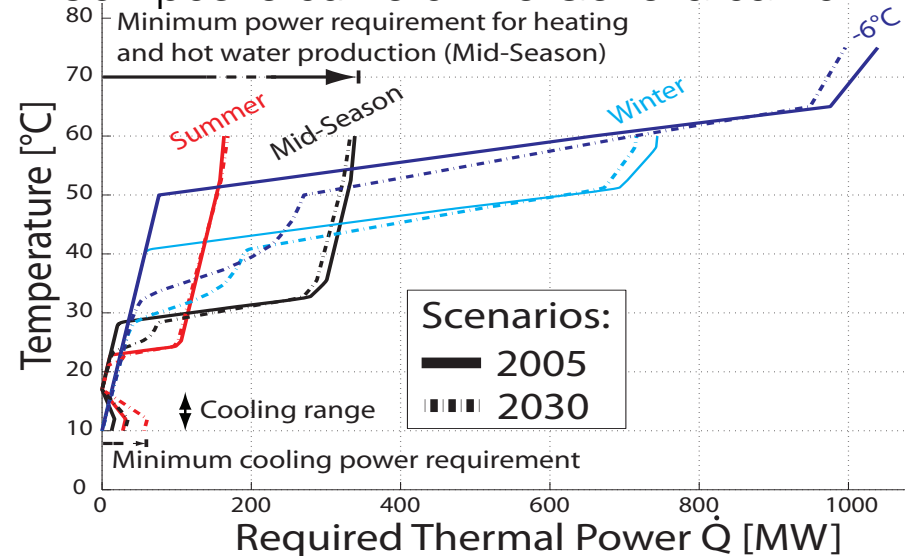
Seasonal temperature variation



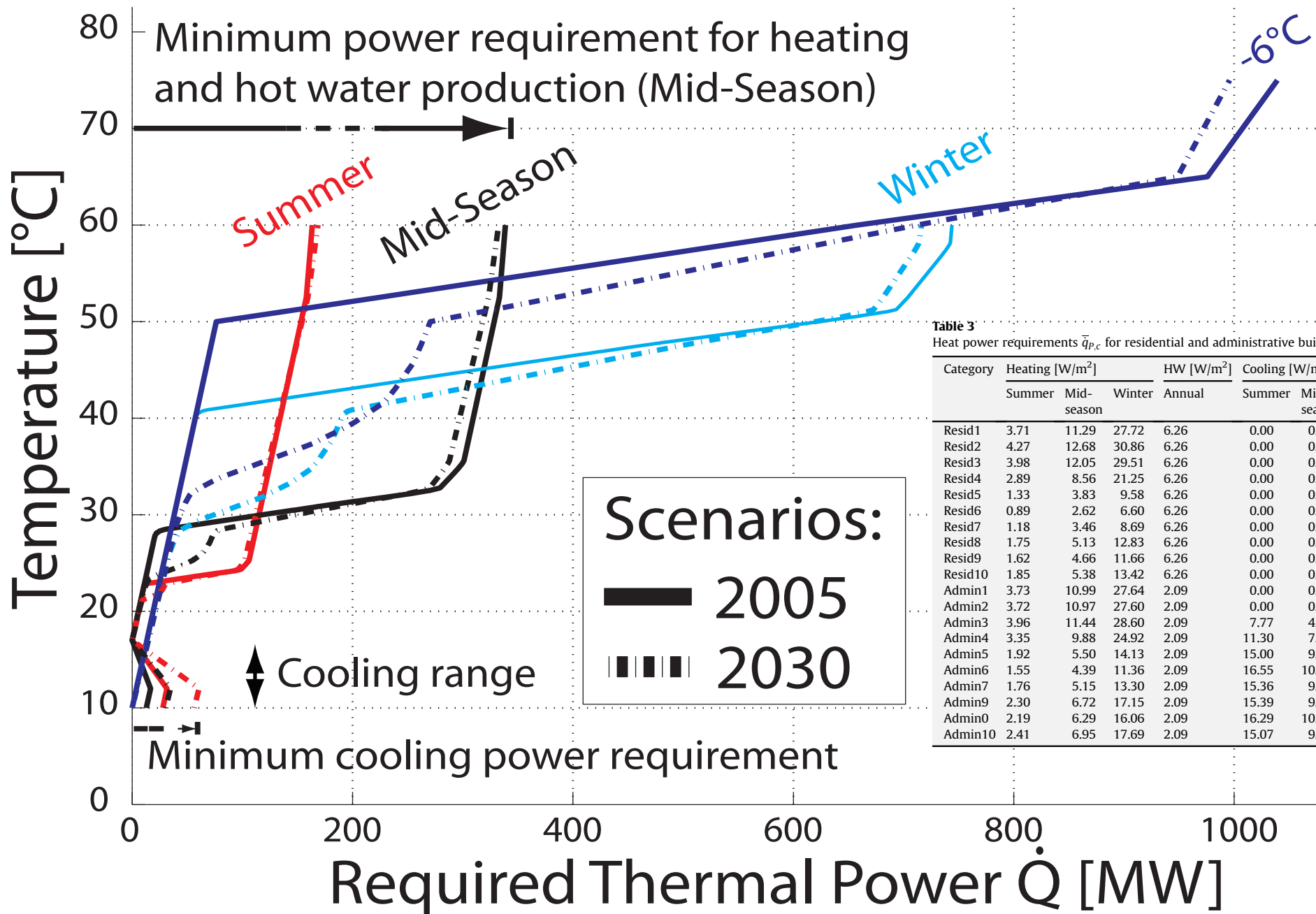
Heating temperature



Composite curve of the Geneva canton



Integrating the demand : the whole canton



The urban system integration

• Multi Energy services

- Electricity
- Heating
- Cooling
- Hot water
- Refrigeration
- Industrial processes

- Heat integration

- Composite curves
- Heat-temperature diagrams
 - thermal distribution

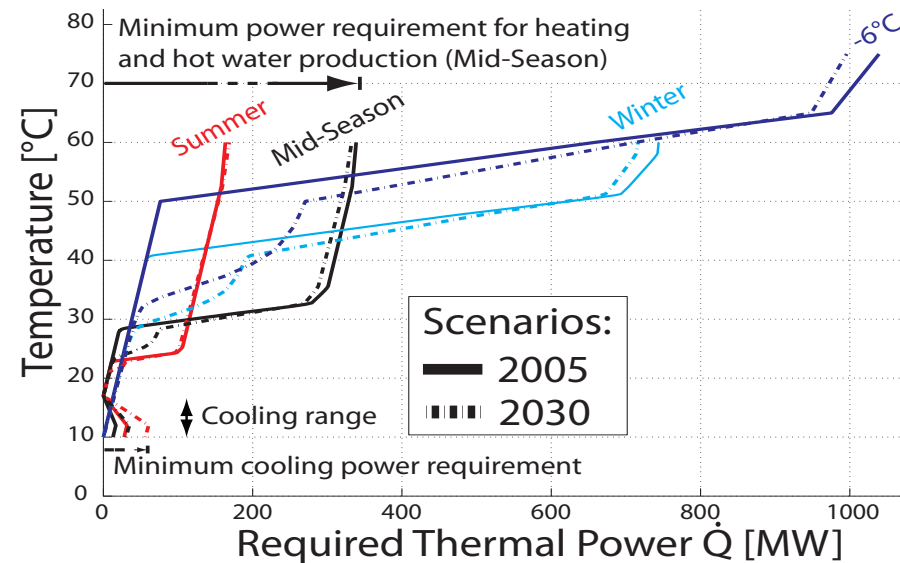
➔ Seasonal profiles

- stochastic !

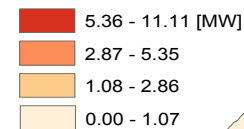
➔ Evolution scenarios

- ➔ buildings stock
- ➔ refurbishment

Composite curve of the Geneva canton

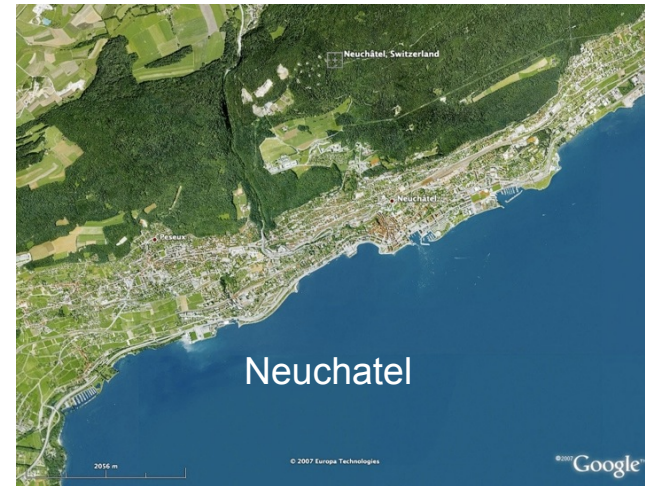


Heating & Hot water production, Power [MW] at -6°C



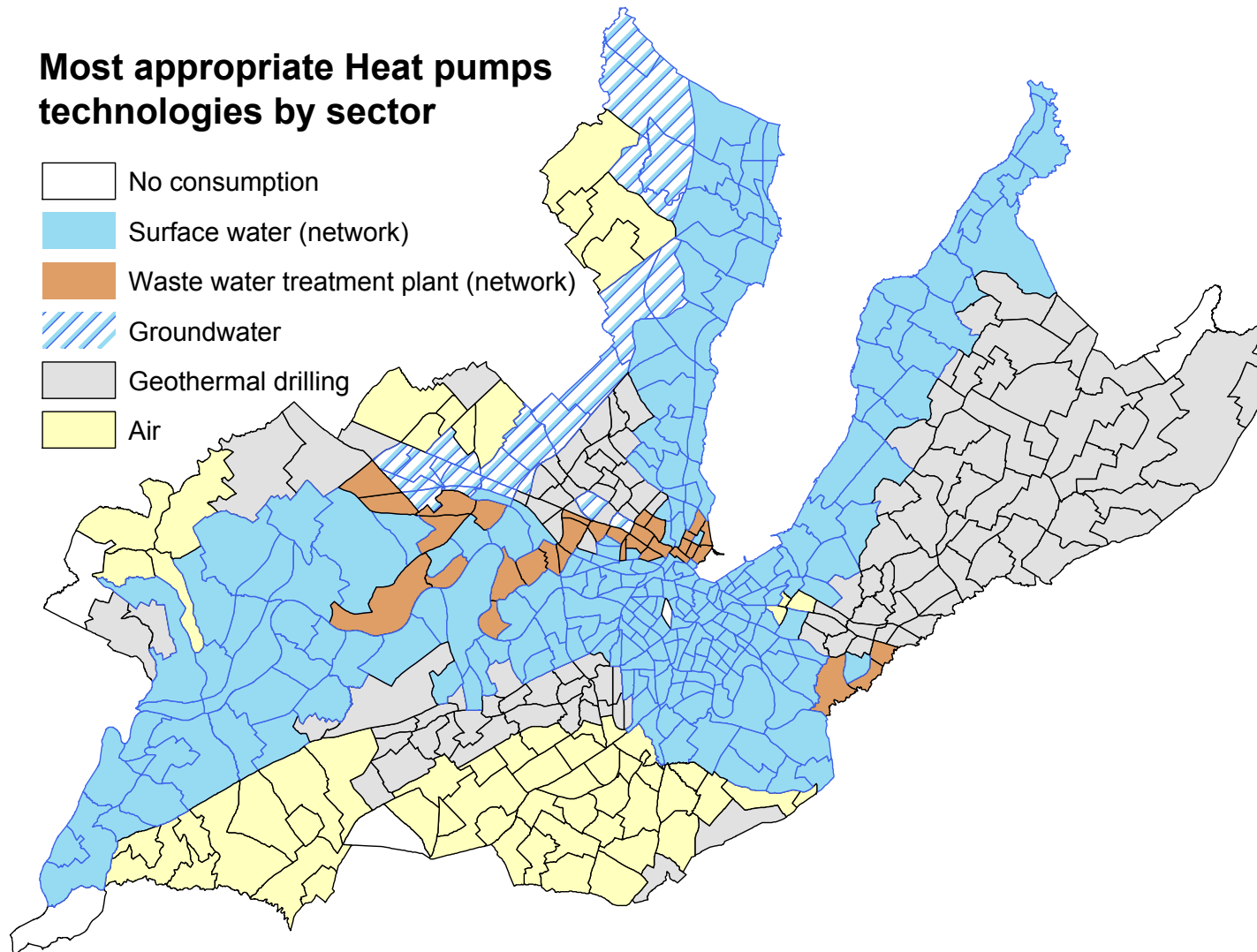
Heat pumps and local renewable resources

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



Resources localisation

Most appropriate Heat pumps technologies by sector

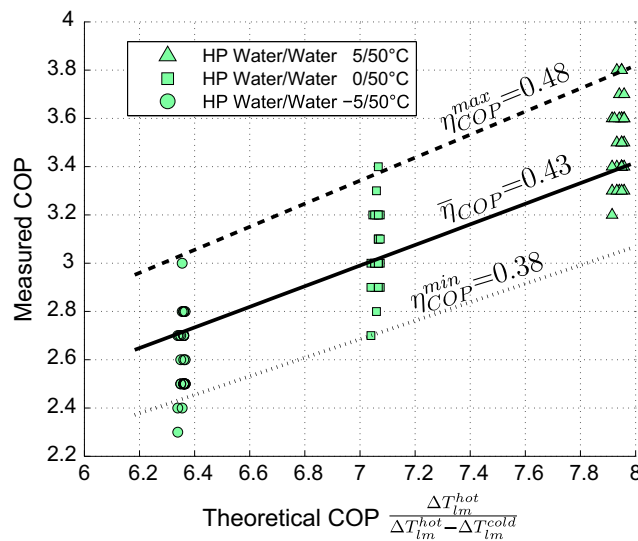


Integrate resources

Table 4

Theoretical COP efficiency factors.

Type	Size	T_{lm}^{cold}	$\eta_{COP}(2005)$	$\eta_{COP}(2030)$
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



Optimal COP Scenario 2030

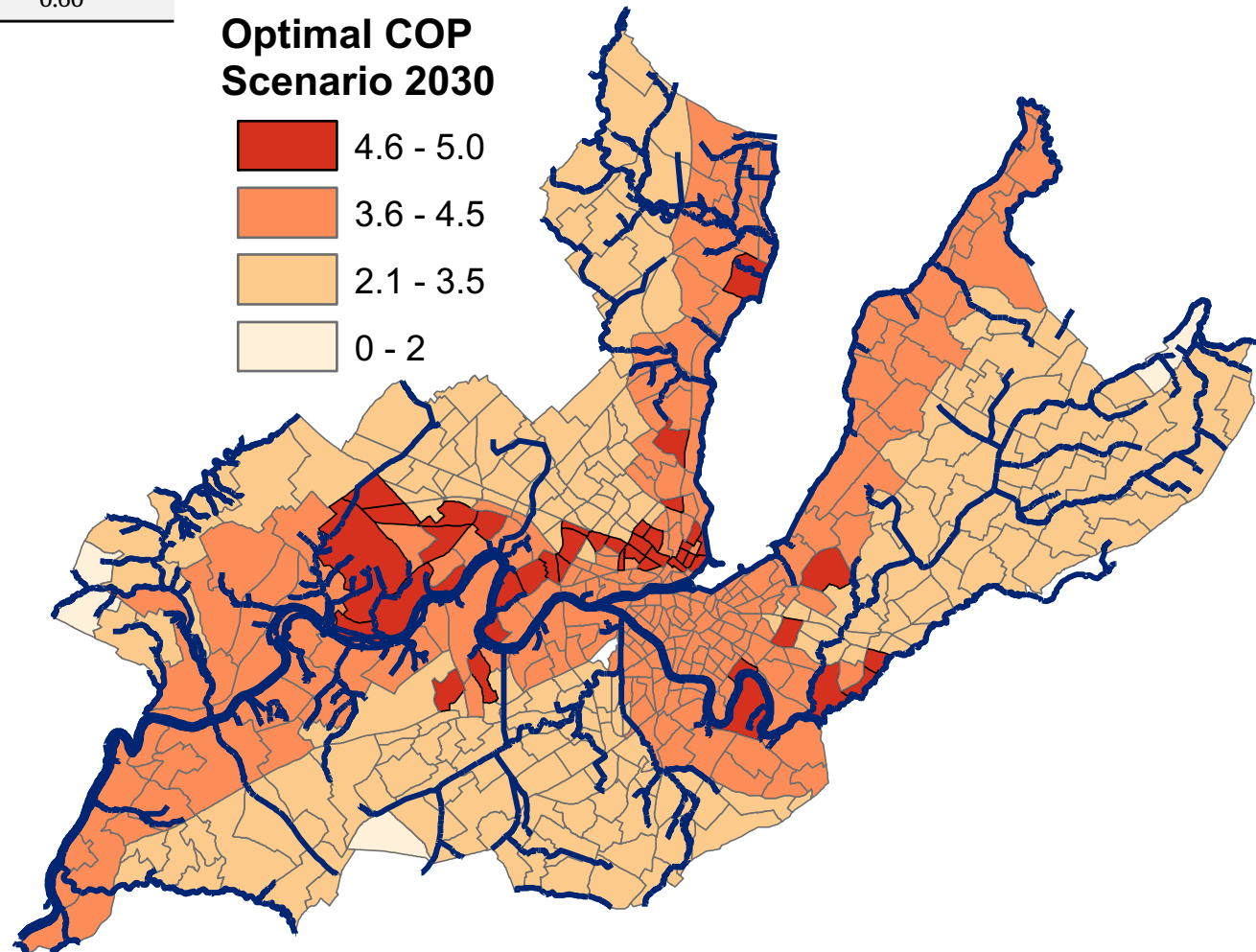
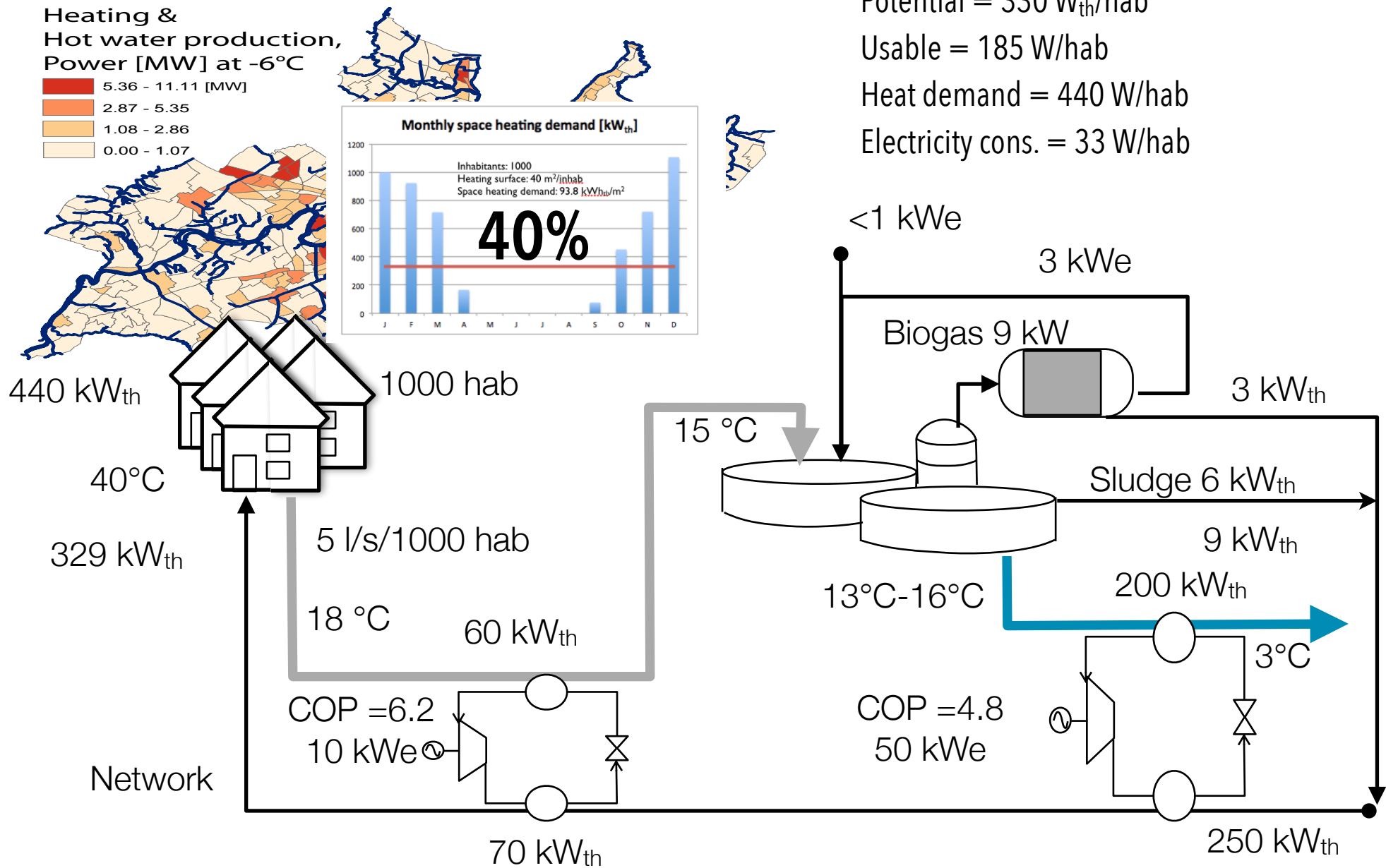


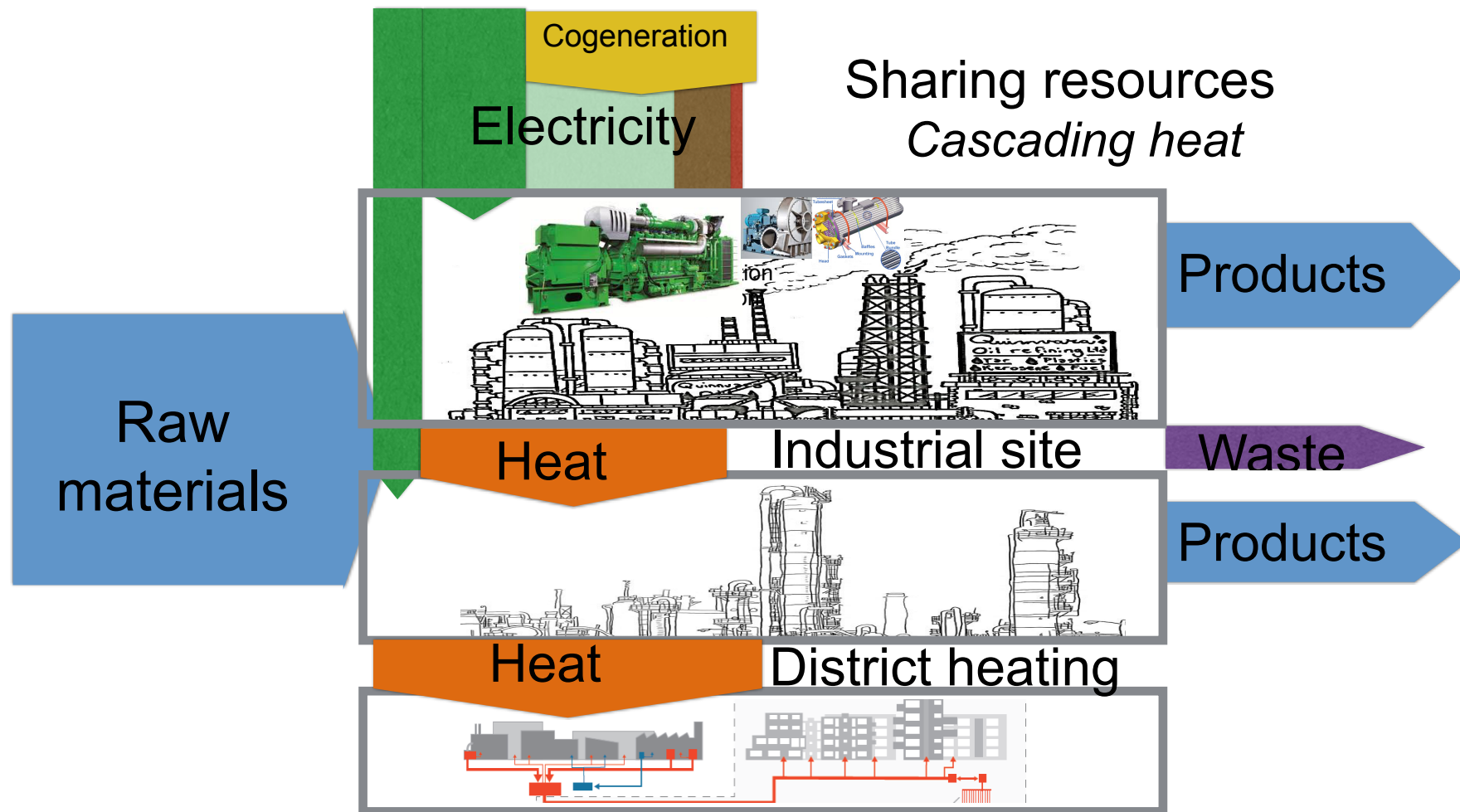
Fig. 13. COP map considering the available resources for heat pumping in 2030.

Waste water reuse District Heating Perspective

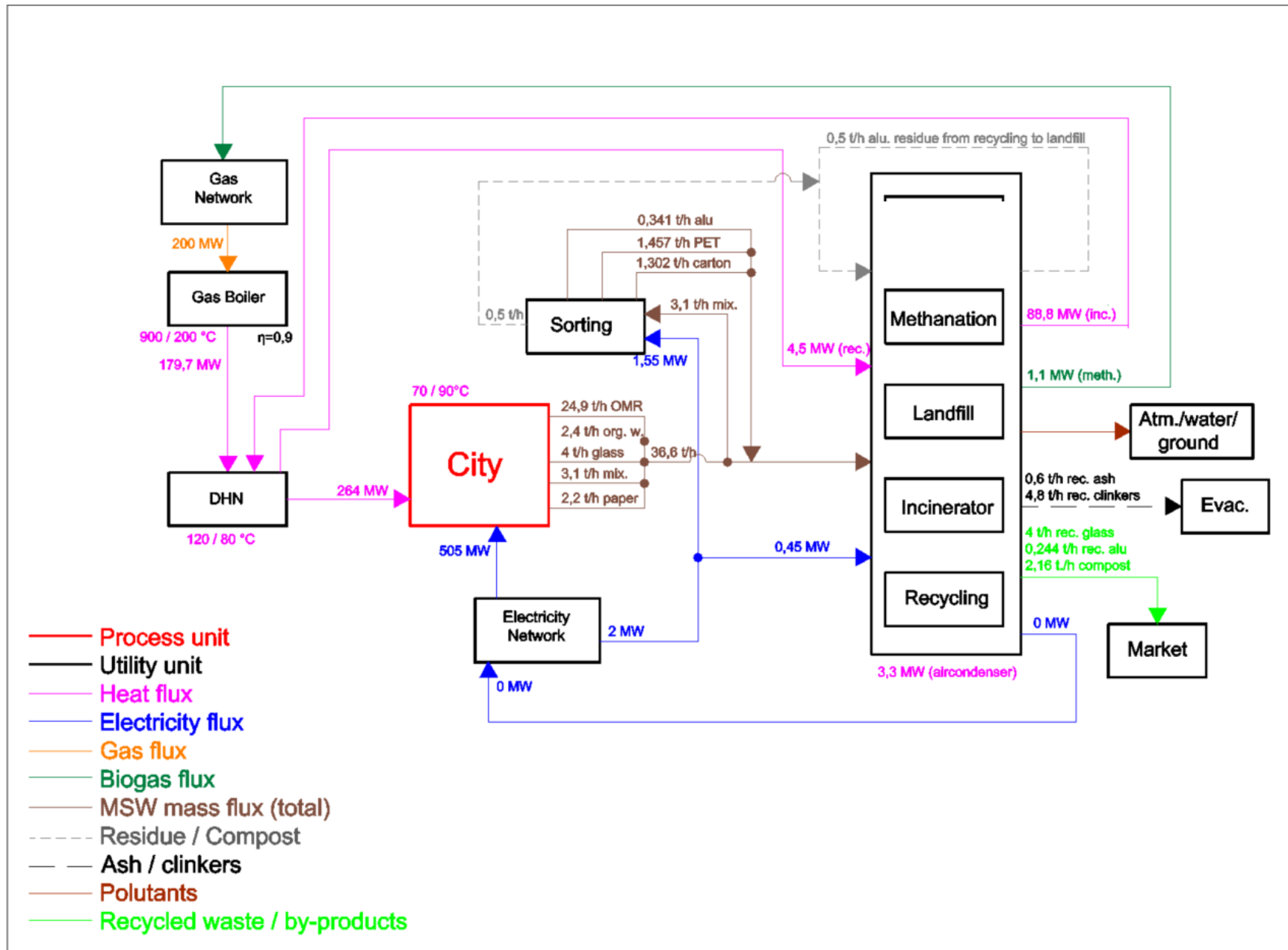


Girardin et al., ENERGIS, A geographical information based system for the evaluation of integrated energy conversion systems in urban areas, Energy, 2010

Industrial Symbiosis : Valorising waste heat



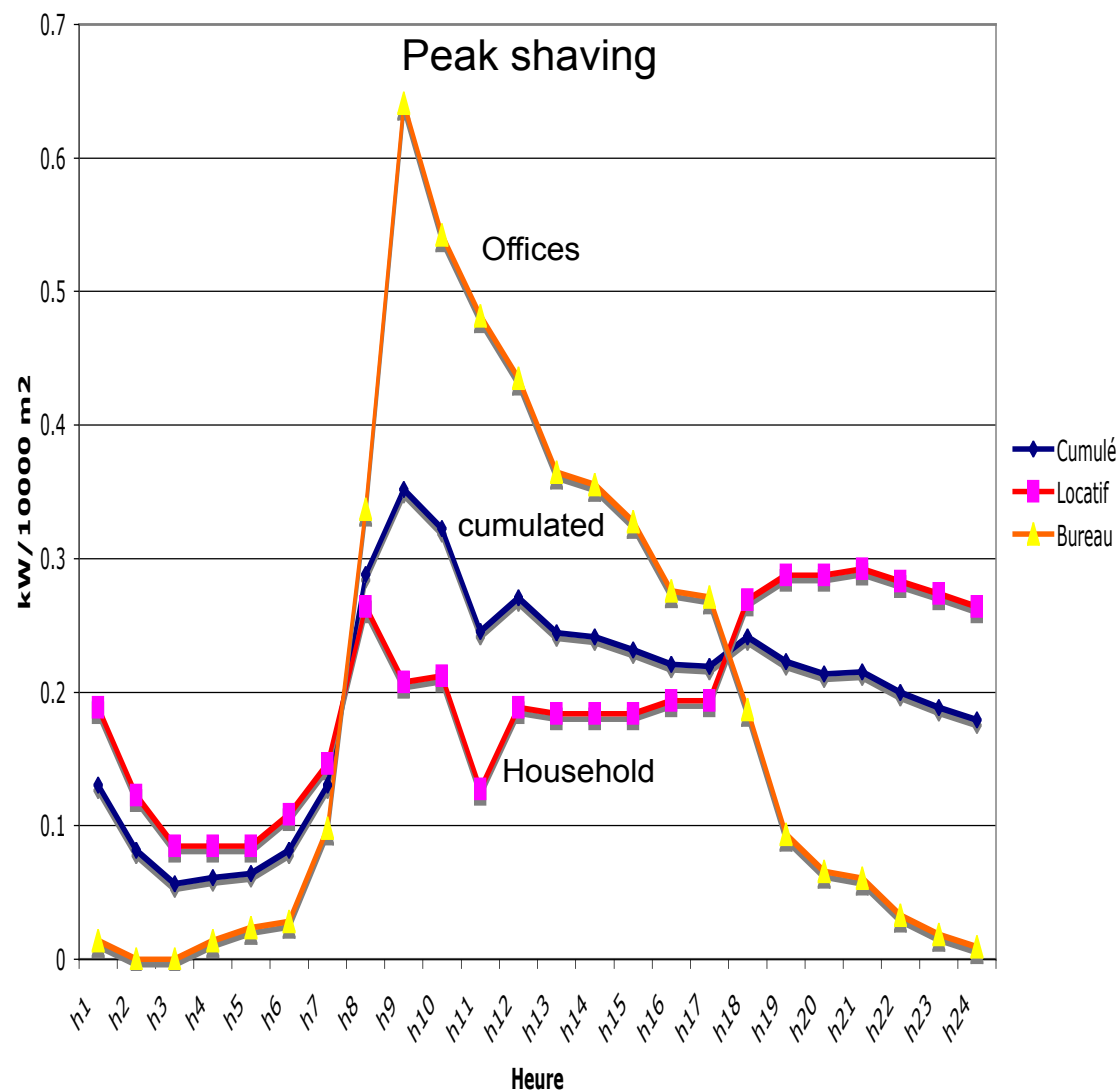
Waste management



District heating : infrastructure development



Journée type Janvier - Consommation chaleur normalisée
Normalised daily requirement (kW/m²)



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

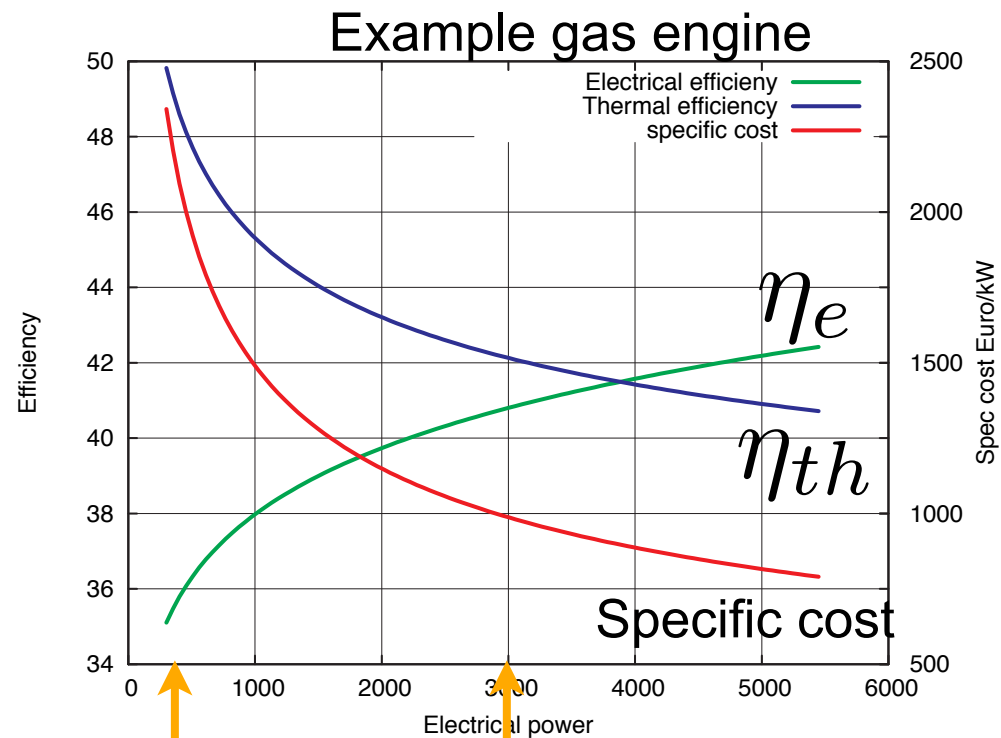


Figure 11: Rendements et prix d'un moteur à gaz pour la cogénération

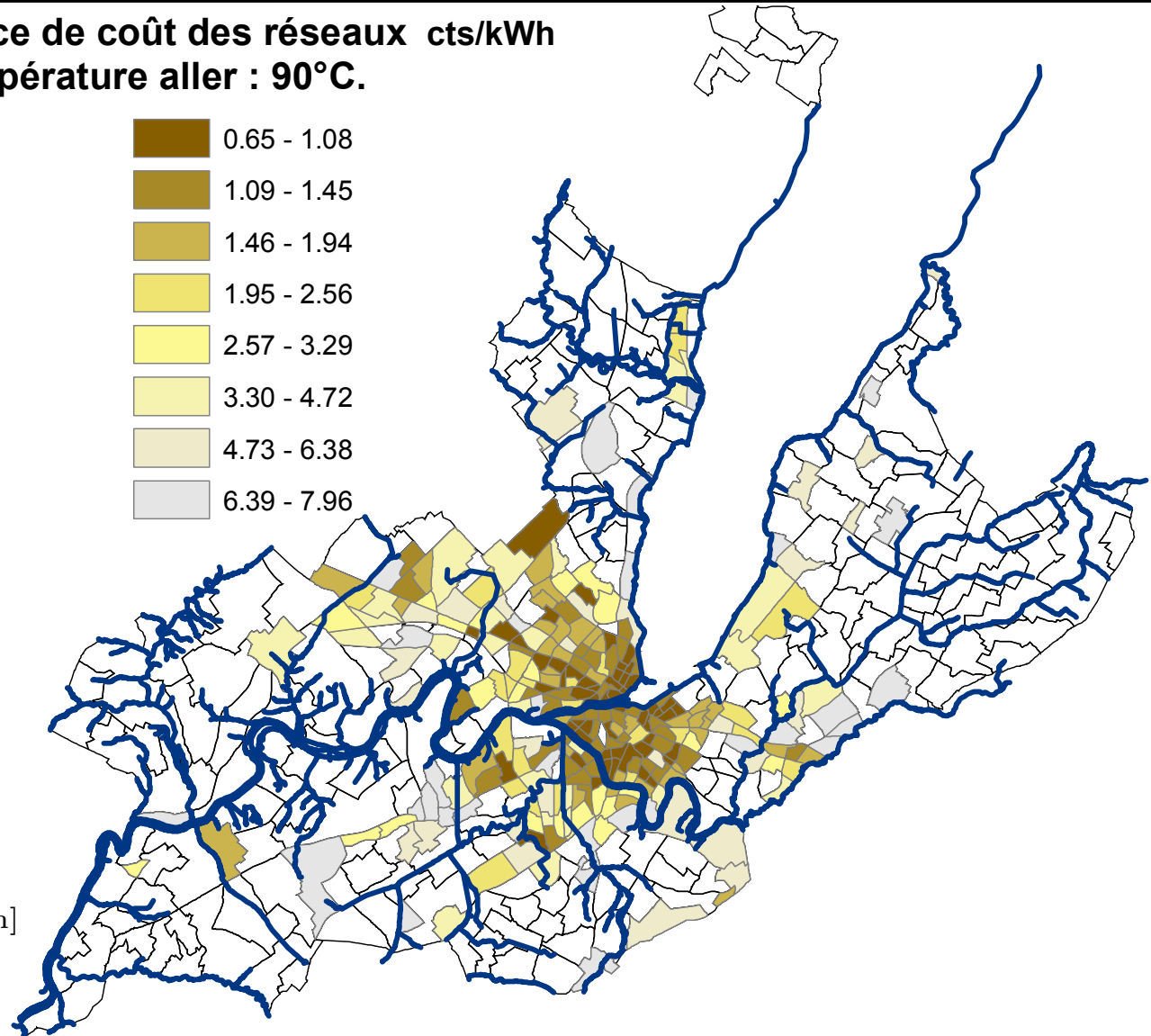
Building

District heating

Heat distribution cost : cts CHF/annual kWh

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

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



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

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

$$\dot{Q}_{DHN} = \dot{m}_{DHN} c_{pfluid} (T_{supply}^* - T_{return})$$

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

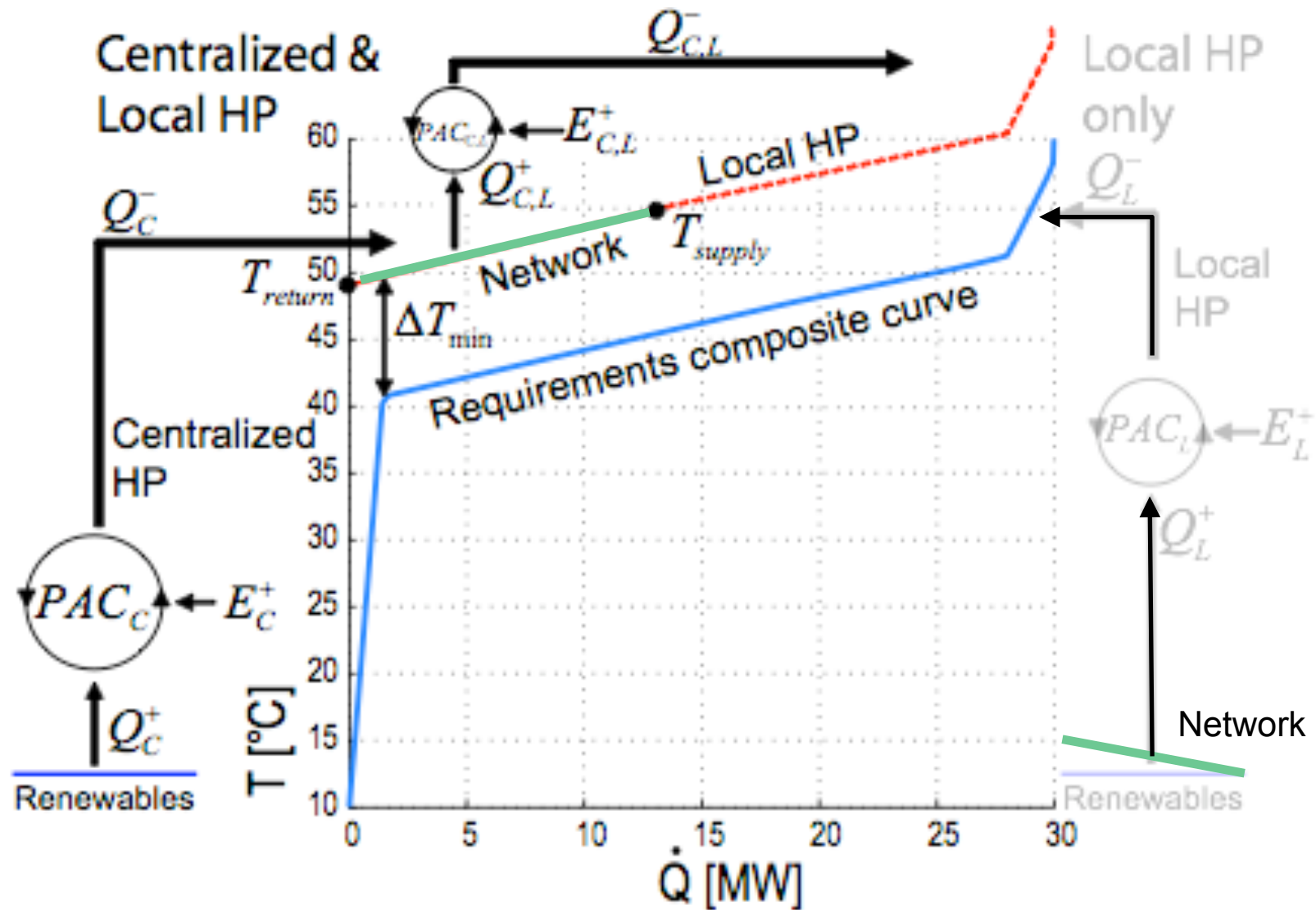
$$C_{DHN} = \frac{(c_1 d_{DHN} + c_2) L_{DHN}}{\dot{Q}_{DHN}} \frac{1}{\tau} \text{ [CHF/kWh]}$$

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

$$c_1 = 7047 \text{ CHF/m}^2 \quad c_2 = 752.8 \text{ CHF/m}$$

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

District heating



What is the temperature of the network

Energy system design

Resources : solar, geothermal, wind, water

Efficiency : refurbishment, heat recovery

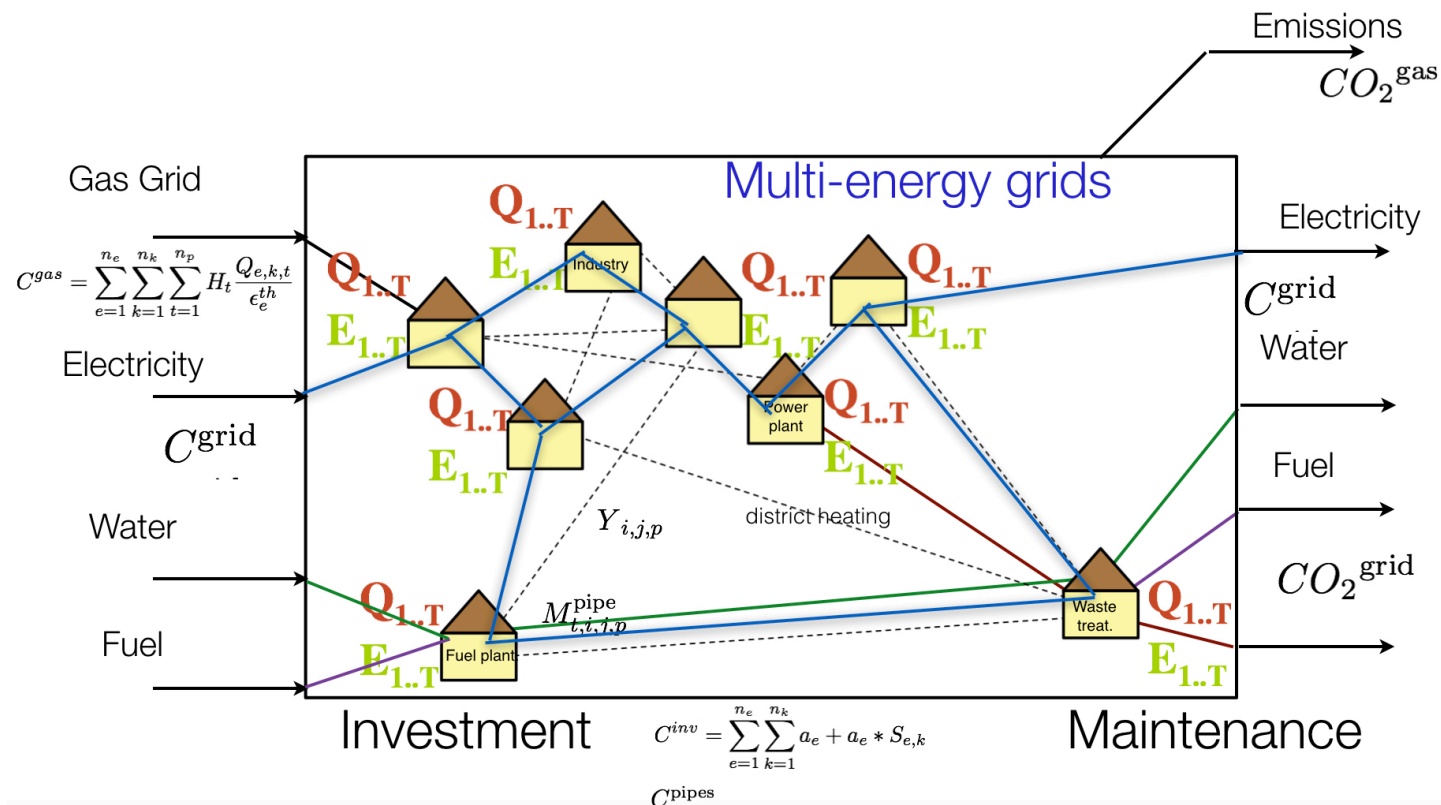
Energy conversion : heat pumps, cogeneration, boilers

Energy management : storage tanks, batteries

Investments : size, location

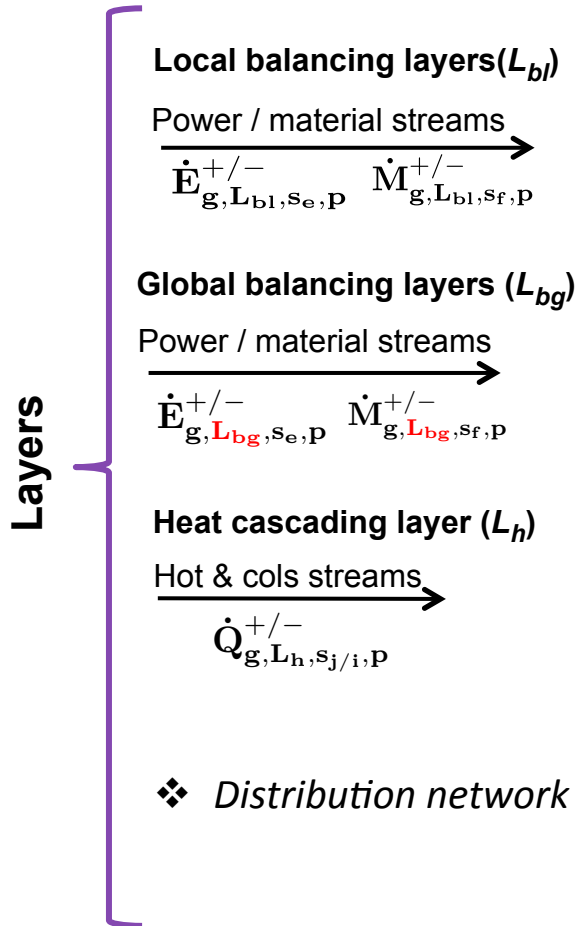
Interconnections : multi-energy grids

Operation : peak shaving, flexibility, security of supply



Superstructure slave optimization model

$$\min \sum_s \text{OPEX}(\underbrace{y_s, y_{s,p}}_{\text{On/off states}}, \underbrace{u_s, u_{s,p}}_{\text{Op. utilization levels}}) + \sum_{p=1}^{N_P} (\underbrace{\dot{I}_p}_{\text{Total impacts}} \times \underbrace{t_{\text{CO}_2}}_{\text{CO}_2\text{-eq tax}} \times \Delta p)$$

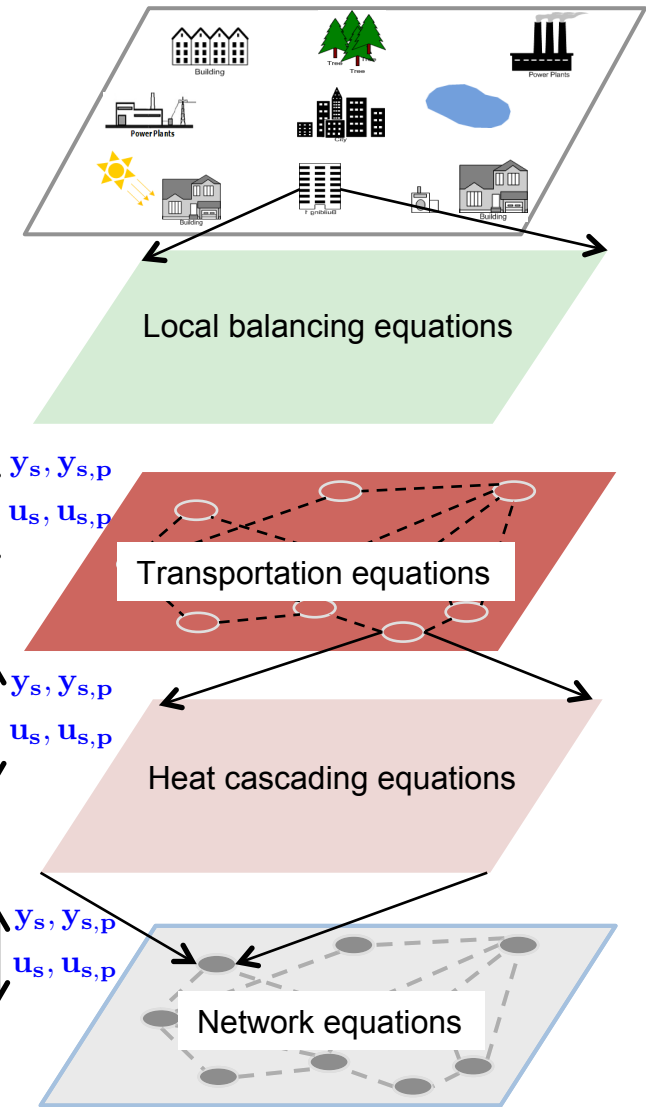


- ❖ *Transportation*
- ✓ *Material flows*
- ✓ *Trade-off between transportation systems*

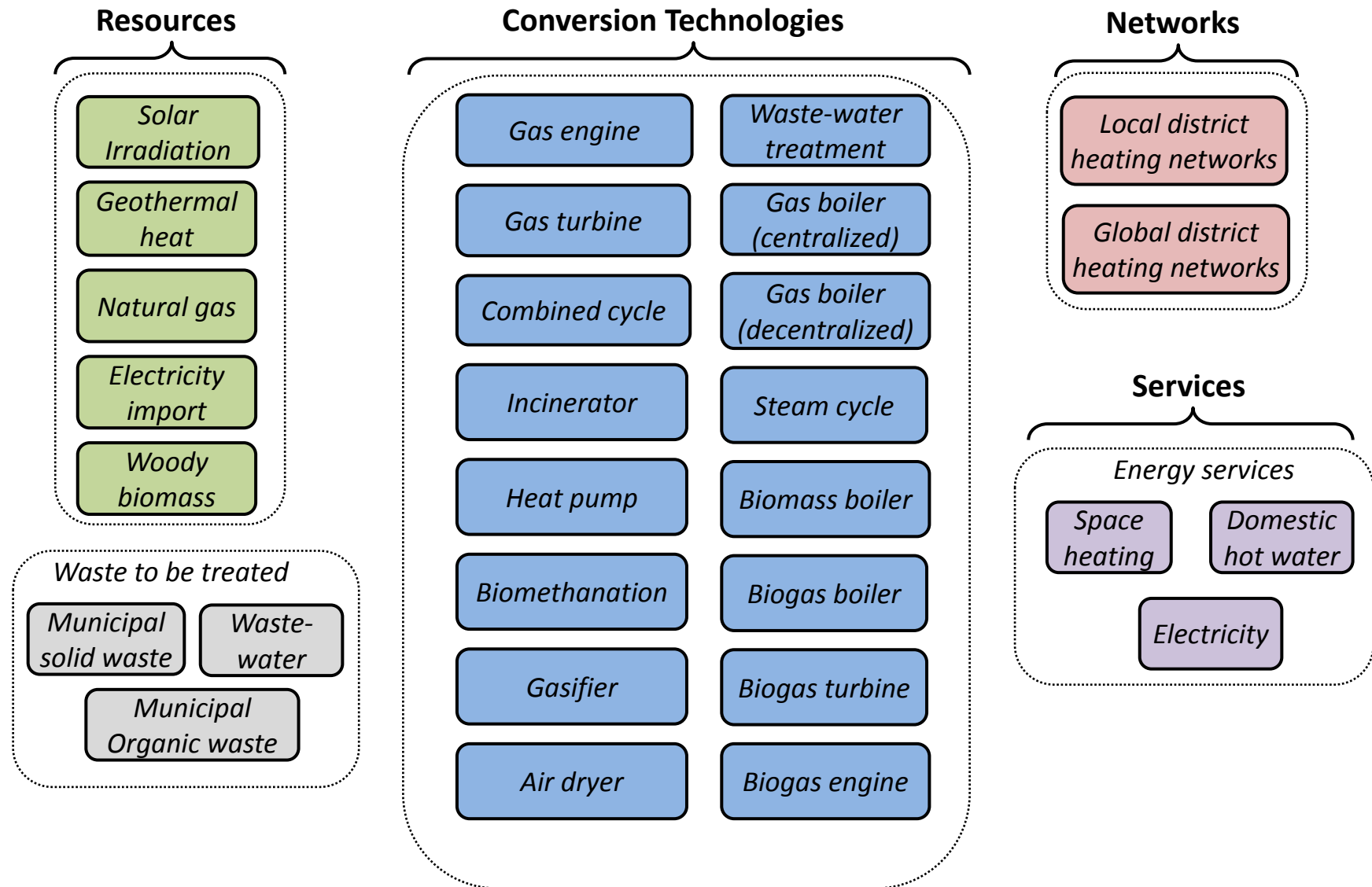
- ✓ *Heat cascade restriction*

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

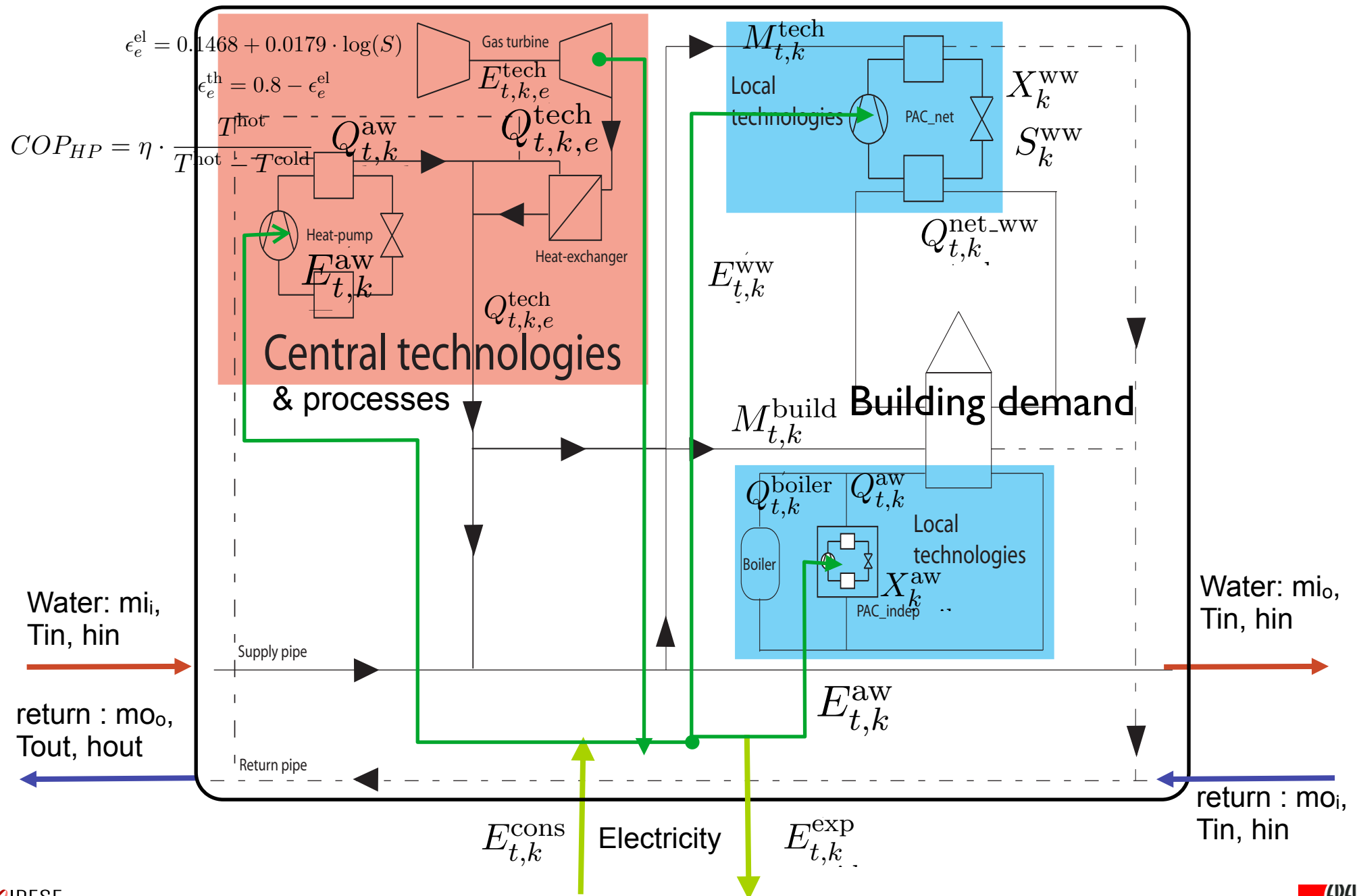
- ❖ *Distribution network*



List of technology options in the data base



Each node is a process with network connections



Multi-period problem (for the day of a month)

node k

Technologies w, @node k period p

Demand @node k, period p

Heat exchange by
heat cascade
model

$$\sum_{w=1}^{n_w} u_{w,k,p} \mathbf{q}_{w,k,p,r} + \sum_{d=1}^{n_d} \mathbf{Q}_{k,p,d,r} + R_{k,p,r+1} - R_{k,p,r} = 0$$

$$R_{k,p,r} \geq 0, \quad R_{k,p,n_r+1} = 0, \quad R_{k,p,1} = 0$$

$$\forall r = 1, \dots, n_r$$

$$\forall p = 1, \dots, n_p$$

$$\forall k = 1, \dots, n_k$$

Electricity balance

$$\sum_{w=1}^{n_w} u_{w,k,p} \mathbf{e}_{w,k,p,r} + \sum_{d=1}^{n_d} \mathbf{e}_{k,p,d,r} + E_{k,p}^+ - E_{k,p}^- = 0$$

$$E_{k,p}^+ \geq 0, \quad E_{k,p}^- \geq 0$$

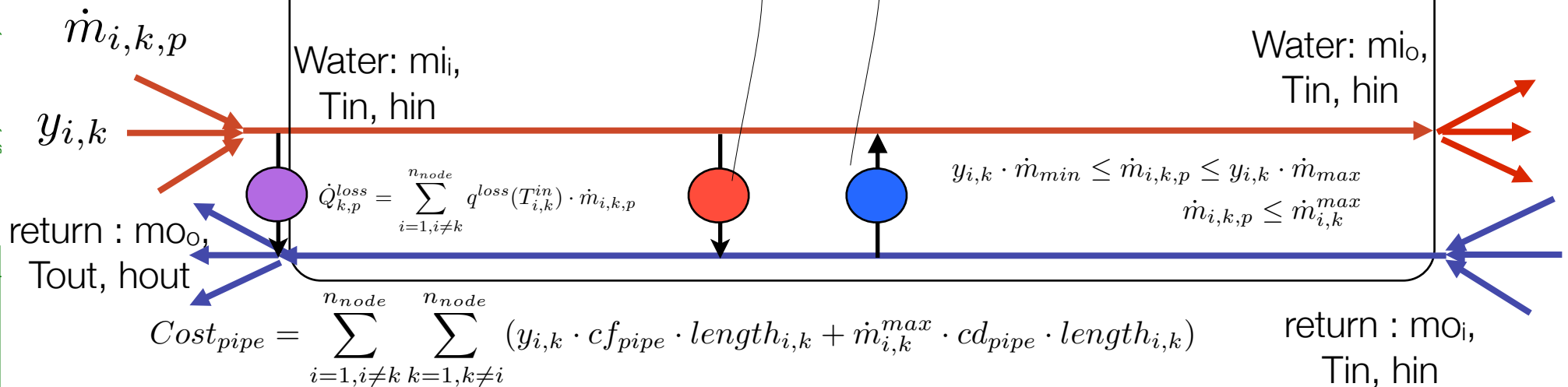
Existence : w in location k

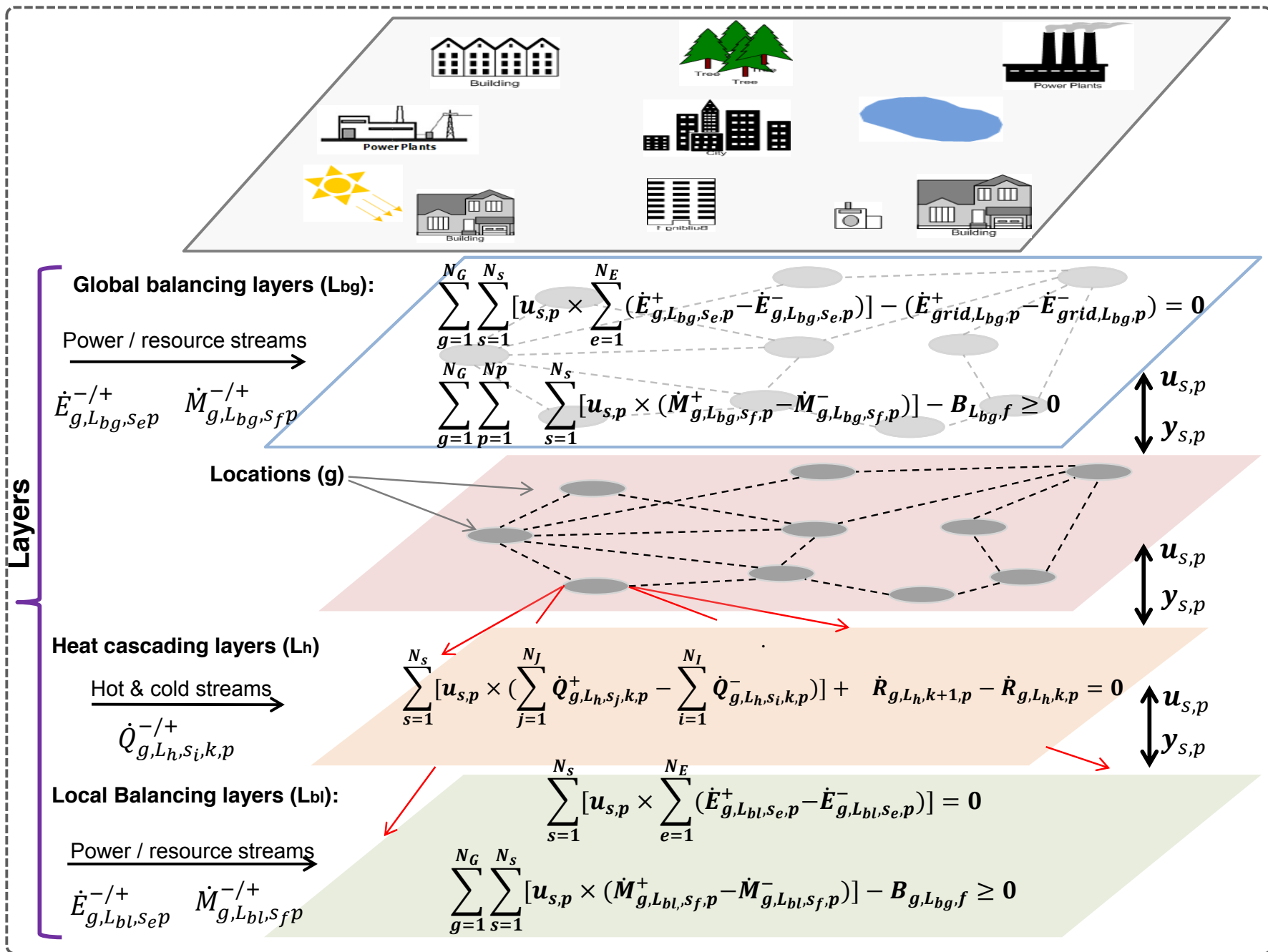
$$y_{w,k,p} \mathbf{u}_{\min_w} \leq u_{w,k,p} \leq y_{w,k,p} \mathbf{u}_{\max_w}$$

$$\forall w = 1, \dots, n_w \quad \forall p = 1, \dots, n_p \quad \forall k = 1, \dots, n_k$$

$$u_{w,k,p} \leq u_{w,k} \quad \forall w, k, p$$

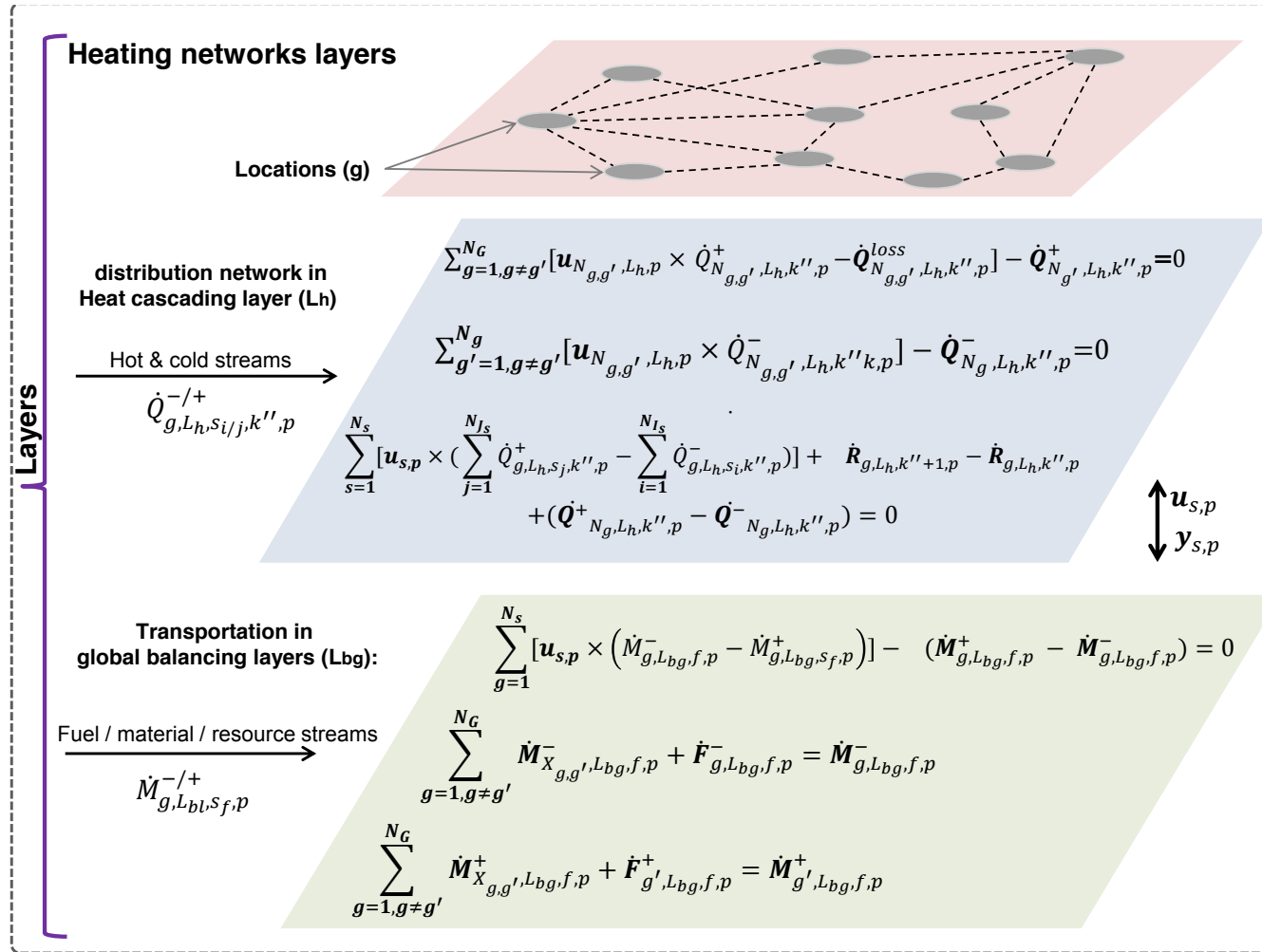
$$y_{w,k} \mathbf{u}_{\min_w} \leq u_{w,k} \leq y_{w,k} \mathbf{u}_{\max_w} \quad \forall k, w$$





District heating supestructure

Routing algorithm



Management of storage during the day (multi-period/multi-time)

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

Demand @node k , period p and time $t(p)$

$$\sum_{w=1}^{n_w} u_{w,k,p} \mathbf{q}_{w,k,p,r} + \sum_{d=1}^{n_d} \mathbf{Q}_{k,p,d,r} + R_{k,p,r+1} - R_{k,p,r} = 0$$

$\forall r = 1, \dots, n_r$
 $\forall p = 1, \dots, n_p$
 $\forall k = 1, \dots, n_k$

$$R_{k,p,r} \geq 0, \quad R_{k,p,n_r+1} = 0, \quad R_{k,p,1} = 0$$

$$\sum_{w=1}^{n_w} u_{w,k,p} \mathbf{e}_{w,k,p,r} + \sum_{d=1}^{n_d} \mathbf{e}_{k,p,d,r} + E_{k,p}^+ - E_{k,p}^- = 0$$

$E_{k,p}^+ \geq 0, \quad E_{k,p}^- \geq 0$

$$y_{w,k,p} \mathbf{u}_{\min_w} \leq u_{w,k,p} \leq y_{w,k,p} \mathbf{u}_{\max_w}$$

$$\forall w = 1, \dots, n_w \quad \forall p = 1, \dots, n_p \quad \forall k = 1, \dots, n_k$$

$$u_{w,k,p} \leq u_{w,k}$$

$$\forall w, k, p$$

$$y_{w,k} \mathbf{u}_{\min_w} \leq u_{w,k} \leq y_{w,k} \mathbf{u}_{\max_w}$$

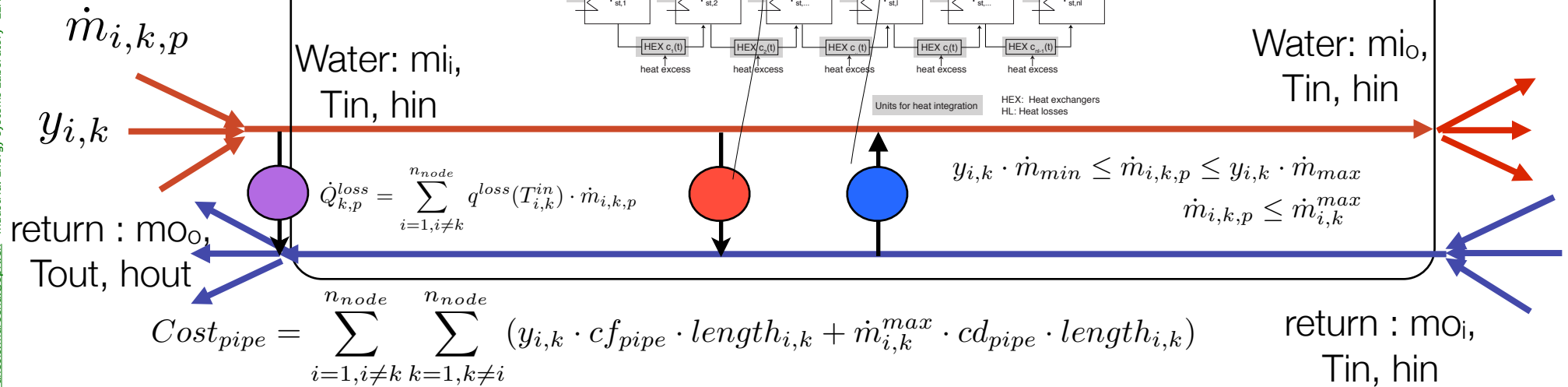
$$\forall k, w$$

Storage system

Buildings inertia
Batteries

Water: $m_{i,j}$,
 T_{in}, h_{in}

Water: $m_{i,o}$,
 T_{in}, h_{in}



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

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

Storage tank model

Storage tank Model

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

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

$\forall l = 1, \dots, nl \quad \forall t = 1, \dots, nt$

$$M_{l,p,t} > 0 \quad M_{0,l} > 0 \quad \forall l = 1, \dots, nl \quad \forall t = 1, \dots, nt \quad (15)$$

$$\sum_{l=1}^{nl} M_{l,t} < M_{tot} \quad \sum_{l=1}^{nl} M_{0,l} < M_{tot} \quad \forall l = 1, \dots, nl \quad \forall t = 1, \dots, nt \quad (16)$$

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

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

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

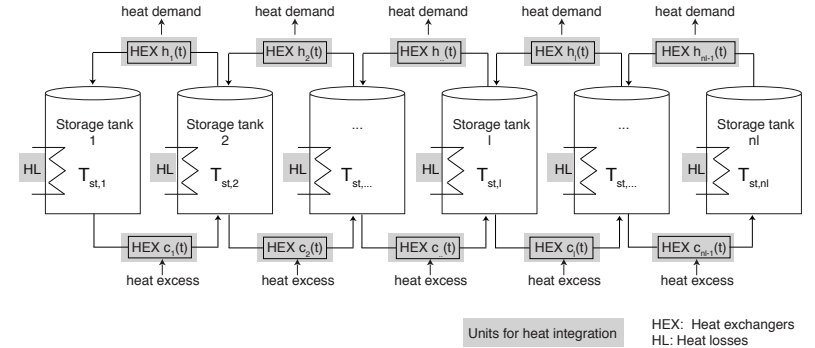
Heat losses in storage tanks

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

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

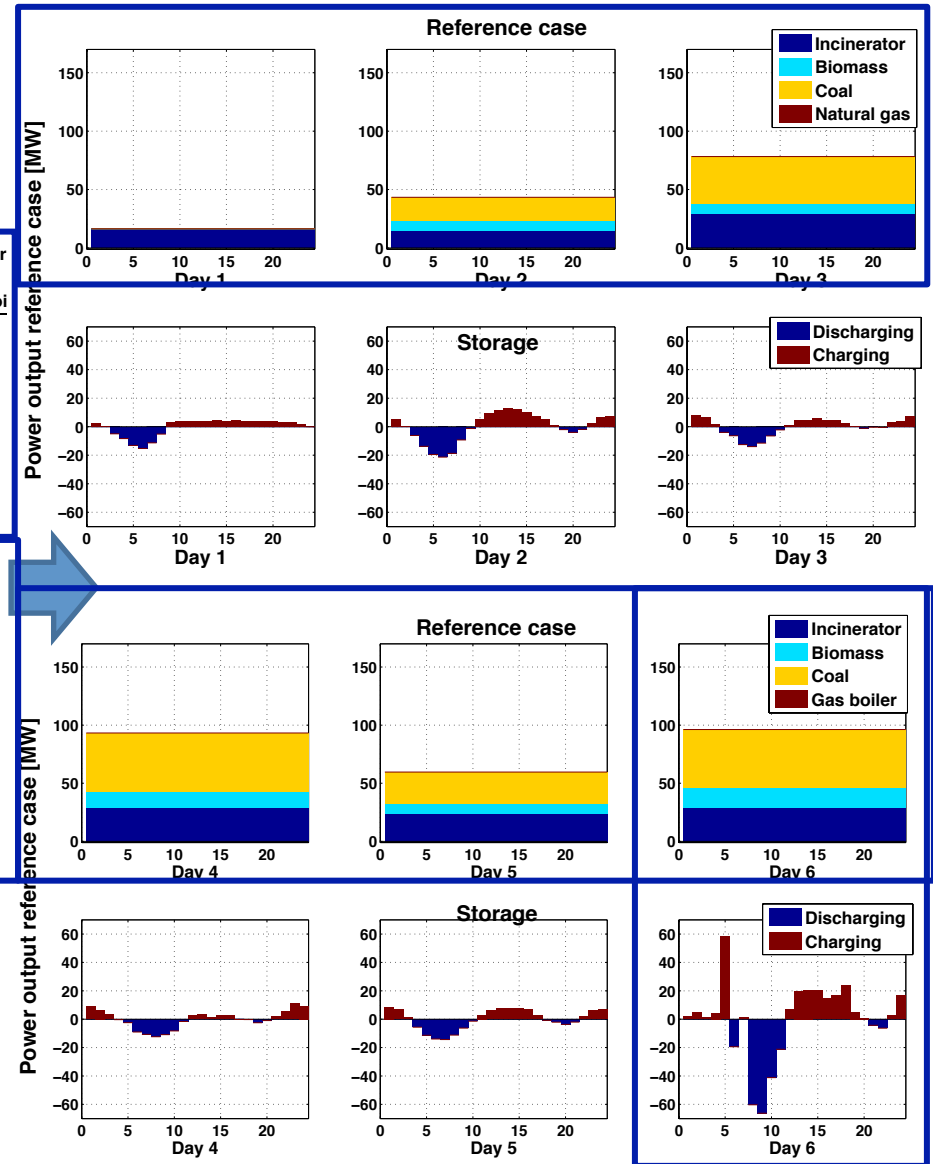
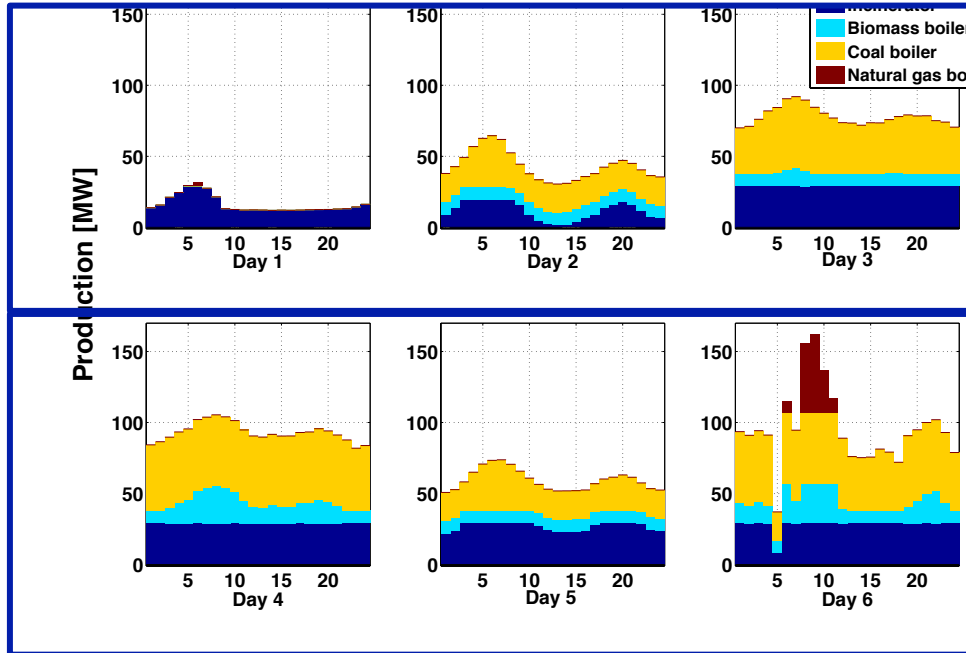
Variables

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 cost for time slice t in period p
$c_{el,p,t}^-$	Electricity selling price for time slice t in period p .
$c_{f,p,t}$	is the fuel price for time slice t in period p .
$\dot{E}_{f,u,p,t}^+$	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).
$f_{u,p,t}$	multiplication factor of unit u for time slice t in period p
$y_{u,p,t}$	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 .
$\dot{Q}_{hts(s),s,k,p,t}^-$	Heat supplied to the heat transfer fluid in the temperature interval k and in time slice t
$\dot{R}_{s,k,p,t}$	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 .
$M_{0,l}$	initial water content of tank l .



Comparison between storage and not in the 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]

CO₂: 197 [kg/MWh]

Heat cost: 46 [€/MWh]

CO₂: 197 [kg/MWh]

10%

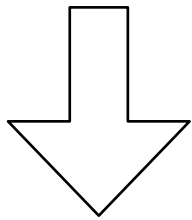
Marginal inv. costs

300 [€/m³/year]

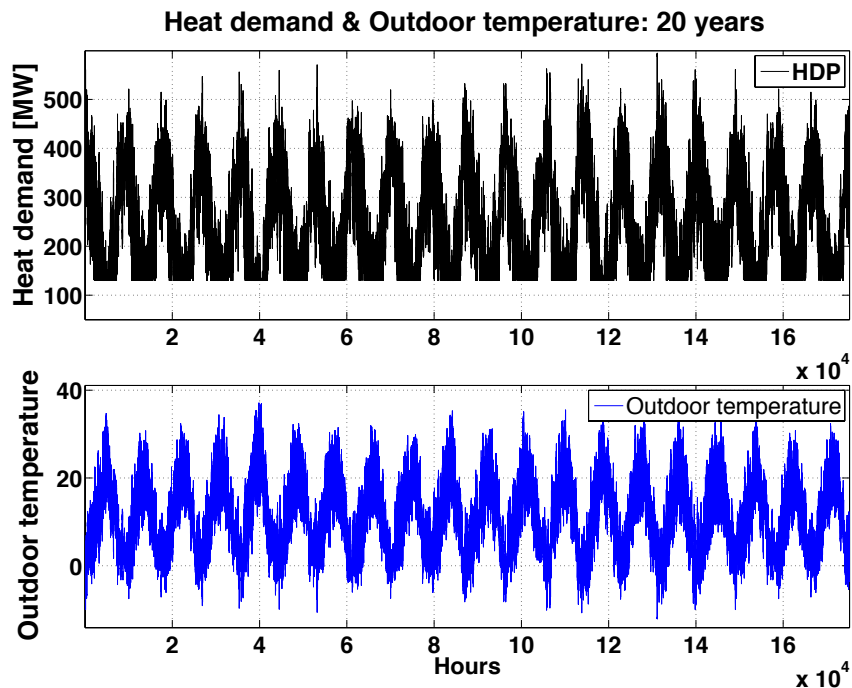
Evaluation of the operational cost

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

20 x 8760 hours



175'200 hours

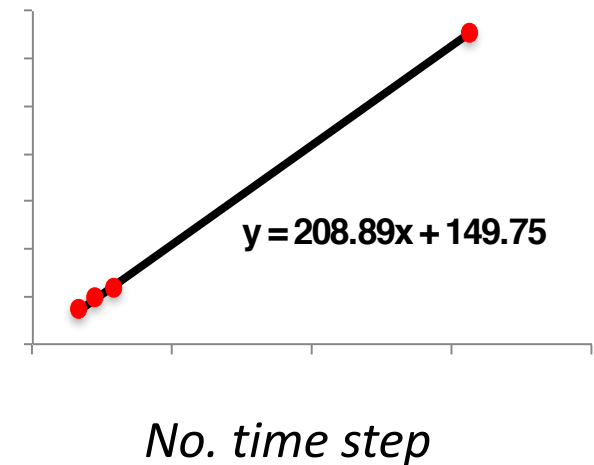


MILP problem size

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

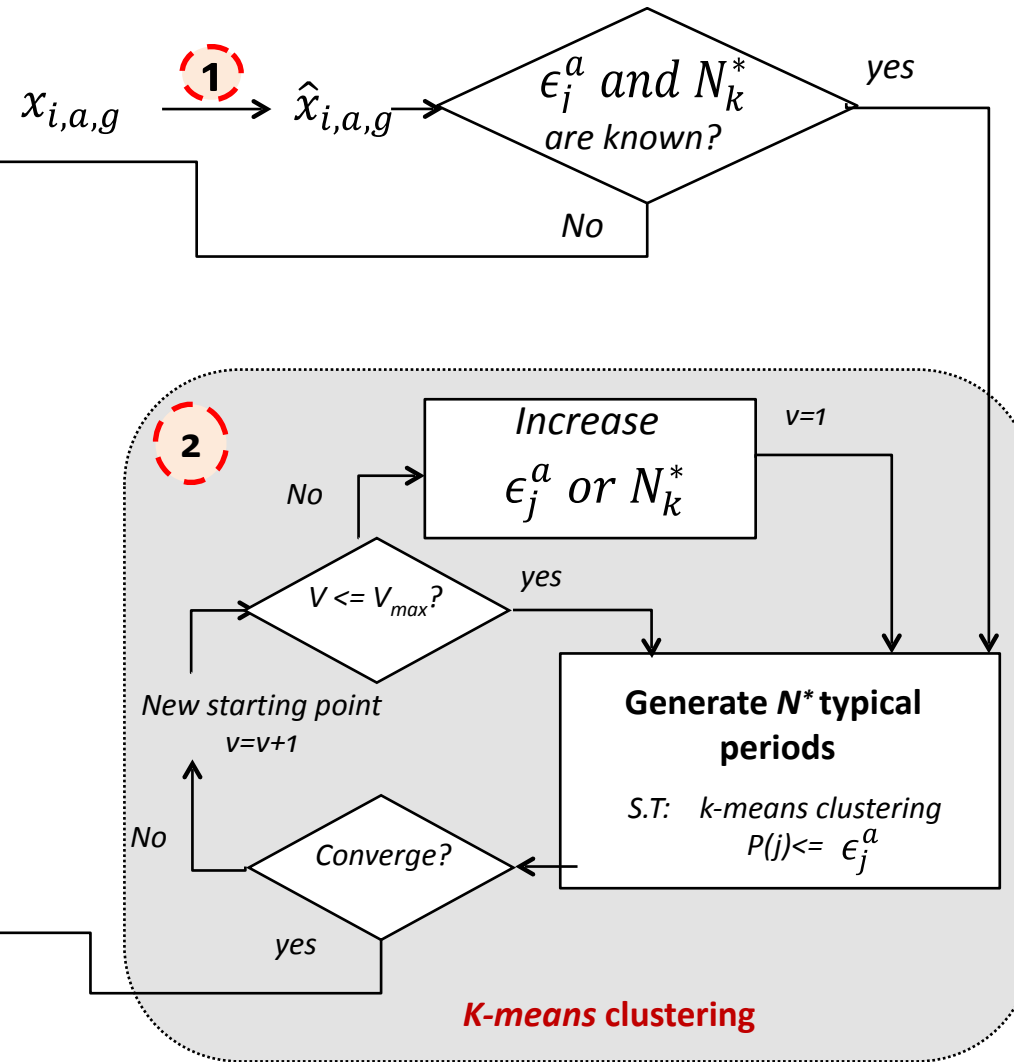
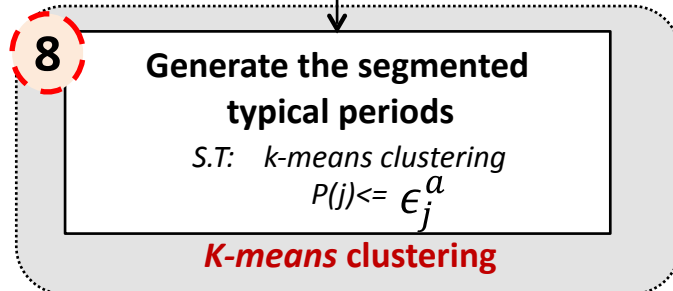
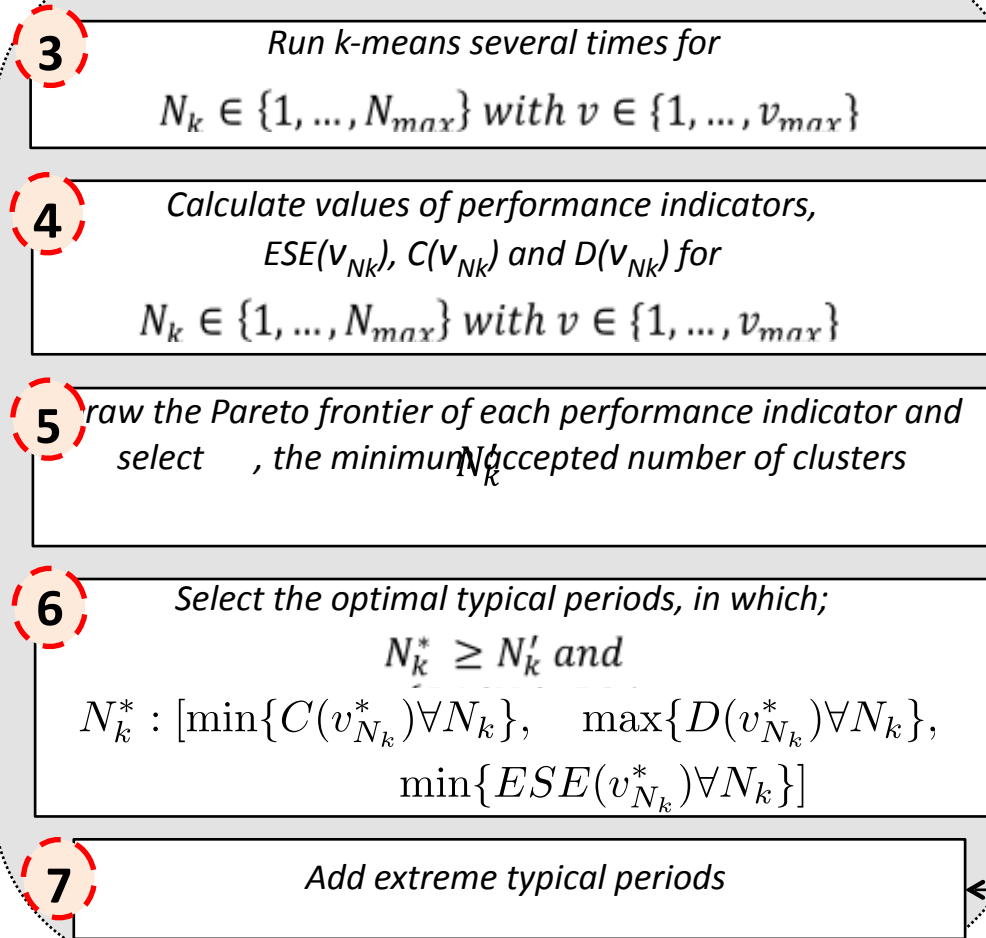
Optimization size



While achieving accurate representation of data!

I-Data structuring: Typical periods selection method

K-means clustering

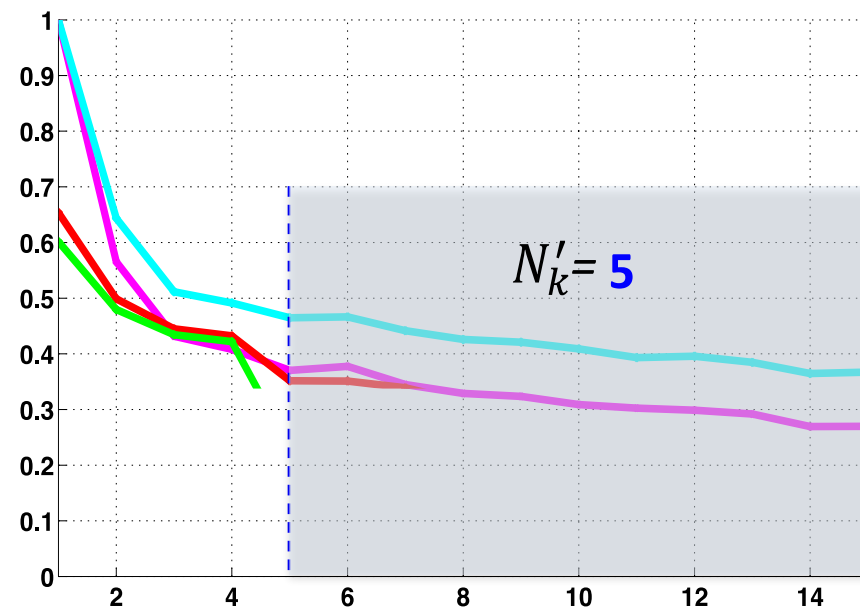


Segmented typical periods: μ_k^*

I-Data structuring: Typical periods selection method

- 5 Draw 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



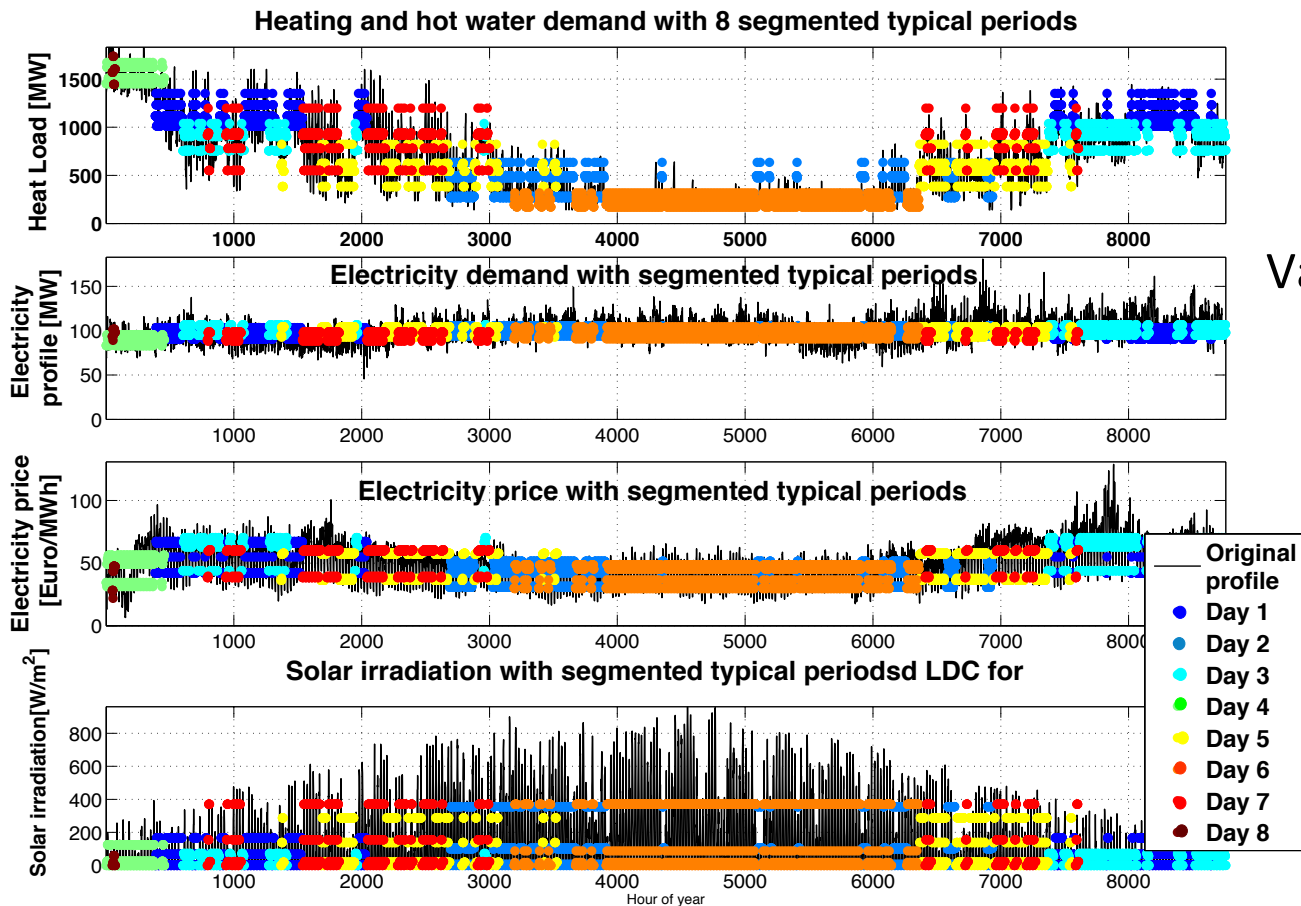
At least we need 5 clusters

Normalized Pareto frontiers of performance indicators for each type of attributes

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

attributes



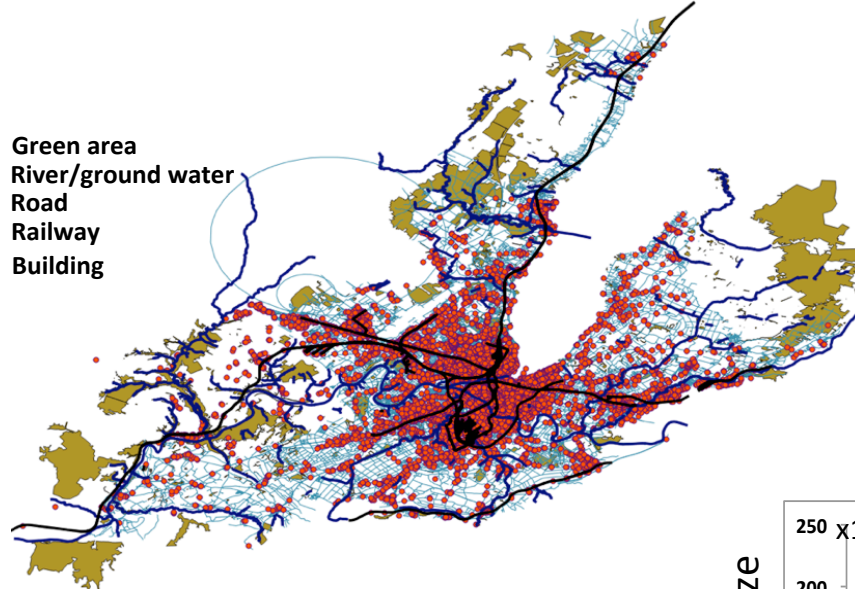
Validation is performed

- 0.3-4.1% errors
- 40 times faster

The difficulty of the urban size

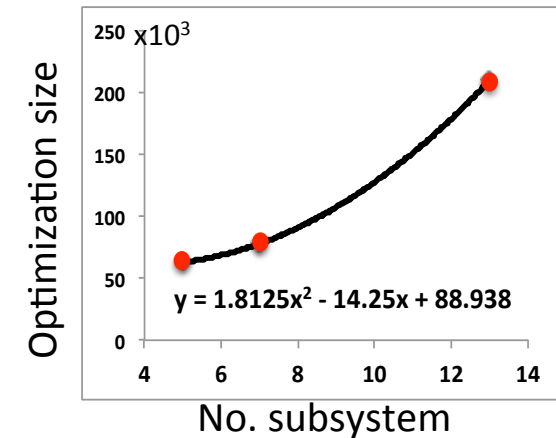
A list of “integrated zones” based on GIS data

■ Green area
■ River/ground water
■ Road
■ Railway
● Building



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

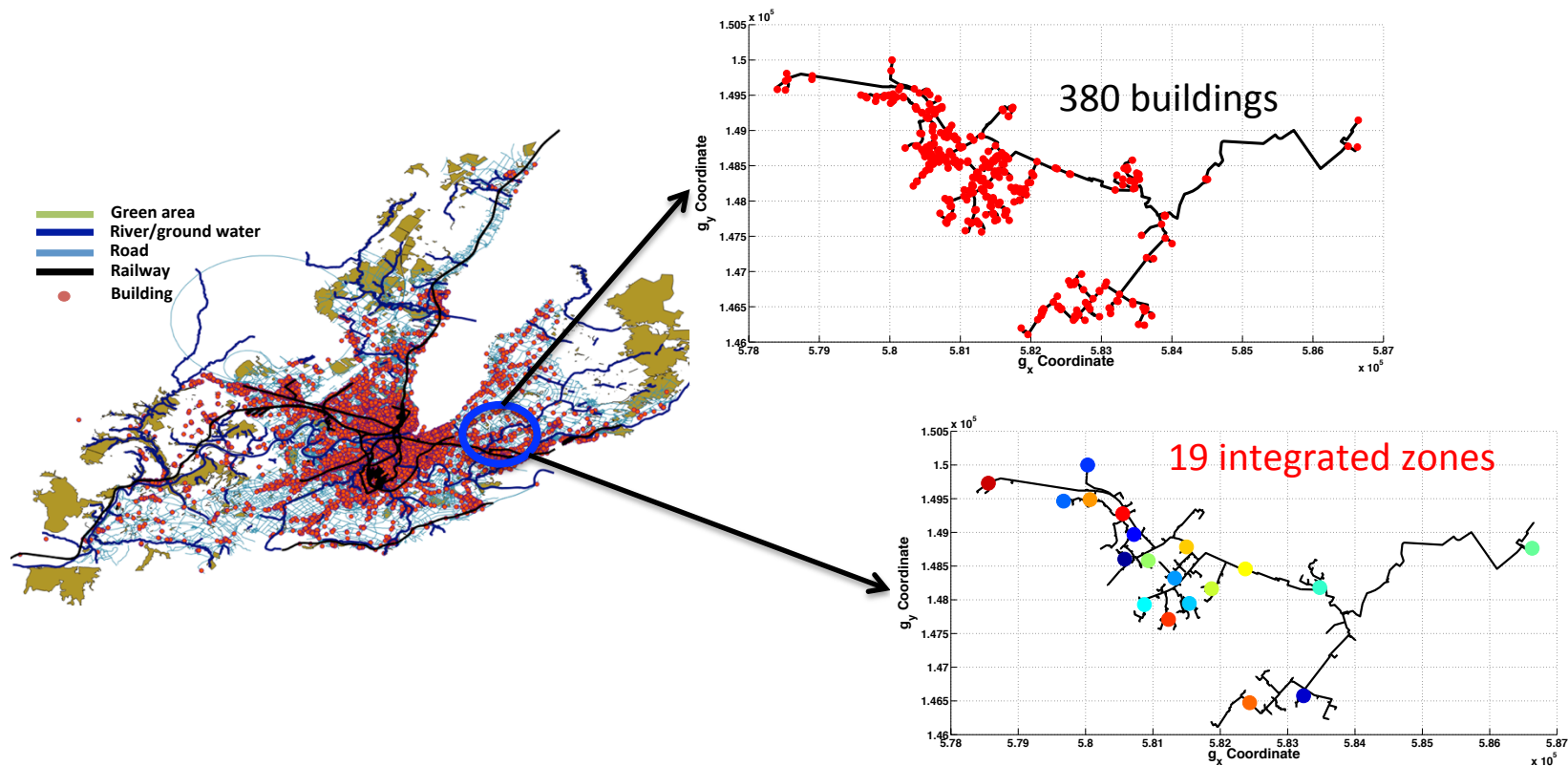


How we can reduce the optimization size and computational load considering the number of subsystems?

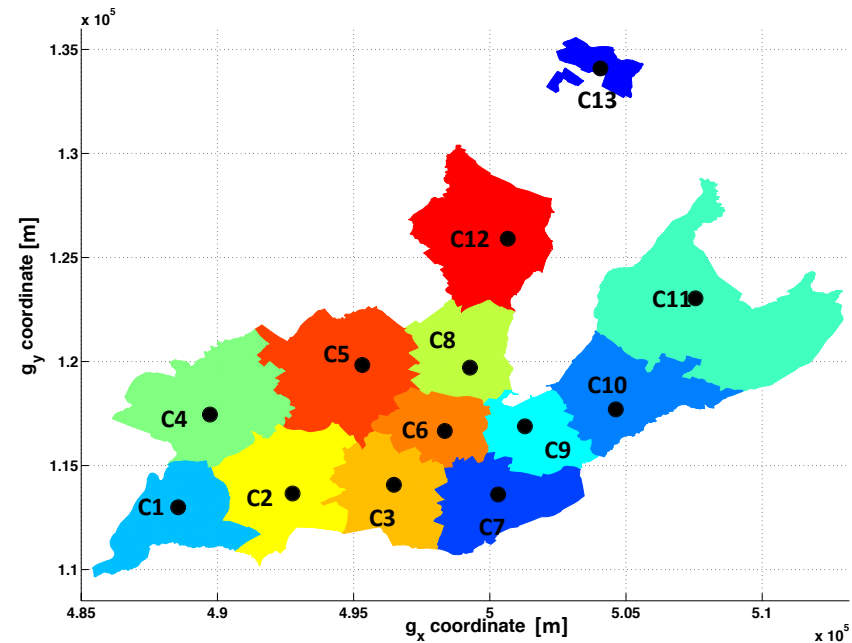
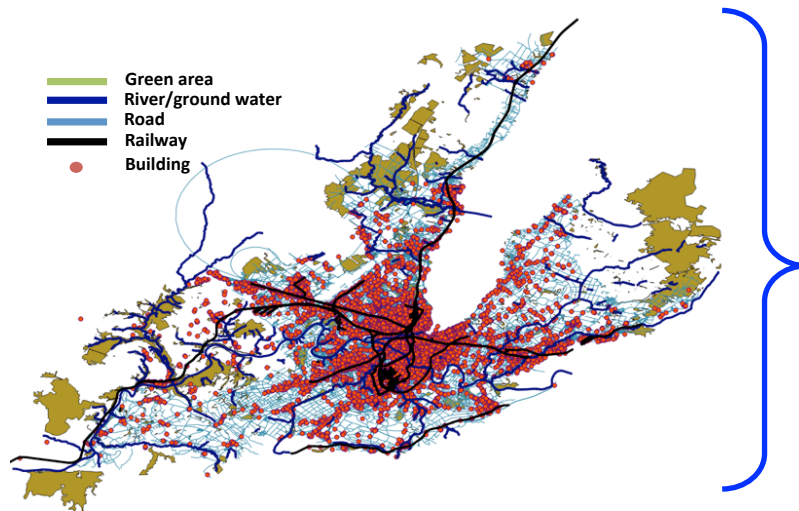
GIS Clustering

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

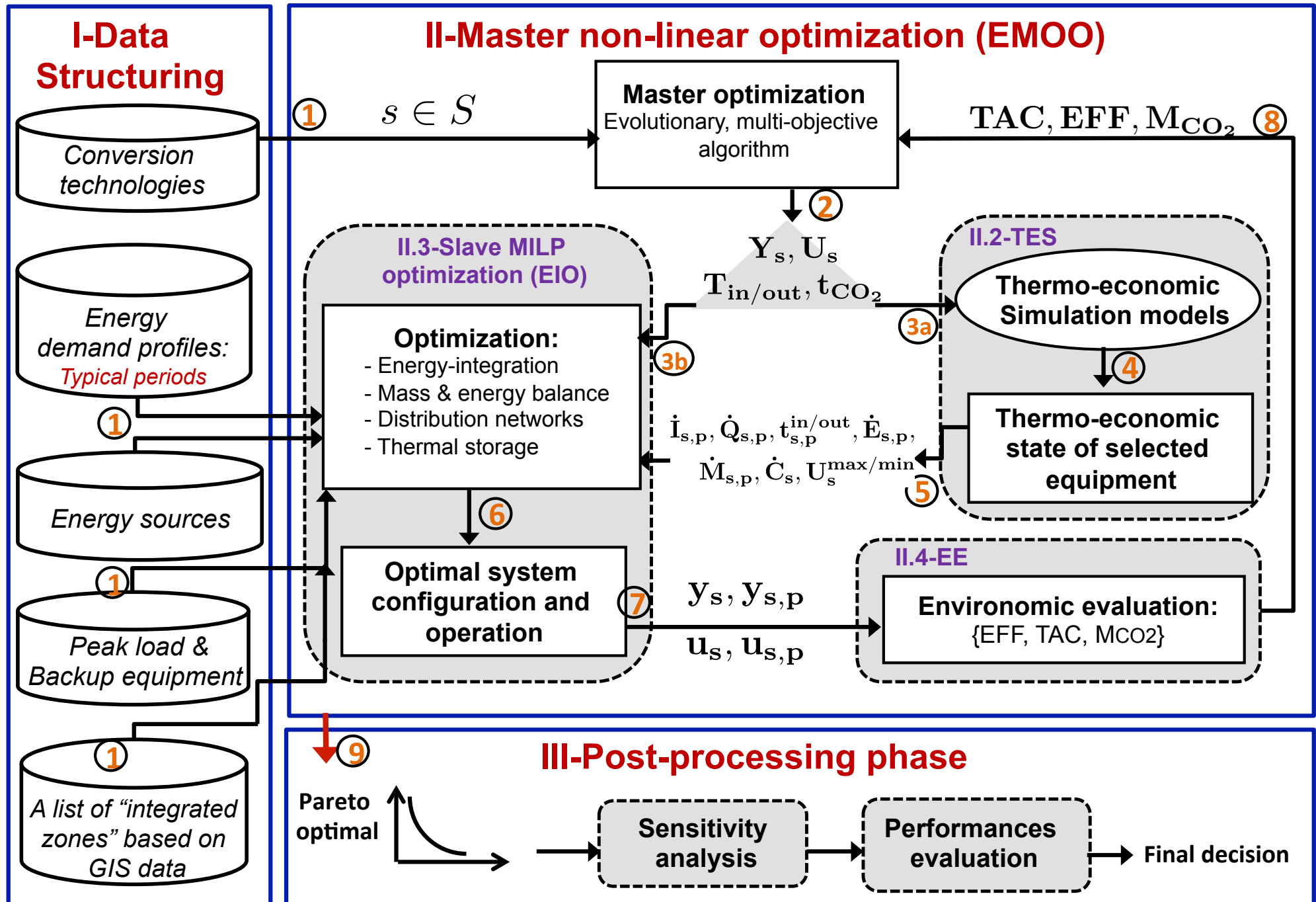


Subsystems	60,000 buildings	13 integrated zones
Constraints ($\times 10^3$)	6,480,000	210

Each building has a probability of being connected to the grid

Reduce the optimization size significantly

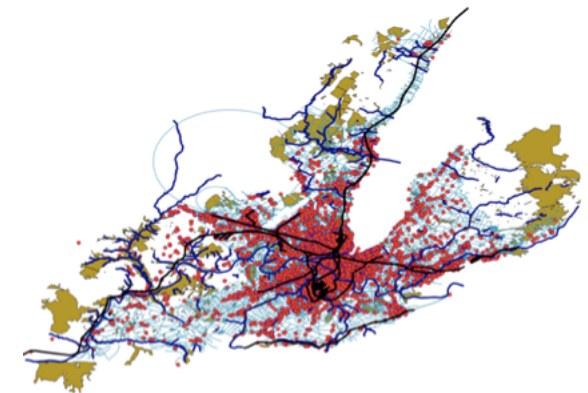
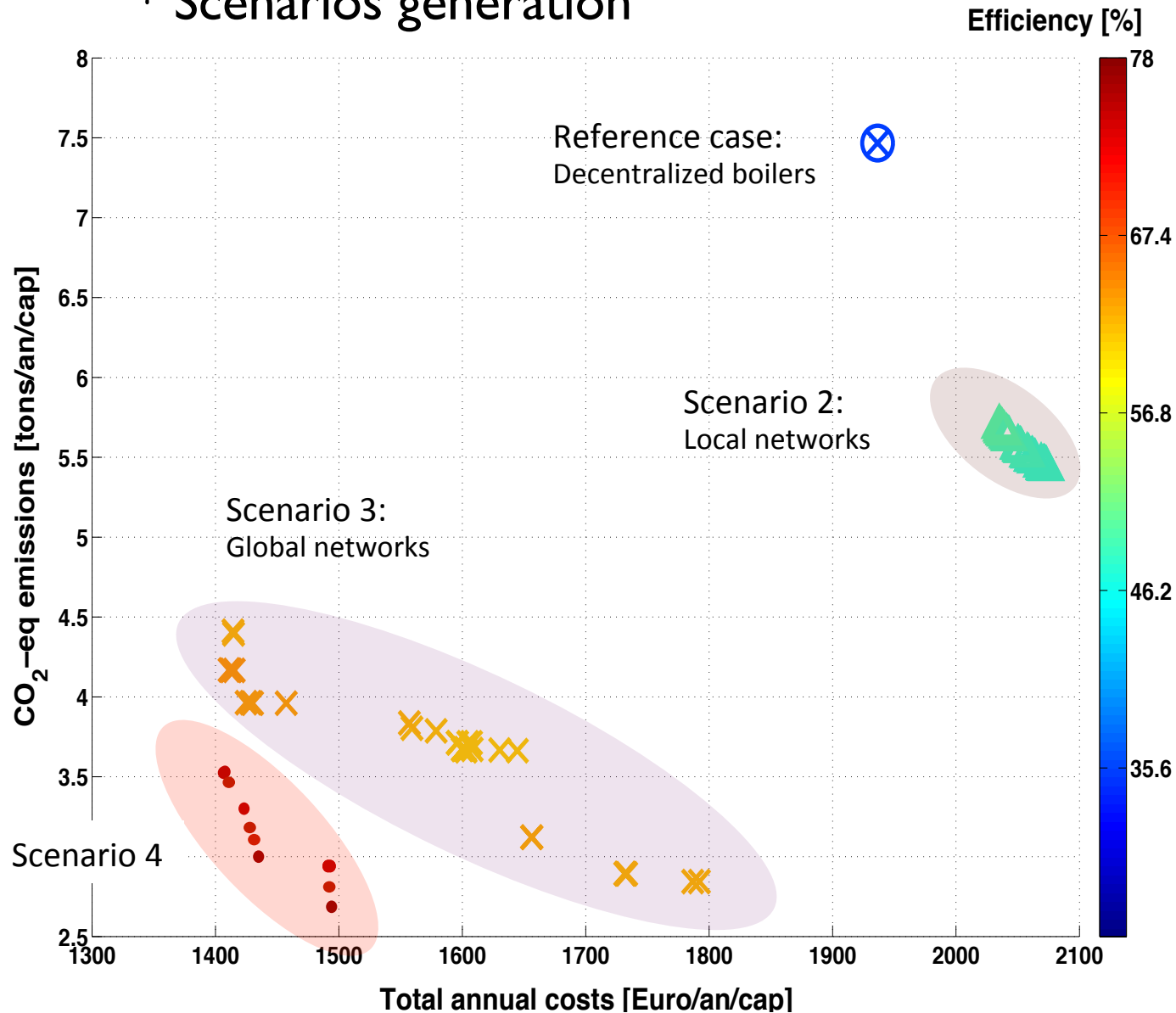
Master slave decomposition



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

Topics covered

- Tools for the analysis and design of more efficient and sustainable industrial and urban energy systems, with a particular focus on:
 - Energy system models
 - System integration : multi-period
 - Optimal system operation : multi-time (typical days)
 - Thermo economic and environomic models
 - Energy system design (location, selection and size of equipment)
 - Superstructures : list of options
 - Multi objective optimisation techniques
 - Decision support