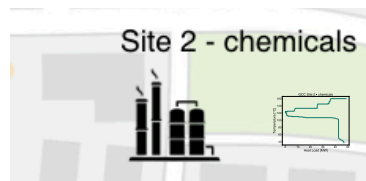
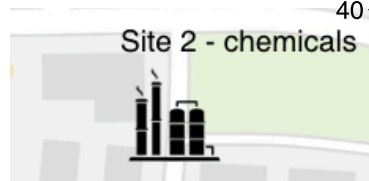
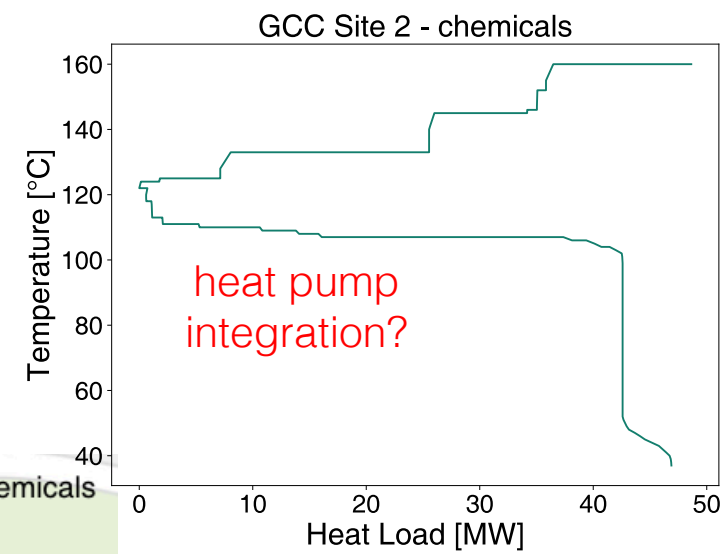
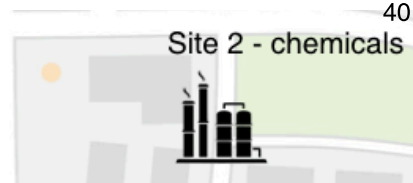
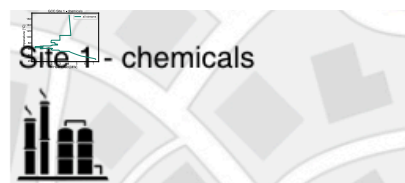
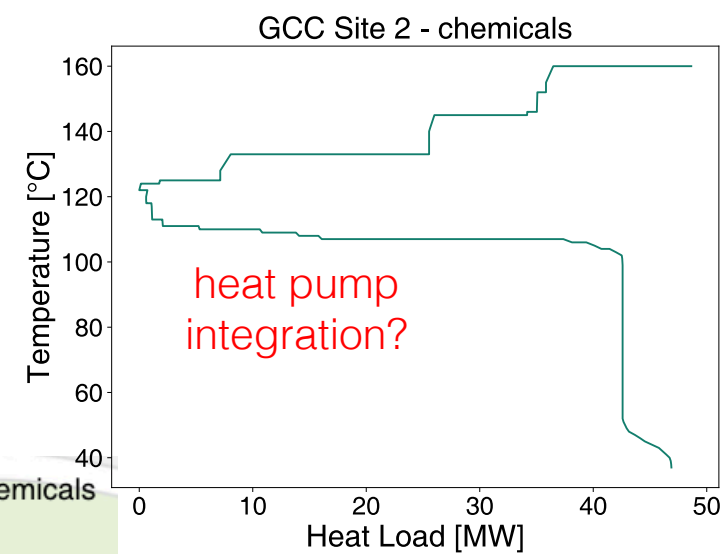


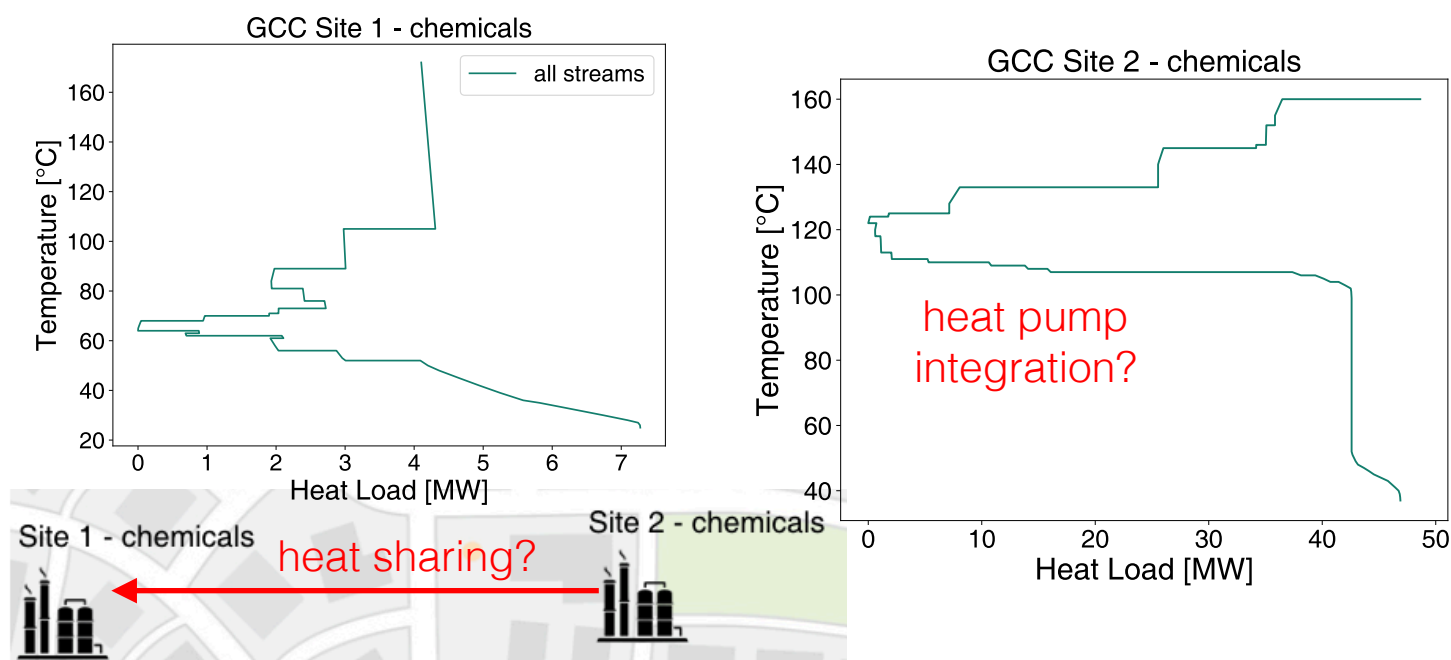
Development of industrial symbiosis

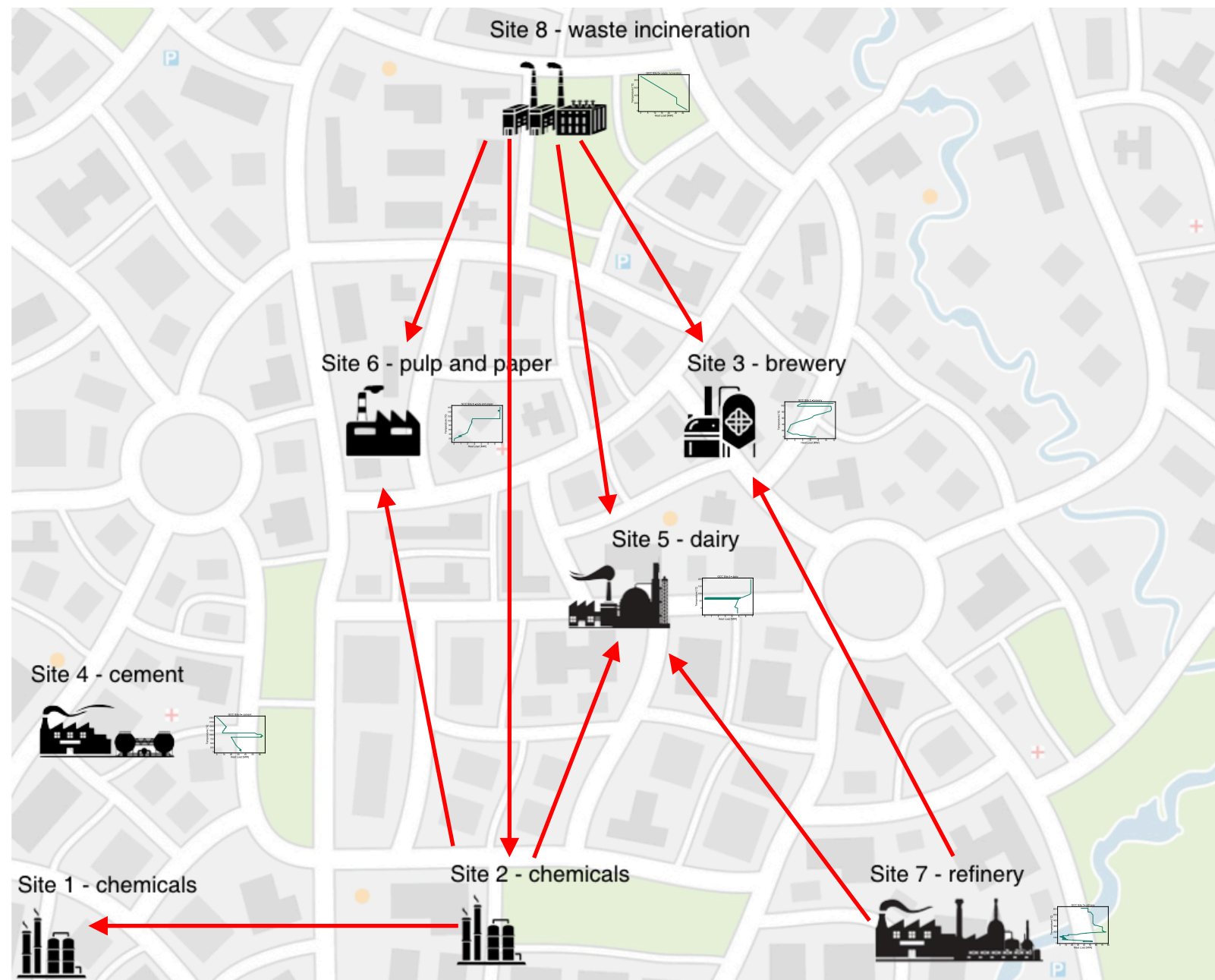
Optimal retrofit and investment planning methodologies for improving energy and resource efficiency in industry, Hür Bütün, PhD Thesis 2019



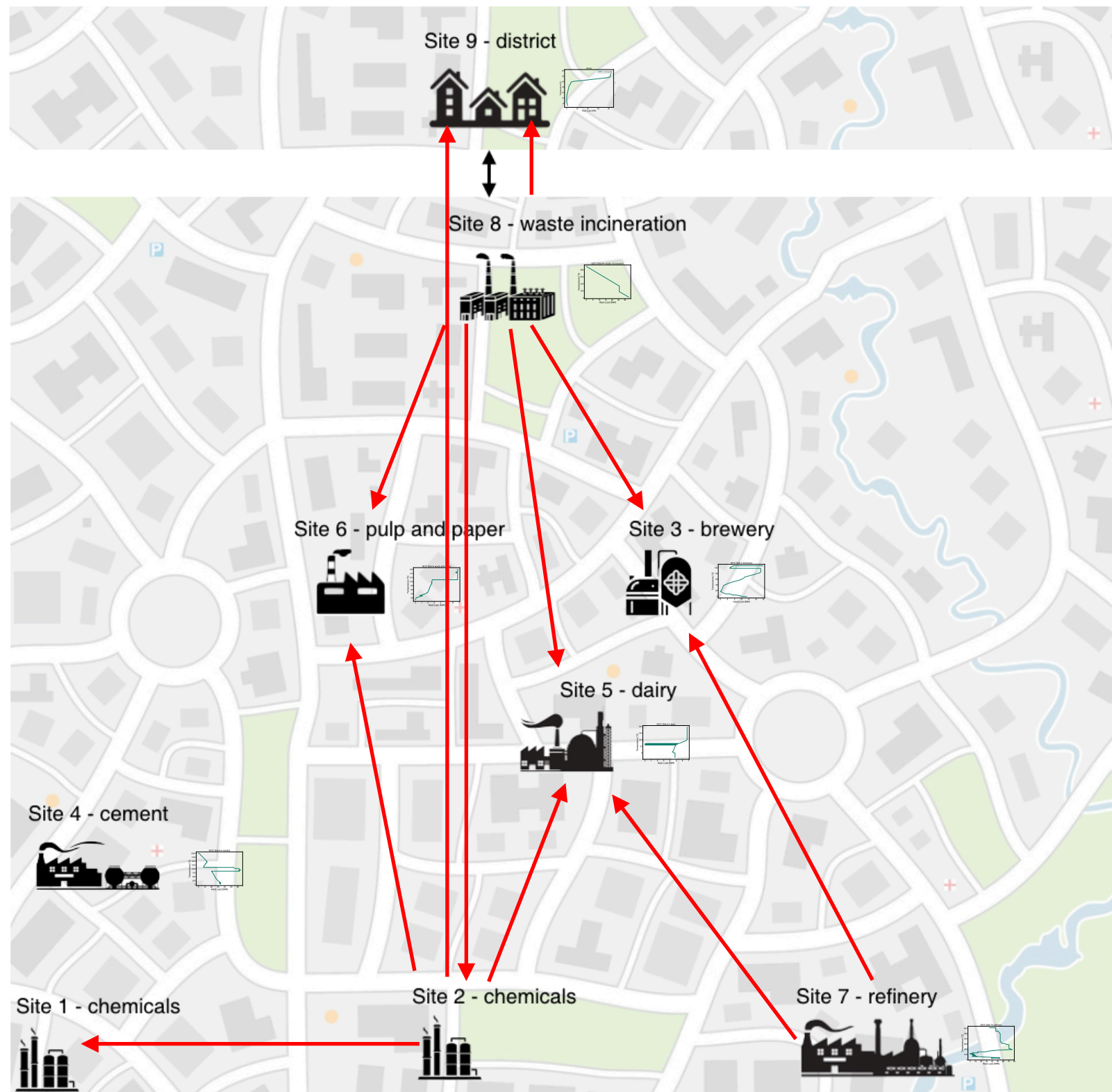


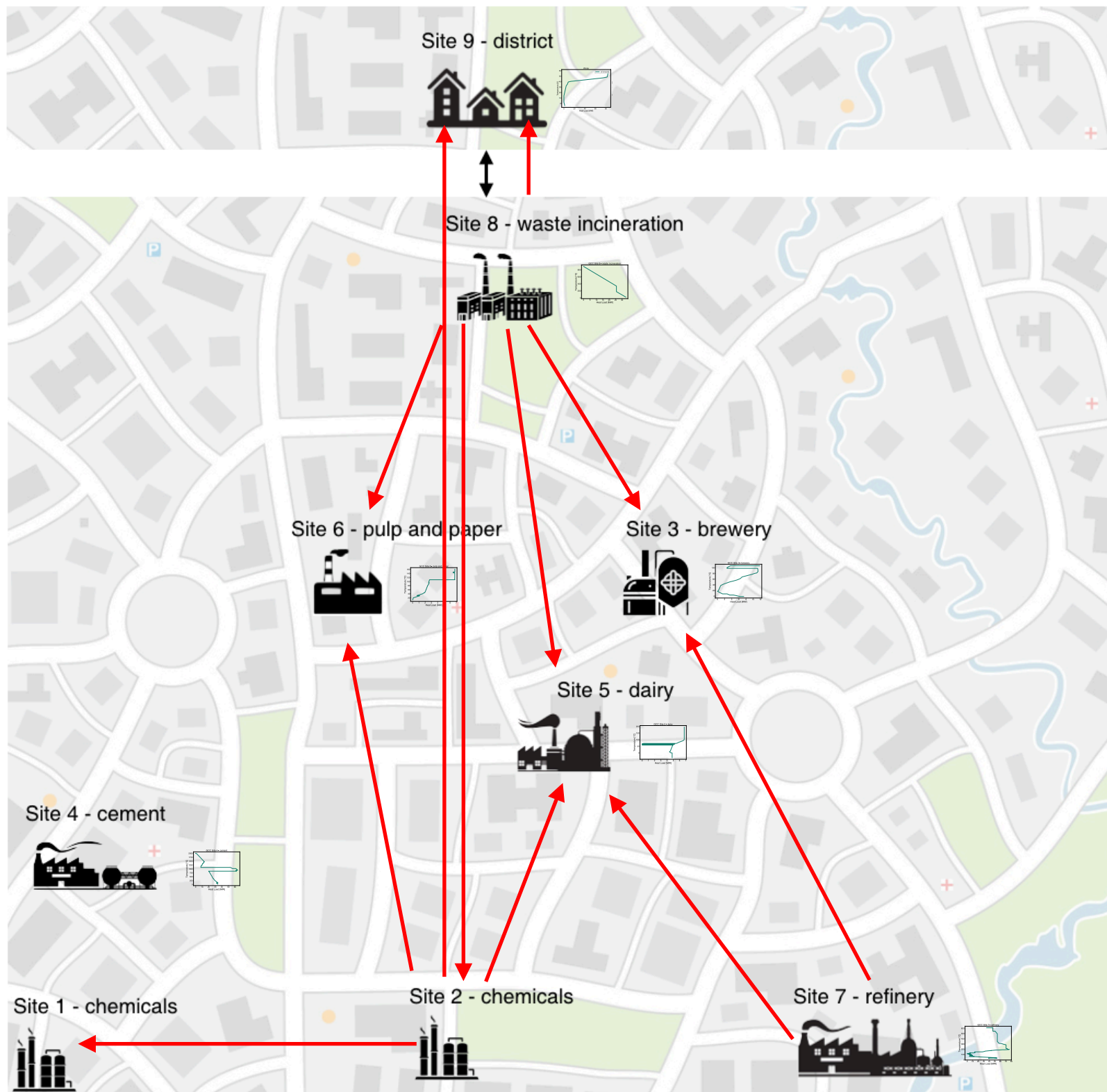






Energy in industrial clusters



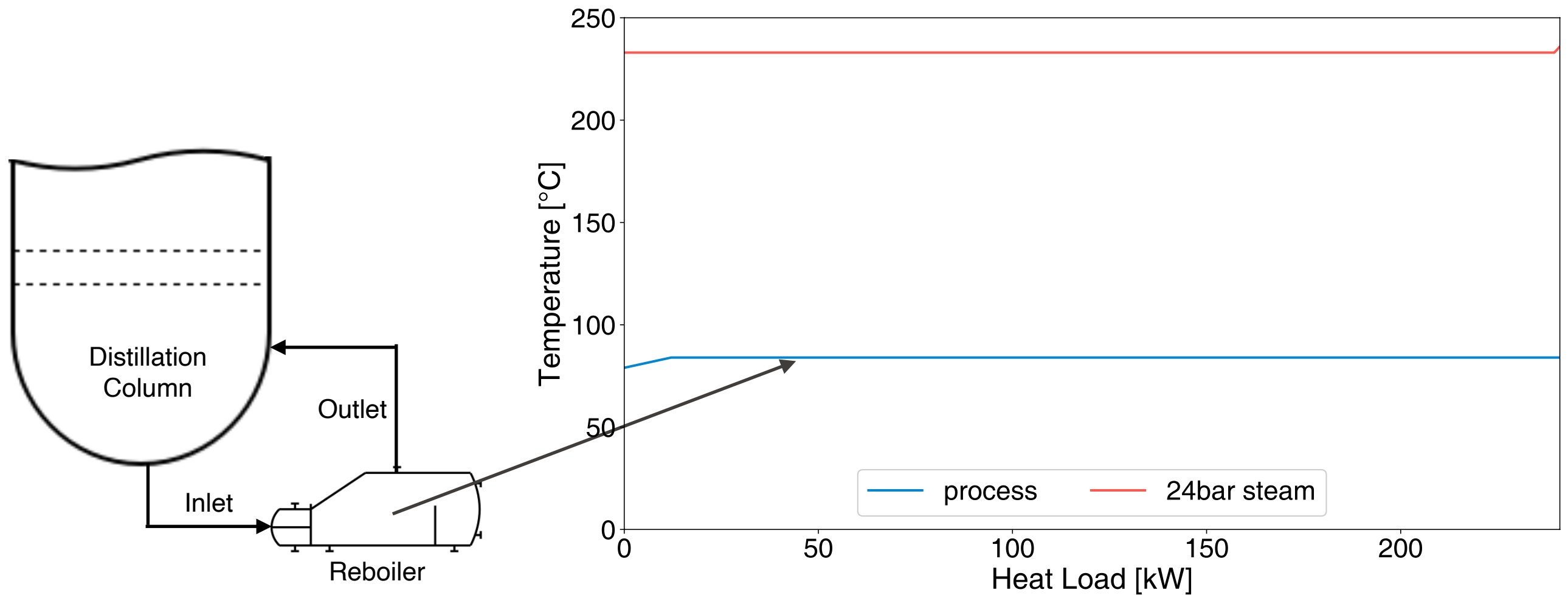


- ❖ industrial plants are complex with several process units operating at different temperature levels
- ❖ what are the **most profitable heat recovery** options?
- ❖ **which technologies** provide the best integration to the processes?
- ❖ what is the impact of **plant layout**?
- ❖ what are the most promising **exchanges between plants**?
- ❖ what is the **optimal pipe size** for sharing energy and resources?
- ❖ what is the **optimal time** for retrofit investments?

challenge: very complex problem

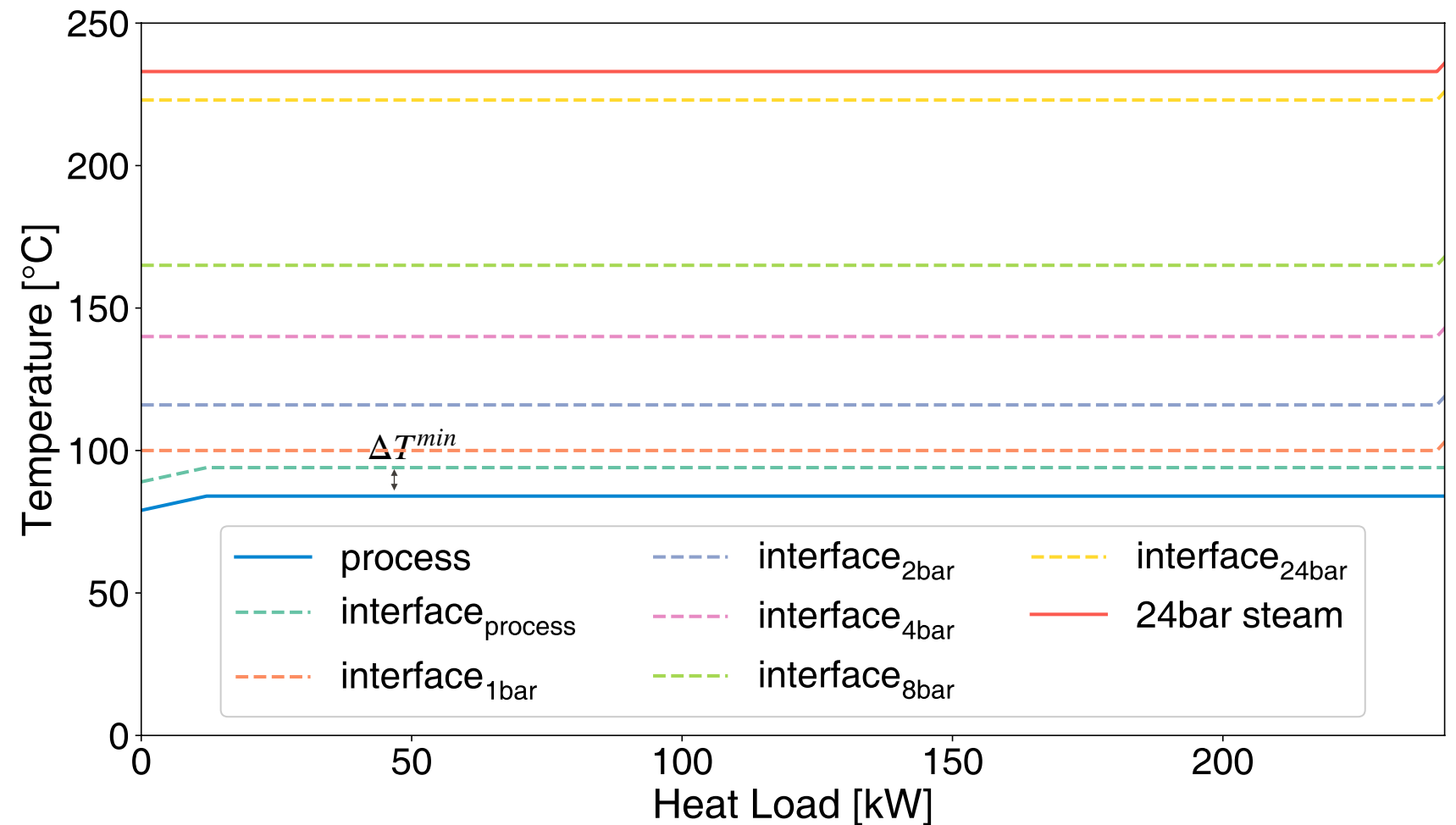
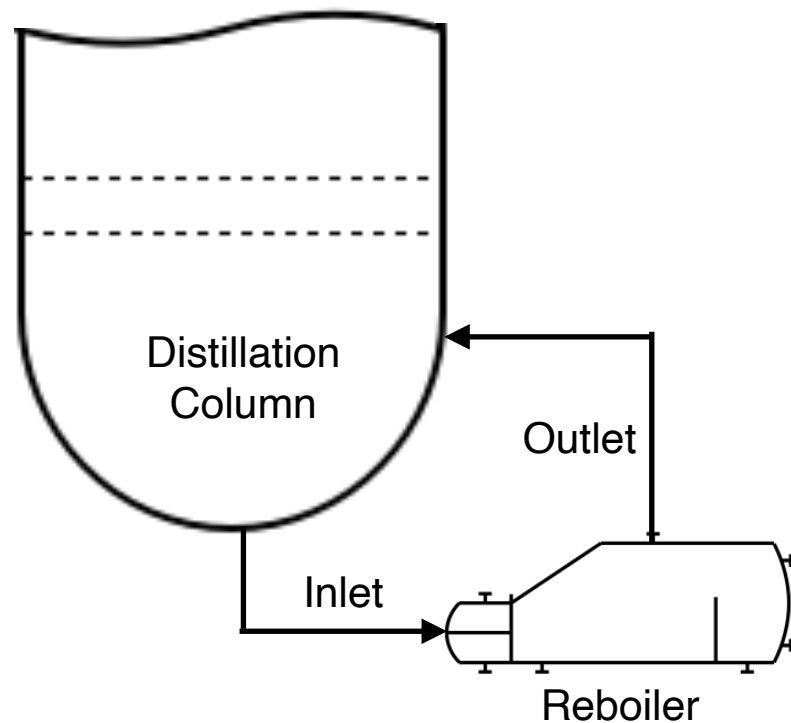
retrofit strategies using optimisation!

Definition of heat transfer interfaces



❖ current utility: 24 bar steam

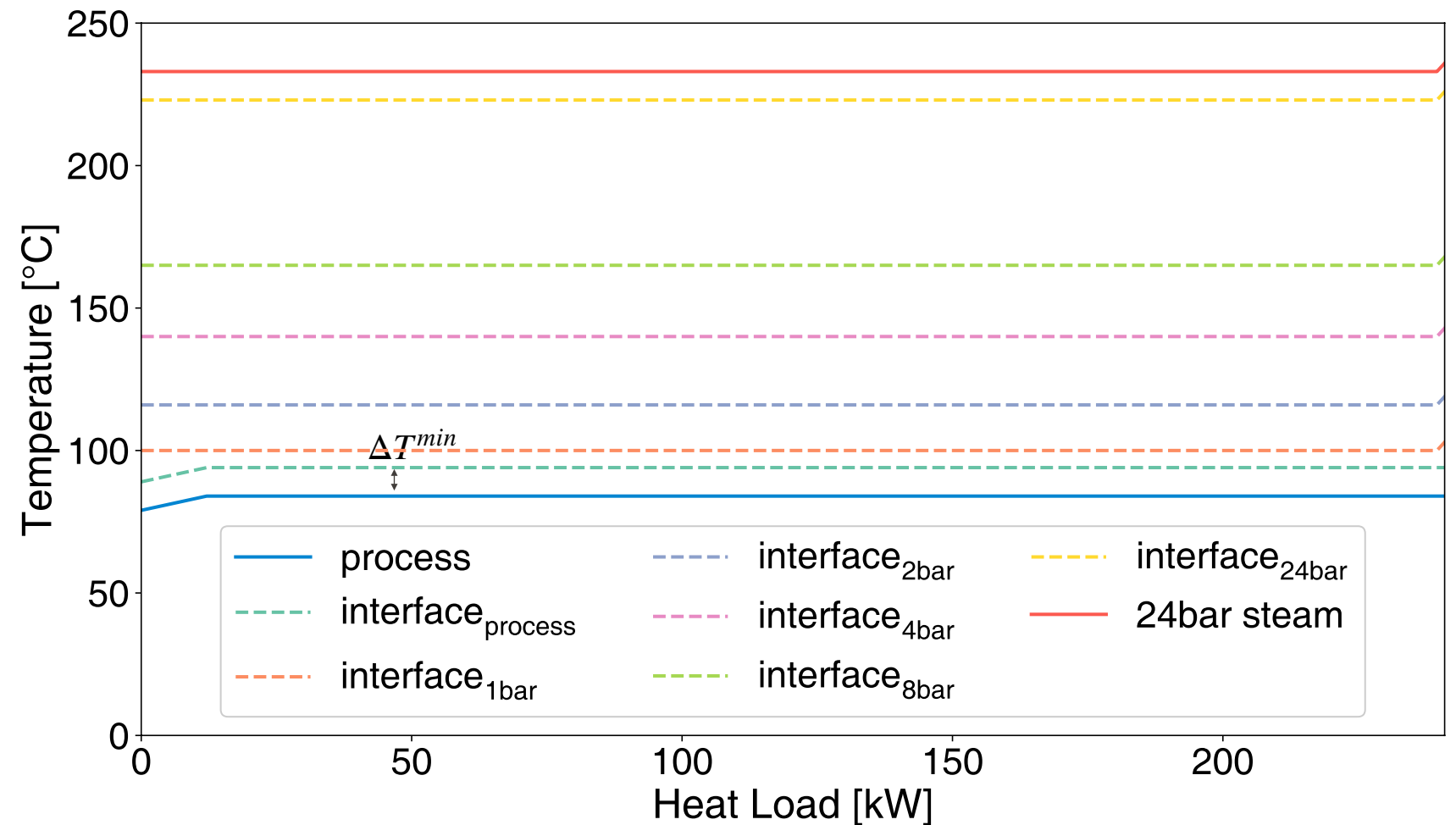
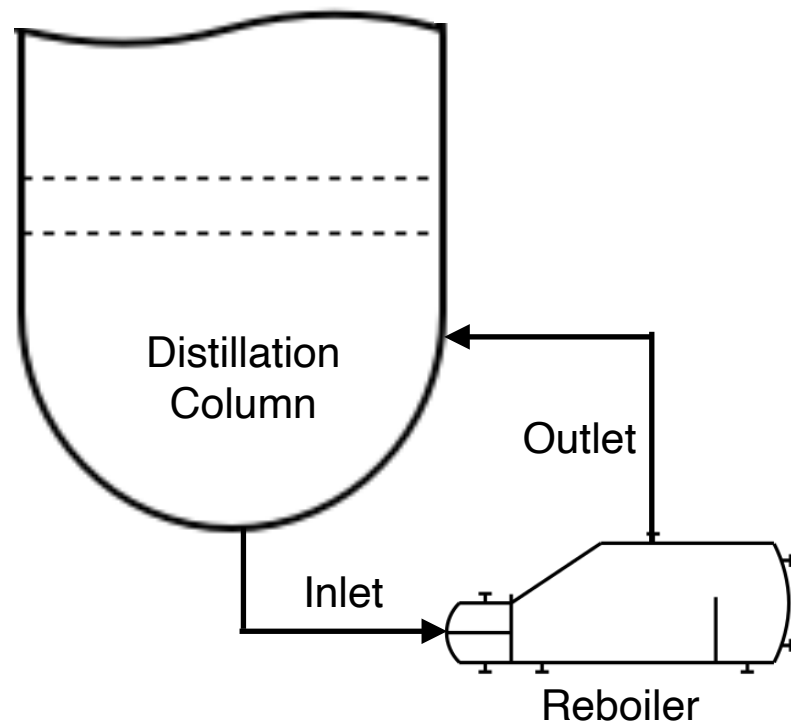
Definition of heat transfer interfaces



- ❖ current utility: 24 bar steam
- ❖ representation of the process with its current utility interface
 - ◆ allow the integration of only the current utility, or a higher temperature source
- ❖ alternative utilities: candidate interfaces

what is the cost of switching interfaces?

Cost of switching interfaces



$$A^{add} = \frac{\dot{q}_{hex}}{V_{new} \cdot LMTD_{new}} - \frac{\dot{q}_{hex}}{V_{cur} \cdot LMTD_{cur}}$$

estimation of additional heat exchanger area

$$c^b = \frac{I_t}{CEPCI_{ref}} \cdot 10^{k1+k2 \cdot \log A^{add} + k3 \cdot (\log A^{add})^2}$$

$$c^{gr} = F^{bm} \cdot c^b$$

$$c^{int} = F^{an} \cdot c^{gr}$$

cost estimation

$$\min \left\{ \sum_{u \in \mathbf{U}} \left[\sum_{t \in \mathbf{TT}} \left(\sum_{sp \in \mathbf{SP}} \left(\sum_{it \in \mathbf{IT}} \left(\sum_{s \in \mathbf{S}} \left(f_{s,t} \cdot \dot{q}_{s,t,k} \right) + \dot{R}_{t,k+1} - \dot{R}_{t,k} \right) \right) \right) \right] \right\} \quad \text{objective function: total cost including interface switching cost}$$

$$F_u^{\min} \cdot y_u \leq f_u \leq F_u^{\max} \cdot y_u \quad \forall u \in \mathbf{U}$$

$$F_u^{\min} \cdot y_{u,t} \leq f_{u,t} \leq F_u^{\max} \cdot y_{u,t} \quad \forall u \in \mathbf{U}, t \in \mathbf{TT}$$

$$f_{u,t} \leq f_u \quad \forall u \in \mathbf{U}, t \in \mathbf{TT}$$

sizing and scheduling constraints [25]

$$y_{u,t} \leq y_u \quad \forall u \in \mathbf{U}, t \in \mathbf{TT}$$

$$y_{u,t} = 1 \quad \forall u \in \mathbf{PU}, t \in \mathbf{TT}$$

$$F_u^{\min}, F_u^{\max} = 1 \quad \forall u \in \mathbf{PU}$$

$$\sum_{it \in \mathbf{IT}} x_{sp,it} = y_u \quad \forall sp \in \mathbf{SP}, u \in \mathbf{PU}$$

interface constraints

$$\sum_{it \in \mathbf{IT}} f_{sp,it,t} = f_{u,t} \quad \forall sp \in \mathbf{SP}, u \in \mathbf{PU}, t \in \mathbf{TT}$$

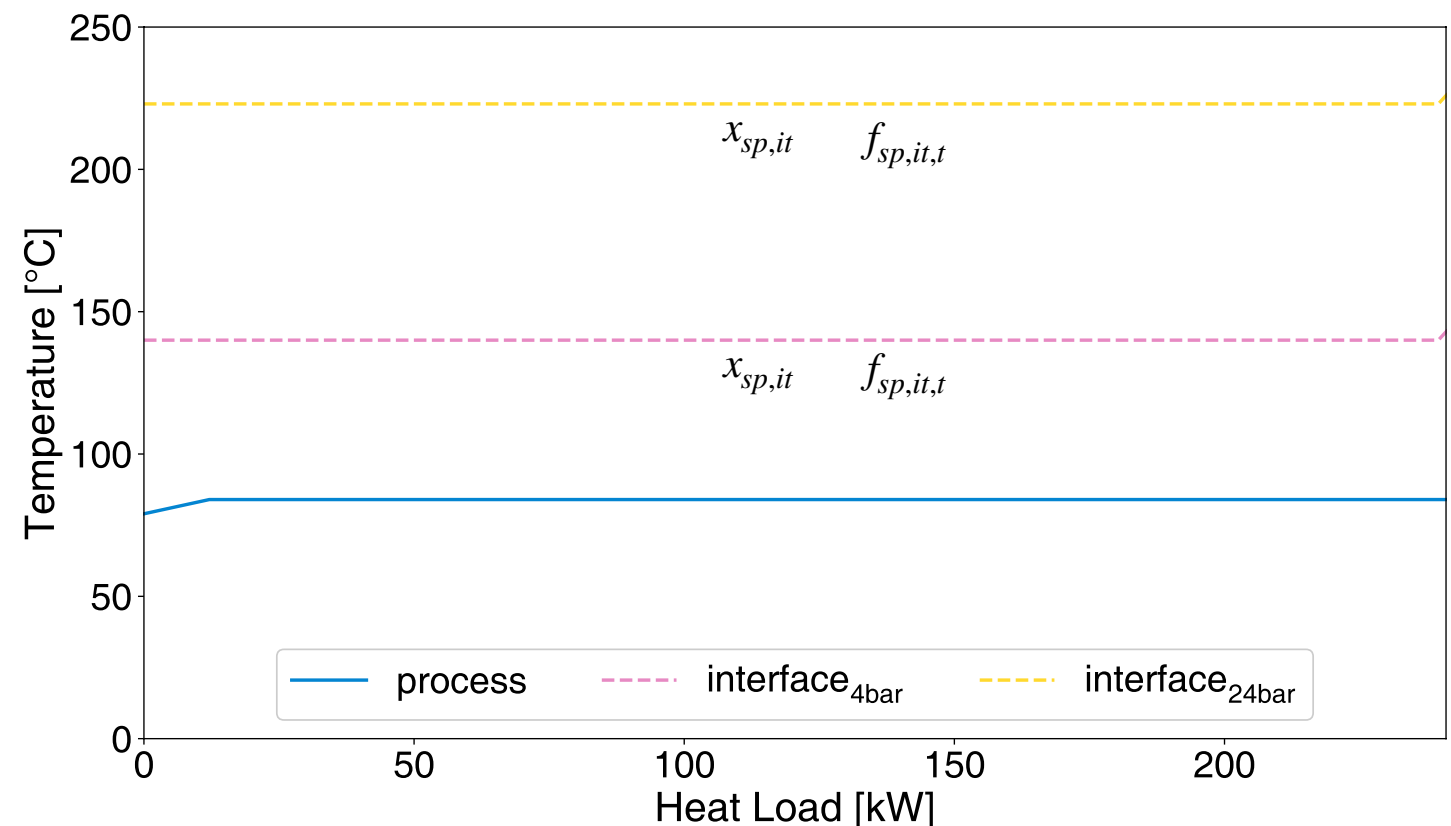
$$\sum_{u \in \mathbf{U}} \sum_{s \in \mathbf{S}} \left(f_{s,t} \cdot \dot{q}_{s,t,k} \right) + \dot{R}_{t,k+1} - \dot{R}_{t,k} = 0 \quad \forall t \in \mathbf{TT}, k \in \mathbf{K}$$

$$\dot{R}_{t,1} = 0, \dot{R}_{t,k+1} = 0 \quad \forall t \in \mathbf{TT}$$

$$\dot{R}_{t,k} \geq 0 \quad \forall t \in \mathbf{TT}, k \in \mathbf{K}$$

heat cascade constraints [25]

$$f_{s,t} = f_{u,t} \quad \forall s \in \mathbf{S}, u \in \mathbf{U}, t \in \mathbf{TT}$$



$$\min \left\{ \sum_{u \in \mathbf{U}} \left[\sum_{t \in \mathbf{TT}} \left(c_{u,t}^{op1} \cdot y_{u,t}' + c_{u,t}^{op2} \cdot f_{u,t}' \right) \cdot t_t^{op} \right] + F^{an} \cdot \left(c_u^{inv1} \cdot y_u + c_u^{inv2} \cdot f_u \right) \right\} + \sum_{sp \in \mathbf{SP}} \sum_{it \in \mathbf{IT}} c_{sp,it}^{int} \cdot x_{sp,it}$$

$$F_u^{min} \cdot y_u \leq f_u \leq F_u^{max} \cdot y_u \quad \forall u \in \mathbf{U}$$

$$F_u^{min} \cdot y_{u,t}' \leq f_{u,t}' \leq F_u^{max} \cdot y_{u,t}' \quad \forall u \in \mathbf{U}, t \in \mathbf{TT}$$

$$f_{u,t}' \leq f_u \quad \forall u \in \mathbf{U}, t \in \mathbf{TT}$$

$$y_{u,t}' \leq y_u \quad \forall u \in \mathbf{U}, t \in \mathbf{TT}$$

$$y_{u,t}' = 1 \quad \forall u \in \mathbf{PU}, t \in \mathbf{TT}$$

$$F_u^{min}, F_u^{max} = 1 \quad \forall u \in \mathbf{PU}$$

$$\sum_{it \in \mathbf{IT}} x_{sp,it} = y_u \quad \forall sp \in \mathbf{SP}, u \in \mathbf{PU}$$

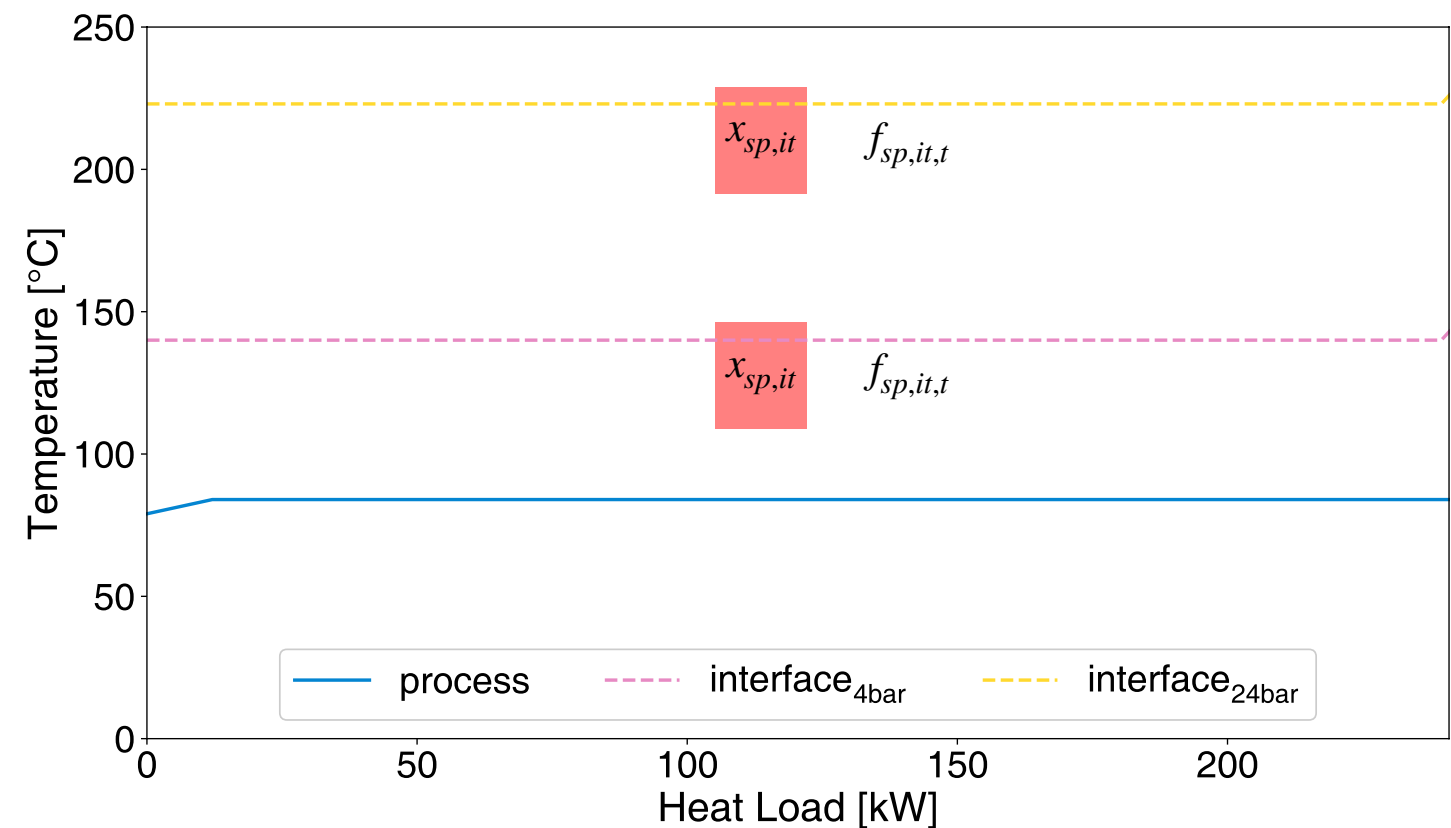
$$\sum_{it \in \mathbf{IT}} f_{sp,it,t} = f_{u,t}' \quad \forall sp \in \mathbf{SP}, u \in \mathbf{PU}, t \in \mathbf{TT}$$

$$\sum_{u \in \mathbf{U}} \sum_{s \in \mathbf{S}} \left(f_{s,t} \cdot \dot{q}_{s,t,k} \right) + \dot{R}_{t,k+1} - \dot{R}_{t,k} = 0 \quad \forall t \in \mathbf{TT}, k \in \mathbf{K}$$

$$\dot{R}_{t,1} = 0, \dot{R}_{t,k+1} = 0 \quad \forall t \in \mathbf{TT}$$

$$\dot{R}_{t,k} \geq 0 \quad \forall t \in \mathbf{TT}, k \in \mathbf{K}$$

$$f_{s,t} = f_{u,t}' \quad \forall s \in \mathbf{S}, u \in \mathbf{U}, t \in \mathbf{TT}$$



$$\min \left\{ \sum_{u \in \mathbf{U}} \left[\sum_{t \in \mathbf{TT}} \left(c_{u,t}^{op1} \cdot y_{u,t}' + c_{u,t}^{op2} \cdot f_{u,t}' \right) \cdot t_t^{op} \right] + F^{an} \cdot \left(c_u^{inv1} \cdot y_u + c_u^{inv2} \cdot f_u \right) \right\} + \sum_{sp \in \mathbf{SP}} \sum_{it \in \mathbf{IT}} c_{sp,it}^{int} \cdot x_{sp,it}$$

$$F_u^{min} \cdot y_u \leq f_u \leq F_u^{max} \cdot y_u \quad \forall u \in \mathbf{U}$$

$$F_u^{min} \cdot y_{u,t}' \leq f_{u,t}' \leq F_u^{max} \cdot y_{u,t}' \quad \forall u \in \mathbf{U}, t \in \mathbf{TT}$$

$$f_{u,t}' \leq f_u \quad \forall u \in \mathbf{U}, t \in \mathbf{TT}$$

$$y_{u,t}' \leq y_u \quad \forall u \in \mathbf{U}, t \in \mathbf{TT}$$

$$y_{u,t}' = 1 \quad \forall u \in \mathbf{PU}, t \in \mathbf{TT}$$

$$F_u^{min}, F_u^{max} = 1 \quad \forall u \in \mathbf{PU}$$

$$\sum_{it \in \mathbf{IT}} x_{sp,it} = y_u \quad \forall sp \in \mathbf{SP}, u \in \mathbf{PU}$$

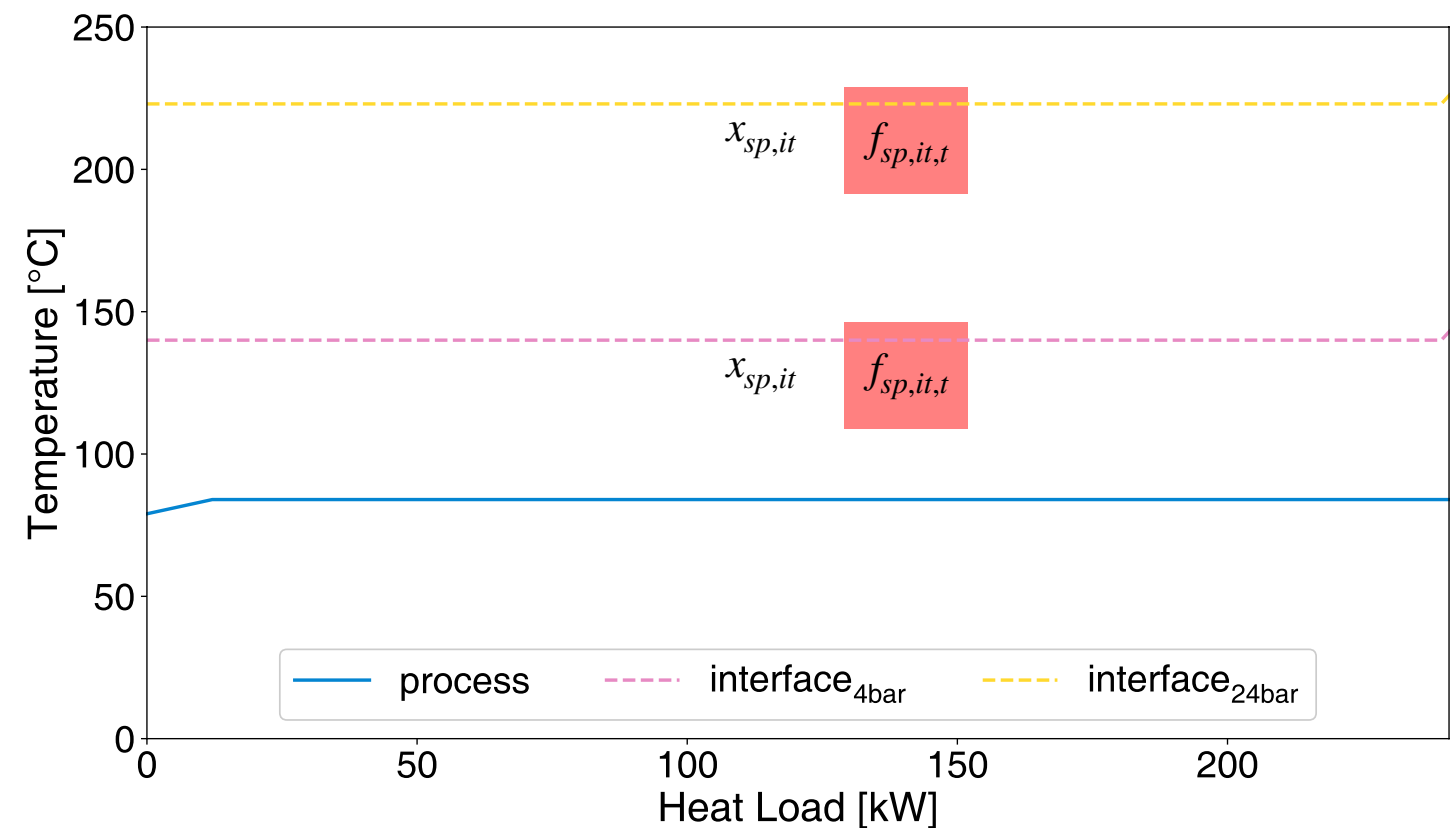
$$\sum_{it \in \mathbf{IT}} f_{sp,it,t} = f_{u,t}' \quad \forall sp \in \mathbf{SP}, u \in \mathbf{PU}, t \in \mathbf{TT}$$

$$\sum_{u \in \mathbf{U}} \sum_{s \in \mathbf{S}} \left(f_{s,t} \cdot \dot{q}_{s,t,k} \right) + \dot{R}_{t,k+1} - \dot{R}_{t,k} = 0 \quad \forall t \in \mathbf{TT}, k \in \mathbf{K}$$

$$\dot{R}_{t,1} = 0, \dot{R}_{t,k+1} = 0 \quad \forall t \in \mathbf{TT}$$

$$\dot{R}_{t,k} \geq 0 \quad \forall t \in \mathbf{TT}, k \in \mathbf{K}$$

$$f_{s,t} = f_{u,t}' \quad \forall s \in \mathbf{S}, u \in \mathbf{U}, t \in \mathbf{TT}$$



Case study: Site 1 - chemicals

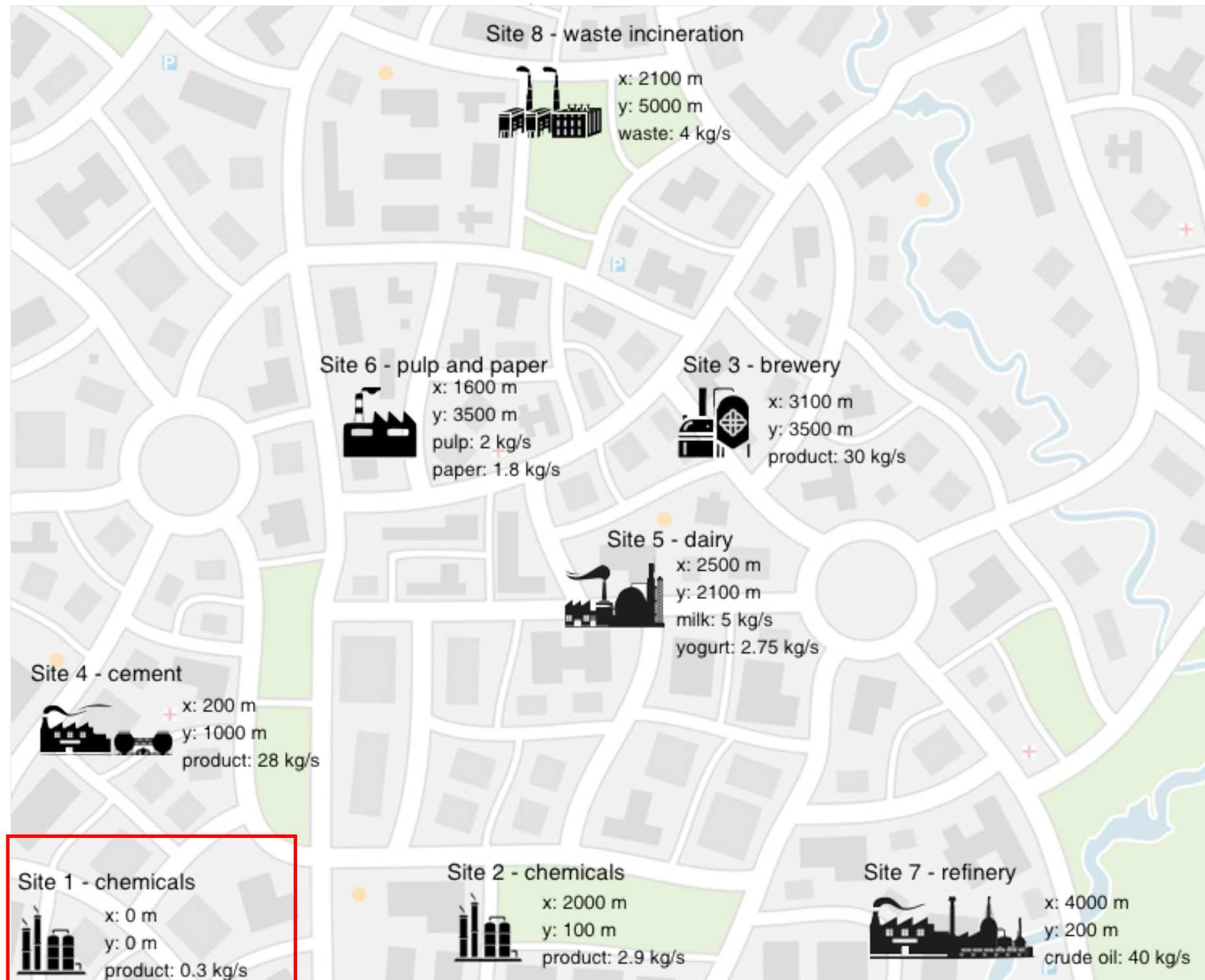


Figure 1.1 - Case study: small chemical plant from an industrial cluster.

Case study: Site 1 - chemicals

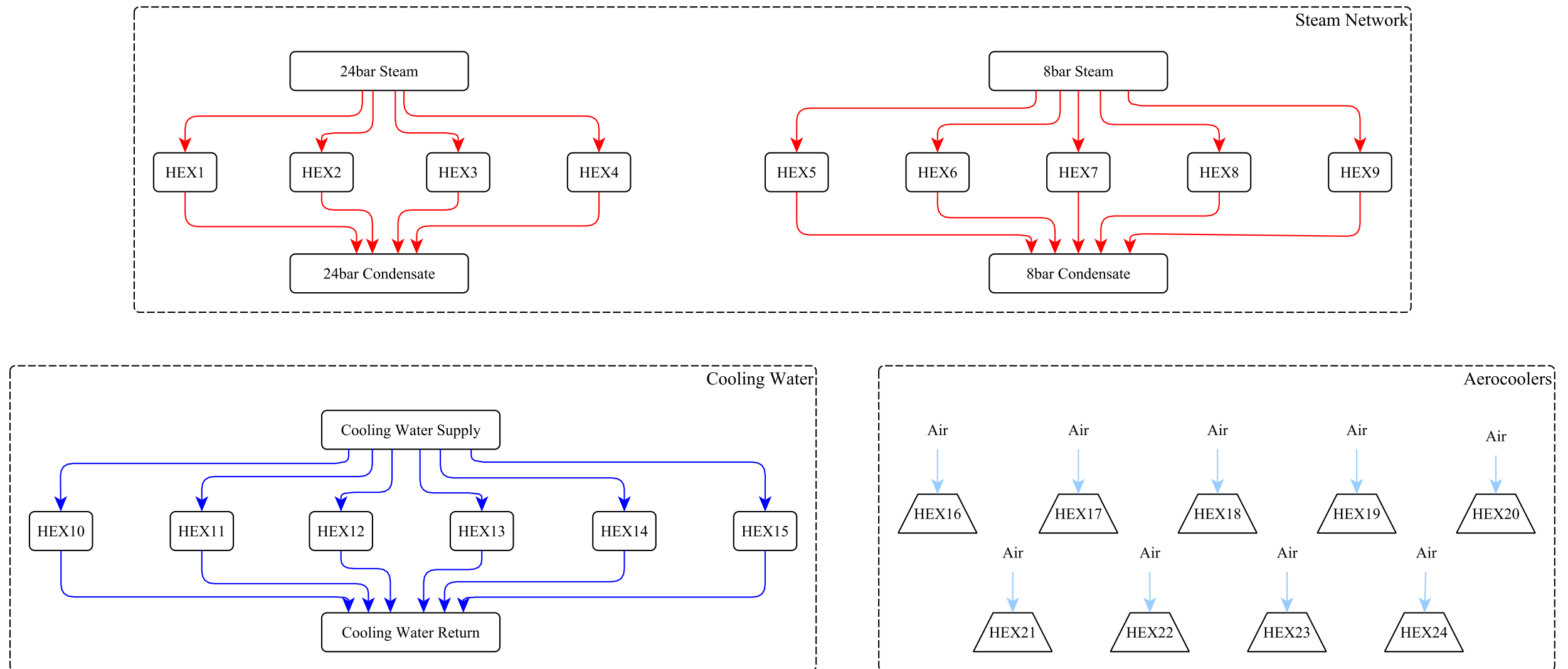
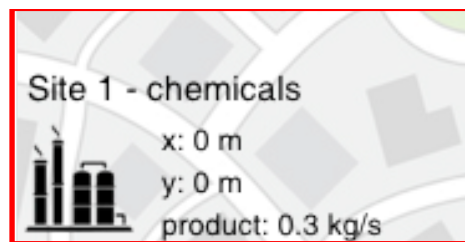


Figure 1.2 - Utility flow diagram of Site 1.



Comparison of energy saving scenarios

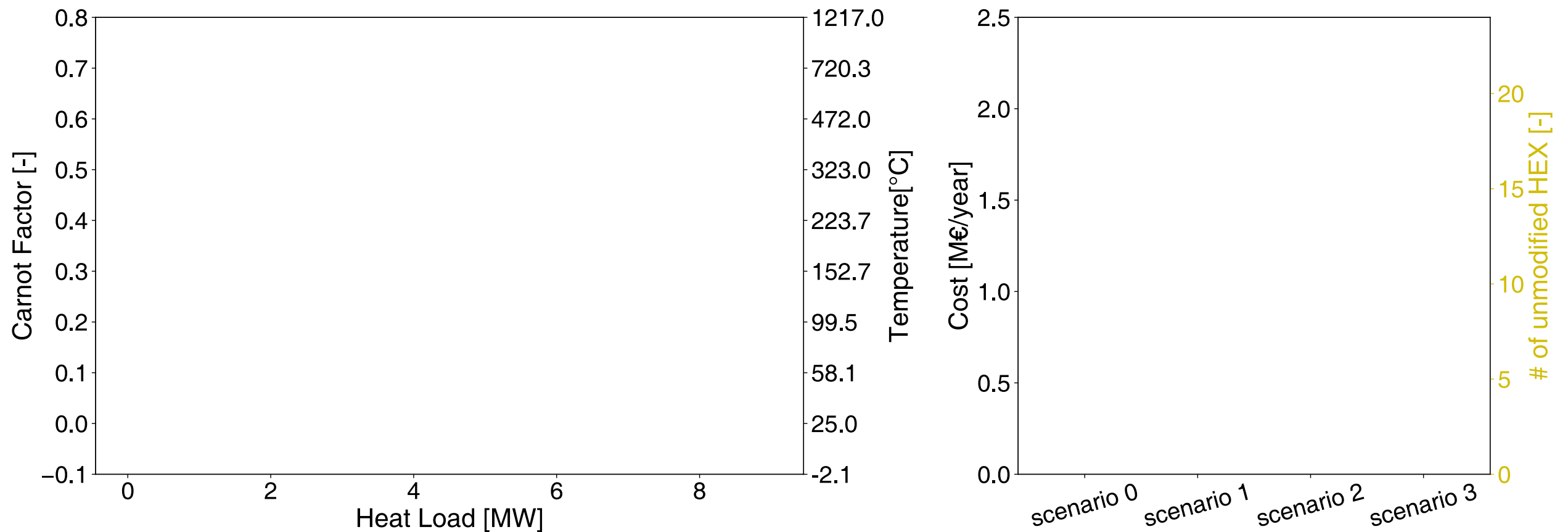


Figure 1.3 - Carnot composite curves (left) and cost comparison (right) of s0 and s1.

- ❖ scenario 0:
 - ◆ business as usual operation
- ❖ scenario 1:
 - ◆ allowing heat recovery
 - ◆ reconnection to the utility system

Cost data:
natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³, electricity selling 60% of purchase

Comparison of energy saving scenarios

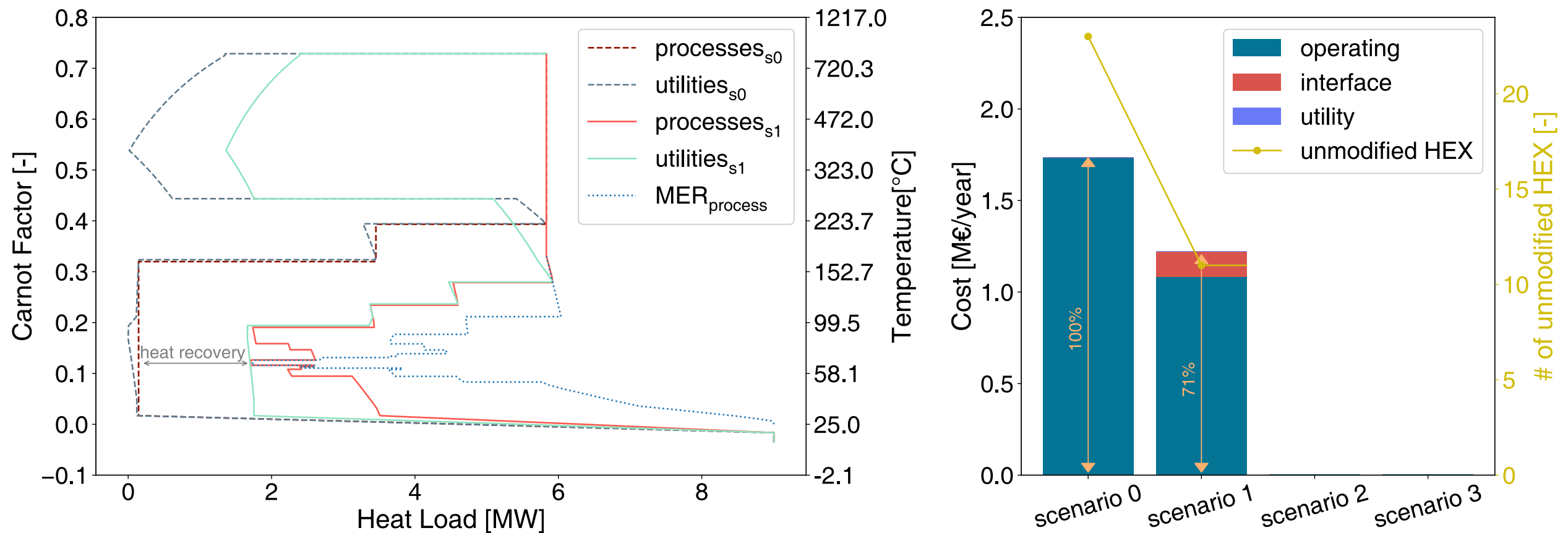


Figure 1.3 - Carnot composite curves (left) and cost comparison (right) of s0 and s1.

❖ heat recovery potential is fully utilised

- ♦ operational benefits of interface change are greater than the investment required

❖ interface changes outside the heat recovery zone:

- ♦ due to benefits of turbinizing steam and cogeneration of heat and electricity

❖ scenario 0:

- ♦ business as usual operation

❖ scenario 1:

- ♦ allowing heat recovery
- ♦ reconnection to the utility system

Cost data:
natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³, electricity selling 60% of purchase

Comparison of energy saving scenarios

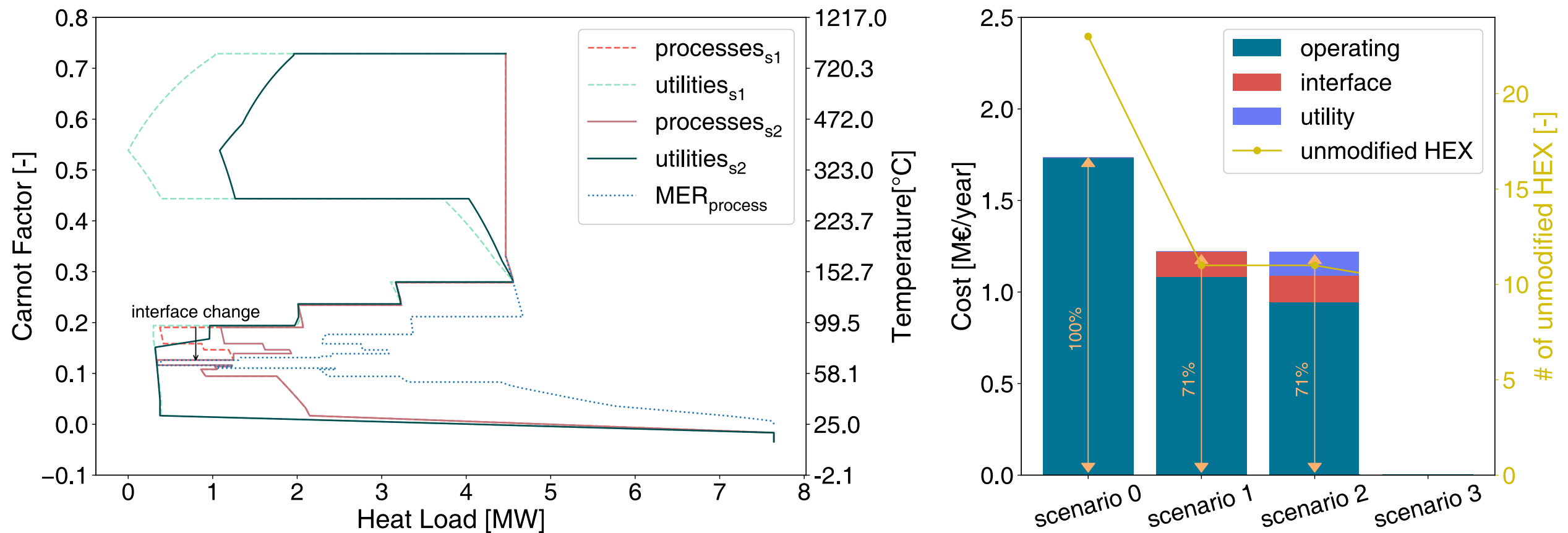


Figure 1.4 - Carnot composite curves (left) and cost comparison (right) of s1 and s2.

❖ interface change in the integration zone of the cogeneration engine

- ♦ engine cooling water

❖ slight improvement in the total cost of the system

- ♦ trade off between operational benefits and investment on the cogeneration engine and heat exchanger area

❖ scenario 1:

- ♦ allowing heat recovery
- ♦ reconnection to the utility system

❖ scenario 2:

- ♦ allowing integration of a cogeneration engine

Cost data:
natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³, electricity selling 60% of purchase

Comparison of energy saving scenarios

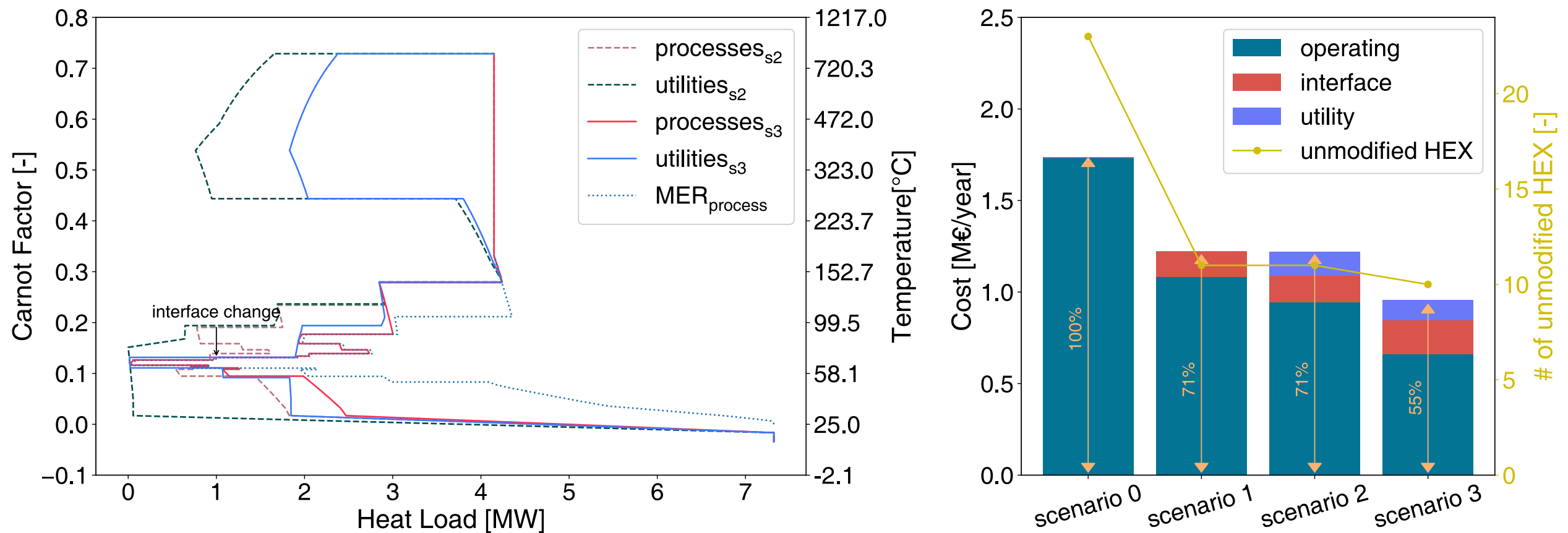


Figure 1.5 - Carnot composite curves (left) and cost comparison (right) of s2 and s3.

- ❖ cogeneration engine is not used anymore
 - ◆ competition with the heat pump
- ❖ interface change in the integration zone of the heat pumps
- ❖ further decrease in total cost
 - ◆ lower operating and investment cost, larger interface cost

- ❖ scenario 2:
 - ◆ allowing integration of a cogeneration engine
- ❖ scenario 3:
 - ◆ allowing integration of heat pumps

Cost data:
natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³, electricity selling 60% of purchase

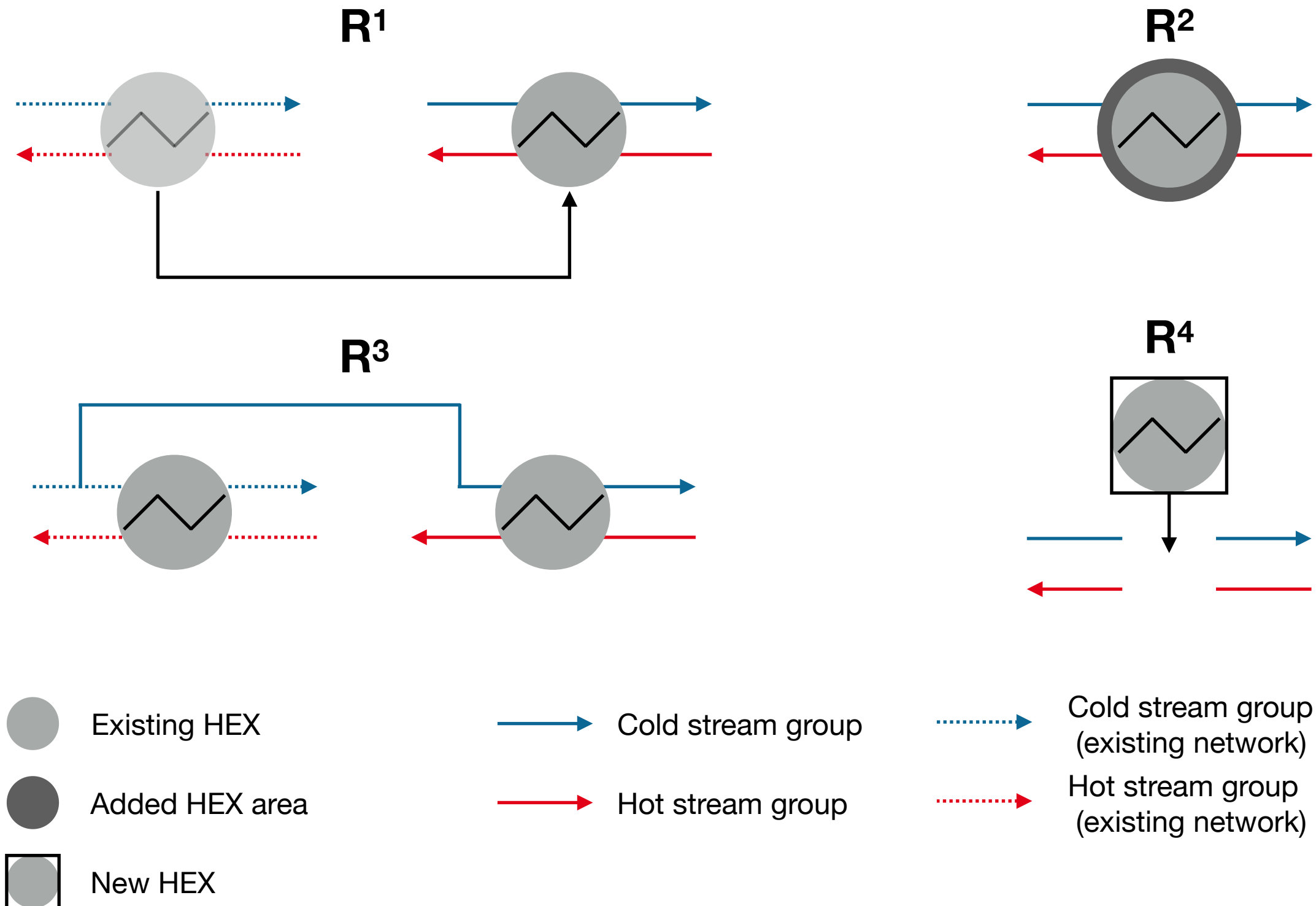


Figure 2.1 - Heat exchanger network retrofit actions.

$$\min \left\{ \sum_{(ig,jg,e) \in \mathbf{R}^1} C_{ig,jg,e}^{move} + \sum_{(ig,jg,e) \in \mathbf{R}^2} C_{ig,jg,e}^{add} + \sum_{(ig,jg) \in \mathbf{R}^3} C_{ig,jg}^{rep} + \sum_{(ig,jg) \in \mathbf{R}^4} C_{ig,jg}^{nh} \right\}$$

$$\dot{R}_{i,t,z,k} + \sum_{j \in \mathbf{CK}_{t,z,k}} \dot{Q}_{i,j,t,z,k} - \dot{q}_{i,t,k} = 0 \quad \forall i \in \mathbf{HK}_{t,z,k}, t \in \mathbf{TT}, z \in \mathbf{ZN}_t, k \in \mathbf{KT}_{t,z}$$

$$\dot{R}_{i,t,z,k-1} - \sum_{j \in \mathbf{CK}_{t,z,k}} \dot{Q}_{i,j,t,z,k} + \dot{q}_{i,t,k} = 0 \quad \forall i \in \mathbf{HK}_{t,z,k}, t \in \mathbf{TT}, z \in \mathbf{ZN}_t, k \in \mathbf{KB}_{t,z}$$

$$\dot{R}_{i,t,z,k} - \dot{R}_{i,t,z,k-1} + \sum_{j \in \mathbf{CK}_{t,z,k}} \dot{Q}_{i,j,t,z,k} - \dot{q}_{i,t,k} = 0$$

$$\dot{q}_{j,t,k} - \sum_{i \in \mathbf{HK}_{t,z,k}} \dot{Q}_{i,j,t,z,k} = 0 \quad \forall j \in \mathbf{CK}_{t,z,k}, t \in \mathbf{TT}, z \in \mathbf{ZN}_t, k \in \mathbf{KZ}_{t,z}$$

$$\frac{y_{ig,jg}}{\text{bigM}} \leq \sum_{(i,j) \in \mathbf{MS}} \sum_{k \in \mathbf{KZ}_{t,z}} \dot{Q}_{i,j,t,z,k} \leq y_{ig,jg} \cdot \text{bigM}$$

$$\sum_{(i,j) \in \mathbf{MS}} \sum_{z \in \mathbf{ZN}_t} \sum_{k \in \mathbf{KZ}_{t,z}} \dot{Q}_{i,j,t,z,k} = \dot{Q}_{ig,jg,t} \quad \forall (ig,jg) \in \mathbf{MG}, t \in \mathbf{TT} : i \in \mathbf{SS}_{ig}, j \in \mathbf{SS}_{jg}$$

$$\dot{Q}_{ig,jg}^{max} = \max_{t \in \mathbf{TT}} (\dot{Q}_{ig,jg,t}) \quad \forall (ig,jg) \in \mathbf{MG}$$

$$A_{i,j,t,z,k} = \dot{Q}_{i,j,t,z,k} \cdot \left(\frac{1}{\text{LMTD}_{t,k}^{hot} \cdot h_i} + \frac{1}{\text{LMTD}_{t,k}^{cold} \cdot h_j} \right)$$

$$A_{ig,jg,t} = \sum_{(i,j) \in \mathbf{MS}} \sum_{z \in \mathbf{ZN}_t} \sum_{k \in \mathbf{KZ}_{t,z}} A_{i,j,t,z,k} \quad \forall (ig,jg) \in \mathbf{MG} : i \in \mathbf{SS}_{ig}, j \in \mathbf{SS}_{jg}$$

$$A_{ig,jg}^{max} = \max_{t \in \mathbf{TT}} (A_{ig,jg,t}) \quad \forall (ig,jg) \in \mathbf{MG}$$

$$ex_{ig,jg,e} \leq y_{ig,jg} \quad \forall (ig,jg) \in \mathbf{MG}, e \in \mathbf{EX}$$

$$\sum_{(ig,jg) \in \mathbf{MG}} ex_{ig,jg,e} \leq 1 \quad \forall e \in \mathbf{EX}$$

$$\sum_{e \in \mathbf{EX}} ex_{ig,jg,e} + n_{ig,jg} - y_{ig,jg} = 0 \quad \forall (ig,jg) \in \mathbf{MG}$$

$$A_{ig,jg}^{slack} \leq \sum_{e \in \mathbf{EX}} ex_{ig,jg,e} \cdot A_e^{ex} \quad \forall (ig,jg) \in \mathbf{MG}$$

$$A_{ig,jg}^{slack} + A_{ig,jg}^{extra} = A_{ig,jg}^{max} \quad \forall (ig,jg) \in \mathbf{MG}$$

$$A_{ig,jg}^{extra} = \sum_{e \in \mathbf{EX}} A_{ig,jg,e}^{add} + A_{ig,jg}^{nh} \quad \forall (ig,jg) \in \mathbf{MG}$$

$$A_{ig,jg,e}^{add} \leq ex_{ig,jg,e} \cdot A_e^{ex} \cdot 0.15 \quad \forall (ig,jg) \in \mathbf{MG}, e \in \mathbf{EX}$$

$$n_{ig,jg} \cdot A^{purc,lb} \leq A_{ig,jg}^{nh} \leq n_{ig,jg} \cdot A^{purc,ub} \quad \forall (ig,jg) \in \mathbf{MG}$$

$$a_{ig,jg,as} \cdot A_{ig,jg,as}^{seg,lb} \leq AL_{ig,jg,as} \leq a_{ig,jg,as} \cdot A_{ig,jg,as}^{seg,ub} \quad \forall (ig,jg) \in \mathbf{MG}$$

$$A_{ig,jg}^{new} = \sum_{as \in \mathbf{AS}} AL_{ig,jg,as} \quad \forall (ig,jg) \in \mathbf{MG}$$

$$\sum_{as \in \mathbf{AS}} a_{ig,jg,as} \leq n_{ig,jg} \quad \forall (ig,jg) \in \mathbf{MG}$$

$$C_{ig,jg}^{nh} = \sum_{as \in \mathbf{AS}} (a_{ig,jg,as} \cdot c_{as}^{nh1} + AL_{ig,jg,as} \cdot c_{as}^{nh2}) \quad \forall (ig,jg) \in \mathbf{MG}$$

$$p_{ig,jg,ps}^{ph} \cdot \dot{q}_{ig,ps}^{lb} \leq \dot{Q}P_{ig,jg,ps}^{ph} \leq p_{ig,jg,ps}^{ph} \cdot \dot{q}_{ig,ps}^{ub} \quad \forall (ig,jg) \in \mathbf{MG}$$

$$\sum_{ps \in \mathbf{PS}} \dot{Q}P_{ig,jg,ps}^{ph} = \dot{Q}_{ig,jg}^{max} \quad \forall (ig,jg) \in \mathbf{MG}$$

Mathematical formulation

$$\min \left\{ \sum_{(ig,jg,e) \in \mathbf{R}^1} C_{ig,jg,e}^{ex} + \sum_{(ig,jg,e) \in \mathbf{R}^2} C_{ig,jg,e}^{add} + \sum_{(ig,jg) \in \mathbf{R}^3} C_{ig,jg}^{ret} + \sum_{(ig,jg) \in \mathbf{R}^4} C_{ig,jg}^{slack} \right\}$$

objective function: HEN retrofit cost [65]

$$\begin{aligned} \dot{R}_{i,t,z,k} + \sum_{j \in \mathbf{CK}_{t,z,k}} \dot{Q}_{i,j,t,z,k} - \dot{q}_{i,t,k} &= 0 \quad \forall i \in \mathbf{HK}_{t,z,k}, t \in \mathbf{TT}, z \in \mathbf{ZN}_t, k \in \mathbf{KT}_{t,z} \\ \dot{R}_{i,t,z,k-1} - \sum_{j \in \mathbf{CK}_{t,z,k}} \dot{Q}_{i,j,t,z,k} + \dot{q}_{i,t,k} &= 0 \quad \forall i \in \mathbf{HK}_{t,z,k}, t \in \mathbf{TT}, z \in \mathbf{ZN}_t, k \in \mathbf{KB}_{t,z} \\ \dot{R}_{i,t,z,k} - \dot{R}_{i,t,z,k-1} + \sum_{j \in \mathbf{CK}_{t,z,k}} \dot{Q}_{i,j,t,z,k} - \dot{q}_{i,t,k} &= 0 \\ \dot{q}_{j,t,k} - \sum_{i \in \mathbf{HK}_{t,z,k}} \dot{Q}_{i,j,t,z,k} &= 0 \quad \forall j \in \mathbf{CK}_{t,z,k}, t \in \mathbf{TT}, z \in \mathbf{ZN}_t, k \in \mathbf{KZ}_{t,z} \end{aligned}$$

heat flow model [14]

$$\begin{aligned} \frac{y_{ig,jg}}{\text{bigM}} &\leq \sum_{(i,j) \in \mathbf{MS}} \sum_{k \in \mathbf{KZ}_{t,z}} \dot{Q}_{i,j,t,z,k} \leq y_{ig,jg} \cdot \text{bigM} \\ \sum_{(i,j) \in \mathbf{MS}} \sum_{z \in \mathbf{ZN}_t} \sum_{k \in \mathbf{KZ}_{t,z}} \dot{Q}_{i,j,t,z,k} &= \dot{Q}_{ig,jg,t} \quad \forall (ig,jg) \in \mathbf{MG}, t \in \mathbf{TT} : i \in \mathbf{SS}_{ig}, j \in \mathbf{SS}_{jg} \\ \dot{Q}_{ig,jg}^{max} &= \max_{t \in \mathbf{TT}} (\dot{Q}_{ig,jg,t}) \quad \forall (ig,jg) \in \mathbf{MG} \end{aligned}$$

$$A_{i,j,t,z,k} = \dot{Q}_{i,j,t,z,k} \cdot \left(\frac{1}{\text{LMTD}_{t,k}^{hot} \cdot h_i} + \frac{1}{\text{LMTD}_{t,k}^{cold} \cdot h_j} \right)$$

$$A_{ig,jg,t} = \sum_{(i,j) \in \mathbf{MS}} \sum_{z \in \mathbf{ZN}_t} \sum_{k \in \mathbf{KZ}_{t,z}} A_{i,j,t,z,k} \quad \forall (ig,jg) \in \mathbf{MG} : i \in \mathbf{SS}_{ig}, j \in \mathbf{SS}_{jg}$$

$$A_{ig,jg}^{max} = \max_{t \in \mathbf{TT}} (A_{ig,jg,t}) \quad \forall (ig,jg) \in \mathbf{MG}$$

$$ex_{ig,jg,e} \leq y_{ig,jg} \quad \forall (ig,jg) \in \mathbf{MG}, e \in \mathbf{EX}$$

$$\sum_{(ig,jg) \in \mathbf{MG}} ex_{ig,jg,e} \leq 1 \quad \forall e \in \mathbf{EX}$$

$$\sum_{e \in \mathbf{EX}} ex_{ig,jg,e} + n_{ig,jg} - y_{ig,jg} = 0 \quad \forall (ig,jg) \in \mathbf{MG}$$

$$A_{ig,jg}^{slack} \leq \sum_{e \in \mathbf{EX}} ex_{ig,jg,e} \cdot A_e^{ex} \quad \forall (ig,jg) \in \mathbf{MG}$$

retrofit model [65]

$$A_{ig,jg}^{slack} + A_{ig,jg}^{extra} = A_{ig,jg}^{max} \quad \forall (ig,jg) \in \mathbf{MG}$$

$$A_{ig,jg}^{extra} = \sum_{e \in \mathbf{EX}} A_{ig,jg,e}^{add} + A_{ig,jg}^{nh} \quad \forall (ig,jg) \in \mathbf{MG}$$

$$A_{ig,jg,e}^{add} \leq ex_{ig,jg,e} \cdot A_e^{ex} \cdot 0.15 \quad \forall (ig,jg) \in \mathbf{MG}, e \in \mathbf{EX}$$

$$n_{ig,jg} \cdot A^{purc,lb} \leq A_{ig,jg}^{nh} \leq n_{ig,jg} \cdot A^{purc,ub} \quad \forall (ig,jg) \in \mathbf{MG}$$

$$a_{ig,jg,as} \cdot A_{ig,jg,as}^{seg,lb} \leq AL_{ig,jg,as} \leq a_{ig,jg,as} \cdot A_{ig,jg,as}^{seg,ub} \quad \forall (ig,jg) \in \mathbf{MG}$$

$$A_{ig,jg}^{new} = \sum_{as \in \mathbf{AS}} AL_{ig,jg,as} \quad \forall (ig,jg) \in \mathbf{MG}$$

$$\sum_{as \in \mathbf{AS}} a_{ig,jg,as} \leq n_{ig,jg} \quad \forall (ig,jg) \in \mathbf{MG}$$

$$C_{ig,jg}^{nh} = \sum_{as \in \mathbf{AS}} (a_{ig,jg,as} \cdot c_{as}^{nh1} + AL_{ig,jg,as} \cdot c_{as}^{nh2}) \quad \forall (ig,jg) \in \mathbf{MG}$$

$$p_{ig,jg,ps}^{ph} \cdot \dot{q}_{ig,ps}^{lb} \leq \dot{Q}P_{ig,jg,ps}^{ph} \leq p_{ig,jg,ps}^{ph} \cdot \dot{q}_{ig,ps}^{ub} \quad \forall (ig,jg) \in \mathbf{MG}$$

$$\sum_{ps \in \mathbf{PS}} \dot{Q}P_{ig,jg,ps}^{ph} = \dot{Q}_{ig,jg}^{max} \quad \forall (ig,jg) \in \mathbf{MG}$$

$$\min \left\{ \sum_{(ig,jg,e) \in \mathbf{R}^1} C_{ig,jg,e}^{ex} + \sum_{(ig,jg,e) \in \mathbf{R}^2} C_{ig,jg,e}^{add} + \sum_{(ig,jg) \in \mathbf{R}^3} C_{ig,jg}^{ret} + \sum_{(ig,jg) \in \mathbf{R}^4} C_{ig,jg}^{rep} \right\}$$

objective function: HEN retrofit cost [65]

$$\begin{aligned} \dot{R}_{i,t,z,k} + \sum_{j \in \mathbf{CK}_{t,z,k}} \dot{Q}_{i,j,t,z,k} - \dot{q}_{i,t,k} &= 0 \quad \forall i \in \mathbf{HK}_{t,z,k}, t \in \mathbf{TT}, z \in \mathbf{ZN}_t, k \in \mathbf{KT}_{t,z} \\ \dot{R}_{i,t,z,k-1} - \sum_{j \in \mathbf{CK}_{t,z,k}} \dot{Q}_{i,j,t,z,k} + \dot{q}_{i,t,k} &= 0 \quad \forall i \in \mathbf{HK}_{t,z,k}, t \in \mathbf{TT}, z \in \mathbf{ZN}_t, k \in \mathbf{KB}_{t,z} \\ \dot{R}_{i,t,z,k} - \dot{R}_{i,t,z,k-1} + \sum_{j \in \mathbf{CK}_{t,z,k}} \dot{Q}_{i,j,t,z,k} - \dot{q}_{i,t,k} &= 0 \\ \dot{q}_{j,t,k} - \sum_{i \in \mathbf{HK}_{t,z,k}} \dot{Q}_{i,j,t,z,k} &= 0 \quad \forall j \in \mathbf{CK}_{t,z,k}, t \in \mathbf{TT}, z \in \mathbf{ZN}_t, k \in \mathbf{KZ}_{t,z} \end{aligned}$$

heat flow model [14]

$$\begin{aligned} \frac{y_{ig,jg}}{\text{bigM}} &\leq \sum_{(i,j) \in \mathbf{MS}} \sum_{k \in \mathbf{KZ}_{t,z}} \dot{Q}_{i,j,t,z,k} \leq y_{ig,jg} \cdot \text{bigM} \\ \sum_{(i,j) \in \mathbf{MS}} \sum_{z \in \mathbf{ZN}_t} \sum_{k \in \mathbf{KZ}_{t,z}} \dot{Q}_{i,j,t,z,k} &= \dot{Q}_{ig,jg,t} \quad \forall (ig,jg) \in \mathbf{MG}, t \in \mathbf{TT} : i \in \mathbf{SS}_{ig}, j \in \mathbf{SS}_{jg} \\ \dot{Q}_{ig,jg}^{max} &= \max_{t \in \mathbf{TT}} (\dot{Q}_{ig,jg,t}) \quad \forall (ig,jg) \in \mathbf{MG} \end{aligned}$$

$$\begin{aligned} A_{i,j,t,z,k} &= \dot{Q}_{i,j,t,z,k} \cdot \left(\frac{1}{\text{LMTD}_{t,k}^{hot} \cdot h_i} + \frac{1}{\text{LMTD}_{t,k}^{cold} \cdot h_j} \right) \\ A_{ig,jg,t} &= \sum_{(i,j) \in \mathbf{MS}} \sum_{z \in \mathbf{ZN}_t} \sum_{k \in \mathbf{KZ}_{t,z}} A_{i,j,t,z,k} \quad \forall (ig,jg) \in \mathbf{MG} : i \in \mathbf{SS}_{ig}, j \in \mathbf{SS}_{jg} \\ A_{ig,jg}^{max} &= \max_{t \in \mathbf{TT}} (A_{ig,jg,t}) \quad \forall (ig,jg) \in \mathbf{MG} \end{aligned}$$

LMTD and area estimation

$$ex_{ig,jg,e} \leq y_{ig,jg} \quad \forall (ig,jg) \in \mathbf{MG}, e \in \mathbf{EX}$$

$$\sum_{(ig,jg) \in \mathbf{MG}} ex_{ig,jg,e} \leq 1 \quad \forall e \in \mathbf{EX}$$

$$\sum_{e \in \mathbf{EX}} ex_{ig,jg,e} + n_{ig,jg} - y_{ig,jg} = 0 \quad \forall (ig,jg) \in \mathbf{MG}$$

$$A_{ig,jg}^{slack} \leq \sum_{e \in \mathbf{EX}} ex_{ig,jg,e} \cdot A_e^{ex} \quad \forall (ig,jg) \in \mathbf{MG}$$

retrofit model [65]

$$A_{ig,jg}^{slack} + A_{ig,jg}^{extra} = A_{ig,jg}^{max} \quad \forall (ig,jg) \in \mathbf{MG}$$

$$A_{ig,jg}^{extra} = \sum_{e \in \mathbf{EX}} A_{ig,jg,e}^{add} + A_{ig,jg}^{nh} \quad \forall (ig,jg) \in \mathbf{MG}$$

$$A_{ig,jg,e}^{add} \leq ex_{ig,jg,e} \cdot A_e^{ex} \cdot 0.15 \quad \forall (ig,jg) \in \mathbf{MG}, e \in \mathbf{EX}$$

$$n_{ig,jg} \cdot A^{purc,lb} \leq A_{ig,jg}^{nh} \leq n_{ig,jg} \cdot A^{purc,ub} \quad \forall (ig,jg) \in \mathbf{MG}$$

$$a_{ig,jg,as} \cdot A_{ig,jg,as}^{seg,lb} \leq AL_{ig,jg,as} \leq a_{ig,jg,as} \cdot A_{ig,jg,as}^{seg,ub} \quad \forall (ig,jg) \in \mathbf{MG}$$

$$A_{ig,jg}^{new} = \sum_{as \in \mathbf{AS}} AL_{ig,jg,as} \quad \forall (ig,jg) \in \mathbf{MG}$$

$$\sum_{as \in \mathbf{AS}} a_{ig,jg,as} \leq n_{ig,jg} \quad \forall (ig,jg) \in \mathbf{MG}$$

piece-wise linear cost constraints

$$C_{ig,jg}^{nh} = \sum_{as \in \mathbf{AS}} (a_{ig,jg,as} \cdot c_{as}^{nh1} + AL_{ig,jg,as} \cdot c_{as}^{nh2}) \quad \forall (ig,jg) \in \mathbf{MG}$$

$$p_{ig,jg,ps}^{ph} \cdot \dot{q}_{ig,ps}^{lb} \leq \dot{Q}_{ig,jg,ps}^{ph} \leq p_{ig,jg,ps}^{ph} \cdot \dot{q}_{ig,ps}^{ub} \quad \forall (ig,jg) \in \mathbf{MG}$$

$$\sum_{ps \in \mathbf{PS}} \dot{Q}_{ig,jg,ps}^{ph} = \dot{Q}_{ig,jg}^{ph} \quad \forall (ig,jg) \in \mathbf{MG}$$

repiping cost constraints

- ❖ main objective: total cost of HEN retrofit

$$\min \left\{ \sum_{(ig,jg,e) \in \mathbf{R}^1} C_{ig,jg,e}^{move} + \sum_{(ig,jg,e) \in \mathbf{R}^2} C_{ig,jg,e}^{add} + \sum_{(ig,jg) \in \mathbf{R}^3} C_{ig,jg}^{rep} + \sum_{(ig,jg) \in \mathbf{R}^4} C_{ig,jg}^{nh} \right\}$$

- ❖ secondary objective: the number of additional heat exchangers

- ♦ written as ϵ -constraint

$$\sum_{(ig,jg) \in \mathbf{AS}} n_{ig,jg} \leq \epsilon$$

- ❖ boundaries of ϵ

- ♦ lower boundary: feasible solution with the smallest number of new heat exchangers

Large scale industrial problem

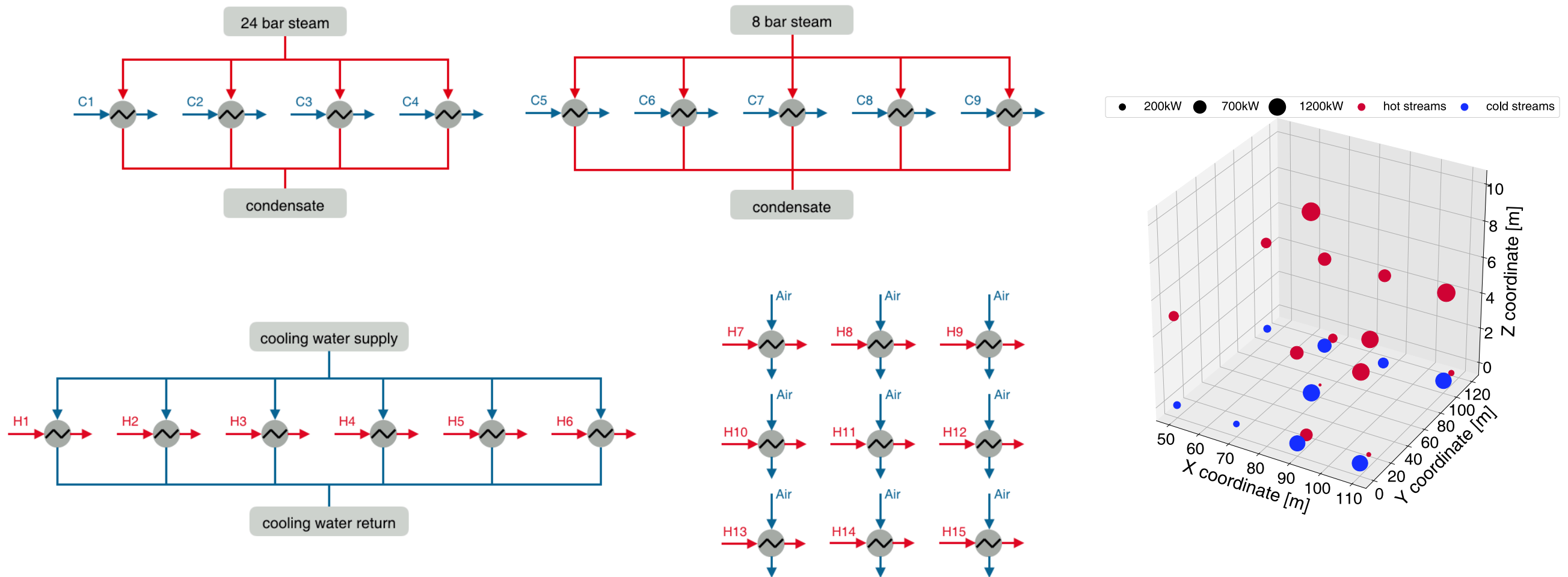
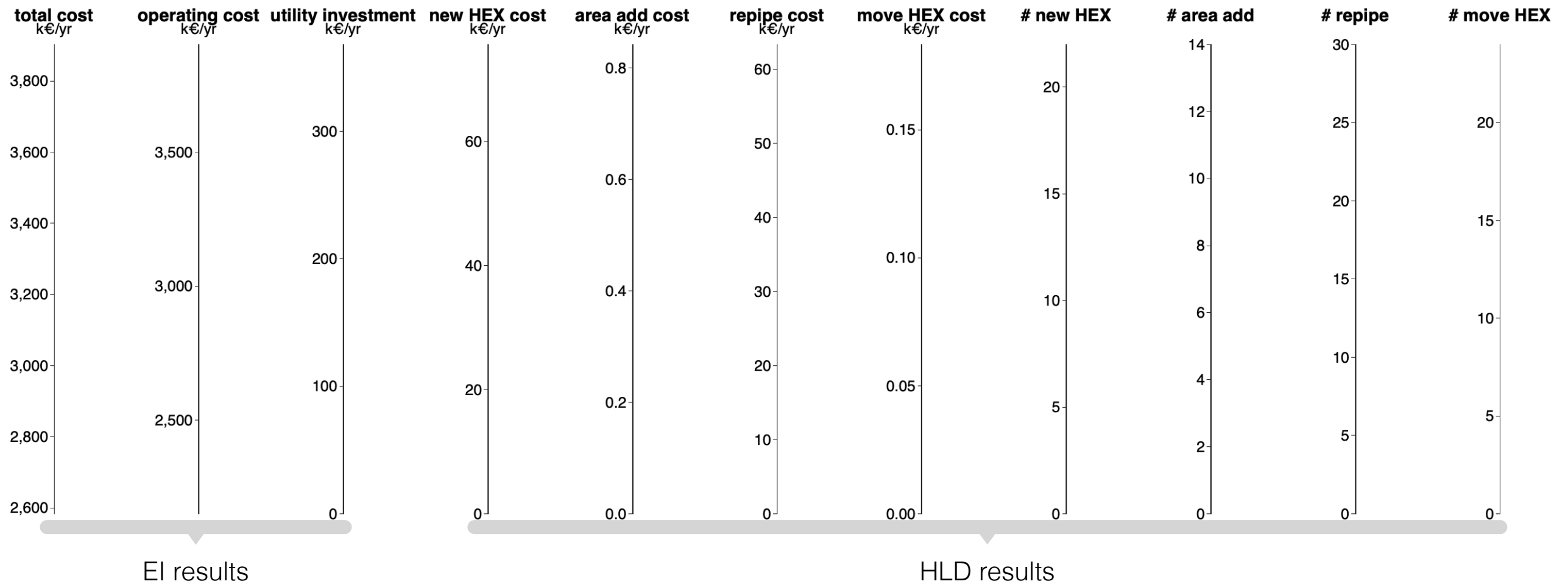


Figure 2.2 - Industrial case study streams (a) and layout of the initial heat exchangers (b)

- ❖ chemical plant with 24 initial heat exchangers
- ❖ 3091 kW of electricity requirement
- ❖ coordinates based on the real plant layout

Large scale industrial problem



*cost data

natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³, electricity selling 60% of purchase

Large scale industrial problem

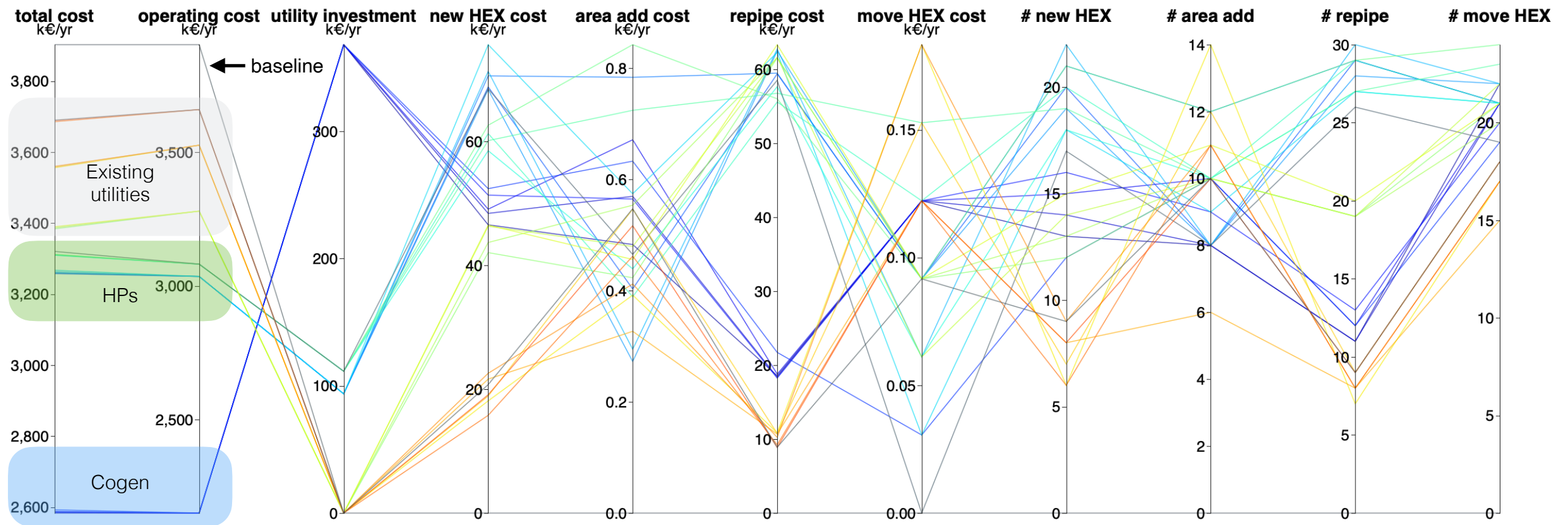


Figure 2.3 - Multiple solutions generated by parametric optimisation; higher total cost moving toward the red side of the colour spectrum.

❖ savings in total cost:

- ◆ 5-13% using the existing utilities, 15-17% with heat pump integration, 33-34% with cogeneration engine integration

❖ solutions with heat pump and cogeneration engine integration rank better than the existing utilities

- ◆ higher utility investment and HEN retrofit cost
- ◆ drastic improvements in operating cost

*cost data

natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³, electricity selling 60% of purchase

Large scale industrial problem

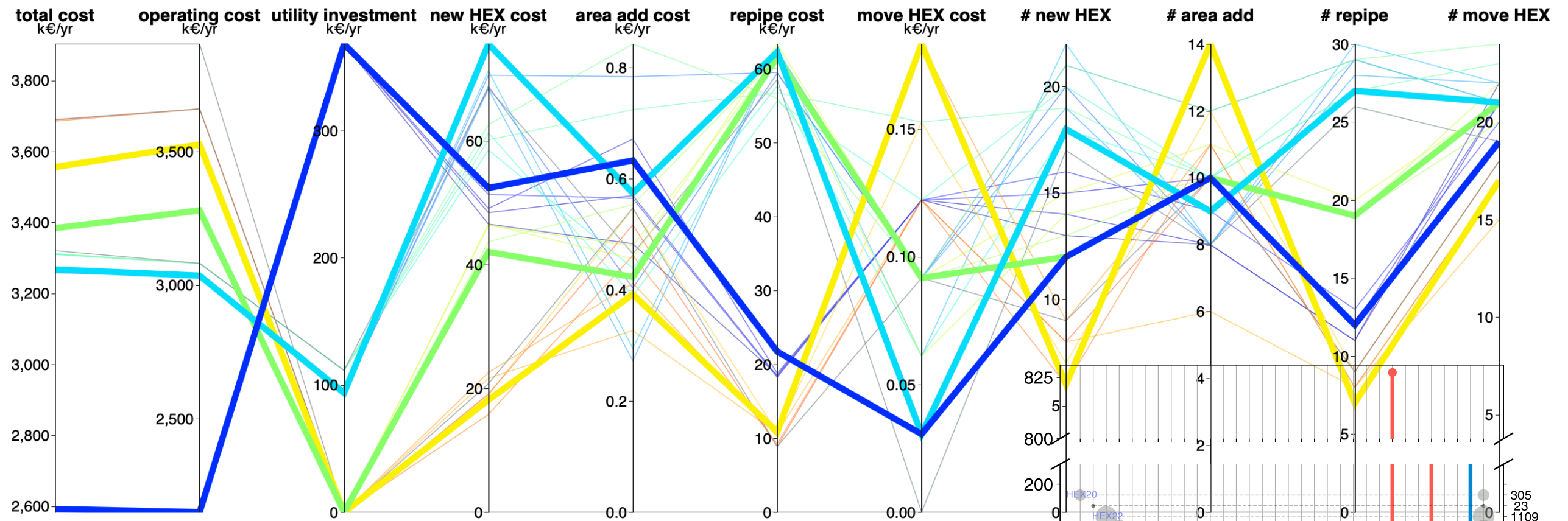
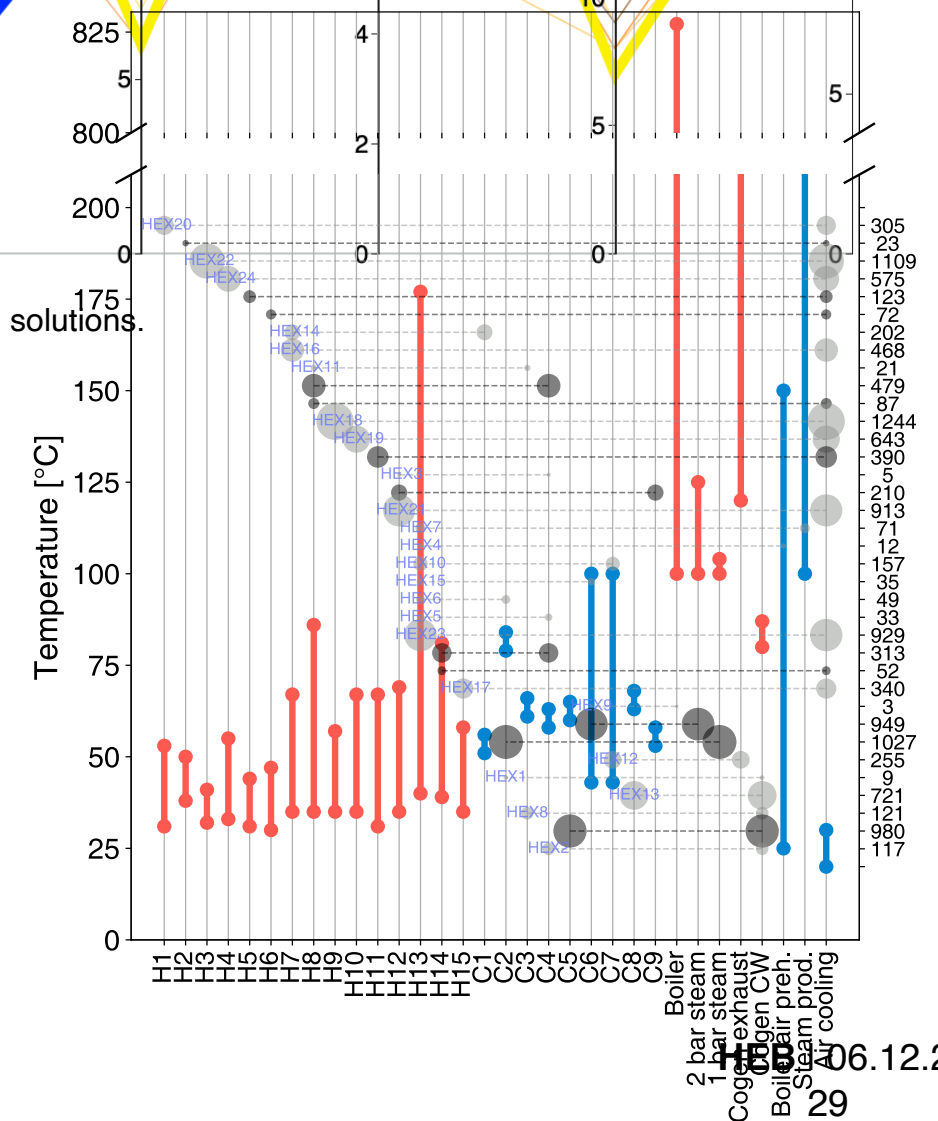


Figure 2.4 - Parallel coordinates with highlighted selected solutions.



*cost data

natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³, electricity selling 60% of purchase

Large scale industrial problem

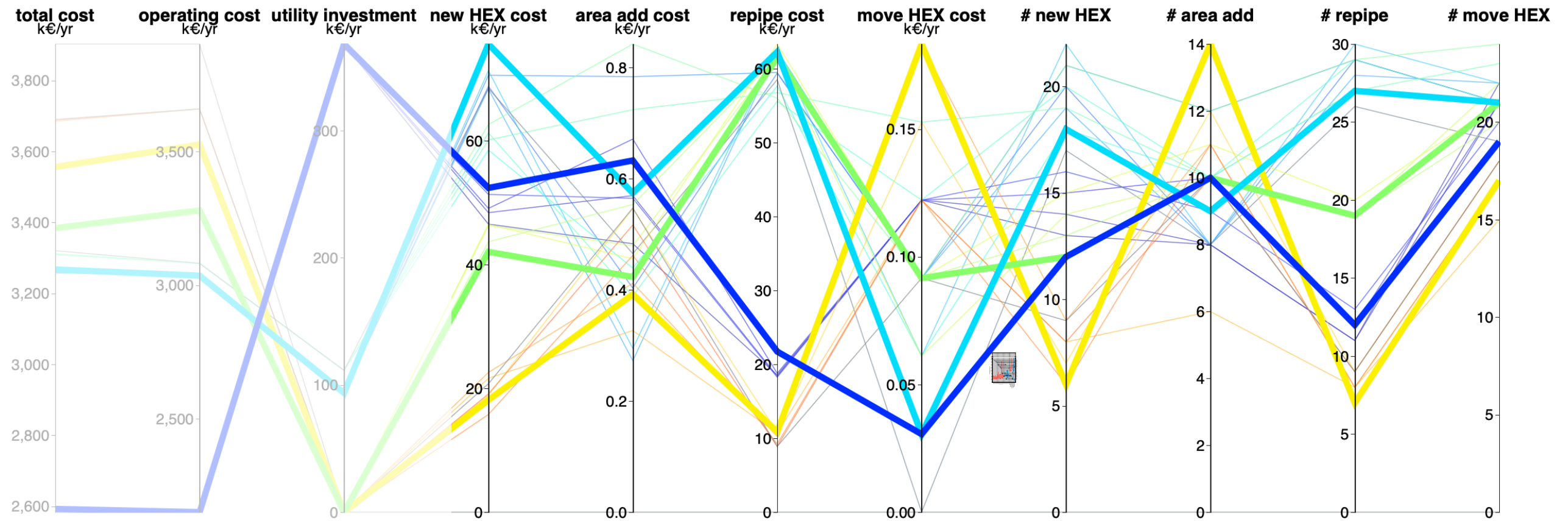
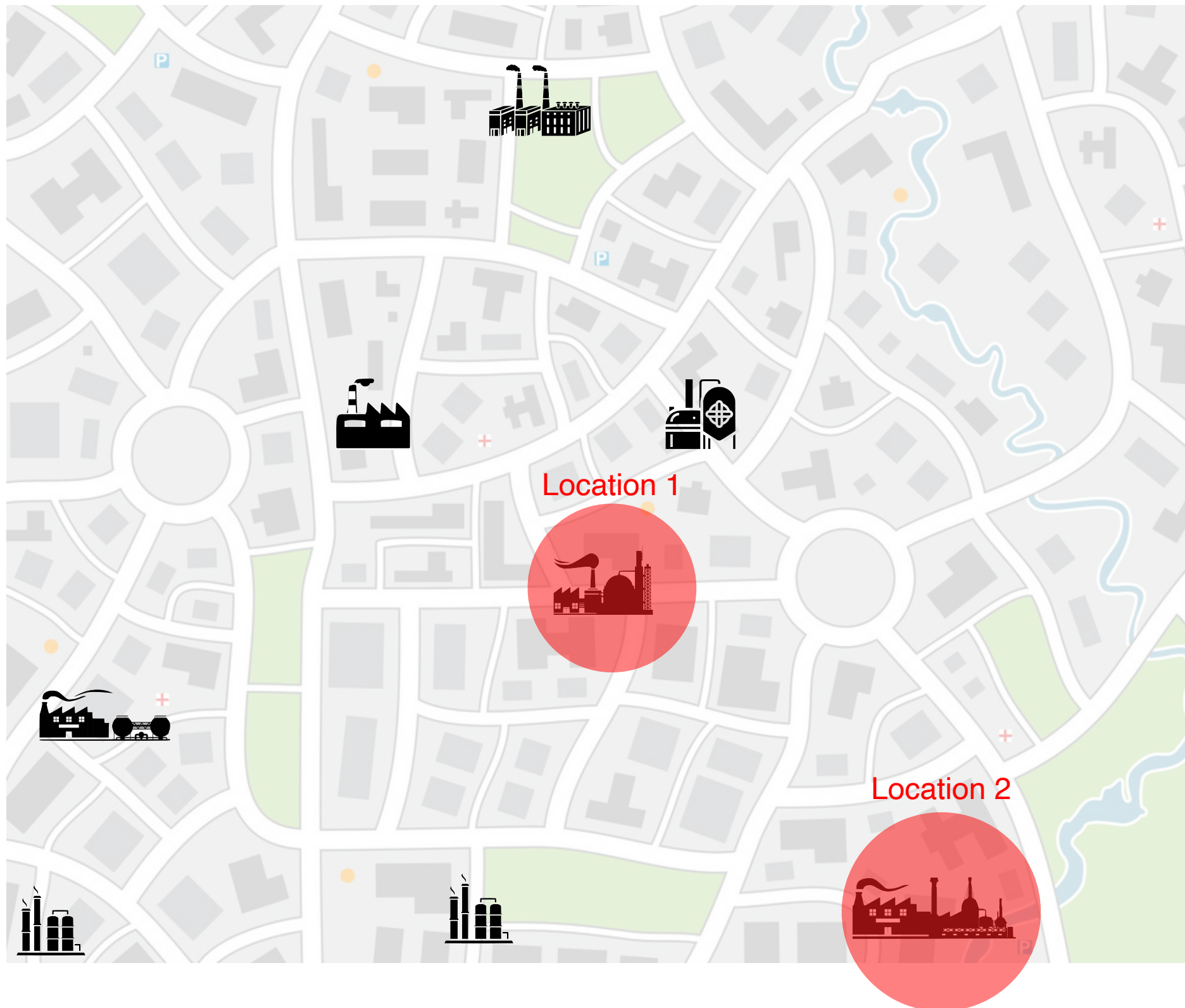


Figure 2.4 - Parallel coordinates with highlighted selected solutions.

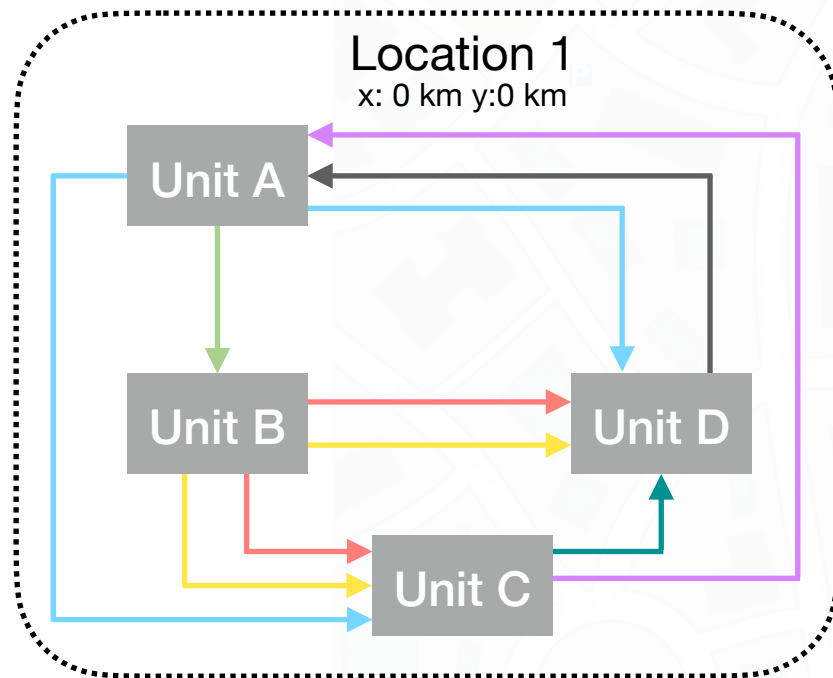
- ❖ new heat exchangers (57%) and repiping (41%) are the main contributors to HEN retrofit cost
- ❖ heat pump integration requires the highest number (17-22) of new heat exchangers
 - ♦ creation of new pinch points
 - ♦ heat pump evaporation and condensation close to the process → low LMTD
- ❖ even with business-as-usual utilities 6 new heat exchangers are required
 - ♦ heat recovery

*cost data
natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³, electricity selling 60% of purchase

Locations and exchanges between them



Locations and exchanges between them

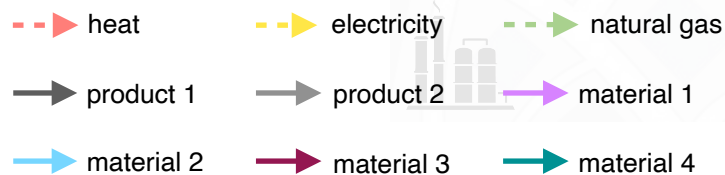
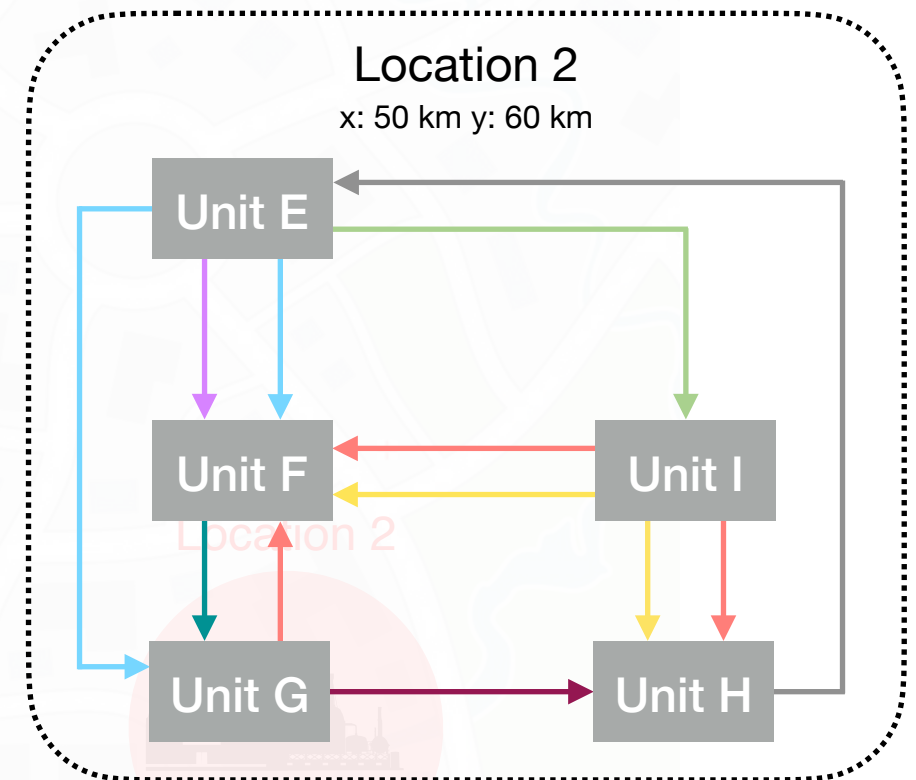


- ❖ Closed mass and energy balance within each location
- ❖ Interaction only with the grid
- ❖ No interactions between plants

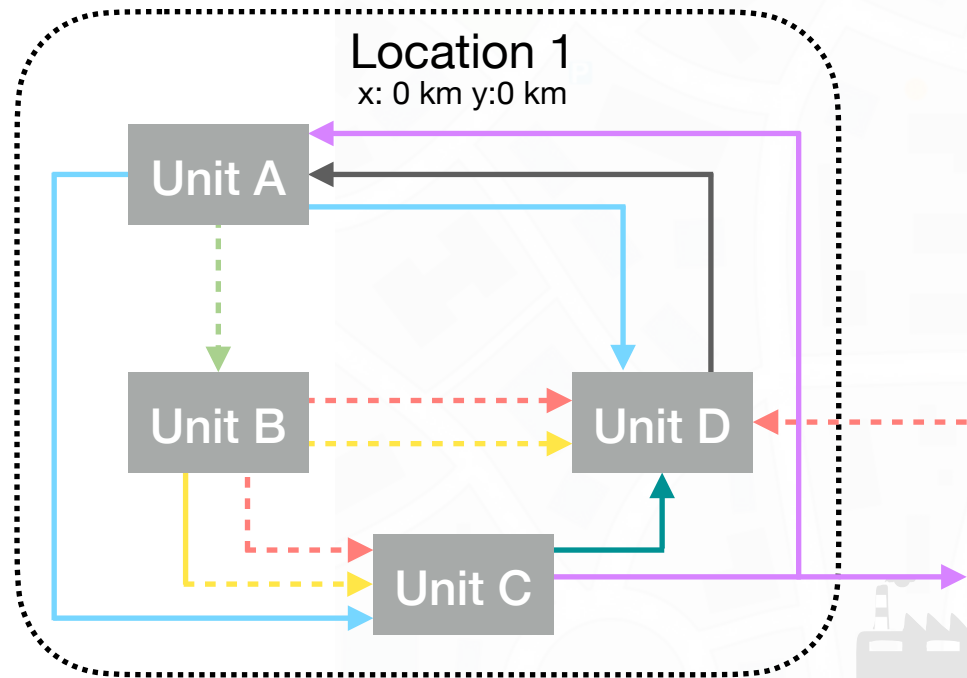
Missed opportunities!



Location 1



Locations and exchanges between them

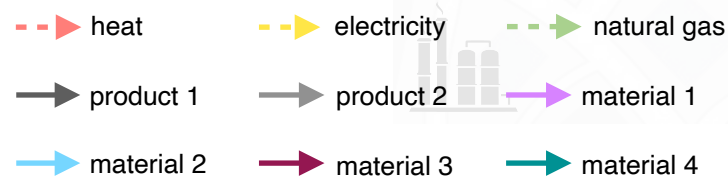
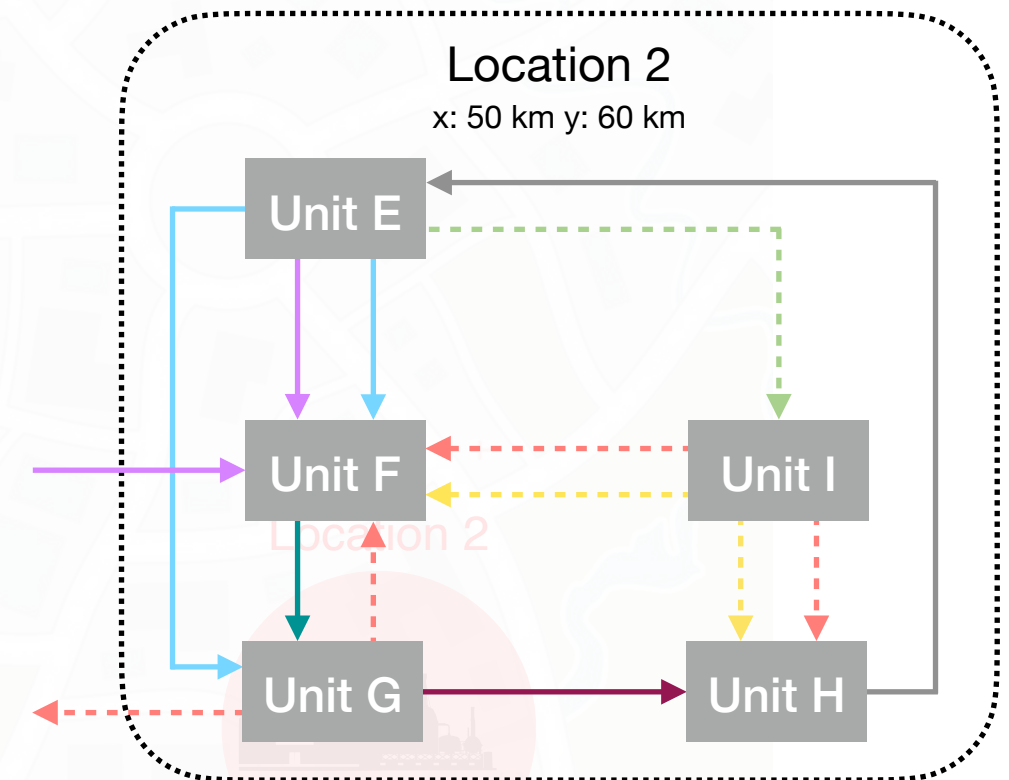


- ❖ Closed mass and energy balance within each location
- ❖ Interaction only with the grid
- ❖ No interactions between plants

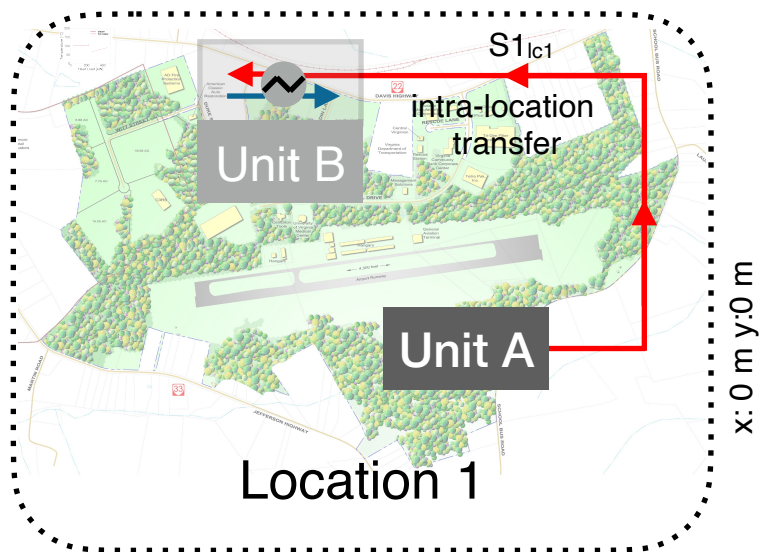
Missed opportunities!

- ❖ Interactions between plants
- ❖ Free flow of heat and resources in the system
- ❖ Exchanges over long distances

Unrealistic targets!



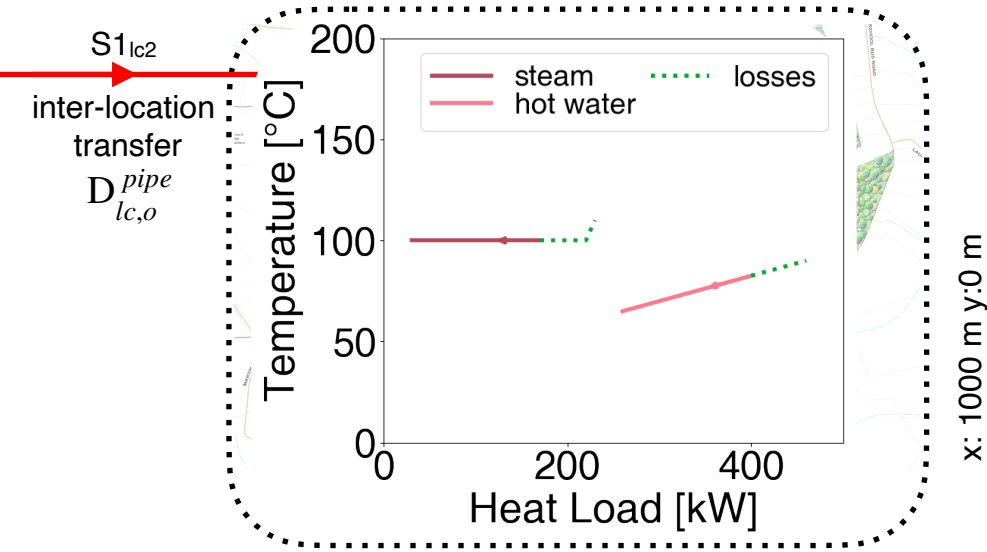
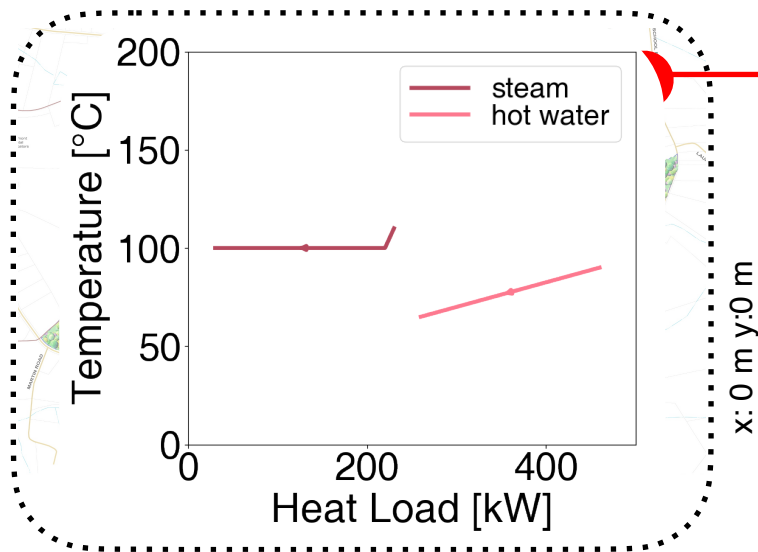
Heat losses and temperature drop



Heat losses and temperature drop



Heat losses and temperature drop



$$x^{ground} = x^{ground'} + \frac{\lambda^{ground}}{h^{amb}}$$

$$X_s^{mut} = \frac{1}{4 \cdot \pi \cdot \lambda^{ground}} \cdot \ln \left[1 + \left(\frac{2 \cdot x^{ground}}{D_{pp}} \right)^2 \right] \quad \forall s \in \mathbf{H}$$

$$X_s^{ground} = \frac{1}{2 \cdot \pi \cdot \lambda^{ground}} \cdot \ln \left(\frac{4 \cdot x^{ground}}{d_s^{ins}} \right) \quad \forall s \in \mathbf{H}$$

$$X_s^{ins} = \frac{1}{2 \cdot \pi \cdot \lambda_s^{ins}} \cdot \ln \left(\frac{d_s^{ins}}{d_s^{pipe}} \right) \quad \forall s \in \mathbf{H}$$

$$W'_s = \frac{X_s^{ground} + X_s^{ins}}{(X_s^{ground} + X_s^{ins})^2 - X_s^{mut2}} \quad W''_s = \frac{X_s^{mut} + X_s^{ins}}{(X_s^{ground} + X_s^{ins})^2 - X_s^{mut2}}$$

$$\dot{q}_{s,lc,o,t}^{sup} = \left[(W'_s - W''_s) \cdot (T_{s,t}^{in} - T_t^{ground}) + W''_s \cdot (T_{s,t}^{in} - T_{s,t}^{out}) \right] \cdot D_{lc,o}^{pipe}$$

$$\dot{q}_{s,lc,o,t}^{ret} = \left[(W'_s - W''_s) \cdot (T_{s,t}^{out} - T_t^{amb}) - W''_s \cdot (T_{s,t}^{in} - T_{s,t}^{out}) \right] \cdot D_{lc,o}^{pipe}$$

$$\frac{1}{V_s} = \frac{1}{h^{amb}} + \frac{x_s^{pipe}}{\lambda_s^{pipe}} + \frac{x_s^{ins}}{\lambda_s^{ins}} \quad \forall s \in \mathbf{H}$$

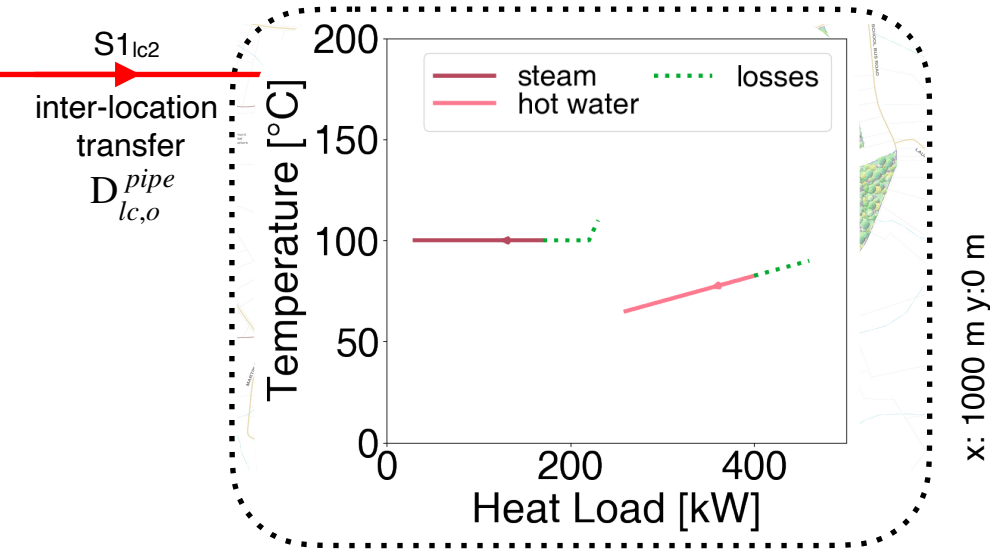
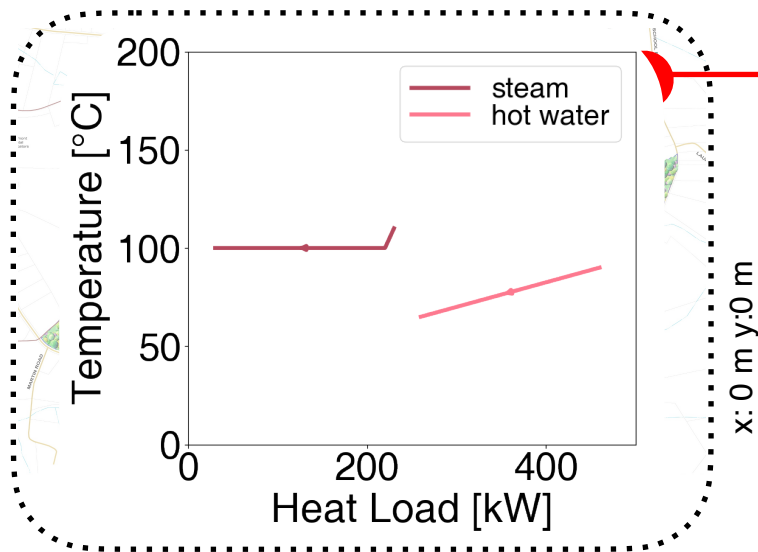
$$A_{s,lc,o}^{pipe} = 2 \cdot \pi \cdot d_s^{ins} \cdot D_{lc,o}^{pipe} \quad \forall s \in \mathbf{H}, lc \in \mathbf{LC}, o \in \mathbf{OL}_{lc}$$

$$\dot{q}_{s,lc,o,t}^{sup} = V_s \cdot A_{s,lc,o}^{pipe} \cdot (T_{s,t}^{in'} - T_t^{amb}) \quad \forall s \in \mathbf{H}, lc \in \mathbf{LC}, o \in \mathbf{OL}_{lc}, t \in \mathbf{TT}$$

$$\dot{q}_{s,lc,o,t}^{ret} = V_s \cdot A_{s,lc,o}^{pipe} \cdot (T_{s,t}^{out'} - T_t^{amb}) \quad \forall s \in \mathbf{H}, lc \in \mathbf{LC}, o \in \mathbf{OL}_{lc}, t \in \mathbf{TT}$$

$$\dot{q}_{s,t} = \dot{q}'_{s,t} - \dot{q}_{s,lc,o,t}^{sup} - \dot{q}_{s,lc,o,t}^{ret} \quad \forall s \in \mathbf{H}, lc \in \mathbf{LC}, o \in \mathbf{OL}_{lc}, t \in \mathbf{TT}$$

Heat losses and temperature drop



$$x_{ground} = x_{ground'} + \frac{\lambda_{ground}}{h_{amb}}$$

$$X_s^{mut} = \frac{1}{4 \cdot \pi \cdot \lambda_{ground}} \cdot \ln \left[1 + \left(\frac{2 \cdot x_{ground}}{D_{pp}} \right)^2 \right] \quad \forall s \in \mathbf{H}$$

$$X_s^{ground} = \frac{1}{2 \cdot \pi \cdot \lambda_{ground}} \cdot \ln \left(\frac{4 \cdot x_{ground}}{d_s^{ins}} \right) \quad \forall s \in \mathbf{H}$$

$$X_s^{ins} = \frac{1}{2 \cdot \pi \cdot \lambda_{ins}} \cdot \ln \left(\frac{d_s^{ins}}{d_s^{pipe}} \right) \quad \forall s \in \mathbf{H}$$

underground heat losses [108]

$$W'_s = \frac{X_s^{ground} + X_s^{ins}}{(X_s^{ground} + X_s^{ins})^2 - X_s^{mut2}} \quad W''_s = \frac{X_s^{mut} + X_s^{ins}}{(X_s^{ground} + X_s^{ins})^2 - X_s^{mut2}}$$

$$\dot{q}_{s,lc,o,t}^{sup} = \left[(W'_s - W''_s) \cdot (T_{s,t}^{in} - T_t^{ground}) + W''_s \cdot (T_{s,t}^{in} - T_{s,t}^{out}) \right] \cdot D_{lc,o}^{pipe}$$

$$\dot{q}_{s,lc,o,t}^{ret} = \left[(W'_s - W''_s) \cdot (T_{s,t}^{out} - T_t^{amb}) - W''_s \cdot (T_{s,t}^{in} - T_{s,t}^{out}) \right] \cdot D_{lc,o}^{pipe}$$

$$\frac{1}{V_s} = \frac{1}{h_{amb}} + \frac{x_s^{pipe}}{\lambda_s^{pipe}} + \frac{x_s^{ins}}{\lambda_s^{ins}} \quad \forall s \in \mathbf{H}$$

$$A_{s,lc,o}^{pipe} = 2 \cdot \pi \cdot d_s^{ins} \cdot D_{lc,o}^{pipe} \quad \forall s \in \mathbf{H}, lc \in \mathbf{LC}, o \in \mathbf{OL}_{lc}$$

$$\dot{q}_{s,lc,o,t}^{sup} = V_s \cdot A_{s,lc,o}^{pipe} \cdot (T_{s,t}^{in'} - T_t^{amb}) \quad \forall s \in \mathbf{H}, lc \in \mathbf{LC}, o \in \mathbf{OL}_{lc}, t \in \mathbf{TT}$$

$$\dot{q}_{s,lc,o,t}^{ret} = V_s \cdot A_{s,lc,o}^{pipe} \cdot (T_{s,t}^{out'} - T_t^{amb}) \quad \forall s \in \mathbf{H}, lc \in \mathbf{LC}, o \in \mathbf{OL}_{lc}, t \in \mathbf{TT}$$

above-ground heat losses

$$\dot{q}_{s,t} = \dot{q}'_{s,t} - \dot{q}_{s,lc,o,t}^{sup} - \dot{q}_{s,lc,o,t}^{ret} \quad \forall s \in \mathbf{H}, lc \in \mathbf{LC}, o \in \mathbf{OL}_{lc}, t \in \mathbf{TT}$$

connection with the MILP

$$\min C^{op} + C^{inv}$$

$$C^{pipe} \leq \epsilon$$

$$F_{u,p}^{\min} \cdot y'_{u,p} \leq f'_{u,p} \leq F_{u,p}^{\max} \cdot y'_{u,p} \quad \forall u \in \mathbf{UU}, p \in \mathbf{P}$$

$$f'_{u,p,t} \leq f'_{u,p} \quad \forall u \in \mathbf{UU}, p \in \mathbf{P}, t \in \mathbf{TT}_p$$

$$F_{u,p,t}^{\min} \cdot y'_{u,p,t} \leq f'_{u,p,t} \leq F_{u,p,t}^{\max} \cdot y'_{u,p,t} \quad \forall u \in \mathbf{UU}, p \in \mathbf{P}, t \in \mathbf{TT}_p$$

$$y'_{u,p,t} \leq y'_{u,p} \quad \forall u \in \mathbf{UU}, p \in \mathbf{P}, t \in \mathbf{TT}_p$$

$$f'_{u,p,t} = 1 \quad \forall u \in \mathbf{PU}, p \in \mathbf{P}, t \in \mathbf{TT}_p$$

$$f_u = 1 \quad \forall u \in \mathbf{PU}, p \in \mathbf{P}$$

$$y'_{u,t} = 1 \quad \forall u \in \mathbf{PU}, p \in \mathbf{P}, t \in \mathbf{TT}_p$$

$$y_{u,p} = 1 \quad \forall u \in \mathbf{PU}, p \in \mathbf{P}$$

$$\dot{e}_{u,t}^{in} = \sum_{es \in \mathbf{ES}_u} \dot{e}_{es,t}^{in} \quad \dot{e}_{u,t}^{out} = \sum_{es \in \mathbf{ES}_u} \dot{e}_{es,t}^{out} \quad \forall u \in \mathbf{U}, t \in \mathbf{TT}$$

$$\dot{E}_{u,t}^{out} = e_{u,t}^{out} \cdot f'_{u,t} \quad \forall u \in \mathbf{U}, t \in \mathbf{TT}$$

$$\dot{E}_{u,t}^{in} = e_{u,t}^{in} \cdot f'_{u,t} + \left(\sum_{o \in \mathbf{OL}_{lc}} \sum_{s \in \mathbf{HI}_u} \dot{E}_{s,t,o}^{pm} \right) + \left(\sum_{o \in \mathbf{OL}_{lc}} \sum_{ly \in \mathbf{L}} \sum_{s \in \mathbf{Z}_{u,ly}} \dot{E}_{s,t,o}^{pm} \right)$$

$$\sum_{u \in \mathbf{U}} \dot{E}_{u,p,t}^{in} = \sum_{u \in \mathbf{U}} \dot{E}_{u,p,t}^{out} \quad \forall p \in \mathbf{P}, t \in \mathbf{TT}_p$$

$$\dot{m}_{ly,u,p,t}^{in} \cdot f'_{u,p,t} = \dot{M}_{u,p,t}^{in} \quad \forall ly \in \mathbf{L}, u \in \mathbf{U}_{ly}, p \in \mathbf{P}, t \in \mathbf{TT}_p$$

$$\dot{m}_{ly,u,p,t}^{out} \cdot f'_{u,p,t} = \dot{M}_{u,p,t}^{out} \quad \forall ly \in \mathbf{L}, u \in \mathbf{U}_{ly}, p \in \mathbf{P}, t \in \mathbf{TT}_p$$

$$\sum_{u \in \mathbf{U}_{ly}} \dot{M}_{u,p,t}^{in} = \sum_{u \in \mathbf{U}_{ly}} \dot{M}_{u,p,t}^{out} \quad \forall ly \in \mathbf{L}, p \in \mathbf{P}, t \in \mathbf{TT}_p$$

$$\left(\sum_{i \in \mathbf{HS}_{lc,k}} \dot{q}_{i,k,p,t} \cdot s_{i,p,t} \right) - \left(\sum_{j \in \mathbf{CS}_{lc,k}} \dot{q}_{j,k,p,t} \cdot s_{j,p,t} \right) - \dot{R}_{lc,k,p,t} = 0$$

$$\dot{R}_{lc,k,p,t} = 0 \quad \forall lc \in \mathbf{LC}, p \in \mathbf{P}, t \in \mathbf{TT}_p, k = \text{first}(\mathbf{K}_{lc}) \text{ or } k = \text{last}(\mathbf{K}_{lc})$$

$$f'_{u,p,t} = s_{s,p,t} \quad \forall u \in \mathbf{U}, s \in \mathbf{H}_u, p \in \mathbf{P}, t \in \mathbf{TT}_p : s \notin \mathbf{HI}$$

$$f'_{u,p,t} = \sum_{lc \in \mathbf{LC}} \sum_{tr \in \mathbf{TR}} b_{sp,lc,tr,p,t} \quad \forall u \in \mathbf{U}, sp \in \mathbf{SP}_u, p \in \mathbf{P}, t \in \mathbf{TT}_p$$

$$s_{s,p,t} = b_{sp,lc,tr,p,t} \quad \forall sp \in \mathbf{SP}, lc \in \mathbf{LC}, tr \in \mathbf{TR}, p \in \mathbf{P}, t \in \mathbf{TT}_p$$

$$\dot{Q}_{sp,o,tr}^{\max} = \max(\dot{q}_{s,t} \cdot b_{sp,t,o,tr}) \quad \forall sp \in \mathbf{SP}, t \in \mathbf{TT}, s \in \mathbf{S}_p, o \in \mathbf{OL}_p, tr \in \mathbf{TR}_p$$

$$\dot{M}_{ly,o,u}^{\max} = \max(\dot{m}_{ly,u,t}^{out} \cdot a_{ly,lc,o,u,t}) \quad \forall ly \in \mathbf{L}, lc \in \mathbf{LC}, o \in \mathbf{OL}_{lc}, u \in \mathbf{U}_{ly}, t \in \mathbf{TT}$$

$$\dot{q}_{sp,o,tr,ps}^{lb} \cdot n_{sp,o,tr,ps}^h \leq \dot{I}_{sp,o,tr,ps}^p \leq \dot{q}_{sp,o,tr,ps}^{ub} \cdot n_{sp,o,tr,ps}^h$$

$$\sum_{ps \in \mathbf{PS}} \dot{I}_{sp,o,tr,ps}^p = \dot{Q}_{sp,o,tr}^{\max} \quad \forall sp \in \mathbf{SP}, o \in \mathbf{OL}_p, tr \in \mathbf{TR}, ps \in \mathbf{PS}$$

$$\sum_{ps \in \mathbf{PS}} n_{sp,o,tr,ps}^h \leq 1 \quad \forall sp \in \mathbf{SP}, o \in \mathbf{OL}_p, tr \in \mathbf{TR}, ps \in \mathbf{PS}$$

$$C_{sp,o,tr}^{pipe_h} = \sum_{ps \in \mathbf{PS}} c_{ps}^{pipe} \cdot F^{tc} \cdot D_{lc,o}^{pipe} \cdot n_{sp,o,tr,ps}^h \quad \forall sp \in \mathbf{SP}, lc \in \mathbf{LC}, o \in \mathbf{OL}_{lc}, tr \in \mathbf{TR}$$

$$C_{ly,u,o}^{pipe_r} = \sum_{ps \in \mathbf{PS}} c_{ps}^{pipe} \cdot F^{tc} \cdot D_{lc,o}^{pipe} \cdot n_{ly,u,o,ps}^r \quad \forall ly \in \mathbf{L}, u \in \mathbf{U}_{ly}, lc \in \mathbf{LC}, o \in \mathbf{OL}_{lc}$$

$$C^{pipe} = \left(\sum_{sp \in \mathbf{SP}} \sum_{o \in \mathbf{OL}_p} \sum_{tr \in \mathbf{TR}} C_{sp,o,tr}^{pipe_h} + \sum_{ly \in \mathbf{L}} \sum_{u \in \mathbf{U}} \sum_{o \in \mathbf{OL}_u} C_{ly,u,o}^{pipe_r} \right) \cdot F^{an}$$

min $C^{op} + C^{inv}$

main objective: total cost excluding piping

$C^{pipe} \leq \epsilon$

constrained objective: piping cost

$$F_{u,p}^{\min} \cdot y'_{u,p} \leq f'_{u,p} \leq F_{u,p}^{\max} \cdot y'_{u,p} \quad \forall u \in \mathbf{UU}, p \in \mathbf{P}$$

$$f'_{u,p,t} \leq f'_{u,p} \quad \forall u \in \mathbf{UU}, p \in \mathbf{P}, t \in \mathbf{TT}_p$$

$$F_{u,p,t}^{\min} \cdot y'_{u,p,t} \leq f'_{u,p,t} \leq F_{u,p,t}^{\max} \cdot y'_{u,p,t} \quad \forall u \in \mathbf{UU}, p \in \mathbf{P}, t \in \mathbf{TT}_p$$

$$y'_{u,p,t} \leq y'_{u,p} \quad \forall u \in \mathbf{UU}, p \in \mathbf{P}, t \in \mathbf{TT}_p$$

$$f'_{u,p,t} = 1 \quad \forall u \in \mathbf{PU}, p \in \mathbf{P}, t \in \mathbf{TT}_p$$

$$f_u = 1 \quad \forall u \in \mathbf{PU}, p \in \mathbf{P}$$

$$y_{u,t} = 1 \quad \forall u \in \mathbf{PU}, p \in \mathbf{P}, t \in \mathbf{TT}_p$$

$$y_{u,p} = 1 \quad \forall u \in \mathbf{PU}, p \in \mathbf{P}$$

$$\dot{e}_{u,t}^{in} = \sum_{es \in \mathbf{ES}_u} \dot{e}_{es,t}^{in} \quad \dot{e}_{u,t}^{out} = \sum_{es \in \mathbf{ES}_u} \dot{e}_{es,t}^{out} \quad \forall u \in \mathbf{U}, t \in \mathbf{TT}$$

$$\dot{E}_{u,t}^{out} = e_{u,t}^{out} \cdot f'_{u,t} \quad \forall u \in \mathbf{U}, t \in \mathbf{TT}$$

$$\dot{E}_{u,t}^{in} = e_{u,t}^{in} \cdot f'_{u,t} + \left(\sum_{o \in \mathbf{OL}_{lc}} \sum_{s \in \mathbf{HI}_u} \dot{E}_{s,t,o}^{pm} \right) + \left(\sum_{o \in \mathbf{OL}_{lc}} \sum_{ly \in \mathbf{L}} \sum_{s \in \mathbf{Z}_{u,ly}} \dot{E}_{s,t,o}^{pm} \right)$$

$$\sum_{u \in \mathbf{U}} \dot{E}_{u,p,t}^{in} = \sum_{u \in \mathbf{U}} \dot{E}_{u,p,t}^{out} \quad \forall p \in \mathbf{P}, t \in \mathbf{TT}_p$$

$$\dot{m}_{ly,u,p,t}^{in} \cdot f'_{u,p,t} = \dot{M}_{u,p,t}^{in} \quad \forall ly \in \mathbf{L}, u \in \mathbf{U}_{ly}, p \in \mathbf{P}, t \in \mathbf{TT}_p$$

$$\dot{m}_{ly,u,p,t}^{out} \cdot f'_{u,p,t} = \dot{M}_{u,p,t}^{out} \quad \forall ly \in \mathbf{L}, u \in \mathbf{U}_{ly}, p \in \mathbf{P}, t \in \mathbf{TT}_p$$

$$\sum_{u \in \mathbf{U}_{ly}} \dot{M}_{u,p,t}^{in} = \sum_{u \in \mathbf{U}_{ly}} \dot{M}_{u,p,t}^{out} \quad \forall ly \in \mathbf{L}, p \in \mathbf{P}, t \in \mathbf{TT}_p$$

$$\left(\sum_{i \in \mathbf{HS}_{lc,k}} \dot{q}_{i,k,p,t} \cdot s_{i,p,t} \right) - \left(\sum_{j \in \mathbf{CS}_{lc,k}} \dot{q}_{j,k,p,t} \cdot s_{j,p,t} \right) - \dot{R}_{lc,k,p,t} = 0$$

$$\dot{R}_{lc,k,p,t} = 0 \quad \forall lc \in \mathbf{LC}, p \in \mathbf{P}, t \in \mathbf{TT}_p, k = \text{first}(\mathbf{K}_{lc}) \text{ or } k = \text{last}(\mathbf{K}_{lc})$$

$$f'_{u,p,t} = s_{s,p,t} \quad \forall u \in \mathbf{U}, s \in \mathbf{H}_u, p \in \mathbf{P}, t \in \mathbf{TT}_p : s \notin \mathbf{HI}$$

$$f'_{u,p,t} = \sum_{lc \in \mathbf{LC}} \sum_{tr \in \mathbf{TR}} b_{sp,lc,tr,p,t} \quad \forall u \in \mathbf{U}, sp \in \mathbf{SP}_u, p \in \mathbf{P}, t \in \mathbf{TT}_p$$

$$s_{s,p,t} = b_{sp,lc,tr,p,t} \quad \forall sp \in \mathbf{SP}, lc \in \mathbf{LC}, tr \in \mathbf{TR}, p \in \mathbf{P}, t \in \mathbf{TT}_p$$

$$\dot{Q}_{sp,o,tr}^{\max} = \max(\dot{q}_{s,t} \cdot b_{sp,t,o,tr}) \quad \forall sp \in \mathbf{SP}, t \in \mathbf{TT}, s \in \mathbf{S}_p, o \in \mathbf{OL}_p, tr \in \mathbf{TR}_p$$

$$\dot{M}_{ly,o,u}^{\max} = \max(\dot{m}_{ly,u,t}^{out} \cdot a_{ly,lc,o,u,t}) \quad \forall ly \in \mathbf{L}, lc \in \mathbf{LC}, o \in \mathbf{OL}_{lc}, u \in \mathbf{U}_{ly}, t \in \mathbf{TT}$$

$$\dot{q}_{sp,o,tr,ps}^{lb} \cdot n_{sp,o,tr,ps}^h \leq \dot{I}_{sp,o,tr,ps}^p \leq \dot{q}_{sp,o,tr,ps}^{ub} \cdot n_{sp,o,tr,ps}^h$$

$$\sum_{ps \in \mathbf{PS}} \dot{I}_{sp,o,tr,ps}^p = \dot{Q}_{sp,o,tr}^{\max} \quad \forall sp \in \mathbf{SP}, o \in \mathbf{OL}_p, tr \in \mathbf{TR}, ps \in \mathbf{PS}$$

$$\sum_{ps \in \mathbf{PS}} n_{sp,o,tr,ps}^h \leq 1 \quad \forall sp \in \mathbf{SP}, o \in \mathbf{OL}_p, tr \in \mathbf{TR}, ps \in \mathbf{PS}$$

$$C_{sp,o,tr}^{pipe_h} = \sum_{ps \in \mathbf{PS}} c_{ps}^{pipe} \cdot F^{tc} \cdot D_{lc,o}^{pipe} \cdot n_{sp,o,tr,ps}^h \quad \forall sp \in \mathbf{SP}, lc \in \mathbf{LC}, o \in \mathbf{OL}_{lc}, tr \in \mathbf{TR}$$

$$C_{ly,u,o}^{pipe_r} = \sum_{ps \in \mathbf{PS}} c_{ps}^{pipe} \cdot F^{tc} \cdot D_{lc,o}^{pipe} \cdot n_{ly,u,o,ps}^r \quad \forall ly \in \mathbf{L}, u \in \mathbf{U}_{ly}, lc \in \mathbf{LC}, o \in \mathbf{OL}_{lc}$$

$$C^{pipe} = \left(\sum_{sp \in \mathbf{SP}} \sum_{o \in \mathbf{OL}_p} \sum_{tr \in \mathbf{TR}} C_{sp,o,tr}^{pipe_h} + \sum_{ly \in \mathbf{L}} \sum_{u \in \mathbf{U}} \sum_{o \in \mathbf{OL}_u} C_{ly,u,o}^{pipe_r} \right) \cdot F^{an}$$

min $C^{op} + C^{inv}$

main objective: total cost excluding piping

$C^{pipe} \leq \epsilon$

constrained objective: piping cost

$$\begin{aligned} F_{u,p}^{\min} \cdot y'_{u,p} &\leq f'_{u,p} \leq F_{u,p}^{\max} \cdot y'_{u,p} \quad \forall u \in \text{UU}, p \in \text{P} \\ f'_{u,p,t} &\leq f'_{u,p} \quad \forall u \in \text{UU}, p \in \text{P}, t \in \text{TT}_p \\ F_{u,p,t}^{\min} \cdot y'_{u,p,t} &\leq f'_{u,p,t} \leq F_{u,p,t}^{\max} \cdot y'_{u,p,t} \quad \forall u \in \text{UU}, p \in \text{P}, t \in \text{TT}_p \\ y'_{u,p,t} &\leq y'_{u,p} \quad \forall u \in \text{UU}, p \in \text{P}, t \in \text{TT}_p \\ f'_{u,p,t} &= 1 \quad \forall u \in \text{PU}, p \in \text{P}, t \in \text{TT}_p \\ f_u &= 1 \quad \forall u \in \text{PU}, p \in \text{P} \\ y_{u,t} &= 1 \quad \forall u \in \text{PU}, p \in \text{P}, t \in \text{TT}_p \\ y_{u,p} &= 1 \quad \forall u \in \text{PU}, p \in \text{P} \end{aligned}$$

sizing and scheduling constraints [25]

$$\begin{aligned} \dot{e}_{u,t}^{\text{in}} &= \sum_{es \in \text{ES}_u} \dot{e}_{es,t}^{\text{in}} \quad \dot{e}_{u,t}^{\text{out}} = \sum_{es \in \text{ES}_u} \dot{e}_{es,t}^{\text{out}} \quad \forall u \in \text{U}, t \in \text{TT} \\ \dot{E}_{u,t}^{\text{out}} &= e_{u,t}^{\text{out}} \cdot f'_{u,t} \quad \forall u \in \text{U}, t \in \text{TT} \\ \dot{E}_{u,t}^{\text{in}} &= e_{u,t}^{\text{in}} \cdot f'_{u,t} + \left(\sum_{o \in \text{OL}_{lc}} \sum_{s \in \text{HI}_u} \dot{E}_{s,t,o}^{\text{pm}} \right) + \left(\sum_{o \in \text{OL}_{lc}} \sum_{ly \in \text{L}} \sum_{s \in \text{Z}_{u,ly}} \dot{E}_{s,t,o}^{\text{pm}} \right) \\ \sum_{u \in \text{U}} \dot{E}_{u,p,t}^{\text{in}} &= \sum_{u \in \text{U}} \dot{E}_{u,p,t}^{\text{out}} \quad \forall p \in \text{P}, t \in \text{TT}_p \\ \dot{m}_{ly,u,p,t}^{\text{in}} \cdot f'_{u,p,t} &= \dot{M}_{u,p,t}^{\text{in}} \quad \forall ly \in \text{L}, u \in \text{U}_{ly}, p \in \text{P}, t \in \text{TT}_p \\ \dot{m}_{ly,u,p,t}^{\text{out}} \cdot f'_{u,p,t} &= \dot{M}_{u,p,t}^{\text{out}} \quad \forall ly \in \text{L}, u \in \text{U}_{ly}, p \in \text{P}, t \in \text{TT}_p \\ \sum_{u \in \text{U}_{ly}} \dot{M}_{u,p,t}^{\text{in}} &= \sum_{u \in \text{U}_{ly}} \dot{M}_{u,p,t}^{\text{out}} \quad \forall ly \in \text{L}, p \in \text{P}, t \in \text{TT}_p \end{aligned}$$

$$\begin{aligned} \left(\sum_{i \in \text{HS}_{lc,k}} \dot{q}_{i,k,p,t} \cdot s_{i,p,t} \right) - \left(\sum_{j \in \text{CS}_{lc,k}} \dot{q}_{j,k,p,t} \cdot s_{j,p,t} \right) - \dot{R}_{lc,k,p,t} &= 0 \\ \dot{R}_{lc,k,p,t} &= 0 \quad \forall lc \in \text{LC}, p \in \text{P}, t \in \text{TT}_p, k = \text{first}(\text{K}_{lc}) \text{ or } k = \text{last}(\text{K}_{lc}) \\ f'_{u,p,t} &= s_{s,p,t} \quad \forall u \in \text{U}, s \in \text{H}_u, p \in \text{P}, t \in \text{TT}_p : s \notin \text{HI} \\ f'_{u,p,t} &= \sum_{lc \in \text{LC}} \sum_{tr \in \text{TR}} b_{sp,lc,tr,p,t} \quad \forall u \in \text{U}, sp \in \text{SP}_u, p \in \text{P}, t \in \text{TT}_p \\ s_{s,p,t} &= b_{sp,lc,tr,p,t} \quad \forall sp \in \text{SP}, lc \in \text{LC}, tr \in \text{TR}, p \in \text{P}, t \in \text{TT}_p \\ \dot{Q}_{sp,o,tr}^{\text{max}} &= \max(\dot{q}_{s,t} \cdot b_{sp,t,o,tr}) \quad \forall sp \in \text{SP}, t \in \text{TT}, s \in \text{S}_p, o \in \text{OL}_p, tr \in \text{TR}_p \\ \dot{M}_{ly,o,u}^{\text{max}} &= \max(\dot{m}_{ly,u,t}^{\text{out}} \cdot a_{ly,lc,o,u,t}) \quad \forall ly \in \text{L}, lc \in \text{LC}, o \in \text{OL}_{lc}, u \in \text{U}_{ly}, t \in \text{TT} \\ \dot{q}_{sp,o,tr,ps}^{\text{lb}} \cdot n_{sp,o,tr,ps}^h &\leq \dot{I}_{sp,o,tr,ps}^p \leq \dot{q}_{sp,o,tr,ps}^{\text{ub}} \cdot n_{sp,o,tr,ps}^h \\ \sum_{ps \in \text{PS}} \dot{I}_{sp,o,tr,ps}^p &= \dot{Q}_{sp,o,tr}^{\text{max}} \quad \forall sp \in \text{SP}, o \in \text{OL}_p, tr \in \text{TR}, ps \in \text{PS} \\ \sum_{ps \in \text{PS}} n_{sp,o,tr,ps}^h &\leq 1 \quad \forall sp \in \text{SP}, o \in \text{OL}_p, tr \in \text{TR}, ps \in \text{PS} \\ C_{sp,o,tr}^{\text{pipe}_h} &= \sum_{ps \in \text{PS}} c_{ps}^{\text{pipe}} \cdot F^{\text{tc}} \cdot D_{lc,o}^{\text{pipe}} \cdot n_{sp,o,tr,ps}^h \quad \forall sp \in \text{SP}, lc \in \text{LC}, o \in \text{OL}_{lc}, tr \in \text{TR} \\ C_{ly,u,o}^{\text{pipe}_r} &= \sum_{ps \in \text{PS}} c_{ps}^{\text{pipe}} \cdot F^{\text{tc}} \cdot D_{lc,o}^{\text{pipe}} \cdot n_{ly,u,o,ps}^r \quad \forall ly \in \text{L}, u \in \text{U}_{ly}, lc \in \text{LC}, o \in \text{OL}_{lc} \\ C^{\text{pipe}} &= \left(\sum_{sp \in \text{SP}} \sum_{o \in \text{OL}_p} \sum_{tr \in \text{TR}} C_{sp,o,tr}^{\text{pipe}_h} + \sum_{ly \in \text{L}} \sum_{u \in \text{U}} \sum_{o \in \text{OL}_u} C_{ly,u,o}^{\text{pipe}_r} \right) \cdot F^{\text{an}} \end{aligned}$$

min $C^{op} + C^{inv}$

main objective: total cost excluding piping

$C^{pipe} \leq \epsilon$

constrained objective: piping cost

$$\begin{aligned} F_{u,p}^{\min} \cdot y_{u,p}' &\leq f_{u,p}' \leq F_{u,p}^{\max} \cdot y_{u,p}' \quad \forall u \in \text{UU}, p \in \text{P} \\ f_{u,p,t}' &\leq f_{u,p}' \quad \forall u \in \text{UU}, p \in \text{P}, t \in \text{TT}_p \\ F_{u,p,t}^{\min} \cdot y_{u,p,t}' &\leq f_{u,p,t}' \leq F_{u,p,t}^{\max} \cdot y_{u,p,t}' \quad \forall u \in \text{UU}, p \in \text{P}, t \in \text{TT}_p \\ y_{u,p,t}' &\leq y_{u,p}' \quad \forall u \in \text{UU}, p \in \text{P}, t \in \text{TT}_p \\ f_{u,p,t}' &= 1 \quad \forall u \in \text{PU}, p \in \text{P}, t \in \text{TT}_p \\ f_u &= 1 \quad \forall u \in \text{PU}, p \in \text{P} \\ y_{u,t}' &= 1 \quad \forall u \in \text{PU}, p \in \text{P}, t \in \text{TT}_p \\ y_{u,p} &= 1 \quad \forall u \in \text{PU}, p \in \text{P} \end{aligned}$$

sizing and scheduling constraints [25]

$$\begin{aligned} \dot{e}_{u,t}^{\text{in}} &= \sum_{es \in \text{ES}_u} \dot{e}_{es,t}^{\text{in}} \quad \dot{e}_{u,t}^{\text{out}} = \sum_{es \in \text{ES}_u} \dot{e}_{es,t}^{\text{out}} \quad \forall u \in \text{U}, t \in \text{TT} \\ \dot{E}_{u,t}^{\text{out}} &= e_{u,t}^{\text{out}} \cdot f_{u,t}' \quad \forall u \in \text{U}, t \in \text{TT} \\ \dot{E}_{u,t}^{\text{in}} &= e_{u,t}^{\text{in}} \cdot f_{u,t}' + \left(\sum_{o \in \text{OL}_{lc}} \sum_{s \in \text{HI}_u} \dot{E}_{s,t,o}^{\text{pm}} \right) + \left(\sum_{o \in \text{OL}_{lc}} \sum_{ly \in \text{L}} \sum_{s \in \text{Z}_{u,ly}} \dot{E}_{s,t,o}^{\text{pm}} \right) \\ \sum_{u \in \text{U}} \dot{E}_{u,p,t}^{\text{in}} &= \sum_{u \in \text{U}} \dot{E}_{u,p,t}^{\text{out}} \quad \forall p \in \text{P}, t \in \text{TT}_p \end{aligned}$$

modified electricity balance

$$\begin{aligned} \dot{m}_{ly,u,p,t}^{\text{in}} \cdot f_{u,p,t}' &= \dot{M}_{u,p,t}^{\text{in}} \quad \forall ly \in \text{L}, u \in \text{U}_{ly}, p \in \text{P}, t \in \text{TT}_p \\ \dot{m}_{ly,u,p,t}^{\text{out}} \cdot f_{u,p,t}' &= \dot{M}_{u,p,t}^{\text{out}} \quad \forall ly \in \text{L}, u \in \text{U}_{ly}, p \in \text{P}, t \in \text{TT}_p \\ \sum_{u \in \text{U}_{ly}} \dot{M}_{u,p,t}^{\text{in}} &= \sum_{u \in \text{U}_{ly}} \dot{M}_{u,p,t}^{\text{out}} \quad \forall ly \in \text{L}, p \in \text{P}, t \in \text{TT}_p \end{aligned}$$

modified mass balance

$$\begin{aligned} \left(\sum_{i \in \text{HS}_{lc,k}} \dot{q}_{i,k,p,t} \cdot s_{i,p,t} \right) - \left(\sum_{j \in \text{CS}_{lc,k}} \dot{q}_{j,k,p,t} \cdot s_{j,p,t} \right) - \dot{R}_{lc,k,p,t} &= 0 \\ \dot{R}_{lc,k,p,t} &= 0 \quad \forall lc \in \text{LC}, p \in \text{P}, t \in \text{TT}_p, k = \text{first}(\text{K}_{lc}) \text{ or } k = \text{last}(\text{K}_{lc}) \\ f_{u,p,t}' &= s_{s,p,t} \quad \forall u \in \text{U}, s \in \text{SP}_u, p \in \text{P}, t \in \text{TT}_p \\ f_{u,p,t}' &= \sum_{lc \in \text{LC}} \sum_{tr \in \text{TR}} b_{sp,lc,tr,p,t} \quad \forall u \in \text{U}, sp \in \text{SP}_u, p \in \text{P}, t \in \text{TT}_p \\ s_{s,p,t} &= b_{sp,lc,tr,p,t} \quad \forall sp \in \text{SP}, lc \in \text{LC}, tr \in \text{TR}, p \in \text{P}, t \in \text{TT}_p \end{aligned}$$

modified heat cascade

$$\begin{aligned} \dot{Q}_{sp,o,tr}^{\text{max}} &= \max(\dot{q}_{s,t} \cdot b_{sp,t,o,tr}) \quad \forall sp \in \text{SP}, t \in \text{TT}, s \in \text{S}_p, o \in \text{OL}_p, tr \in \text{TR}_p \\ \dot{M}_{ly,o,u}^{\text{max}} &= \max(\dot{m}_{ly,u,t}^{\text{out}} \cdot a_{ly,lc,o,u,t}) \quad \forall ly \in \text{L}, lc \in \text{LC}, o \in \text{OL}_{lc}, u \in \text{U}_{ly}, t \in \text{TT} \\ \dot{q}_{sp,o,tr,ps}^{\text{lb}} \cdot n_{sp,o,tr,ps}^h &\leq \dot{I}_{sp,o,tr,ps}^p \leq \dot{q}_{sp,o,tr,ps}^{\text{ub}} \cdot n_{sp,o,tr,ps}^h \\ \sum_{ps \in \text{PS}} \dot{I}_{sp,o,tr,ps}^p &= \dot{Q}_{sp,o,tr}^{\text{max}} \quad \forall sp \in \text{SP}, o \in \text{OL}_p, tr \in \text{TR}, ps \in \text{PS} \\ \sum_{ps \in \text{PS}} n_{sp,o,tr,ps}^h &\leq 1 \quad \forall sp \in \text{SP}, o \in \text{OL}_p, tr \in \text{TR}, ps \in \text{PS} \\ C_{sp,o,tr}^{\text{pipe}_h} &= \sum_{ps \in \text{PS}} c_{ps}^{\text{pipe}} \cdot F^{tc} \cdot D_{lc,o}^{\text{pipe}} \cdot n_{sp,o,tr,ps}^h \quad \forall sp \in \text{SP}, lc \in \text{LC}, o \in \text{OL}_{lc}, tr \in \text{TR} \\ C_{ly,u,o}^{\text{pipe}_r} &= \sum_{ps \in \text{PS}} c_{ps}^{\text{pipe}} \cdot F^{tc} \cdot D_{lc,o}^{\text{pipe}} \cdot n_{ly,u,o,ps}^r \quad \forall ly \in \text{L}, u \in \text{U}_{ly}, lc \in \text{LC}, o \in \text{OL}_{lc} \\ C^{\text{pipe}} &= \left(\sum_{sp \in \text{SP}} \sum_{o \in \text{OL}_p} \sum_{tr \in \text{TR}} C_{sp,o,tr}^{\text{pipe}_h} + \sum_{ly \in \text{L}} \sum_{u \in \text{U}} \sum_{o \in \text{OL}_u} C_{ly,u,o}^{\text{pipe}_r} \right) \cdot F^{\text{an}} \end{aligned}$$

min $C^{op} + C^{inv}$

main objective: total cost excluding piping

$C^{pipe} \leq \epsilon$

constrained objective: piping cost

$$\begin{aligned} F_{u,p}^{\min} \cdot y_{u,p}' &\leq f_{u,p}' \leq F_{u,p}^{\max} \cdot y_{u,p}' \quad \forall u \in \text{UU}, p \in \text{P} \\ f_{u,p,t}' &\leq f_{u,p}' \quad \forall u \in \text{UU}, p \in \text{P}, t \in \text{TT}_p \\ F_{u,p,t}^{\min} \cdot y_{u,p,t}' &\leq f_{u,p,t}' \leq F_{u,p,t}^{\max} \cdot y_{u,p,t}' \quad \forall u \in \text{UU}, p \in \text{P}, t \in \text{TT}_p \\ y_{u,p,t}' &\leq y_{u,p}' \quad \forall u \in \text{UU}, p \in \text{P}, t \in \text{TT}_p \\ f_{u,p,t}' &= 1 \quad \forall u \in \text{PU}, p \in \text{P}, t \in \text{TT}_p \\ f_u &= 1 \quad \forall u \in \text{PU}, p \in \text{P} \\ y_{u,t}' &= 1 \quad \forall u \in \text{PU}, p \in \text{P}, t \in \text{TT}_p \\ y_{u,p} &= 1 \quad \forall u \in \text{PU}, p \in \text{P} \end{aligned}$$

sizing and scheduling constraints [25]

$$\begin{aligned} \dot{e}_{u,t}^{\text{in}} &= \sum_{es \in \text{ES}_u} \dot{e}_{es,t}^{\text{in}} \quad \dot{e}_{u,t}^{\text{out}} = \sum_{es \in \text{ES}_u} \dot{e}_{es,t}^{\text{out}} \quad \forall u \in \text{U}, t \in \text{TT} \\ \dot{E}_{u,t}^{\text{out}} &= e_{u,t}^{\text{out}} \cdot f_{u,t}' \quad \forall u \in \text{U}, t \in \text{TT} \\ \dot{E}_{u,t}^{\text{in}} &= e_{u,t}^{\text{in}} \cdot f_{u,t}' + \left(\sum_{o \in \text{OL}_{lc}} \sum_{s \in \text{HI}_u} \dot{E}_{s,t,o}^{\text{pm}} \right) + \left(\sum_{o \in \text{OL}_{lc}} \sum_{ly \in \text{L}} \sum_{s \in \text{Z}_{u,ly}} \dot{E}_{s,t,o}^{\text{pm}} \right) \\ \sum_{u \in \text{U}} \dot{E}_{u,p,t}^{\text{in}} &= \sum_{u \in \text{U}} \dot{E}_{u,p,t}^{\text{out}} \quad \forall p \in \text{P}, t \in \text{TT}_p \end{aligned}$$

modified electricity balance

$$\begin{aligned} \dot{m}_{ly,u,p,t}^{\text{in}} \cdot f_{u,p,t}' &= \dot{M}_{u,p,t}^{\text{in}} \quad \forall ly \in \text{L}, u \in \text{U}_{ly}, p \in \text{P}, t \in \text{TT}_p \\ \dot{m}_{ly,u,p,t}^{\text{out}} \cdot f_{u,p,t}' &= \dot{M}_{u,p,t}^{\text{out}} \quad \forall ly \in \text{L}, u \in \text{U}_{ly}, p \in \text{P}, t \in \text{TT}_p \\ \sum_{u \in \text{U}_{ly}} \dot{M}_{u,p,t}^{\text{in}} &= \sum_{u \in \text{U}_{ly}} \dot{M}_{u,p,t}^{\text{out}} \quad \forall ly \in \text{L}, p \in \text{P}, t \in \text{TT}_p \end{aligned}$$

modified mass balance

$$\begin{aligned} \left(\sum_{i \in \text{HS}_{lc,k}} \dot{q}_{i,k,p,t} \cdot s_{i,p,t} \right) - \left(\sum_{j \in \text{CS}_{lc,k}} \dot{q}_{j,k,p,t} \cdot s_{j,p,t} \right) - \dot{R}_{lc,k,p,t} &= 0 \\ \dot{R}_{lc,k,p,t} &= 0 \quad \forall lc \in \text{LC}, p \in \text{P}, t \in \text{TT}_p, k = \text{first}(\text{K}_{lc}) \text{ or } k = \text{last}(\text{K}_{lc}) \\ f_{u,p,t}' &= s_{s,p,t} \quad \forall u \in \text{U}, s \in \text{SP}_u, p \in \text{P}, t \in \text{TT}_p \\ f_{u,p,t}' &= \sum_{lc \in \text{LC}} \sum_{tr \in \text{TR}} b_{sp,lc,tr,p,t} \quad \forall u \in \text{U}, sp \in \text{SP}_u, p \in \text{P}, t \in \text{TT}_p \\ s_{s,p,t} &= b_{sp,lc,tr,p,t} \quad \forall sp \in \text{SP}, lc \in \text{LC}, tr \in \text{TR}, p \in \text{P}, t \in \text{TT}_p \end{aligned}$$

modified heat cascade

$$\begin{aligned} \dot{Q}_{sp,o,tr}^{\text{max}} &= \max(\dot{q}_{s,t} \cdot b_{sp,t,o,tr}) \quad \forall sp \in \text{SP}, t \in \text{TT}, s \in \text{S}_p, o \in \text{OL}_p, tr \in \text{TR}_p \\ \dot{M}_{ly,o,u}^{\text{max}} &= \max(\dot{m}_{ly,u,t}^{\text{out}} \cdot a_{ly,lc,o,u,t}) \quad \forall ly \in \text{L}, lc \in \text{LC}, o \in \text{OL}_{lc}, u \in \text{U}_{ly}, t \in \text{TT} \\ \dot{q}_{sp,o,tr,ps}^{\text{lb}} \cdot n_{sp,o,tr,ps}^h &\leq \dot{I}_{sp,o,tr,ps}^p \leq \dot{q}_{sp,o,tr,ps}^{\text{ub}} \cdot n_{sp,o,tr,ps}^h \\ \sum_{ps \in \text{PS}} \dot{I}_{sp,o,tr,ps}^p &= \dot{Q}_{sp,o,tr}^{\text{max}} \quad \forall sp \in \text{SP}, o \in \text{OL}_p, tr \in \text{TR}, ps \in \text{PS} \\ \sum_{ps \in \text{PS}} n_{sp,o,tr,ps}^h &\leq 1 \quad \forall sp \in \text{SP}, o \in \text{OL}_p, tr \in \text{TR}, ps \in \text{PS} \end{aligned}$$

piping constraints

$$\begin{aligned} C_{sp,o,tr}^{\text{pipe}_h} &= \sum_{ps \in \text{PS}} c_{ps}^{\text{pipe}} \cdot F^{\text{tc}} \cdot D_{lc,o}^{\text{pipe}} \cdot n_{sp,o,tr,ps}^h \quad \forall sp \in \text{SP}, lc \in \text{LC}, o \in \text{OL}_{lc}, tr \in \text{TR} \\ C_{ly,u,o}^{\text{pipe}_r} &= \sum_{ps \in \text{PS}} c_{ps}^{\text{pipe}} \cdot F^{\text{tc}} \cdot D_{lc,o}^{\text{pipe}} \cdot n_{ly,u,o,ps}^r \quad \forall ly \in \text{L}, u \in \text{U}_{ly}, lc \in \text{LC}, o \in \text{OL}_{lc} \\ C^{\text{pipe}} &= \left(\sum_{sp \in \text{SP}} \sum_{o \in \text{OL}_p} \sum_{tr \in \text{TR}} C_{sp,o,tr}^{\text{pipe}_h} + \sum_{ly \in \text{L}} \sum_{u \in \text{U}} \sum_{o \in \text{OL}_u} C_{ly,u,o}^{\text{pipe}_r} \right) \cdot F^{\text{an}} \end{aligned}$$

Case study: an industrial cluster

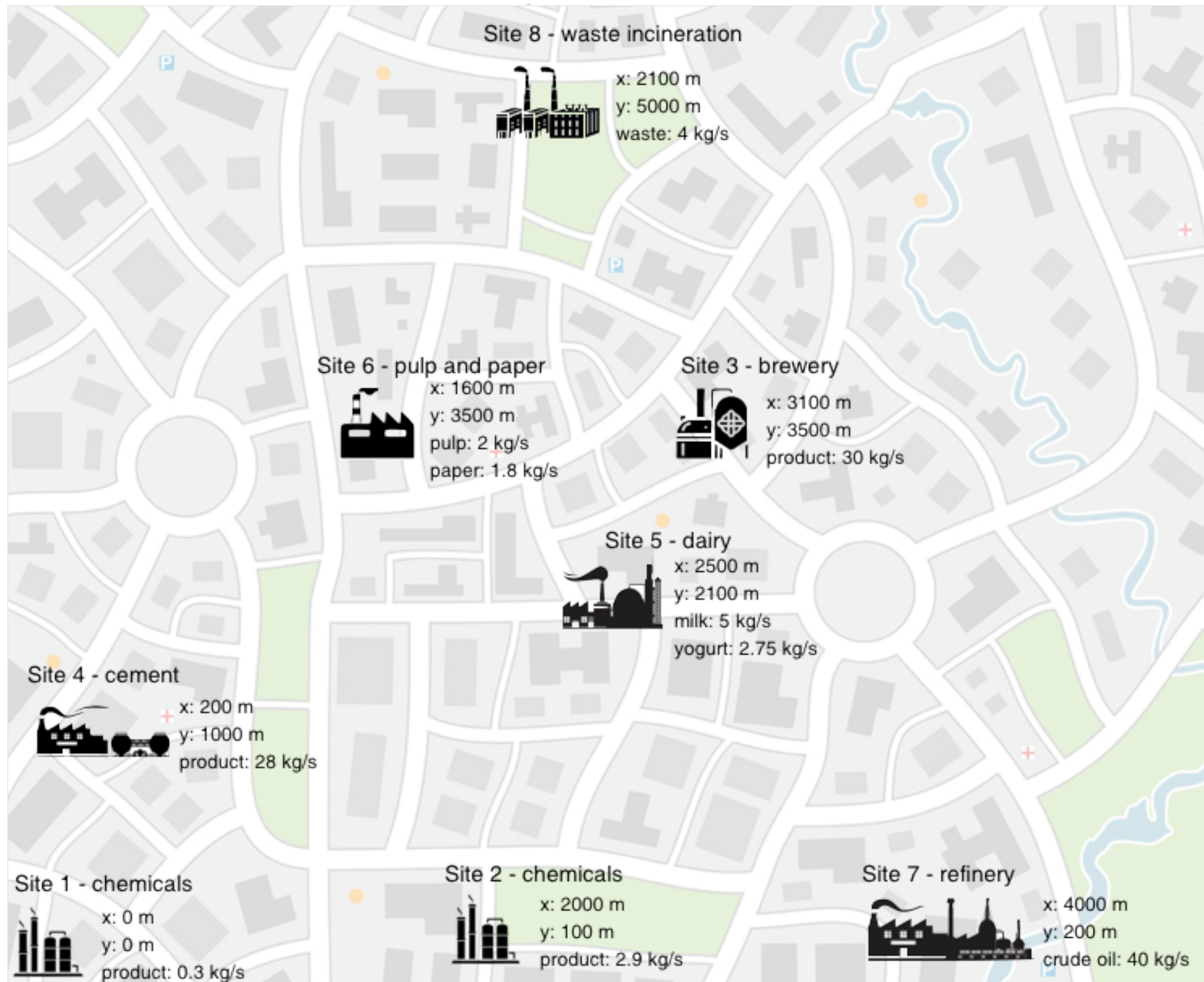
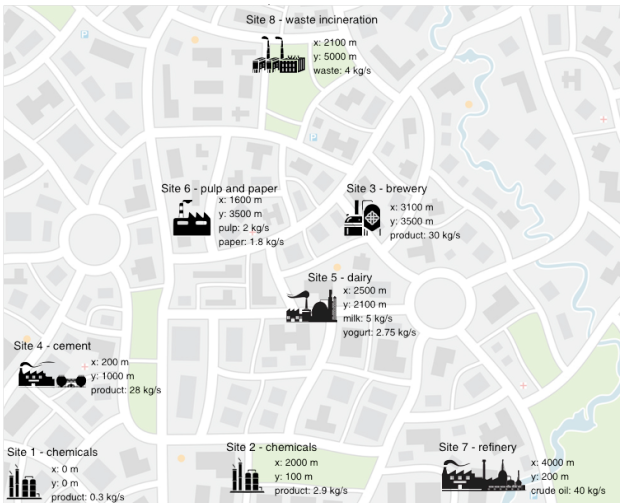
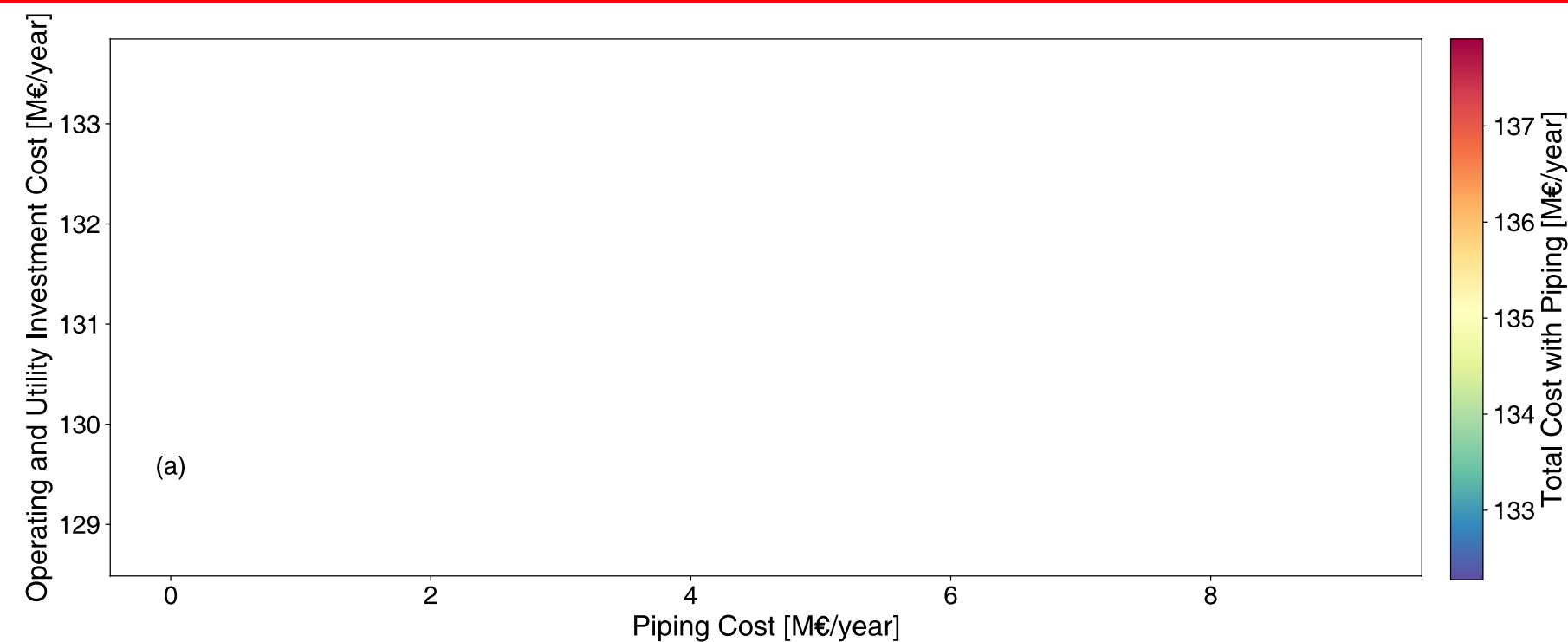


Figure 3.1 - Layout of the case study: an industrial cluster.

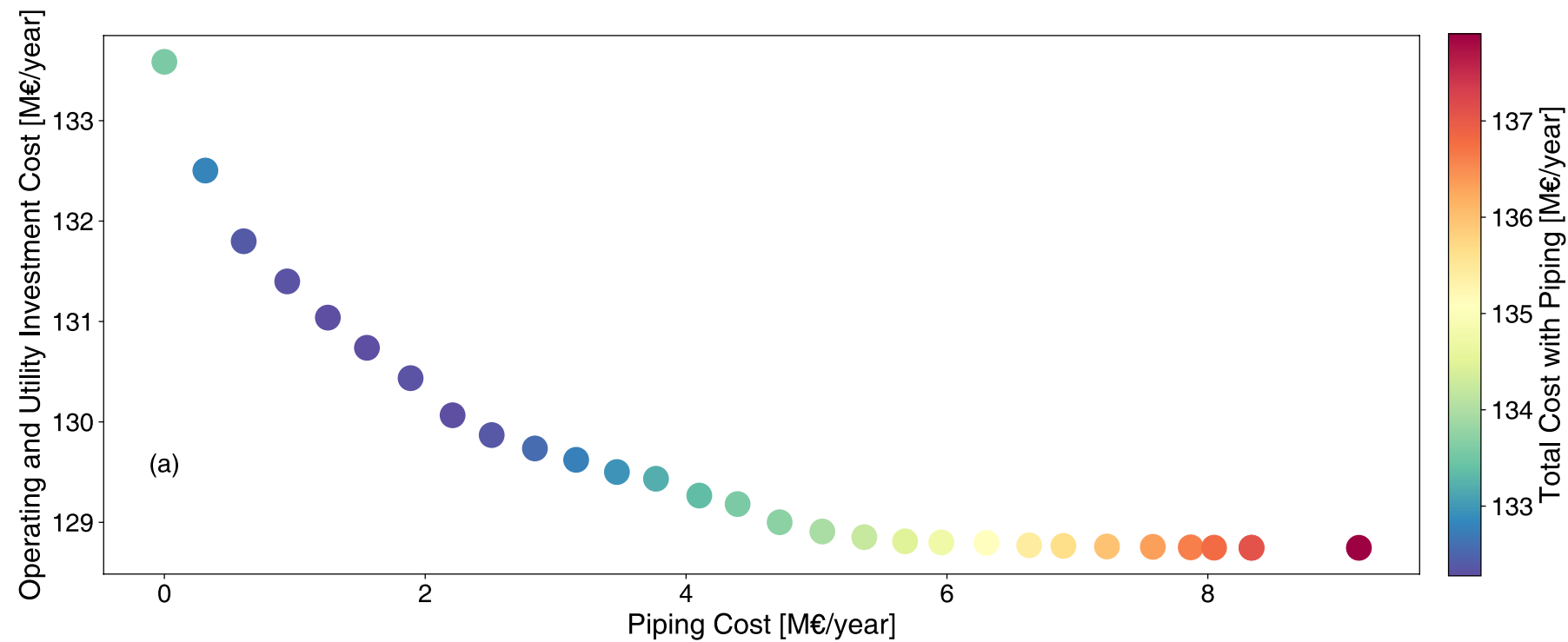
Interactions within the industrial cluster



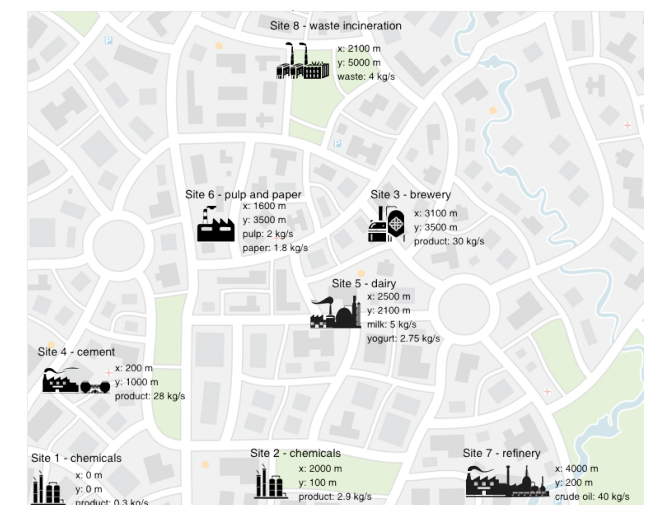
*cost data
natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water:
0.07 €/m³, electricity selling 60% of purchase

Figure 3.2 - Parametric optimisation results for an industrial complex (a) pareto frontier; (b) investment cost breakdown and heat sharing.

Interactions within the industrial cluster



- ❖ 30 optimal solutions with different piping expenditure

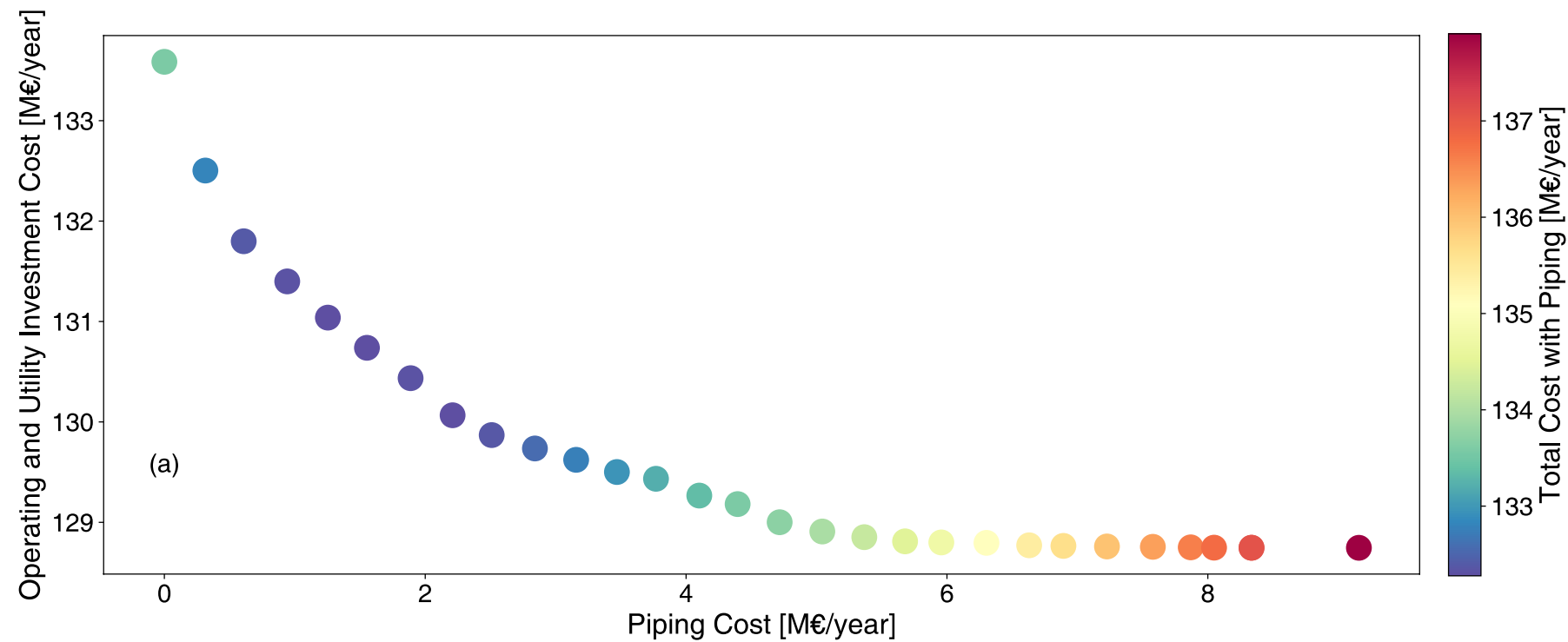


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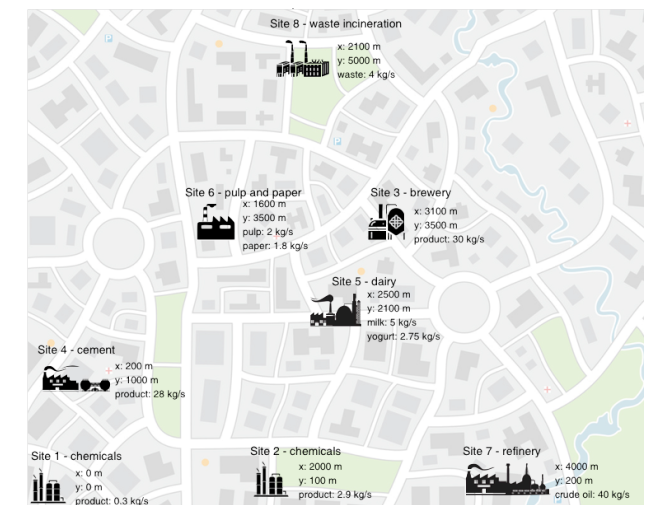
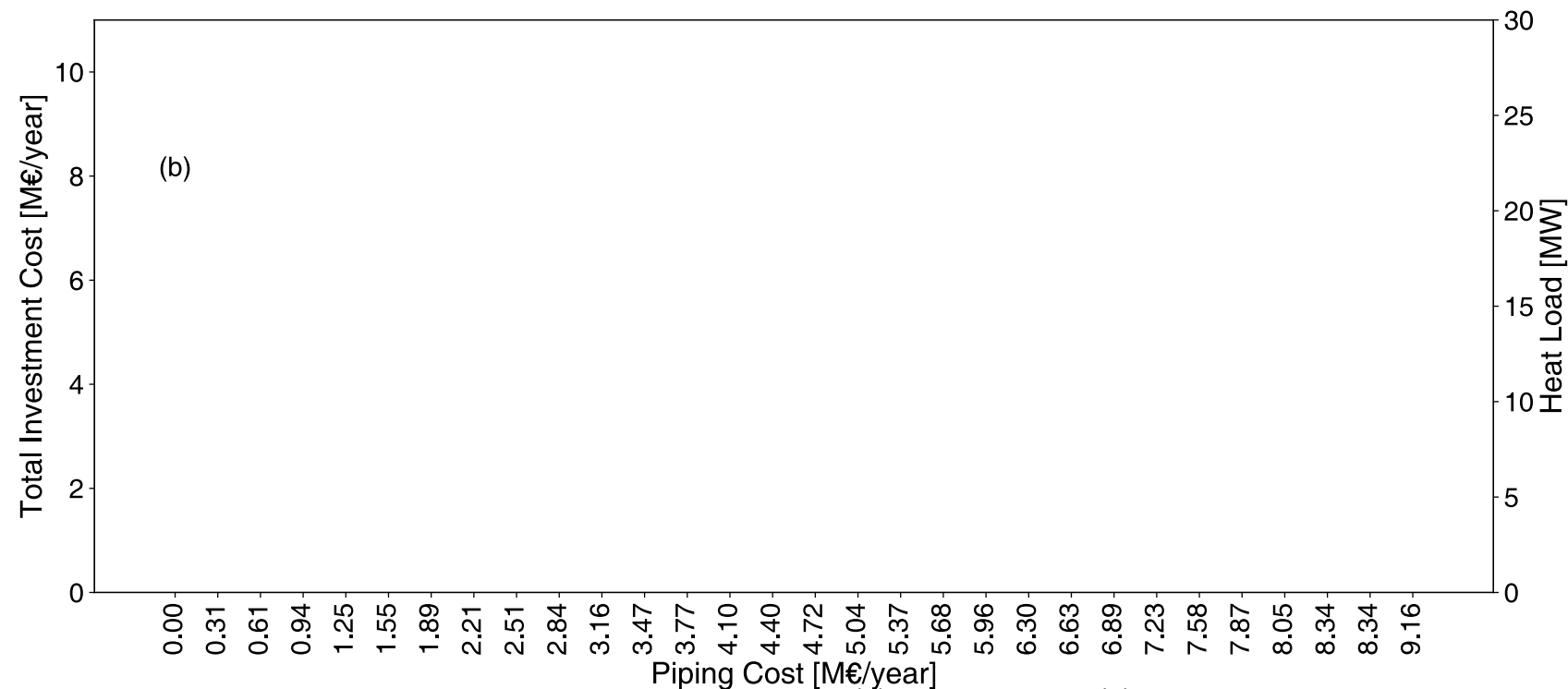
natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³, electricity selling 60% of purchase

Figure 3.2 - Parametric optimisation results for an industrial complex (a) pareto frontier; (b) investment cost breakdown and heat sharing.

Interactions within the industrial cluster



❖ 30 optimal solutions with different piping expenditure

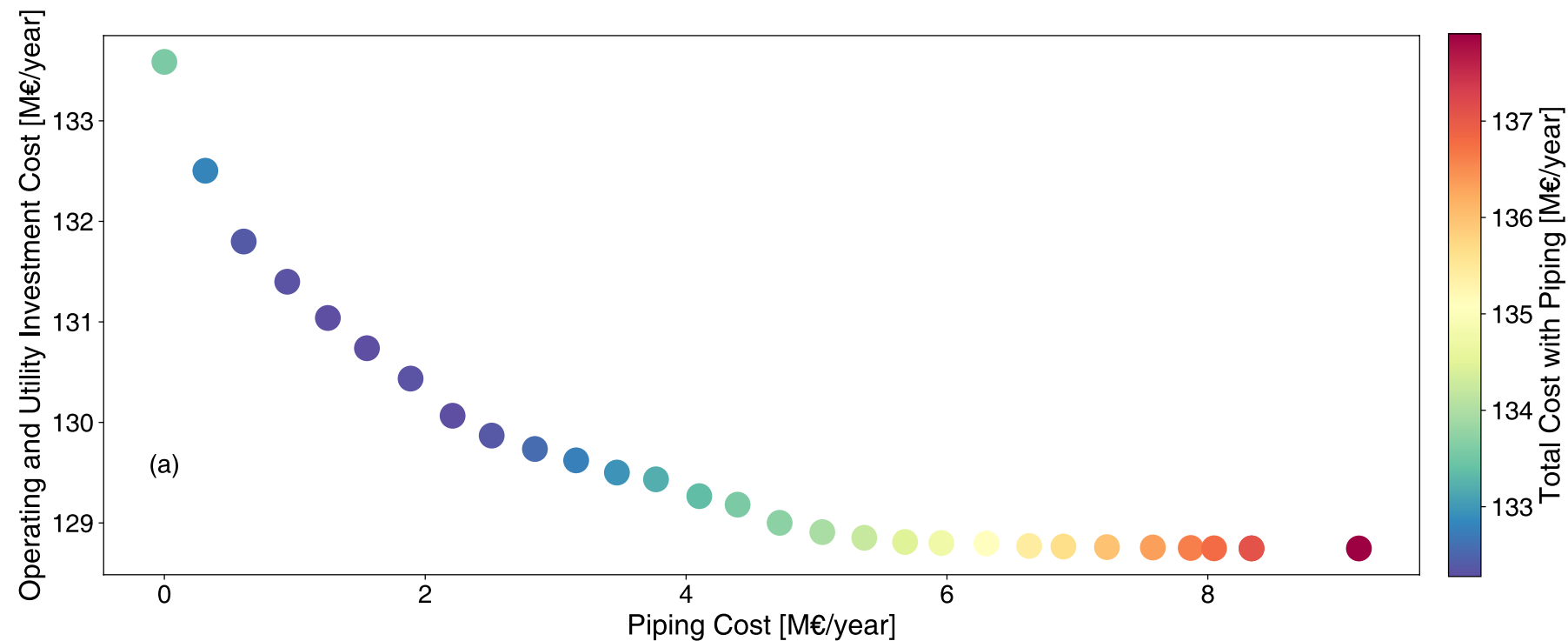


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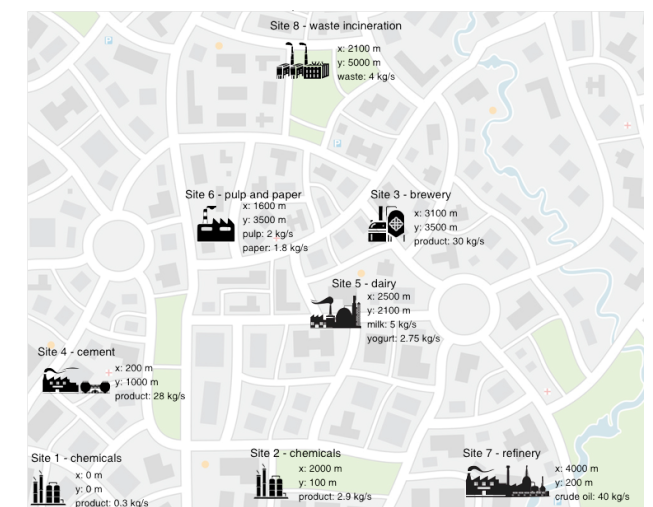
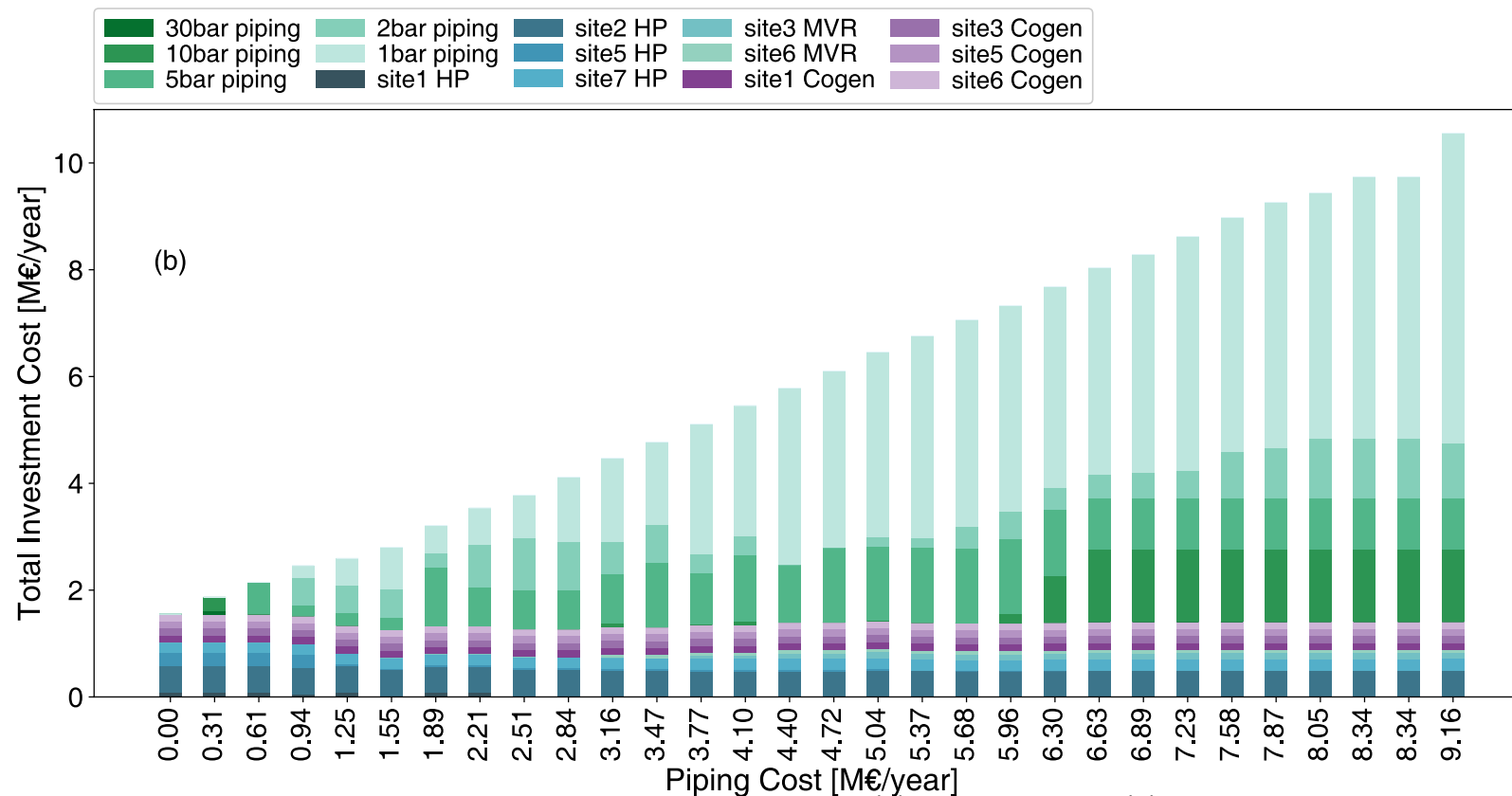
natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³, electricity selling 60% of purchase

Figure 3.2 - Parametric optimisation results for an industrial complex (a) pareto frontier; (b) investment cost breakdown and heat sharing.

Interactions within the industrial cluster



- ❖ 30 optimal solutions with different piping expenditure
- ❖ different configurations for investment
- ♦ piping cost dominates the investments

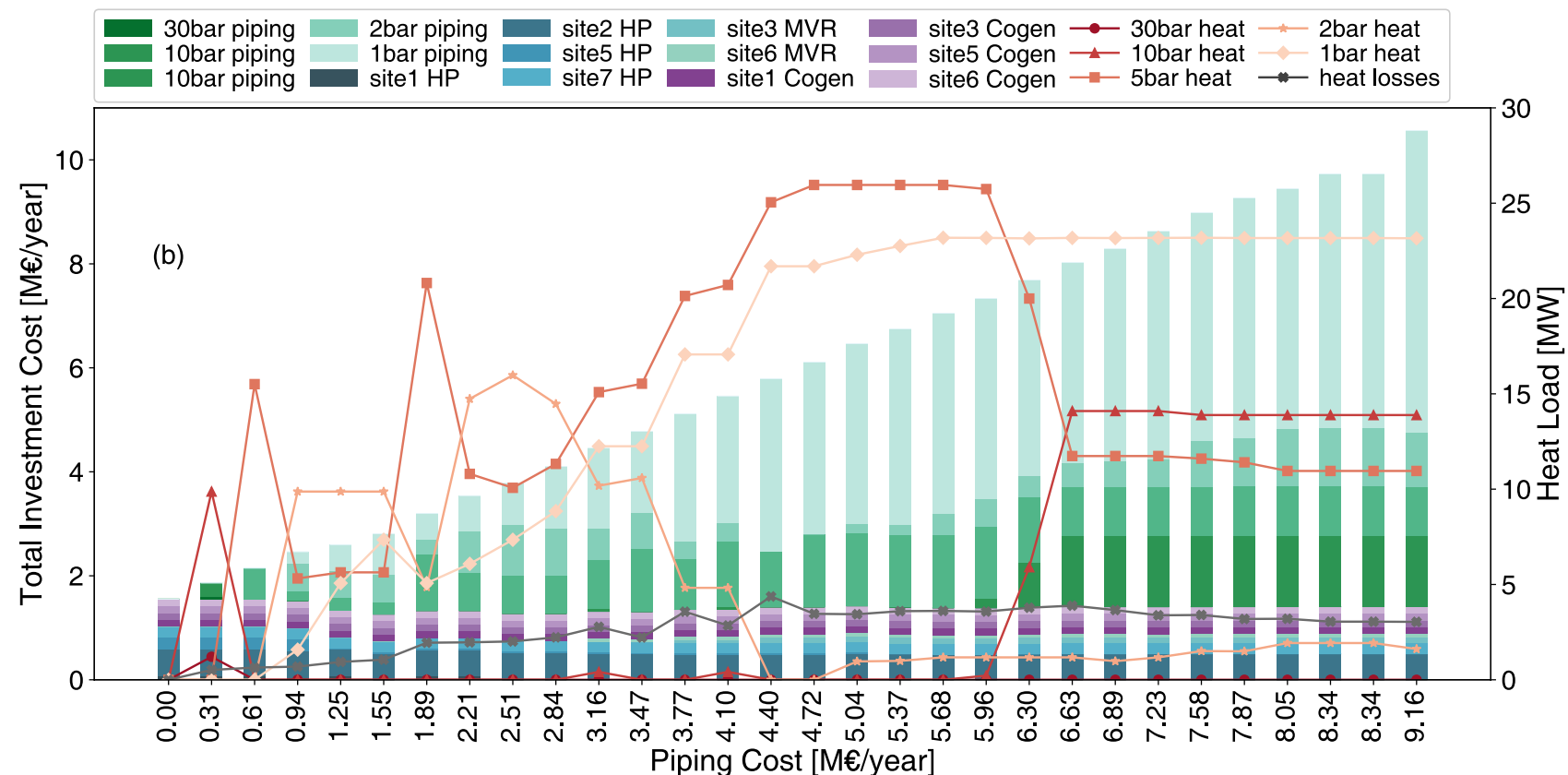
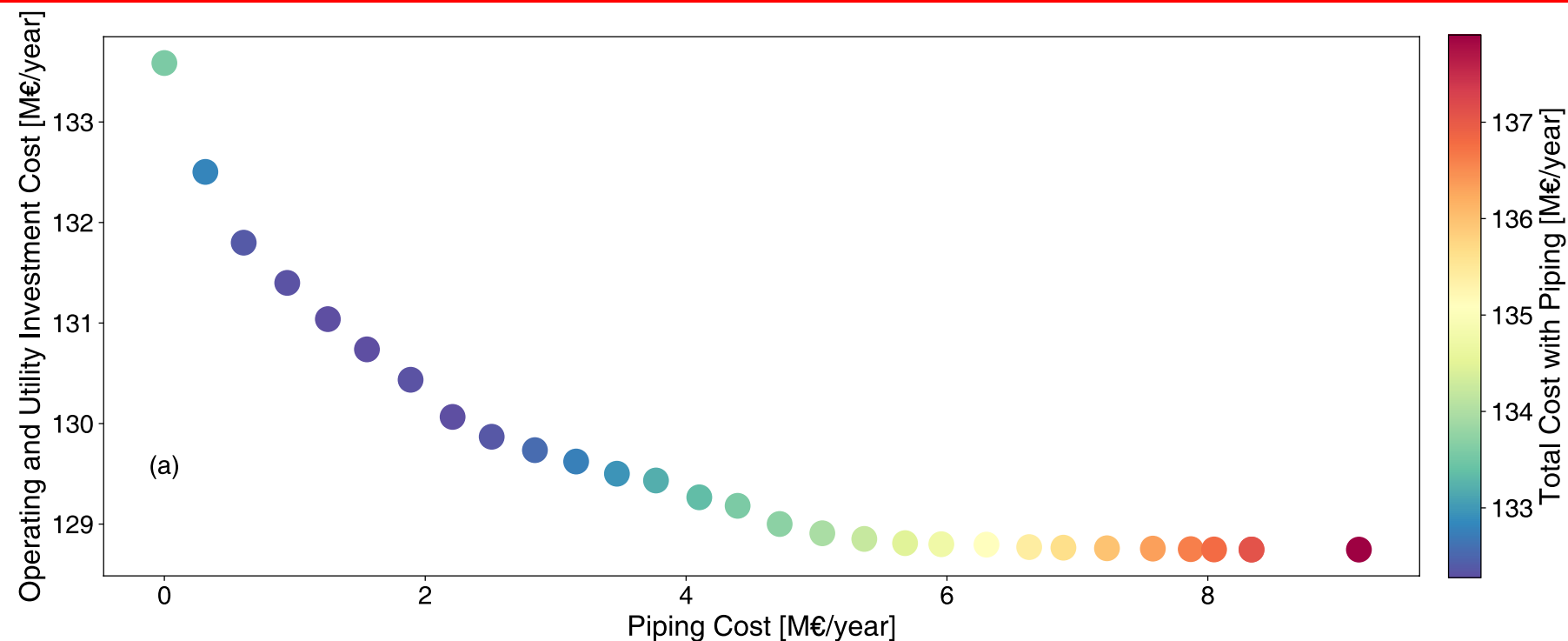


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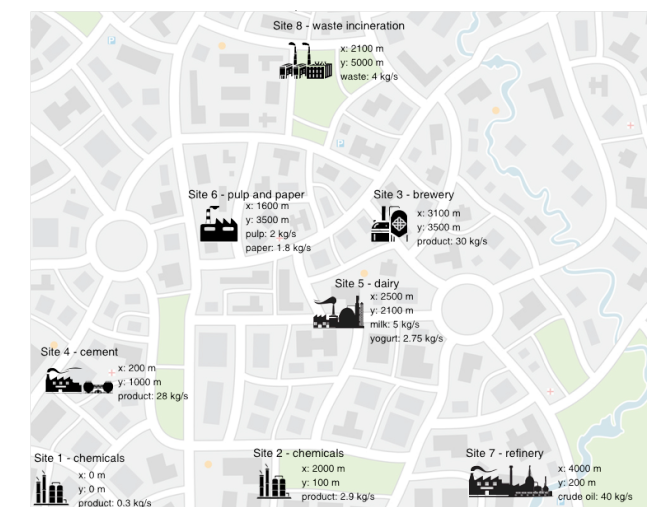
natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³, electricity selling 60% of purchase

Figure 3.2 - Parametric optimisation results for an industrial complex (a) pareto frontier; (b) investment cost breakdown and heat sharing.

Interactions within the industrial cluster



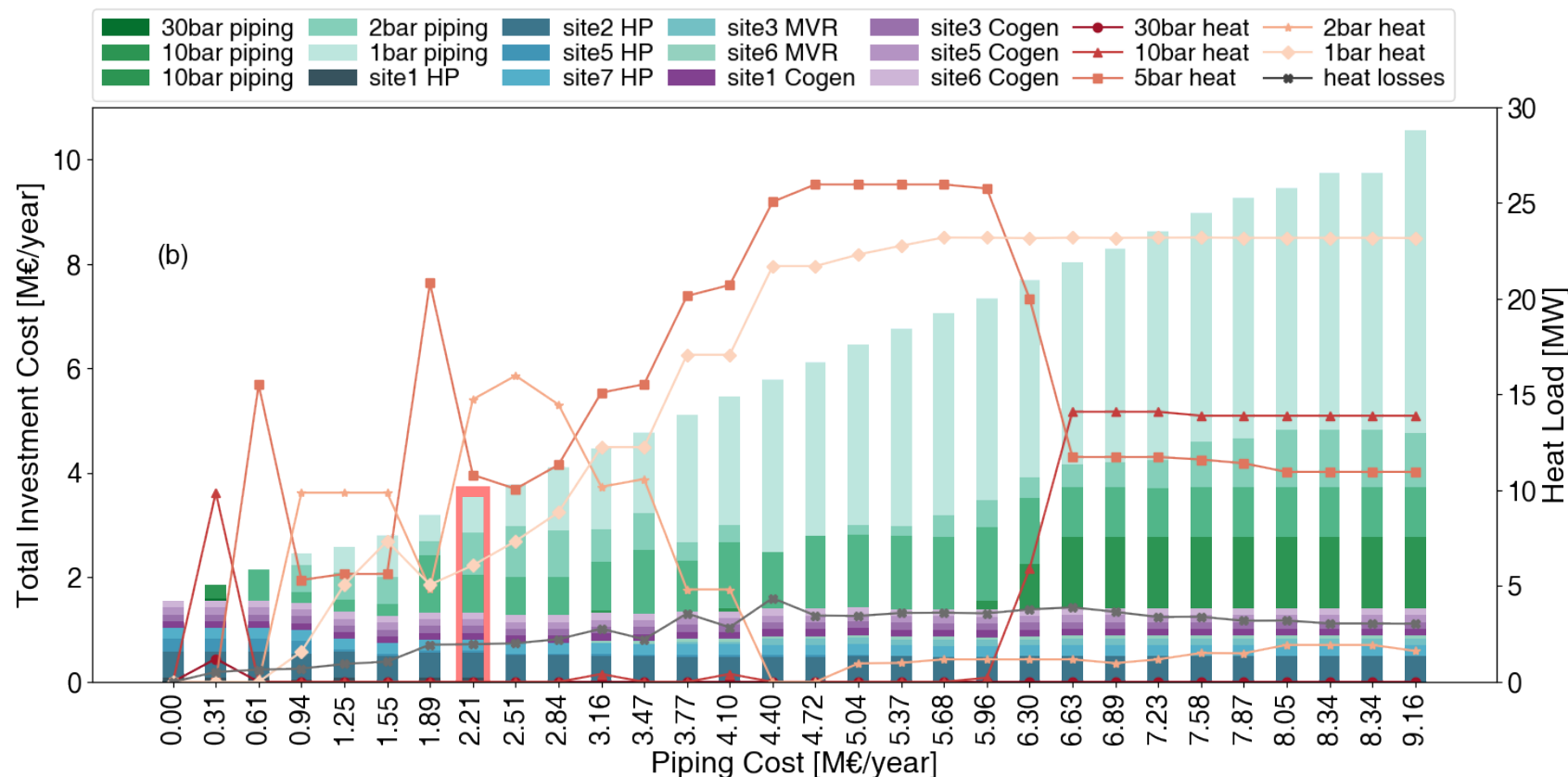
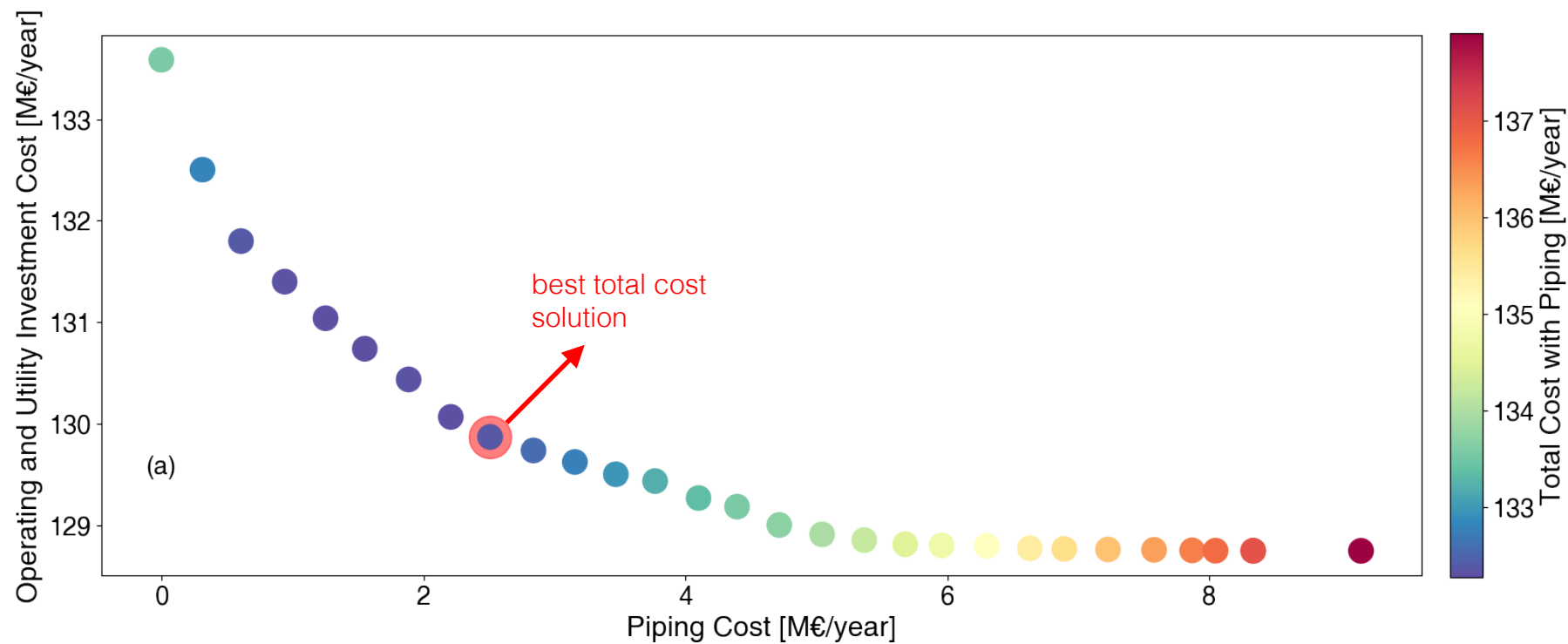
- ❖ 30 optimal solutions with different piping expenditure
- ❖ different configurations for investment
- ❖ piping cost dominates the investments
- ❖ steam sharing at multiple pressure levels



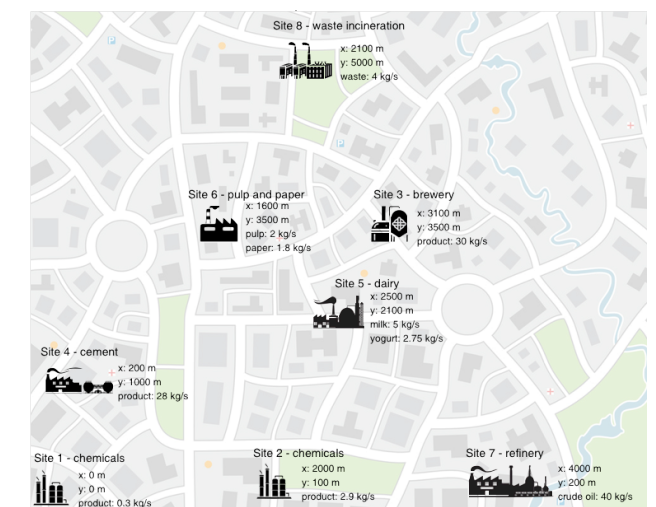
*cost data
natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³, electricity selling 60% of purchase

Figure 3.2 - Parametric optimisation results for an industrial complex (a) pareto frontier; (b) investment cost breakdown and heat sharing.

Interactions within the industrial cluster



- ❖ 30 optimal solutions with different piping expenditure
- ❖ different configurations for investment
- ❖ piping cost dominates the investments
- ❖ steam sharing at multiple pressure levels

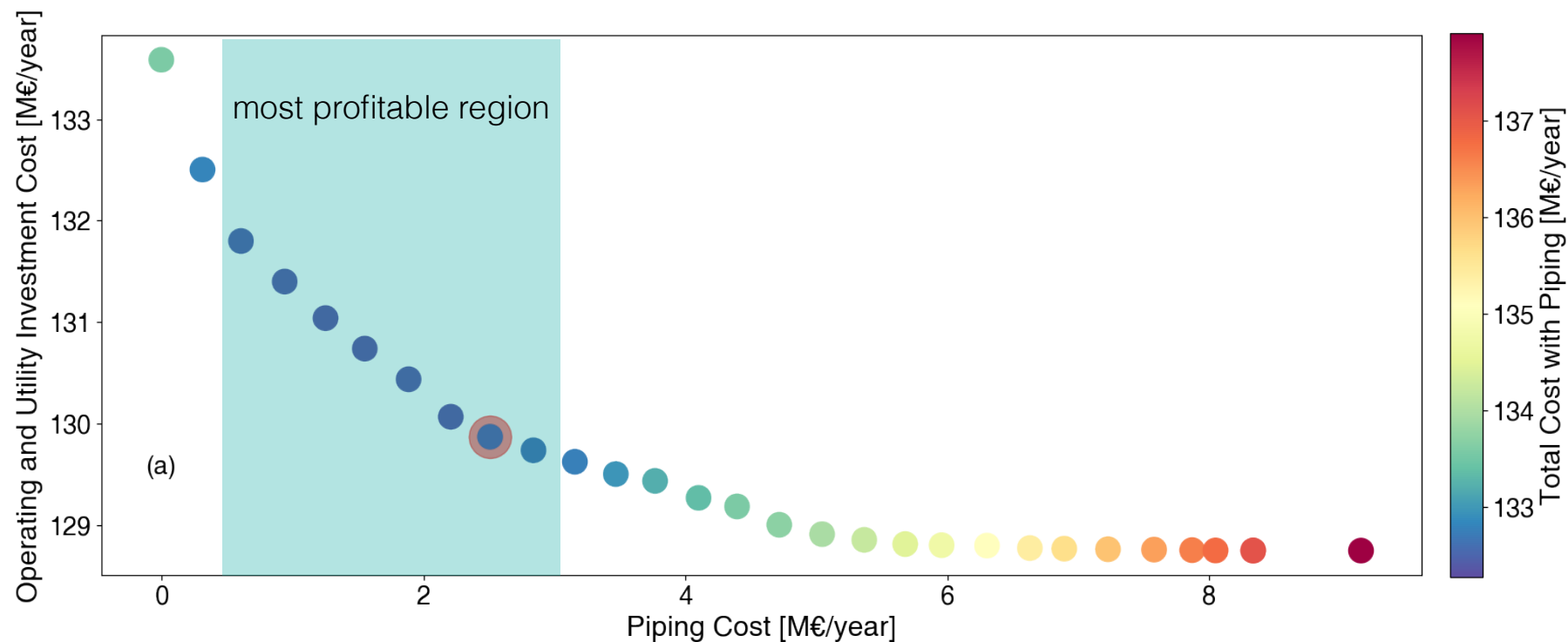


*cost data

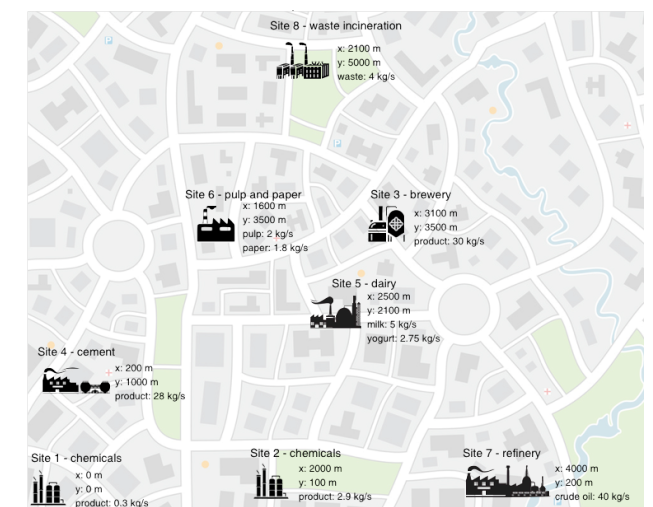
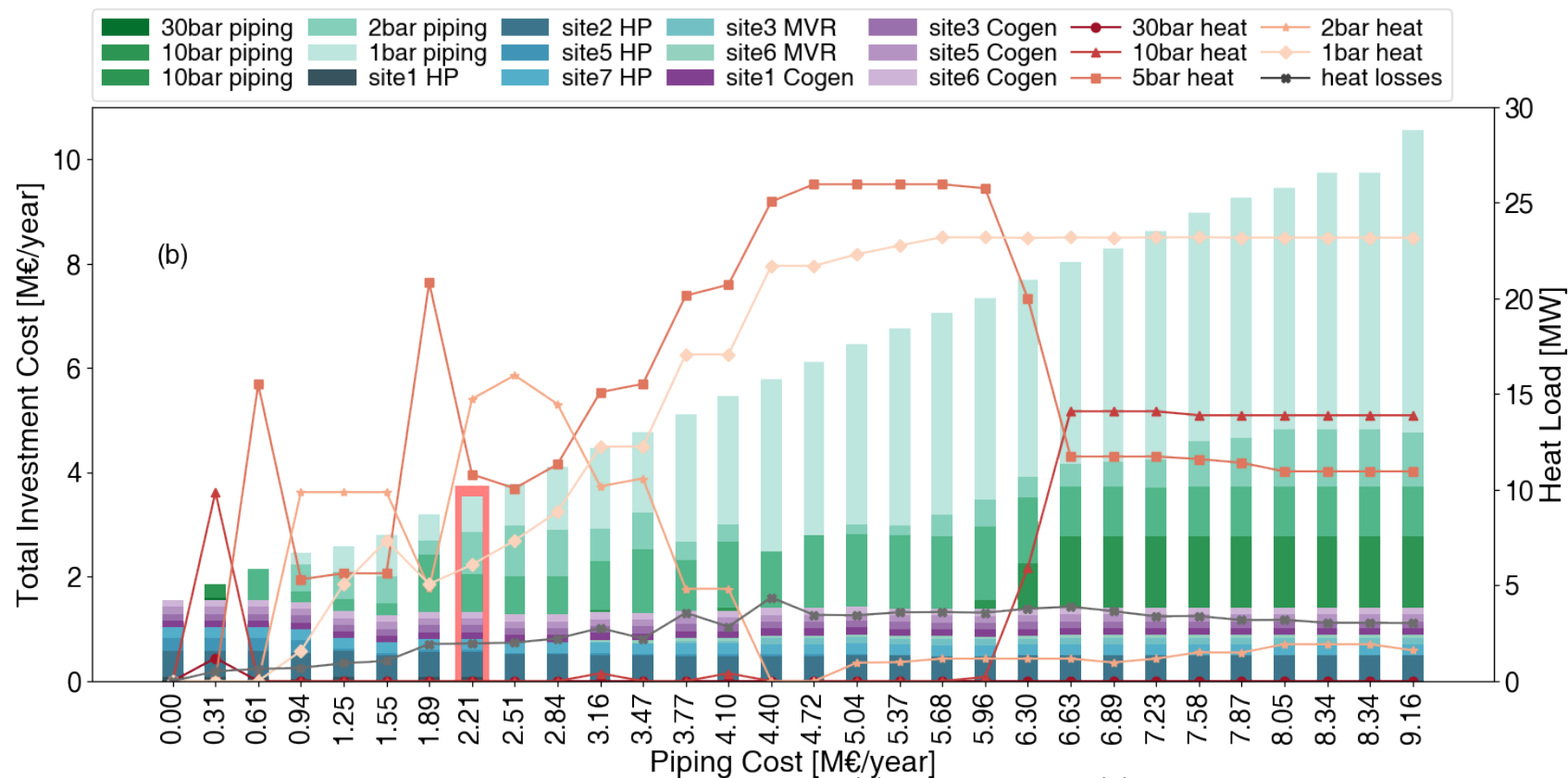
natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³, electricity selling 60% of purchase

Figure 3.2 - Parametric optimisation results for an industrial complex (a) pareto frontier; (b) investment cost breakdown and heat sharing.

Interactions within the industrial cluster



- ❖ 30 optimal solutions with different piping expenditure
- ❖ different configurations for investment
- ❖ piping cost dominates the investments
- ❖ steam sharing at multiple pressure levels

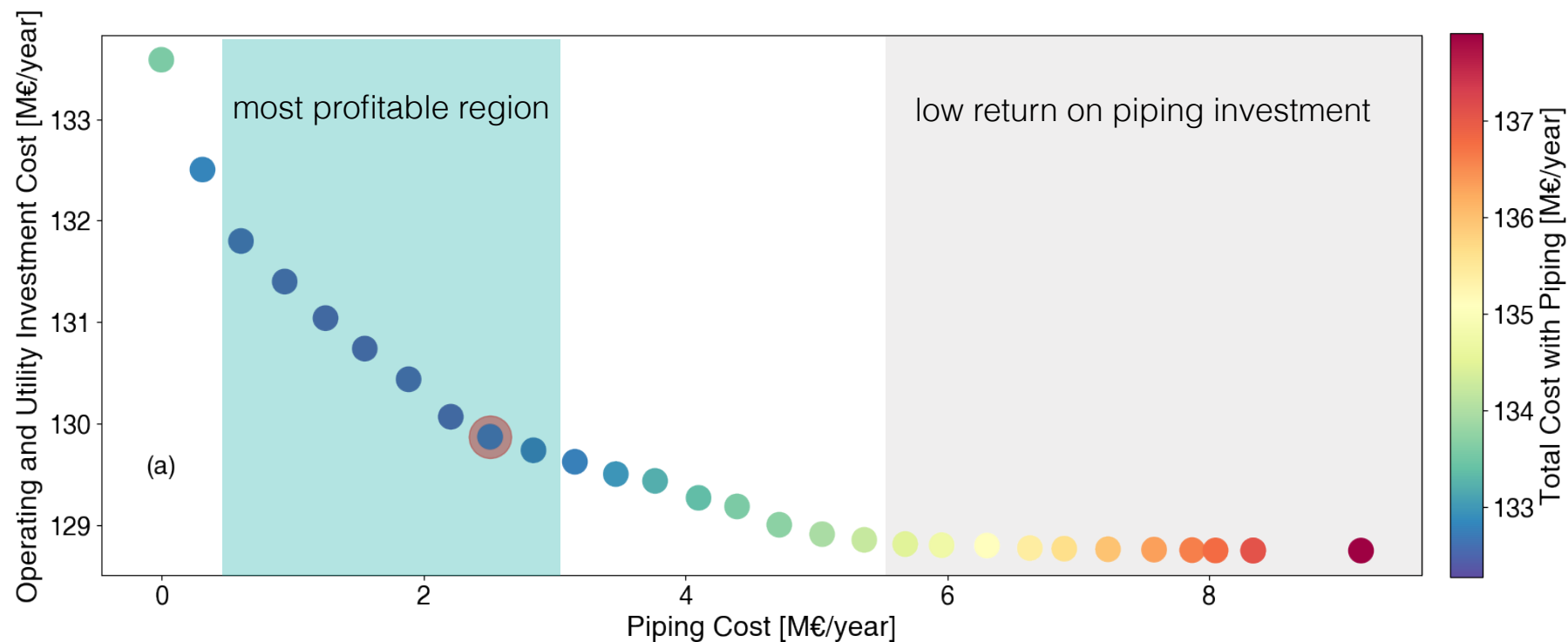


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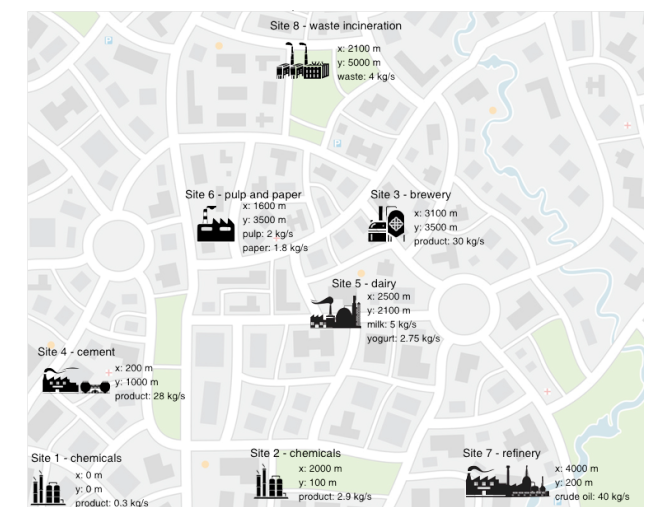
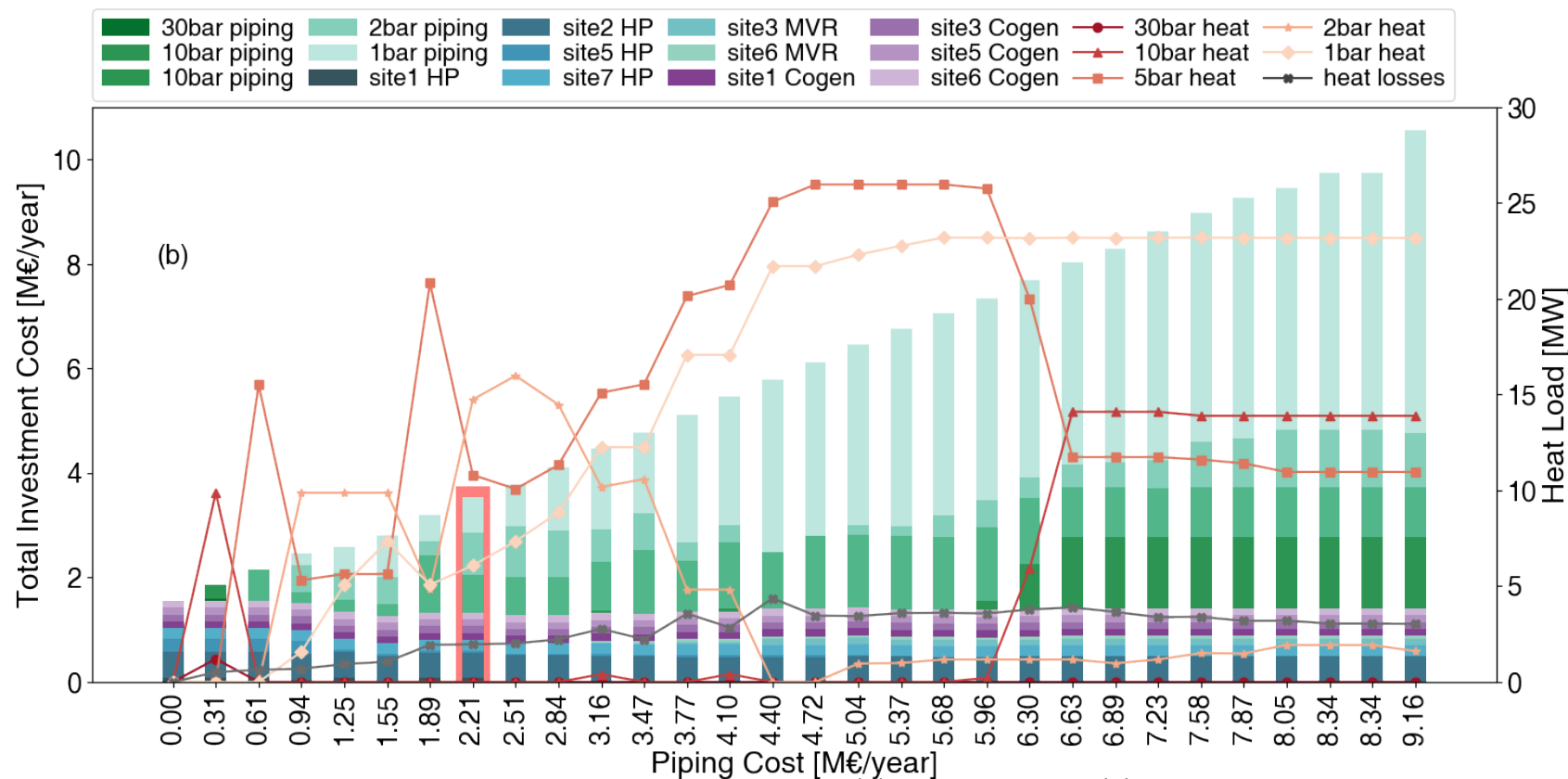
natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³, electricity selling 60% of purchase

Figure 3.2 - Parametric optimisation results for an industrial complex (a) pareto frontier; (b) investment cost breakdown and heat sharing.

Interactions within the industrial cluster



- ❖ 30 optimal solutions with different piping expenditure
- ❖ different configurations for investment
- ❖ piping cost dominates the investments
- ❖ steam sharing at multiple pressure levels



*cost data

natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³, electricity selling 60% of purchase

Figure 3.2 - Parametric optimisation results for an industrial complex (a) pareto frontier; (b) investment cost breakdown and heat sharing.

Involvement of a third party for investment

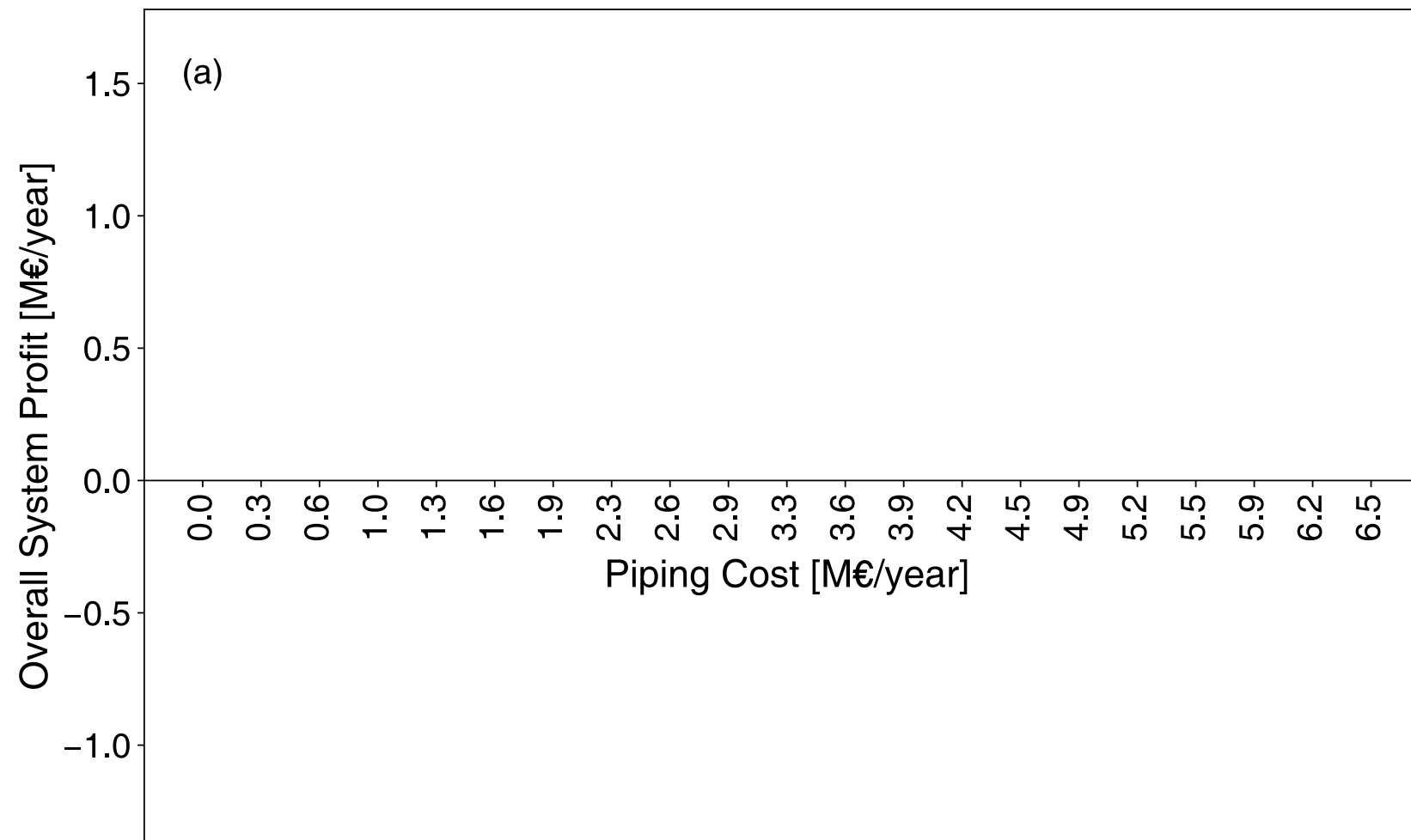


Figure 3.4 - Overall profitability (a) and steam price (b) considering the premium charged by a third party.

*cost data

natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³, electricity selling 60% of purchase

Involvement of a third party for investment

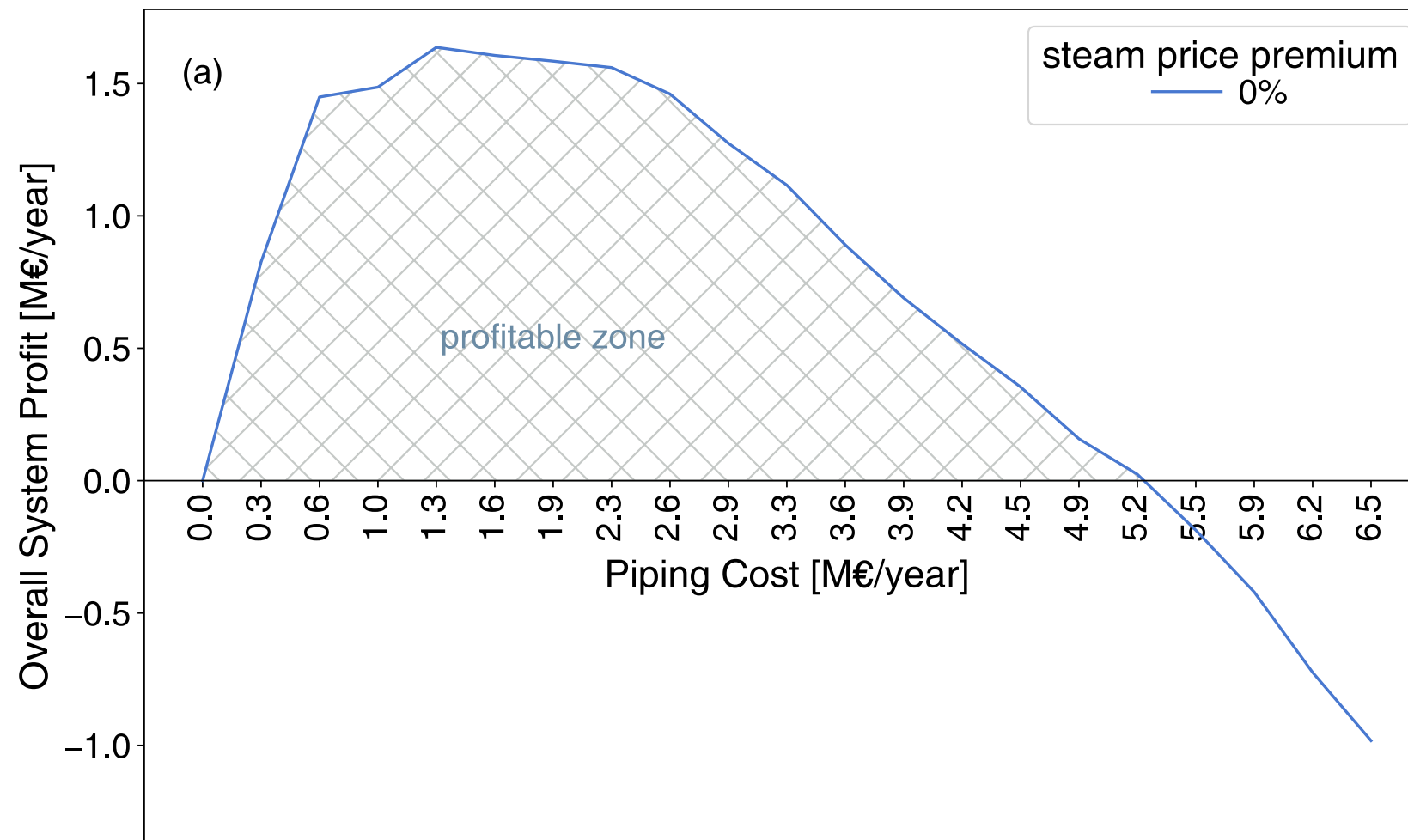


Figure 3.4 - Overall profitability (a) and steam price (b) considering the premium charged by a third party.

❖ 0% steam price premium: non-profit organisations, shared investment by the industrial cluster

*cost data

natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³, electricity selling 60% of purchase

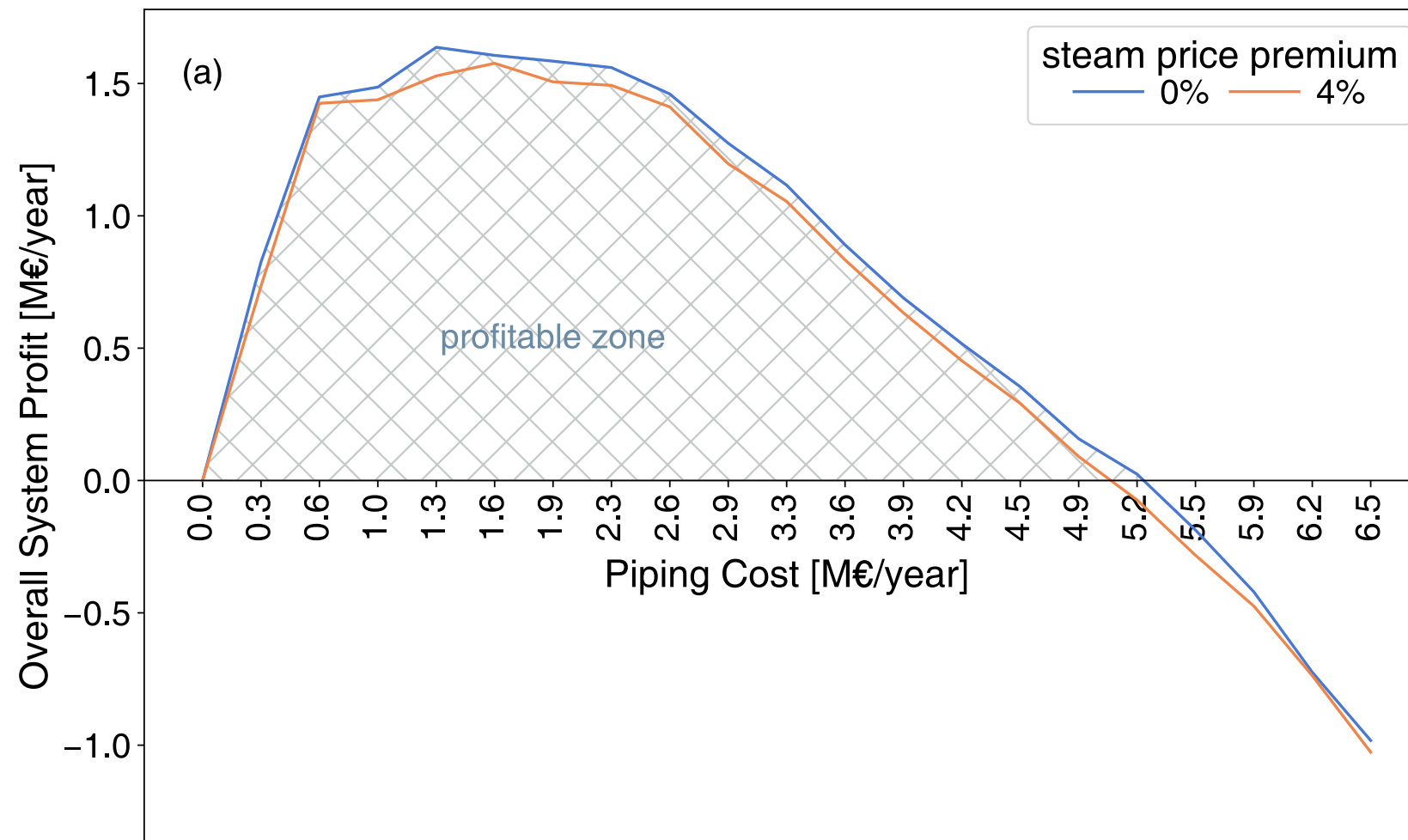


Figure 3.4 - Overall profitability (a) and steam price (b) considering the premium charged by a third party.

- ❖ 0% steam price premium: non-profit organisations, shared investment by the industrial cluster
- ❖ involvement of a utility company: profiting from installing pipes

Involvement of a third party for investment

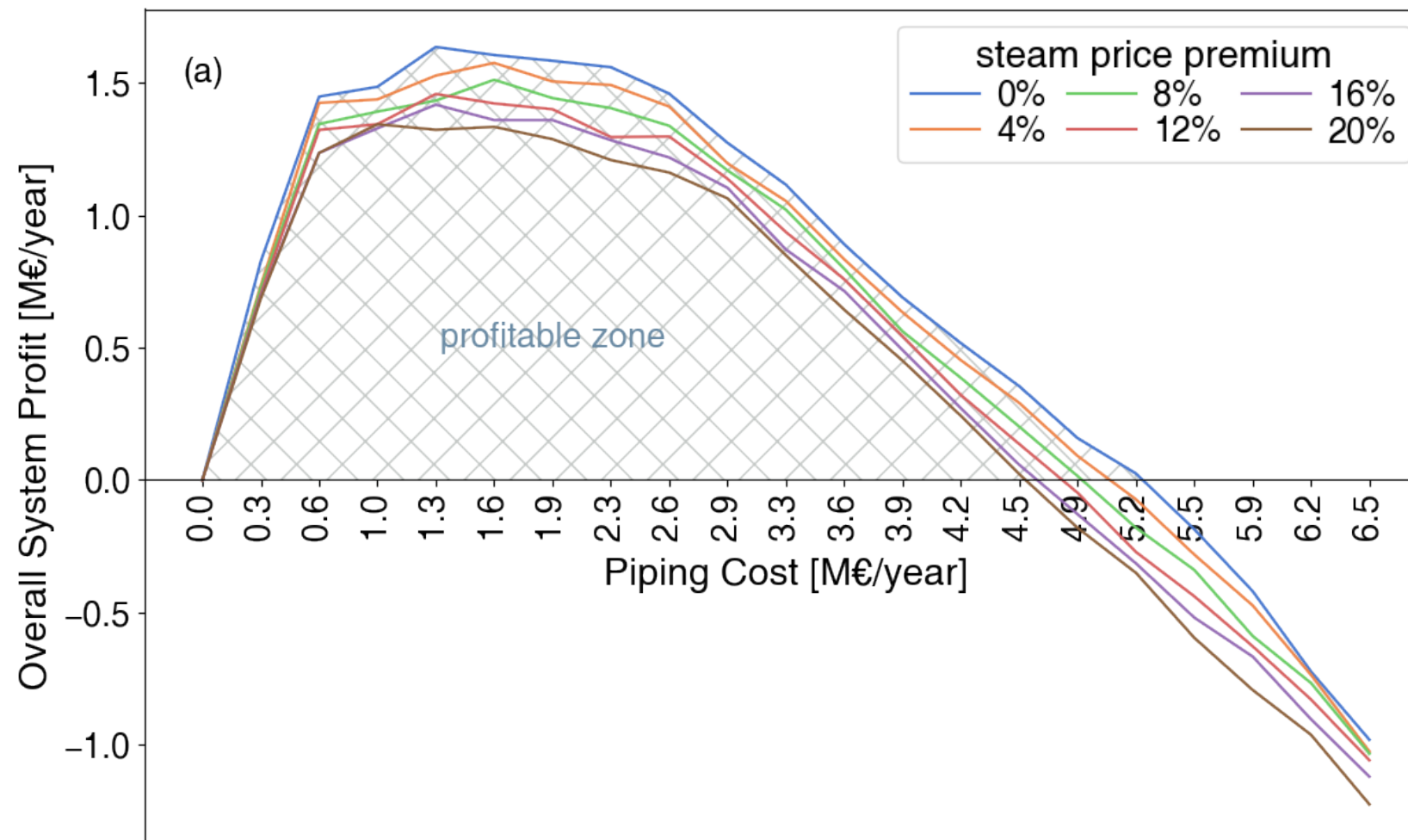


Figure 3.4 - Overall profitability (a) and steam price (b) considering the premium charged by a third party.

- ❖ 0% steam price premium: non-profit organisations, shared investment by the industrial cluster
- ❖ involvement of a utility company: profiting from installing pipes
- ❖ increasing third party profit → lower overall system profit

*cost data

natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³, electricity selling 60% of purchase

Involvement of a third party for investment

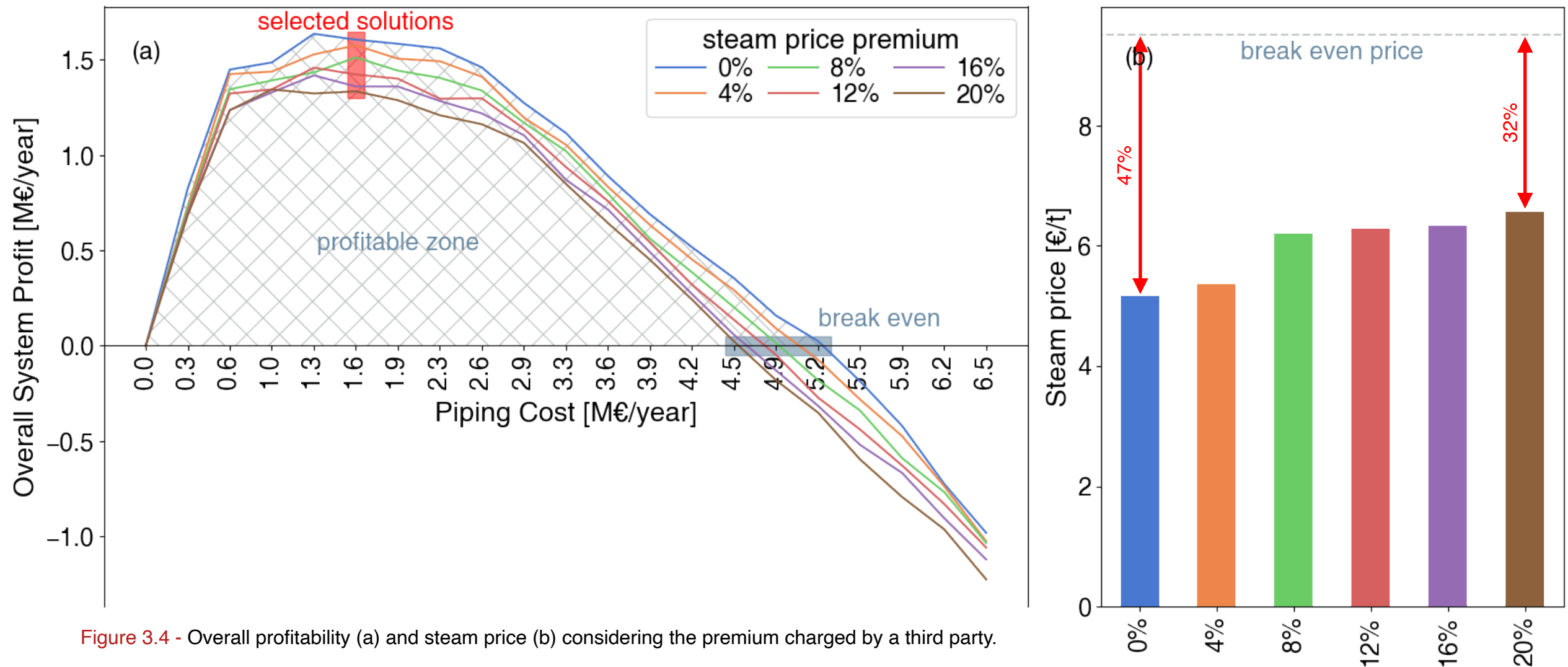
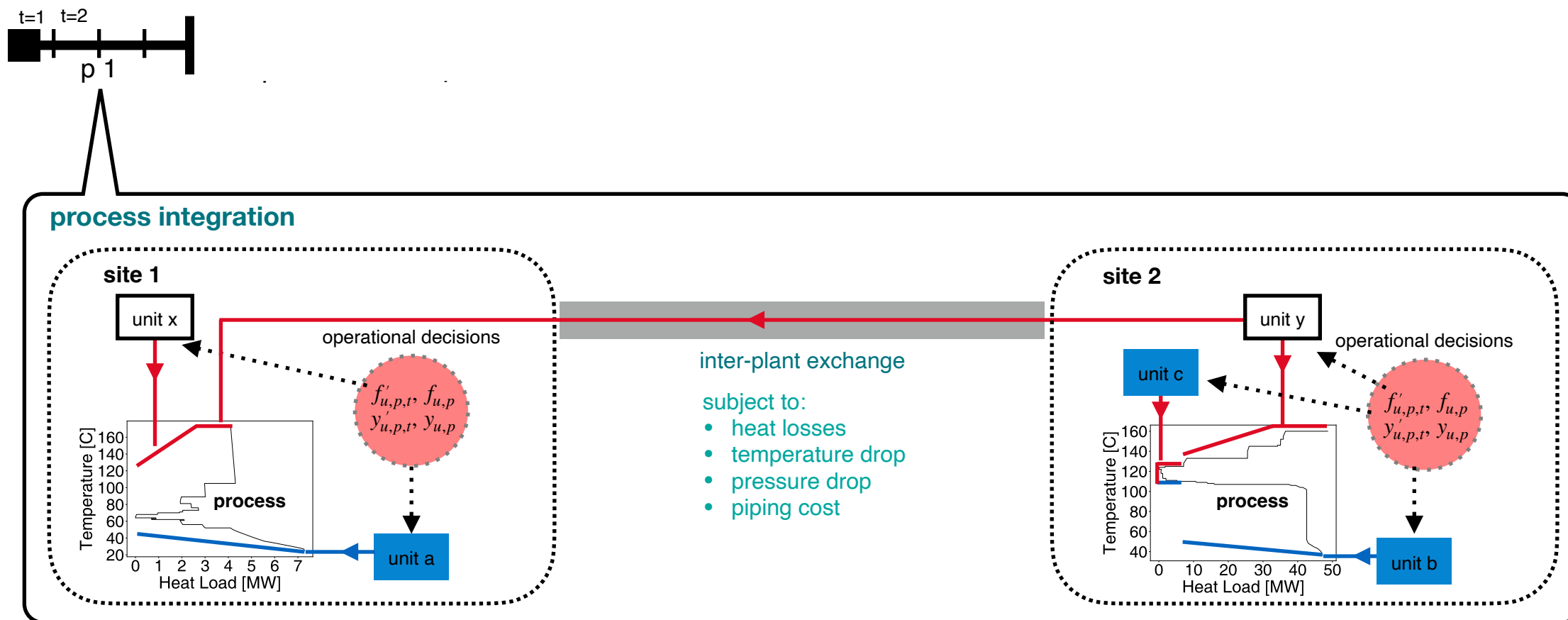


Figure 3.4 - Overall profitability (a) and steam price (b) considering the premium charged by a third party.

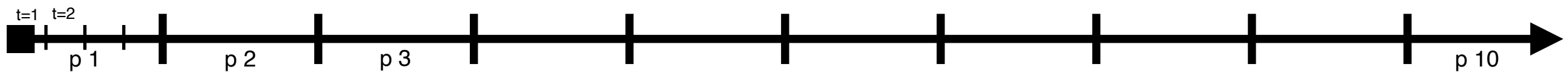
- ❖ 0% steam price premium: non-profit organisations, shared investment by the industrial cluster
- ❖ involvement of a utility company: profiting from installing pipes
- ❖ increasing third party profit → lower overall system profit
- ❖ third party profit up to 20%
- ❖ 32 - 47% lower steam prices for the industries considering the third party profit

*cost data
natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³, electricity selling 60% of purchase

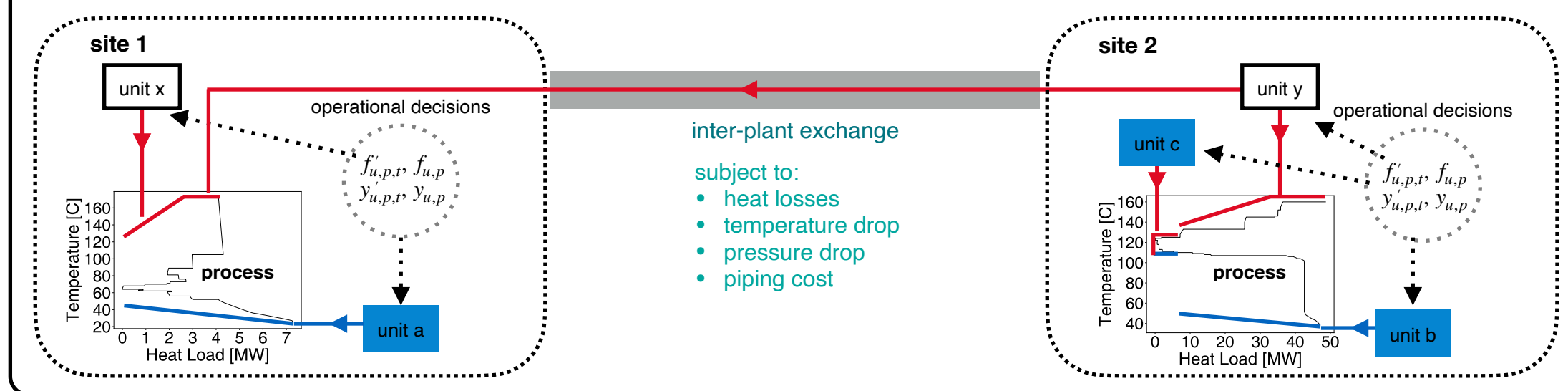


legend:

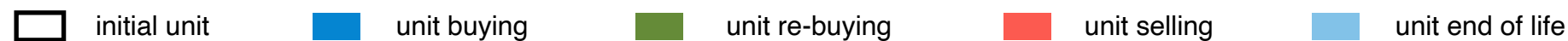
initial unit
 unit buying
 unit re-buying
 unit selling
 unit end of life



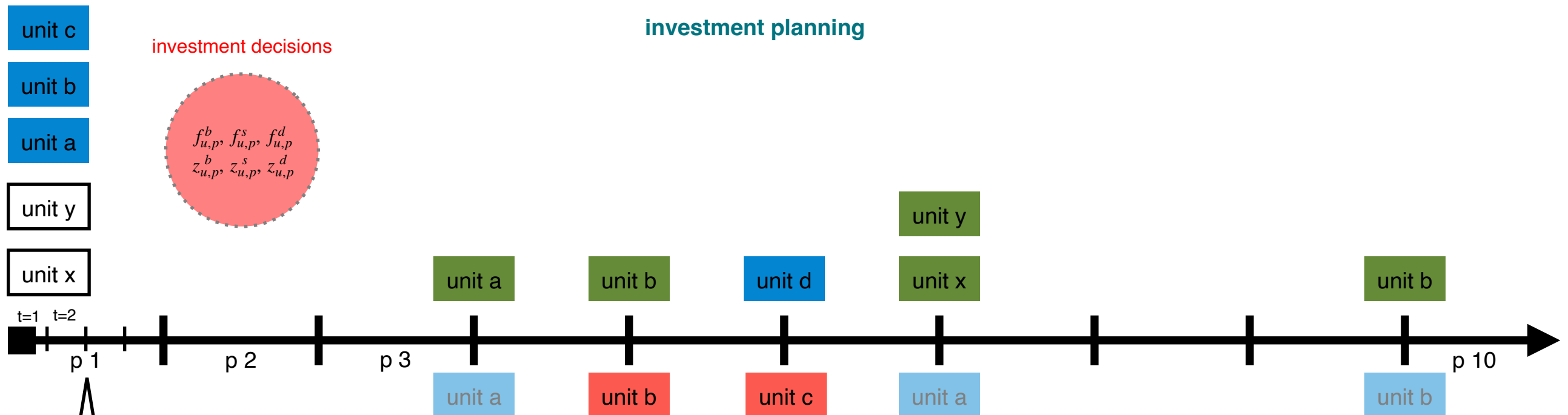
process integration



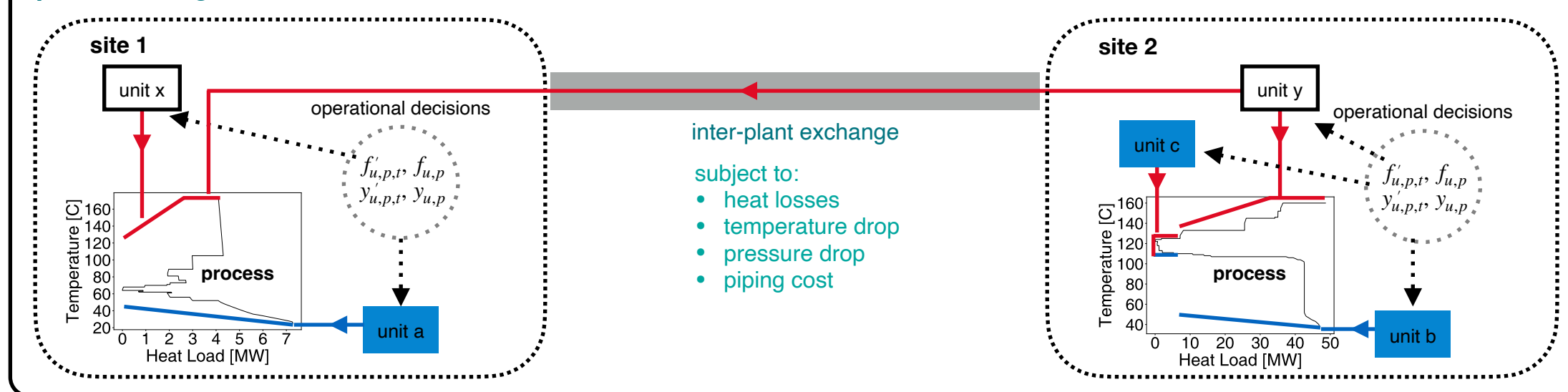
legend:



Long term investment planning



process integration



legend:

 initial unit
  unit buying
  unit re-buying
  unit selling
  unit end of life

$$\max \sum_{p \in \mathbf{P}} \left[\frac{C_p^{cf}}{(1+i)^p} \right]$$

$$z_{u,p}^e = \sum_{pp \in \{1..p\}} (z_{u,pp}^b - z_{u,pp}^s - z_{u,pp}^d) \quad \forall u \in \mathbf{NU}, p \in \mathbf{P}$$

$$z_{u,p}^e = 1 + \sum_{pp \in \{1..p\}} (z_{u,pp}^b - z_{u,pp}^s - z_{u,pp}^d) \quad \forall u \in \mathbf{BU}, p \in \mathbf{P}$$

$$z_{u,p}^d + z_{u,p}^s = 0 \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p = 1$$

$$z_{u,p}^d + z_{u,p}^s \leq z_{u,p-1}^e \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1$$

$$z_{u,p}^d + z_{u,p}^s \leq 1 \quad \forall u \in \mathbf{BU}, p \in \mathbf{P} : p = 1$$

$$z_{u,p}^b \cdot F_u^{min} \leq f_{u,p}^b \leq z_{u,p}^b \cdot F_u^{max} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$f_{u,p}^e = F_u^{init} + f_{u,p}^b - (f_{u,p}^s + f_{u,p}^d) \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p = 1$$

$$f_{u,p}^e = f_{u,p-1}^e + f_{u,p}^b - (f_{u,p}^s + f_{u,p}^d) \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1$$

$$y_{u,p} \leq z_{u,p}^e \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$f_{u,p} \leq f_{u,p}^e \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$z_{u,p}^e \leq l_{u,p} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$l_{u,p} \leq z_{u,p}^e \cdot \text{LI}_u^{lt} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$l_{u,p} = \left(z_{u,p}^b \cdot \text{LI}_u^{lt} \right) + \left(\text{LI}_u^{lt} - \text{LI}_u^{init} \right) \cdot \left(1 - z_{u,p}^s - z_{u,p}^d \right) \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p = 1$$

$$l_{u,p} = l_{u,p-1} - z_{u,p-1}^e + \left(\text{LI}_u^{lt} \cdot z_{u,p}^b \right) - l_{u,p}^s \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1$$

$$l_{u,p-1} - l_{u,p}^s \leq \left(1 - z_{u,p}^b \right) \cdot \text{LI}_u^{lt} + 1 \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1$$

$$l_{u,p-1} \leq \left(1 - z_{u,p}^d \right) \cdot \text{LI}_u^{lt} + 1 \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1$$

$$\left(1 - z_{u,p-1}^e \right) \cdot \text{LI}_u^{lt} + \left(1 - z_{u,p-1}^s \right) \cdot \text{LI}_u^{lt} + l_{u,p-1} \leq 2 \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1$$

$$l_{u,p}^s \geq l_{u,p-1} - z_{u,p-1}^e - \left(1 - z_{u,p-1}^s \right) \cdot \text{LI}_u^{lt} \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p \neq 1$$

$$l_{u,p}^s \leq l_{u,p-1} - z_{u,p-1}^e \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p \neq 1$$

$$l_{u,p}^s \leq z_{u,p-1}^s \cdot \text{LI}_u^{lt} \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p \neq 1$$

$$\max \sum_{p \in \mathbf{P}} \left[\frac{C_p^{cf}}{(1+i)^p} \right] \quad \text{objective function: net present value}$$

$$z_{u,p}^e = \sum_{pp \in \{1..p\}} (z_{u,pp}^b - z_{u,pp}^s - z_{u,pp}^d) \quad \forall u \in \mathbf{NU}, p \in \mathbf{P}$$

$$z_{u,p}^e = 1 + \sum_{pp \in \{1..p\}} (z_{u,pp}^b - z_{u,pp}^s - z_{u,pp}^d) \quad \forall u \in \mathbf{BU}, p \in \mathbf{P}$$

$$z_{u,p}^d + z_{u,p}^s = 0 \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p = 1$$

$$z_{u,p}^d + z_{u,p}^s \leq z_{u,p-1}^e \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1$$

$$z_{u,p}^d + z_{u,p}^s \leq 1 \quad \forall u \in \mathbf{BU}, p \in \mathbf{P} : p = 1$$

$$z_{u,p}^b \cdot F_u^{\min} \leq f_{u,p}^b \leq z_{u,p}^b \cdot F_u^{\max} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$f_{u,p}^e = F_u^{\text{init}} + f_{u,p}^b - (f_{u,p}^s + f_{u,p}^d) \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p = 1$$

$$f_{u,p}^e = f_{u,p-1}^e + f_{u,p}^b - (f_{u,p}^s + f_{u,p}^d) \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1$$

$$y_{u,p} \leq z_{u,p}^e \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$f_{u,p} \leq f_{u,p}^e \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$z_{u,p}^e \leq l_{u,p} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$l_{u,p} \leq z_{u,p}^e \cdot \text{LI}_u^{lt} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$l_{u,p} = \left(z_{u,p}^b \cdot \text{LI}_u^{lt} \right) + \left(\text{LI}_u^{lt} - \text{LI}_u^{\text{init}} \right) \cdot \left(1 - z_{u,p}^s - z_{u,p}^d \right) \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p = 1$$

$$l_{u,p} = l_{u,p-1} - z_{u,p-1}^e + \left(\text{LI}_u^{lt} \cdot z_{u,p}^b \right) - l_{u,p}^s \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1$$

$$l_{u,p-1} - l_{u,p}^s \leq \left(1 - z_{u,p}^b \right) \cdot \text{LI}_u^{lt} + 1 \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1$$

$$l_{u,p-1} \leq \left(1 - z_{u,p}^d \right) \cdot \text{LI}_u^{lt} + 1 \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1$$

$$\left(1 - z_{u,p-1}^e \right) \cdot \text{LI}_u^{lt} + \left(1 - z_{u,p-1}^s \right) \cdot \text{LI}_u^{lt} + l_{u,p-1} \leq 2 \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1$$

$$l_{u,p}^s \geq l_{u,p-1} - z_{u,p-1}^e - \left(1 - z_{u,p-1}^s \right) \cdot \text{LI}_u^{lt} \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p \neq 1$$

$$l_{u,p}^s \leq l_{u,p-1} - z_{u,p-1}^e \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p \neq 1$$

$$l_{u,p}^s \leq z_{u,p-1}^s \cdot \text{LI}_u^{lt} \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p \neq 1$$

❖ net present value: cumulative cash flow discounted with interest rate

$$\max \sum_{p \in \mathbf{P}} \left[\frac{C_p^{cf}}{(1+i)^p} \right] \quad \text{objective function: net present value}$$

$$\begin{aligned} z_{u,p}^e &= \sum_{pp \in \{1..p\}} (z_{u,pp}^b - z_{u,pp}^s - z_{u,pp}^d) \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} \\ z_{u,p}^e &= 1 + \sum_{pp \in \{1..p\}} (z_{u,pp}^b - z_{u,pp}^s - z_{u,pp}^d) \quad \forall u \in \mathbf{BU}, p \in \mathbf{P} \\ z_{u,p}^d + z_{u,p}^s &= 0 \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p = 1 \\ z_{u,p}^d + z_{u,p}^s &\leq z_{u,p-1}^e \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1 \\ z_{u,p}^d + z_{u,p}^s &\leq 1 \quad \forall u \in \mathbf{BU}, p \in \mathbf{P} : p = 1 \end{aligned}$$

unit existence constraints

$$\begin{aligned} z_{u,p}^b \cdot F_u^{\min} &\leq f_{u,p}^b \leq z_{u,p}^b \cdot F_u^{\max} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} \\ f_{u,p}^e &= F_u^{\text{init}} + f_{u,p}^b - (f_{u,p}^s + f_{u,p}^d) \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p = 1 \\ f_{u,p}^e &= f_{u,p-1}^e + f_{u,p}^b - (f_{u,p}^s + f_{u,p}^d) \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1 \end{aligned}$$

sizing constraints

$$\begin{aligned} y_{u,p} &\leq z_{u,p}^e \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} \\ f_{u,p} &\leq f_{u,p}^e \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} \end{aligned}$$

connection to PI

$$z_{u,p}^e \leq l_{u,p} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$l_{u,p} \leq z_{u,p}^e \cdot \text{LI}_u^{lt} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$l_{u,p} = \left(z_{u,p}^b \cdot \text{LI}_u^{lt} \right) + \left(\text{LI}_u^{lt} - \text{LI}_u^{\text{init}} \right) \cdot \left(1 - z_{u,p}^s - z_{u,p}^d \right) \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p = 1$$

$$l_{u,p} = l_{u,p-1} - z_{u,p-1}^e + \left(\text{LI}_u^{lt} \cdot z_{u,p}^b \right) - l_{u,p}^s \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1$$

$$l_{u,p-1} - l_{u,p}^s \leq \left(1 - z_{u,p}^b \right) \cdot \text{LI}_u^{lt} + 1 \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1$$

$$l_{u,p-1} \leq \left(1 - z_{u,p}^d \right) \cdot \text{LI}_u^{lt} + 1 \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1$$

$$\left(1 - z_{u,p-1}^e \right) \cdot \text{LI}_u^{lt} + \left(1 - z_{u,p-1}^s \right) \cdot \text{LI}_u^{lt} + l_{u,p-1} \leq 2 \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1$$

$$l_{u,p}^s \geq l_{u,p-1} - z_{u,p-1}^e - \left(1 - z_{u,p-1}^s \right) \cdot \text{LI}_u^{lt} \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p \neq 1$$

$$l_{u,p}^s \leq l_{u,p-1} - z_{u,p-1}^e \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p \neq 1$$

$$l_{u,p}^s \leq z_{u,p-1}^s \cdot \text{LI}_u^{lt} \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p \neq 1$$

- ❖ net present value: cumulative cash flow discounted with interest rate
- ❖ a units existence and size are dependent on the commissioning / decommissioning actions

$$\max \sum_{p \in \mathbf{P}} \left[\frac{C_p^{cf}}{(1+i)^p} \right] \quad \text{objective function: net present value}$$

$$\begin{aligned} z_{u,p}^e &= \sum_{pp \in \{1..p\}} (z_{u,pp}^b - z_{u,pp}^s - z_{u,pp}^d) \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} \\ z_{u,p}^e &= 1 + \sum_{pp \in \{1..p\}} (z_{u,pp}^b - z_{u,pp}^s - z_{u,pp}^d) \quad \forall u \in \mathbf{BU}, p \in \mathbf{P} \\ z_{u,p}^d + z_{u,p}^s &= 0 \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p = 1 \\ z_{u,p}^d + z_{u,p}^s &\leq z_{u,p-1}^e \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1 \\ z_{u,p}^d + z_{u,p}^s &\leq 1 \quad \forall u \in \mathbf{BU}, p \in \mathbf{P} : p = 1 \end{aligned}$$

unit existence constraints

$$\begin{aligned} z_{u,p}^b \cdot F_u^{\min} &\leq f_{u,p}^b \leq z_{u,p}^b \cdot F_u^{\max} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} \\ f_{u,p}^e &= F_u^{\text{init}} + f_{u,p}^b - (f_{u,p}^s + f_{u,p}^d) \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p = 1 \\ f_{u,p}^e &= f_{u,p-1}^e + f_{u,p}^b - (f_{u,p}^s + f_{u,p}^d) \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1 \end{aligned}$$

sizing constraints

$$\begin{aligned} y_{u,p} &\leq z_{u,p}^e \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} \\ f_{u,p} &\leq f_{u,p}^e \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} \end{aligned}$$

connection to PI

$$\begin{aligned} z_{u,p}^e &\leq l_{u,p} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} \\ l_{u,p} &\leq z_{u,p}^e \cdot \text{LI}_u^{lt} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} \\ l_{u,p} &= \left(z_{u,p}^b \cdot \text{LI}_u^{lt} \right) + \left(\text{LI}_u^{lt} - \text{LI}_u^{\text{init}} \right) \cdot \left(1 - z_{u,p}^s - z_{u,p}^d \right) \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p = 1 \\ l_{u,p} &= l_{u,p-1} - z_{u,p-1}^e + \left(\text{LI}_u^{lt} \cdot z_{u,p}^b \right) - l_{u,p}^s \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1 \\ l_{u,p-1} - l_{u,p}^s &\leq \left(1 - z_{u,p}^b \right) \cdot \text{LI}_u^{lt} + 1 \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1 \\ l_{u,p-1} &\leq \left(1 - z_{u,p}^d \right) \cdot \text{LI}_u^{lt} + 1 \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1 \\ \left(1 - z_{u,p-1}^e \right) \cdot \text{LI}_u^{lt} + \left(1 - z_{u,p-1}^s \right) \cdot \text{LI}_u^{lt} + l_{u,p-1} &\leq 2 \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1 \\ l_{u,p}^s &\geq l_{u,p-1} - z_{u,p-1}^e - \left(1 - z_{u,p-1}^s \right) \cdot \text{LI}_u^{lt} \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p \neq 1 \\ l_{u,p}^s &\leq l_{u,p-1} - z_{u,p-1}^e \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p \neq 1 \\ l_{u,p}^s &\leq z_{u,p-1}^s \cdot \text{LI}_u^{lt} \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p \neq 1 \end{aligned}$$

unit life constraints

- ❖ net present value: cumulative cash flow discounted with interest rate
- ❖ a units existence and size are dependent on the commissioning / decommissioning actions
- ❖ units age after each period
 - ◆ unit life triggers commissioning / decommissioning actions

$$C_p^{cf} = \left(C_p^s + C_p^{sc} - C_p^{inv} \right) + \left(c^{op_{cur}} - C_p^{op} \right) \quad \forall p \in \mathbf{P}$$

$$C_p^{op} = \sum_{u \in \mathbf{U}} \left[\sum_{t \in \mathbf{TT}_p} \left(c_u^{op1} \cdot y_{u,p} + c_u^{op2} \cdot f_{u,p} \right) \cdot \Delta t_t^{op} \right] \quad \forall u \in \mathbf{U}, p \in \mathbf{P}$$

$$C_p^{inv} = \sum_{u \in \mathbf{IU}} \left(C_{u,p}^b + C_{u,p}^{mt} + C_{u,p}^{lr} C_{u,p}^{fr} + C_{u,p}^{oh} + C_{u,p}^{en} \right) + C_p^{ph} + C_p^{pr} \quad \forall p \in \mathbf{P}$$

$$C_{u,p}^b = c_u^{inv1} \cdot z_{u,p}^b + c_u^{inv2} \cdot f_{u,p}^b \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{mt} = C_{u,p}^b \cdot F_u^{mt} \cdot \left(1 - z_{u,p}^{bb} \right) \quad \forall u \in \mathbf{NU}, p \in \mathbf{P}$$

$$C_{u,p}^{lr} = C_{u,p}^b \cdot F_u^{lr} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{fr} = C_{u,p}^b \cdot F_u^{fr} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{oh} = C_{u,p}^b \cdot F_u^{oh} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{en} = C_{u,p}^b \cdot F_u^{en} \cdot \left(1 - z_{u,p}^{bb} \right) \quad \forall u \in \mathbf{NU}, p \in \mathbf{P}$$

$$z_{u,p}^{bb} = 0 \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p = 1$$

$$z_{u,p}^{bb} \leq \sum_{pp \in \{1..p-1\}} z_{u,pp}^b \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p \neq 1$$

$$z_{u,p}^{bb} \geq z_{u,pp}^b \quad \forall u \in \mathbf{NU}, p \in \mathbf{P}, pp \in \{1..p-1\} : p \neq 1$$

$$C_{u,p}^{rv} = c_u^b \cdot \left(1 - 2 \cdot r_u^{dep} \right)^{LI_u^{init}} \quad \forall u \in \mathbf{BU}, p \in \mathbf{P} : p = 1$$

$$C_{u,p}^{rv} = 0 \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p = 1$$

$$C_{u,p}^{rv} = \left(C_{u,p-1}^b - C_{u,p-1}^{sv} - C_{u,p-1}^{dv} \right) + C_{u,p-1}^{rv} - C_{u,p-1}^{dep} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1$$

$$C_{u,p}^{dep} = \left[\left(C_{u,p}^b - C_{u,p}^{sv} - C_{u,p}^{dv} \right) + C_{u,p}^{rv} \right] \cdot r_u^{dep} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{sv} = C_{u,p}^{rv} \cdot z_{u,p}^s \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{dv} = C_{u,p}^{rv} \cdot z_{u,p}^d \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{sc} = c_u^{sal} \cdot z_{u,p}^d \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^s = \max \left(C_{u,p}^{sv}, c_u^{sal} \right) \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_p^{cf} = \left(C_p^s + C_p^{sc} - C_p^{inv} \right) \quad \text{cash flow calculation} \quad \forall p \in \mathbf{P}$$

$$C_p^{op} = \sum_{u \in \mathbf{U}} \left[\sum_{t \in \mathbf{TT}_p} \left(c_u^{op1} \cdot y_{u,p} + c_u^{op2} \cdot f_{u,p} \right) \cdot \Delta t_t^{op} \right] \quad \forall u \in \mathbf{U}, p \in \mathbf{P}$$

$$C_p^{inv} = \sum_{u \in \mathbf{IU}} \left(C_{u,p}^b + C_{u,p}^{mt} + C_{u,p}^{lr} + C_{u,p}^{fr} + C_{u,p}^{oh} + C_{u,p}^{en} \right) + C_p^{ph} + C_p^{pr} \quad \forall p \in \mathbf{P}$$

$$C_{u,p}^b = c_u^{inv1} \cdot z_{u,p}^b + c_u^{inv2} \cdot f_{u,p}^b \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{mt} = C_{u,p}^b \cdot F_u^{mt} \cdot \left(1 - z_{u,p}^{bb} \right) \quad \forall u \in \mathbf{NU}, p \in \mathbf{P}$$

$$C_{u,p}^{lr} = C_{u,p}^b \cdot F_u^{lr} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{fr} = C_{u,p}^b \cdot F_u^{fr} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{oh} = C_{u,p}^b \cdot F_u^{oh} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{en} = C_{u,p}^b \cdot F_u^{en} \cdot \left(1 - z_{u,p}^{bb} \right) \quad \forall u \in \mathbf{NU}, p \in \mathbf{P}$$

$$z_{u,p}^{bb} = 0 \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p = 1$$

$$z_{u,p}^{bb} \leq \sum_{pp \in \{1..p-1\}} z_{u,pp}^b \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p \neq 1$$

$$z_{u,p}^{bb} \geq z_{u,pp}^b \quad \forall u \in \mathbf{NU}, p \in \mathbf{P}, pp \in \{1..p-1\} : p \neq 1$$

$$C_{u,p}^{rv} = c_u^b \cdot \left(1 - 2 \cdot r_u^{dep} \right)^{LI_u^{init}} \quad \forall u \in \mathbf{BU}, p \in \mathbf{P} : p = 1$$

$$C_{u,p}^{rv} = 0 \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p = 1$$

$$C_{u,p}^{rv} = \left(C_{u,p-1}^b - C_{u,p-1}^{sv} - C_{u,p-1}^{dv} \right) + C_{u,p-1}^{rv} - C_{u,p-1}^{dep} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1$$

$$C_{u,p}^{dep} = \left[\left(C_{u,p}^b - C_{u,p}^{sv} - C_{u,p}^{dv} \right) + C_{u,p}^{rv} \right] \cdot r_u^{dep} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{sv} = C_{u,p}^{rv} \cdot z_{u,p}^s \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{dv} = C_{u,p}^{rv} \cdot z_{u,p}^d \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{sc} = c_u^{sal} \cdot z_{u,p}^d \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^s = \max \left(C_{u,p}^{sv}, c_u^{sal} \right) \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

❖ operating cost and investment cost are the major contributors to the annual cash flow

$$C_p^{cf} = (C_p^s + C_p^{sc} - C_p^{inv}) - (C_p^{rv} - C_p^{dep}) \quad \forall p \in \mathbf{P}$$

cash flow calculation

$$C_p^{op} = \sum_{u \in \mathbf{U}} \left[\sum_{t \in \mathbf{TT}_p} (C_{u,p}^{op1} + C_{u,p}^{op2} + C_{u,p}^{op3}) \right] \quad \forall u \in \mathbf{U}, p \in \mathbf{P}$$

operating cost calculation

$$C_p^{inv} = \sum_{u \in \mathbf{IU}} (C_{u,p}^b + C_{u,p}^{mt} + C_{u,p}^{lr} + C_{u,p}^{fr} + C_{u,p}^{oh} + C_{u,p}^{en}) + C_p^{ph} + C_p^{pr} \quad \forall p \in \mathbf{P}$$

$$C_{u,p}^b = c_u^{inv1} \cdot z_{u,p}^b + c_u^{inv2} \cdot f_{u,p}^b \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{mt} = C_{u,p}^b \cdot F_u^{mt} \cdot (1 - z_{u,p}^{bb}) \quad \forall u \in \mathbf{NU}, p \in \mathbf{P}$$

$$C_{u,p}^{lr} = C_{u,p}^b \cdot F_u^{lr} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{fr} = C_{u,p}^b \cdot F_u^{fr} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{oh} = C_{u,p}^b \cdot F_u^{oh} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{en} = C_{u,p}^b \cdot F_u^{en} \cdot (1 - z_{u,p}^{bb}) \quad \forall u \in \mathbf{NU}, p \in \mathbf{P}$$

$$z_{u,p}^{bb} = 0 \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p = 1$$

$$z_{u,p}^{bb} \leq \sum_{pp \in \{1..p-1\}} z_{u,pp}^b \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p \neq 1$$

$$z_{u,p}^{bb} \geq z_{u,pp}^b \quad \forall u \in \mathbf{NU}, p \in \mathbf{P}, pp \in \{1..p-1\} : p \neq 1$$

$$C_{u,p}^{rv} = c_u^b \cdot (1 - 2 \cdot r_u^{dep})^{LI_u^{init}} \quad \forall u \in \mathbf{BU}, p \in \mathbf{P} : p = 1$$

$$C_{u,p}^{rv} = 0 \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p = 1$$

$$C_{u,p}^{rv} = (C_{u,p-1}^b - C_{u,p-1}^{sv} - C_{u,p-1}^{dv}) + C_{u,p-1}^{rv} - C_{u,p-1}^{dep} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1$$

$$C_{u,p}^{dep} = \left[(C_{u,p}^b - C_{u,p}^{sv} - C_{u,p}^{dv}) + C_{u,p}^{rv} \right] \cdot r_u^{dep} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{sv} = C_{u,p}^{rv} \cdot z_{u,p}^s \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{dv} = C_{u,p}^{rv} \cdot z_{u,p}^d \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{sc} = c_u^{sal} \cdot z_{u,p}^d \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^s = \max(C_{u,p}^{sv}, c_u^{sal}) \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

- ❖ operating cost and investment cost are the major contributors to the annual cash flow
- ❖ operating cost: natural gas, electricity and water consumption

$$C_p^{cf} = (C_p^s + C_p^{sc} - C_p^{inv}) - (C_p^{rv} - C_p^{dep}) \quad \forall p \in \mathbf{P}$$

cash flow calculation

$$C_p^{op} = \sum_{u \in \mathbf{U}} \left[\sum_{t \in \mathbf{TT}_p} (C_{u,p}^{op1} + C_{u,p}^{op2} + C_{u,p}^{op3}) \right] \quad \forall u \in \mathbf{U}, p \in \mathbf{P}$$

operating cost calculation

$$C_p^{inv} = \sum_{u \in \mathbf{IU}} (C_{u,p}^b + C_{u,p}^{mt} + C_{u,p}^{lr} + C_{u,p}^{fr} + C_{u,p}^{oh} + C_{u,p}^{en}) + C_p^{ph} + C_p^{pr} \quad \forall p \in \mathbf{P}$$

$$C_{u,p}^b = c_u^{inv1} \cdot z_{u,p}^b + c_u^{inv2} \cdot f_{u,p}^b \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{mt} = C_{u,p}^b \cdot F_u^{mt} \cdot (1 - z_{u,p}^{bb}) \quad \forall u \in \mathbf{NU}, p \in \mathbf{P}$$

$$C_{u,p}^{lr} = C_{u,p}^b \cdot F_u^{lr} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{fr} = C_{u,p}^b \cdot F_u^{fr} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{oh} = C_{u,p}^b \cdot F_u^{oh} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{en} = C_{u,p}^b \cdot F_u^{en} \cdot (1 - z_{u,p}^{bb}) \quad \forall u \in \mathbf{NU}, p \in \mathbf{P}$$

investment cost calculation

$$z_{u,p}^{bb} = 0 \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p = 1$$

$$z_{u,p}^{bb} \leq \sum_{pp \in \{1..p-1\}} z_{u,pp}^b \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p \neq 1$$

$$z_{u,p}^{bb} \geq z_{u,pp}^b \quad \forall u \in \mathbf{NU}, p \in \mathbf{P}, pp \in \{1..p-1\} : p \neq 1$$

$$C_{u,p}^{rv} = c_u^b \cdot (1 - 2 \cdot r_u^{dep})^{LI_u^{init}} \quad \forall u \in \mathbf{BU}, p \in \mathbf{P} : p = 1$$

$$C_{u,p}^{rv} = 0 \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p = 1$$

$$C_{u,p}^{rv} = (C_{u,p-1}^b - C_{u,p-1}^{sv} - C_{u,p-1}^{dv}) + C_{u,p-1}^{rv} - C_{u,p-1}^{dep} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1$$

$$C_{u,p}^{dep} = \left[(C_{u,p}^b - C_{u,p}^{sv} - C_{u,p}^{dv}) + C_{u,p}^{rv} \right] \cdot r_u^{dep} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{sv} = C_{u,p}^{rv} \cdot z_{u,p}^s \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{dv} = C_{u,p}^{rv} \cdot z_{u,p}^d \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{sc} = c_u^{sal} \cdot z_{u,p}^d \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^s = \max(C_{u,p}^{sv}, c_u^{sal}) \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

- ❖ operating cost and investment cost are the major contributors to the annual cash flow
- ❖ operating cost: natural gas, electricity and water consumption
- ❖ investment cost: purchase of equipment, material, labour, freight, overhead and engineering

$$C_p^{cf} = (C_p^s + C_p^{sc} - C_p^{inv}) - (C_p^{rv} - C_p^{dep}) \quad \forall p \in \mathbf{P}$$

cash flow calculation

$$C_p^{op} = \sum_{u \in \mathbf{U}} \left[\sum_{t \in \mathbf{TT}_p} (C_{u,p}^{op1} + C_{u,p}^{op2} + C_{u,p}^{op3}) \right] \quad \forall u \in \mathbf{U}, p \in \mathbf{P}$$

operating cost calculation

$$C_p^{inv} = \sum_{u \in \mathbf{IU}} (C_{u,p}^b + C_{u,p}^{mt} + C_{u,p}^{lr} + C_{u,p}^{fr} + C_{u,p}^{oh} + C_{u,p}^{en}) + C_p^{ph} + C_p^{pr} \quad \forall p \in \mathbf{P}$$

$$C_{u,p}^b = c_u^{inv1} \cdot z_{u,p}^b + c_u^{inv2} \cdot f_{u,p}^b \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{mt} = C_{u,p}^b \cdot F_u^{mt} \cdot (1 - z_{u,p}^{bb}) \quad \forall u \in \mathbf{NU}, p \in \mathbf{P}$$

$$C_{u,p}^{lr} = C_{u,p}^b \cdot F_u^{lr} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{fr} = C_{u,p}^b \cdot F_u^{fr} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{oh} = C_{u,p}^b \cdot F_u^{oh} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{en} = C_{u,p}^b \cdot F_u^{en} \cdot (1 - z_{u,p}^{bb}) \quad \forall u \in \mathbf{NU}, p \in \mathbf{P}$$

investment cost calculation

$$z_{u,p}^{bb} = 0 \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p = 1$$

$$z_{u,p}^{bb} \leq \sum_{pp \in \{1..p-1\}} z_{u,pp}^b \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p \neq 1$$

$$z_{u,p}^{bb} \geq z_{u,pp}^b \quad \forall u \in \mathbf{NU}, p \in \mathbf{P}, pp \in \{1..p-1\} : p \neq 1$$

$$C_{u,p}^{rv} = c_u^b \cdot (1 - 2 \cdot r_u^{dep})^{LI_u^{init}} \quad \forall u \in \mathbf{BU}, p \in \mathbf{P} : p = 1$$

$$C_{u,p}^{rv} = 0 \quad \forall u \in \mathbf{NU}, p \in \mathbf{P} : p = 1$$

$$C_{u,p}^{rv} = (C_{u,p-1}^b - C_{u,p-1}^{sv} - C_{u,p-1}^{dv}) + C_{u,p-1}^{rv} - C_{u,p-1}^{dep} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1$$

$$C_{u,p}^{dep} = \left[(C_{u,p-1}^b - C_{u,p-1}^{sv} - C_{u,p-1}^{dv}) + C_{u,p-1}^{rv} - C_{u,p-1}^{dep} \right] \cdot r_u^{dep} \quad \forall u \in \mathbf{IU}, p \in \mathbf{P} : p \neq 1$$

depreciation and remaining value calculation

$$C_{u,p}^{sv} = C_{u,p}^{rv} \cdot z_{u,p}^s \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{dv} = C_{u,p}^{rv} \cdot z_{u,p}^d \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^{sc} = c_u^{sal} \cdot z_{u,p}^d \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

$$C_{u,p}^s = \max(C_{u,p}^{sv}, c_u^{sal}) \quad \forall u \in \mathbf{IU}, p \in \mathbf{P}$$

- ❖ operating cost and investment cost are the major contributors to the annual cash flow
- ❖ operating cost: natural gas, electricity and water consumption
- ❖ investment cost: purchase of equipment, material, labour, freight, overhead and engineering
- ❖ double declining depreciation



- ❖ large problem size:
 - ♦ full problem with 20 years horizon: ~25k binary variables
- ❖ difficult problem to solve
 - ♦ 8h without an integer solution
- ❖ bottleneck: connections between the plants
- ❖ solution strategy:
 - ♦ solve the problem without installing pipes between the plants
 - ♦ find an integer solution
 - ♦ terminate the first step
 - ♦ additional constraints for piping
 - ♦ feed the initial solution to the solver
 - ♦ solve the full problem with piping

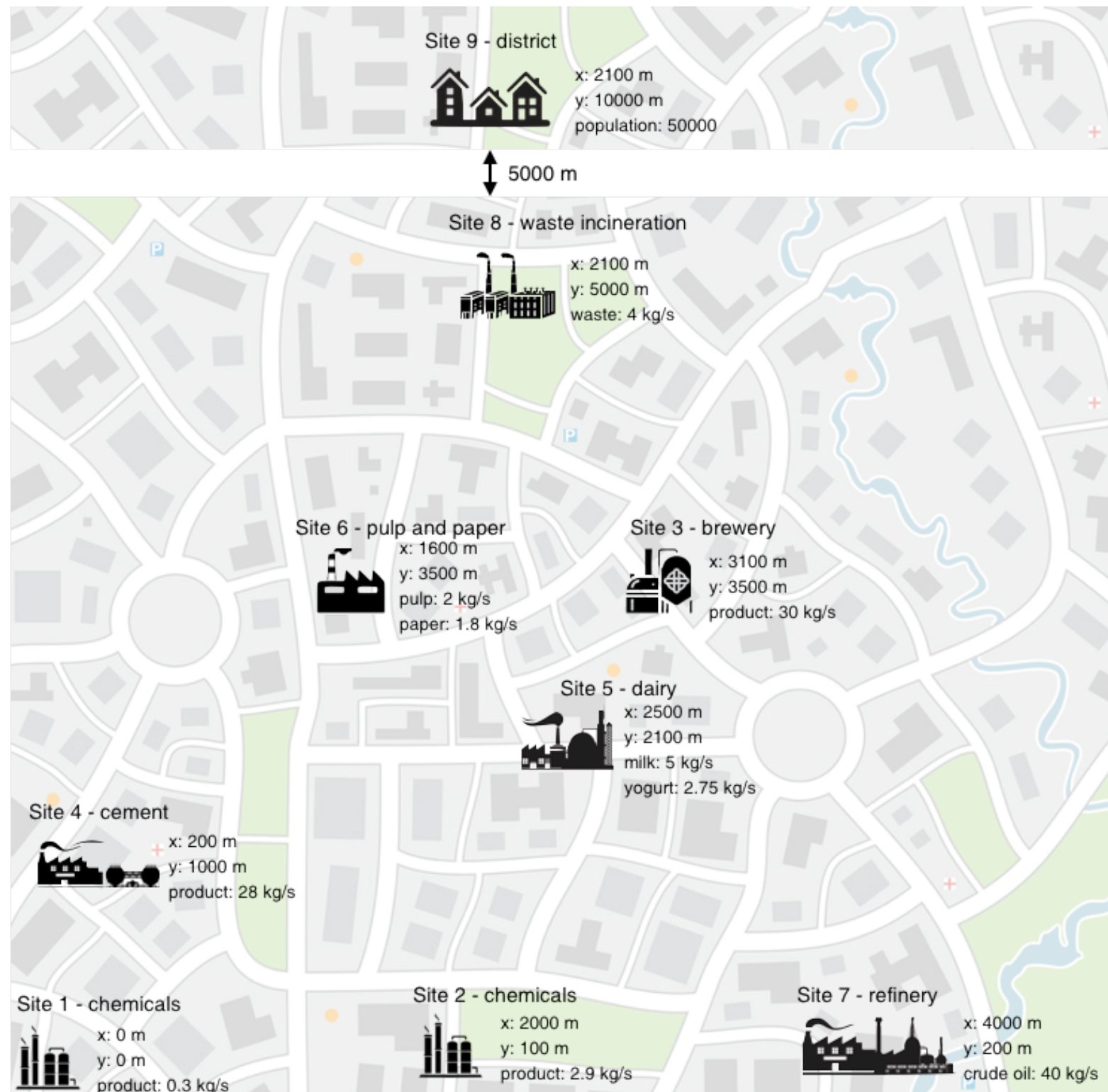


Figure 4.1 - Layout of the case study: an industrial cluster with a neighbouring district

No budget limitation, 20 years horizon

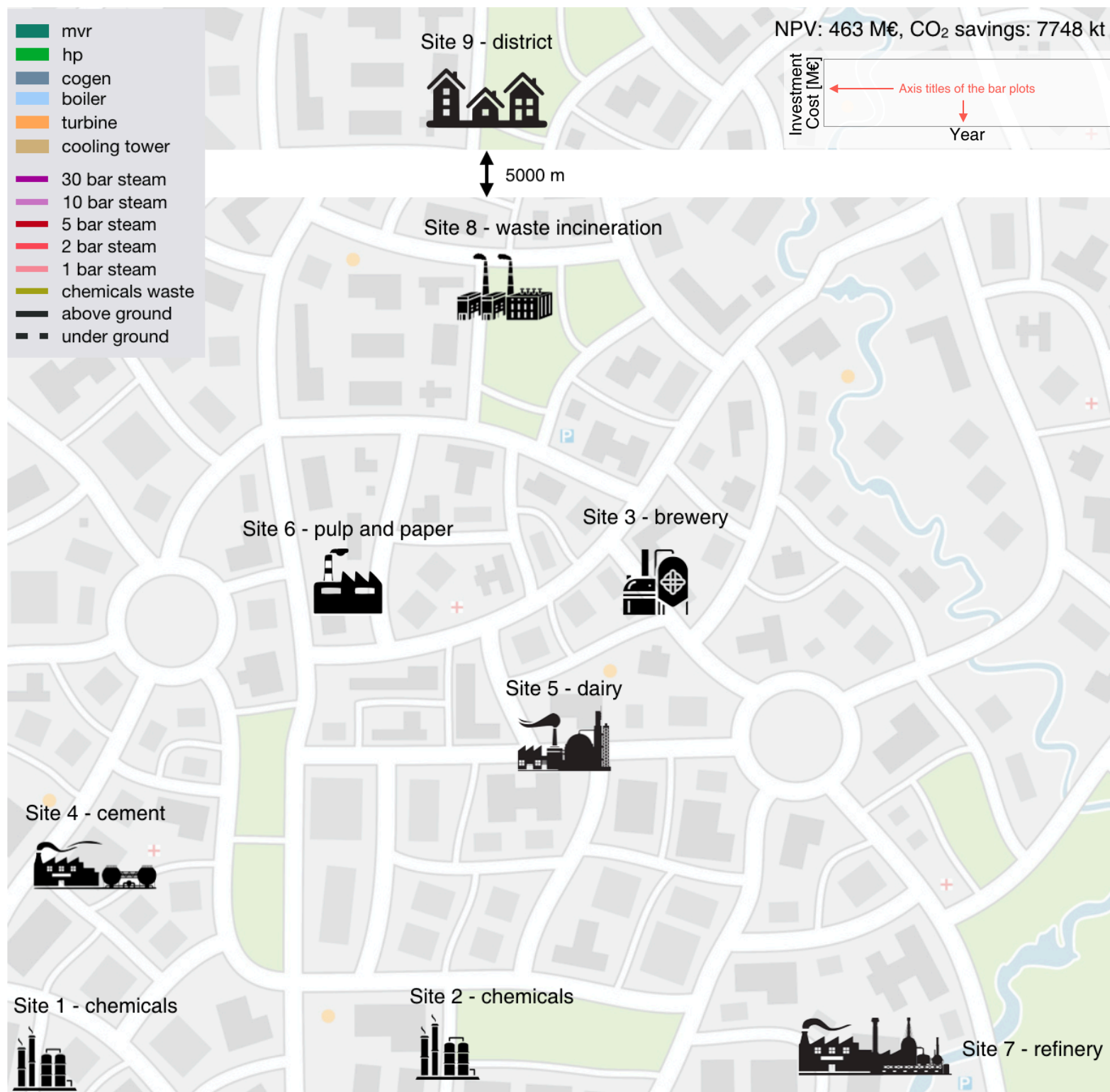


Figure 4.2 - Optimal investment planning without budget constraints.

*cost data

natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³,
electricity selling 60% of purchase

No budget limitation, 20 years horizon

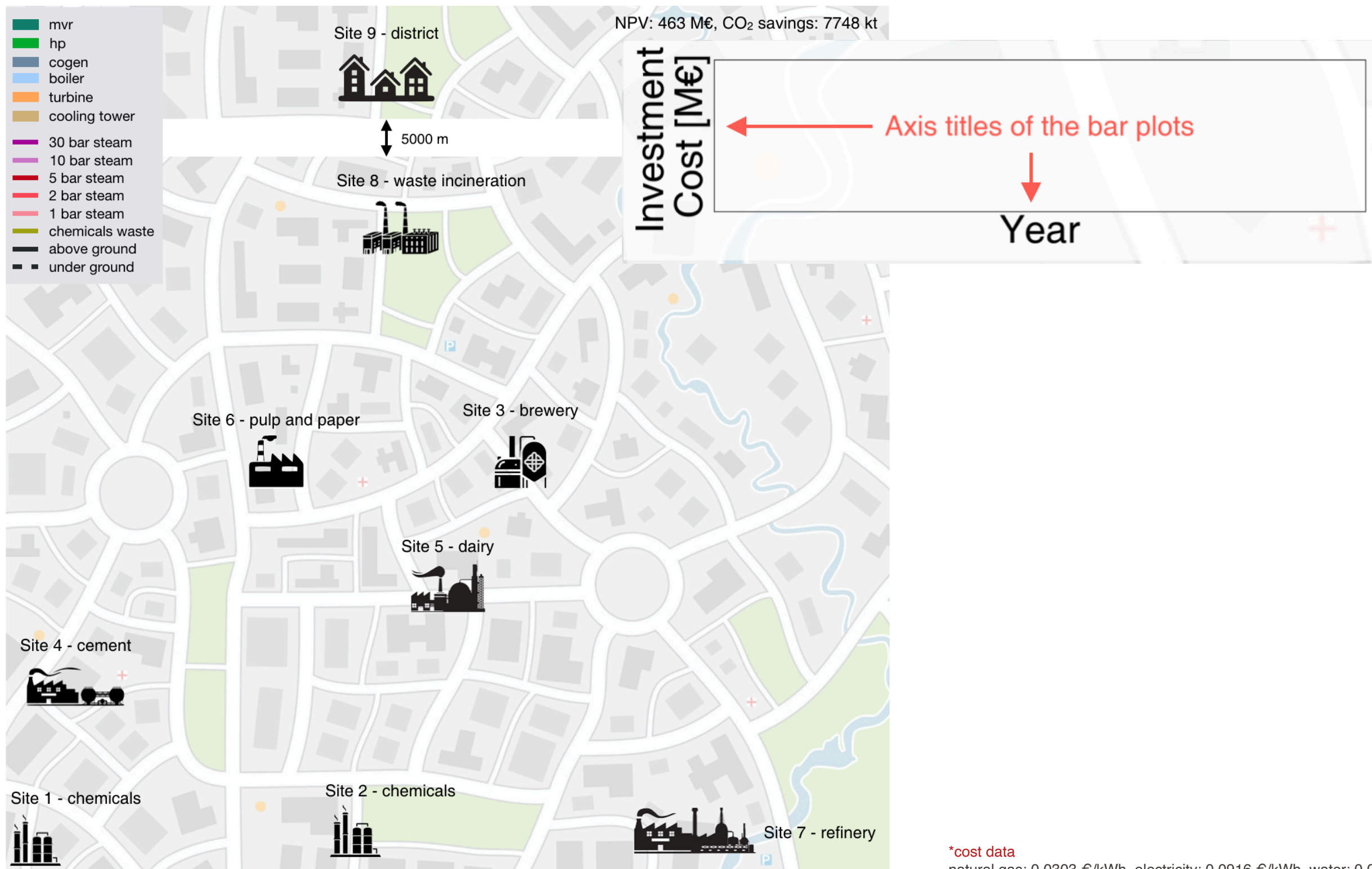


Figure 4.2 - Optimal investment planning without budget constraints.

No budget limitation, 20 years horizon

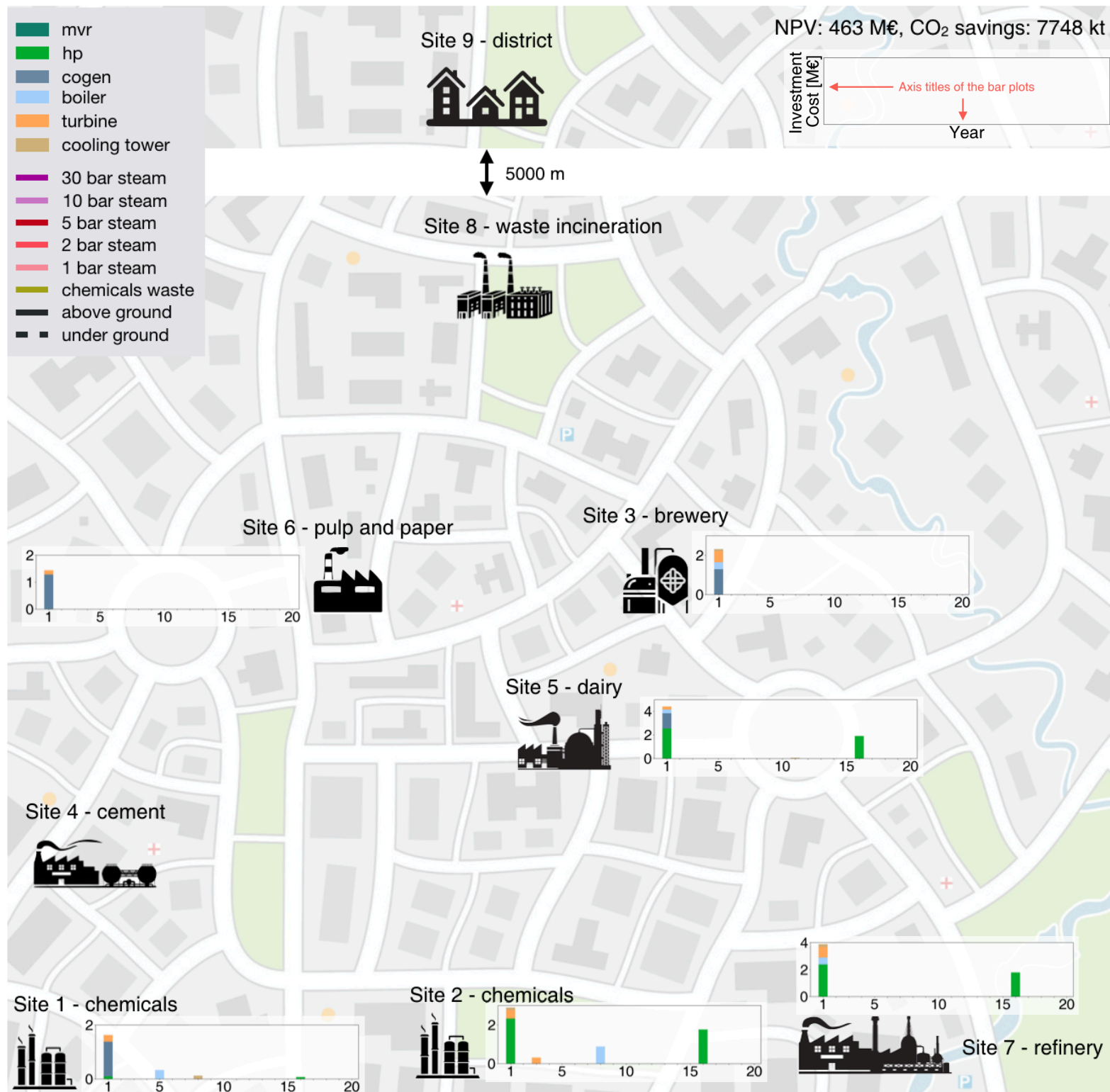


Figure 4.2 - Optimal investment planning without budget constraints.

- ❖ cogeneration engine integration
 - ♦ site 1,3,5, and 6
 - ♦ low temperature processes
- ❖ heat pump integration
 - ♦ site 1, 2 and 7
 - ♦ heat transfer across the pinch with small temperature lift

*cost data

natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³,
electricity selling 60% of purchase

No budget limitation, 20 years horizon

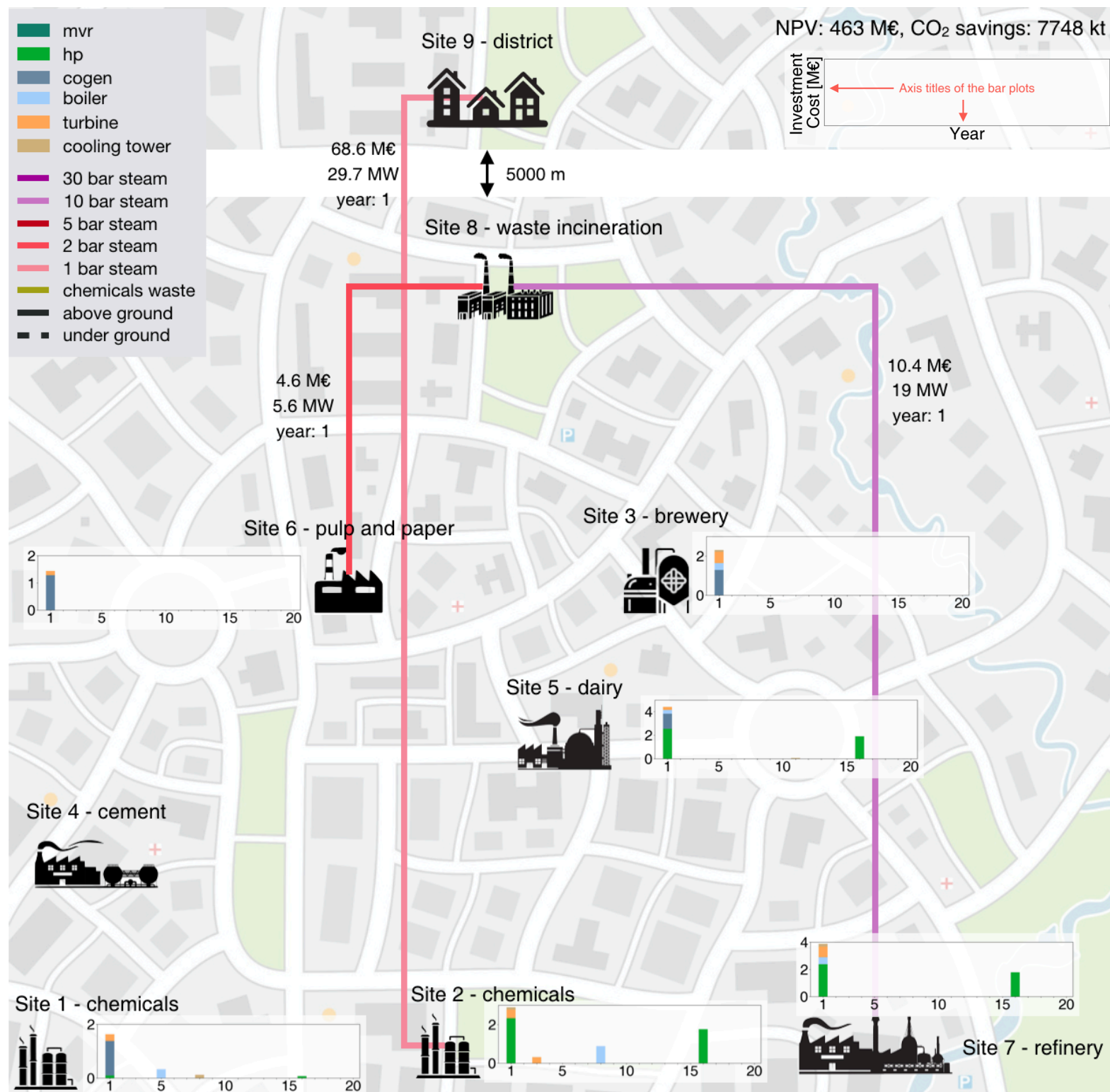


Figure 4.2 - Optimal investment planning without budget constraints.

- ❖ cogeneration engine integration
 - ♦ site 1,3,5, and 6
 - ♦ Low temperature processes
- ❖ heat pump integration
 - ♦ site 1, 2 and 7
 - ♦ heat transfer across the pinch with small temperature lift
- ❖ high pressure heat sharing between Site 8 and 7
- ❖ low pressure steam sharing with the district
 - ♦ due to high energy prices for non-industrial users

*cost data

natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³, electricity selling 60% of purchase

No budget limitation, 20 years horizon

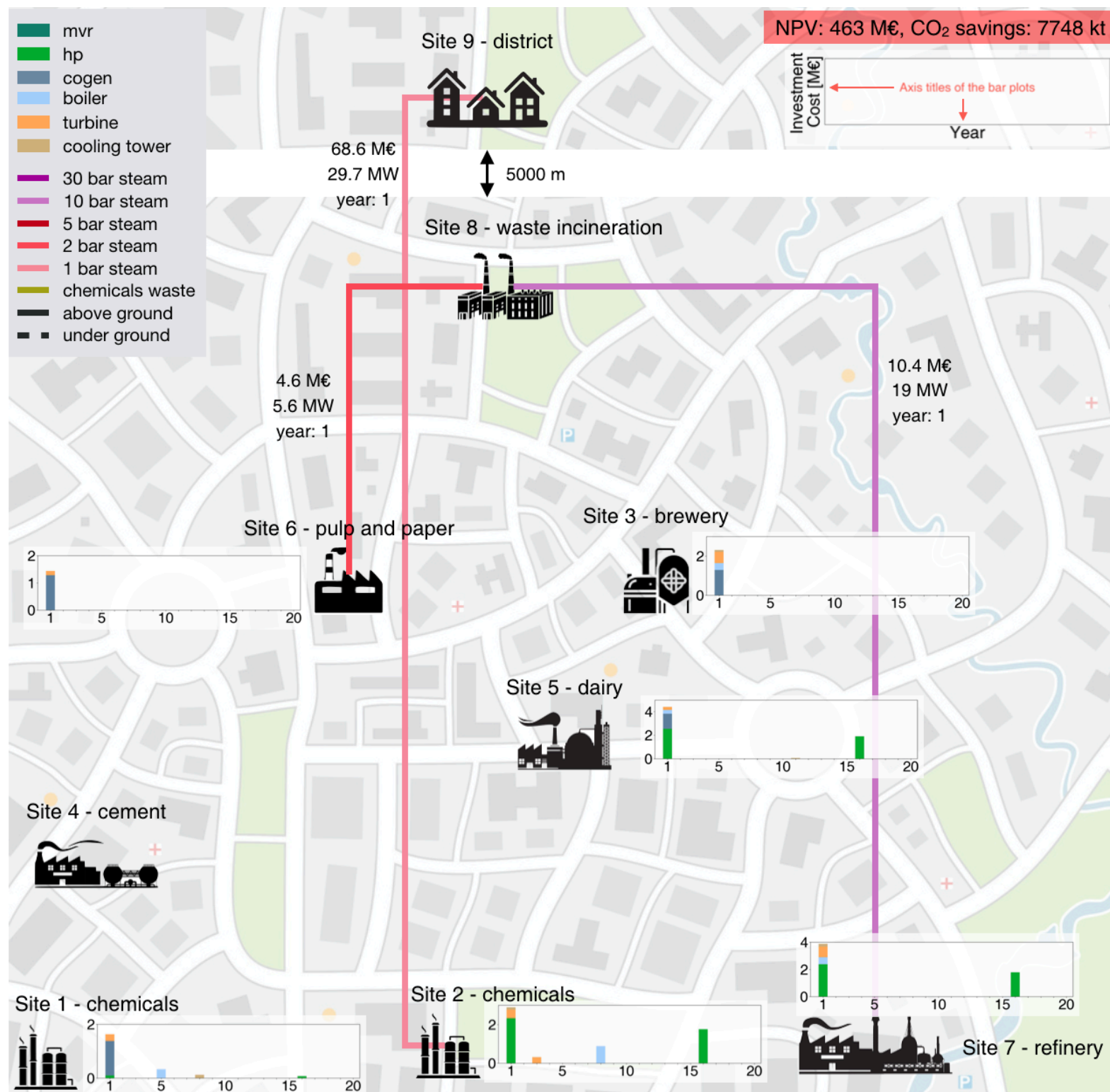


Figure 4.2 - Optimal investment planning without budget constraints.

- ❖ cogeneration engine integration
 - ♦ site 1,3,5, and 6
 - ♦ Low temperature processes
- ❖ heat pump integration
 - ♦ site 1, 2 and 7
 - ♦ heat transfer across the pinch with small temperature lift
- ❖ high pressure heat sharing between Site 8 and 7
- ❖ low pressure steam sharing with the district
 - ♦ due to high energy prices for non-industrial users
- ❖ 107 M€ investment
 - ♦ mostly in the first year
 - ♦ only replacing ageing equipment afterwards

*cost data

natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³, electricity selling 60% of purchase

80M€ budget, 5 years of investment

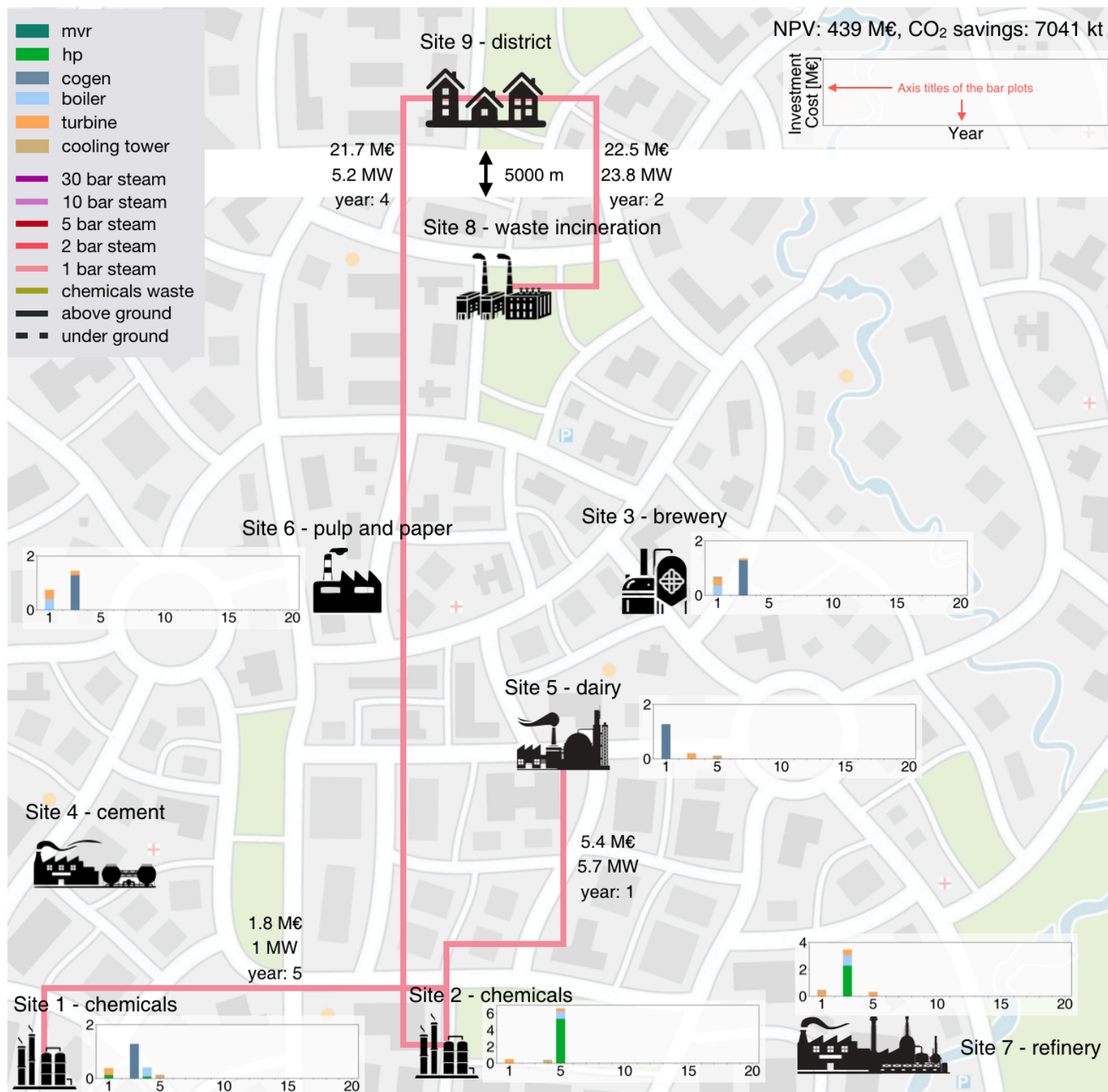


Figure 4.3 - Optimal investment decisions with 5 years of investment and 16 M€ annual budget.

- ❖ similar investment decisions on energy conversion systems
- ♦ cogeneration engines and heat pumps

*cost data

natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³, electricity selling 60% of purchase

80M€ budget, 5 years of investment

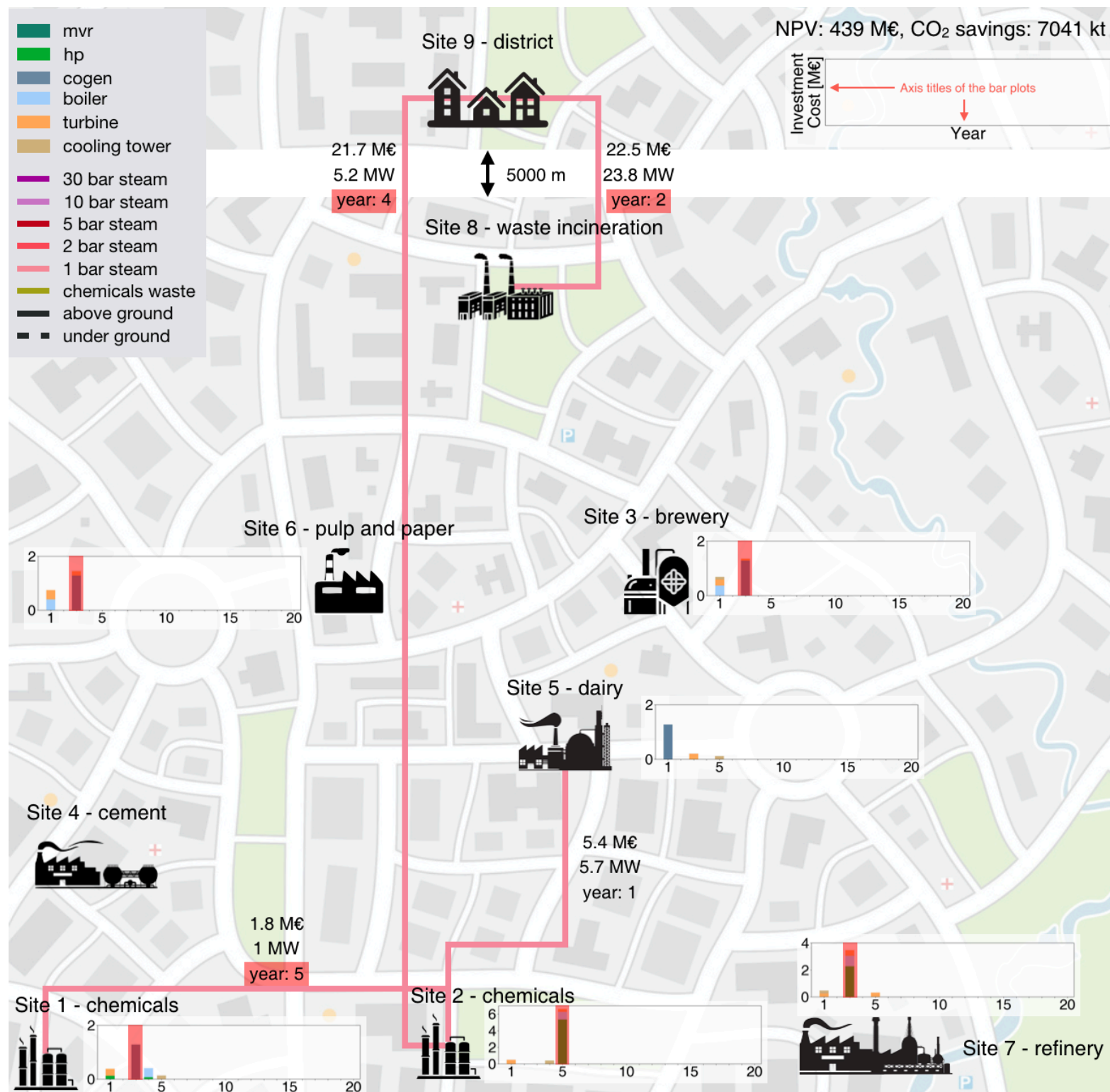


Figure 4.3 - Optimal investment decisions with 5 years of investment and 16 M€ annual budget.

- ❖ similar investment decisions on energy conversion systems
 - ♦ cogeneration engines and heat pumps
- ❖ impact of budget restrictions
 - ♦ no large piping investments
 - ♦ investment decisions are spread over 5 years

*cost data

natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³, electricity selling 60% of purchase

80M€ budget, 5 years of investment

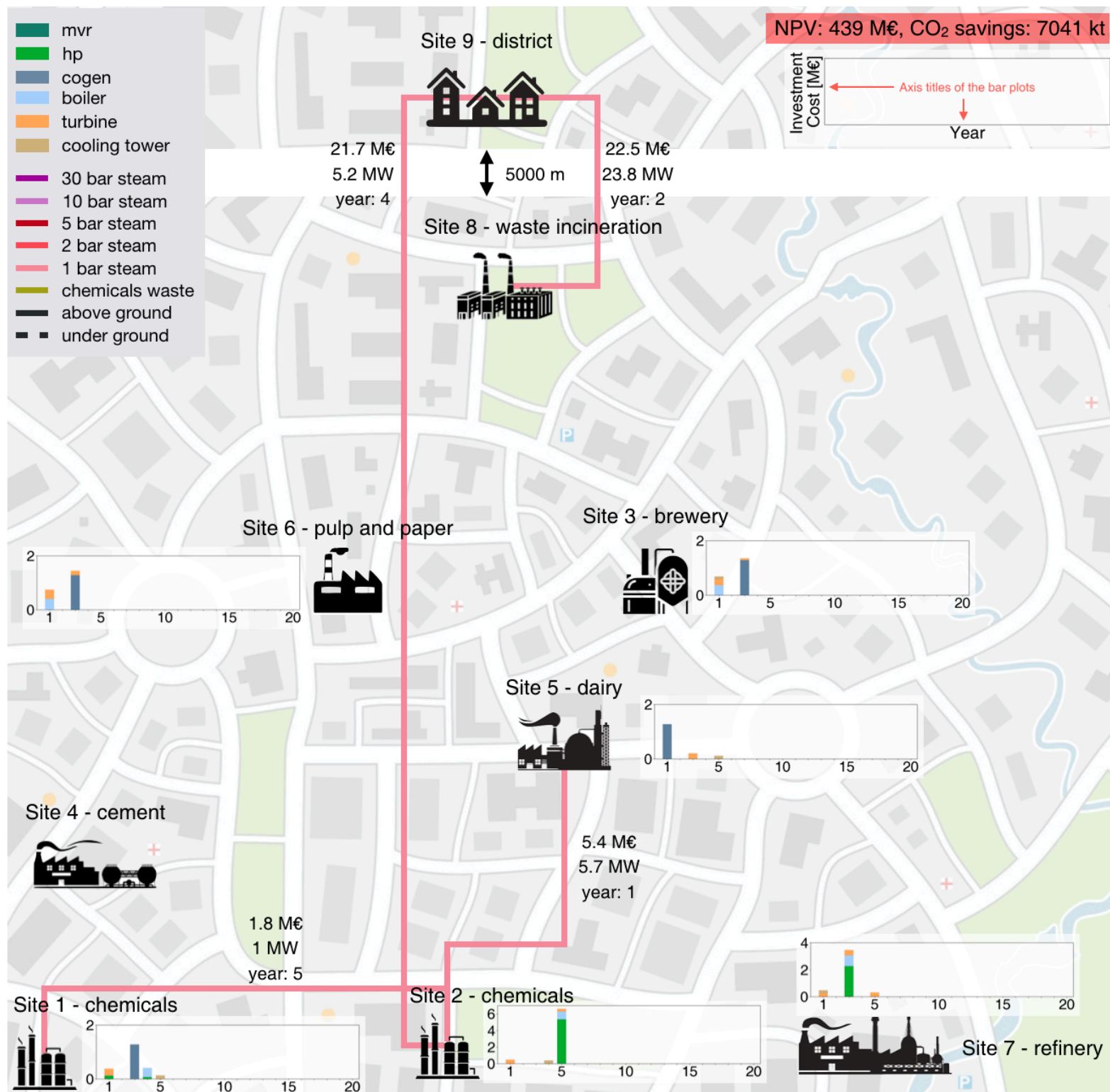


Figure 4.3 - Optimal investment decisions with 5 years of investment and 16 M€ annual budget.

- ❖ similar investment decisions on energy conversion systems
 - ♦ cogeneration engines and heat pumps
- ❖ impact of budget restrictions
 - ♦ no large piping investments
 - ♦ investment decisions are spread over 5 years
- ❖ 5% decrease in NPV
- ❖ 9% decrease in CO₂ savings

*cost data

natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³, electricity selling 60% of purchase

80M€ budget, 10 years of investment

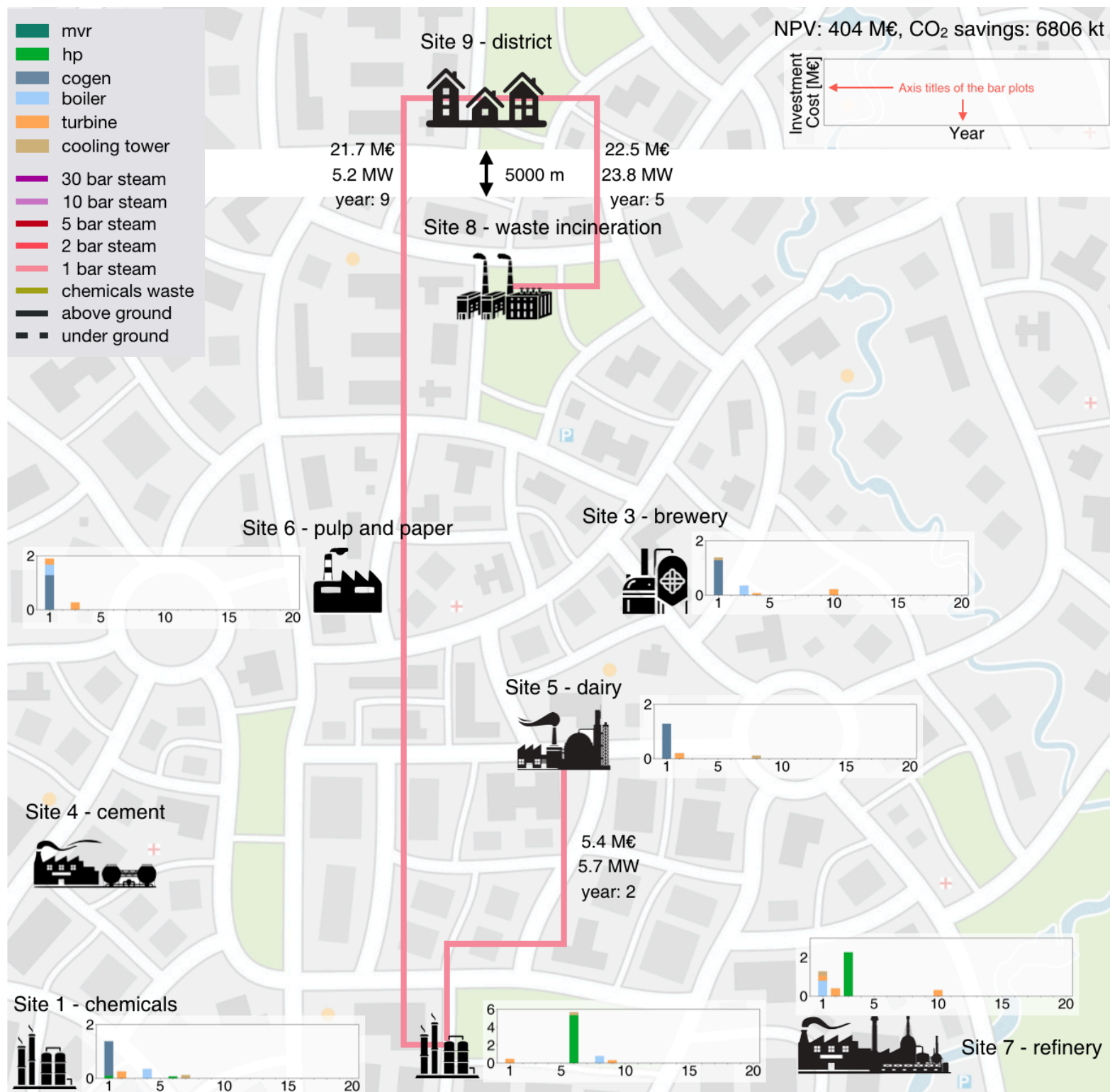


Figure 4.4 - Optimal investment decisions with 5 years of investment and 8 M€ annual budget.

- ❖ investments on energy conversion systems are prioritised
- ❖ decrease in the number of simultaneous investments
 - ♦ due to low annual budget
- ❖ periods with no significant investment
 - ♦ saving budget for large investments

*cost data

natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³, electricity selling 60% of purchase

80M€ budget, 10 years of investment

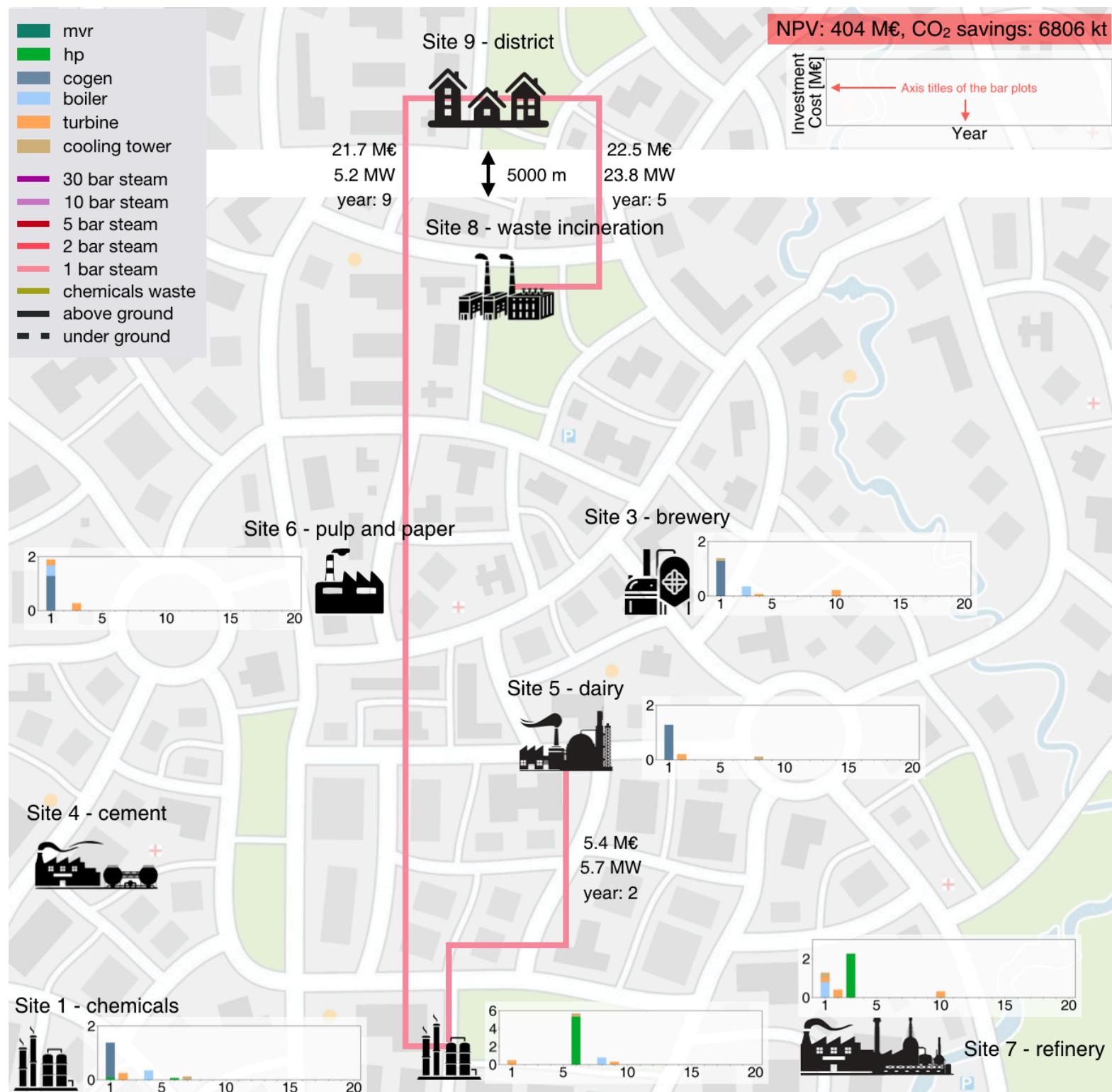
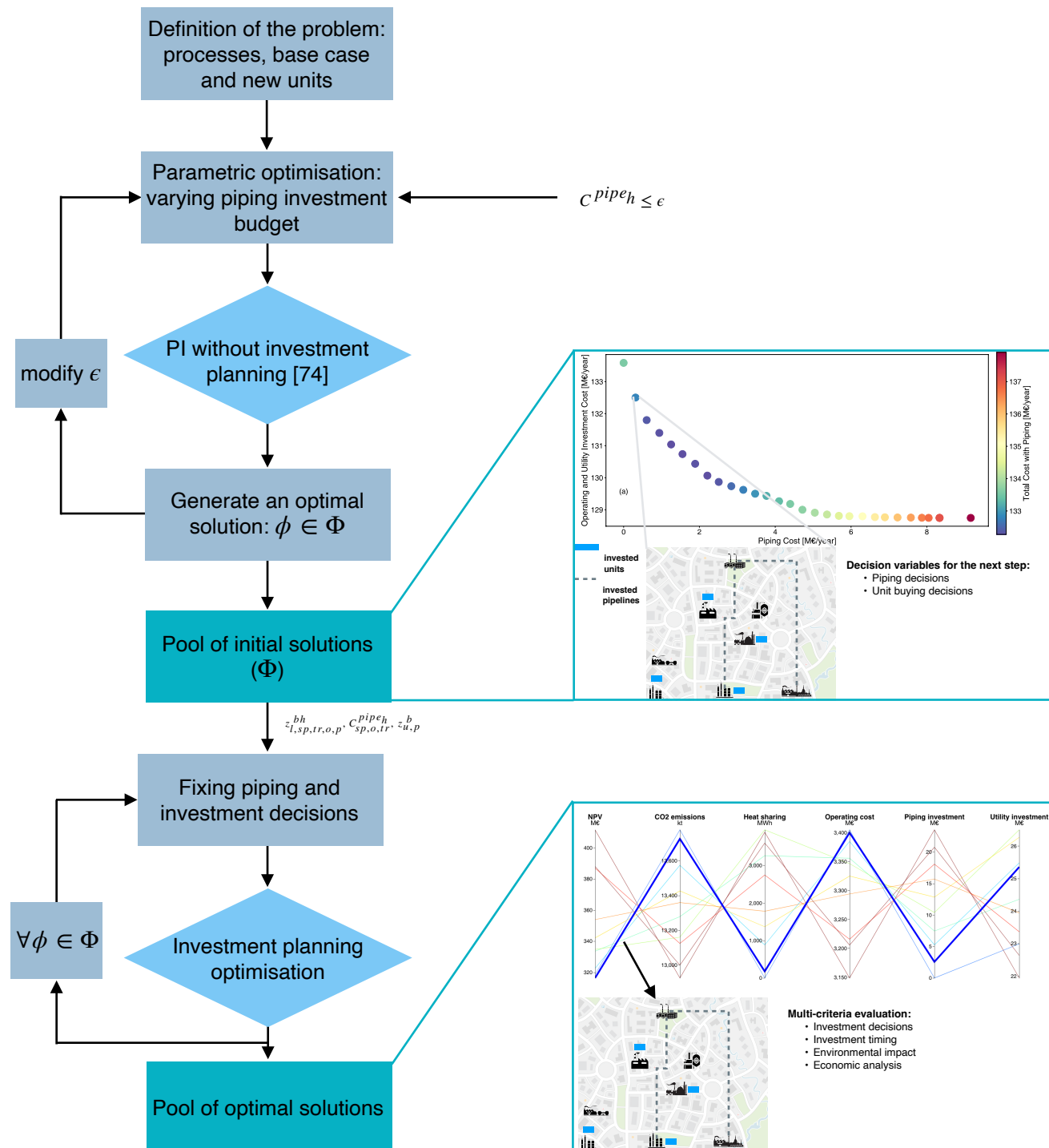


Figure 4.4 - Optimal investment decisions with 5 years of investment and 8 M€ annual budget.

- ❖ investments on energy conversion systems are prioritised
- ❖ decrease in the number of simultaneous investments
 - ♦ due to low annual budget
- ❖ periods with no significant investment
 - ♦ saving budget for large investments
- ❖ 13% decrease in NPV
- ❖ 12% decrease in CO₂ savings

*cost data

natural gas: 0.0303 €/kWh, electricity: 0.0916 €/kWh, water: 0.07 €/m³, electricity selling 60% of purchase



- ❖ large problem size:
 - ♦ full problem with 20 years horizon: ~25k binary variables
- ❖ difficult problem to solve
 - ♦ 8h to reach 5% optimality gap with the solution strategy
- ❖ parametric optimisation solution strategy:
 - ♦ solve the problem without investment planning (chapter 3)
 - ♦ generate multiple solutions with different piping cost allowance
 - ♦ fix the investment decisions for investment planning except for investment time
 - ♦ solve the full problem to get optimal investment planning

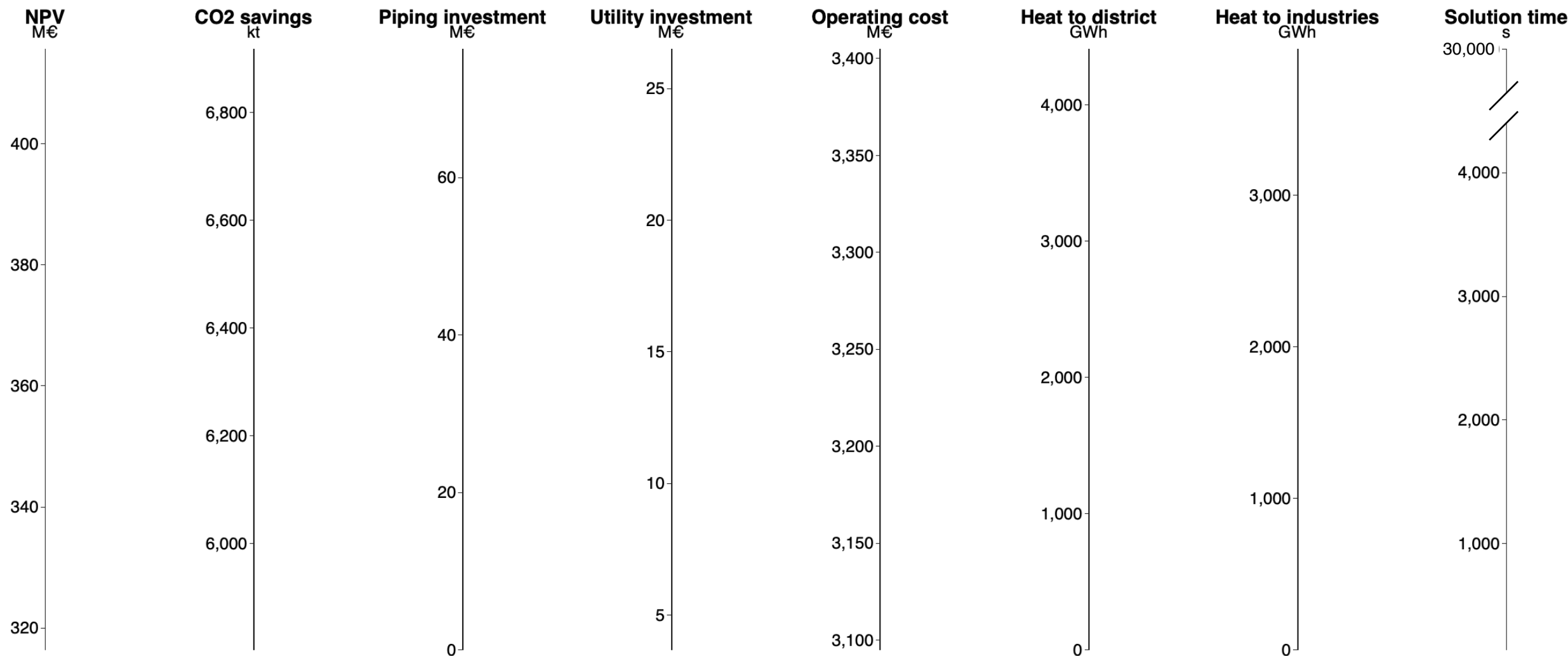


Figure 4.5 - Multiple solutions generated by parametric optimisation; the higher the NPV, the colder the line colour.

Parametric optimisation

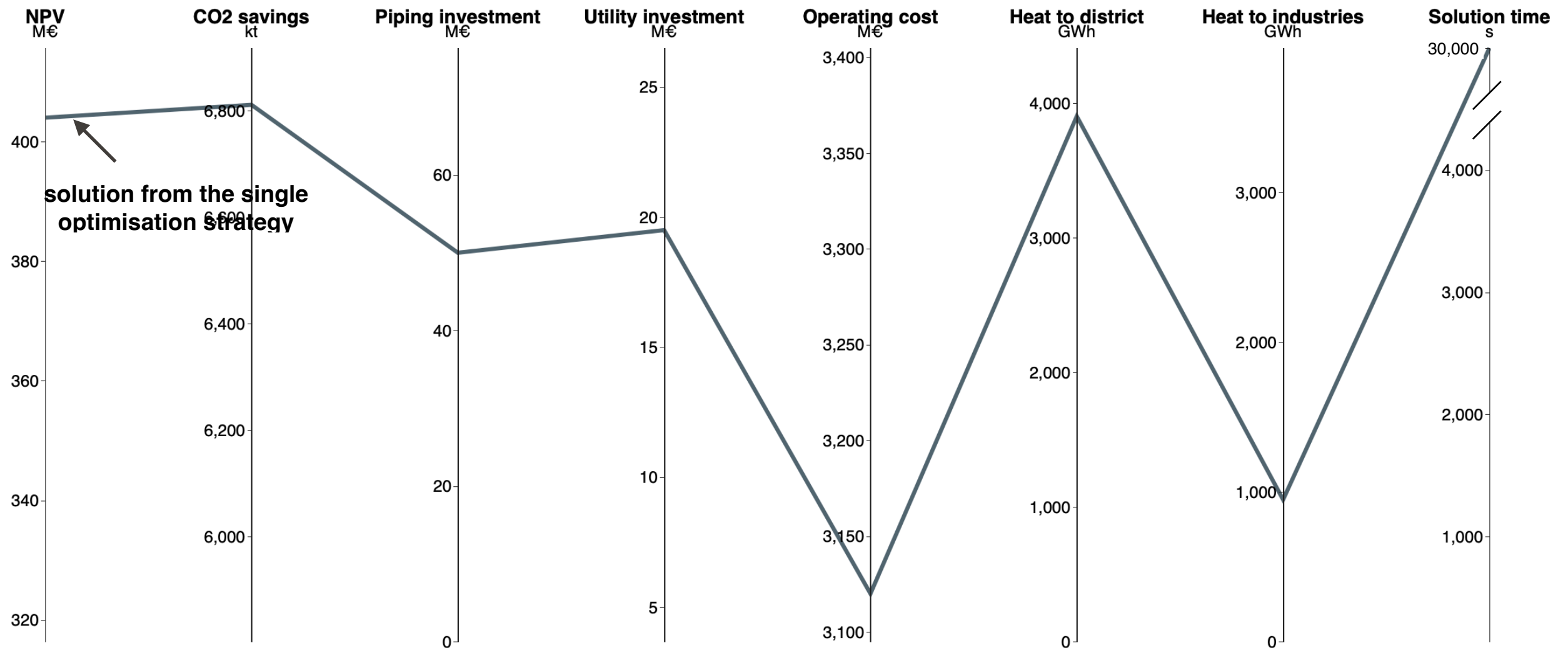


Figure 4.5 - Multiple solutions generated by parametric optimisation; the higher the NPV, the colder the line colour.

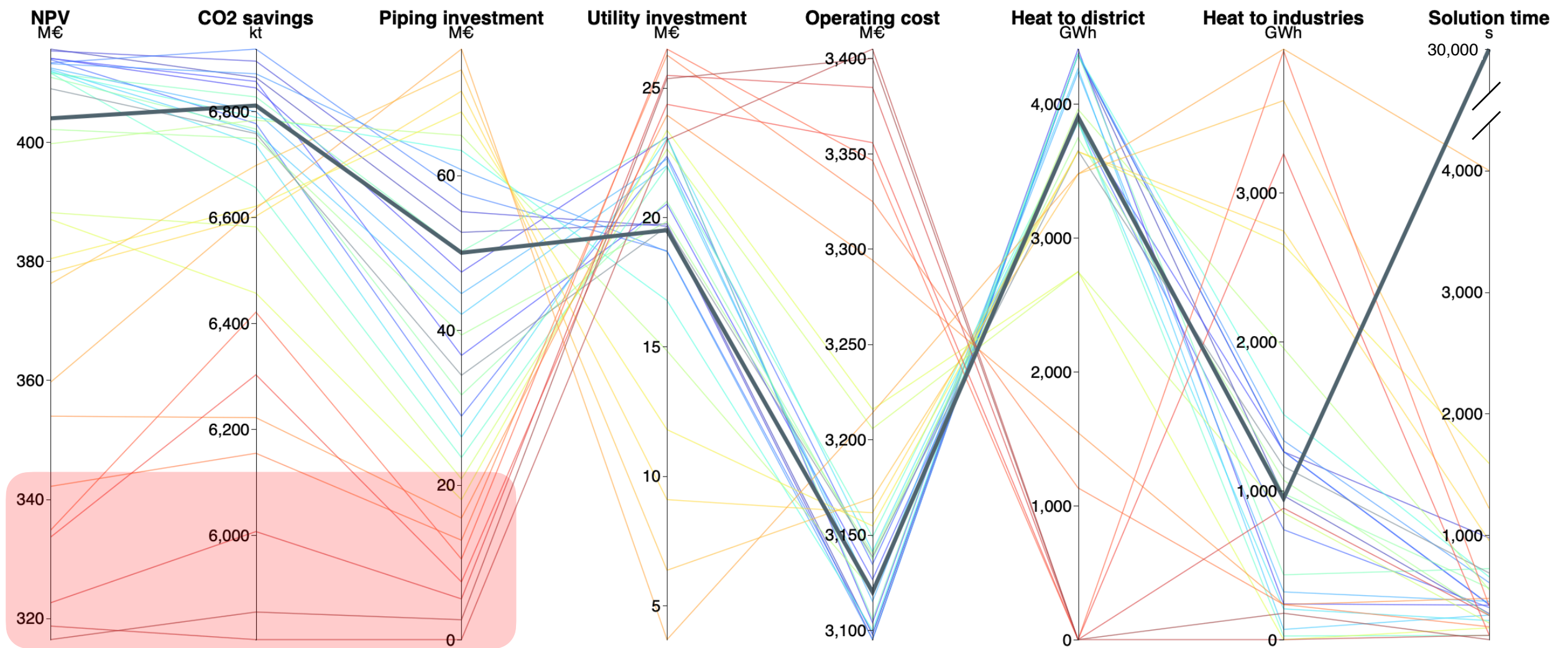


Figure 4.5 - Multiple solutions generated by parametric optimisation; the higher the NPV, the colder the line colour.

❖ low piping allowance → low NPV and CO₂ savings

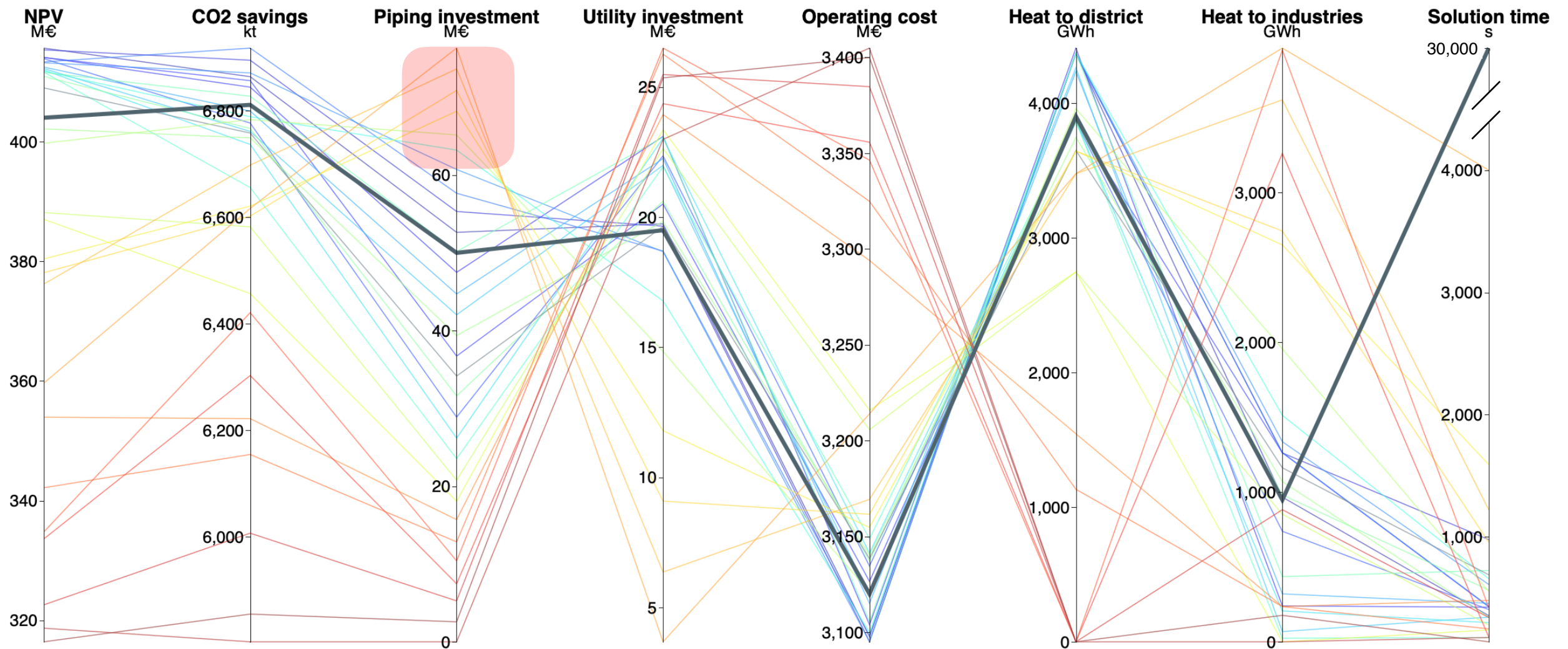


Figure 4.5 - Multiple solutions generated by parametric optimisation; the higher the NPV, the colder the line colour.

- ❖ low piping allowance → low NPV and CO₂ savings
- ❖ increasing piping investment does not **always** bring operational benefits

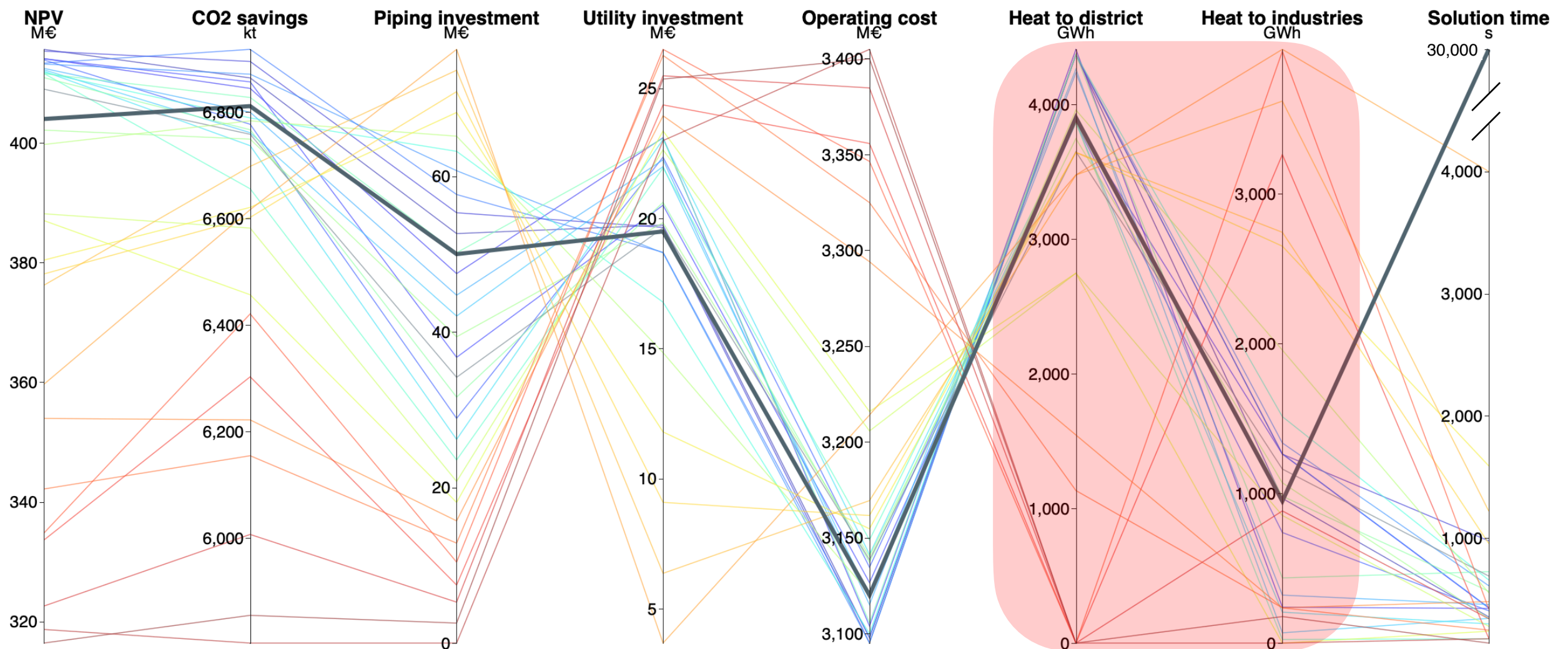


Figure 4.5 - Multiple solutions generated by parametric optimisation; the higher the NPV, the colder the line colour.

- ❖ low piping allowance → low NPV and CO₂ savings
- ❖ increasing piping investment does not **always** bring operational benefits
- ❖ inverse relationship between heat to district and industries
 - ♦ sharing industrial excess heat with district is more beneficial

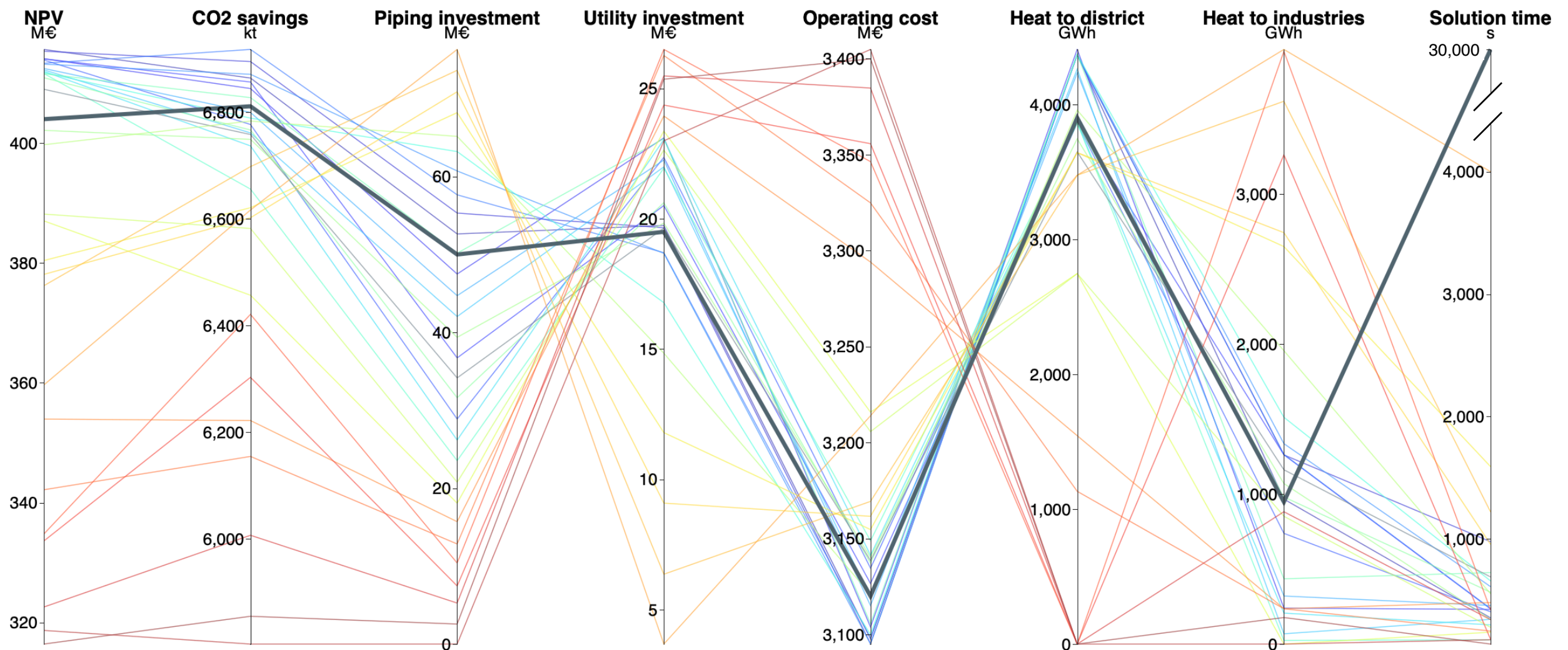
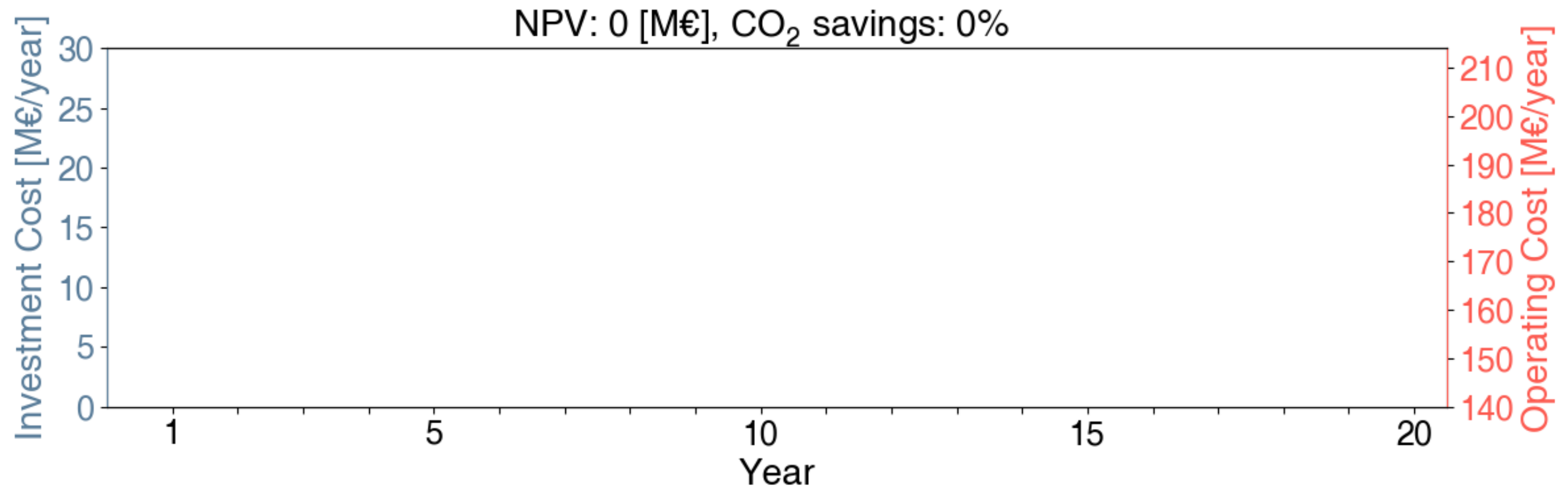


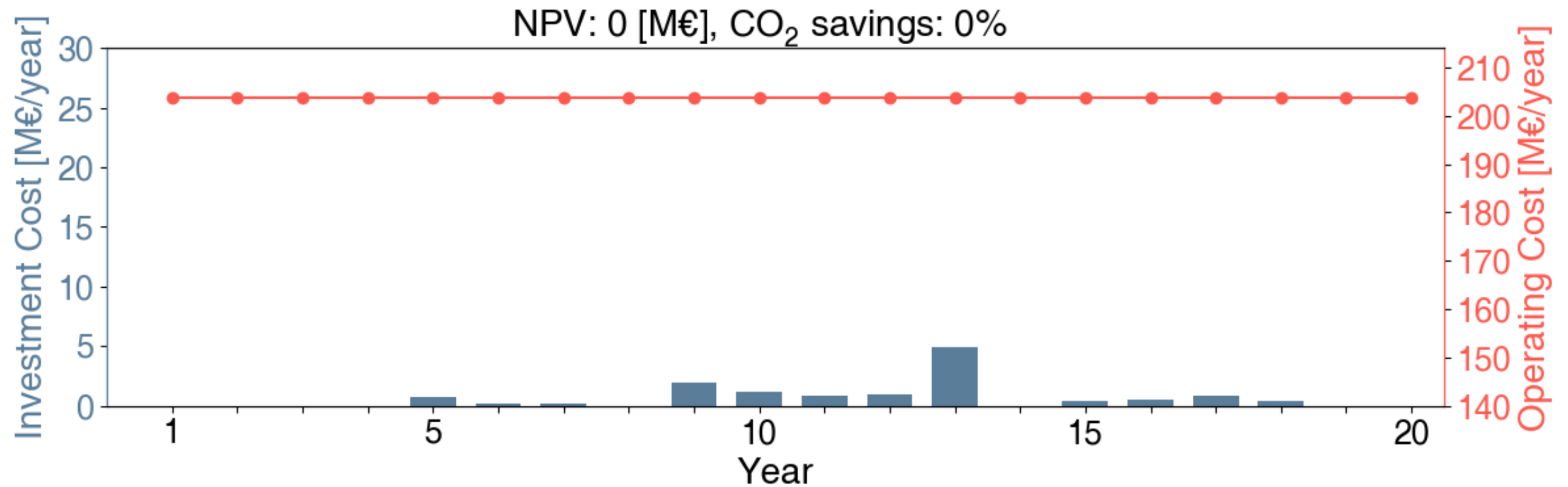
Figure 4.5 - Multiple solutions generated by parametric optimisation; the higher the NPV, the colder the line colour.

- ❖ low piping allowance → low NPV and CO₂ savings
- ❖ increasing piping investment does not **always** bring operational benefits
- ❖ inverse relationship between heat to district and industries
 - ♦ sharing industrial excess heat with district is more beneficial
- ❖ parametric optimisation strategy performs better in NPV, CO₂ savings and solution time

Comparison with baseline



Comparison with baseline



❖ baseline: investment only at the end of lifetime of the equipment, operations business as usual

Comparison with baseline

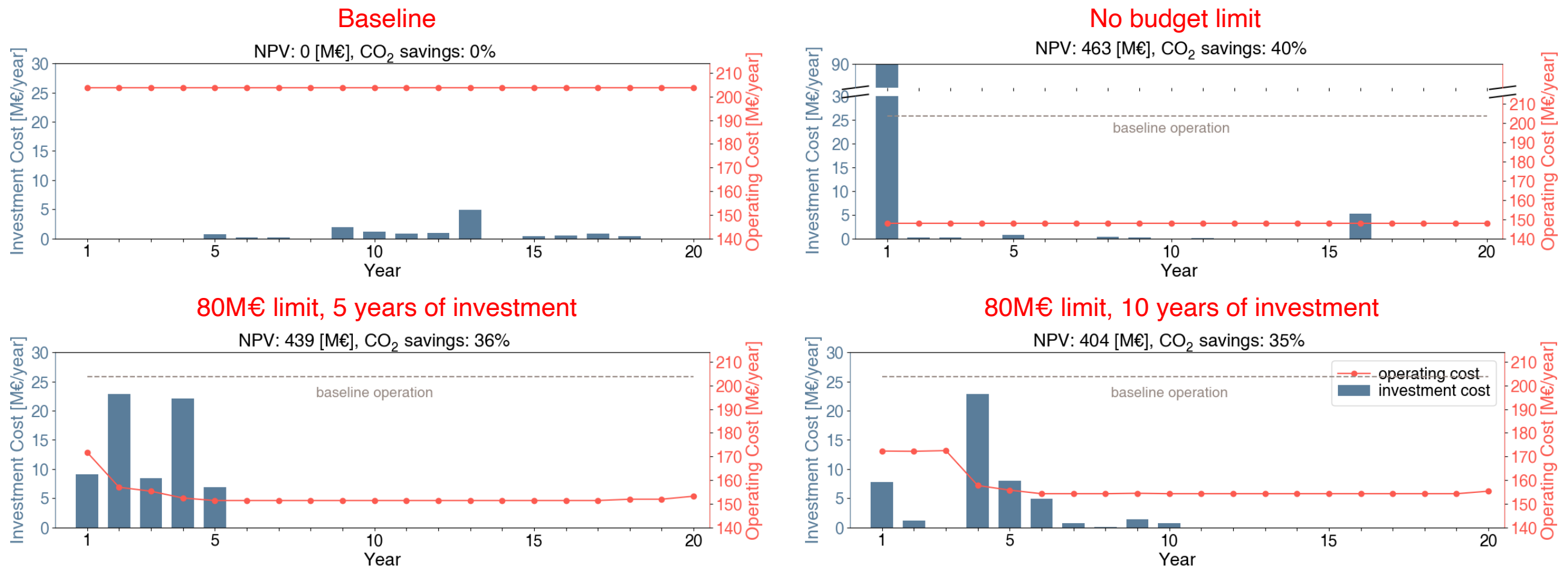


Figure 4.6 - Comparison of operating and investment costs of the optimal solutions with the baseline.

- ❖ baseline: investment only at the end of lifetime of the equipment, operations business as usual
- ❖ no budget limit: 27% reduction in operating cost, ~90 M€ investment in the first year
- ❖ budget limit: 16-26% reduction in operating cost, maximum investment < 25 M€
- ❖ applying investment planning strategy with / without budget constraints:
 - ♦ investments totalling up to 107 M€
 - ♦ operating cost savings > 50 M€, CO₂ savings > 35%
 - ♦ payback time ~ 2 years

Energy

152 | June 2018

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Energies

12(17), 3338 | August 2019

Bütün H., Kantor I., Maréchal F. Incorporating Location Aspects in Process Integration Methodology.

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