EPFL

Efficiency Increase by Systematic Heat Pumping Integration in Industrial Processes

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IPESE
Industrial Process and Energy Systems Engineering

EPFL Defossilizing industry : thematics

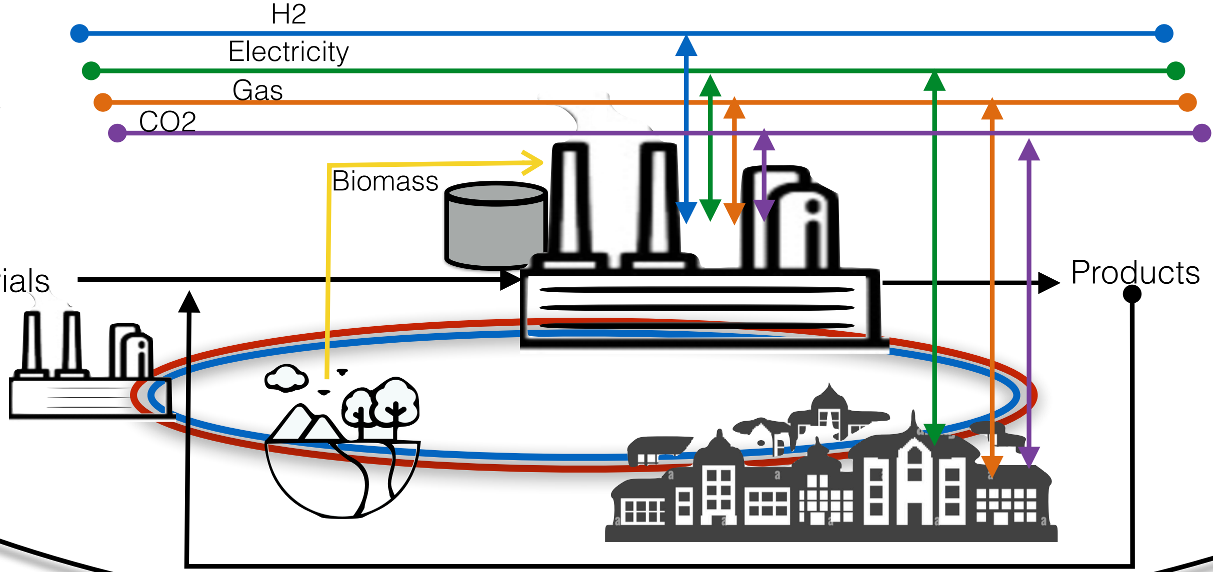
Heat valorisation
Heat pumping
Waste heat to electricity

Energy conversion
Renewable energy sources
Combined Heat and Power
Combined Heat and Fuel

Efficiency
Materials recovery
Heat recovery

Technology efficiency
Optimal operation
Technology improvement
Technology innovation

CO2
Capture, reuse, sequestrate



Energy Audits
Energy Drivers
Efficiency KPI
Monitoring

Energy system integration
Energy grids
Heat and electricity storage
Hydrogen
Power2Tanks2Power

System expansion
District heating/cooling
Industrial symbiosis
Waste-water-energy
Circular economy

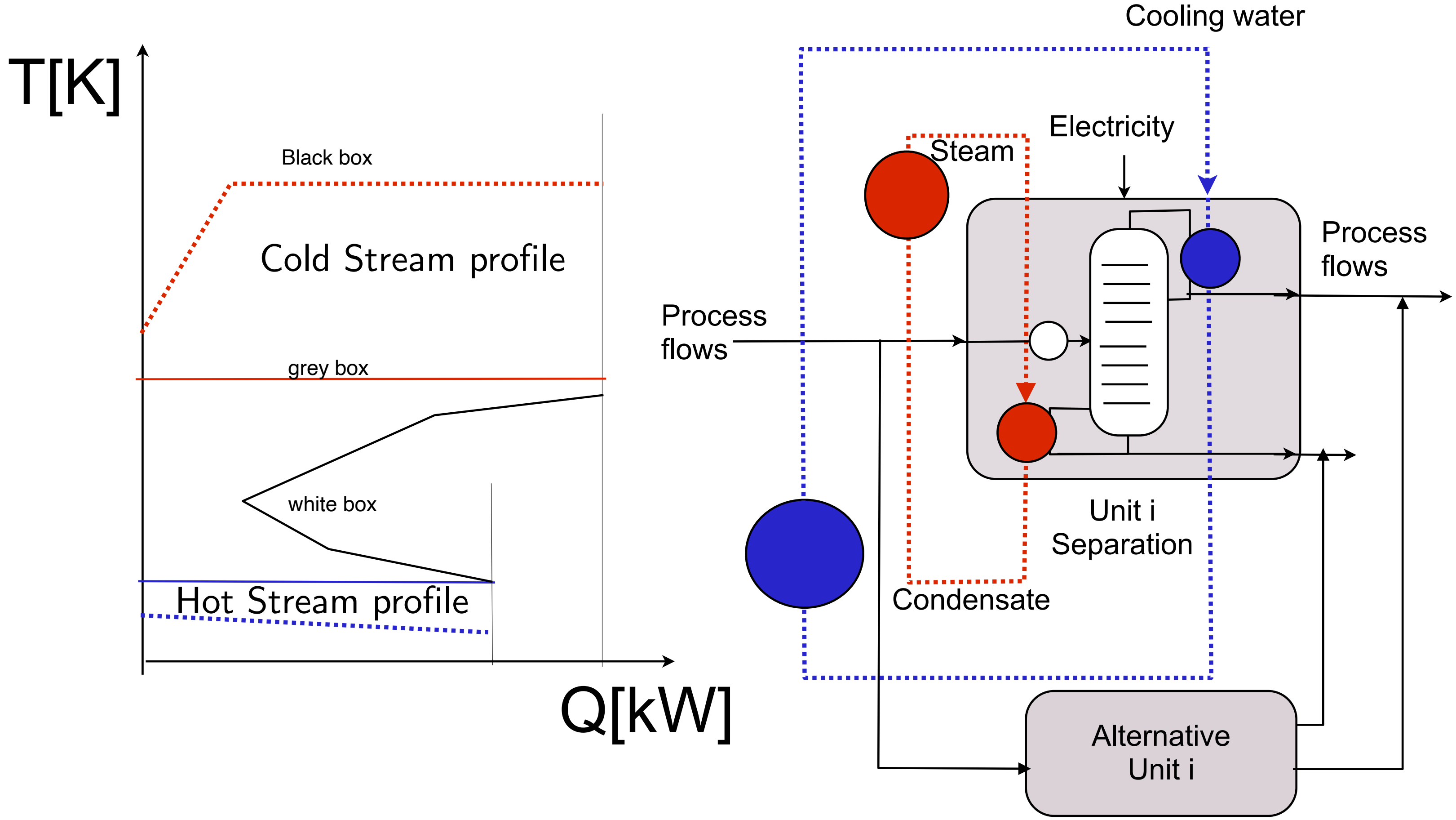
Sustainability metrics
CO2 footprint
Resources usage
Environmental impact

Thermodynamic metrics
Energy Efficiency
Mass balances
Exergy

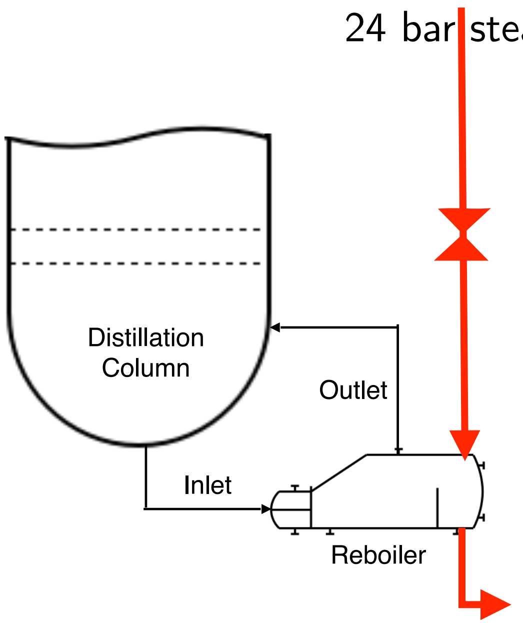
Economic metrics
CAPEX-OPEX
Technology Readiness
Retrofit and pay-back

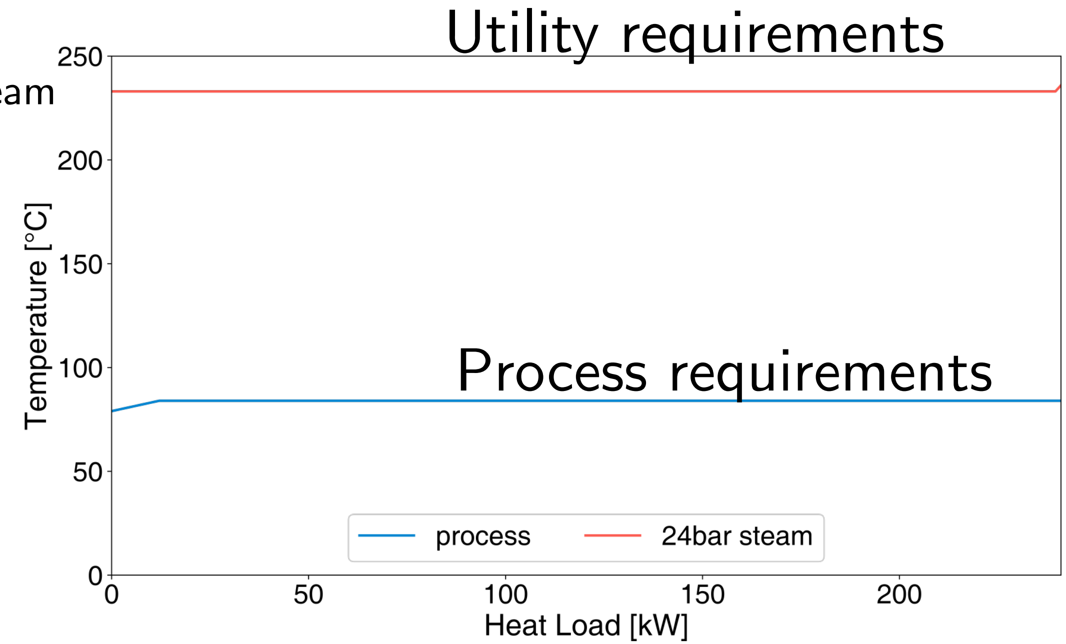
Unit Operation energetics : Heat transfer Interfaces

- Same unit operation : different heating and cooling profiles



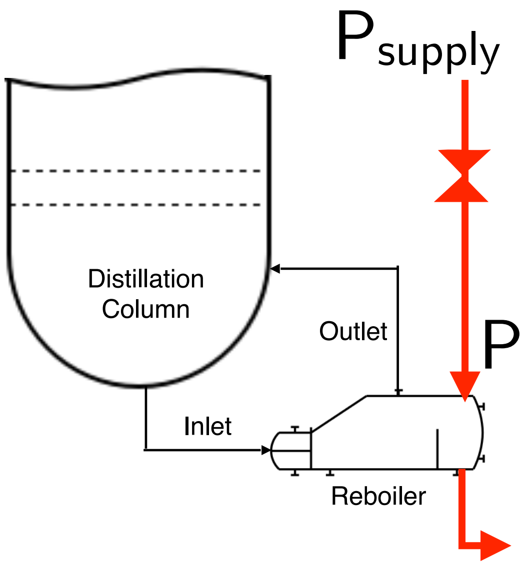
Heat exchanger transfer interfaces

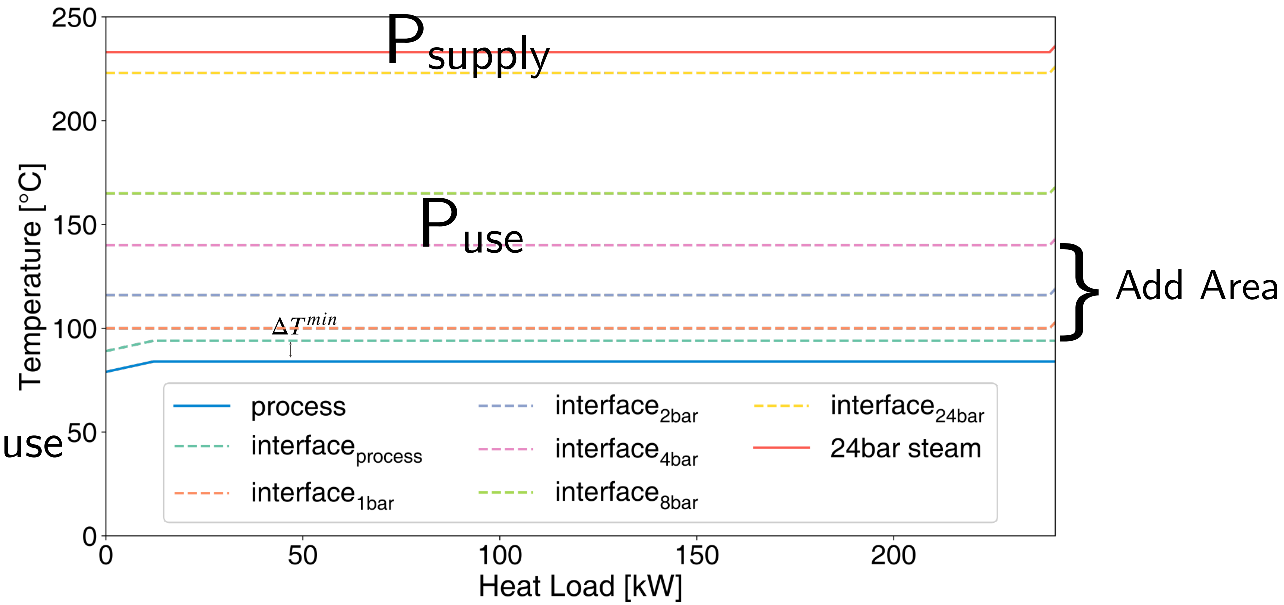




- current utility: 24 bar steam

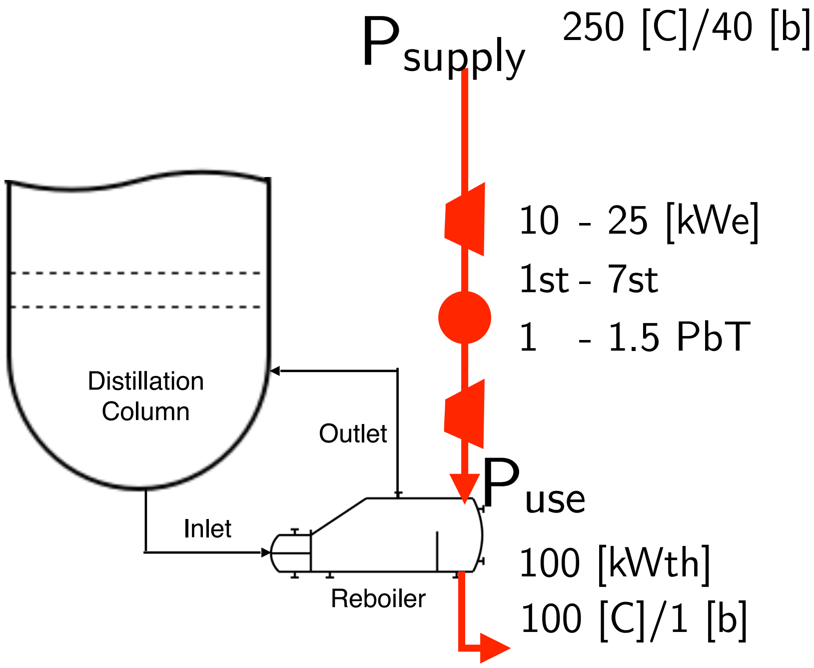
Analysing heat transfer interfaces





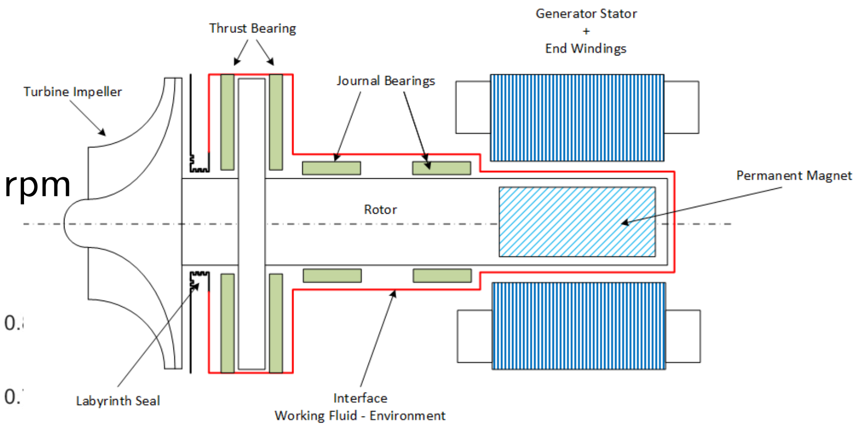
- current utility: 24 bar steam
- representation of the process with its current utility interface
  - allow the integration of only the current utility, or a higher temperature source
- Possible different heat exchange area => investment if $P_{supply} < P_{use}$

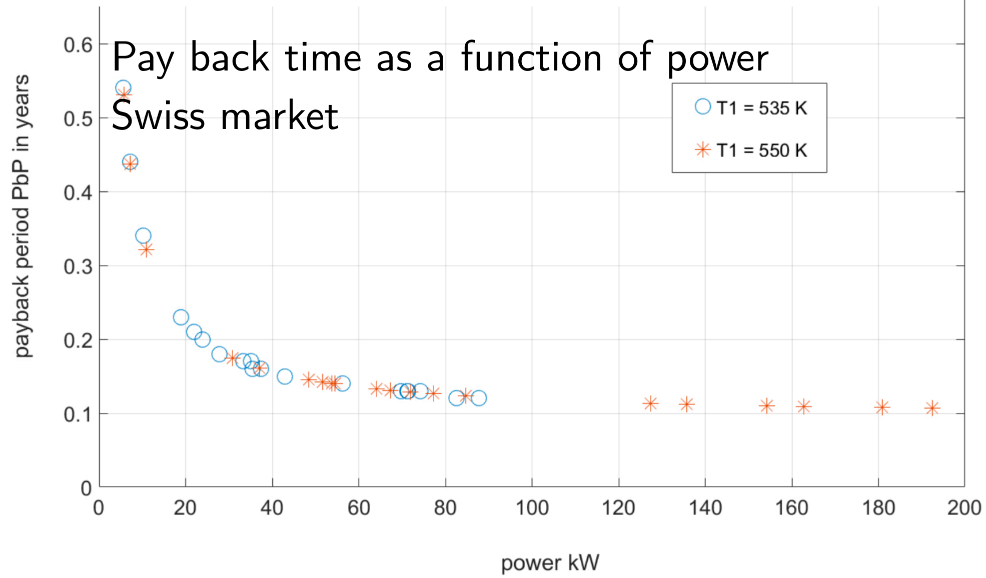
Replacing valves by Oil free Micro-Turbines



Micro-turbine design

100000 rpm
Oil free



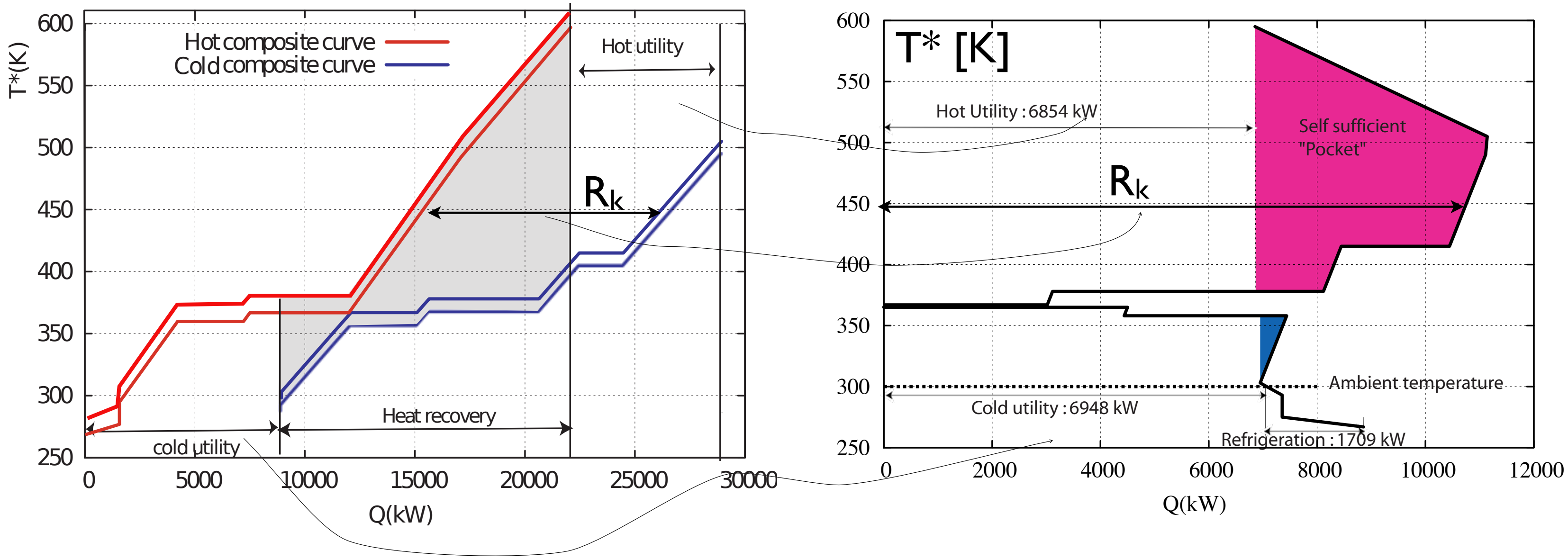


- Replace valves by micro turbines
- Pay back is low even for small flowrates
- multi stages => 3x the power but Pay Back *1.5

Weickgenannt A, Kantor I, Maréchal F, Schiffmann J. On the Application of Small-Scale Turbines in Industrial Steam Networks. Energies. 2021 Jan;14(11):3149.

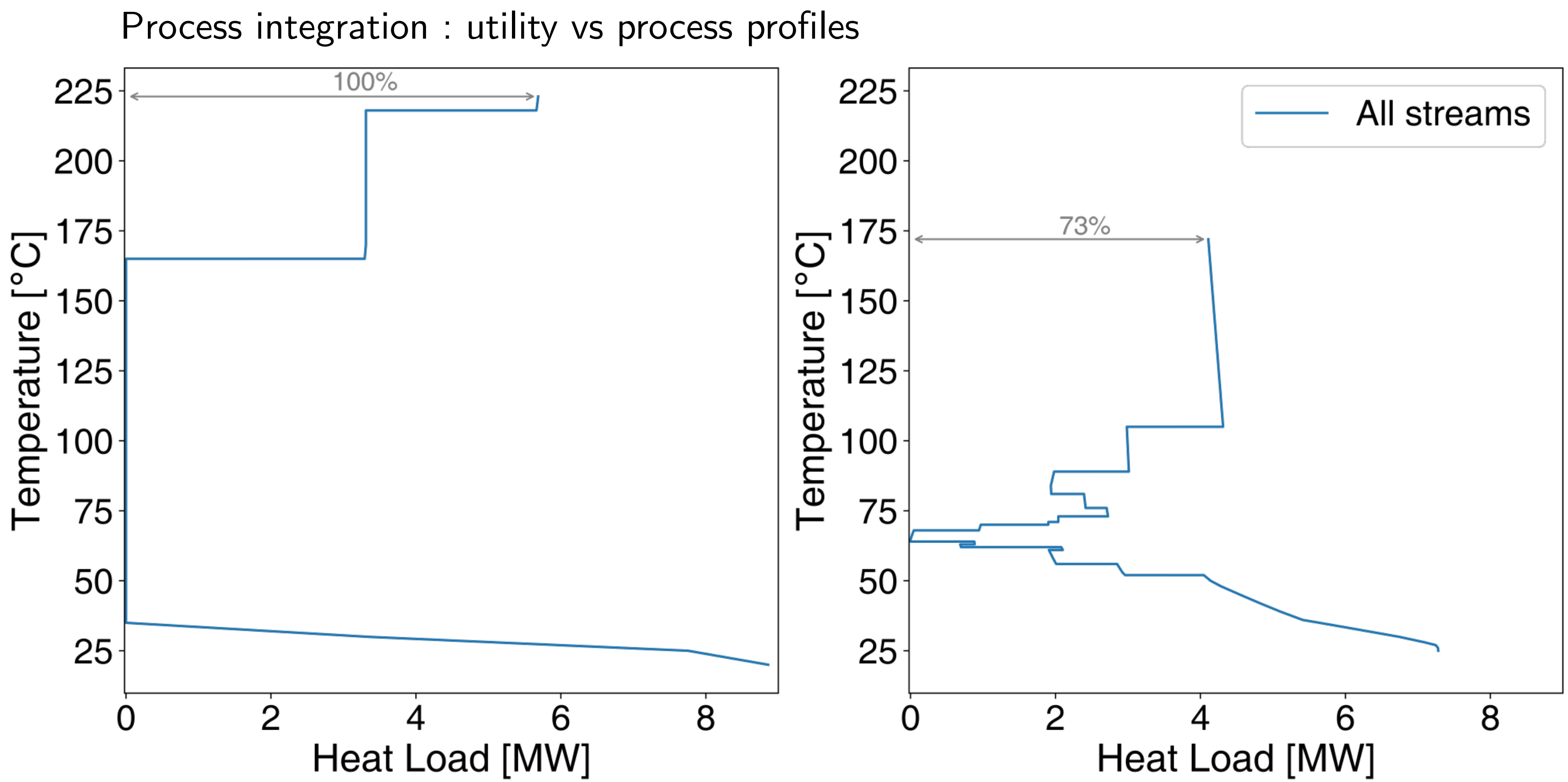
Heat recovery and heat cascade

- Corrected temperature $T^* = T + / - (\Delta T_{min}/2)$
- Graphical plot of the heat cascade : $[R_r, T^*_r]$ $r=1,n_r$



The Grand composite is the heat cascade representation in the corrected temperature domain. it represents the flow of energy in the system from higher temperatures to lower temperature. Above the pinch point is also represents the heat-temperature profile of the heat to be supplied to the system and below the pinch it represents the heat-temperature profile of the heat available in the process and to be removed from the system.

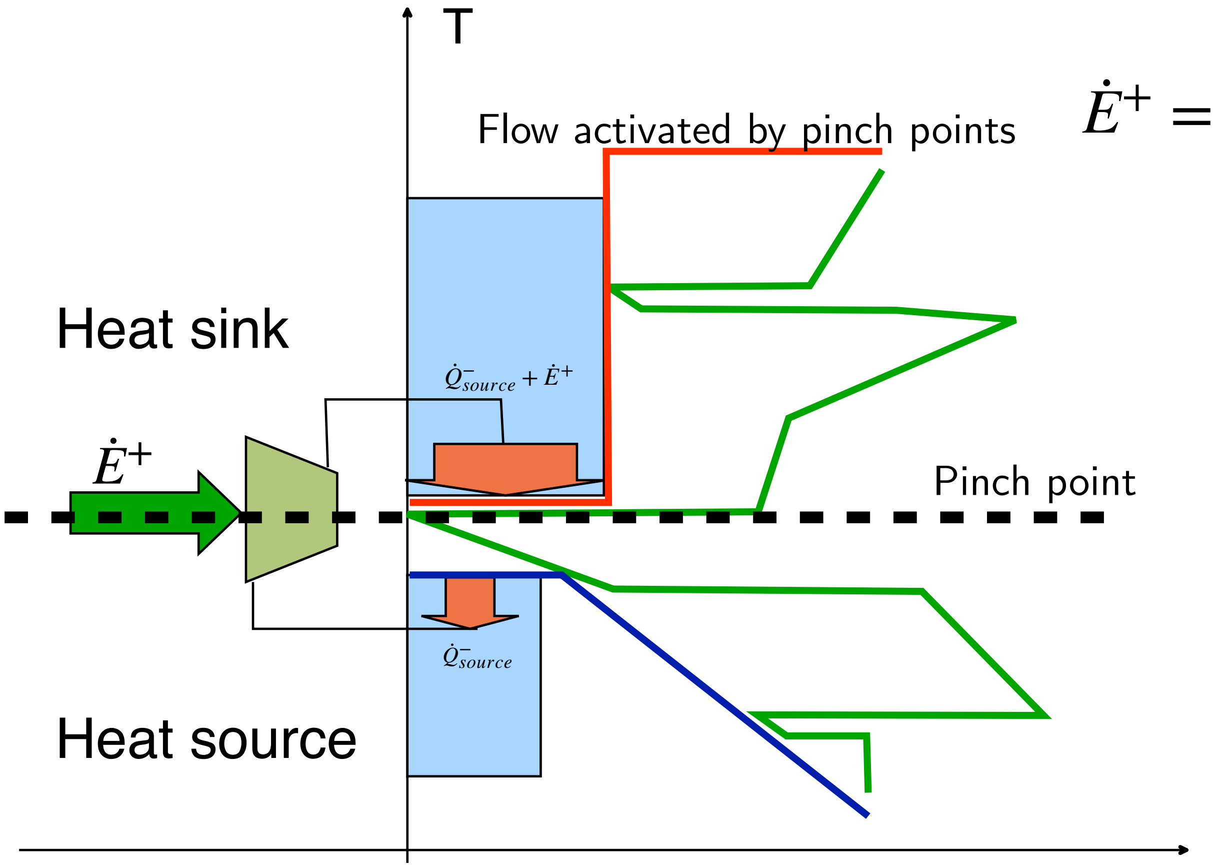
Heat recovery and heat cascade as a function of the interfaces



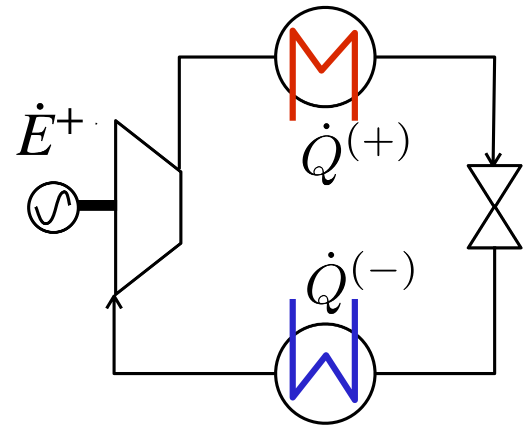
- ❖27% decrease in hot utility by heat recovery
- ❖Lower pressure utility
- ❖cogen or heat pumping ?

Integrating heat pumps from heat source to heat sink

$$\text{Savings Hot Utility} = c^{+}_{heat} \cdot (\dot{Q}^{-}_{source} + \dot{E}^{+}) - c^{+}_{elec} \cdot \dot{E}^{+}$$

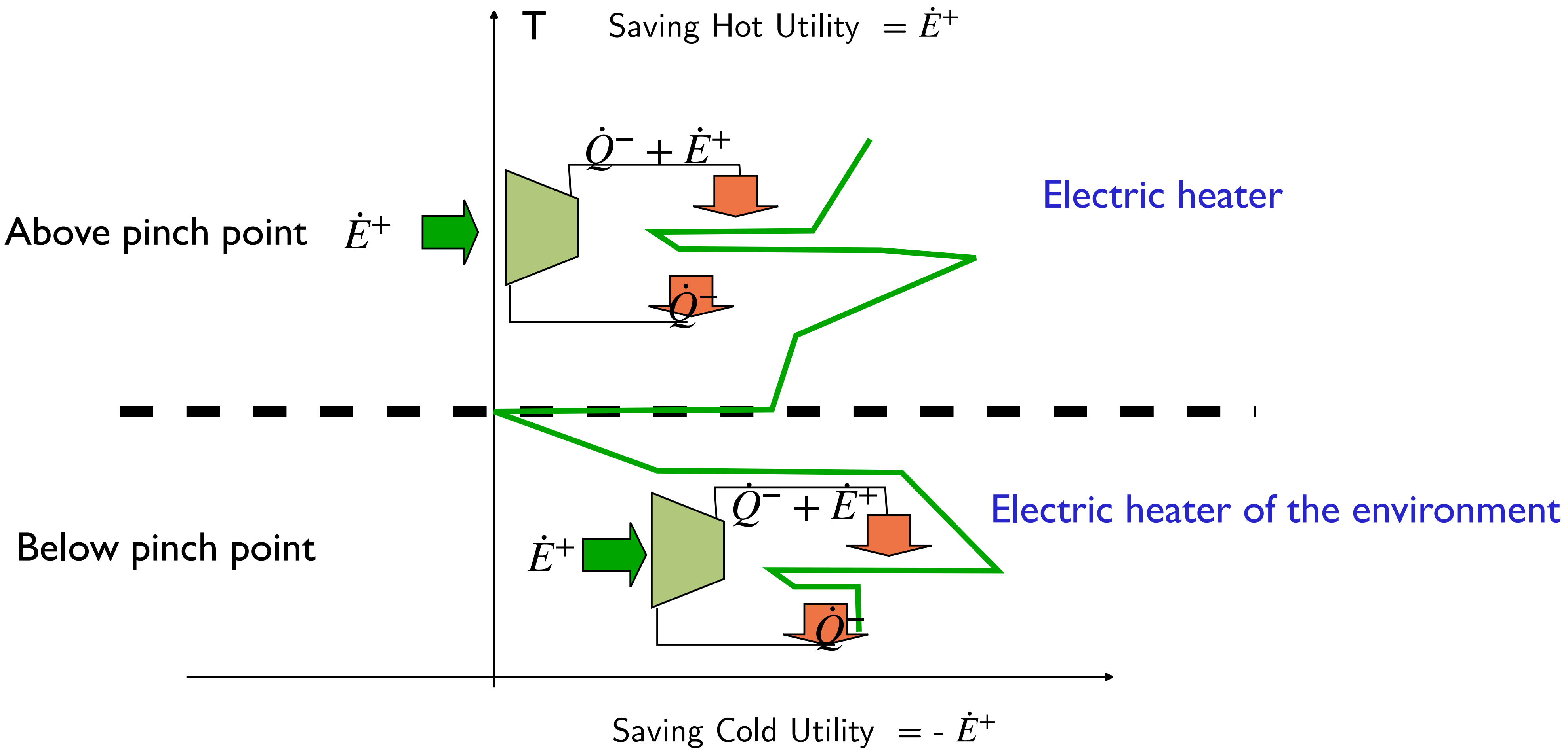


$$\dot{E}^{+} = \dot{Q}^{+}_{sink} \cdot \frac{1}{\eta_{Carnot}} \cdot \frac{\tilde{T}_{sink} - \tilde{T}_{source}}{\tilde{T}_{sink}}$$



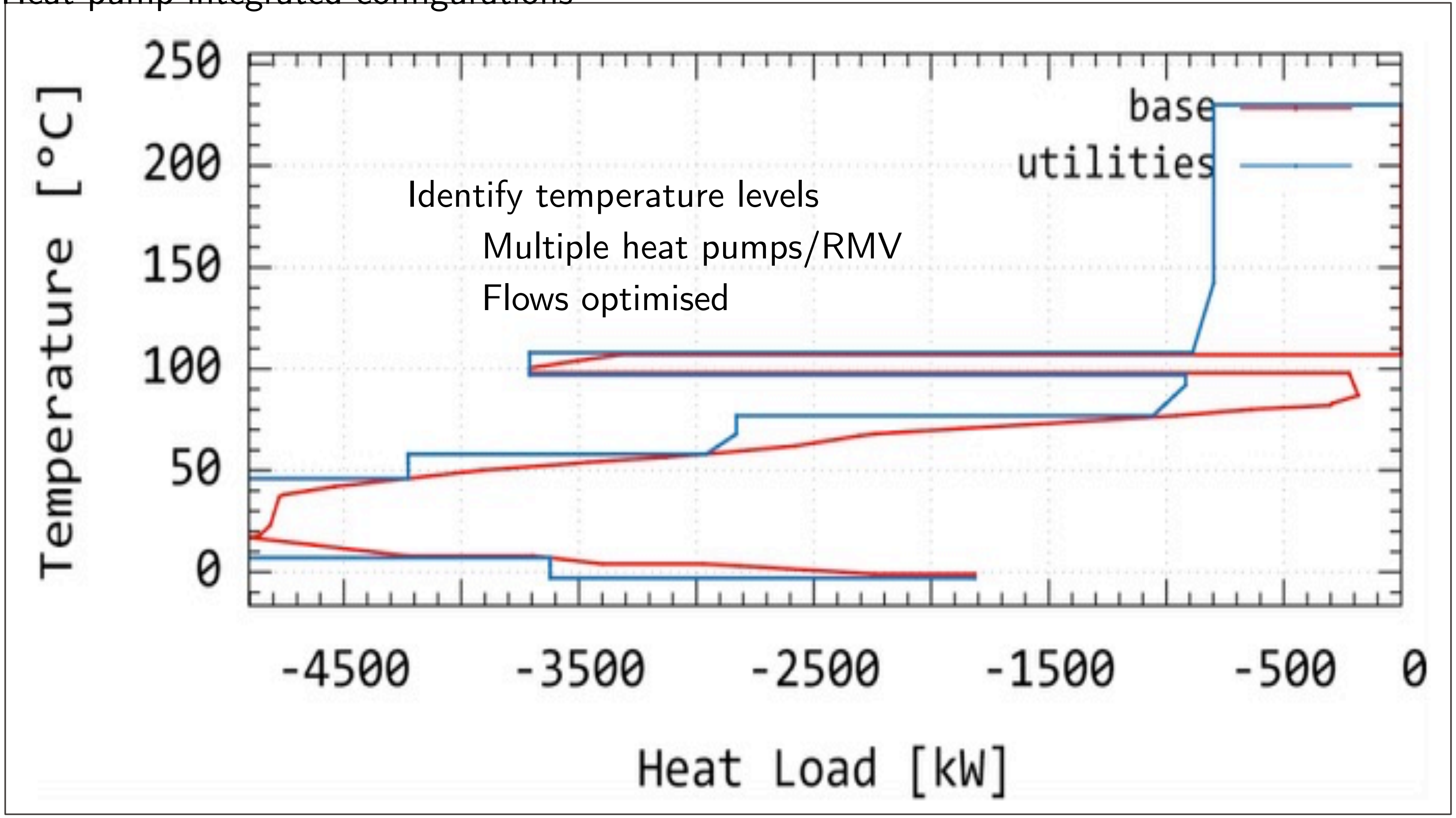
$$\text{Savings Cold Utility} = c^{+}_{cold} \cdot \dot{Q}^{-}_{source}$$

Miss placed heat pumps : above or below the pinch



Multi stage heat pump integration

Heat-pump integrated configurations

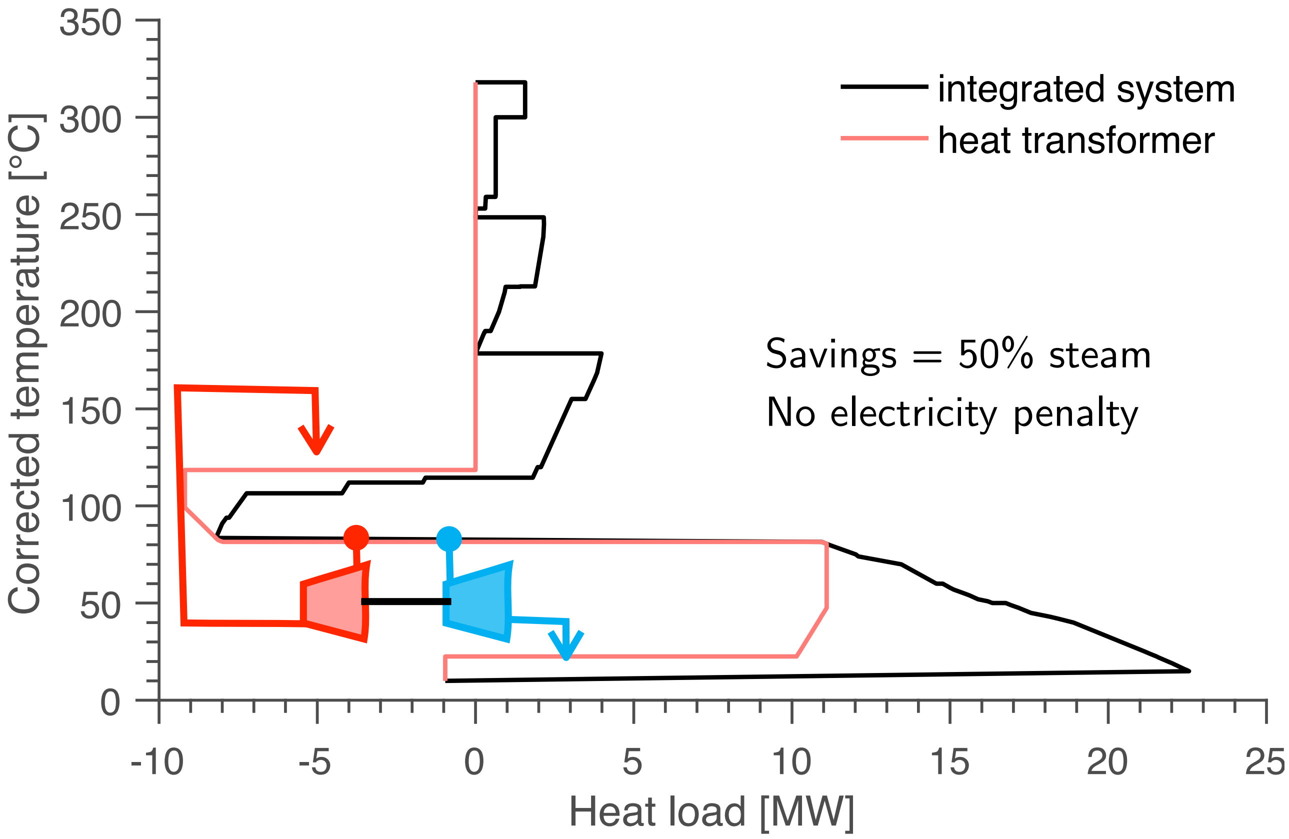


Identify temperature levels

- Multiple heat pumps/RMV
- Flows optimised

Wallerand, A. S., Kermani, M., Kantor, I., & Maréchal, F. (2018). Optimal heat pump integration in industrial processes. *Applied Energy*, *219*, 68-92.

Heat pumps and waste heat valorisation



Heat pump + ORC

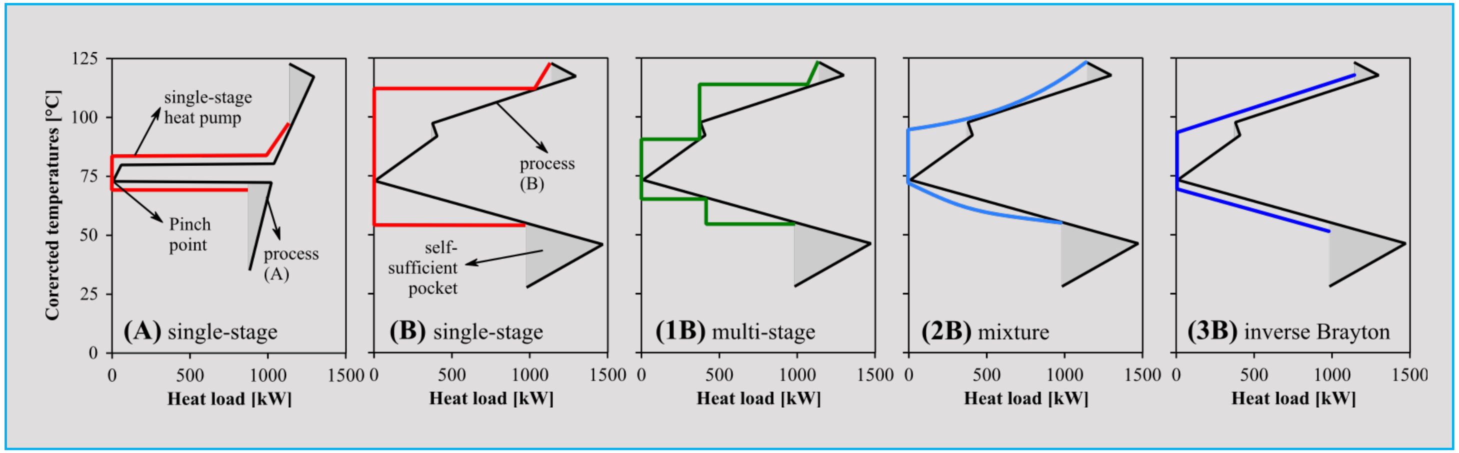
- Superstructure
- Fluids
- Turbines
- Optimisation

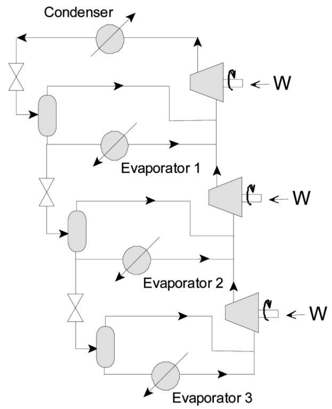
Kermani et al., Applied Energy, 2019

Heat pump integration : problem statement

A.S. Wallerand 2018. EPFL Thesis

- Heat pump type ?
- Working fluid ?
- Operating conditions ?
- Multi-stage compression / expansion ?
- Subcooling/preheating ?
- Flash drums ?
- Compressor types ?





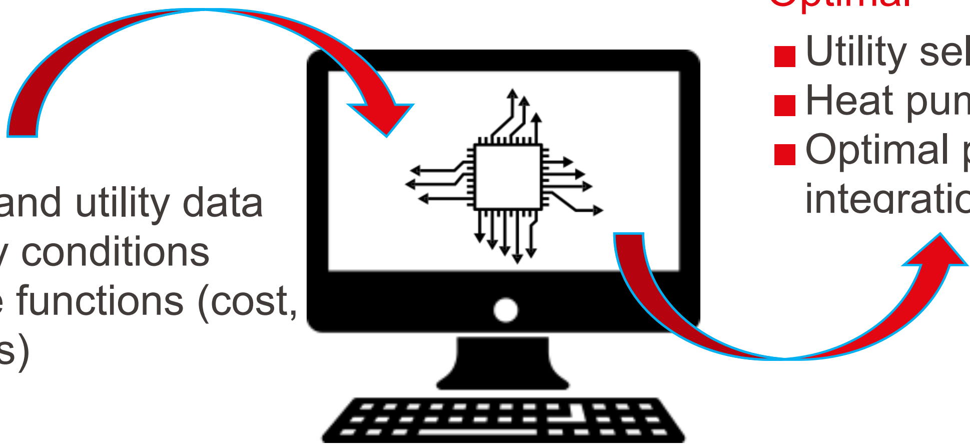
All adapted from: Del Nogal et al. (2008)

Systematic approach: superstructure optimisation

[1] Wallerand et al. 2018
[2] A.S. Wallerand. EPFL Thesis, Lausanne

Computer aided process engineering

- Process and utility data
- Boundary conditions
- Objective functions (cost, emissions)



Optimal

- Utility selection & sizing
- Heat pump design
- Optimal process integration

SCCER EFFICIENCY OF INDUSTRIAL PROCESSES

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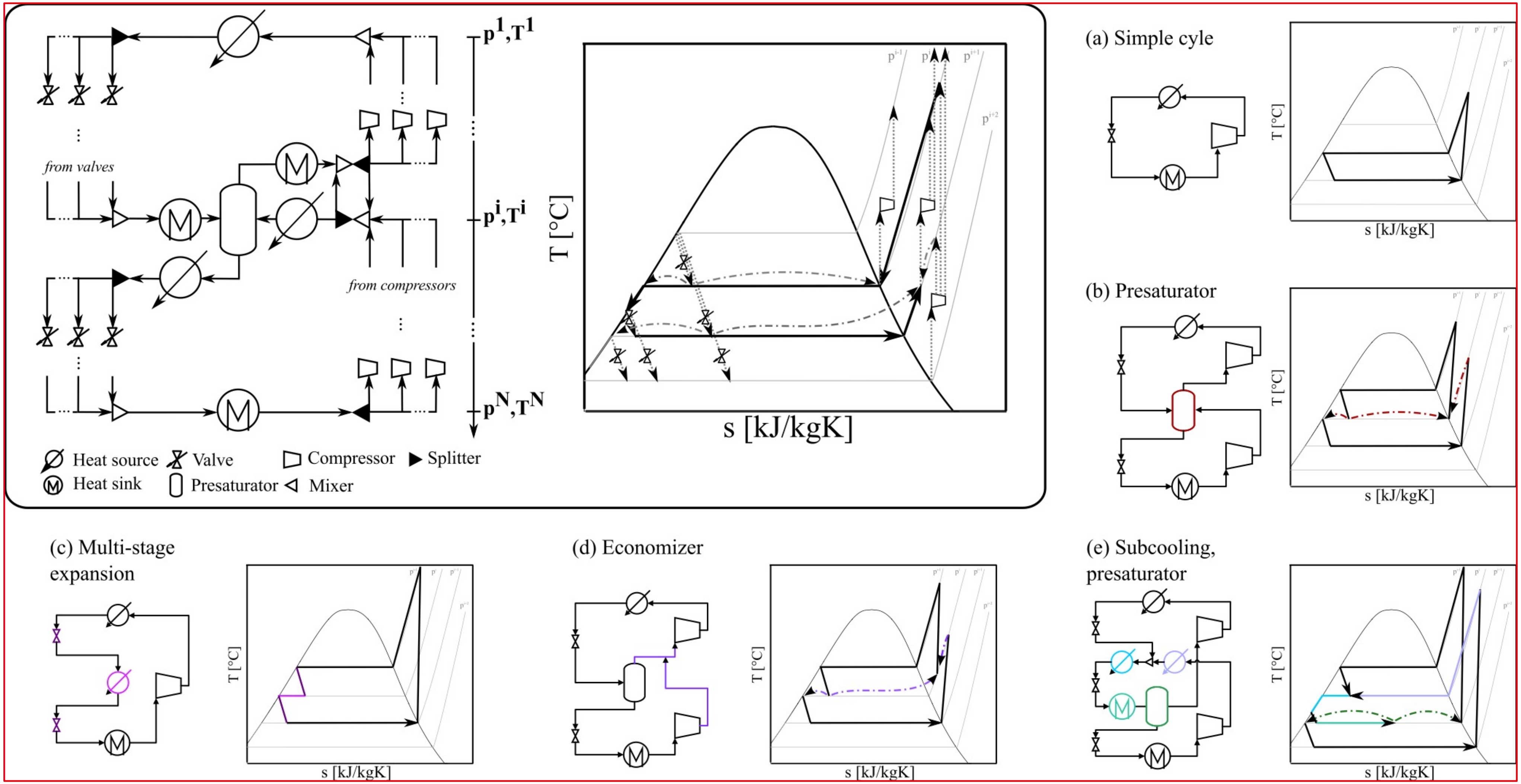
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

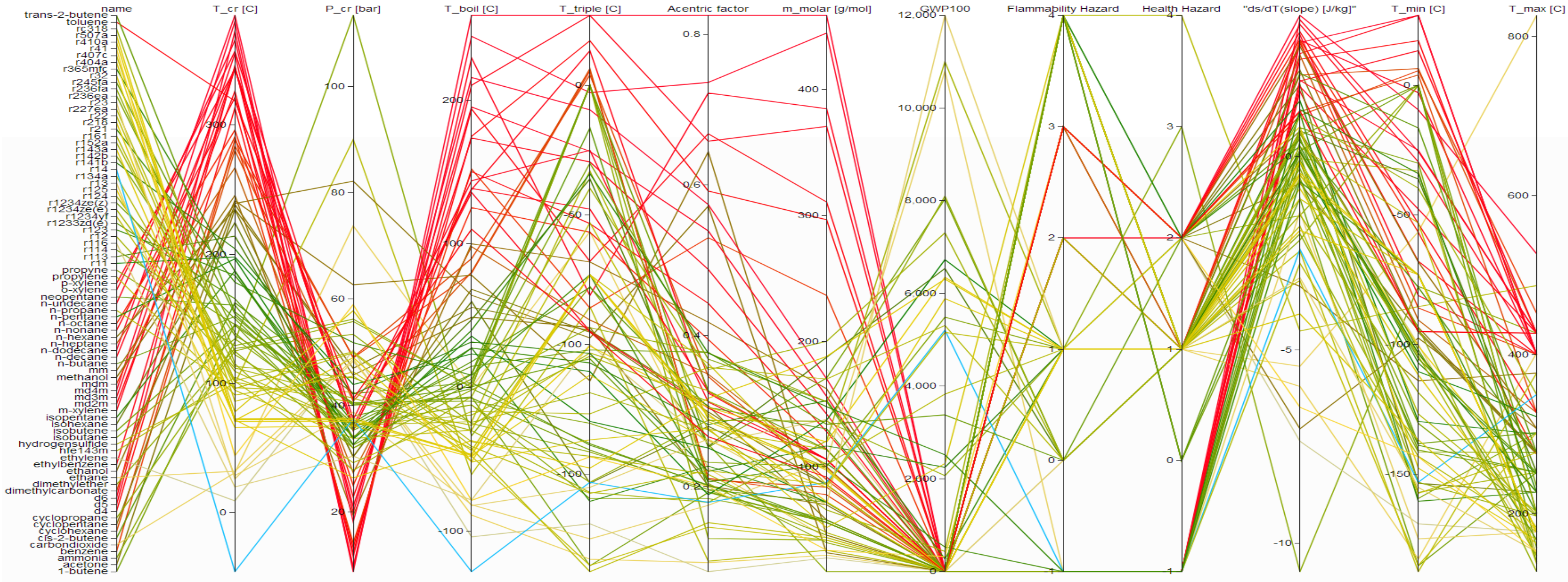
Bundesamt für Energie BFE
Swiss Federal Office of Energy SFOE

Systematic approach: superstructure model



Fluid data base

working fluids and their thermo-physical properties



Technology data base : compressors

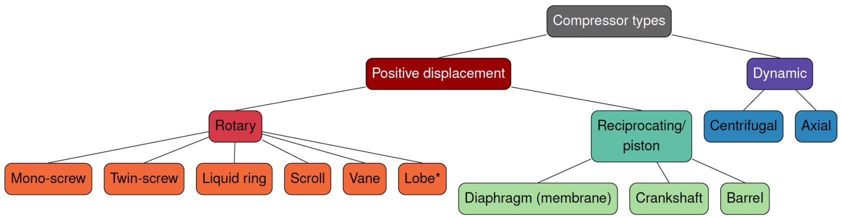
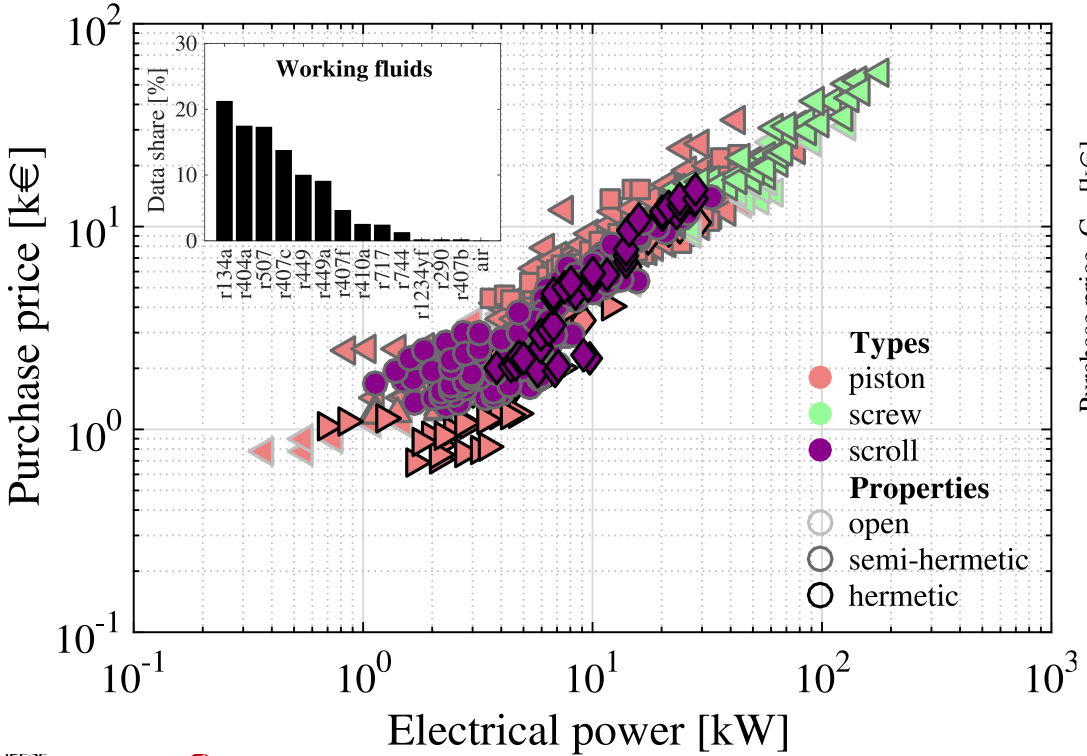
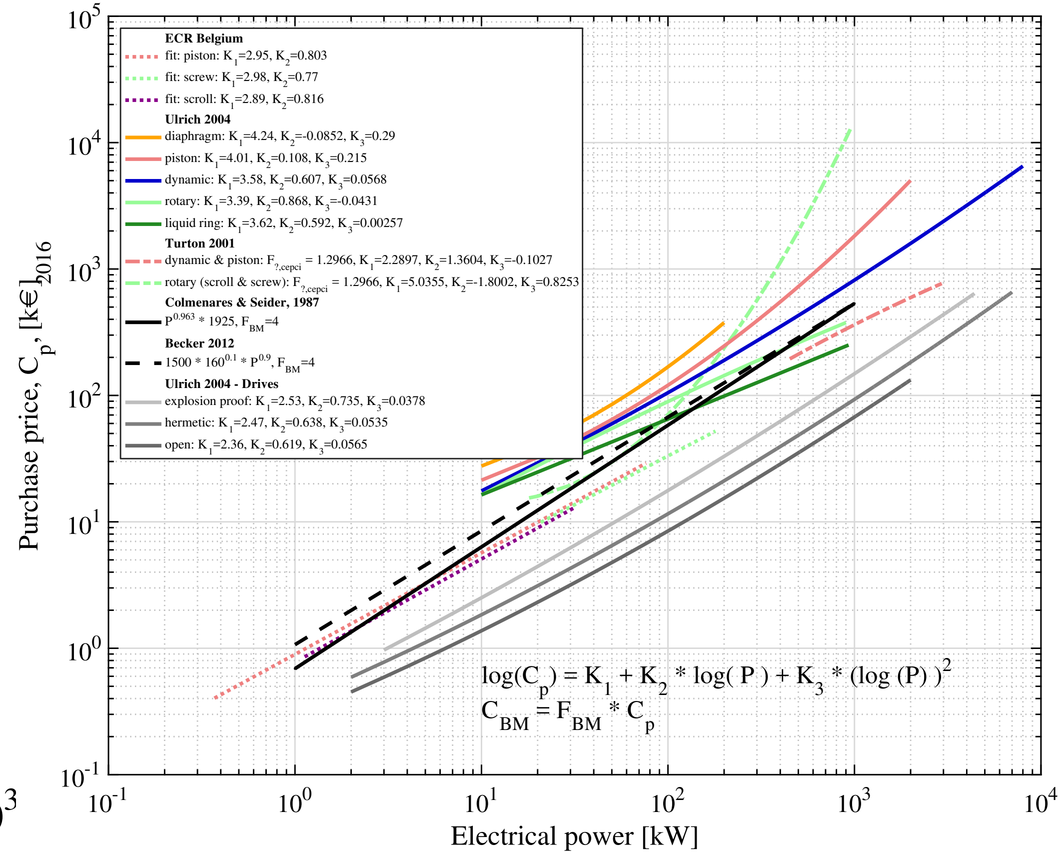


Figure 2: Tree diagram of compressor types, adapted from Wikipedia [8] with inspiration from Favrat [9]. Novel technologies are marked with asterisk (*).



Cost function review



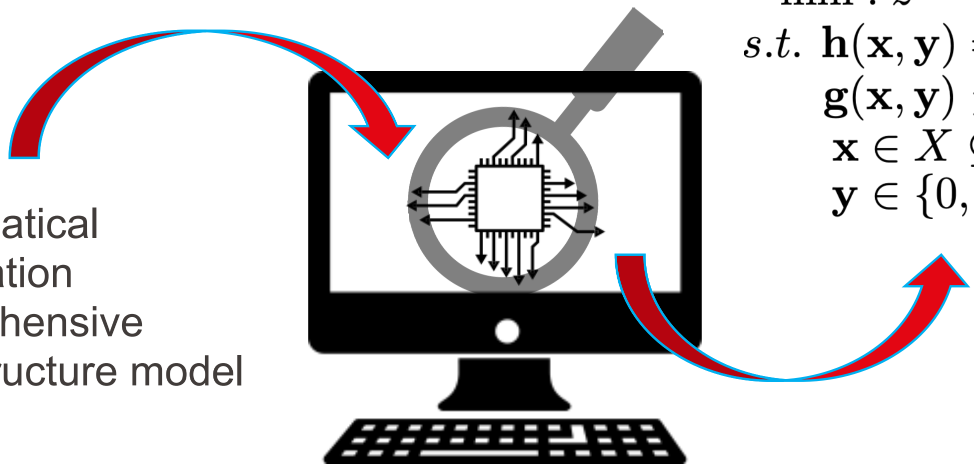
[1] A.Wallerand, BFE 2019

[2] Kantor et al., ECOS proceedings, 2018

Systematic approach: superstructure optimisation

[1] Wallerand et al. 2018
[2] A.S. Wallerand. EPFL Thesis, Lausanne

- Mathematical optimisation
- Comprehensive superstructure model



$$
\begin{aligned}
\min : z &= f(\mathbf{x}, \mathbf{y}) \\
s.t.\ \mathbf{h}(\mathbf{x}, \mathbf{y}) &= 0 \\
\mathbf{g}(\mathbf{x}, \mathbf{y}) &\leq 0 \\
\mathbf{x} &\in X \subseteq \mathbb{R}^n \\
\mathbf{y} &\in \{0, 1\}^m
\end{aligned}
$$

- find
  - sizes
  - fluids
  - configuration
  - operating conditions

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eip

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Bundesamt für Energie BFE
Swiss Federal Office of Energy SFOE

Optimisation to select and calculate flows in the system

$$\min_{R_r, y_w, f_w, E^+, E^-} \left(\sum_{w=1}^{n_w} C2_w f_w + C_{el^+} E^+ - C_{el^-} E^-\right) * t + \sum_{w=1}^{n_w} C1_w y_w + \frac{1}{\tau}\left(\sum_{w=1}^{n_w} (CI1_w y_w + CI2_w f_w)\right)$$

Operating cost

Fixed maintenance

Investment

Subject to : Heat cascade constraints

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

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

Electricity consumption

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

Electricity production

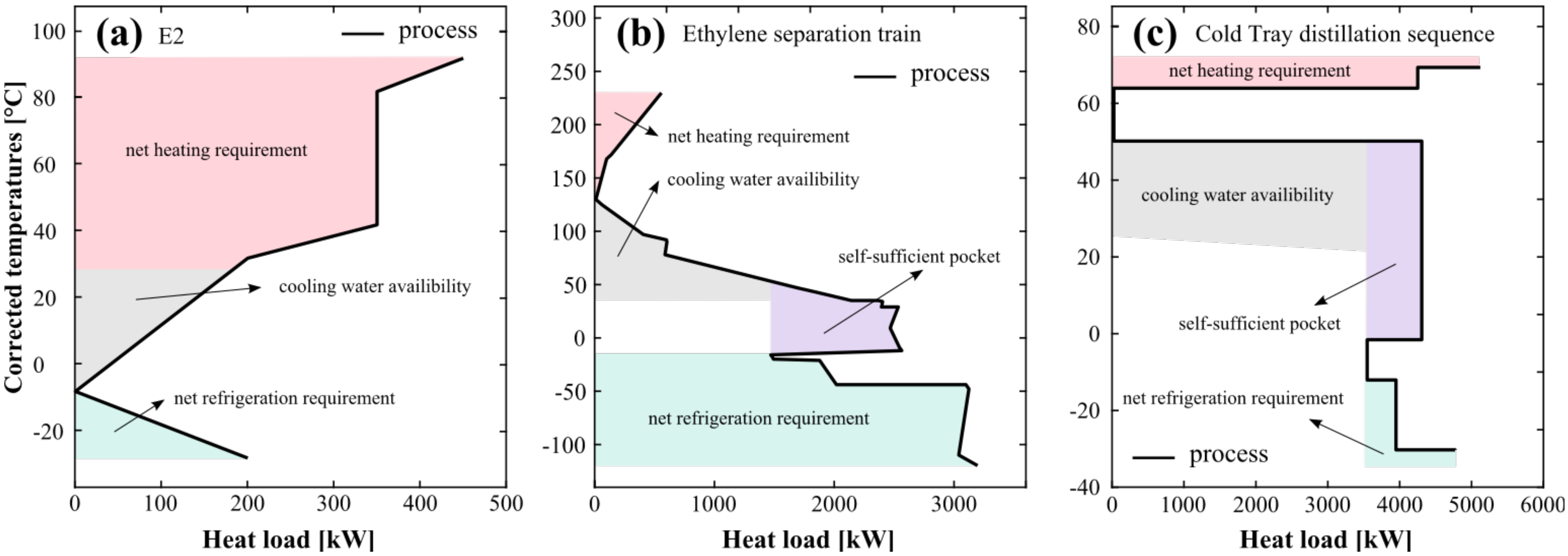
$$\sum_{w=1}^{n_w} f_w e_w + E^+ - E_c - E^- = 0$$

Energy conversion Technology selection

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

Systematic approach: validation

[1] Wallerand et al. 2018
[2] A.S. Wallerand. EPFL Thesis, Lausanne



Systematic approach : validation

[1] Wallerand et al. 2018
[2] A.S. Wallerand. EPFL Thesis, Lausanne
[3] Shelton and Grossmann 1986
[4] Colmenares and Seider 1989
[5] Colmenares and Seider 1987

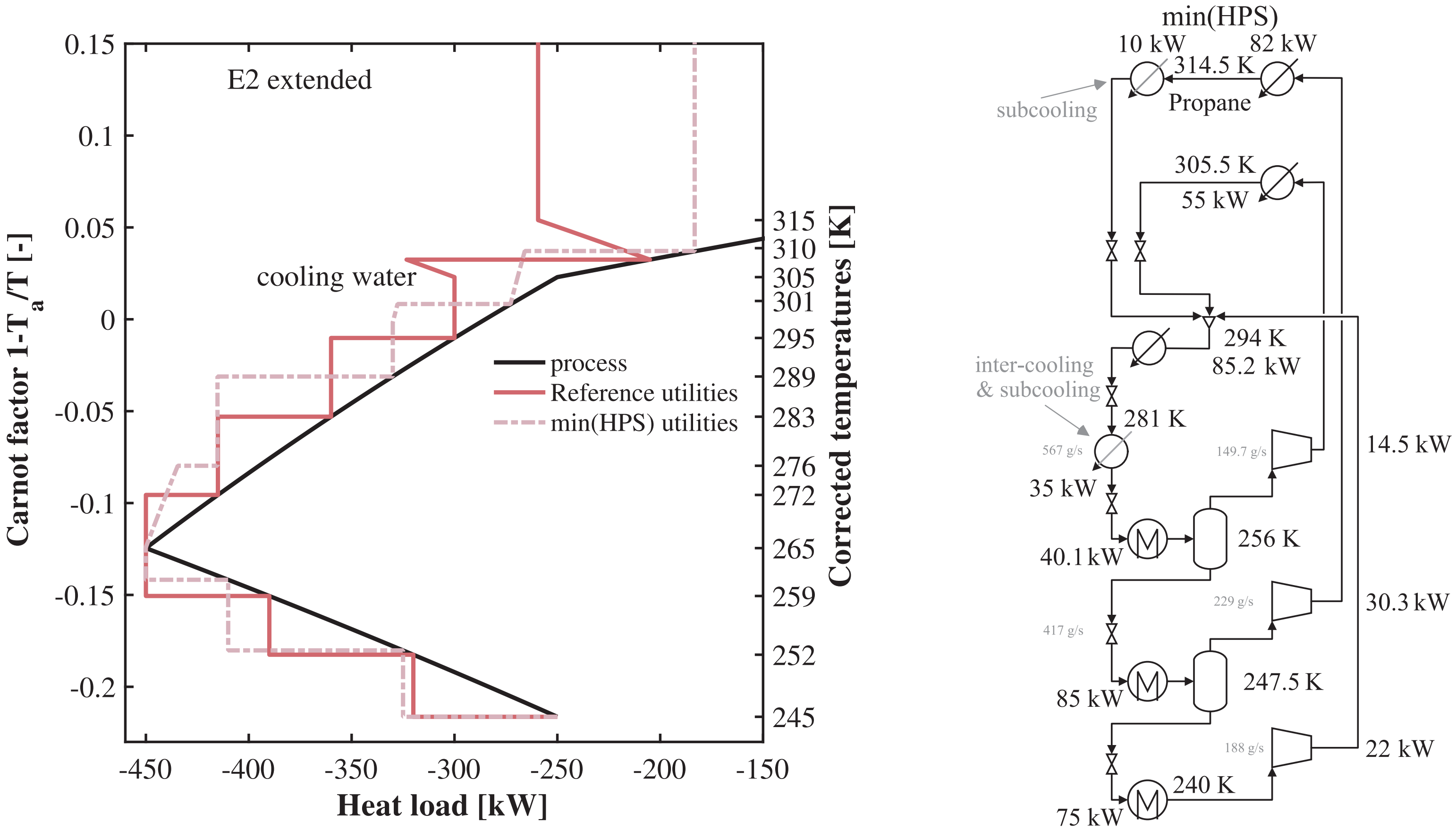
Improvement vs state of the art

Literature comparison[1,2]

		E2[3]		***Ethylene***[4]		***Cold Tray***[5]	
		Reference	min(HPS)	Reference	min(HPS)	Reference	min(HPS)
Opex							
Cooling water	$/y	0	0	25,020	23,150	29,930	4,810
Steam	$/y	10,460	10,370	0	0	287,090	39,310
Electricity	$/y	27,620	28,040	327,580	223,340	96,370	189,900
Capex							
No. of compressors	#	6	4	5	5	3	5
Compressors	$/y	54,710	49,630	230,810	159,140	56,380	109,220
TAC	$/y	92,790	88,050	583,410	405,630	469,770	343,230
Improvement	%	0	5.1%	0%	30.5%	0%	26.9%
$COP_{refrigeration}$	-	4.4	4.3	1.8	2.6	5.3	5.8

A multiple levels heat pumping system integration

CARNOT Integrated composite curves : the area between the two curves defines the exergy losses in the heat transfer



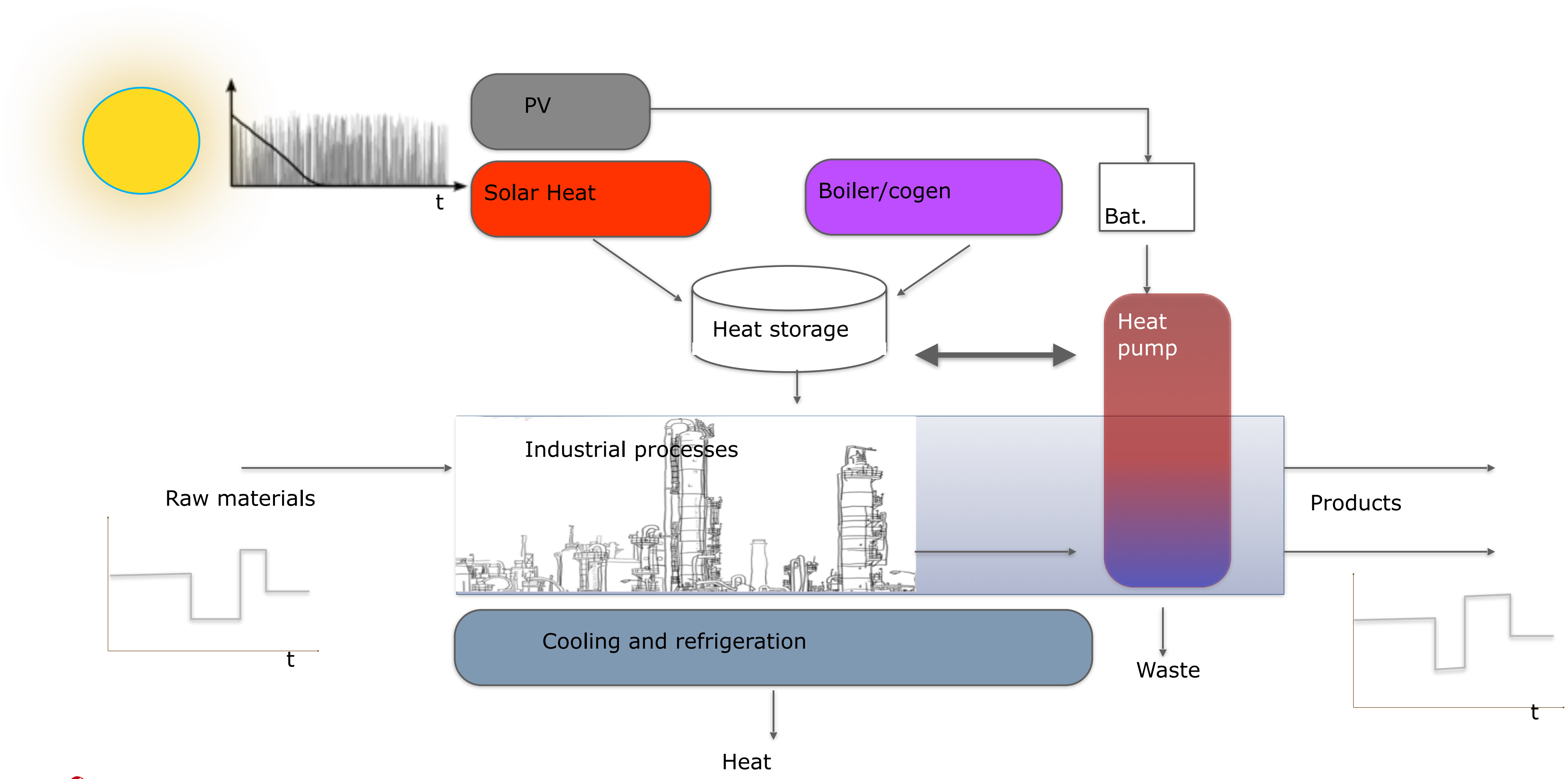
(a) Integrated composite curves of optimized and reference case.

(b) Flowsheet of optimum case.

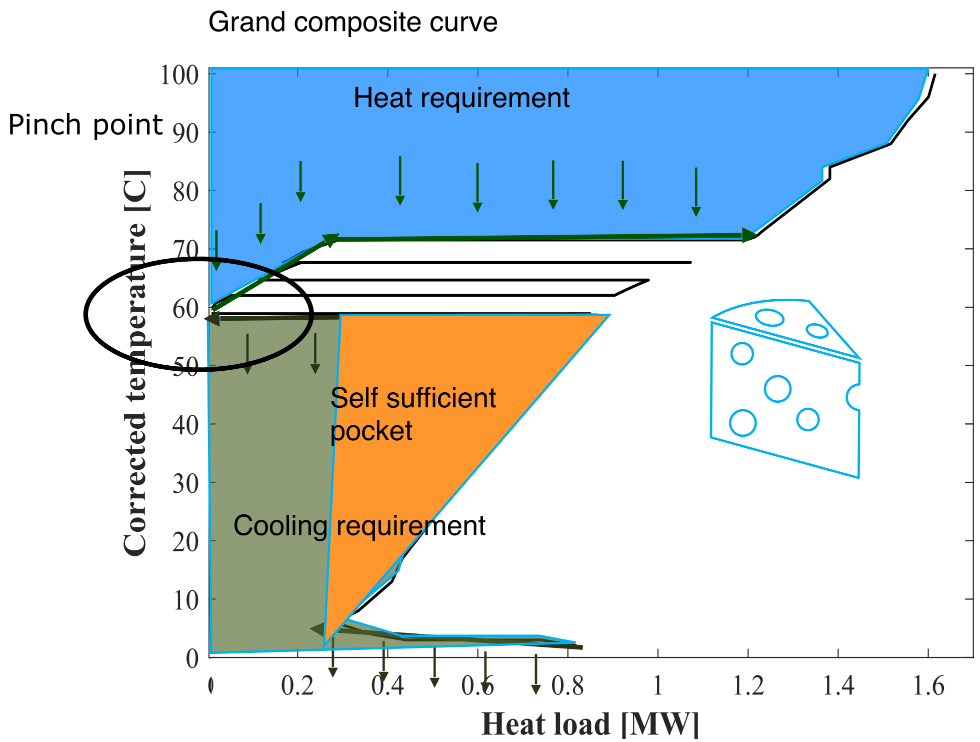
[1] Wallerand et al. 2018

Fig. 15. Extended case *E2* minimum TAC solution.

Integrating renewable energy

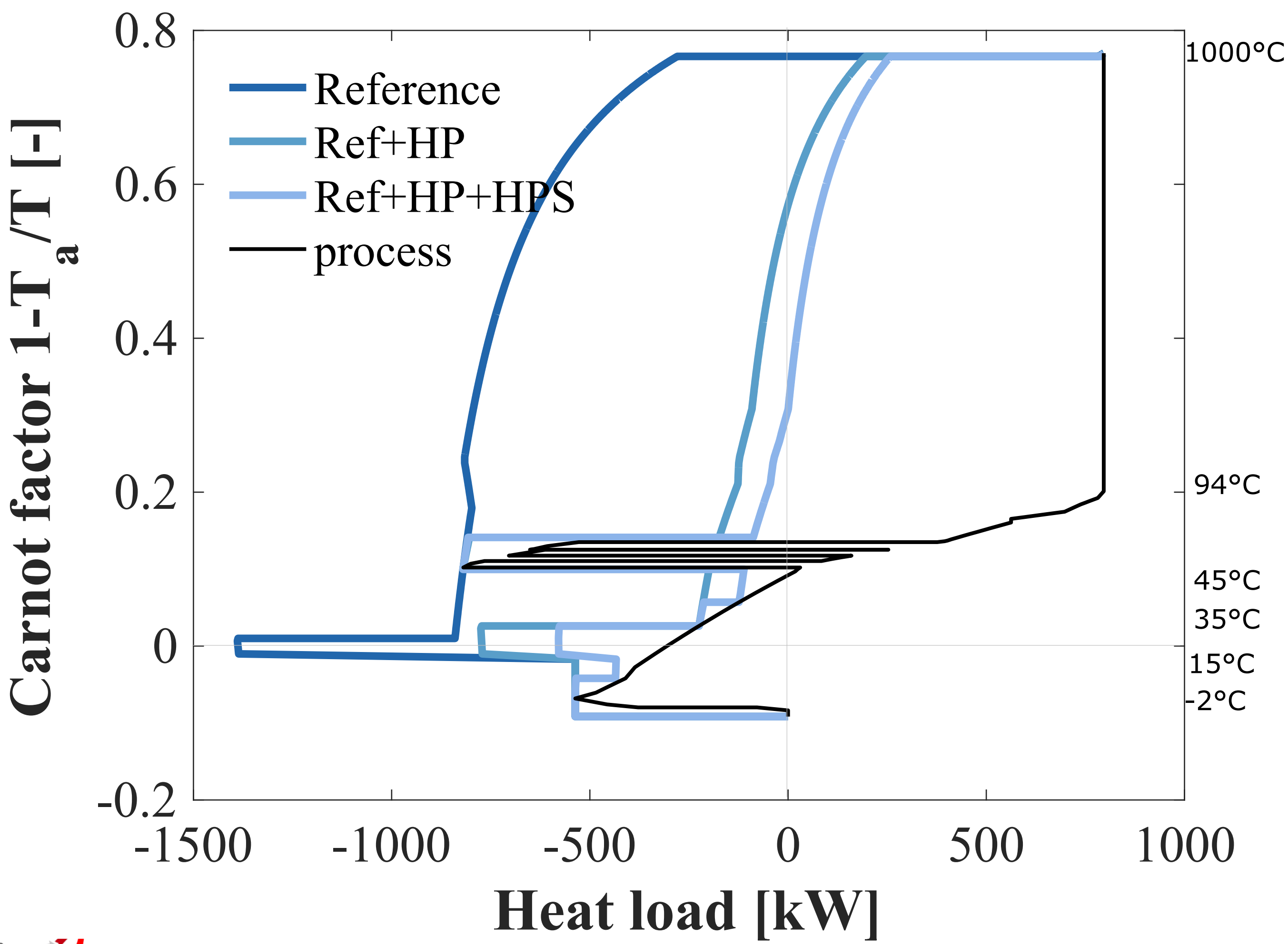


Dairy process



Dairy case study: heat pump integration

Exergy integrated composite curves



Boiler

Reference
48 kWh/t_{raw}

Ref+HP
27 kWh/t_{raw}

Ref+HP+HPS
24 kWh/t_{raw}

-44%

-50%

Relative COP
27–>24 kWh_{ng}/t_{raw}
4.598 —> 4.603 kWh_{el}/t_{raw}
–> dCOP = dQ/dE = 650

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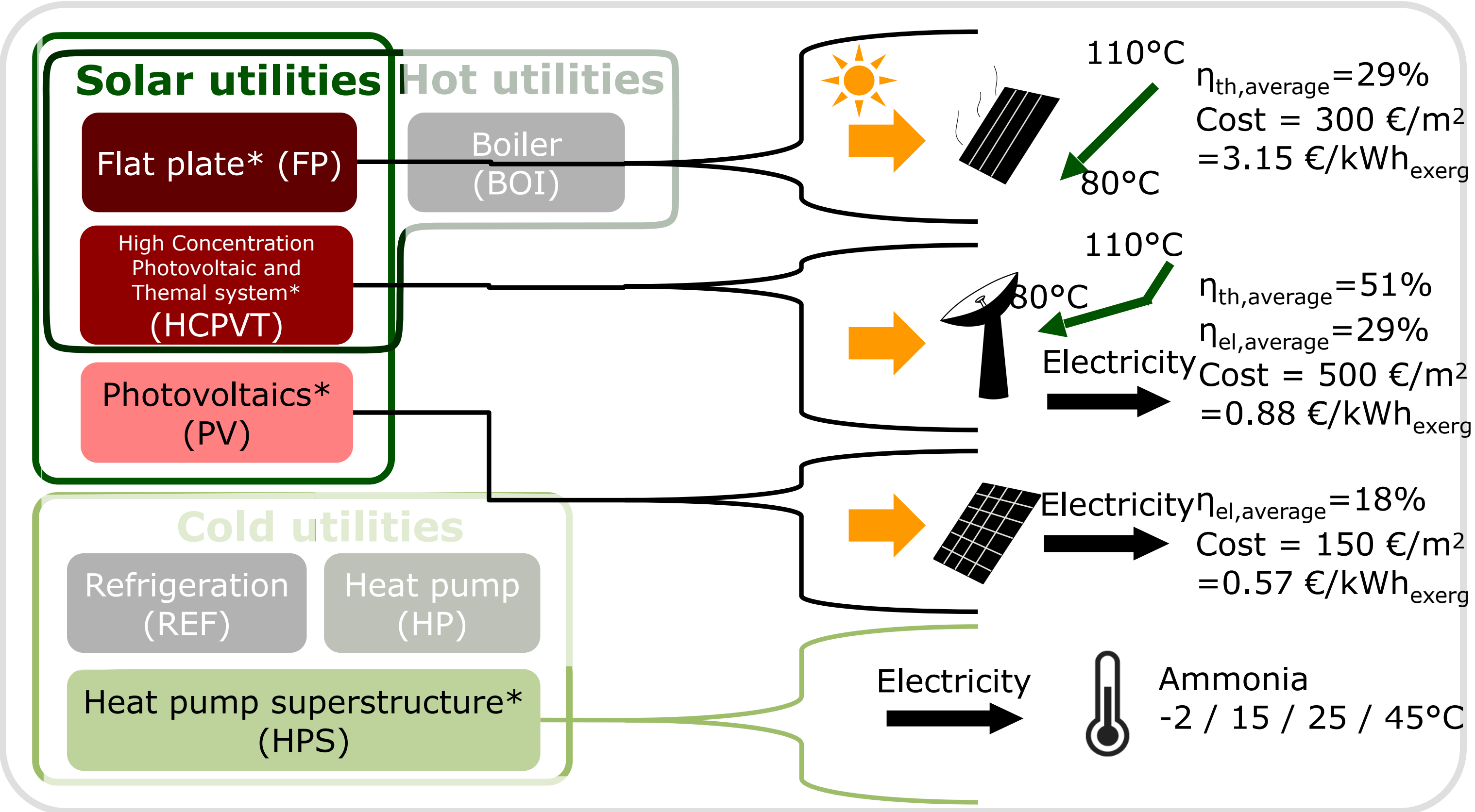
Engineering

Case study: Solar energy and heat-pumps



(1) Tehnomont, Solarna Oprema Pula. SKT 100; (2) SunTech, HyPro, STP 290S-20; (3) Airlight Energy Holding SA

Targeting problem : multi-period problem

$$\min_{R_r^p, y_w^p, u_w^p, y_w^{max}, u_w^{max}} \sum_{p=1}^{P}\left(\sum_{w=1}^{W} \mathrm{OP}_{1,p}^{w} \cdot y_p^w + \mathrm{OP}_{2,p}^{w} \cdot u_p^w\right) \cdot \Delta t_p \cdot occ_p + ann \cdot \sum_{w=1}^{W} \mathrm{IV}_1^w \cdot y^{w,max} + \mathrm{IV}_2^w \cdot u^{w,max}$$

$u_p^w \in ¢^+ \quad \forall w \in \mathrm{W}, p \in \mathrm{P}$

$y_p^w \in \{0,1\} \quad \forall w \in \mathrm{W}, p \in \mathrm{P}$

P={1,2,3...,240}

subject to
heat cascade constraints:

$$\sum_{w=1}^{W} u_p^w \cdot \mathrm{Q}_{p,r}^w + \sum_{s=1}^{S} \mathrm{Q}_{s,r} \cdot \mathrm{L}_{s,r} + R_{p,r+1} - R_{p,r} = 0 \quad \forall p \in \mathrm{P}, r \in \mathrm{RT}$$

thermodynamic feasibility:

$$R_{p,1} = 0, R_{p,N_{RT}+1} = 0, R_{p,r} \geq 0 \quad \forall r \in 1,\ldots,N_{RT}+1, p \in P$$

maximum size of operation and existence of technology w:

$$u^{w,max} - u_p^w \geq 0 \quad \forall w \in W, p \in P$$

$$y^{w,max} - y_p^w \geq 0 \quad \forall w \in W, p \in P$$

$$\mathrm{U}^{w,min} \cdot y_p^w \leq u_p^w \leq \mathrm{U}^{w,max} \cdot y_p^w \quad \forall w \in W, p \in P$$

Solar technologies

$$u^{ws,max} - u_p^{ws} = 0 \quad \forall ws \in W_s, p \in P$$

Targeting problem : multi-period + storage problem

$$\min_{R_r^p, y_w^p, u_w^p, y_w^{\max}, u_w^{\max}} \sum_{p=1}^{P}\left(\sum_{w=1}^{W} \mathrm{OP}_{1,p}^{w} \cdot y_p^w + \mathrm{OP}_{2,p}^{w} \cdot u_p^w\right) \cdot \Delta t_p \cdot \mathrm{occ}_p + \mathrm{ann} \cdot \sum_{w=1}^{W} \mathrm{IV}_1^w \cdot y^{w,\max} + \mathrm{IV}_2^w \cdot u^{w,\max}$$

$u_p^w \in \text{¢}^{+} \quad \forall w \in \mathrm{W}, p \in \mathrm{P}$

$y_p^w \in \{0,1\} \quad \forall w \in \mathrm{W}, p \in \mathrm{P}$

P={1,2,3...,240}

subject to

Storage model

$$M_{S,t} - M_{0,S} = \sum_{st=1}^{t} d_t \cdot \left(\dot{M}_{h,S,st} + \dot{M}_{h_{losteq},S,st} - \dot{M}_{c,S,st}\right)$$

$S \in STO : S = 1, \ \forall \ t = 1, \ldots T$

$$M_{S,t} - M_{0,S} = \sum_{ts=1}^{t} d_{ts} \cdot \left(\dot{M}_{c,S-1,ts} + \dot{M}_{h,S,ts} + \dot{M}_{h_{losteq},S,ts} - \dot{M}_{c,S,ts} + \dot{M}_{h,S+1,ts} - \dot{M}_{h_{losteq},S-1,ts}\right)$$

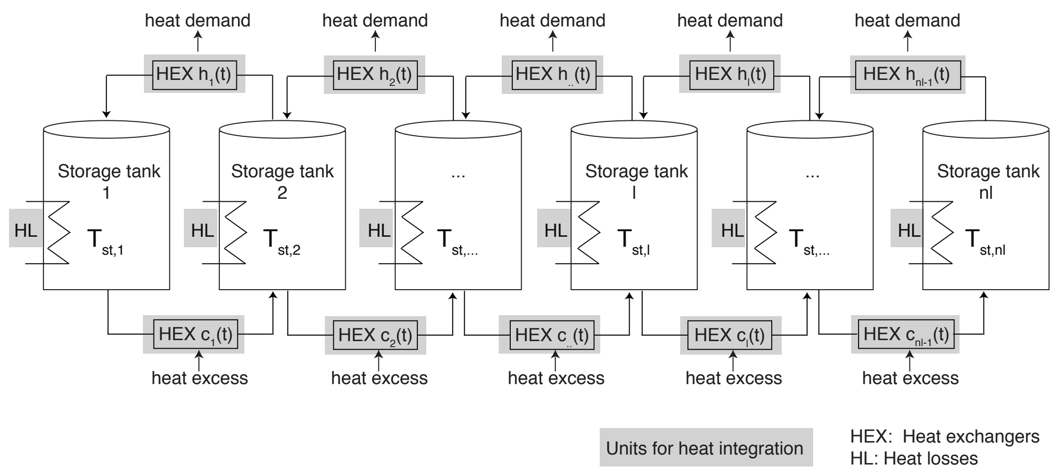
$\forall \ S \in STO : S = 2, \ldots N_S - 1, \ \forall \ t = 1, \ldots T$

$$M_{S,t} - M_{0,S} = \sum_{ts=1}^{t} d_{ts} \cdot \left(\dot{M}_{c,S-1,ts} - \dot{M}_{h,S-1,ts} - \dot{M}_{h_{lost},S-1,ts}\right)$$

$\forall \ S \in STO, \ S = N_S, \ \forall \ t = 1, \ldots T$

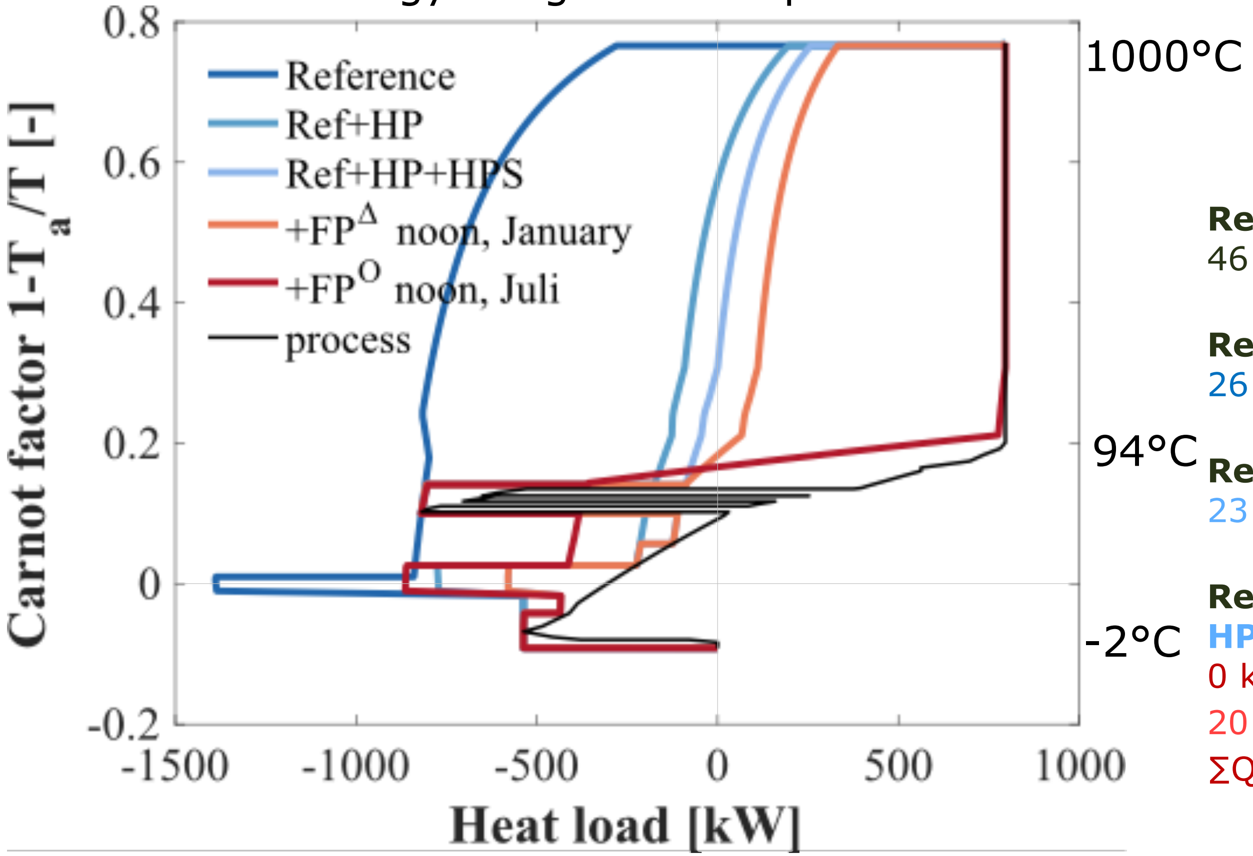
$y_u^t = 0 - 1$

$y_u = 0 - 1 \quad \forall \ u \ \in \ FU$



Integrating solar heat

Exergy integrated composite curves



Reference
46 kWh/t_{raw}

-60%

Ref+HP
26 kWh/t_{raw}

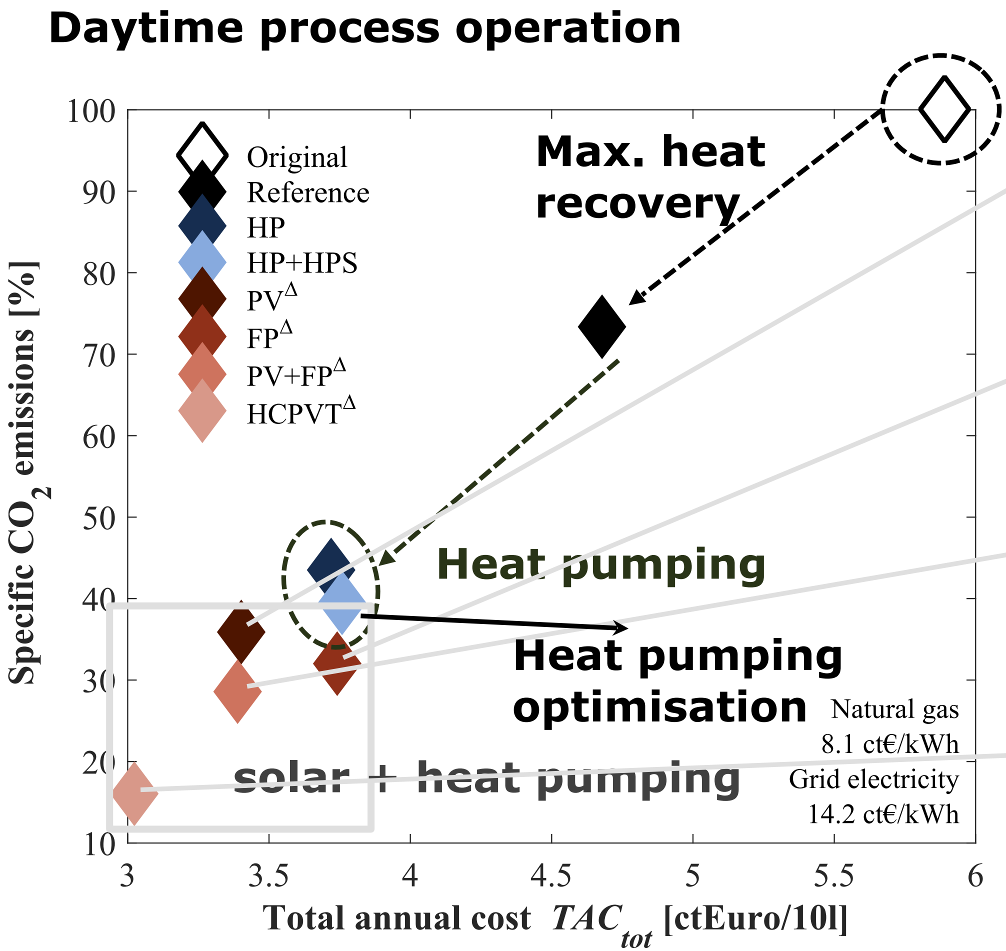
-64%

Ref+HP+HPS
23 kWh/t_{raw}

-100%

Ref+HP+ HPS+Solar
0 kWh/t_{raw}
20 kWh/t_{raw}
ΣQ_t kWh/t_{raw}

Comparison of the different solutions



Photovolatic Electricity (150€/m2)
2'245m2 → 2.38m2/10t

Flat plate thermal Heat (300€/m2)
1'369m2 →1.45 m2/10t

Plate plate + PV Hybrid
Low efficiency

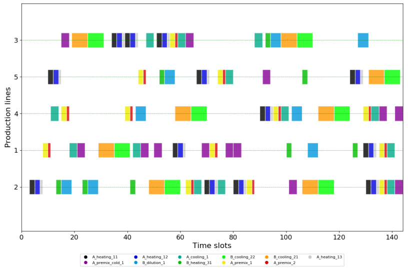
HCPVT Hybrid (500€/m2)
High efficiency
1'988m2→ 2.10m2/10t

Connected to the grid : optimal predictive strategic operation

Status of inventory+ equipment

Electricity mix predictions

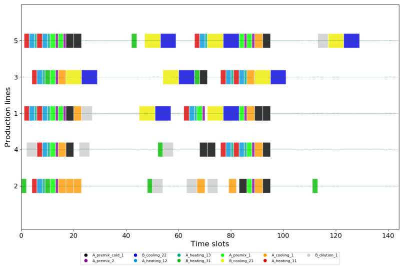
50 hours ahead prediction (ENTSOE)



Minimisation of the energy consumption

Utility market

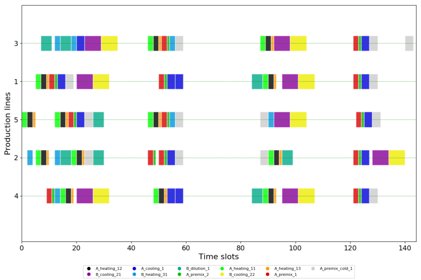
Electricity consumption [MWh]	Operating cost [EUR]	CO2 emissions [kgCO2eq]
32.3	745.5	958.5



Minimisation of the operating cost

Electricity market

Electricity consumption [MWh]	Operating cost [EUR]	CO2 emissions [kgCO2eq]
32.3	640.1	870.2
	-14.2 %	



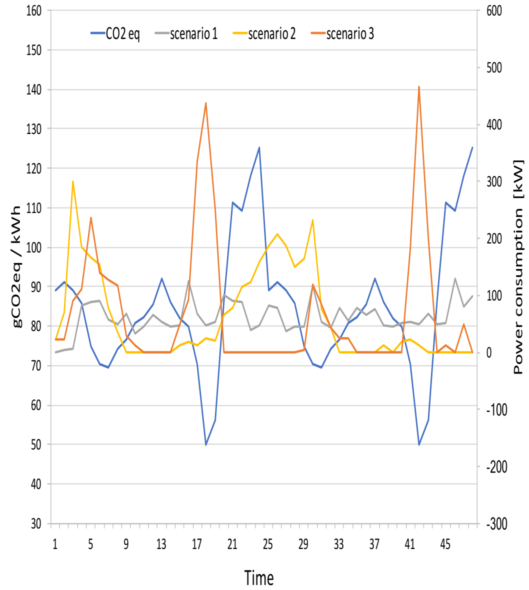
Minimisation of CO2 equivalent emissions

CO2 market

Electricity consumption [kWh]	Operating cost [EUR]	CO2 emissions [gCO2eq]
32.3	747.5	690.0
		-27.9 %

Strategic planning

integrating with the electricity mix



Santecchia et al, 2019 under preparation

and Energy Systems Engineering

EPFL

Conclusions : industrial heat pump integration

- Process integration of industrial heat pumps
    - System pinch is the key
    - System boundaries
        - integrate waste treatment and urban integration
    - Heat pumps integrates with other utilities
        - cogeneration - waste heat valorisation
    - Heat storage and optimal strategic operation
- Methods
    - System energetics analysis
    - Heat exchange interfaces
    - Grand composite => temperature levels
    - Super-structure => fluids + system configuration for temperature levels
    - Optimisation => selection and flows
    - Integrated composite curves => exergy losses

EPFL

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