EPFL

Efficiency Increase by Systematic Heat Pumping Integration in Industrial Processes

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IPESE
Industrial Process
and Energy Systems
Engineering

Defossilizing industry : thematics

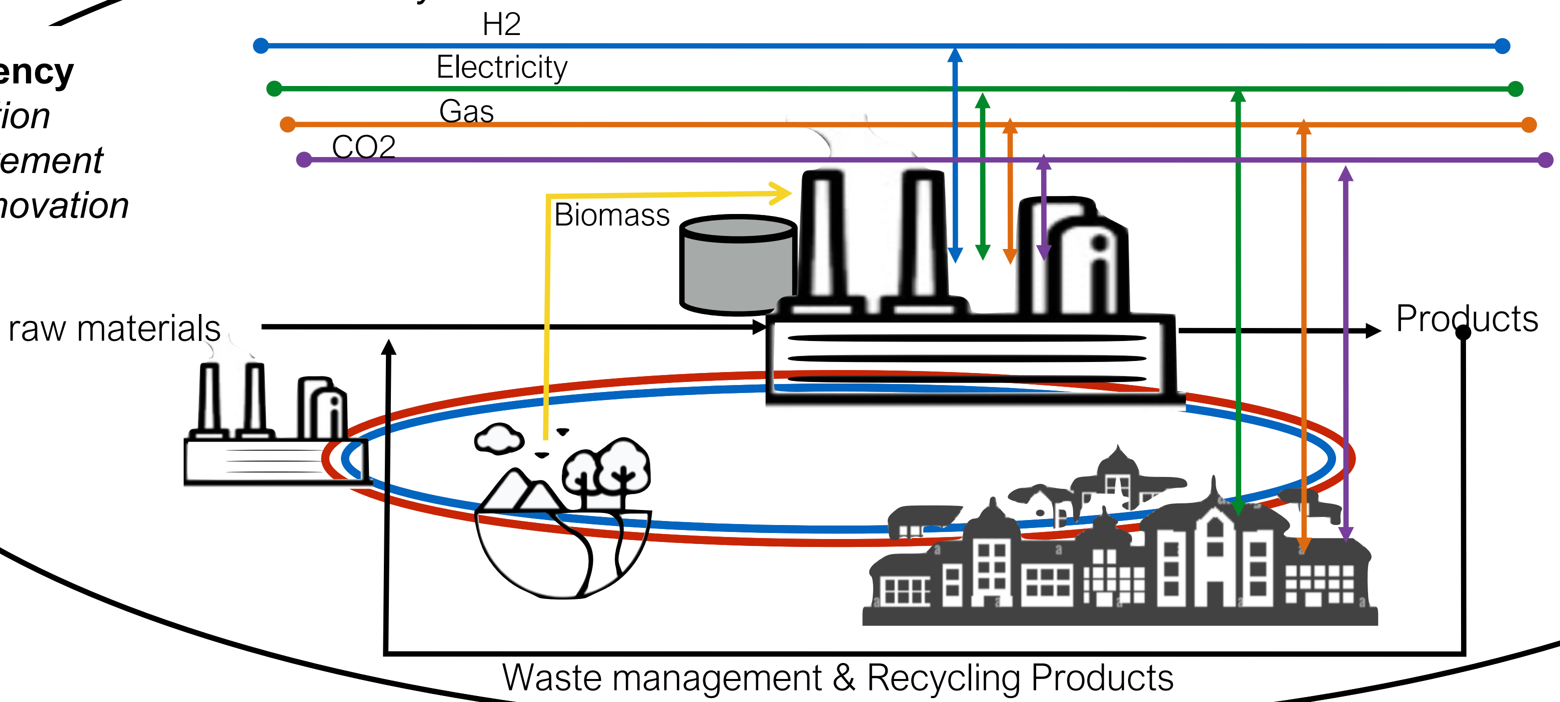
Efficiency
Materials recovery
Heat recovery

Heat valorisation
Heat pumping
Waste heat to electricity

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

Technology efficiency
Optimal operation
Technology improvement
Technology innovation

Energy Audits
Energy Drivers
Efficiency KPI
Monitoring



CO2
Capture, reuse, sequestrate

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

Energy efficiency : understanding the use of energy

Audit : flows & energy

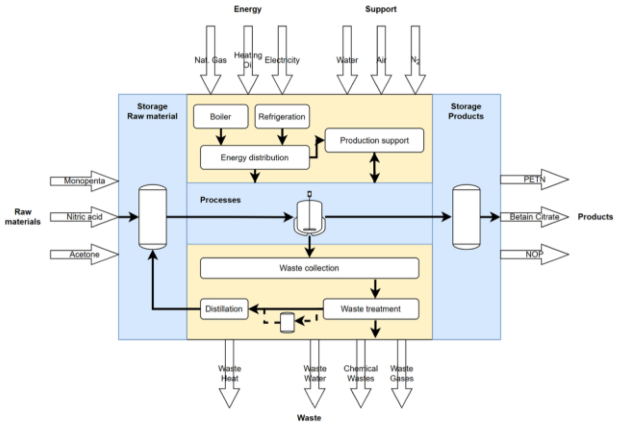


FIGURE 2.1—Mass and energy flows of the main units

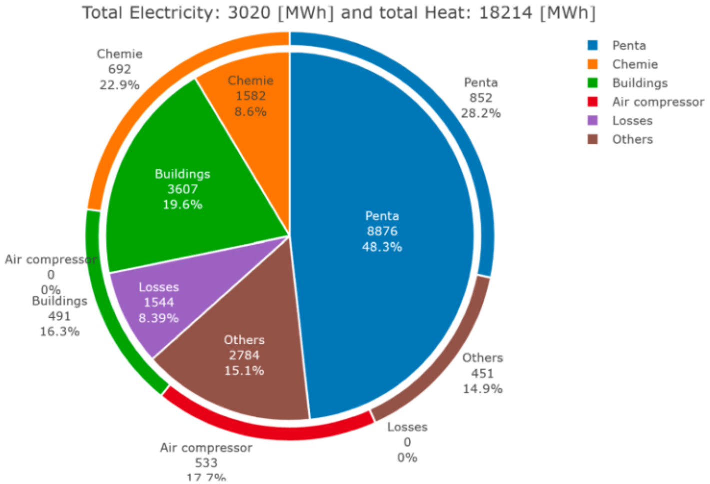


FIGURE 2.4—Energy consumption by type and consumer

Recovery

Heat recovery targeting

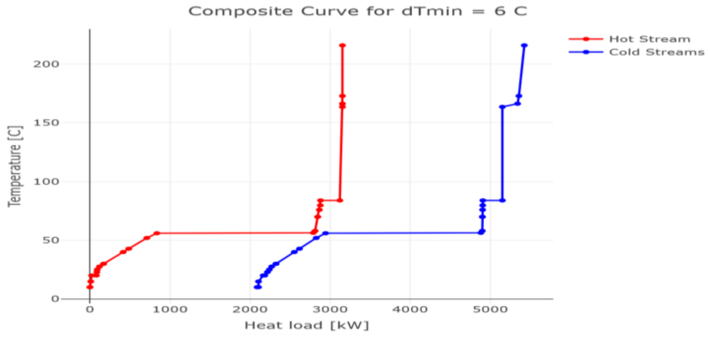
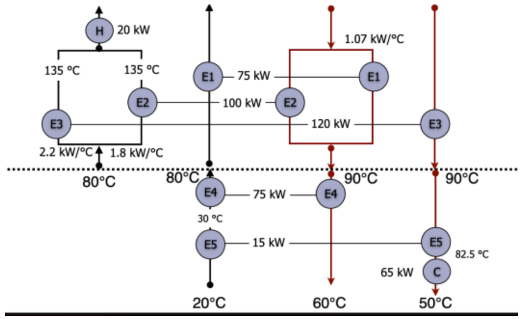


FIGURE 6.2—Composite curve for MER

Heat exchangers



Conversion

- Heat pumps
- MVR
- Cogeneration
- Waste - Water

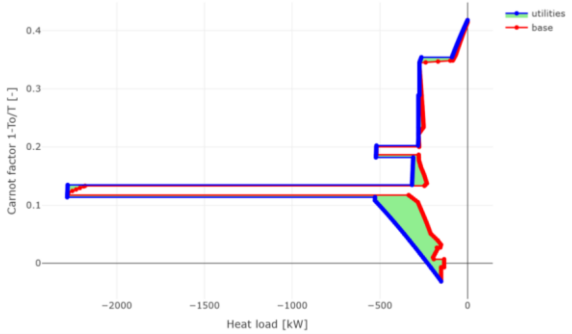
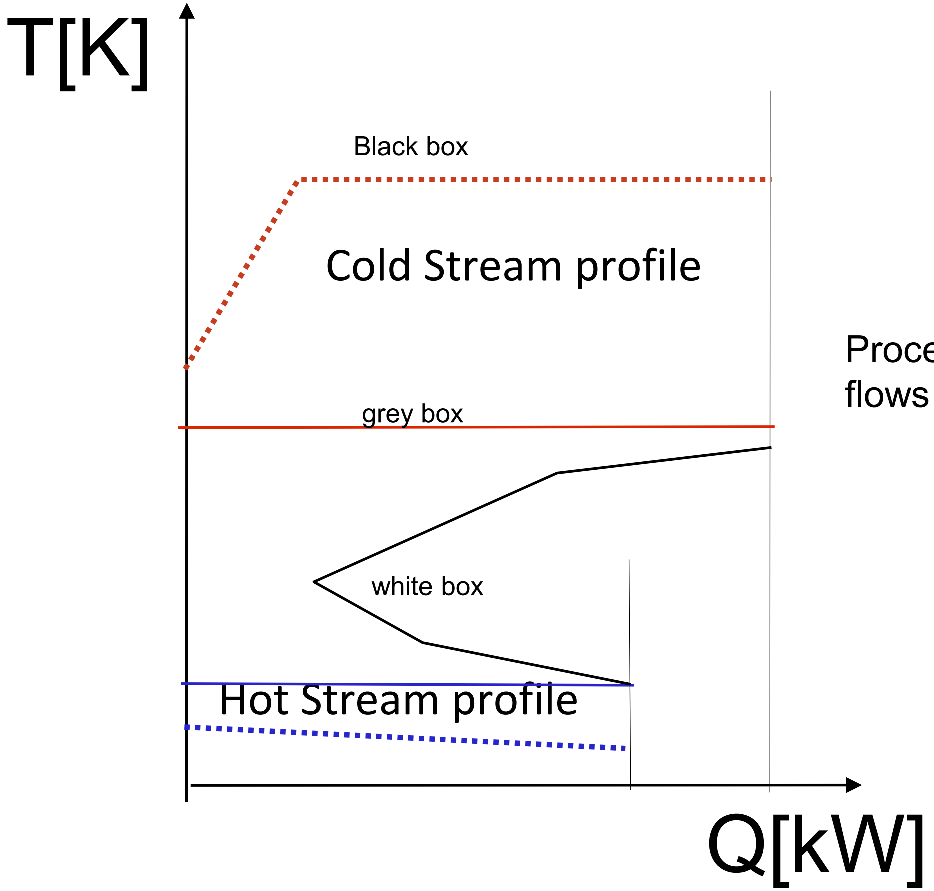
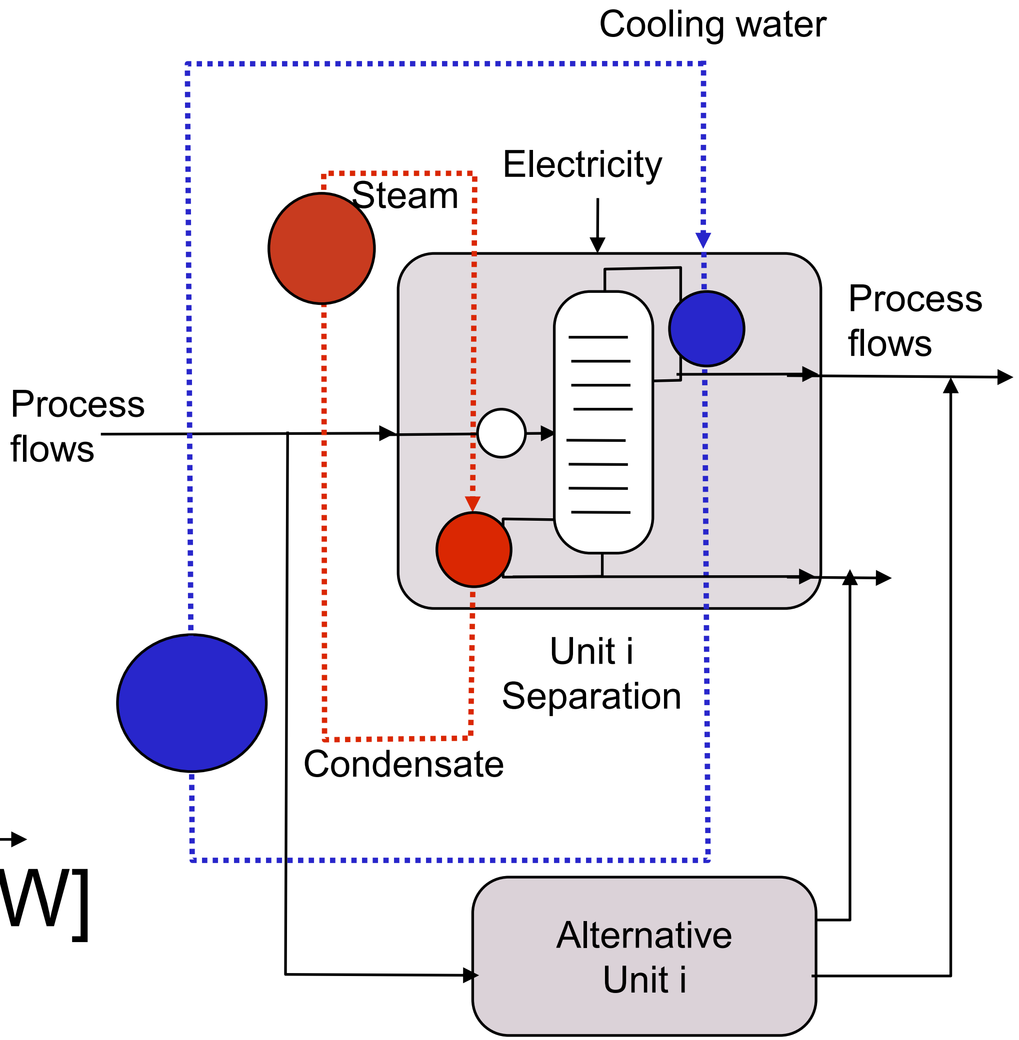


FIGURE 9.5—Carnot Composite Curve for optimized utilities

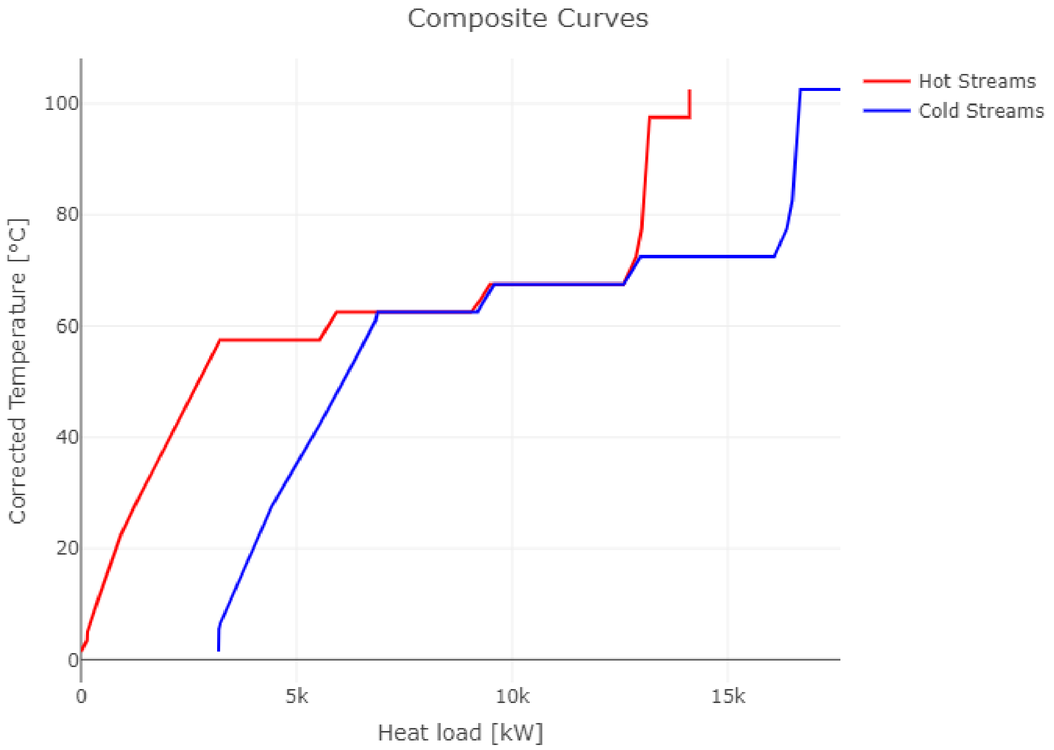
- Same unit operation : different heating and cooling profiles

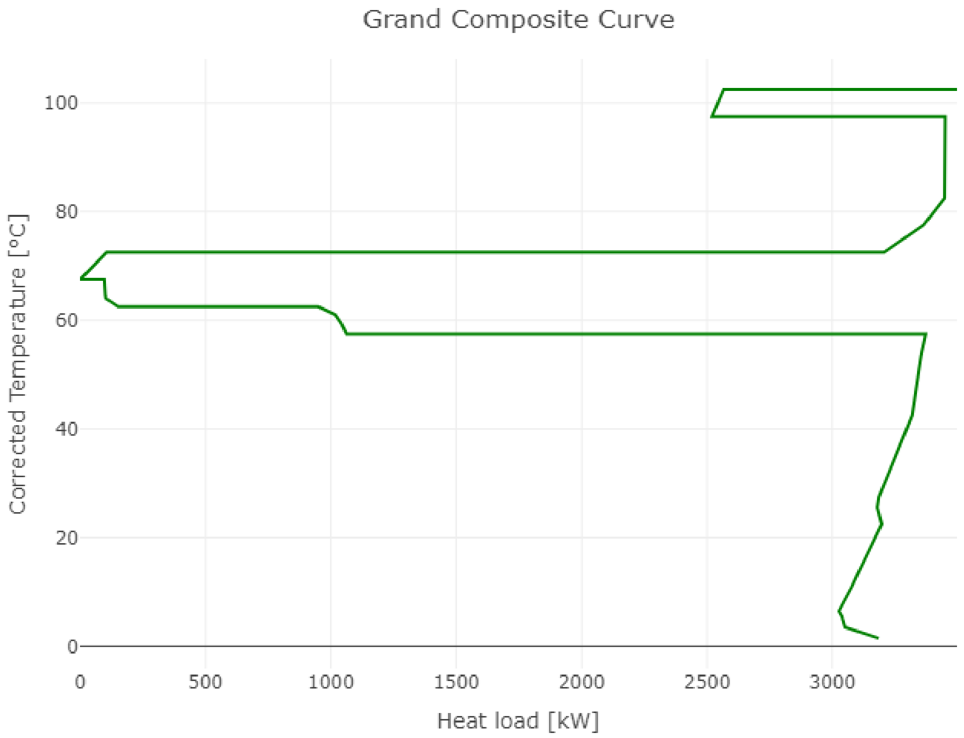




Heat recovery and heat cascade

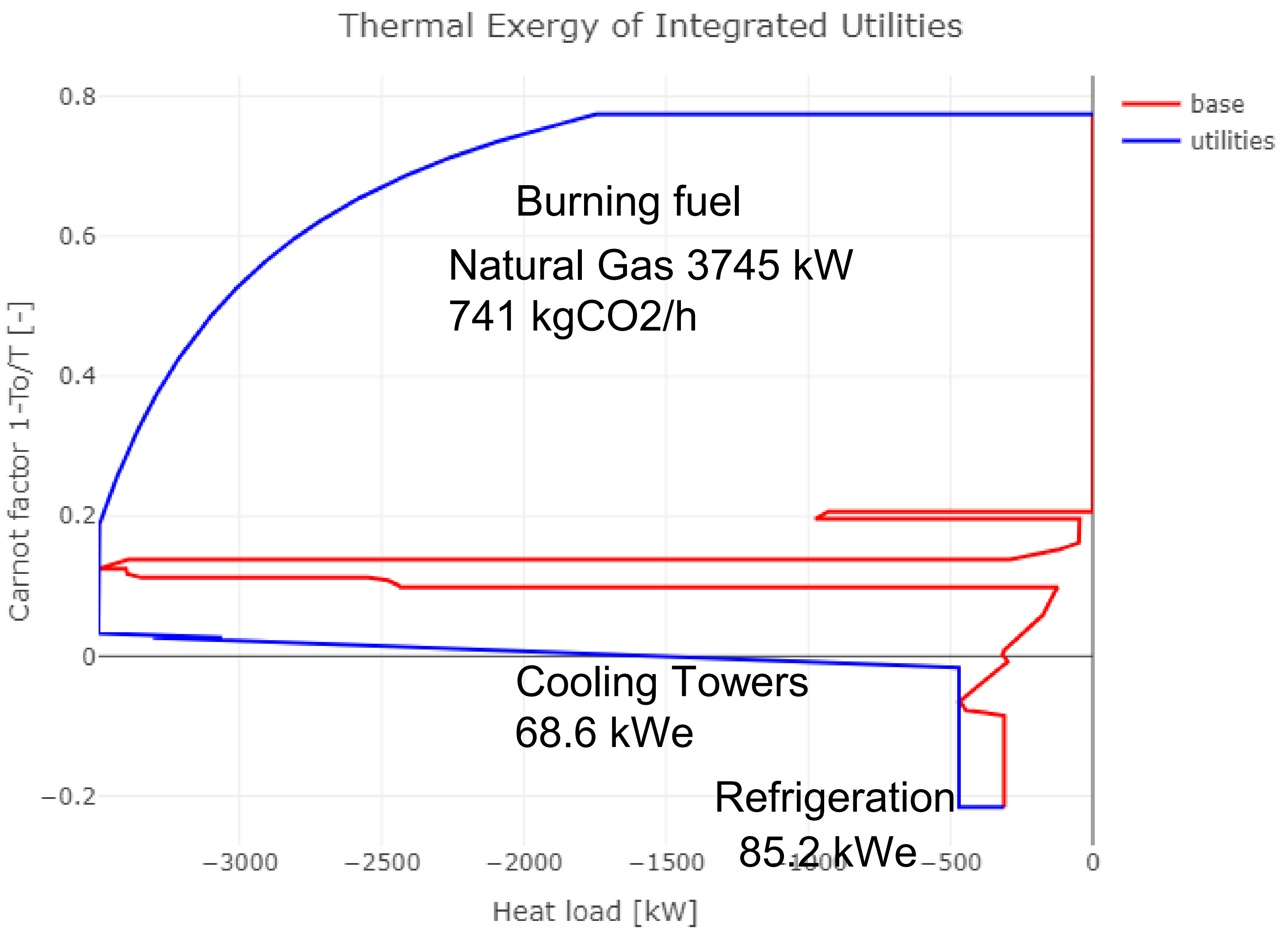
- Corrected temperature $T^* = T +/-(\Delta T_{min}/2)$
- Graphical plot of the heat cascade : [R_r, T^*_r] r=1,n_r





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.

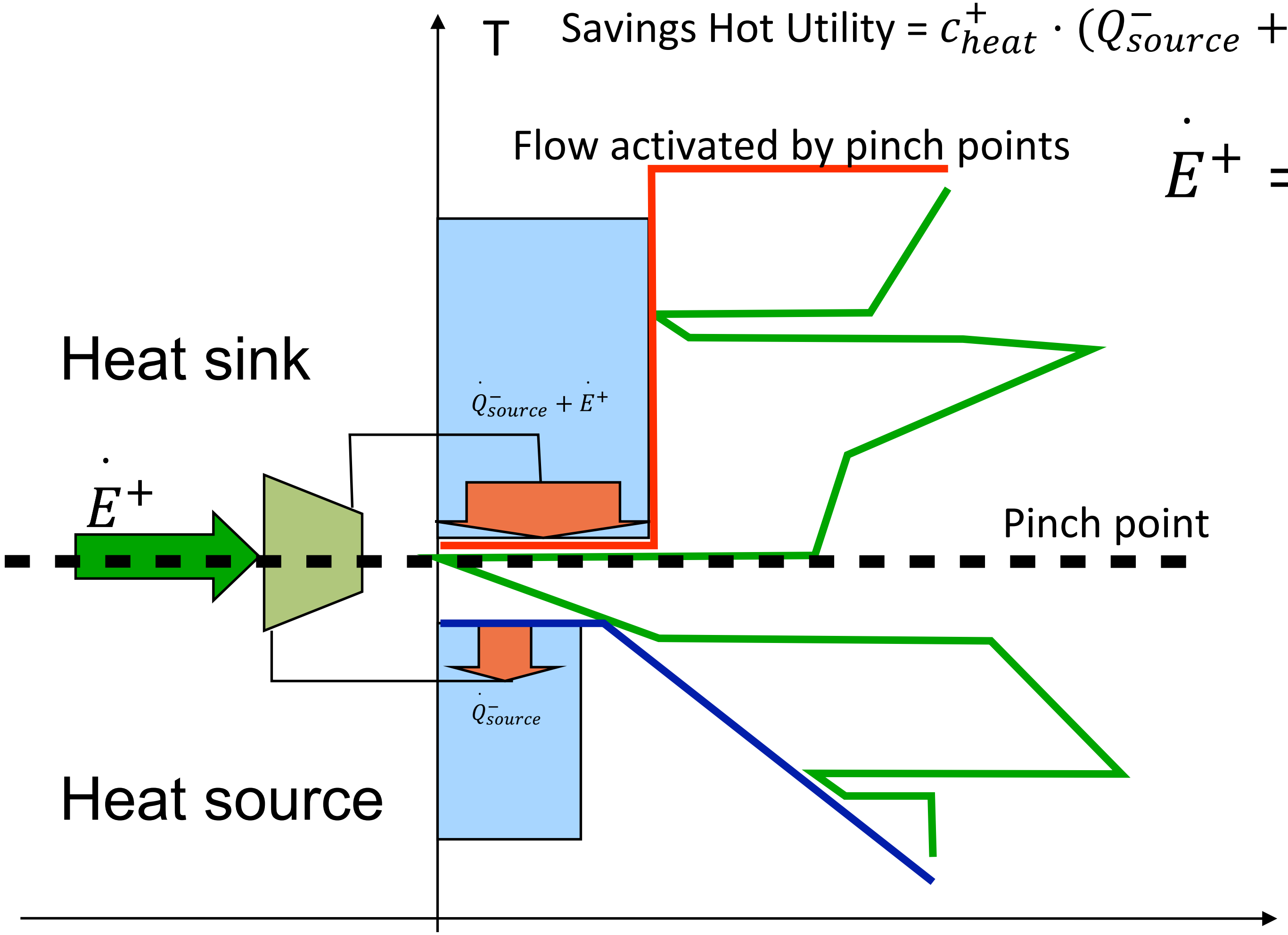
Closing the energy balance

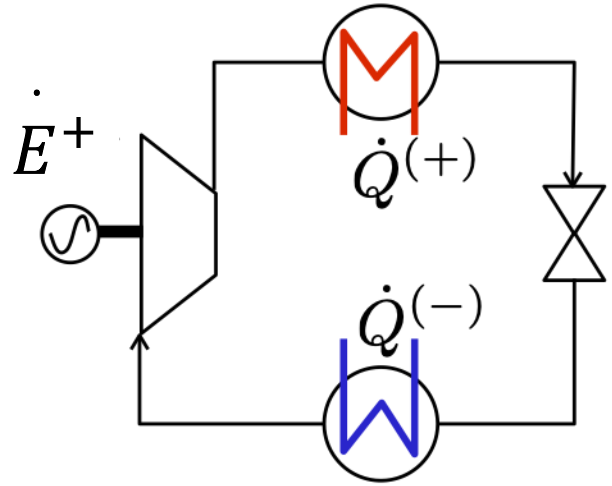


Integrating heat pumps from heat source to heat sink

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

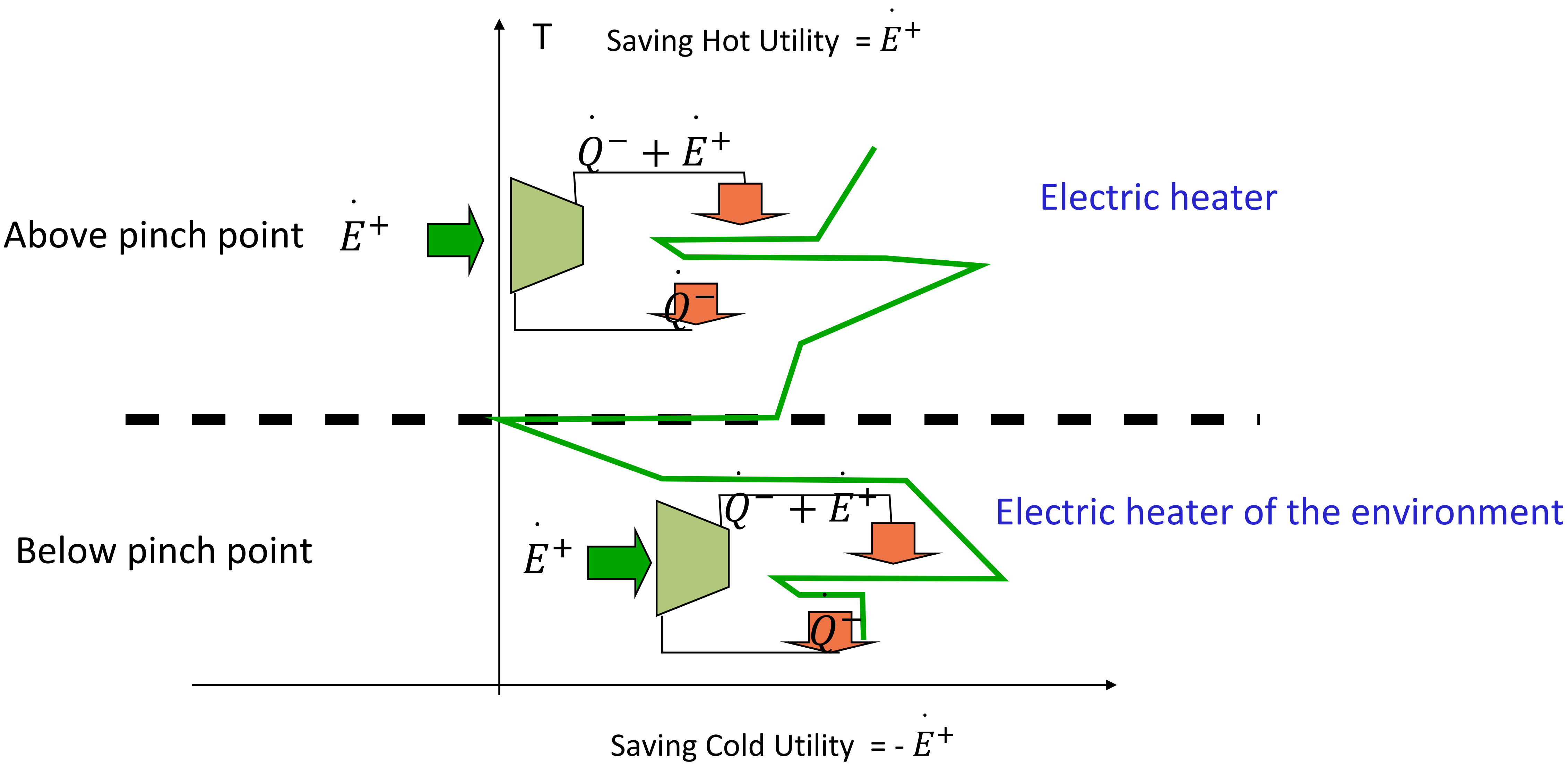
$$\dot{E}^{+} = \dot{Q}^{+}_{sink} \cdot \frac{1}{\eta_{Carnot}} \cdot \frac{\tilde{T}_{sink} - \tilde{T}_{source}}{\tilde{T}_{sink}}$$





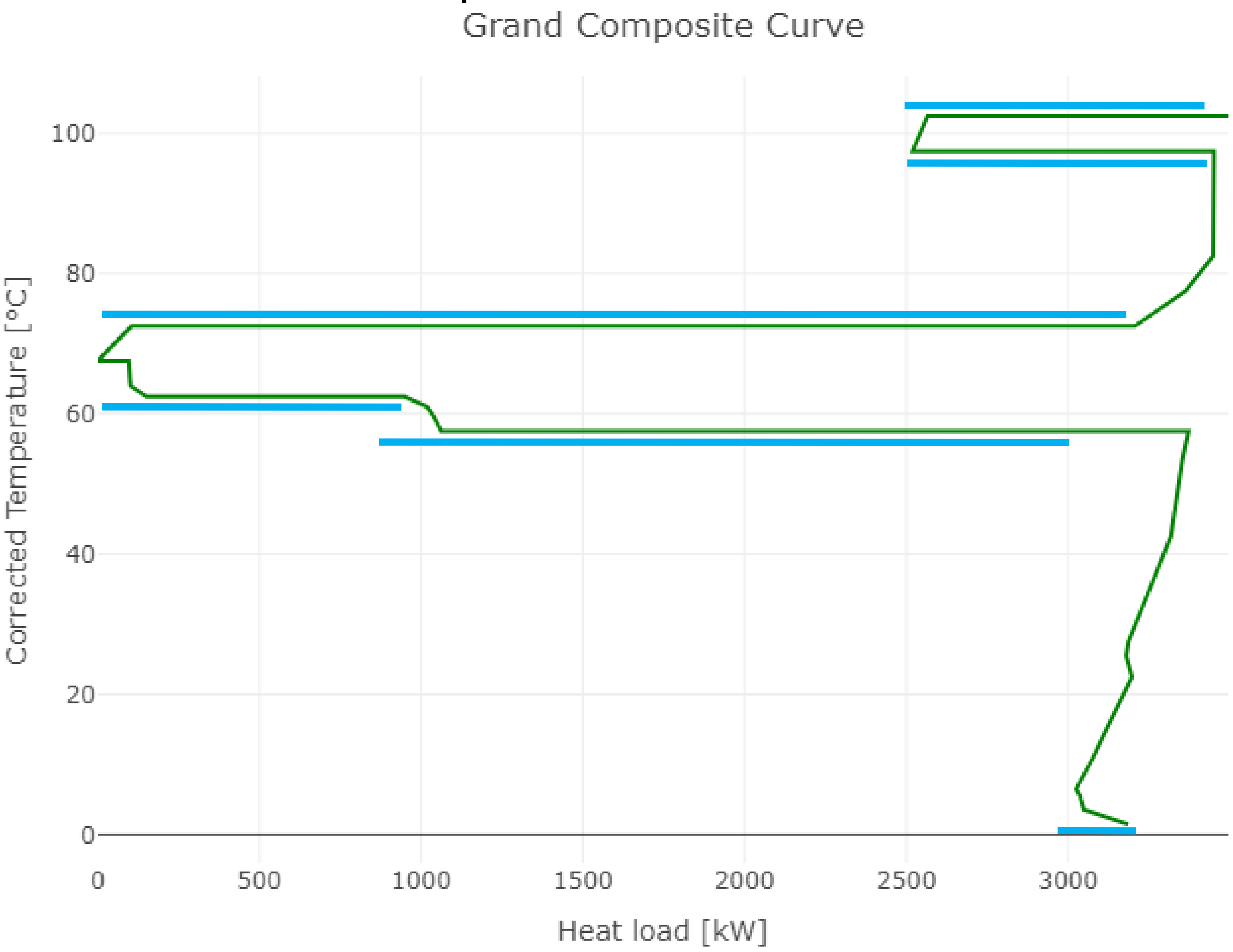
Savings Cold Utility = $c^{+}_{cold} \cdot \dot{Q}^{-}_{source}$

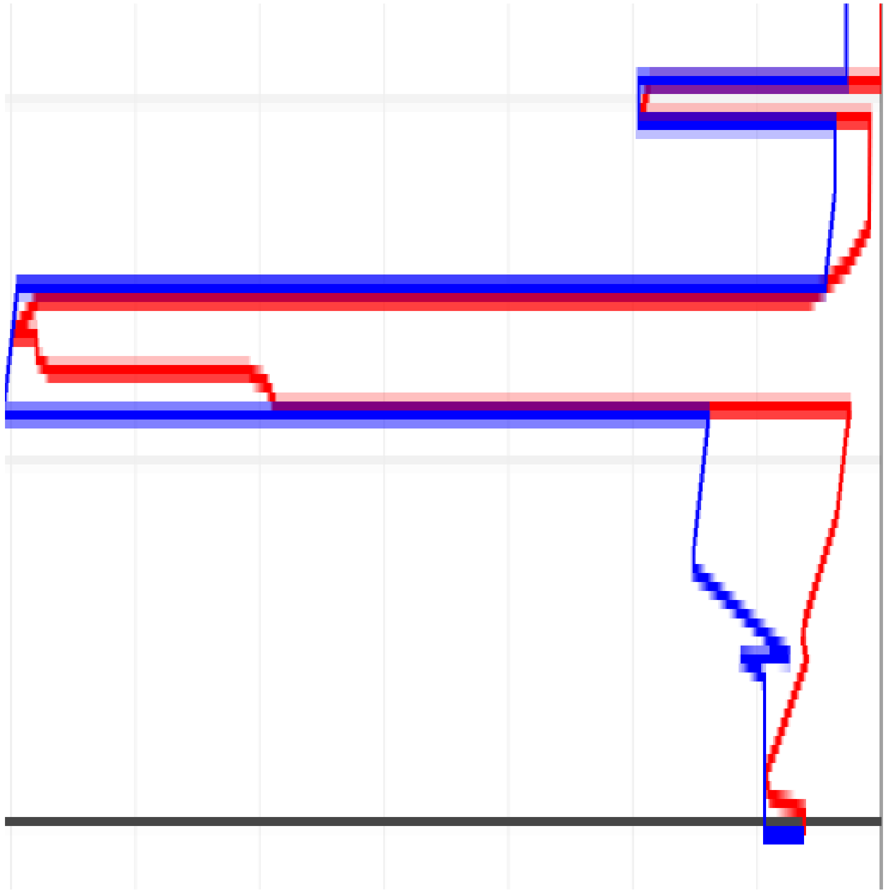
Miss placed heat pumps : above or below the pinch



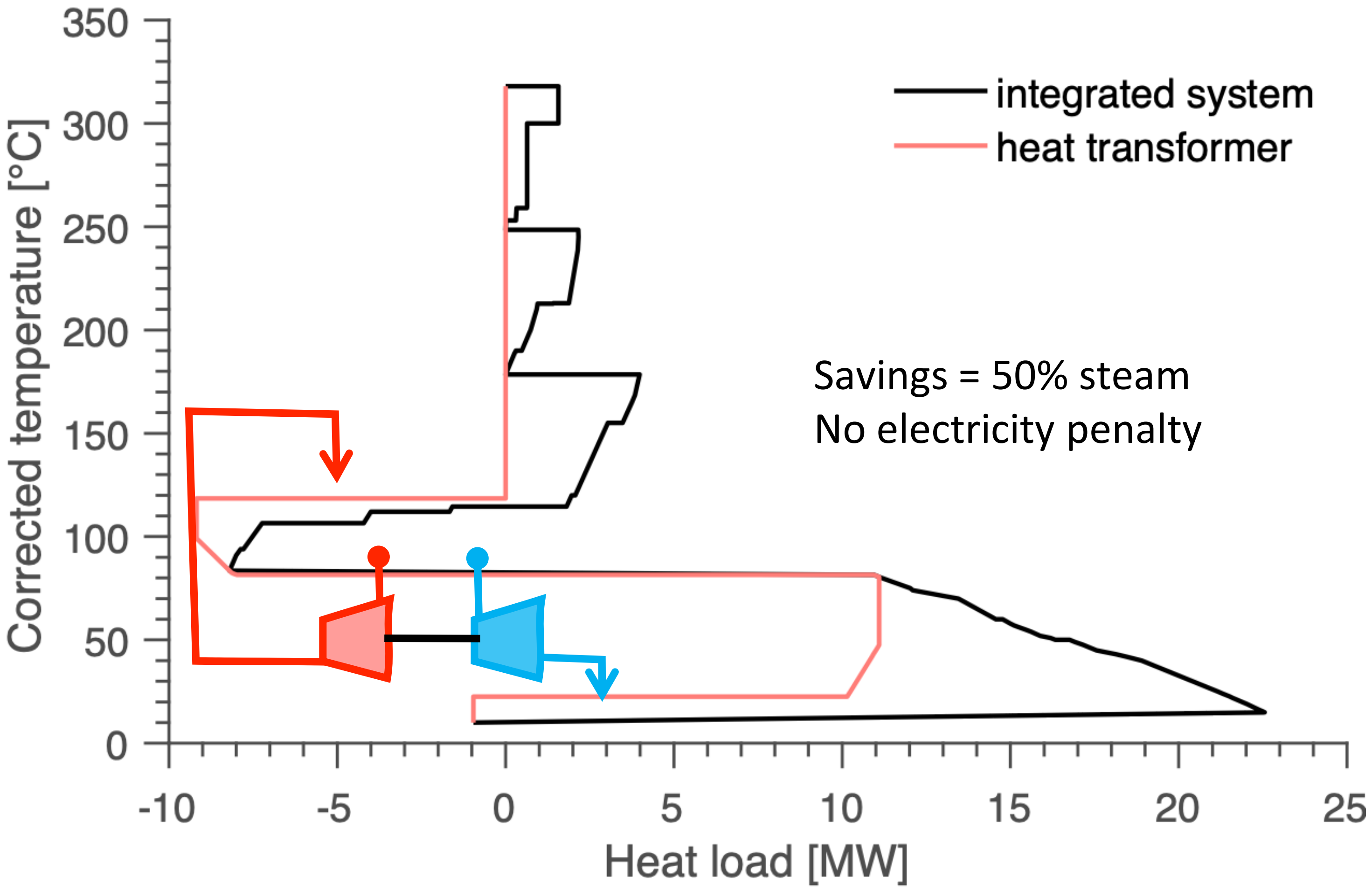
Identify temperature levels

Temperature levels → Multi-stage heat pumps





Heat pumps and waste heat valorisation



Heat pump + ORC

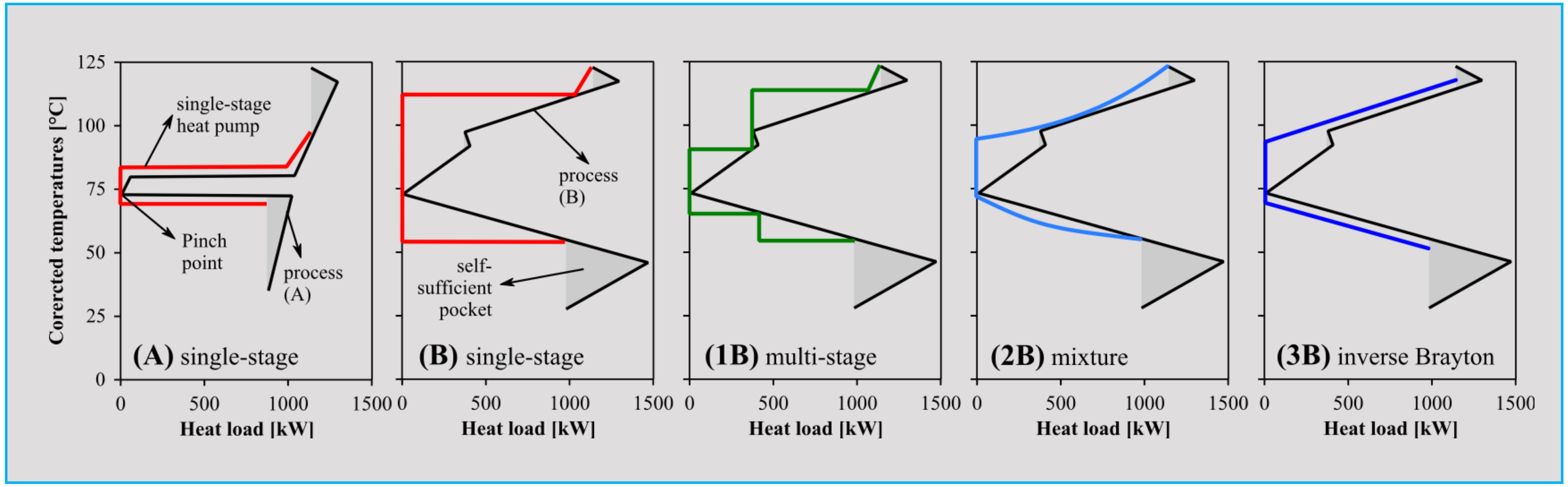
- Superstructure
- Fluids
- Turbines
- Optimisation

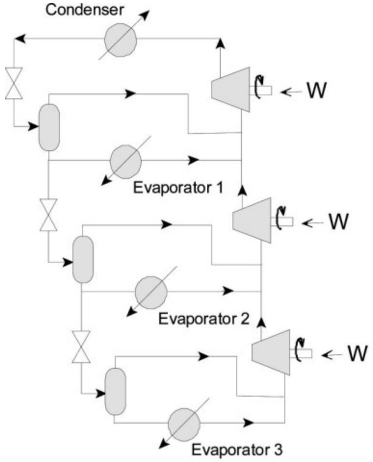
Kermani et al., Applied Energy, 2019

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 ?



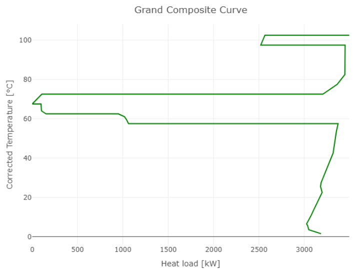


All adapted from: Del Nogal et al. (2008)

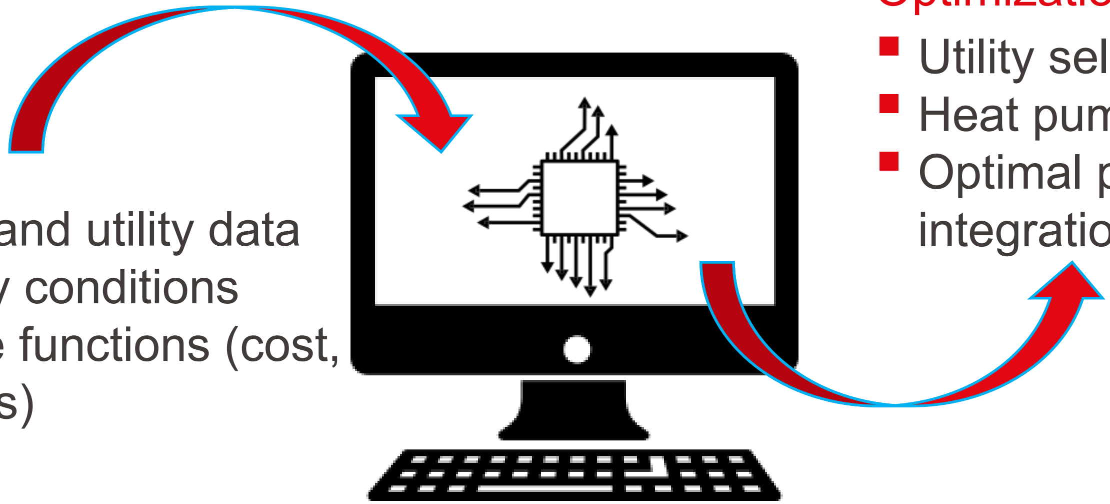
Systematic approach: superstructure optimisation

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

Computer aided process engineering

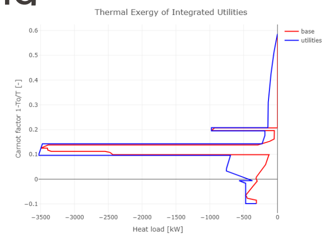


- Process and utility data
- Boundary conditions
- Objective functions (cost, emissions)



Optimization

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



SCCER
EFFICIENCY OF INDUSTRIAL PROCESSES

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Bundesamt für Energie BFE
Swiss Federal Office of Energy SFOE

IPESE
Industrial Process and Energy Systems Engineering

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Federal Office of Energy SFOE

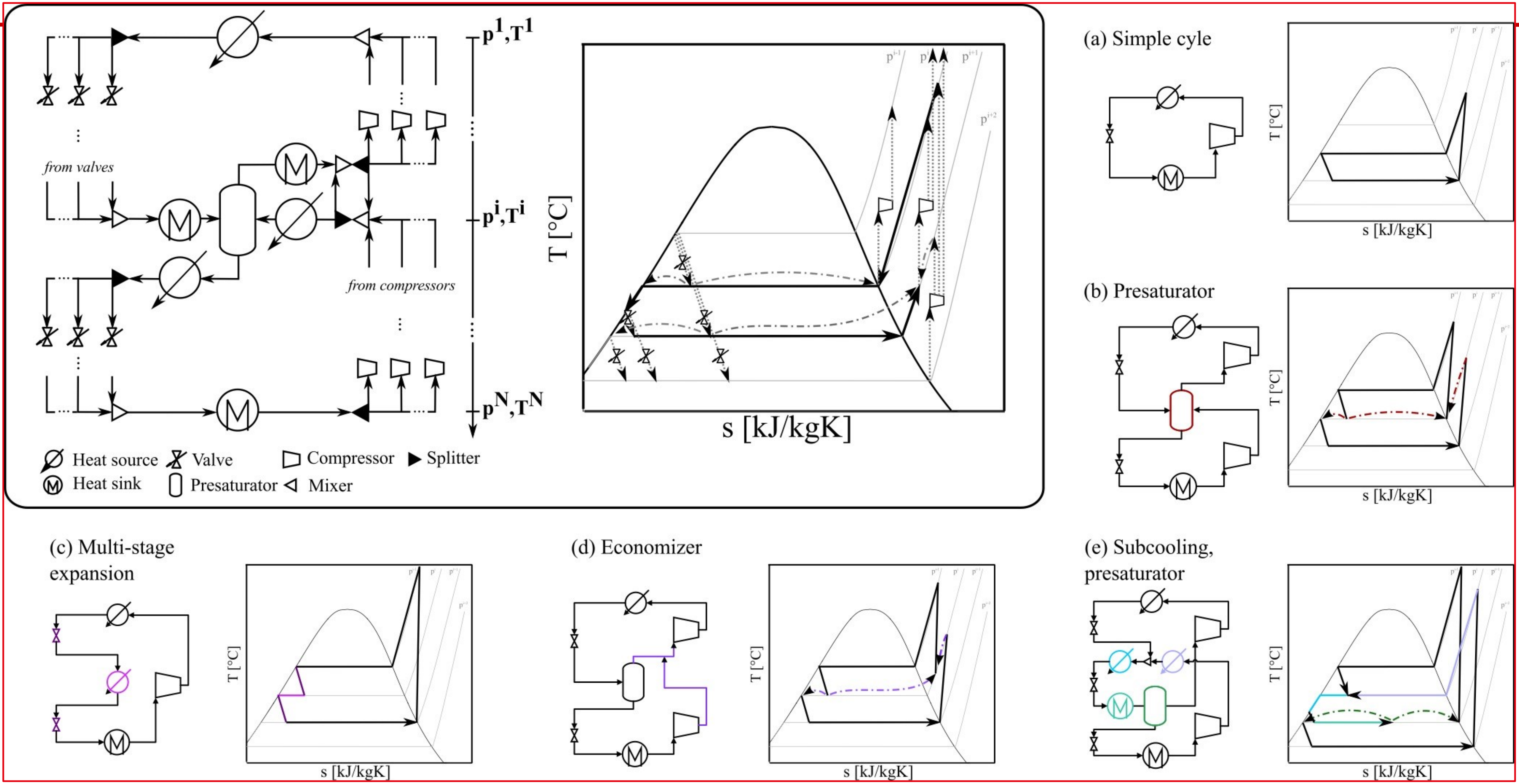
OST
Eastern Switzerland University of Applied Sciences

CSDENGINEERS+
INGENIOUS BY NATURE

HEIG-VD

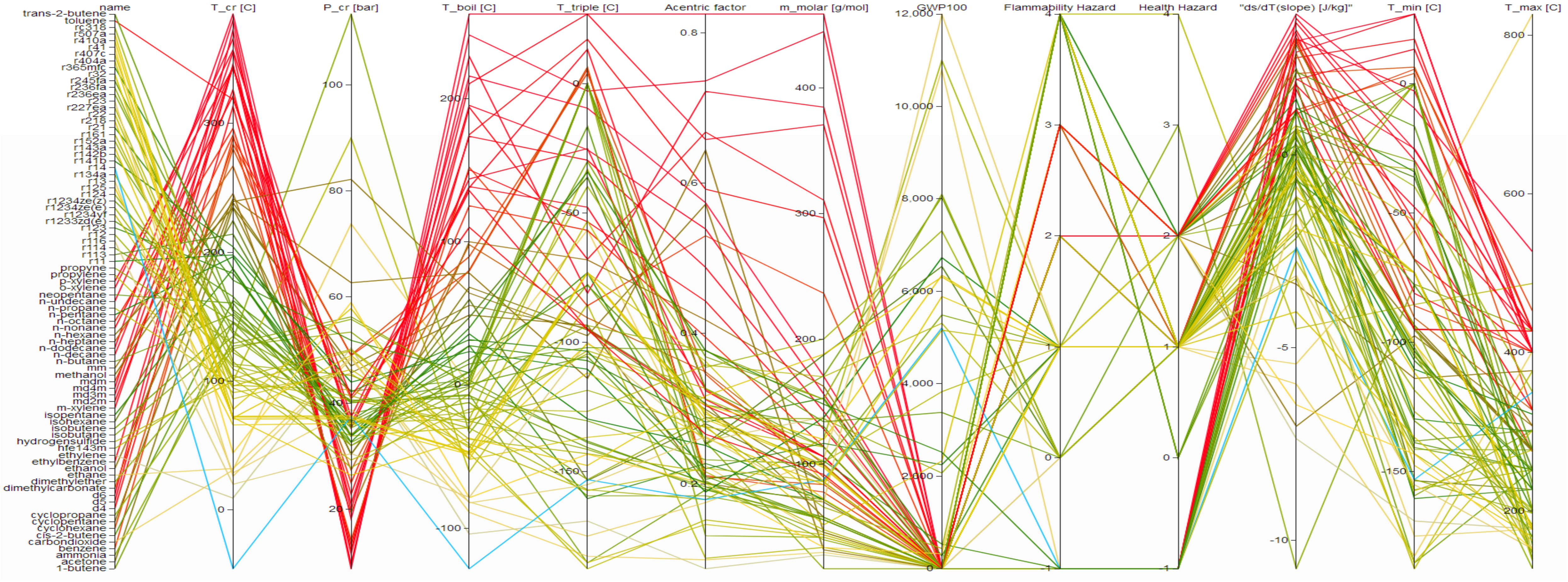
EPFL

Systematic approach: superstructure model



Fluid data base

working fluids and their thermo-physical properties



Technology data base : compressors

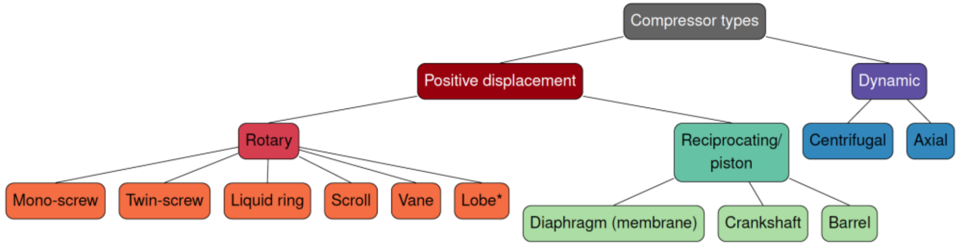
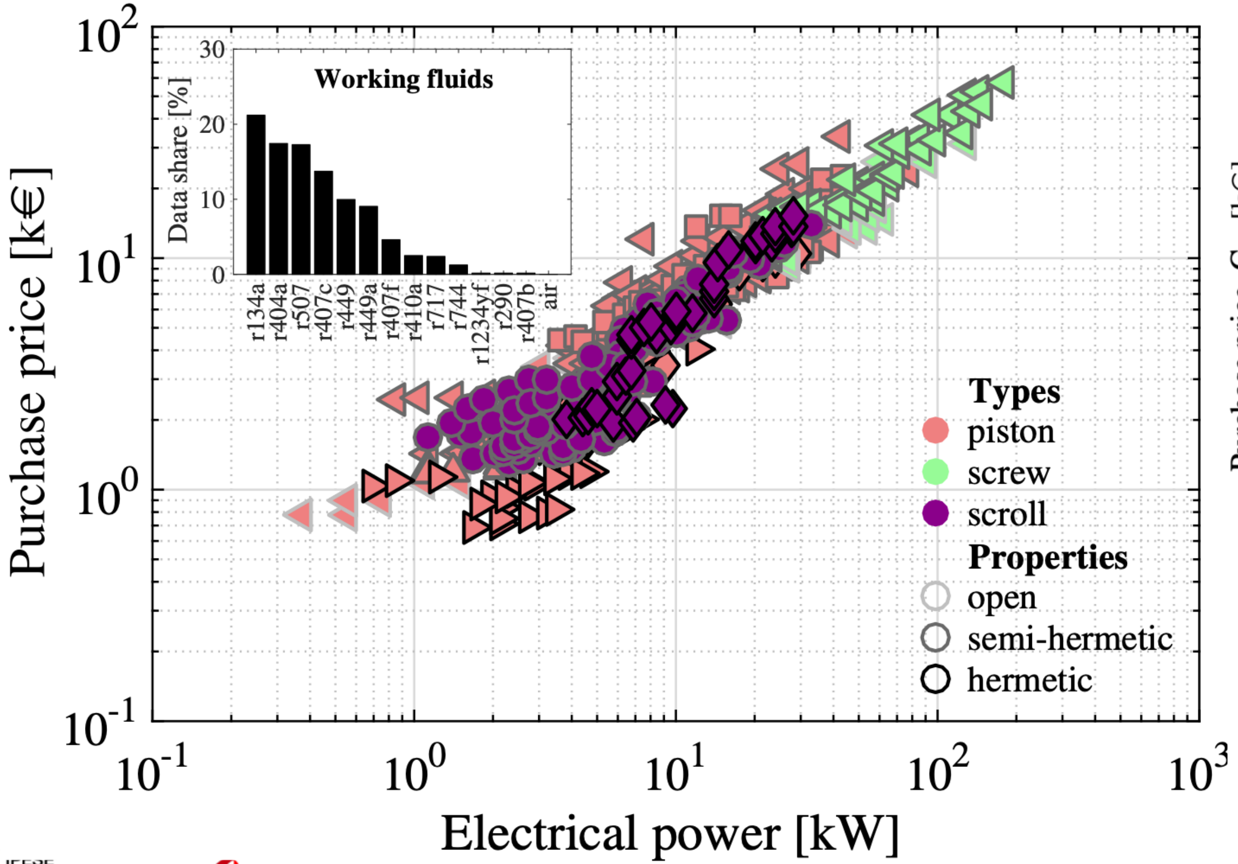
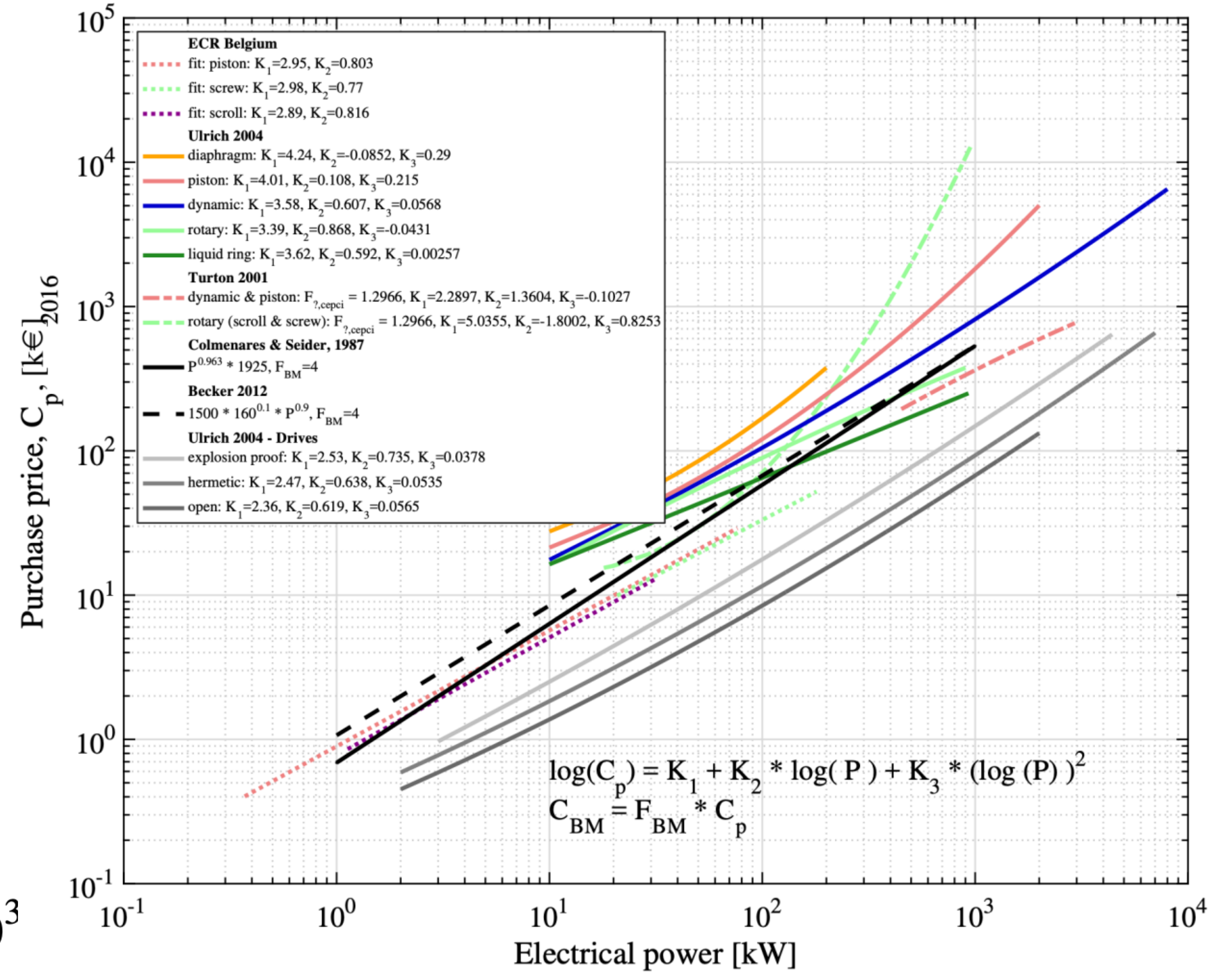


Figure 2: Tree diagram of compressor types, adapted from Wikipedia [8] with inspiration from Favrat [9]. Novel technologies are marked with asterisk (*).



Cost function review



[1] A.Wallerand, BFE 2019
[2] Kantor et al., ECOS proceedings, 2018

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

Electricity consumption

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

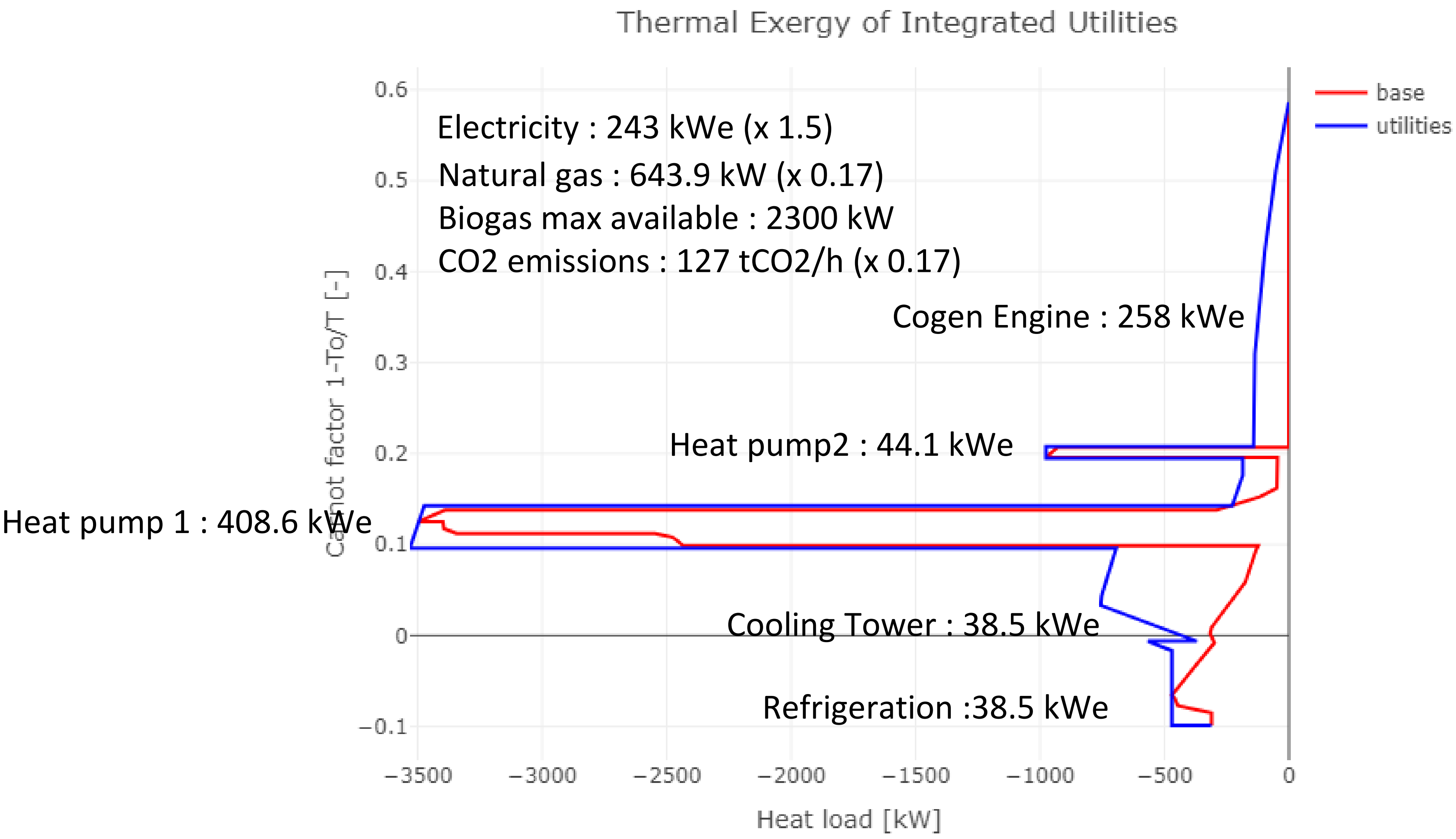
Electricity production

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

Energy conversion Technology selection

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

System integration results



Carnot Integrated Composite Curve before fluid selection

Conclusions : industrial heat pump integration

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