Energy conversion system integration

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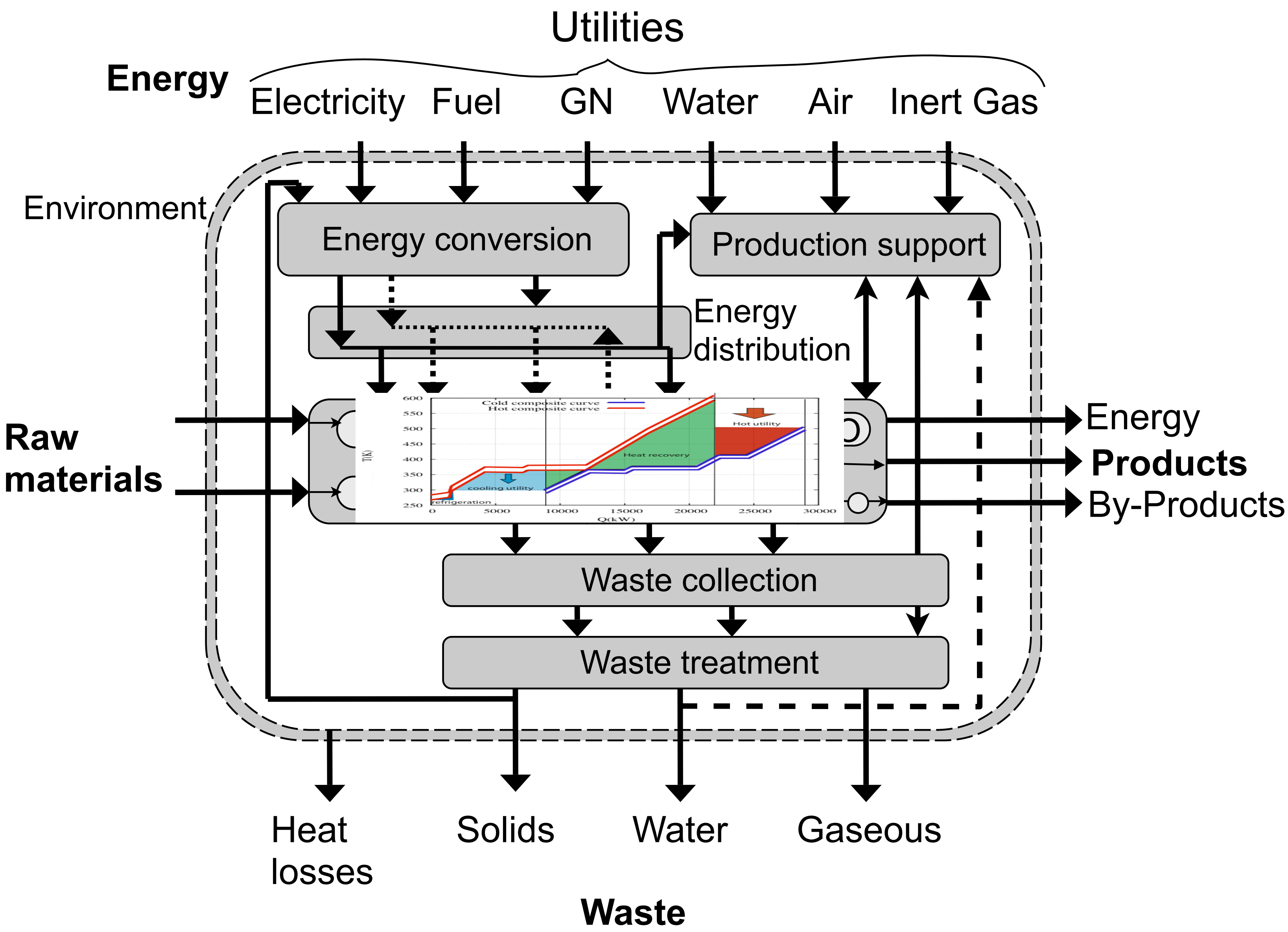
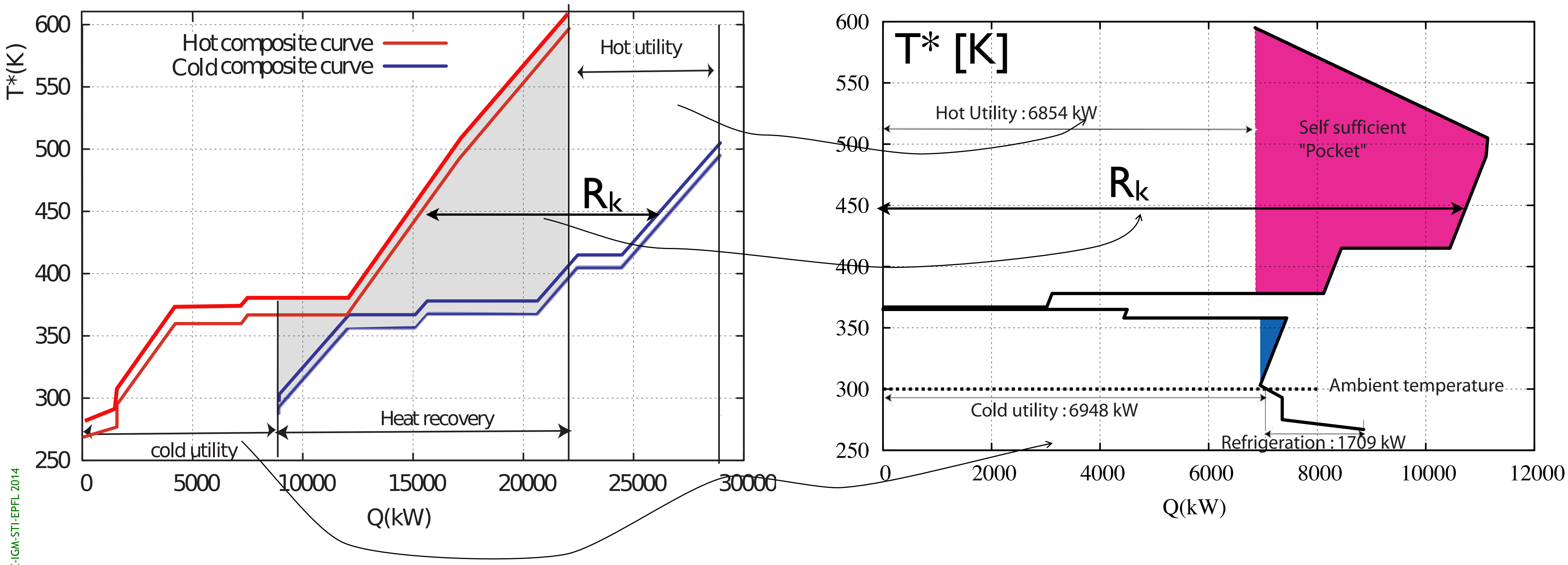
EPFL

Energy conversion system



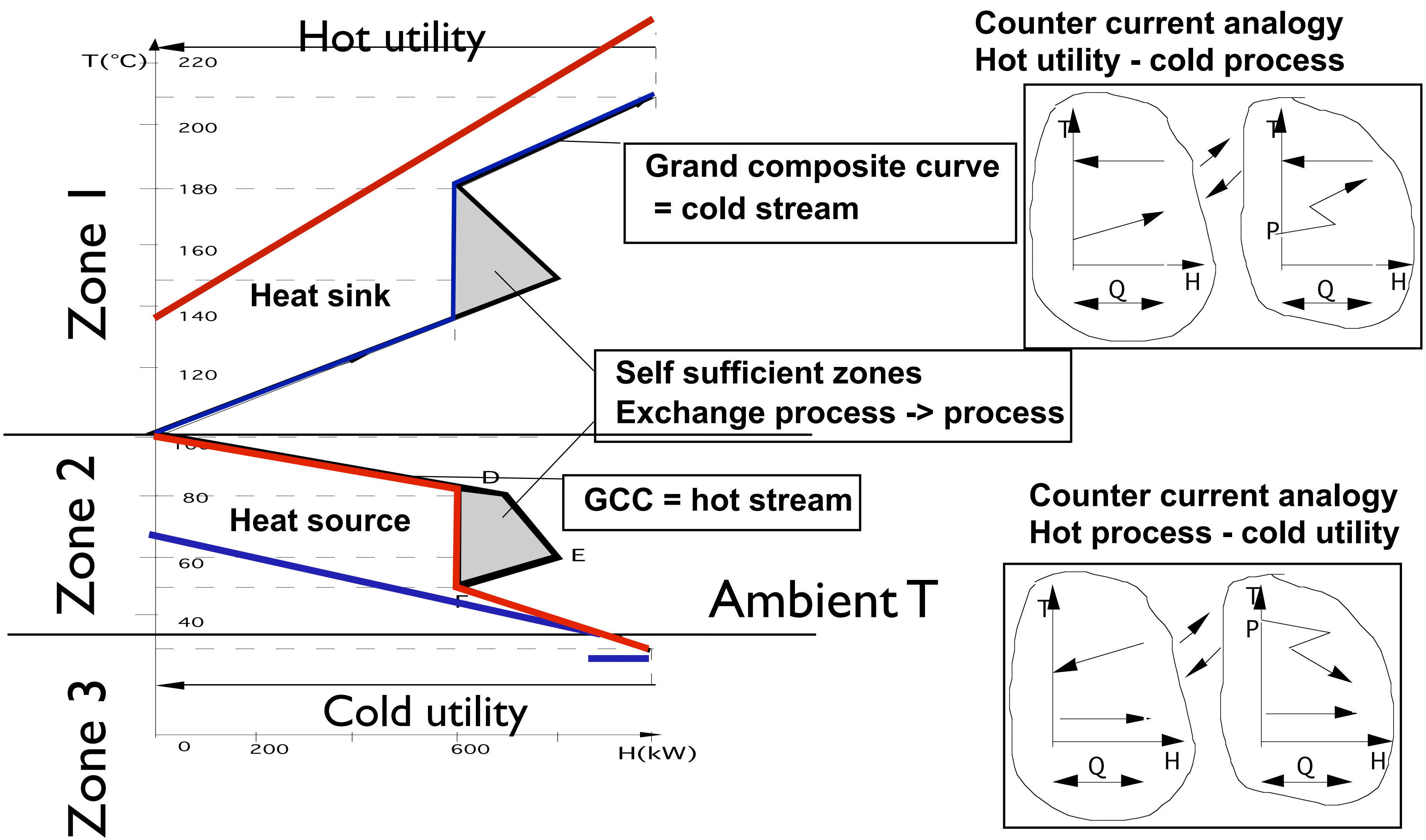
Grand composite curve/Heat cascade

- Corrected temperature domain
- Graphical plot of the heat cascade : [R_r, T^*_r] $r=1,n_r$



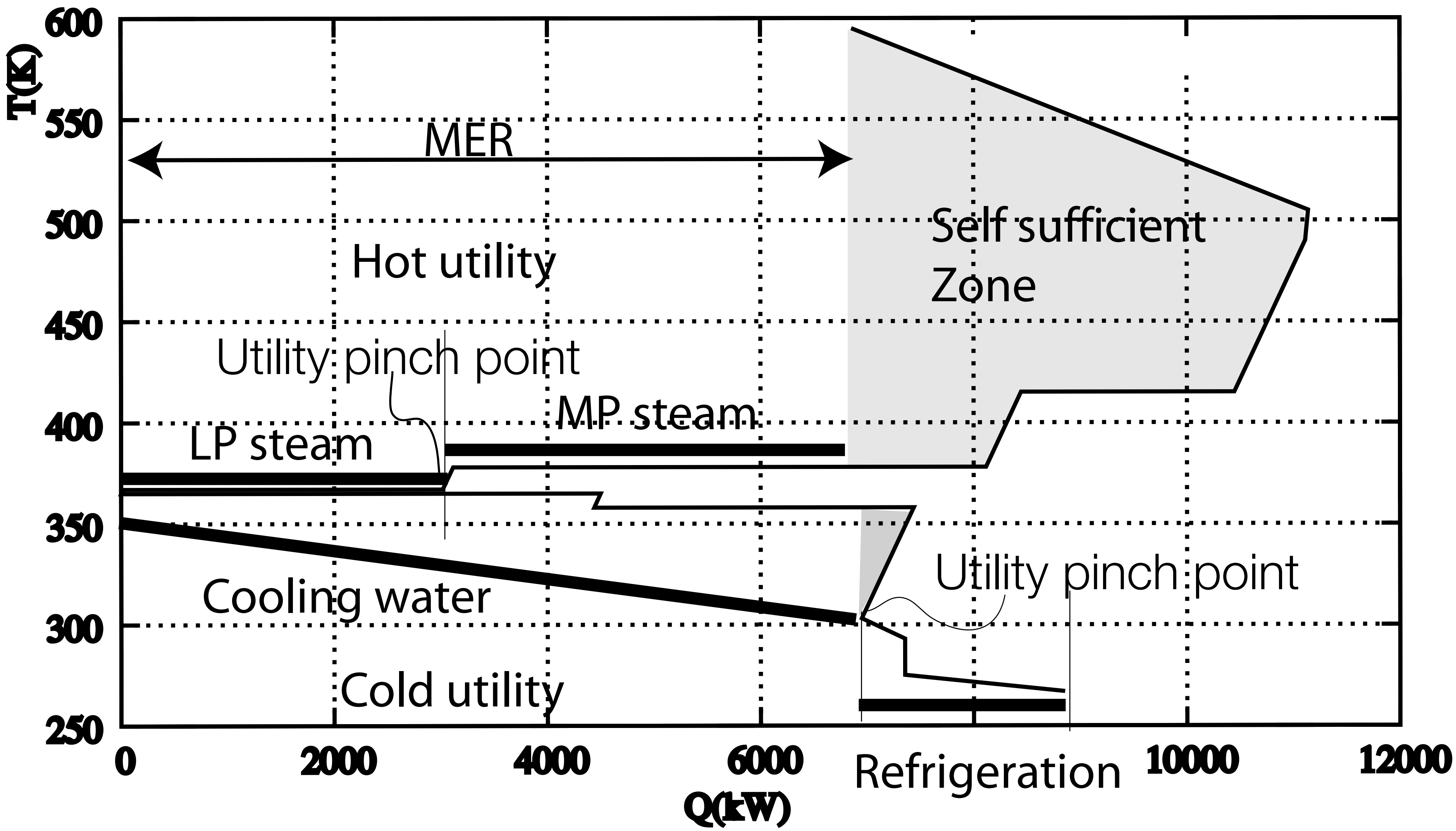
The Grand composite is the heat cascade representation in the corrected temperature domain. it represents the flow of energy in the system from higher temperatures to lower temperature. Above the pinch point is also represents the heat-temperature profile of the heat to be supplied to the system and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

Grand composite and utility integration

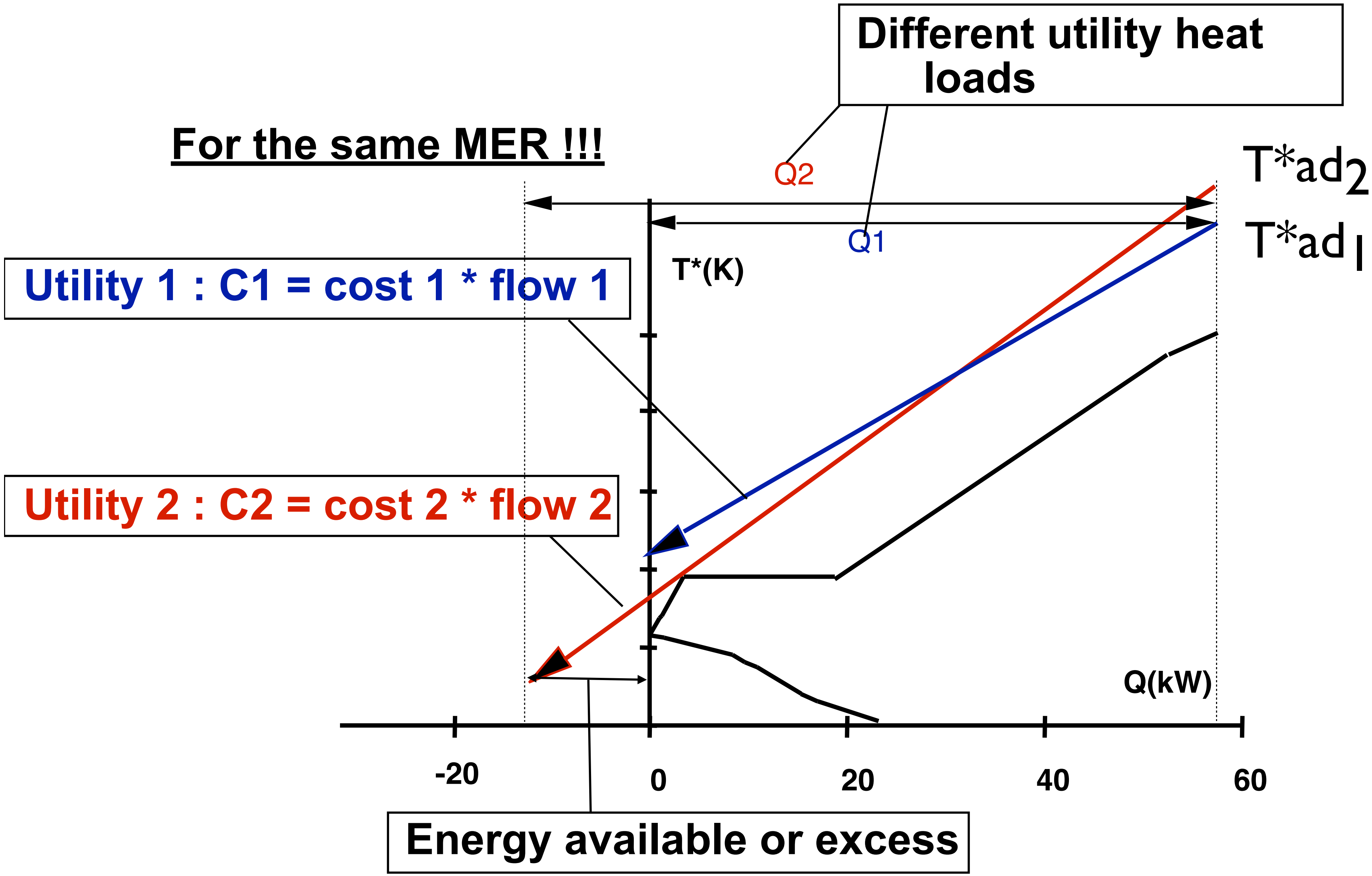


Multiple utilities

Maximise the use of the cheapest utility

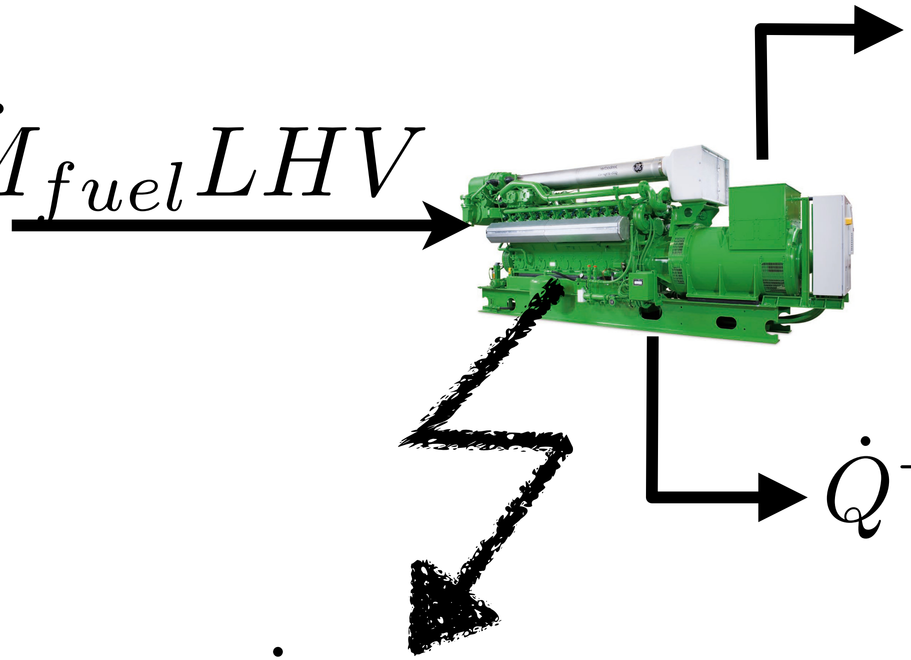


Different fuels



Cogeneration system : Energy Balance

$$\dot{M}_{fuel}LHV$$



$$\dot{E}^{-} = \eta_e \dot{M}_{fuel}LHV$$

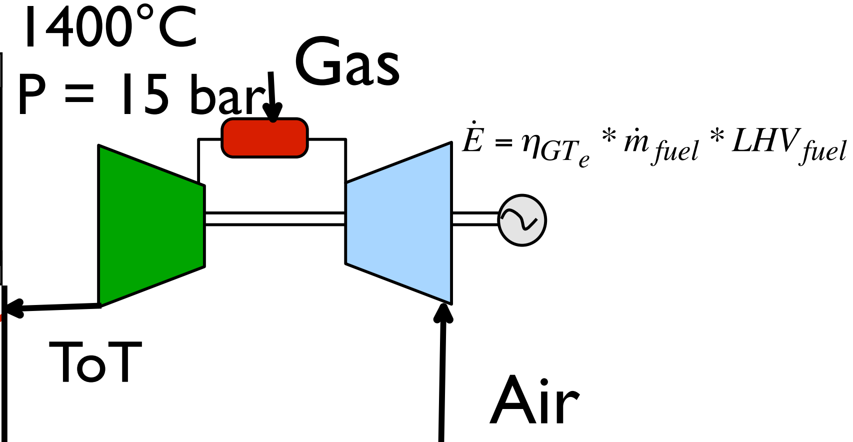
$$\dot{Q}^{-} = \eta_{th} \dot{M}_{fuel}LHV$$

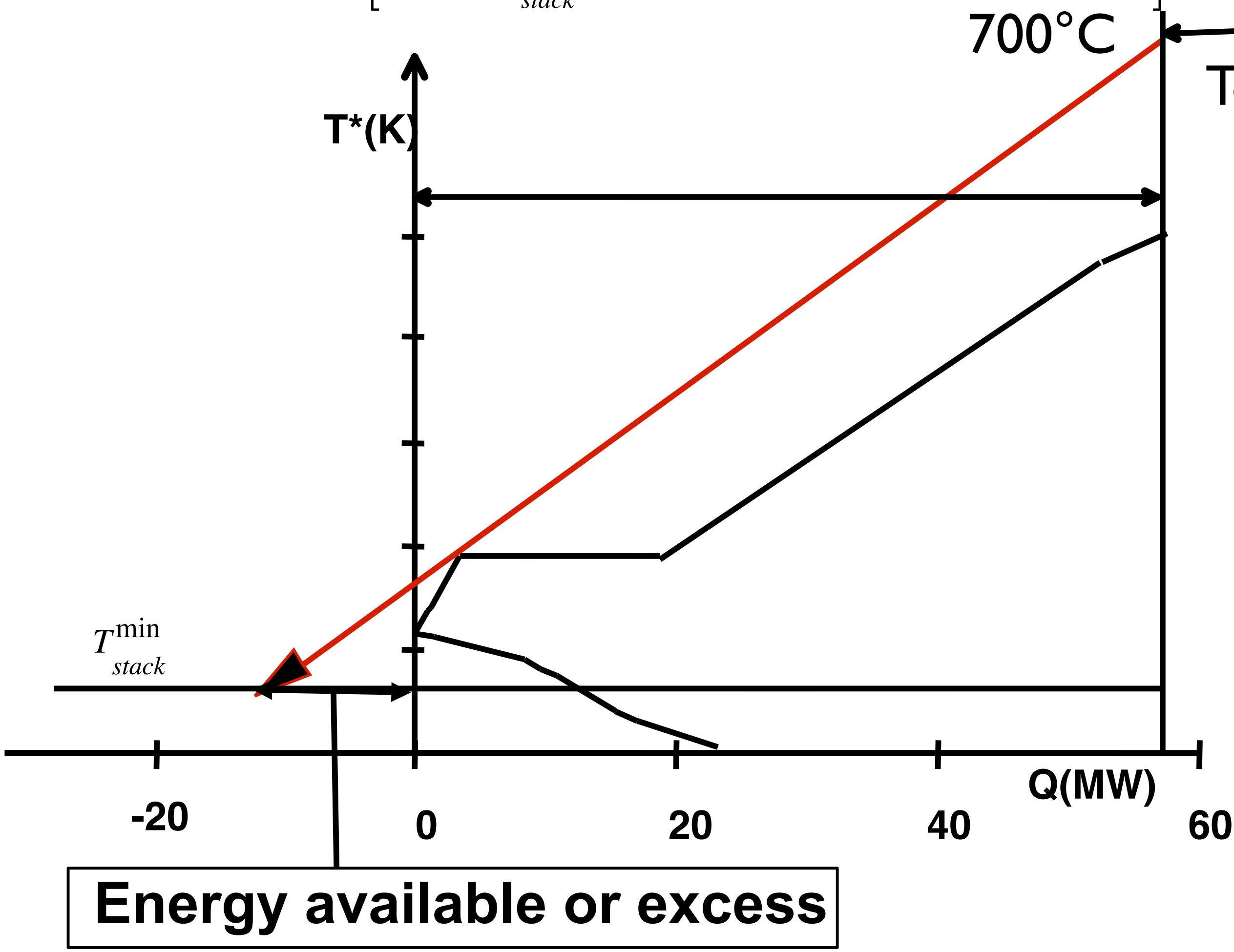
$$\dot{Q}^{-}_{losses} = (1 - \eta_e - \eta_{th})\dot{M}_{fuel}LHV$$

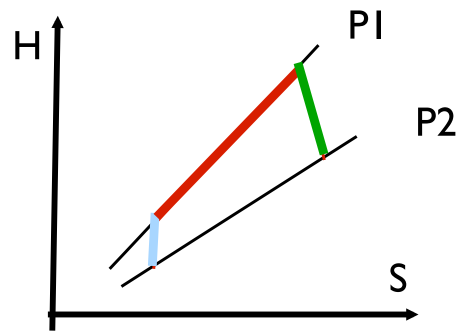
$$CAPEX = A + B \cdot (\dot{E}^{-})^{c}$$

Cogeneration : gas turbines

$$\dot{m}_{fuel} = \max_{k}\left[\frac{\dot{Q}_{mer_k}}{\frac{\eta_{GT_{th}} * LHV_{fuel}}{(T_{oT} - T^{min}_{stack})} * \left[T_{oT} - \max\left(T^{min}_{stack}, \left(T^{*}_{k} + \Delta T_{min}/2_{f}\right)\right)\right]}\right]$$







$\eta_{GT_e} = 30 - 38\%$

$\eta_{GT_{t_{gc}}} = 55 - 47\%$

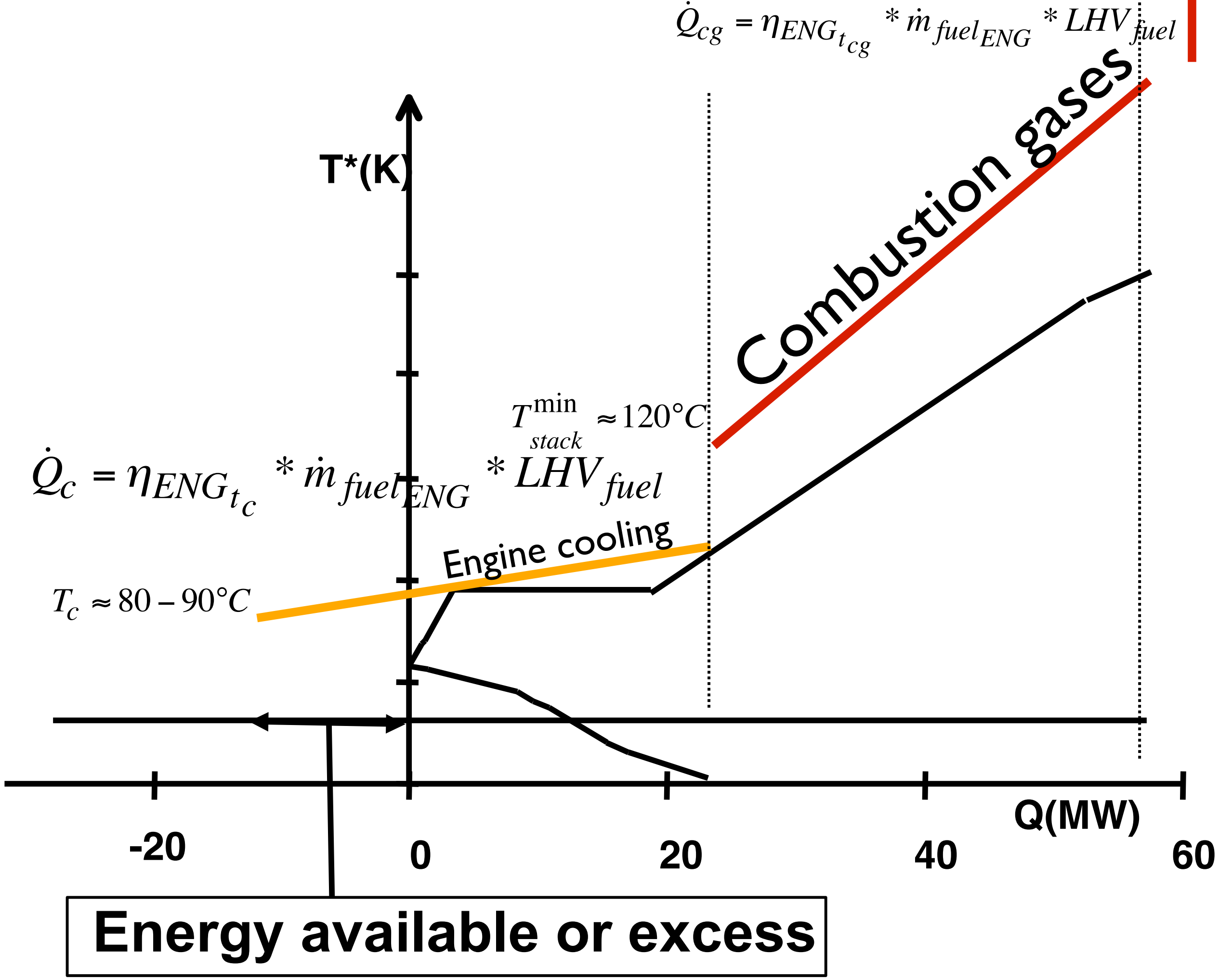
=> 120°C

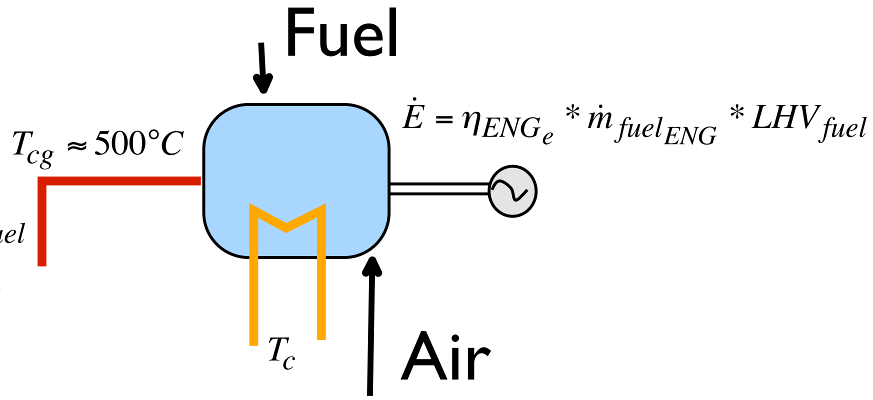
$\eta_{GT} = 85\%$

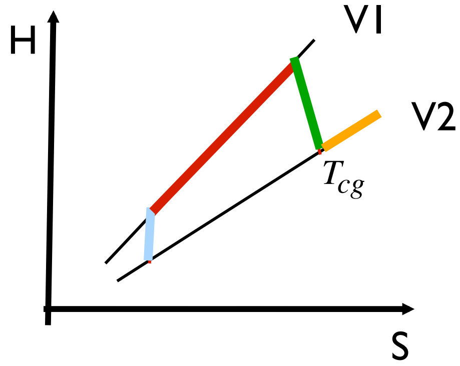
CAPEX = 1000 - 2500 CHF/kWe
Size = 50000 - 1000 kWe

Cogeneration engines

CAPEX = 800 - 4000 CHF/kWe
Size = 10000 - 100 kWe







$\eta_e = 35\%$

$\eta_{t_{cooling}} = 30\%$

$\eta_{t_{cg}} = 25\%$ => 120°C

$\eta_{total} = 80 - 90\%$

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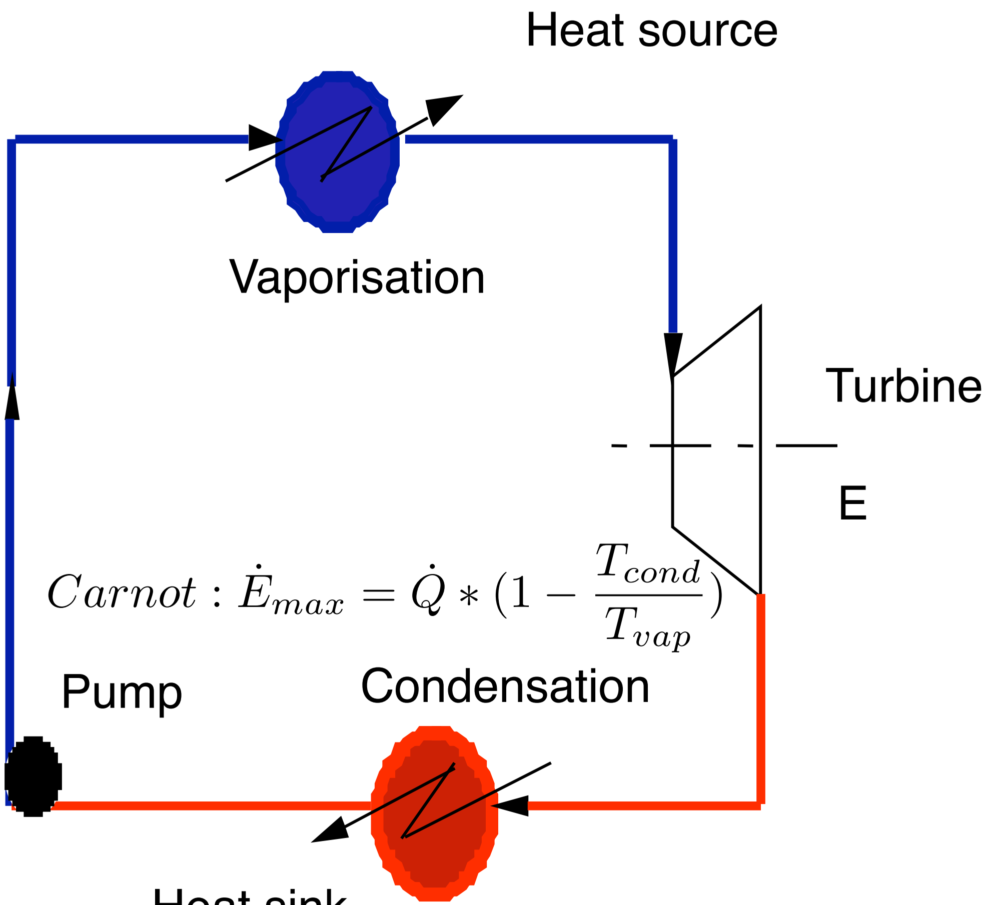
Combined heat and power

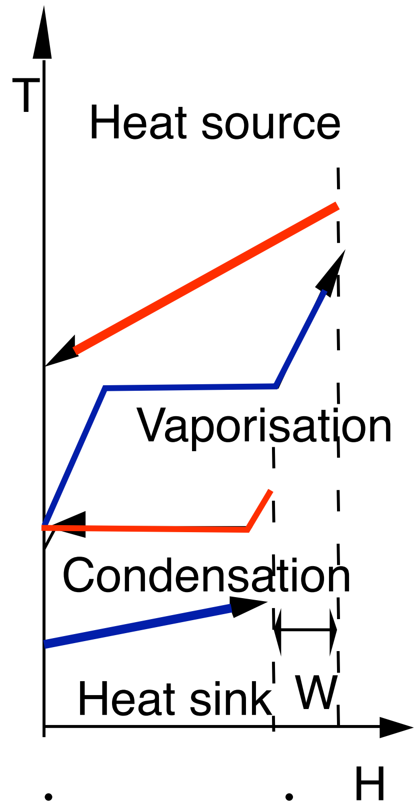
Example : Rankine cycle

$$\dot{E} = \eta_{Carnot} \cdot \dot{Q}_{hot} \cdot \left(1 - \frac{\tilde{T}_{low}}{\tilde{T}_{hot}}\right)$$

$$\eta_{Carnot} \approx 0.55$$



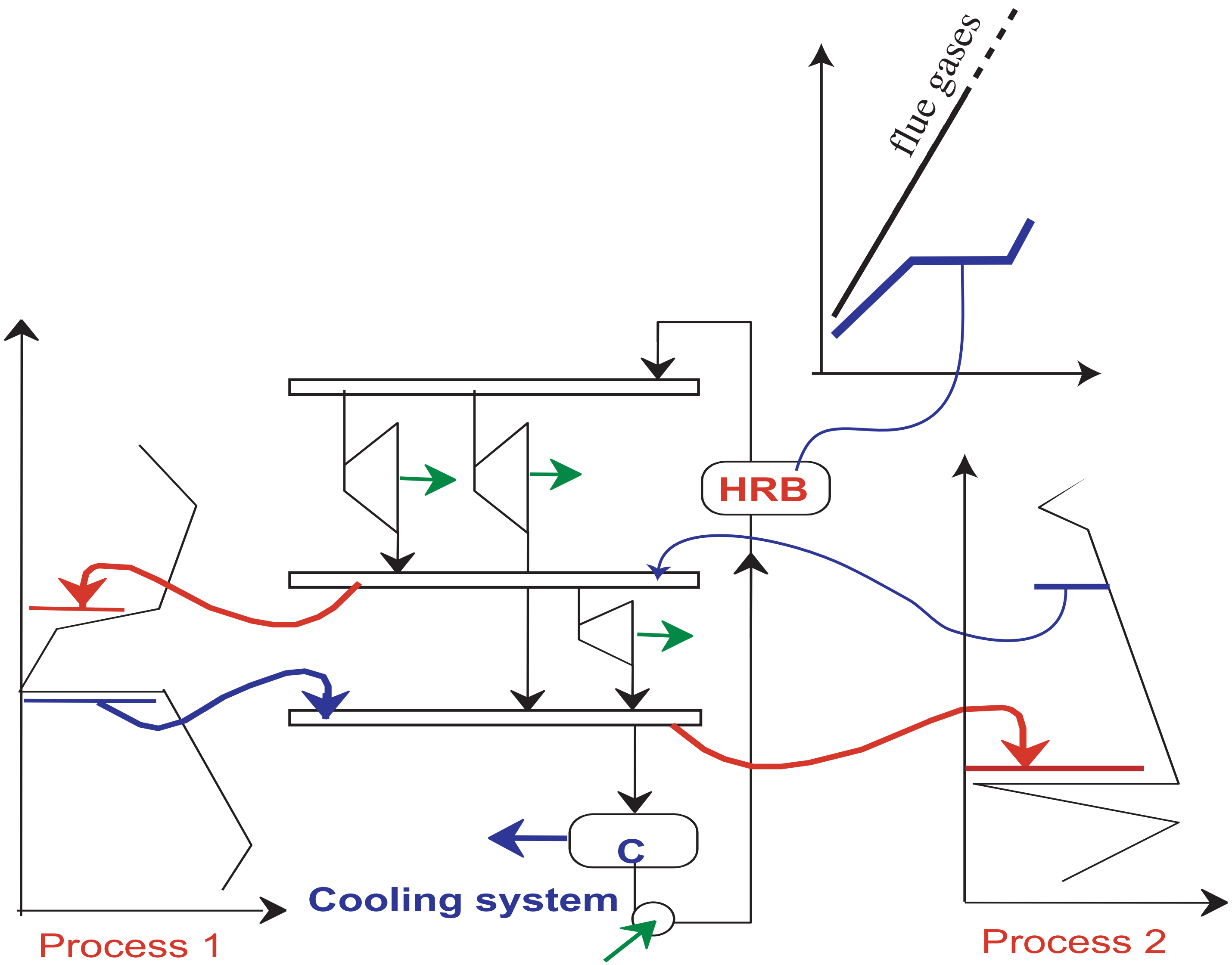
$$Carnot : \dot{E}_{max} = \dot{Q} * \left(1 - \frac{T_{cond}}{T_{vap}}\right)$$



$$\dot{Q}_{low} = \dot{Q}_{hot} - \dot{E}$$

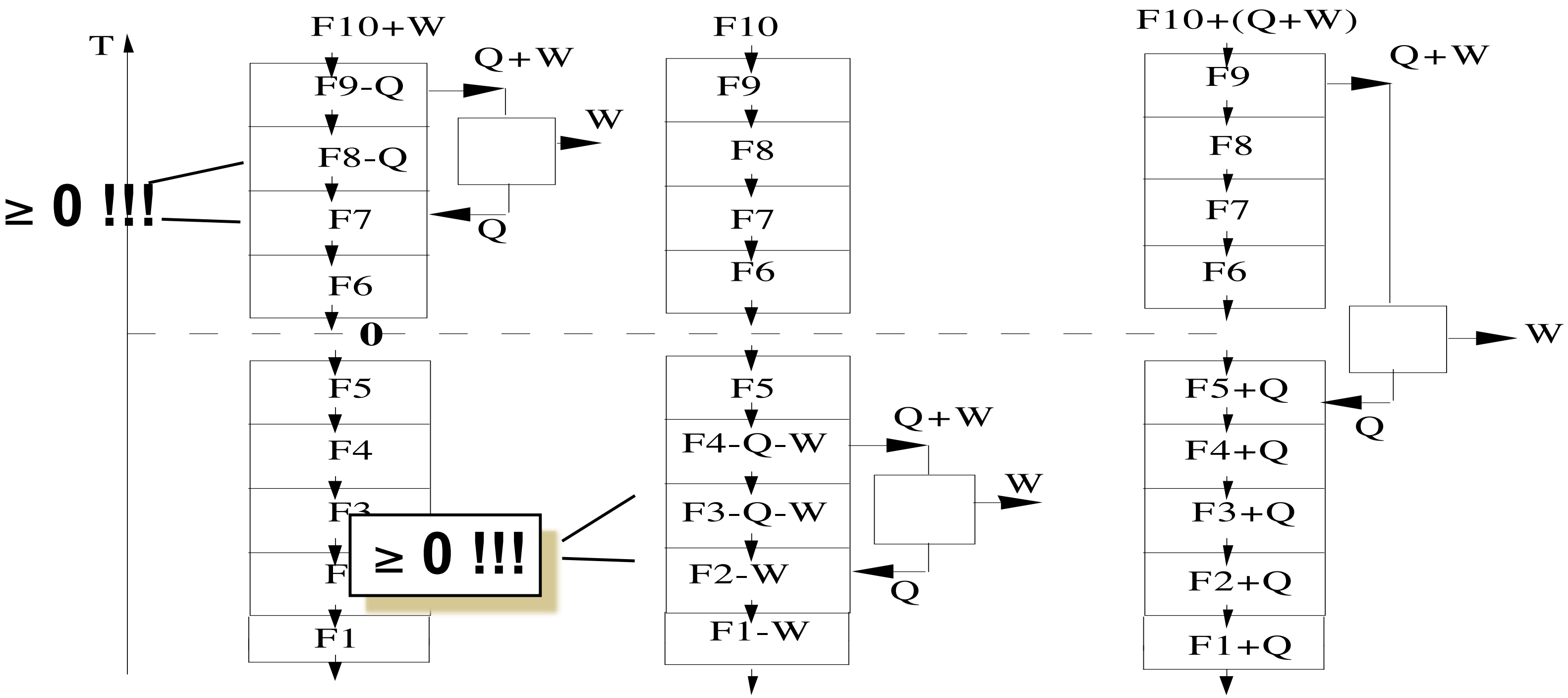
Carnot Factor between the high (source) and the low (sink) temperature of the source can be used to approximate the mechanical power production. The 0.55 efficiency with respect to Carnot is a good aproximation. Mean temperatures are logarithmic mean temperatures.

Steam network integration



How to integrate mechanical power production ?

Above the pinch point : 1 thermal kW = 1mechanical kW	Below the pinch point : 1 cold utility kW = 1 mechanical kW	Across the pinch point: Separate production



The pinch constraints limit the CHP production

The cogeneration unit integrates a hot and a cold stream in the heat cascade. The flow will therefore be limited by the activation of a utility pinch point. This pinch point will define the maximum combined production of heat and electricity for the selected system.

Profitability of a cogeneration system

- + Operating costs (CHF/s -> CHF/an)

$$\dot{M}^{+}_{fuel} \cdot c^{+}_{fuel} \cdot t + Maint + h_{mp} c_{mp}$$

mp : men power

- + Investments (CHF -> CHF/an)

$$IC_{cog} = \left(\frac{i(1+i)^{ny_{ex}}}{(1+i)^{ny_{ex}} - 1}\right) I_{inst}$$

i : expected interest rate
ny_{ex} : expected number of years of operation

- - Revenue (CHF/s -> CHF/an)

$$\underbrace{\dot{E}^{-} \cdot c^{-}_{e} \cdot t + \dot{Q}^{-} \cdot c^{-}_{q} \cdot t}_{\text{Net Export revenue}} - \underbrace{\dot{E}^{+} \cdot c^{+}_{e} \cdot t - \frac{\dot{Q}^{+}}{\eta_{th_b}} \cdot c^{+}_{fuel_b} \cdot t}_{\text{Avoided cost}}$$

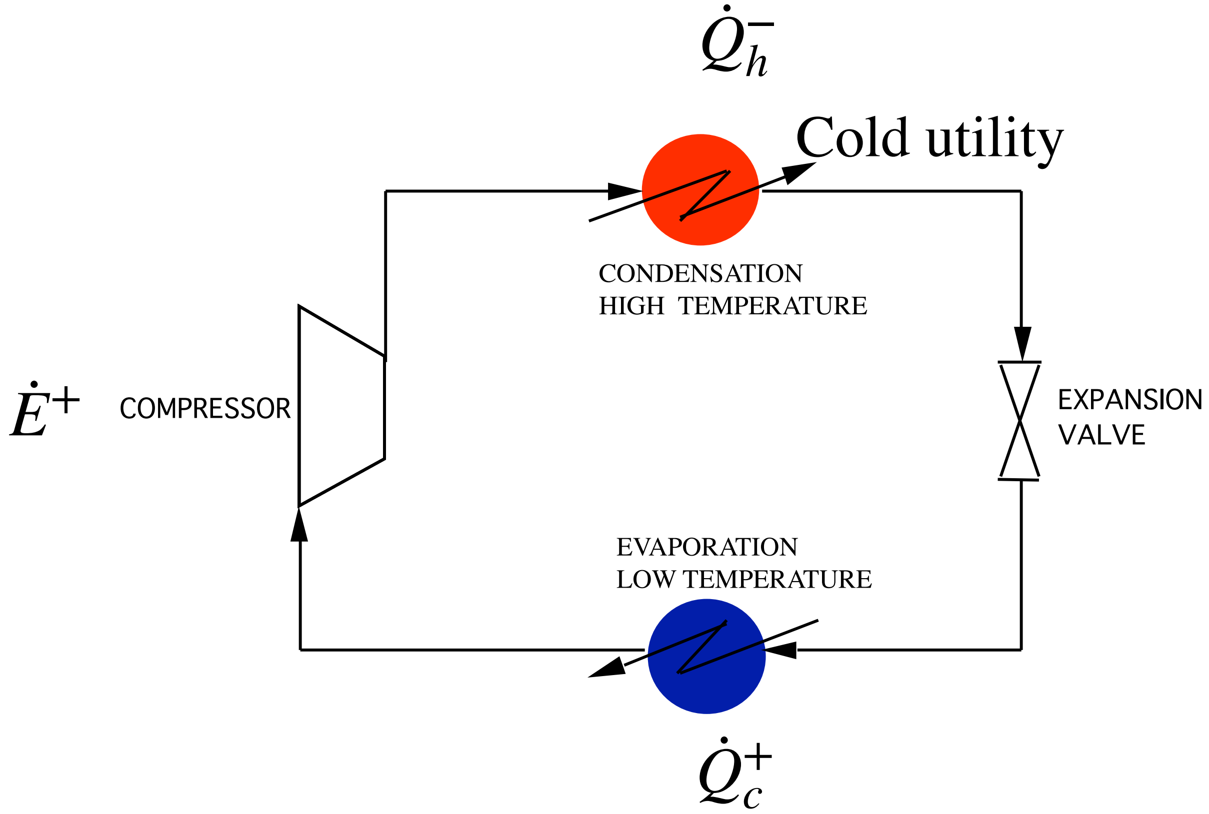
Net Export revenue Avoided cost

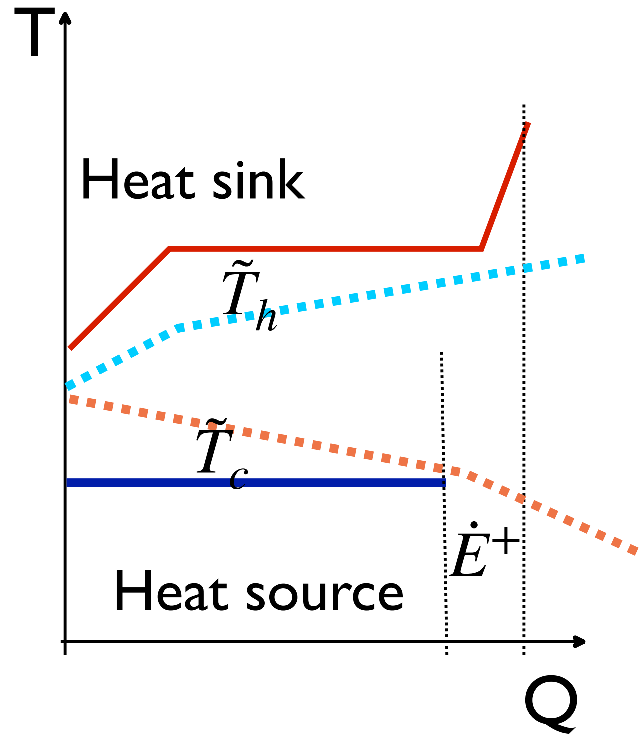
The benefit of the system mainly depends on the negociated prices for Electricity (net balance to be considered) and heat

Importance of the operating time : t

- Explain the conditions of integration of heat pumping systems.

Heat pump and refrigeration





$$COP = \frac{\dot{Q}_h^-}{\dot{E}^+} = \frac{1}{\eta_{Carnot}} \cdot \frac{\tilde{T}_h}{\tilde{T}_h - \tilde{T}_c}$$

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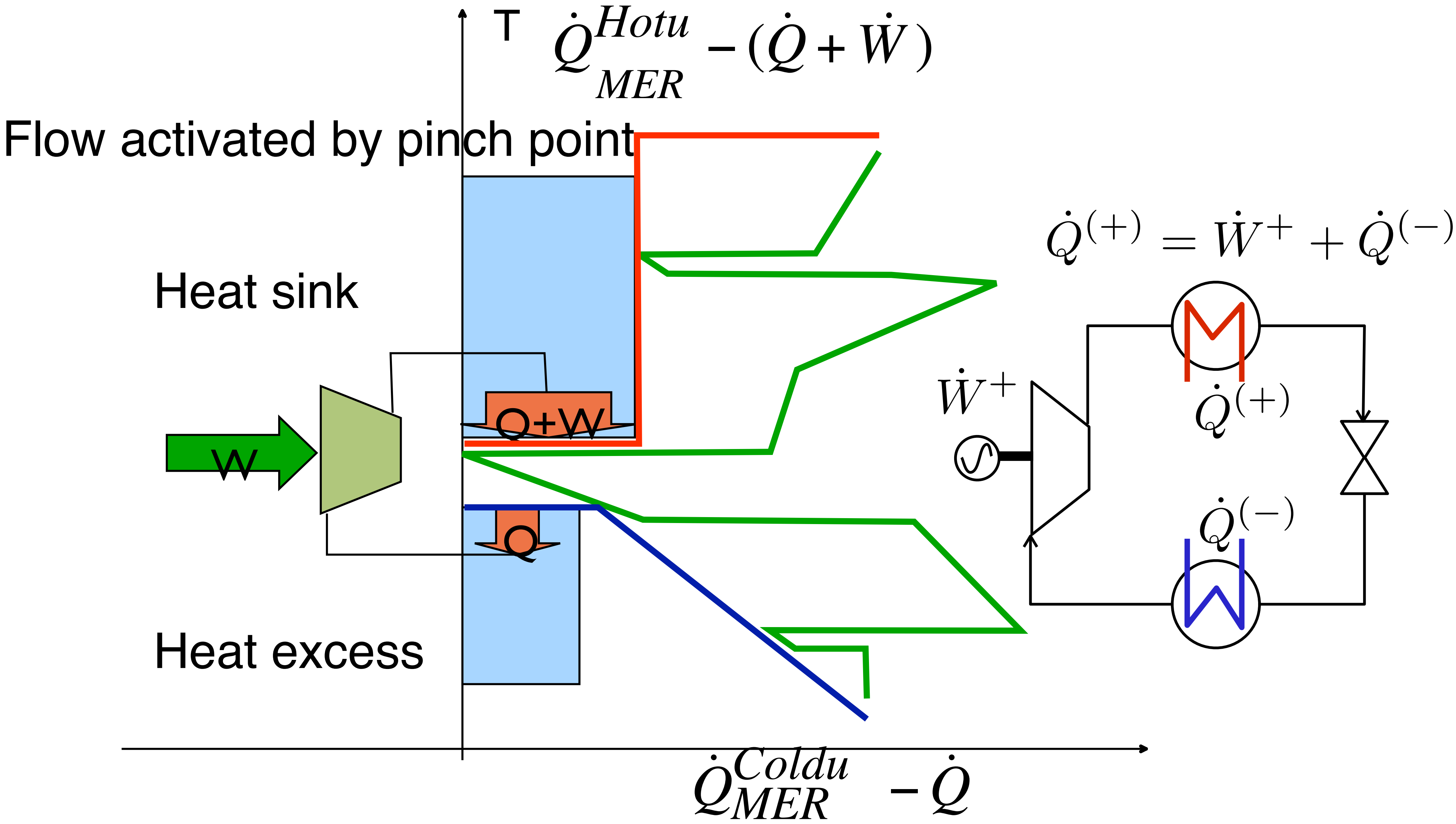
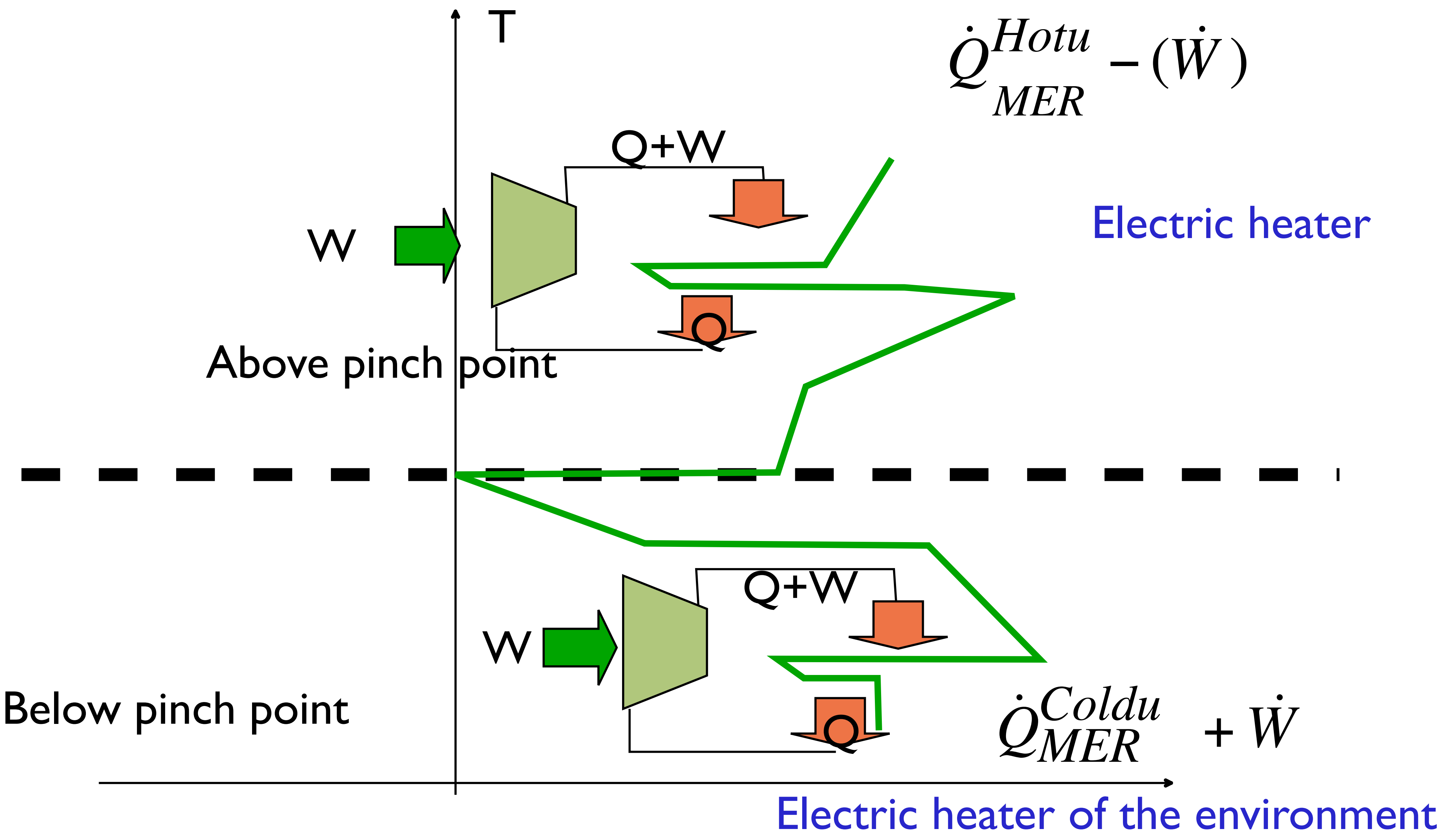
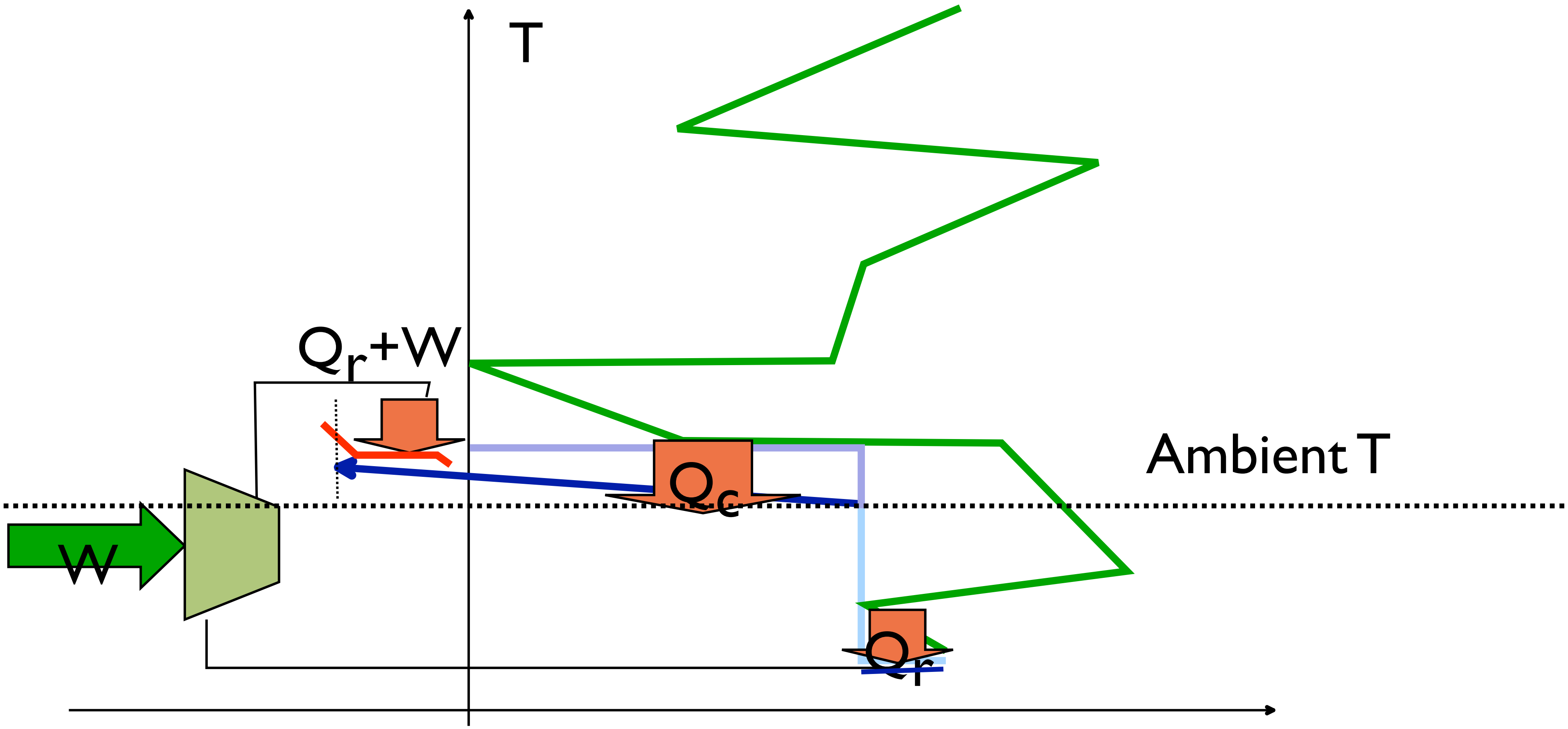
Heat pumping always from below to above the pinch



Miss placed heat pumps : above or below the pinch



Refrigeration

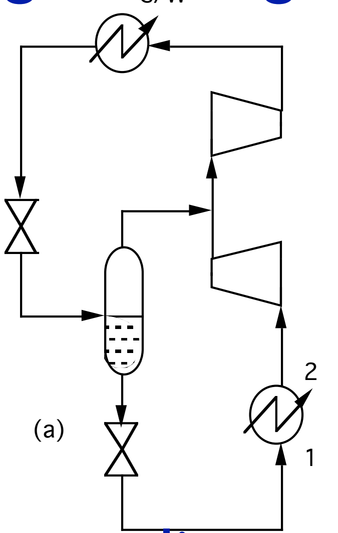


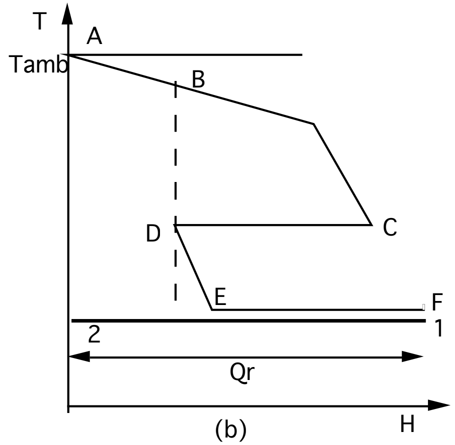
$$\dot{Q}_c + \dot{Q}_r + \dot{W} = \dot{Q}_{MER}^{Coldu} + \dot{W}$$

Increasing the flow of the cold water

Refrigeration cycle integration

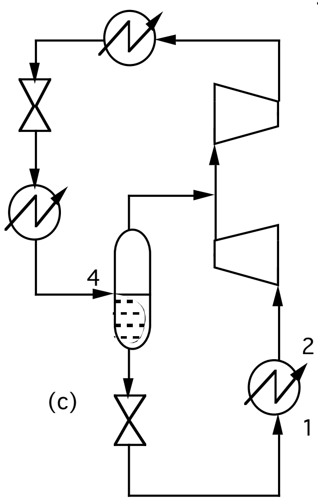
Single stage cooling

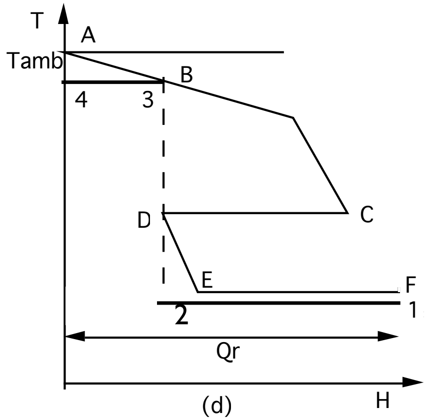




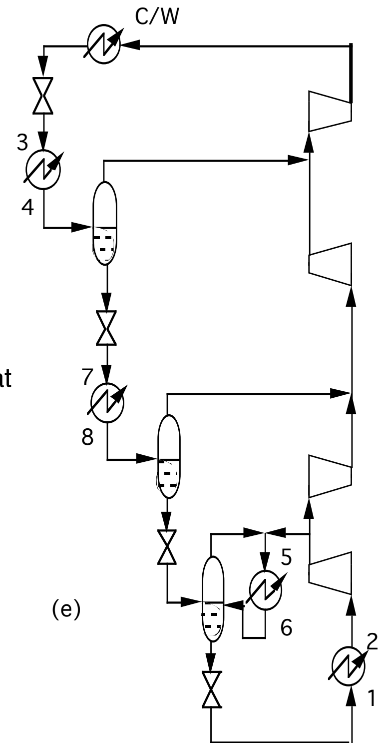
Two stages cooling

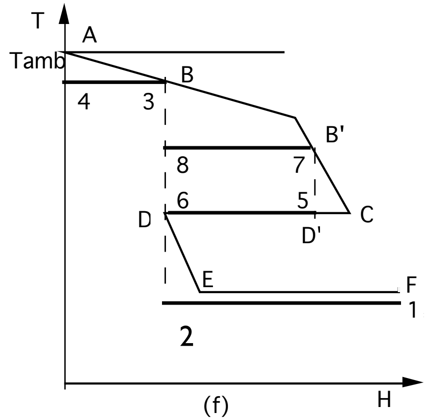
Two stages with intermediate cooling (system integration)
Two stages allows to not recompress a fluid that is already vapour in the intermediate pressure)





Three stages cooling + condensation





The 3 stages presented has the equivalent of a heat pump at D-C level that allow to use cooling at higher temperature (B') and therefore with lower compression cost.

The system integration plays here an important role. Refrigeration consume high value energy (electricity) it therefore requires careful integration. The solutions explained above show that there are a lot of options for the refrigeration system integration, including the choice of the fluids, the operating conditions and the system configuration

Integration of the energy conversion system

- Energy conversion units with unknown flowrates

Technology w with nominal flow

Hot/cold streams

$$T^{in}_{w,i}, P^{in}_{w,i}, \dot{m}_{w,i}, x_{w,i}$$

$$q_w = \dot{m}_{w,i}(h^{in}_{w,i} - h^{out}_{w,i})$$

$$T^{out}_{w,i}, P^{out}_{w,i}, \dot{m}_{w,i}, x_{w,i}$$

Mechanical power/electricity

$$e_w$$

Costs

$$C1_w, C2_w, CI1_w, CI2_w$$

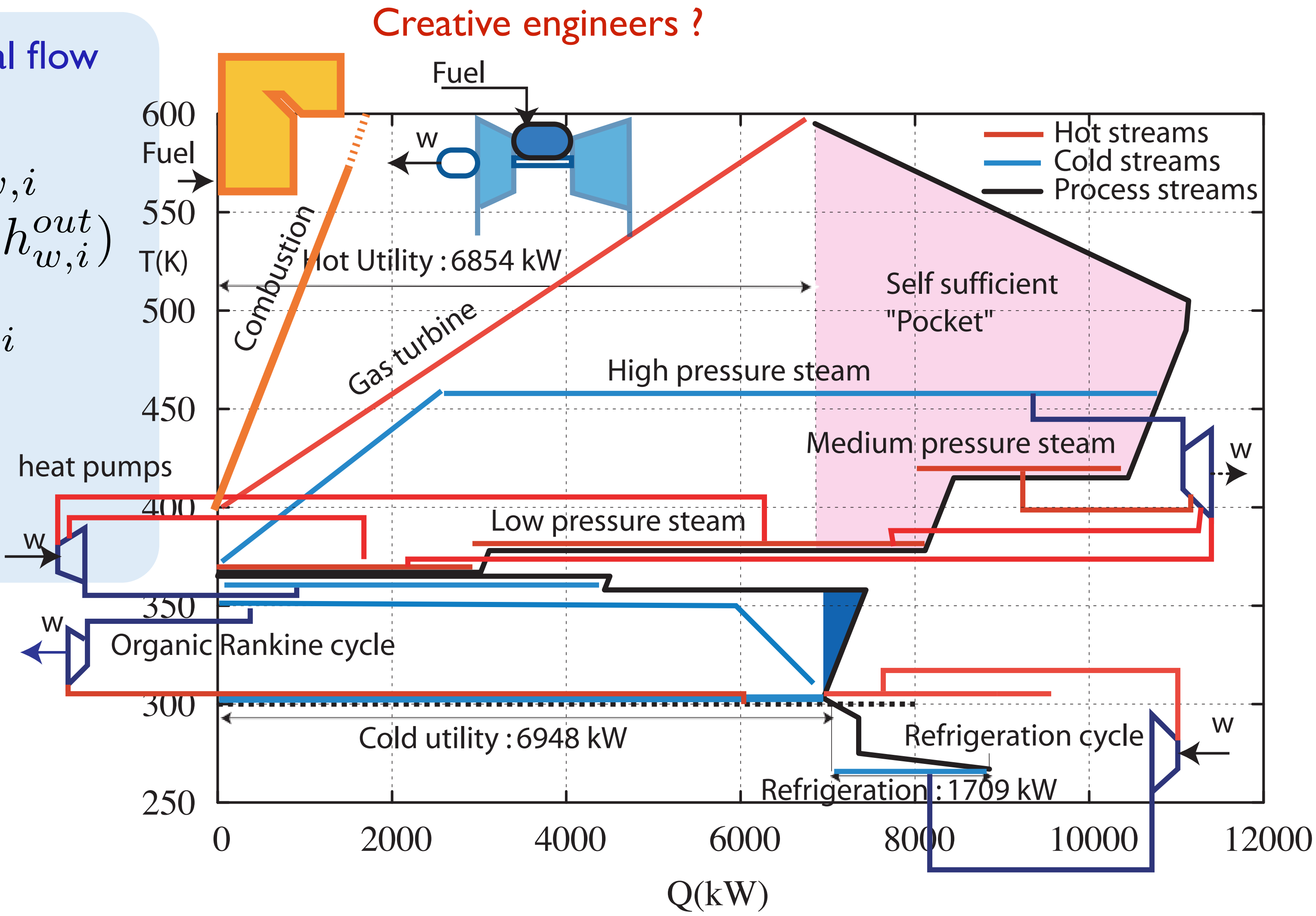
Decision variables

Level of usage of w

$$f_w$$

Buy/use technology w ?

$$y_w$$



by simulation we can generate the hot and cold streams associated to a predefined level of usage (or flow).
the questions are : do I use the technology ? if yes what is the level of usage.

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MILP (Mixed Integer Linear Programming) formulation

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

Operating cost

Fixed maintenance

Investment

Subject to : Heat cascade constraints

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

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

Electricity consumption

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

Electricity production

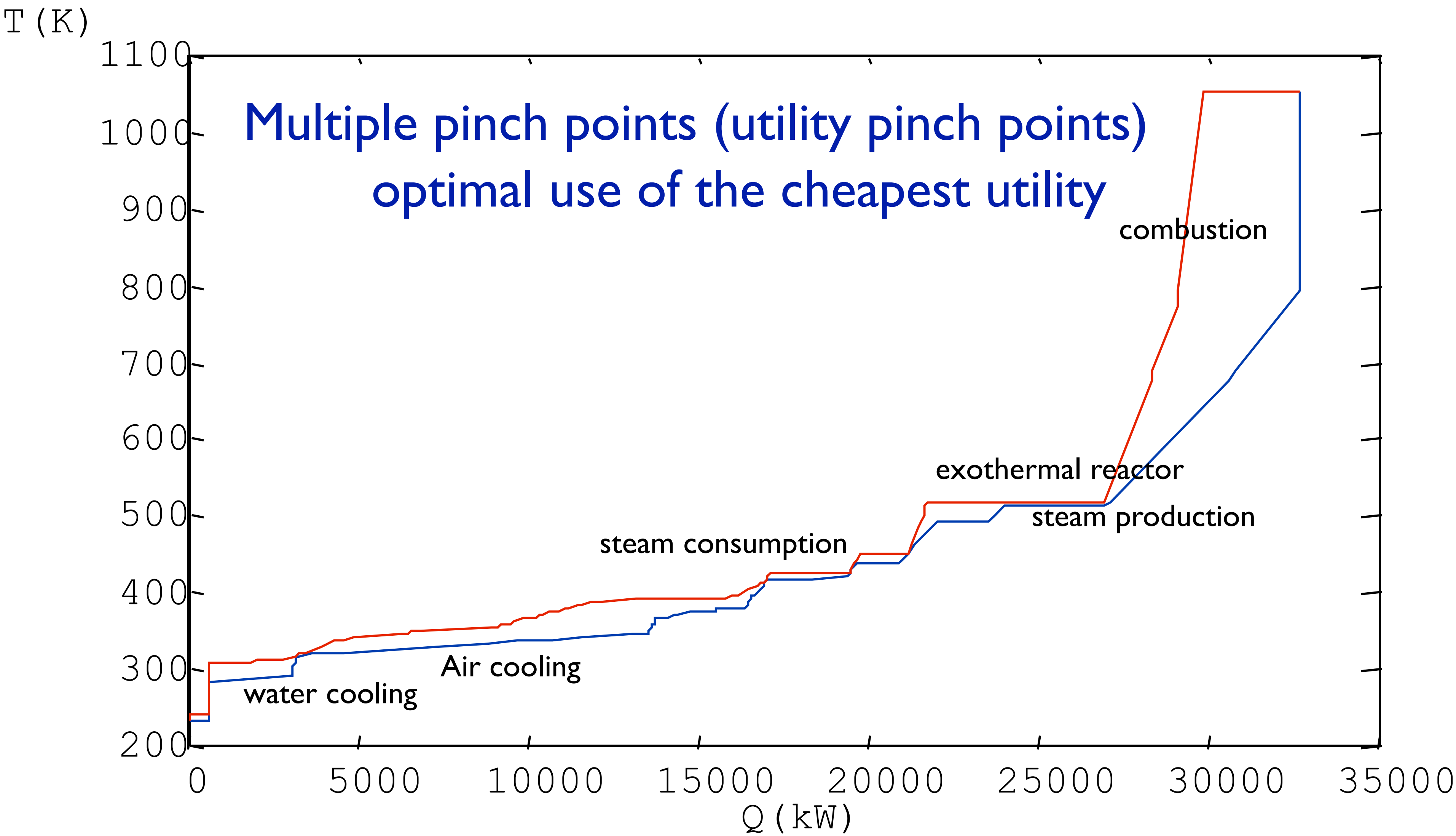
$$\sum_{w=1}^{n_w} f_w e_w + E^+ - E_c - E^- = 0$$

Energy conversion Technology selection

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

The mixed integer linear programming formulation allows to solve the heat recovery by using the heat cascade in the list of constraints, the electricity balance , differentiating import and export and considering the cost of the energy resources used in the system. flows in the system are calculated to close the energy balance and existence of a energy conversion solution is decided using an integer variable. The min and max bounds are used to avoid the usage of technologies that are out of the range of their typical application

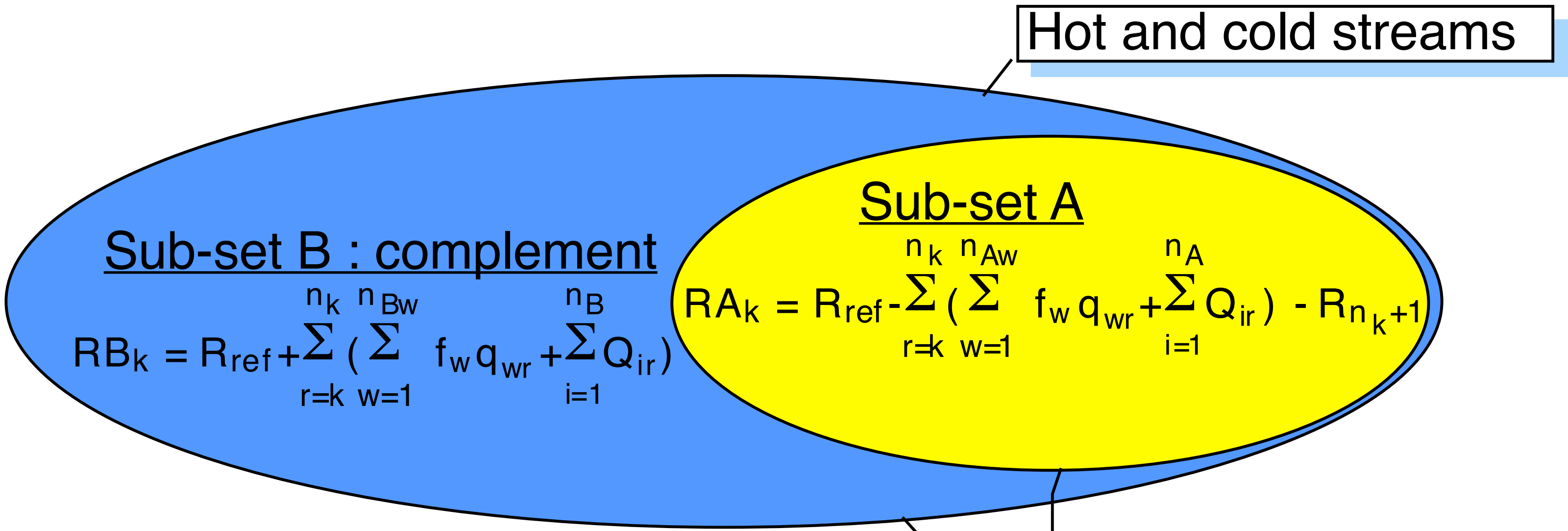
Results : Balanced composite curves



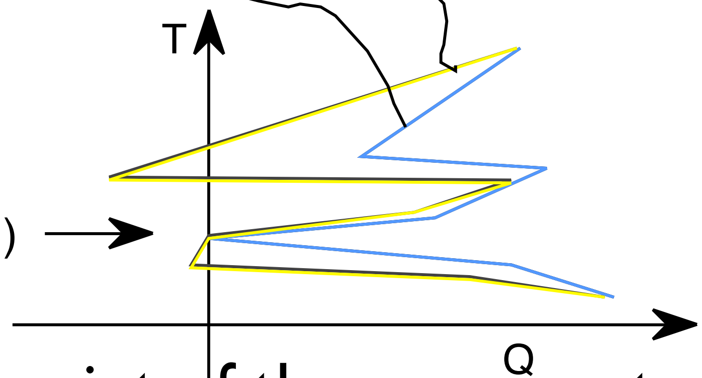
The balanced composite curves include the process and the utility streams. The balance is now closed has no magic hot or cold utility is used.

Evaluate : the Integrated Composite Curves

The goal is to understand the solutions



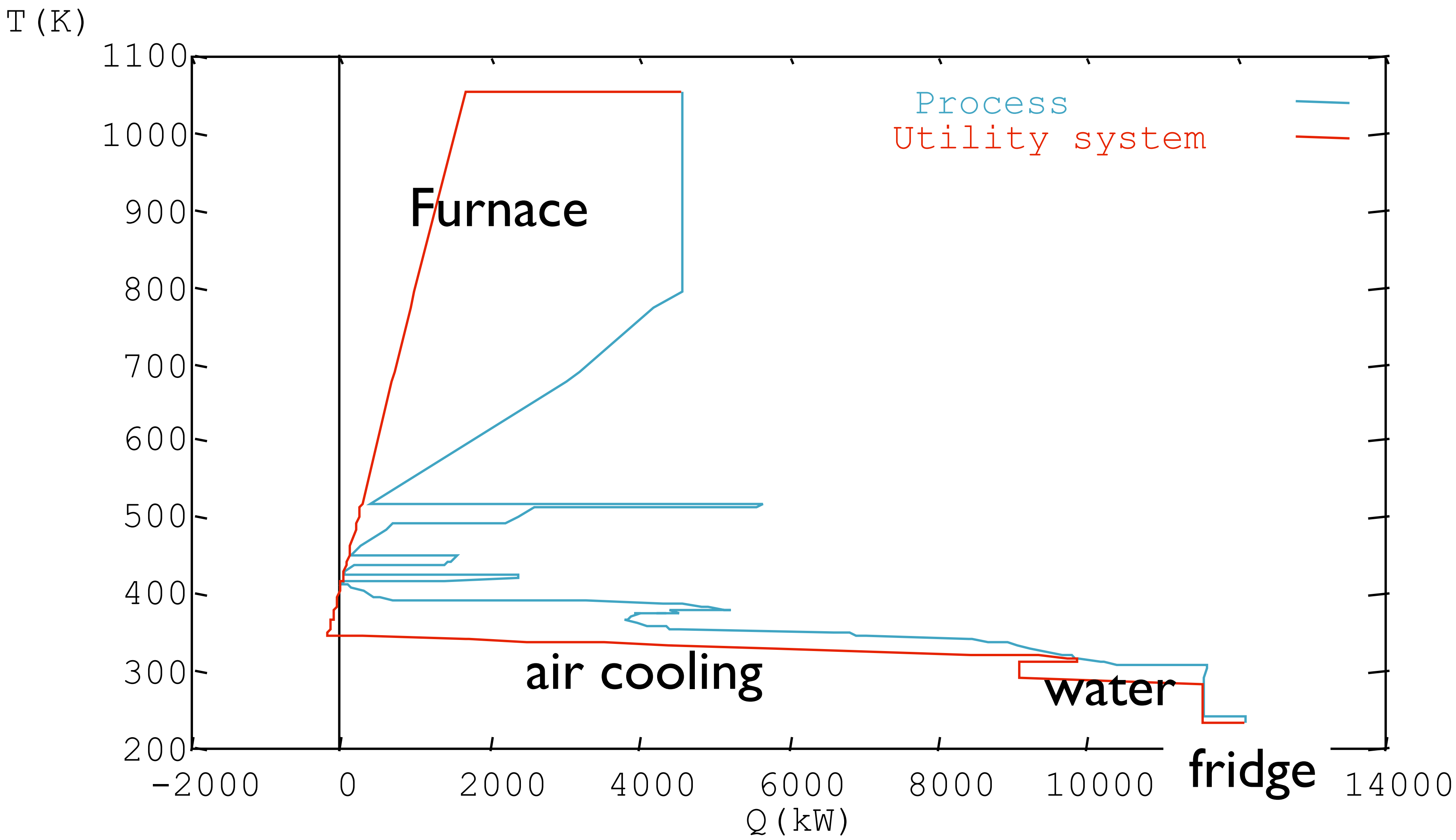
$$RB_{kp} = 0 \Rightarrow R_{ref} = - \sum_{r=kp}^{n_k} \left(\sum_{w=1}^{n_{Bw}} f_w q_{wr} + \sum_{i=1}^{n_B} Q_{ir} \right)$$



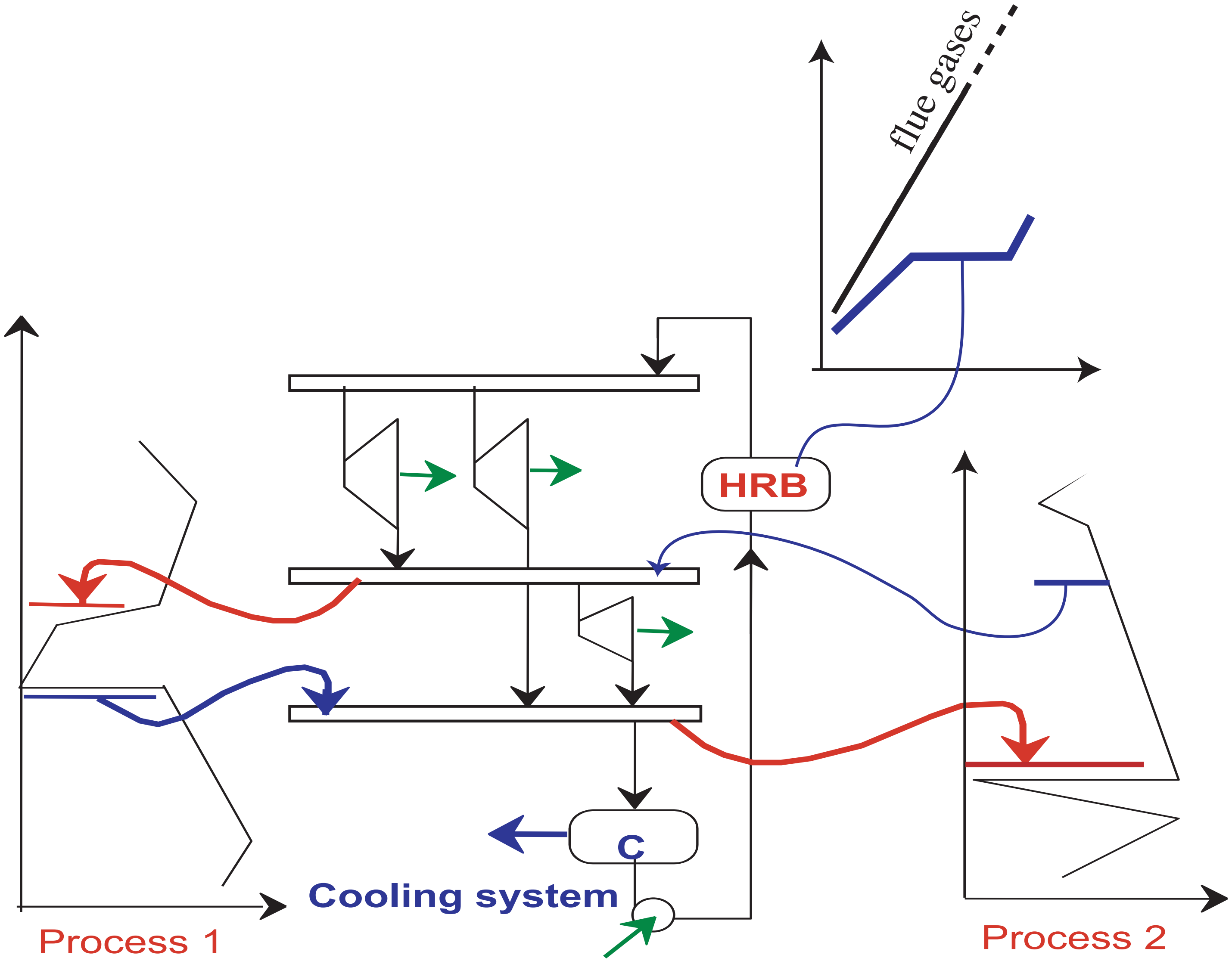
Choose a reference : pinch point of the process streams

The integrated composite curve represent the way a sub-system is integrated with the remaining system.

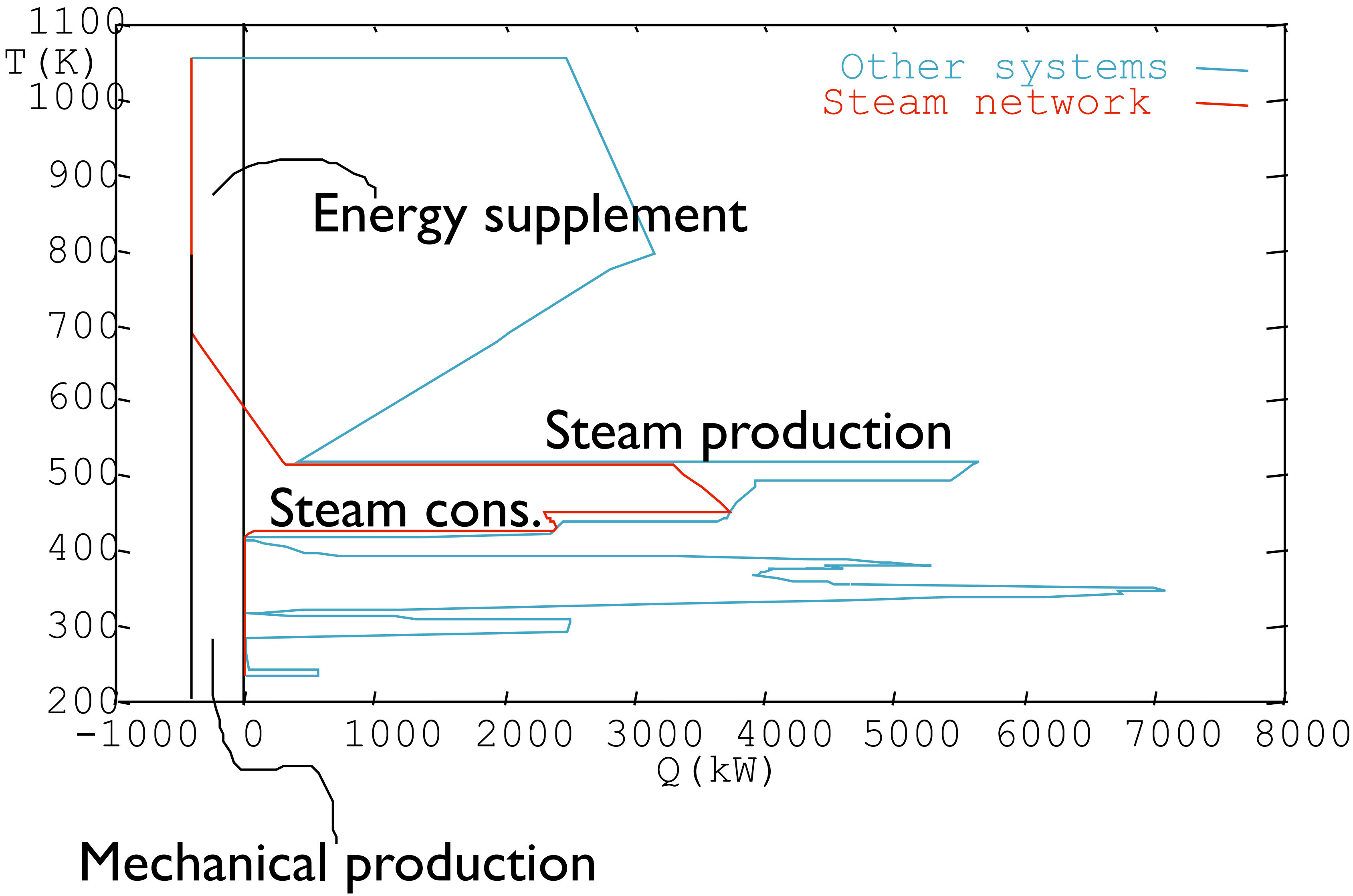
ICC for utility system integration



Steam network integration



ICC of the steam network



Note that for a closed cycle like refrigeration or Rankine, the sum the hot stream - the sum of the cold stream is the net mechanical power (i.e. the distance between the two extreme points is equal to the mechanical power). Here for the steam cycle. Note that it is therefore easy to very that the cogeneration cycle is well located wrt the pinch point.