Utility Integration by optimisation

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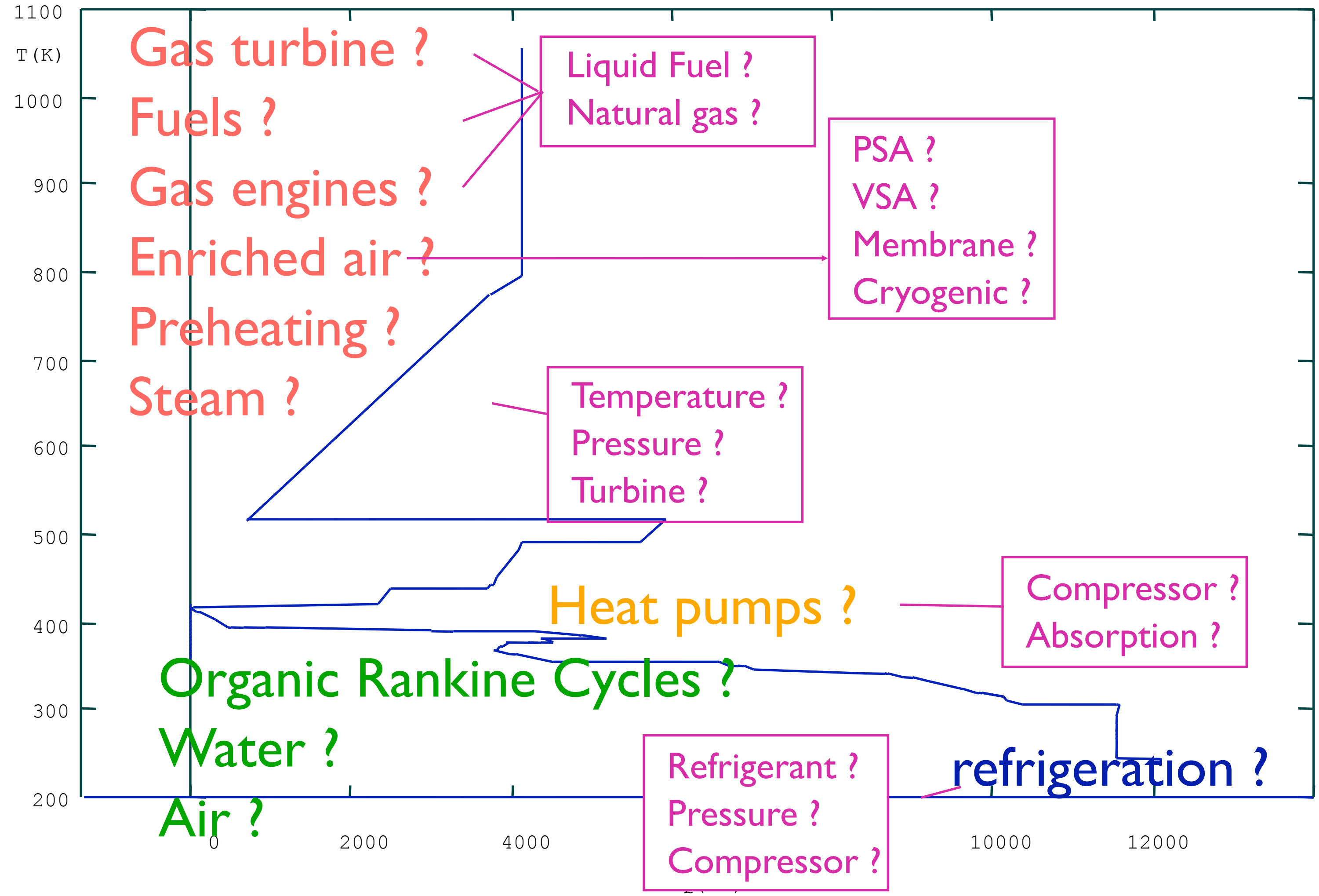
Utilities


1100
T(K)
1000
900
800
700
600
500
400
300
200
0
2000
4000
10000
12000
Gas turbine ?
Fuels ?
Gas engines ?
Enriched air ?
Preheating ?
Steam ?
Liquid Fuel ?
Natural gas ?
PSA ?
VSA ?
Membrane ?
Cryogenic ?
Temperature ?
Pressure ?
Turbine ?
Heat pumps ?
Compressor ?
Absorption ?
Organic Rankine Cycles ?
Water ?
Air ?
Refrigerant ?
Pressure ?
Compressor ?
refrigeration ?

Integration of the energy conversion system

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

$$e_w$$

Cost

s $C1_w, C2_w, CI1_w, CI2_w$

Decision variables

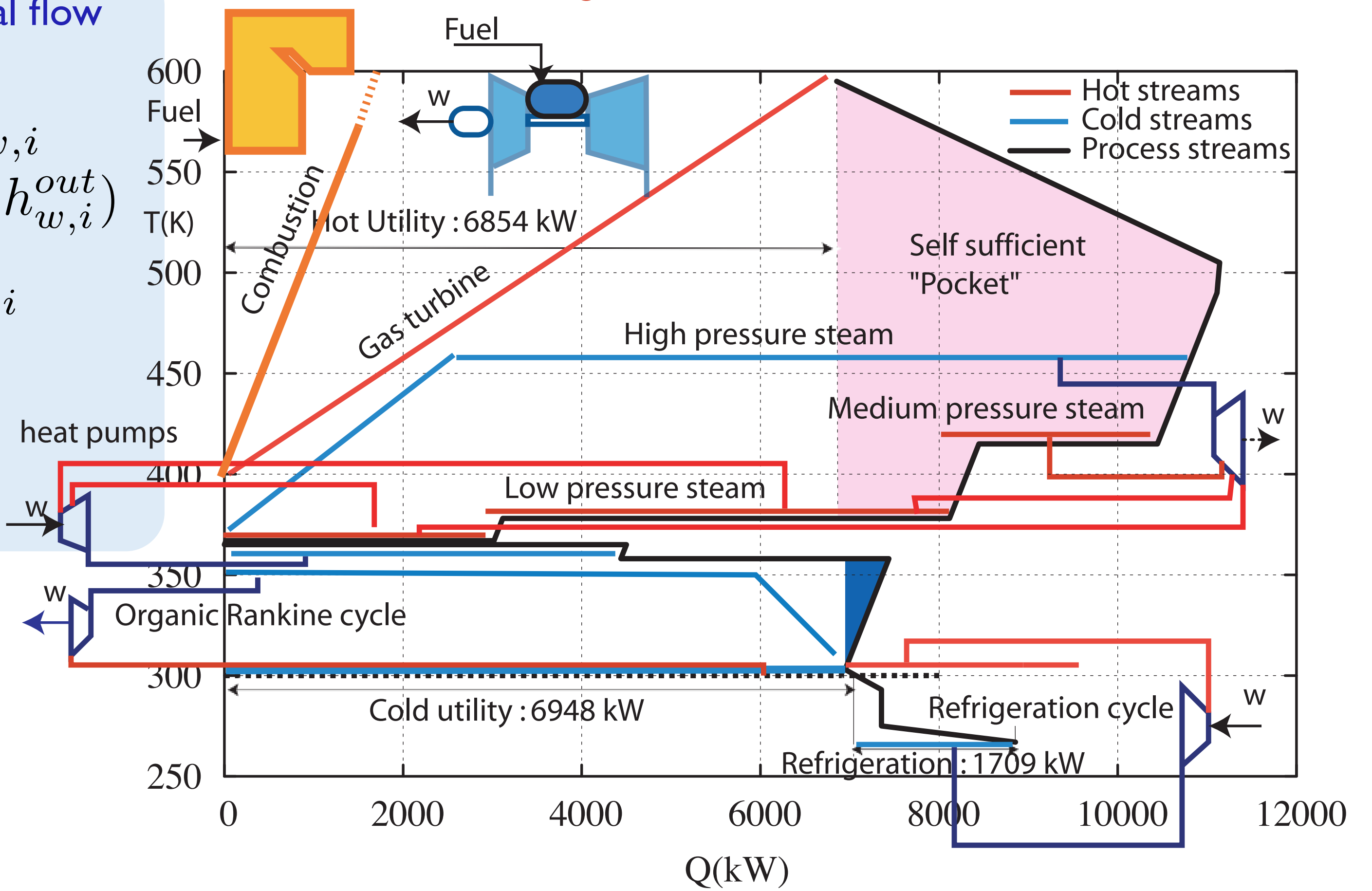
Level of usage of w

$$f_w$$

Buy/use technology w ?

$$y_w$$

Creative engineers ?



MILP formulation

Operating cost

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

Fixed maintenance

$$+ \sum_{w=1}^{n_w} C1_w y_w + \frac{1}{\tau}\left(\sum_{w=1}^{n_w} (CI1_w y_w + CI2_w f_w)\right)$$

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

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

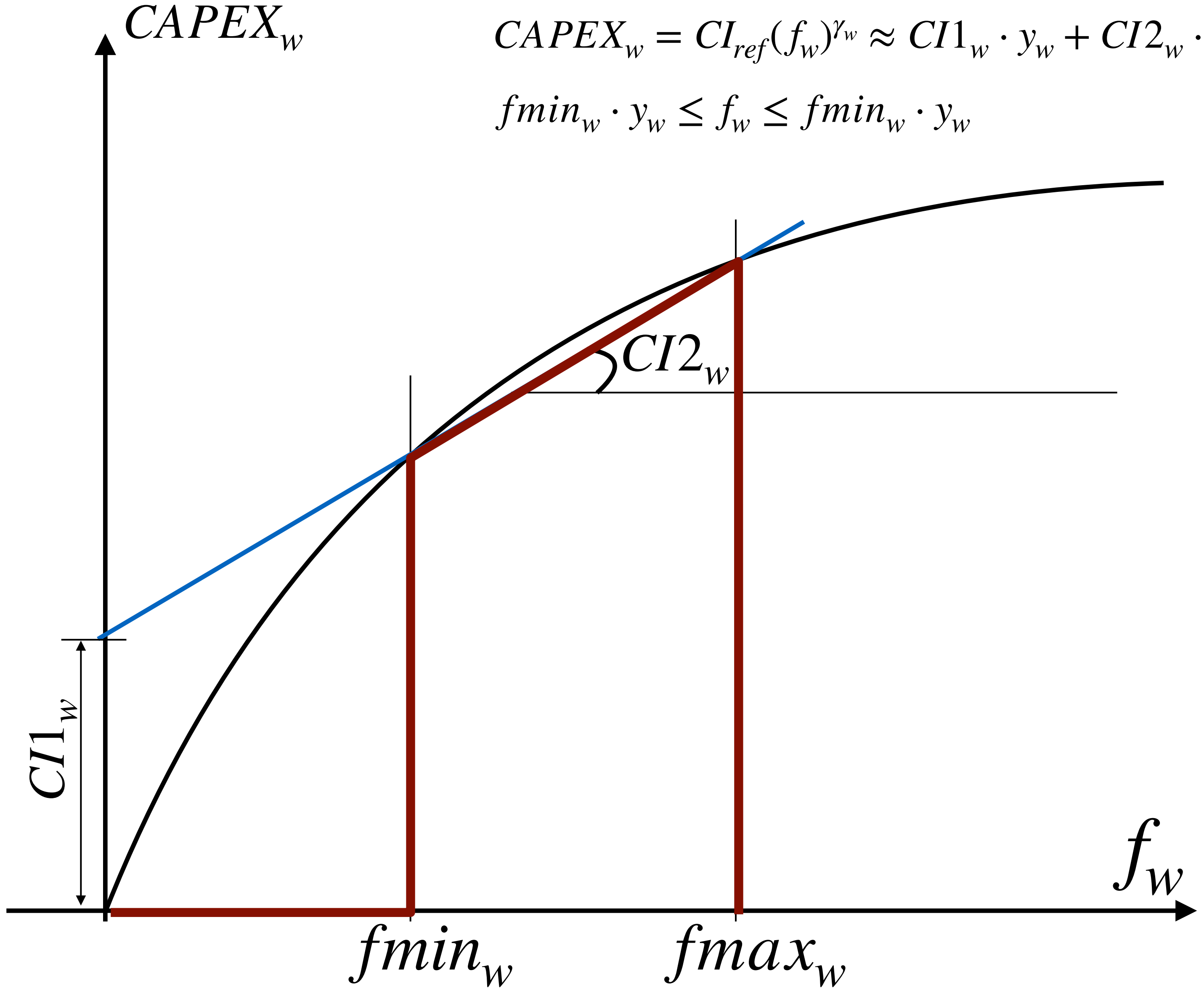
Energy conversion Technology selection

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

Linearisation of non linear function

$$CAPEX_w = CI_{ref}(f_w)^{\gamma_w} \approx CI1_w \cdot y_w + CI2_w \cdot f_w$$

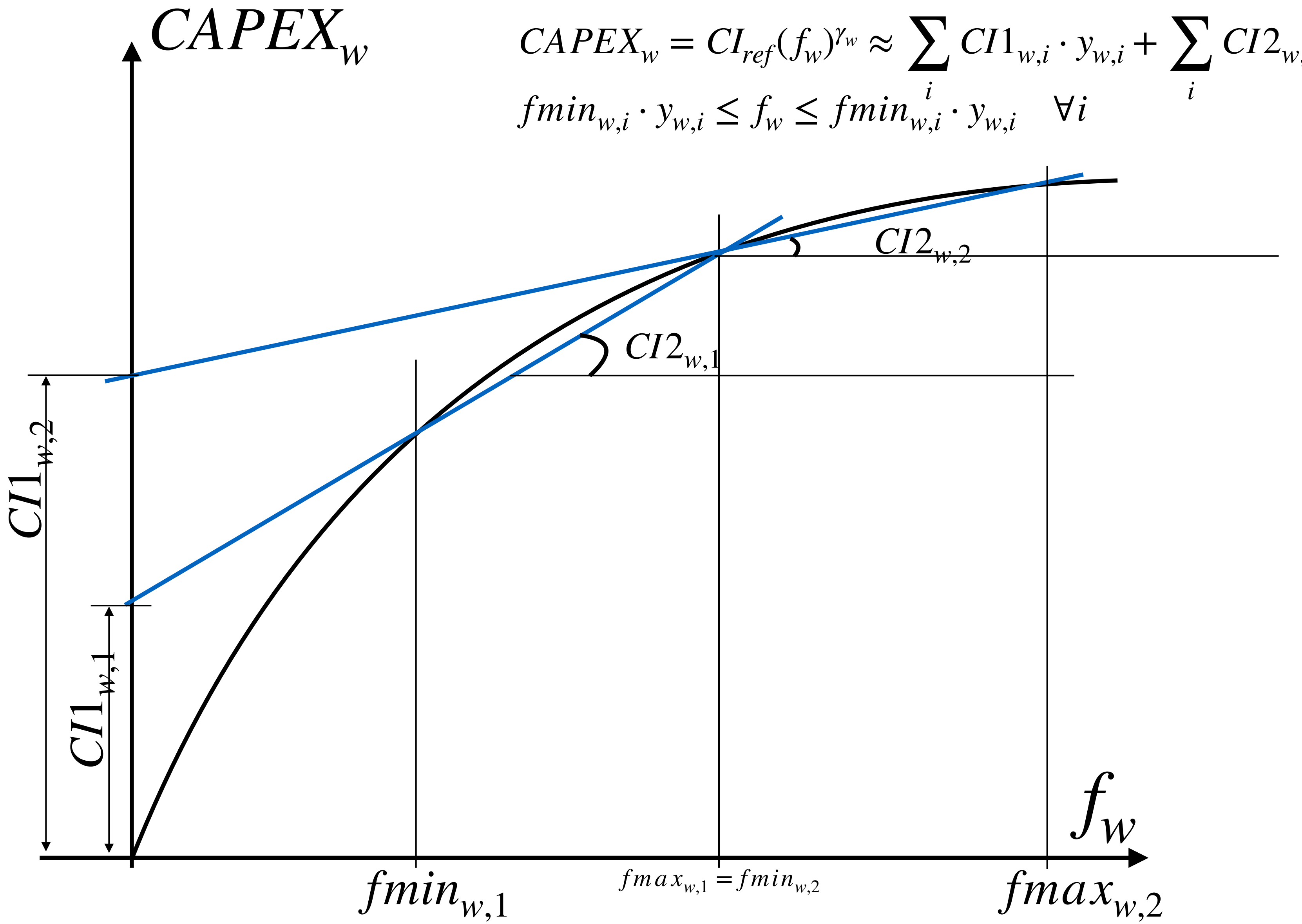
$$fmin_w \cdot y_w \leq f_w \leq fmin_w \cdot y_w$$



Piecewise linearisation of non linear function

$$CAPEX_w = CI_{ref}(f_w)^{\gamma_w} \approx \sum_i CI1_{w,i} \cdot y_{w,i} + \sum_i CI2_{w,i} \cdot f_w$$

$$fmin_{w,i} \cdot y_{w,i} \leq f_w \leq fmin_{w,i} \cdot y_{w,i} \quad \forall i$$



MILP problems

Mixed Integer Problems

- MILP
  - Mixed Integer Linear Programming problems
    - Linear constraints & objective
    - continuous and integer variables
- MINLP
  - Mixed Integer Non Linear Programming problems
    - Non linear constraints & objective
    - continuous and integer variables

MILP : Branch & Bound Method

- Solve LP at each node
  - start with integer variables = continuous

$$0 \leq z_i \leq 1 \quad \forall i = 1, ..., 3$$

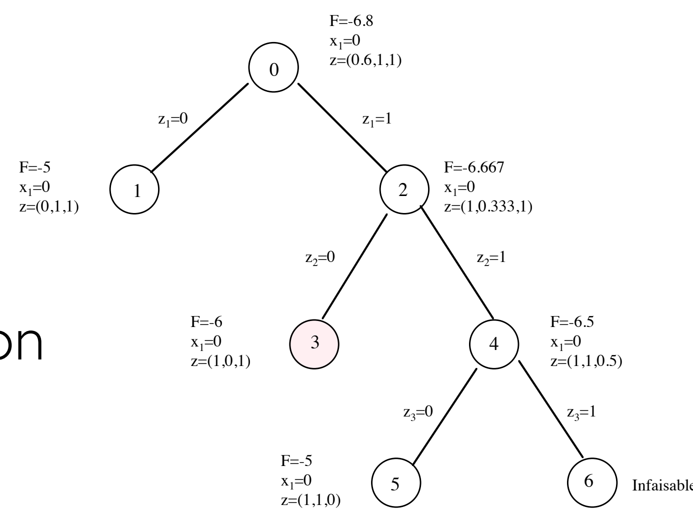
- Progressively "integerify" by systematically adding constraints (Branch)

$$z_i = 1 \text{ or } 0 \text{ for i in Nodes} \quad 0 \leq z_j \leq 1 \quad \forall j \neq i$$

➡the objective is worsening

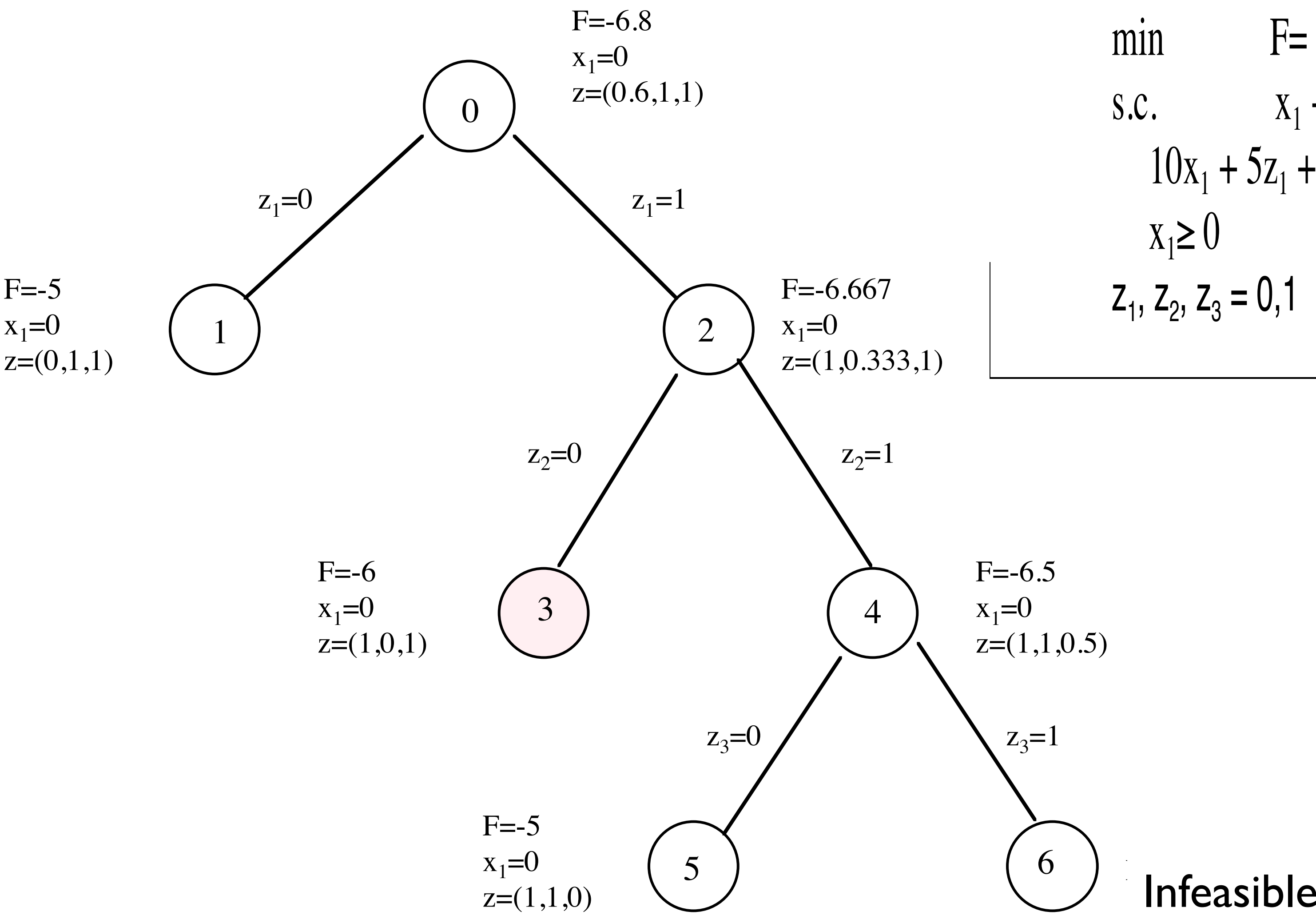
- **when a set where all zi is integer**
  - define the bound (the objective function will never be worse then this value
- **re-explore the branches**
  - cut the three exploration when the objective function reaches the bound

$$\begin{aligned} \text{min} \quad & F = 2x_1 - 3z_1 - 2z_2 - 3z_3 \\ \text{s.c.} \quad & x_1 + z_1 + z_2 + z_3 \geq 2 \\ & 10x_1 + 5z_1 + 3z_2 + 4z_3 \leq 10 \\ & x_1 \geq 0 \\ & z_1, z_2, z_3 = 0,1 \end{aligned}$$



MILP : Branch & Bound Method

$$
\begin{aligned}
\min \quad & F = 2x_1 - 3z_1 - 2z_2 - 3z_3 \\
\text{s.c.} \quad & x_1 + z_1 + z_2 + z_3 \geq 2 \\
& 10x_1 + 5z_1 + 3z_2 + 4z_3 \leq 10 \\
& x_1 \geq 0 \\
& z_1, z_2, z_3 = 0,1
\end{aligned}
$$



MILP optimization

- **Linear programming**
  - optimum defined by constraints
    - max/min
    - Pinch points
  - Cost may create strange results
    - if electricity is cheaper than the fuel, a heat pump becomes an electrical heater
  - Integer variables for technology selection
    - Can be used to select among options
- **Heat balance constraints**
  - if the hot and cold utility have not the appropriate levels no solution is found
  - max flows may prevent to close the balance
  - max flows may prevent convergence

$$y_i \cdot f_{min} \leq f \leq y_i \cdot f_{max}$$

$$1. \leq 0.000001 \cdot 1'000'000$$

$$\text{is } y_i = 0.000001 =?\ 0 \text{ or } 1$$

- **Additional constraints**
  - have to be satisfied
- **Need to analyze solutions**

Logical constraints

At least 1 of 4	$\sum_{i=1}^{4} y_i \geq 1$
At most 1 of 4	$\sum_{i=1}^{4} y_i \leq 1$
y1 or y2	$y_1 + y_2 = 1$
if y1 then y2	$\mathrm{y}_2 \geq y_1$
if y1 then not y2	$\mathrm{y}_\mathrm{b} \leq (1 - y_a)$

Generating order list of Integer Sets Solutions

- Integer cut constraint
  - assuming that we know already k solutions
  - problem k + 1 is defined by adding to the previous MILP problem the integer cut constraint

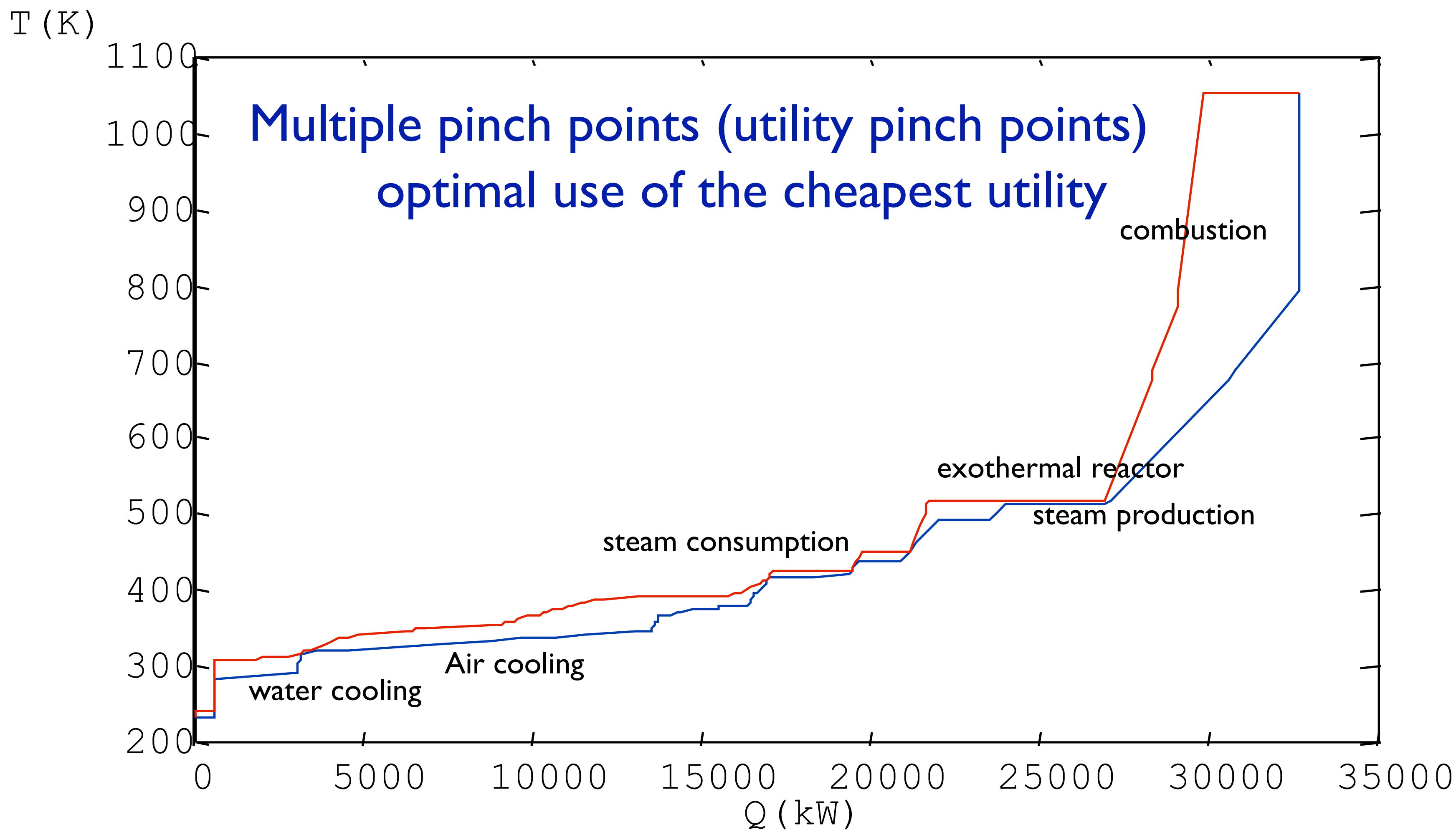
$Problem^{k+1}$:

$Problem^k$

$$\sum_{i=1}^{n_y}(2y_i^k - 1) * y_i \leq \sum_{i=1}^{n_y} y_i^k$$

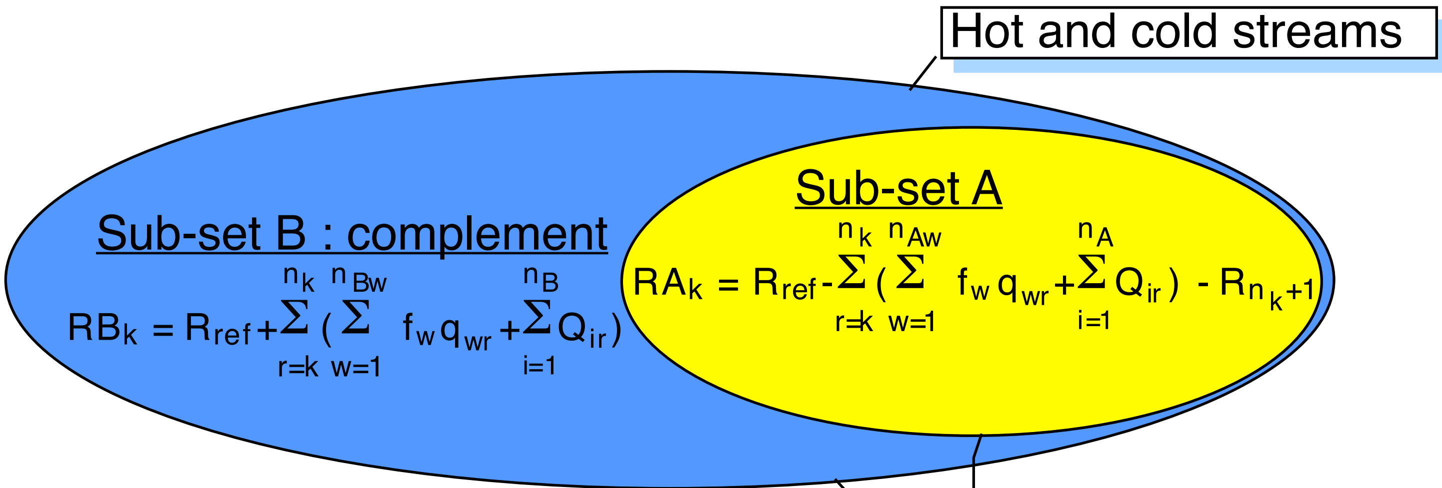
where y_i^k value of y_i in solution of problem k

Results : Balanced composite curves



Evaluate : the Integrated Composite Curves

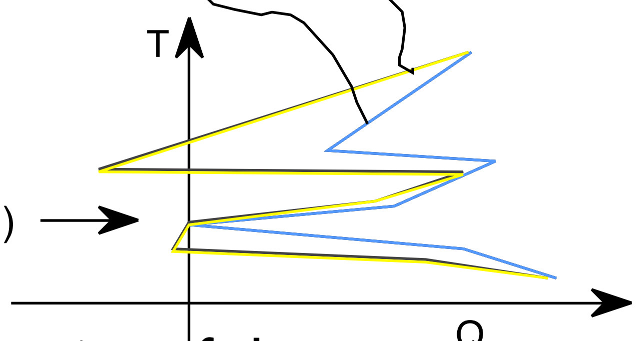
The goal is to understand the solutions



$$RB_k = R_{ref} + \sum_{r=k}^{n_k} \left(\sum_{w=1}^{n_{Bw}} f_w q_{wr} + \sum_{i=1}^{n_B} Q_{ir} \right)$$

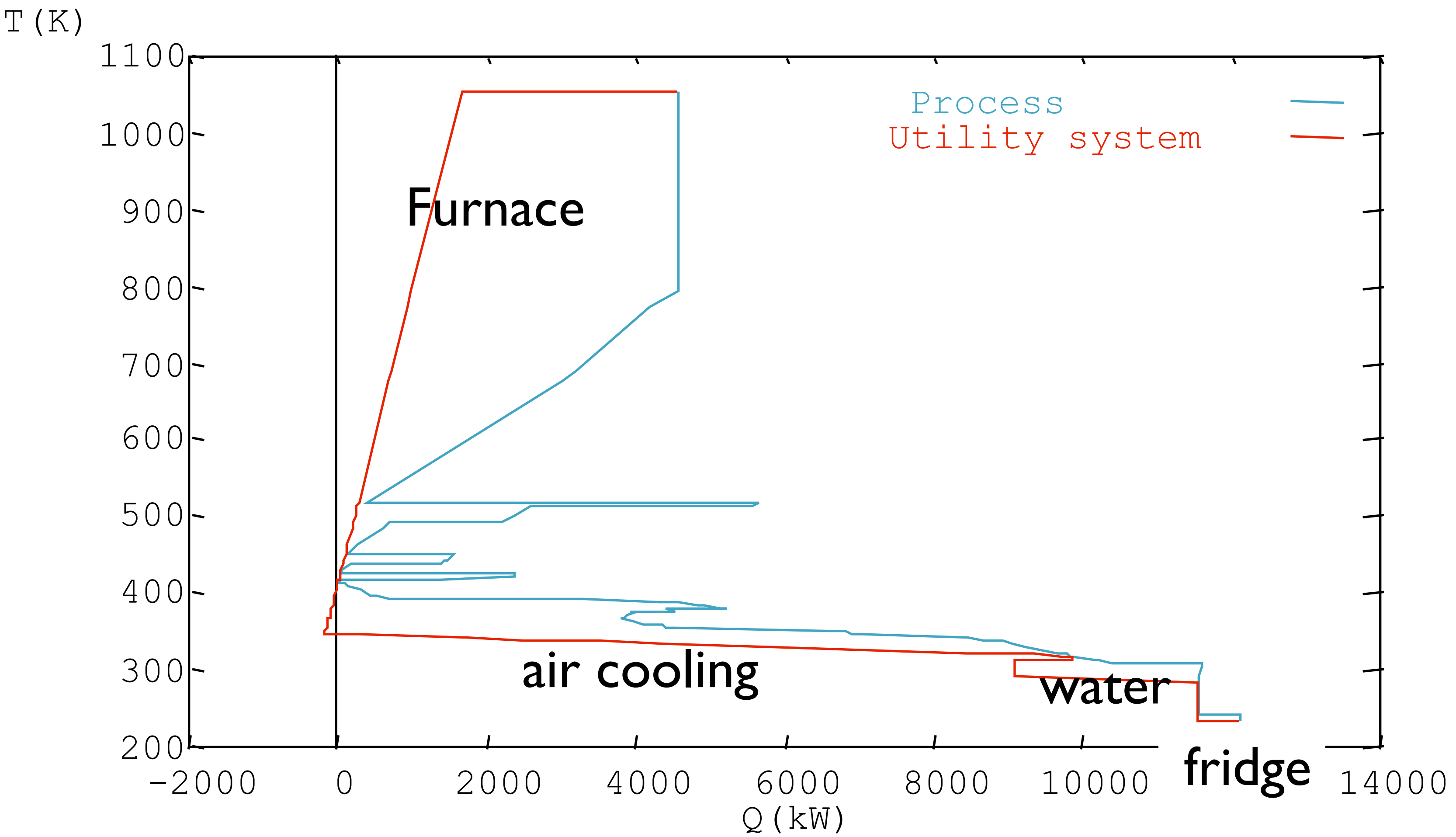
$$RA_k = R_{ref} - \sum_{r=k}^{n_k} \left(\sum_{w=1}^{n_{Aw}} f_w q_{wr} + \sum_{i=1}^{n_A} Q_{ir} \right) - R_{n_k+1}$$

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

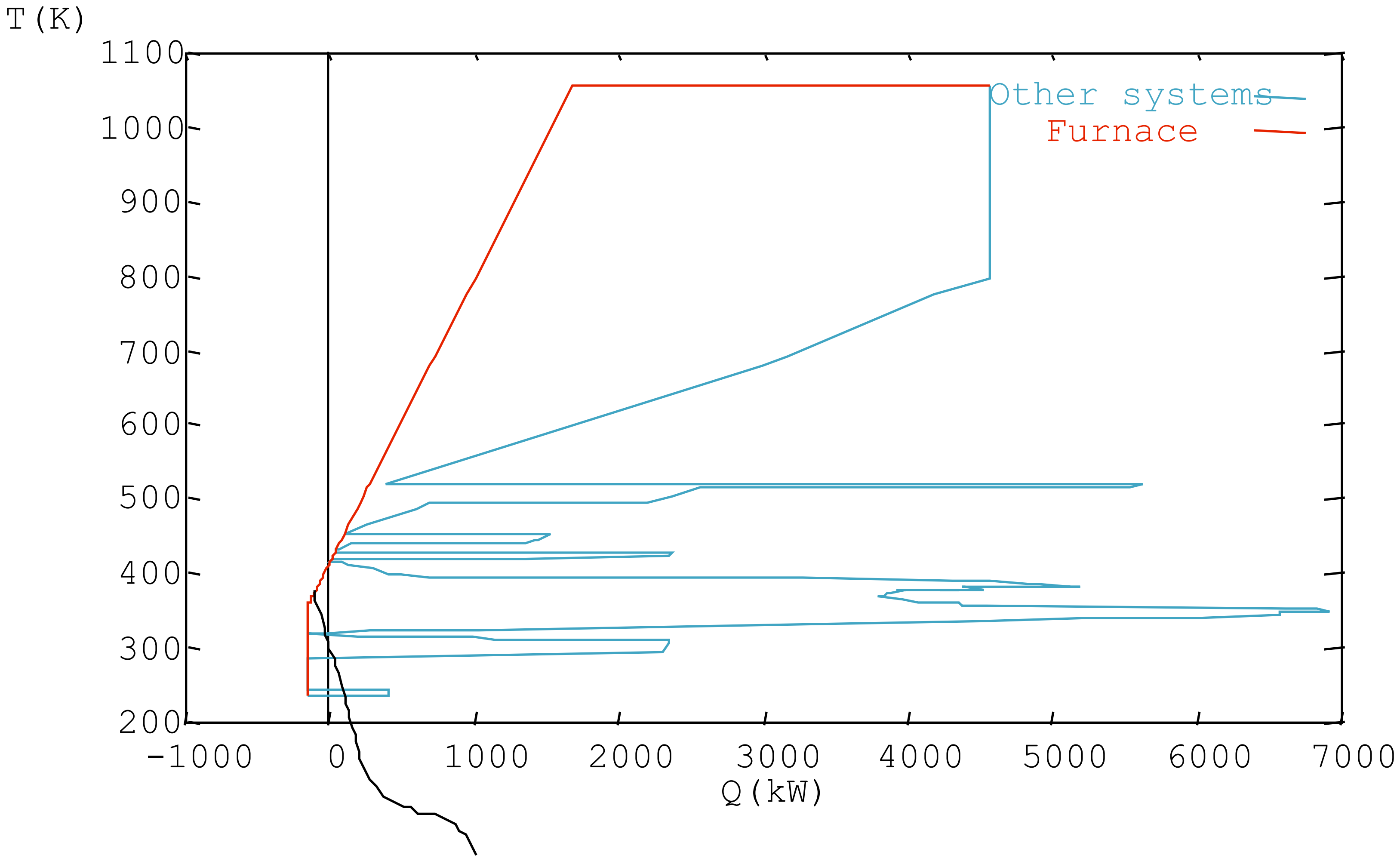


Choose a reference : pinch point of the process streams

ICC for utility system integration

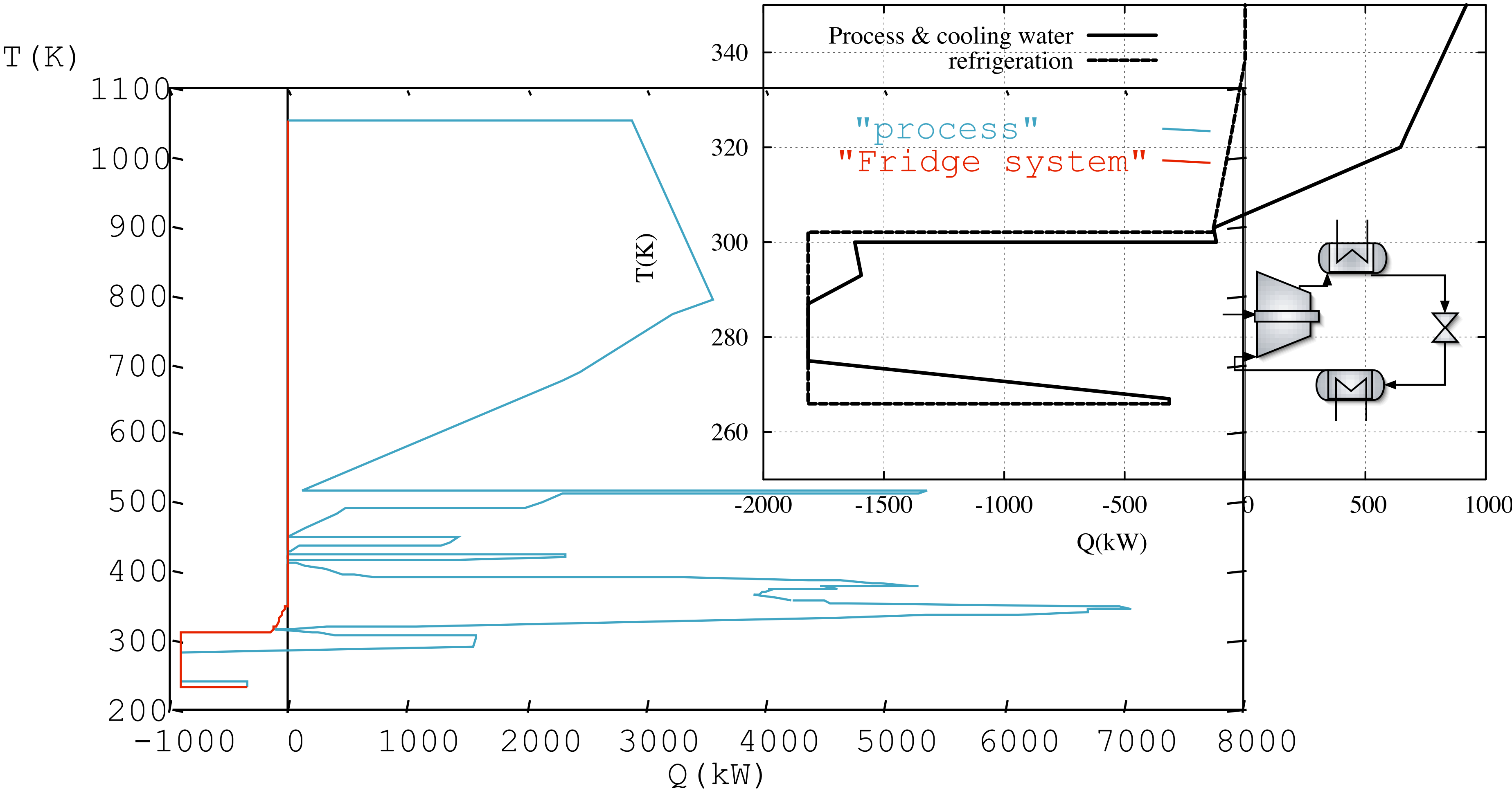


ICC for the integration of the fumes

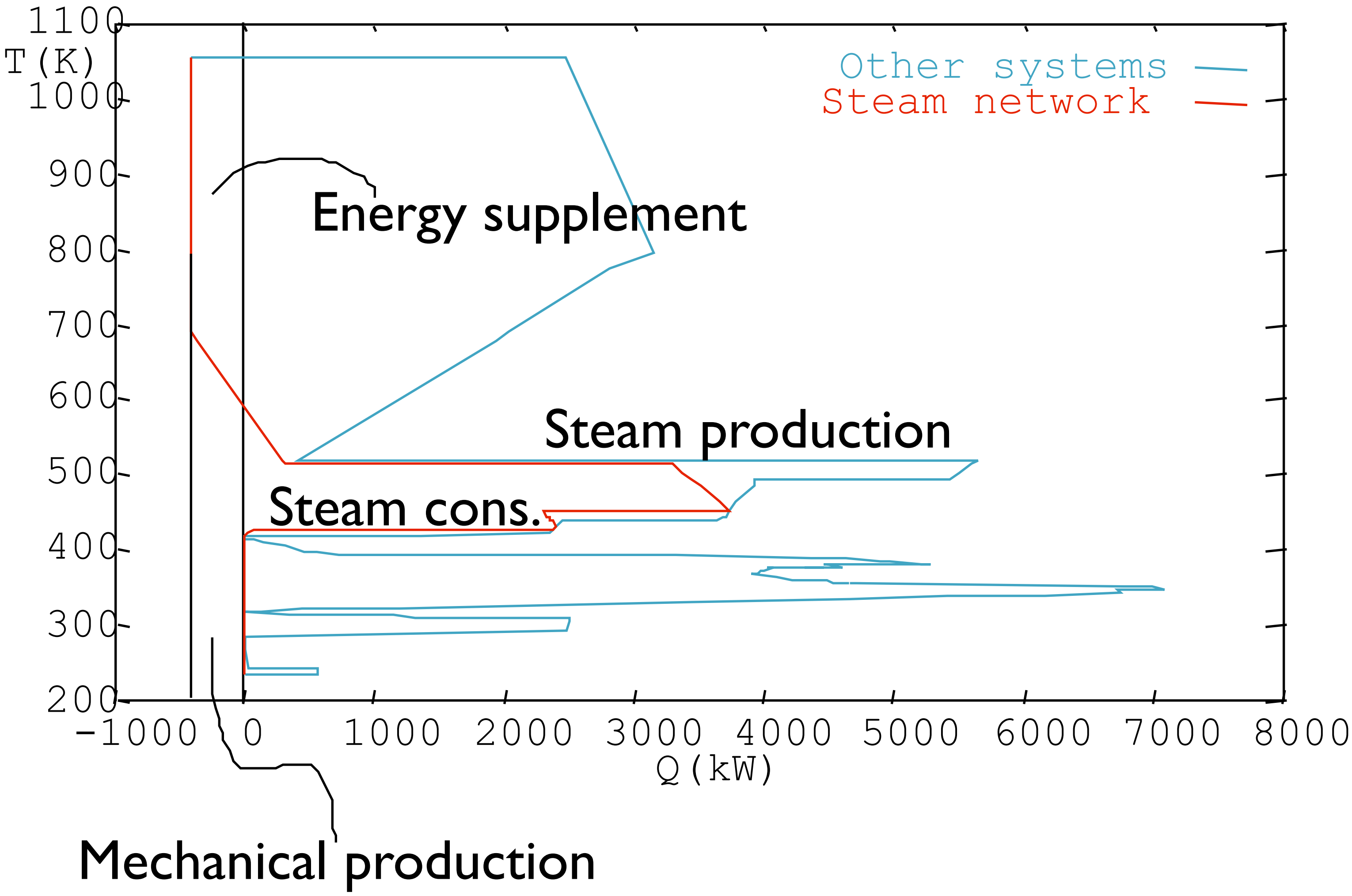


Excess of heat in the fumes

ICC for refrigeration cycle integration



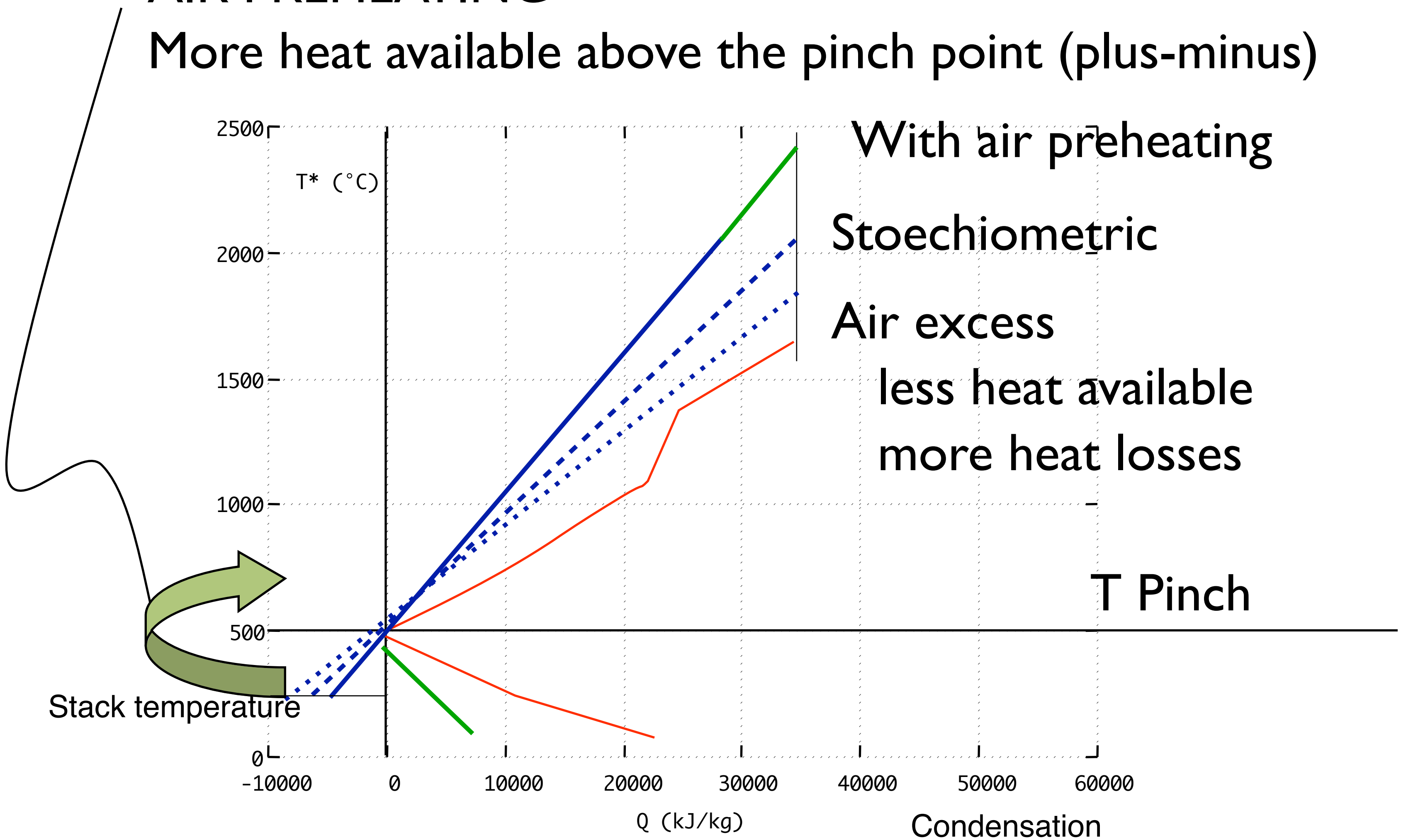
ICC of the steam network



COMBUSTION INTEGRATION : Plus-Minus

AIR PREHEATING

More heat available above the pinch point (plus-minus)

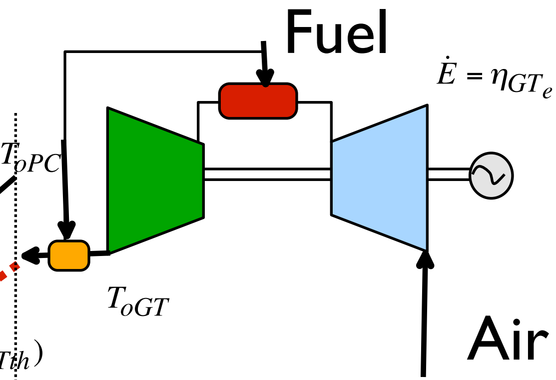


Gas Turbine : fixed size

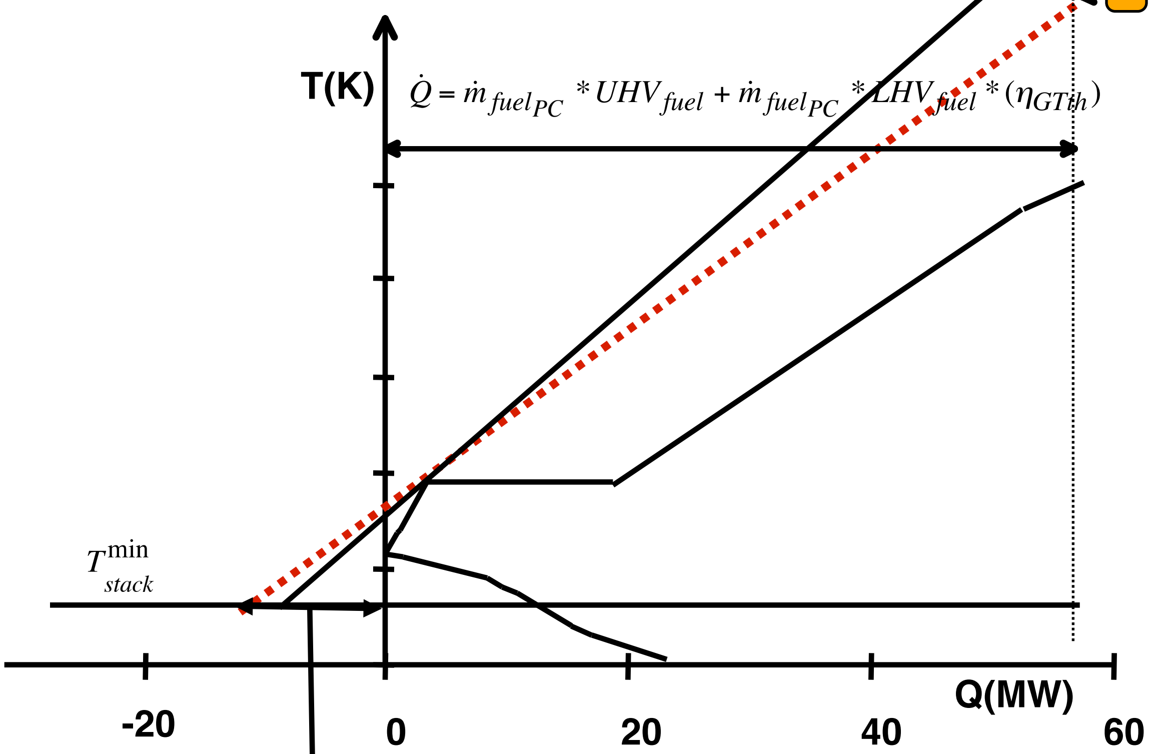
$$T_{oPC} = T_0 + \frac{\dot{m}_{fuel_{PC}} + \dot{m}_{fuel_{GT}} * (1-\eta_{GT_e})}{\frac{\dot{m}_{fuel_{PC}}}{(T_{ad}-T_0)} + \frac{\dot{m}_{fuel_{GT}} * (1-\eta_{GT_e})}{(T_{oT}-T_0)}}$$

$$\dot{Q}_{GT} = \dot{m}_{fuel_{GT}} * LHV_{fuel} * \eta_{GT_{th}}$$

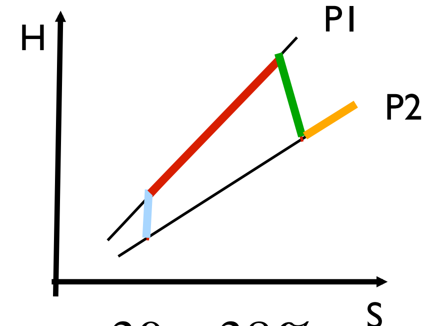
$$\dot{E} = \eta_{GT_e} * \dot{m}_{fuel_{GT}} * LHV_{fuel}$$



$$\dot{Q} = \dot{m}_{fuel_{PC}} * UHV_{fuel} + \dot{m}_{fuel_{PC}} * LHV_{fuel} * (\eta_{GTth})$$



Energy available or excess

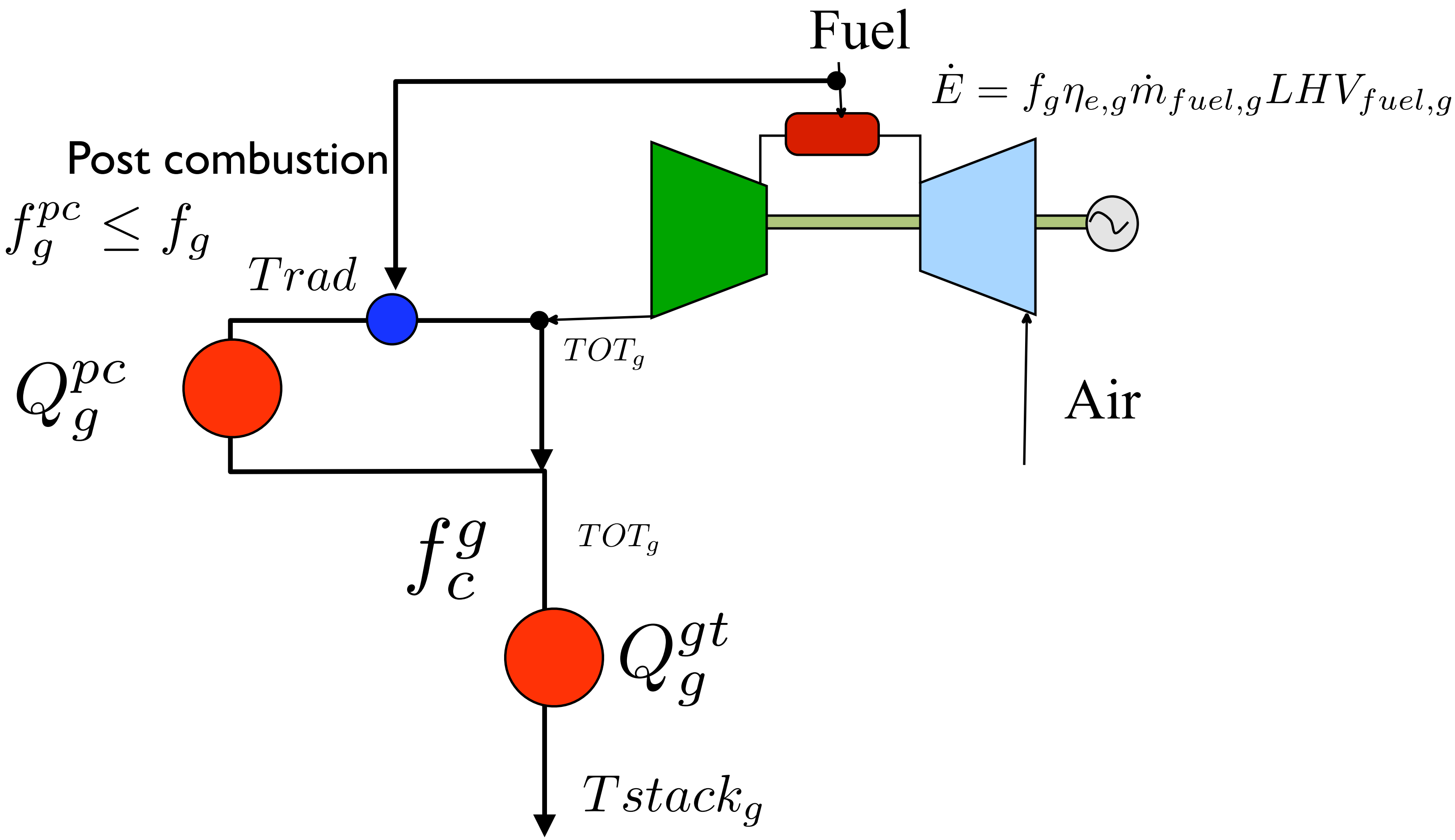


$$\eta_{GT_e} = 30-38\%$$

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

$$\eta_{GT} = 85\%$$

Targeting model : combustion and gas turbine



Targeting the optimal integration : model

- MILP formulation

Gas turbine g : hot stream from T_{OT} to T_{stack}

$$Q_g^{gt} = f_g * \dot{m}_g * cpf_g * (TOT_g - Tstack_g)$$

unknown

$$f_g^{min} * y_g \leq f_g \leq y_g * f_g^{max}$$

Fuel balance

$$\sum_{c=1}^{n_{cgt}} f_c^g * LHV_c - \sum_{g=1}^{n_g} y_g * FCI_g + f_g * FCP_g = 0$$

Electricity

$$W_{gt} - \sum_{g=1}^{n_g} y_g * WI_g + f_g * WP_g = 0$$

Part load efficiency

Operating cost

$$\sum_{g=1}^{n_g} (y_g * OCI_g + f_g * OCP_g) - OC_{gt} = 0$$

Investments

$$\sum_{g=1}^{n_g} y_g * ICI_g - IC_{gt} = 0$$

Combustion model

Post combustion — Hot stream from Trad to $T_O T$

$$Q_g^{pc} = f_g^{pc} * \dot{m}_g * cpf_g * (Trad - TOT_g) \qquad f_g^{pc} \leq f_g$$

O2 balance

Post comb — Air — Enriched air — Fuels

$$\sum_{g=1}^{n_g} f_g^{pc} * \dot{m}_g * x_g^{O_2} + f_{air} * x_{air}^{O_2} - \sum_{a=1}^{n_a} f_a * \dot{m}_a * x_a^{O_2} - \sum_{c=1}^{n_c} f_c^c * \kappa_c^{O_2} \geq 0$$

Heat above Trad

Fuels — Air

$$\sum_{c=1}^{n_c} (f_c * (LHV_c + (cp_{air} * \frac{\kappa_c^{O_2}}{x_{air}^{O_2}} * (Trad - T_0)))) - f_{air} * cp_{air} * (Trad - T_0)$$

Enriched air — Post comb — Preheating

$$- \sum_{a=1}^{n_a} f_a * \dot{m}_a * cp_a * (Trad - TO_a) - \sum_{g=1}^{n_g} Q_g^{pc} + Q_{prh} - Q_{rad} = 0$$

Heat from Trad to stack

Air — Fuels

$$f_{air} * cp_{air} * (Trad - Tstack) + \sum_{c=1}^{n_c} (f_c * (\dot{m}_c^f * cpf_c - cp_{air} * \frac{\kappa_c^{O_2}}{x_{air}^{O_2}}) * (Trad - Tstack))$$

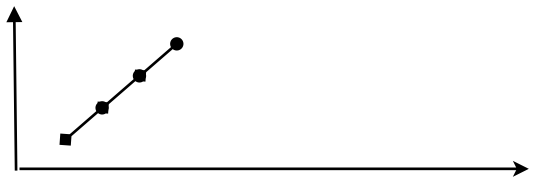
Enriched air

$$+ \sum_{a=1}^{n_a} f_a * \dot{m}_a * cp_a * (Trad - Tstack) - Q_{cnv} = 0 \quad (11$$

Outlet temperature calculation

Define n streams as segments

Stream i : from T_i^{air} to $T_{i+1}^{air} = T_i^{air} + \Delta T$



Add linear constraints

$$f_{air} \geq fa_i \qquad \forall i = 1, ..., n_i \tag{19a}$$

$$Q_{prh} = \sum_{i=1}^{n_i} fa_i cp_{air,i}(T_{i+1} - T_i) \tag{19b}$$

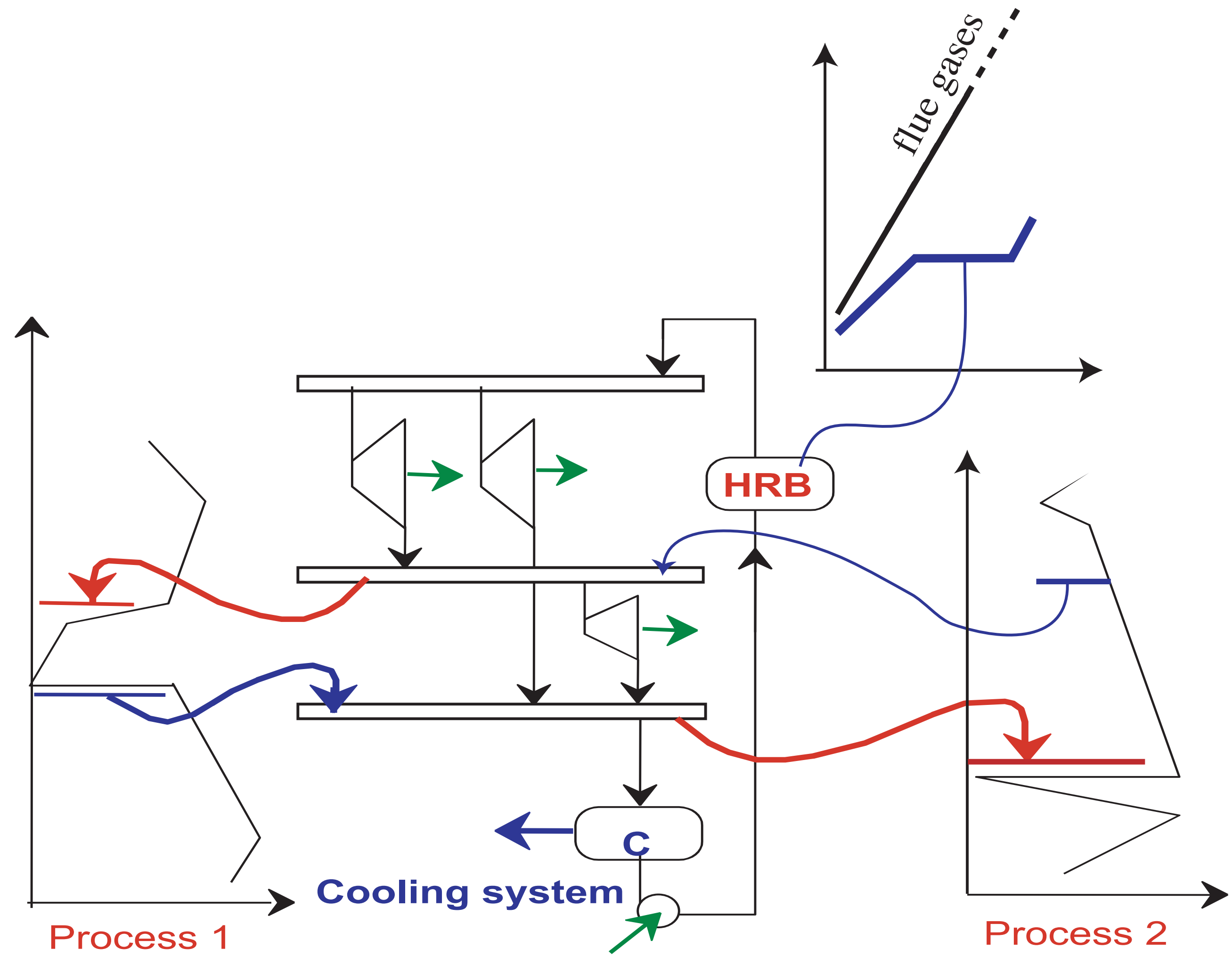
fa_i the flowrate of air preheated from T_i to T_{i+1}.

$cp_{air,i}$ the specific heat capacity of the air flowrate between T_i to T_{i+1}.

Compute the temperature a posteriori

(1) solve the model and compute the optimal flowrates in each interval (fa_i);
(2) compute the resulting temperature To_{n_i} by solving from i =1 to n_i , $To_i = \frac{(fa_{i-1} - fa_i)To_{i-1} + fa_i * T_{i+1}}{fa_{i-1}}$ with $To_0 = Ta_{in}$ the inlet temperature of the stream a.

Steam network integration



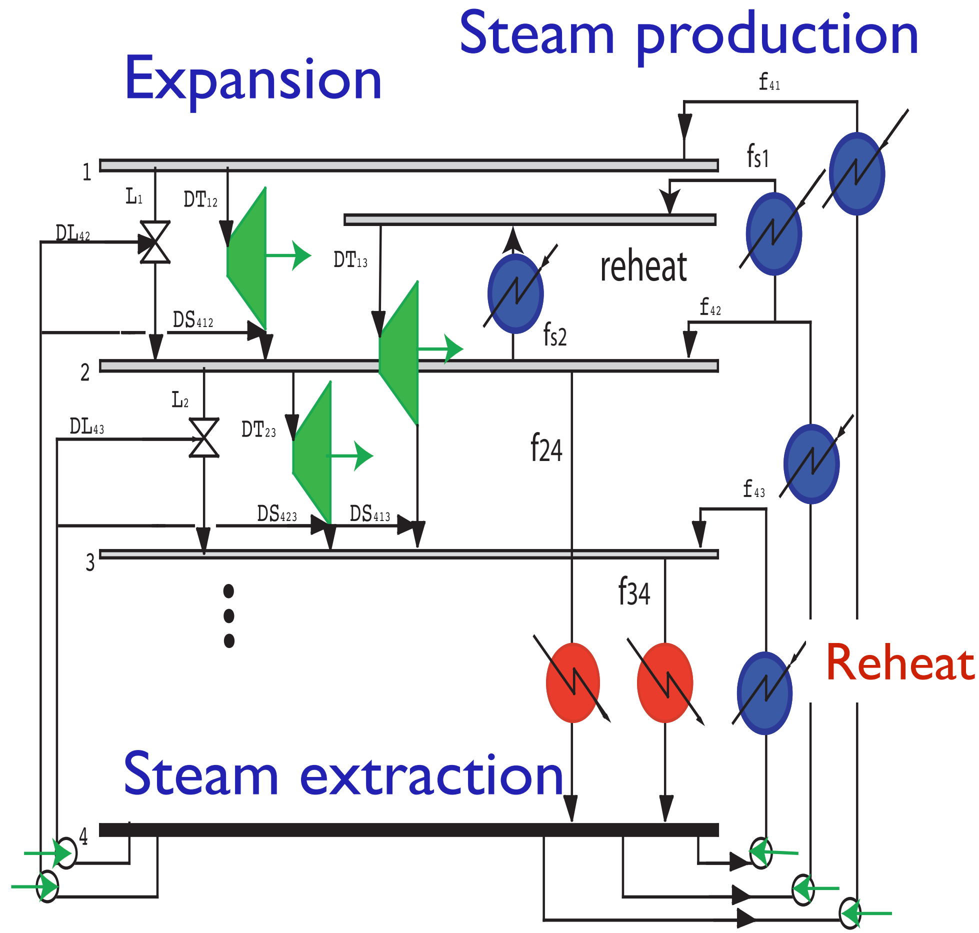
Steam cycle superstructure

- Systematic generation
- Only T,P for each level
  - Mechanical power

$$w_{i,j} = min((h_i - h_j), \eta_{is}(h_i - h_{is}(P_i, T_i, Pj))$$

  - Hot & cold streams
- DTmin/2
- Level heat&mass balance

[1] F. Marechal and B. Kalitventzeff. Targeting the optimal integration of steam networks. *Computers and Chemical Engineering*, 23:s133–s136, 1999.



MILP model with the steam cycle

Heat cascade equation

$$i = 1, ..., n_v; j = 1, ..., n_u; k = 1, ..., n_k$$

$$\sum_{w \in \{(j,k);(k,i);c\}} f_w q_{w,r} + \sum_{s=1}^{n_s} Q_{s,r} + R_{r+1} - R_r = 0 \qquad \forall r = 1, ..., n_r$$

$$R_r \leq 0 \qquad \forall r = 1, ..., n_r; R_{n_{r+1}} = 0; R_1 = 0$$

Pressure level balance

IN

OUT

$$\sum_{i=1}^{n_v} k_{i,w} f^t_{i,w} + \sum_{k=1}^{n_k} f_{k,w} - \sum_{k=1}^{n_k} f_{w,k} - \sum_{i=1}^{n_v} f_{w,i} - \sum_{i=1}^{n_u} f^t_{w,i} = 0 \qquad \forall w$$

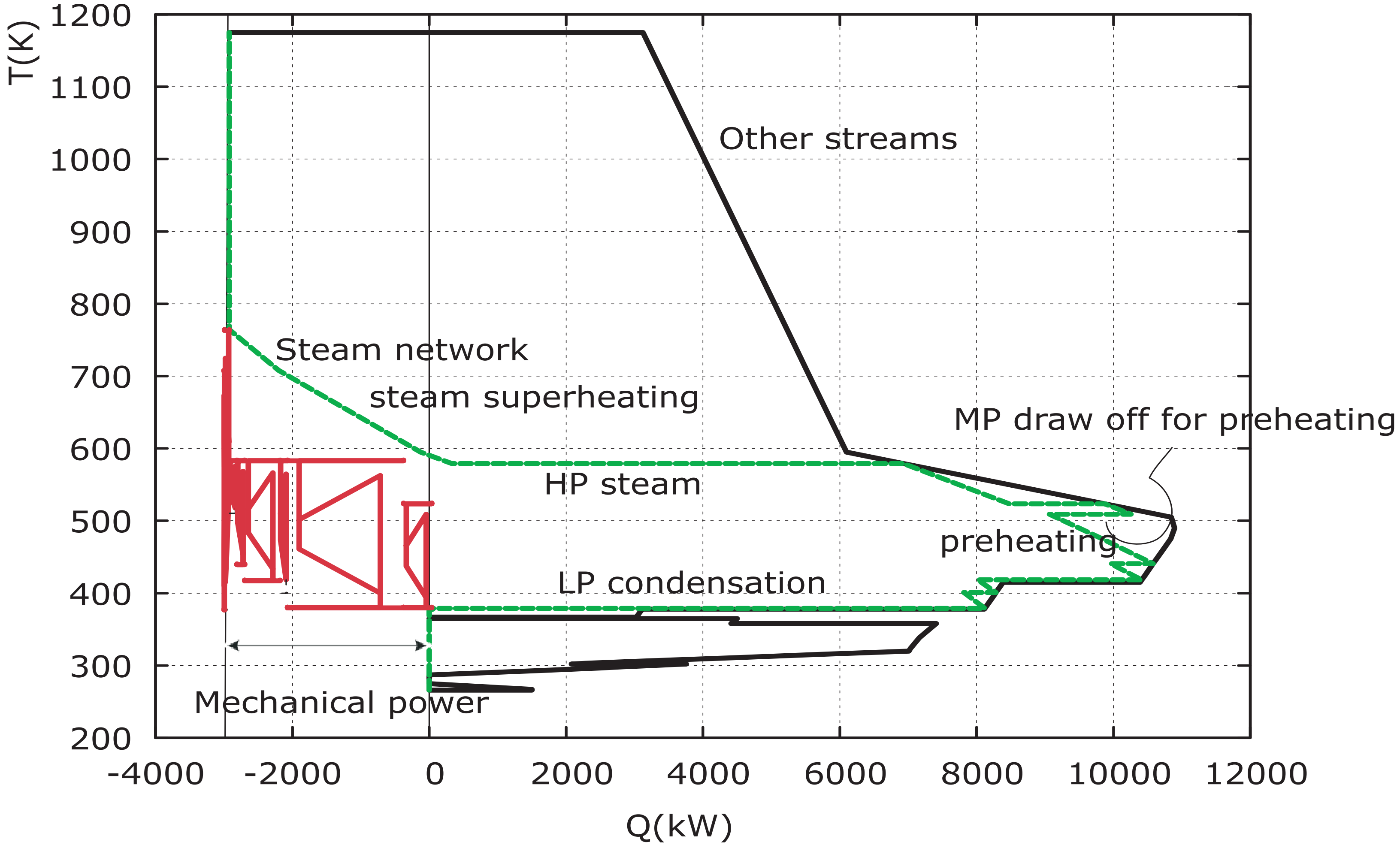
Mechanical power balance

$$\sum_{w \in \{(i,j)\}} f^t_w w_w - \sum_{w \in \{(k,i)\}} f_w w p_w = W$$

Existence of heat exchange or expansion

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

Integrated composite curve : steam network

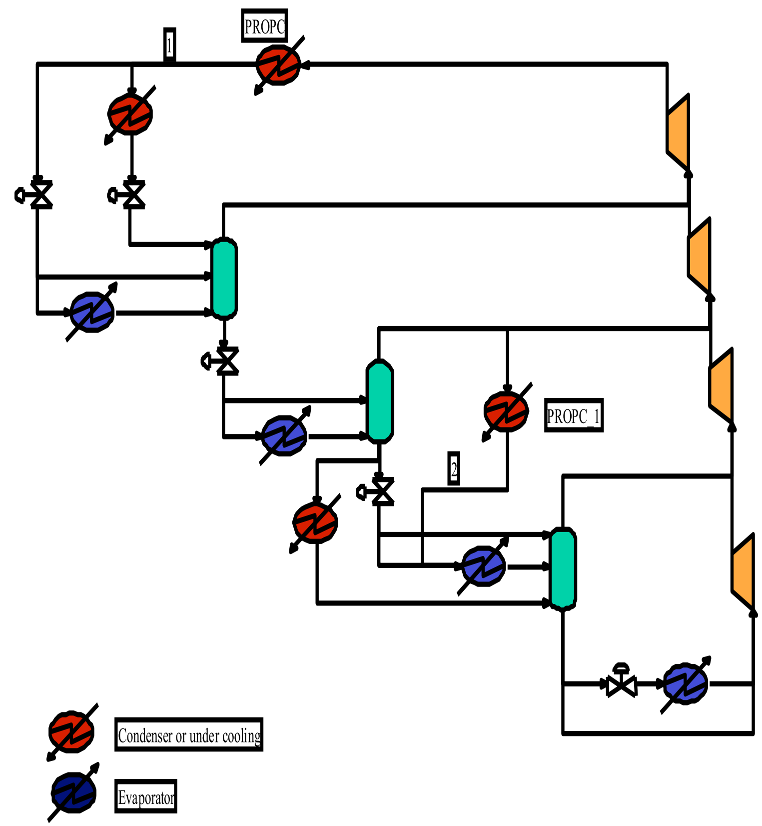


The refrigeration system

- Multi components
- Multi pressure levels
- Methane : 1 level
- Ethylene : 3 levels
- Propylene : 4 levels

Cycle	T evaporator (K)
METH1	136
ETH1	171,6
ETH2	199,25
ETH3	212,51
PROP1	233
PROP2	248
PROP3	277
PROP4	291

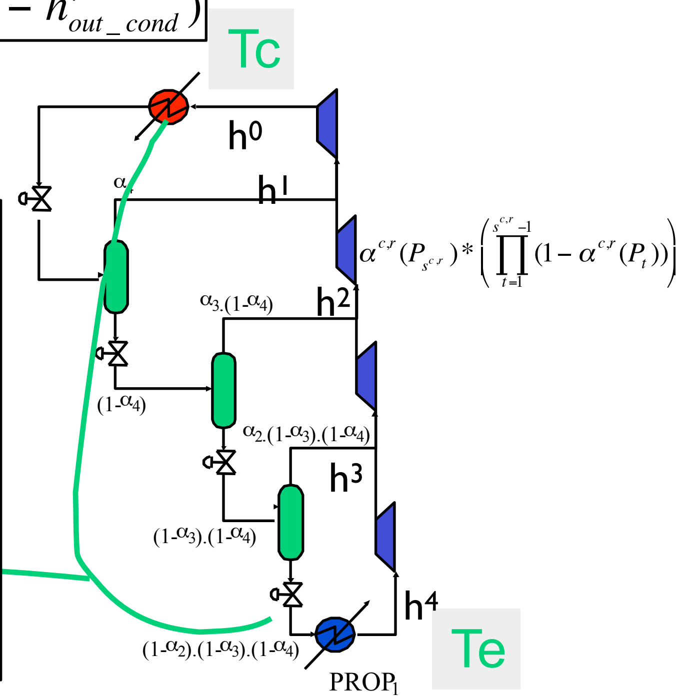
Complex systems



Refrigeration effect : reference flow = flow in the condenser

Condenser : hot stream

$$q^{c,r}_{cond} = (h^{r}_{out\_comp} - h^{r}_{out\_cond})$$



Compression : mechanical power

$$w^{c,r} = \left\{ \prod_{t=1}^{n_s^{c,r}-1} ((1-\alpha^{c,r}(P_t)) \right\} * (h^{r}_{out\_comp} - h^{c,r}_{sat-vap}(P_{n_s^{c,r}})))$$

$$+ \sum_{s=1}^{n_s^{c,r}} \alpha^{c,r}(P_s) * \left\{ \prod_{t=1}^{s-1} ((1-\alpha^{c,r}(P_t)) \right\} * (h^{r}_{out\_comp} - h^{c,r}_{sat-vap}(P_s)))$$

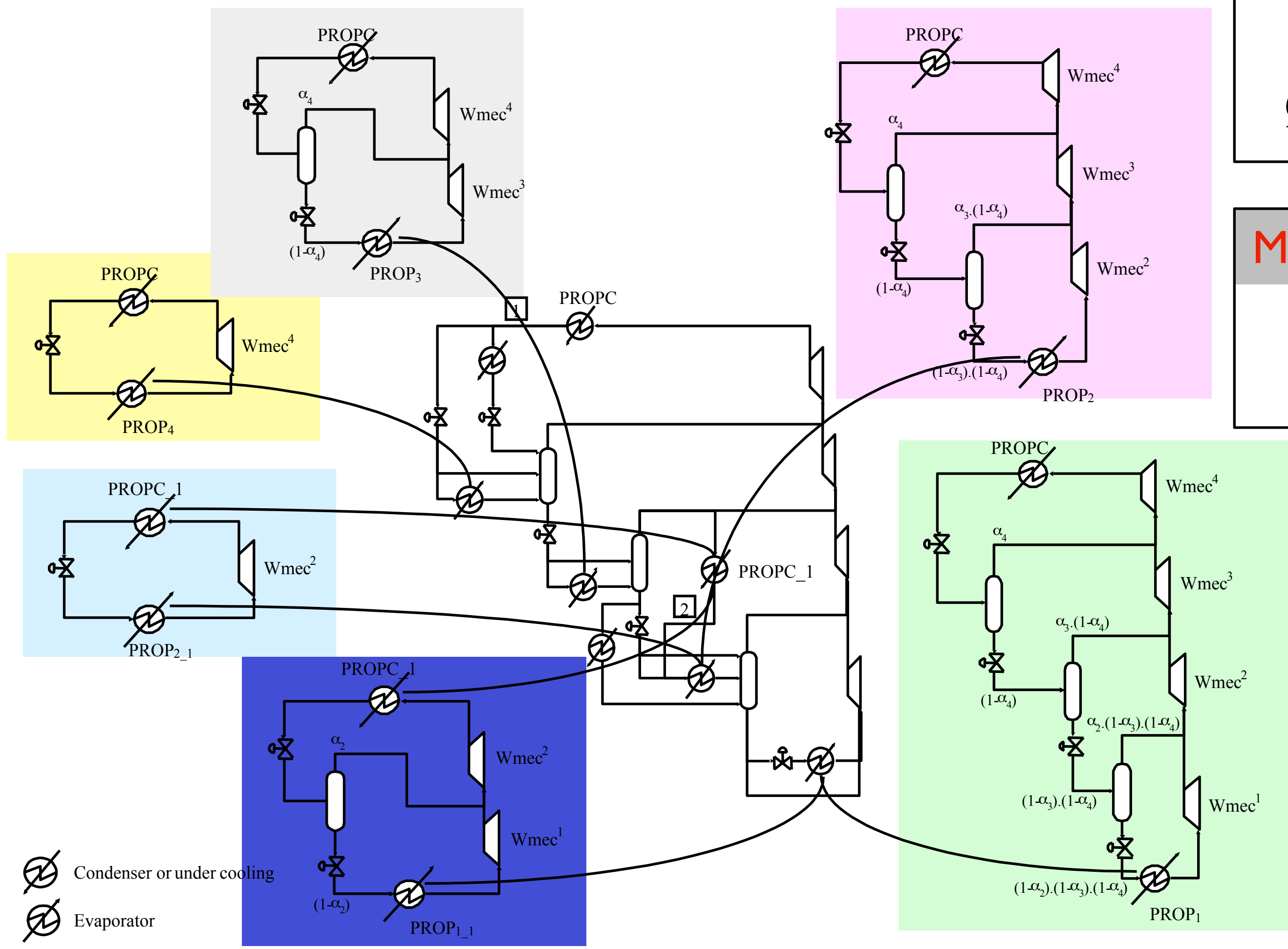
$w_{PROP\_1} = (1-\alpha_1).(1-\alpha_2).(1-\alpha_3).(h^4 - h^0) + \alpha_3(1-\alpha_1).(1-\alpha_2).(h^3 - h^0)$

$+ \alpha_2(1-\alpha_1).(h^2 - h^0) + \alpha_1(h^1 - h^0)$

Evaporation : cold stream

$$q^{c,r}_{eva} = (h^{r}_{out\_cond} - h^{c,r}_{sat\_vap}(P_{n_s^{c,r}})) = \left\{ \prod_{t=1}^{n_s^{c,r}} ((1-\alpha^{c,r}(P_t)) \right\} * (h^{c,r}_{sat\_liq}(P_{n_s^{c,r}}) - h^{c,r}_{sat\_vap}(P_{n_s^{c,r}}))$$

Propylene cycle model



Heat load in the condenser

$$Q^r_{cond} = \sum_{c=1}^{n_c^r} f^{c,r} * q^{c,r}_{cond}$$

Mechanical power

$$W^r = \sum_{c=1}^{n_c^r} f^{c,r} * w^{c,r}$$

Optimisation model

- Goal : to compute the optimal flow-rate in each effect

$$\underset{R_k, y_w, f_w}{\text{Minimise}} \sum_{w=1}^{n_w} \left(y_w C1_w + f_w C2_w \right) + Cel * EL_i - Cel_o * EL_o$$

subject to :

heat balance of the temperature interval k

$$\sum_{w=1}^{n_w} f_w q_{wk} + \sum_{r=1}^{n_r} \sum_{c=1}^{n_c^r} f^{c,r} q_{cond,k}^{c,r} - \sum_{r=1}^{n_r} \sum_{c=1}^{n_c^r} f^{c,r} q_{eva,k}^{c,r} + \sum_{i=1}^{n} Q_{ik} + R_{k+1} - R_k = 0$$

$$Wc_r - \sum_{c=1}^{n_c^r} f^{c,r} * w^{c,r} = 0$$

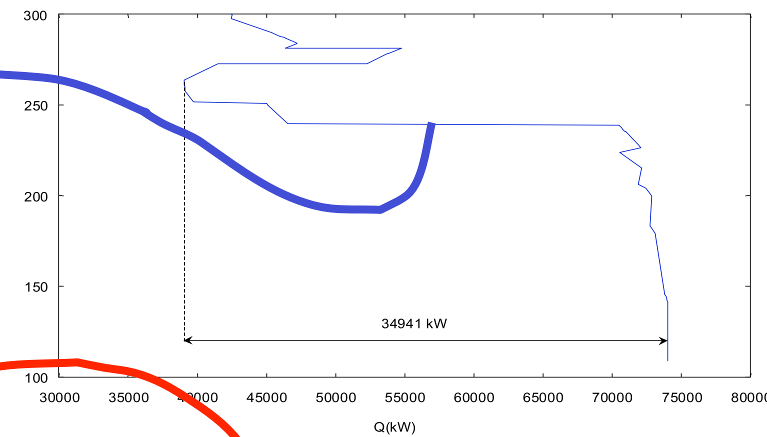
$$f\min^{c,r} y^{c,r} \le f^{c,r} \le f\max^{c,r} y^{c,r}, \qquad y^{c,r} \varepsilon \{0,1\}$$

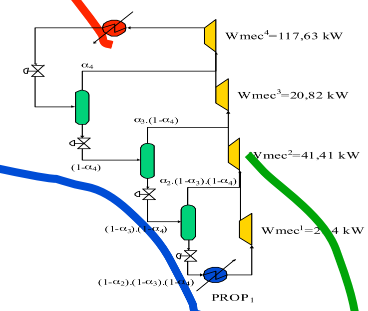
$$\text{Electricity production : } \sum_{w=1}^{n_w} f_w * w_w - \sum_{r=1}^{nr} Wc_r + EL_i - EL_o = 0$$

$$\text{consumption: } \sum_{w=1}^{n_w} f_w * w_w - \sum_{r=1}^{nr} Wc_r + EL_i \ge 0$$

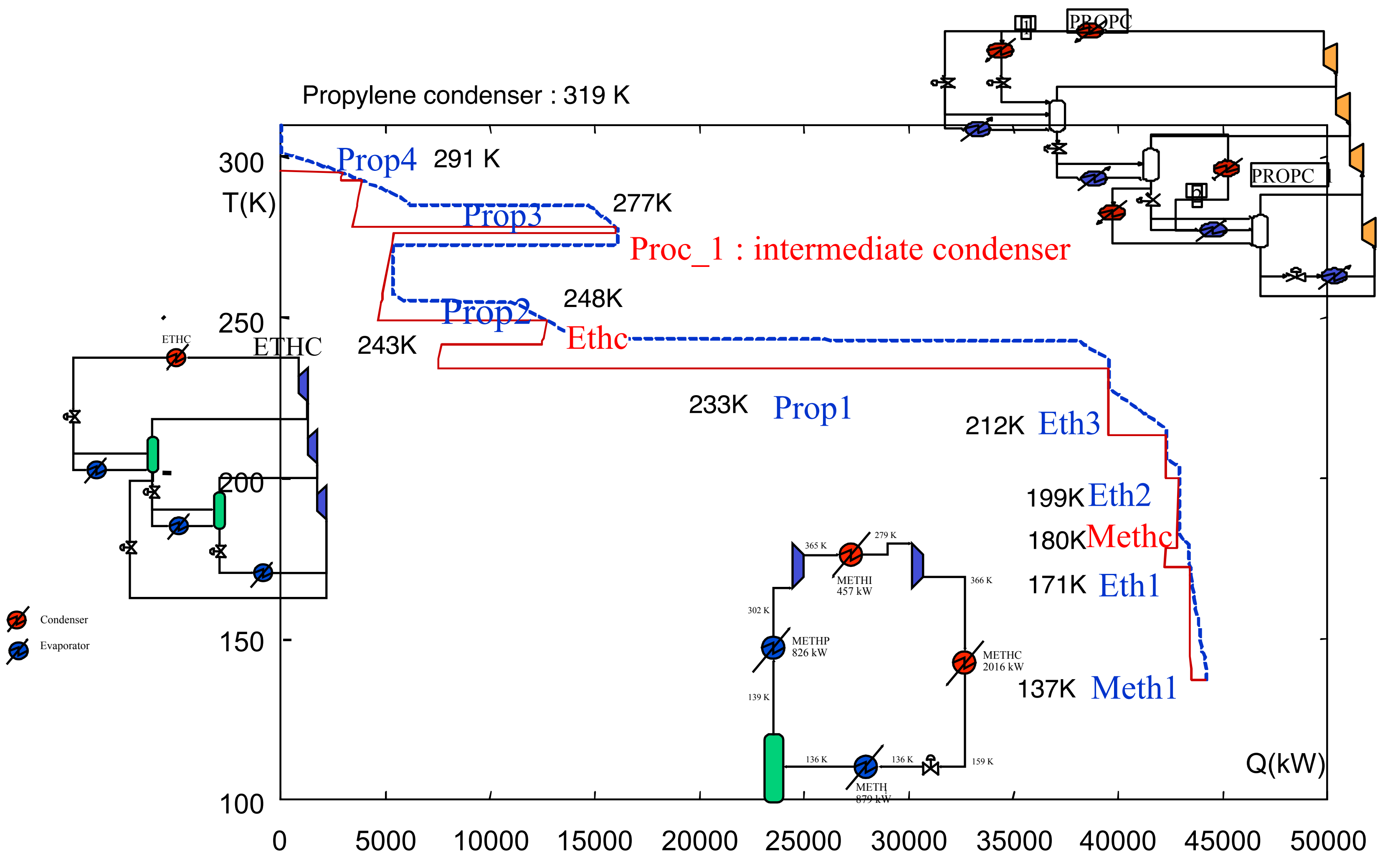
$$f\min_w y_w \le f_w \le f\max_w y_w, y_w \varepsilon \{0,1\}$$

$$R_k \ge 0 \quad \forall k = 1,\dots,n_k + 1 \qquad R_1 = 0, R_{n_k+1} = 0$$





Integrated process and refrigeration system



After process modifications

	Actual	Optimized	Simulation	Off streams
	Wmec	Wmec	Wmec	Wmec
	kW	kW	kW	kW
PROP1	17297	12685	-	10924
PROP2	5314	4281	-	4114
PROP3	6598	4759	-	4589
PROP4	1489	377	-	357
PROP1_1	1520	2029	-	2061
PROP2_1	0	0	-	0
Total propylene	**32218**	**24131**	**26284**	**22045**
ETH1	919	705	-	281
ETH2	312	463	-	248
ETH3	1378	655	-	343
Total ethylene	**2609**	**1823**	**2001**	**872**
METH1	746	655	655	0
Off streams contribution	0	0	-	-827
TOTAL	***35573***	***26609***	***28940***	***22090***

17%

38%