Laboratory for Industrial Energy Systems
LENI -ISE-STI-EPFL

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Applications de l'analyse exergétique pour la conception des systèmes de conversion d'énergie intégrés

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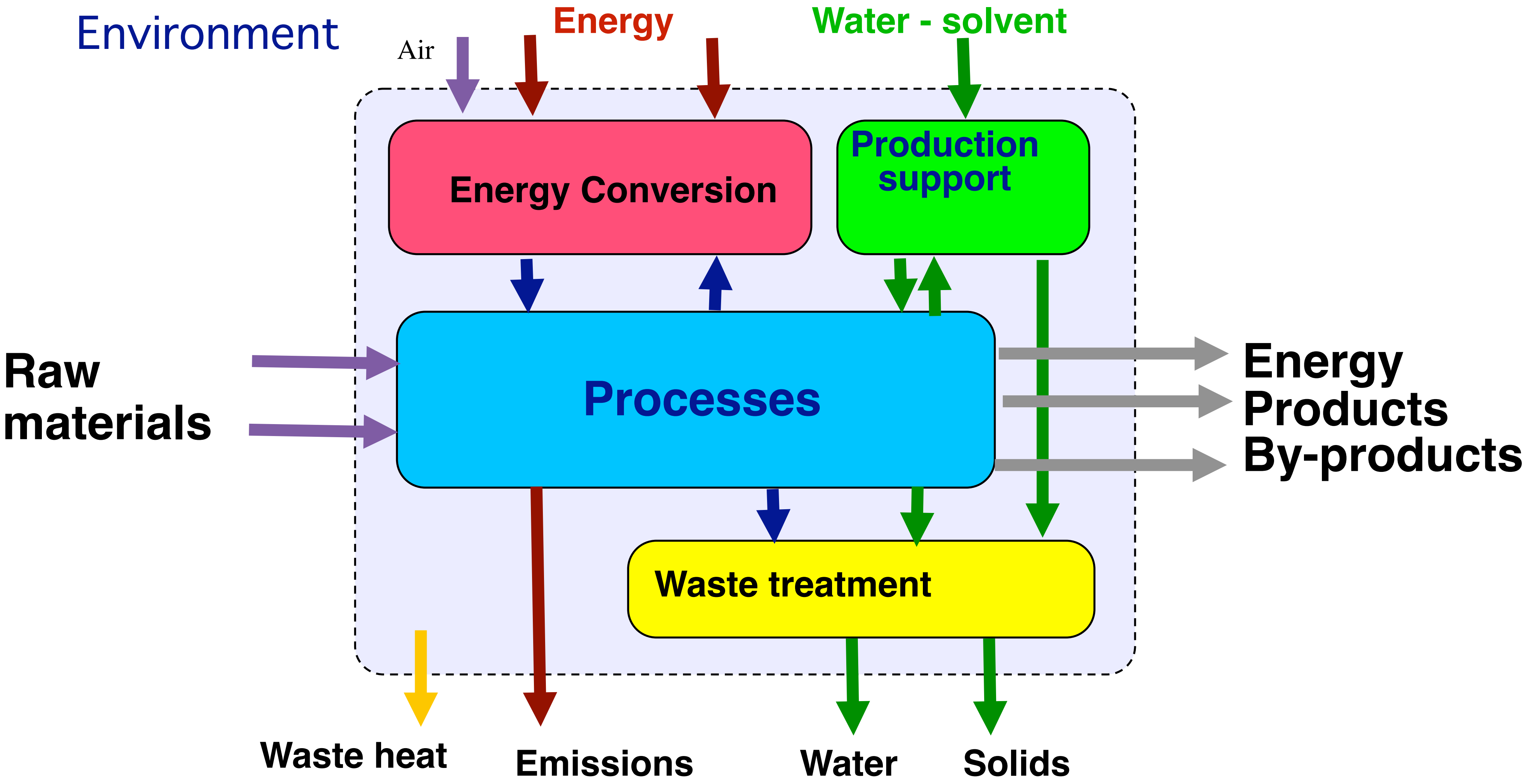
Process system integration



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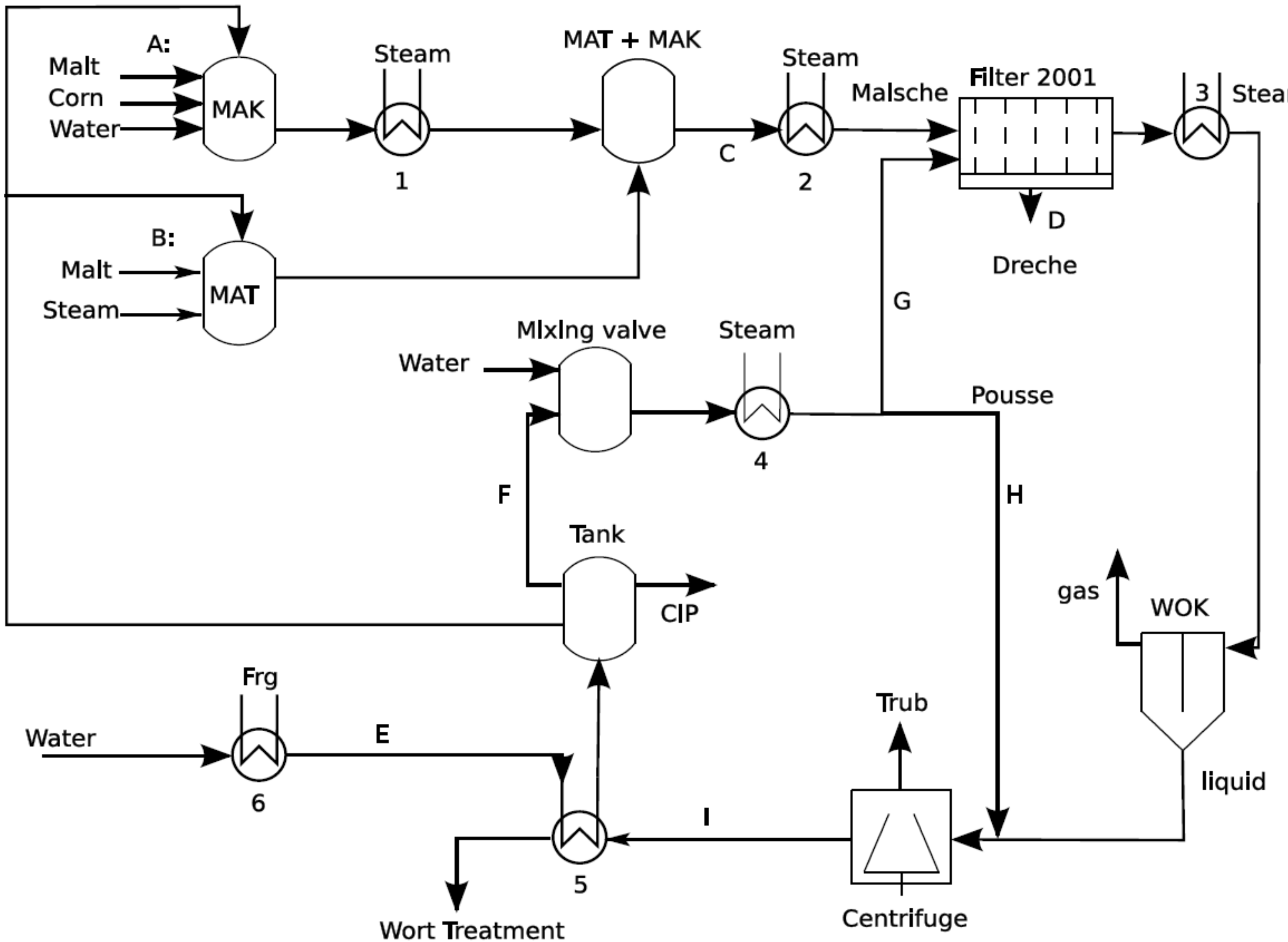
Exergy and process intergation

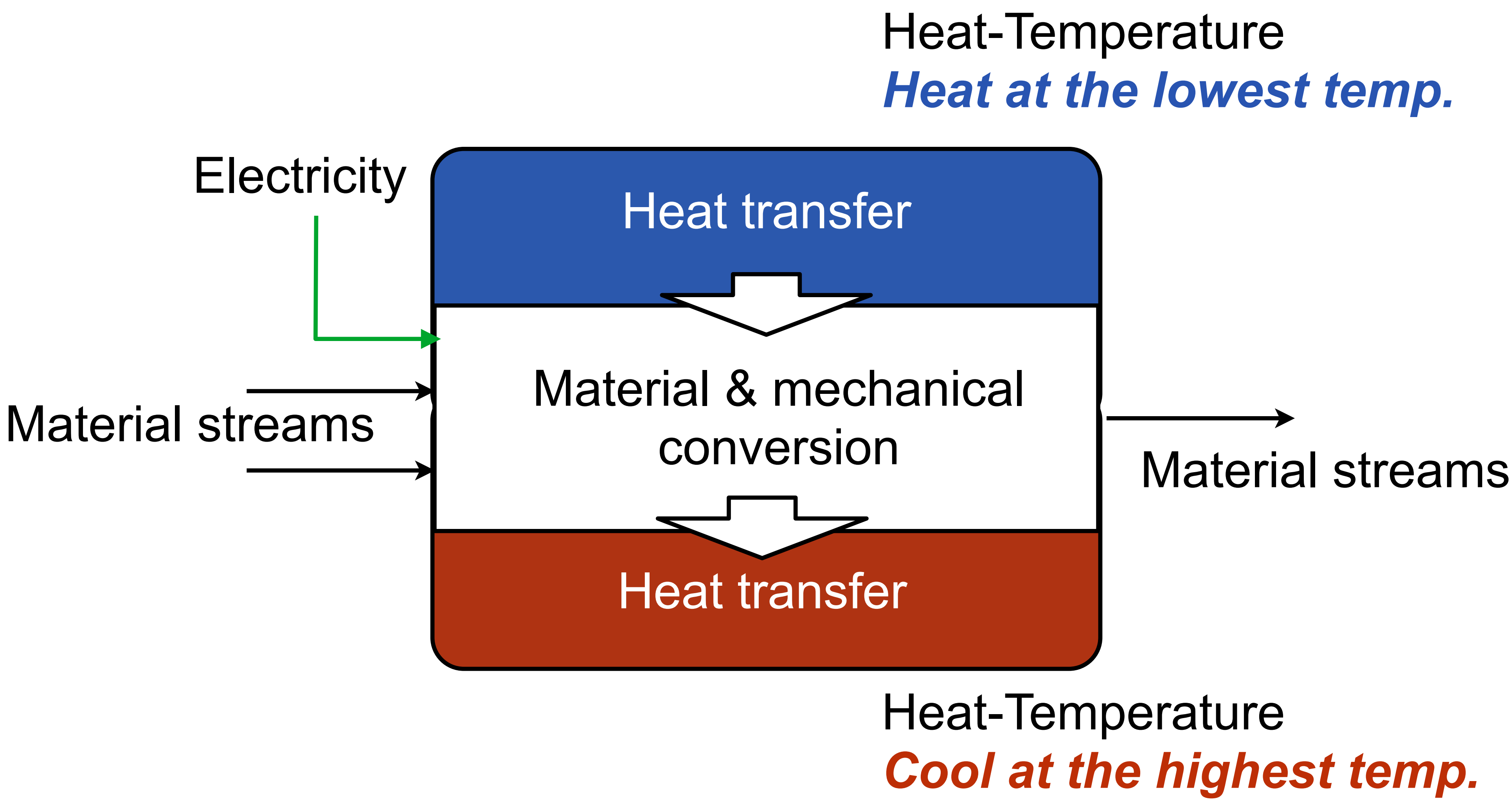
- Process unit analysis
  - ☑ Analyse the requirements
- Energy conversion integration
  - ☑ Polygeneration and utility integration
- Evaluate the results

Process description : list of process units



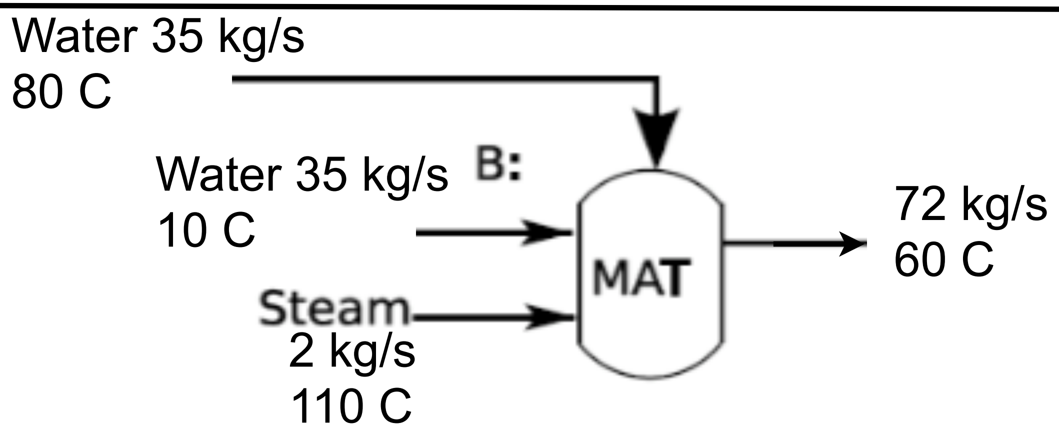
The heat transfer requirement interface

Process unit operation



Unit operation analysis

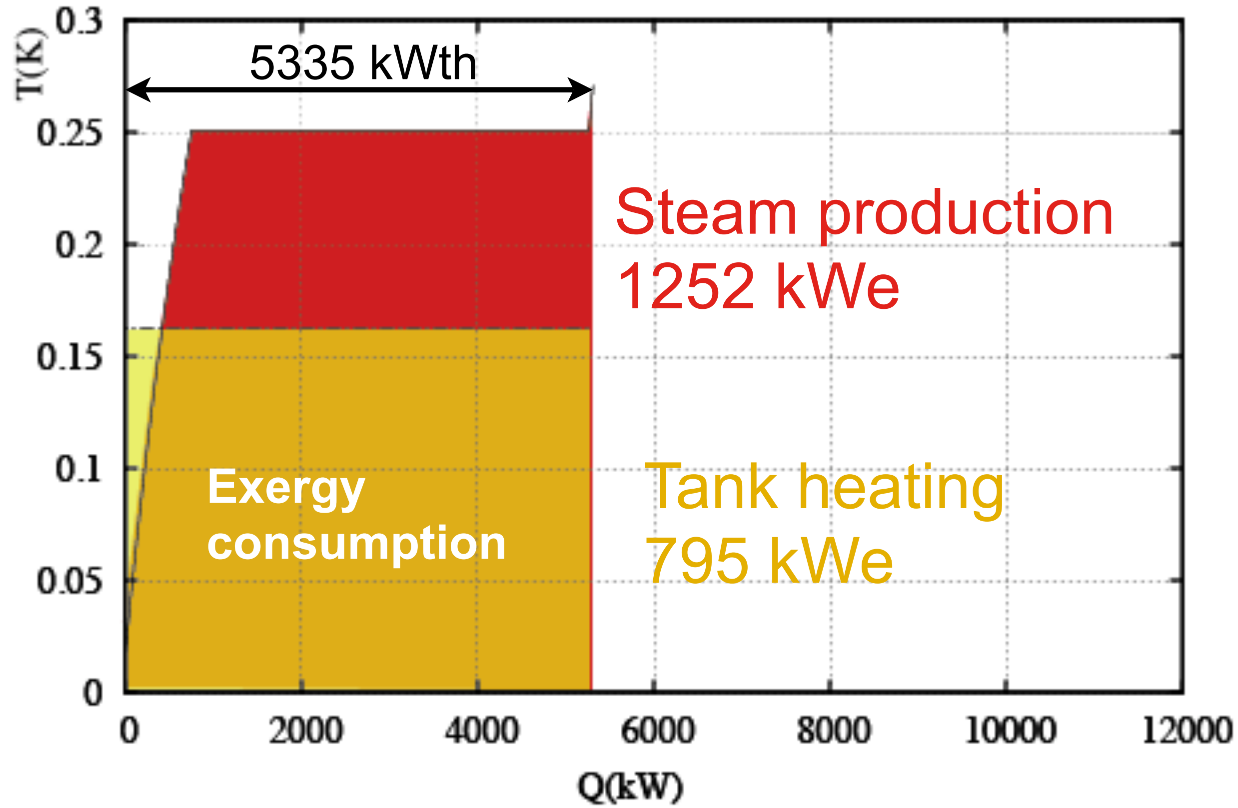
Mixing tank



$$d\dot{E} = d\dot{Q} * (1 - \frac{T_a}{T})$$

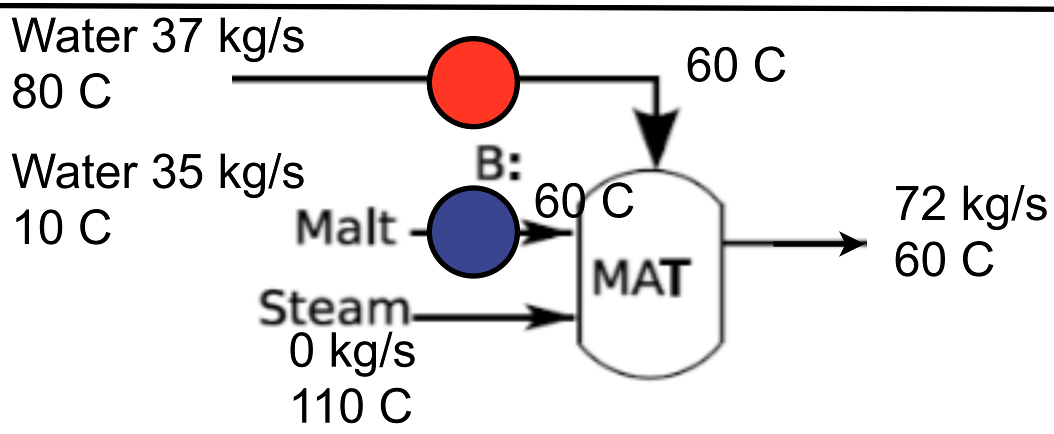
$$\dot{E} = \dot{Q}(1 - \frac{T_a}{T_{lm}})$$

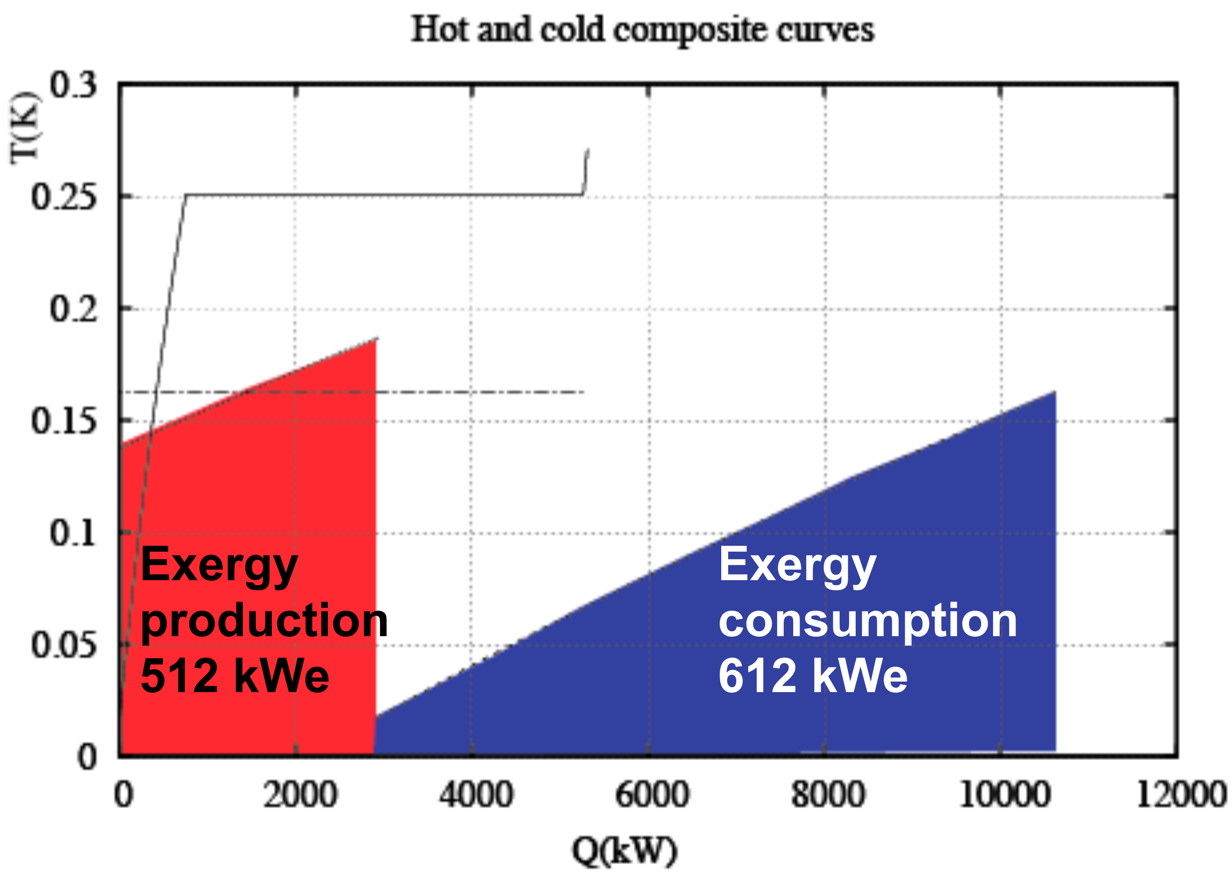
$$T_{lm} = \frac{T_1 - T_2}{ln\frac{T_1}{T_2}}$$



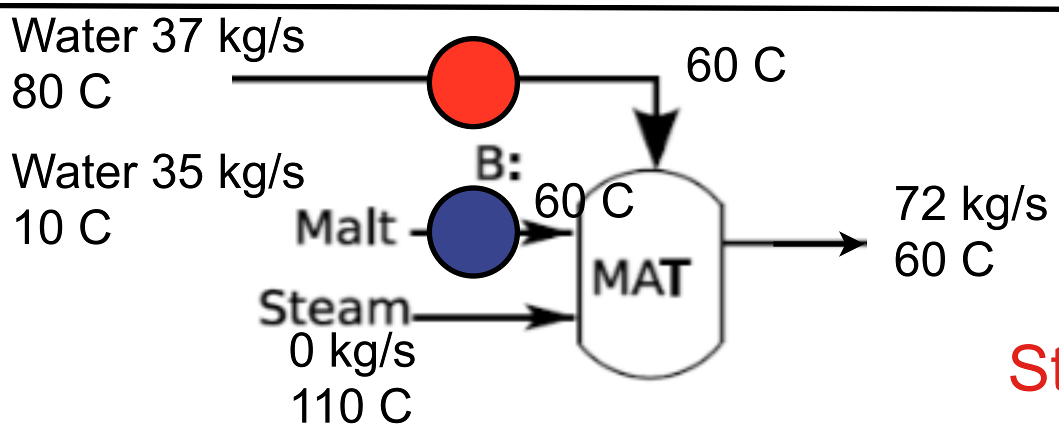
Analyse unit operation

Mixing tank





Analyse unit operation



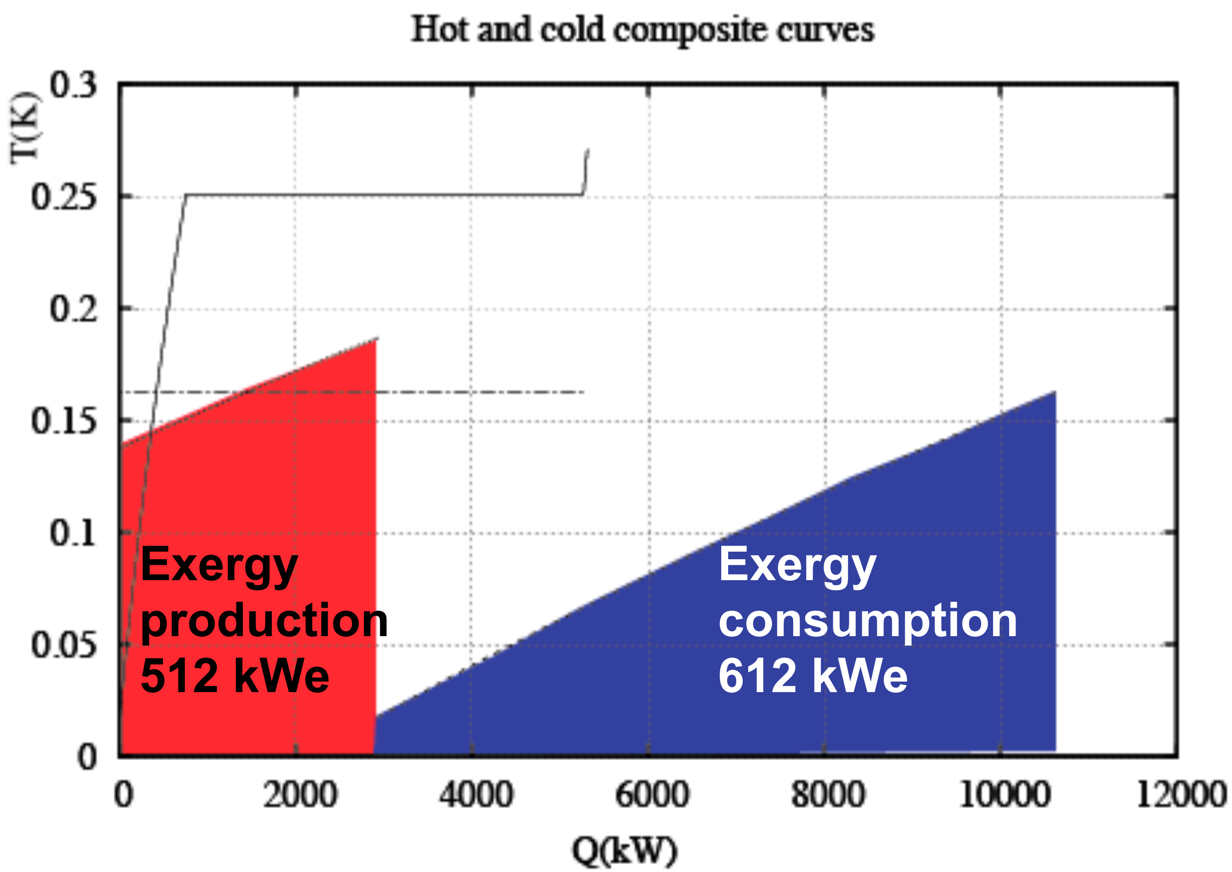
Mixing tank

Heat req. : 5335 kWth

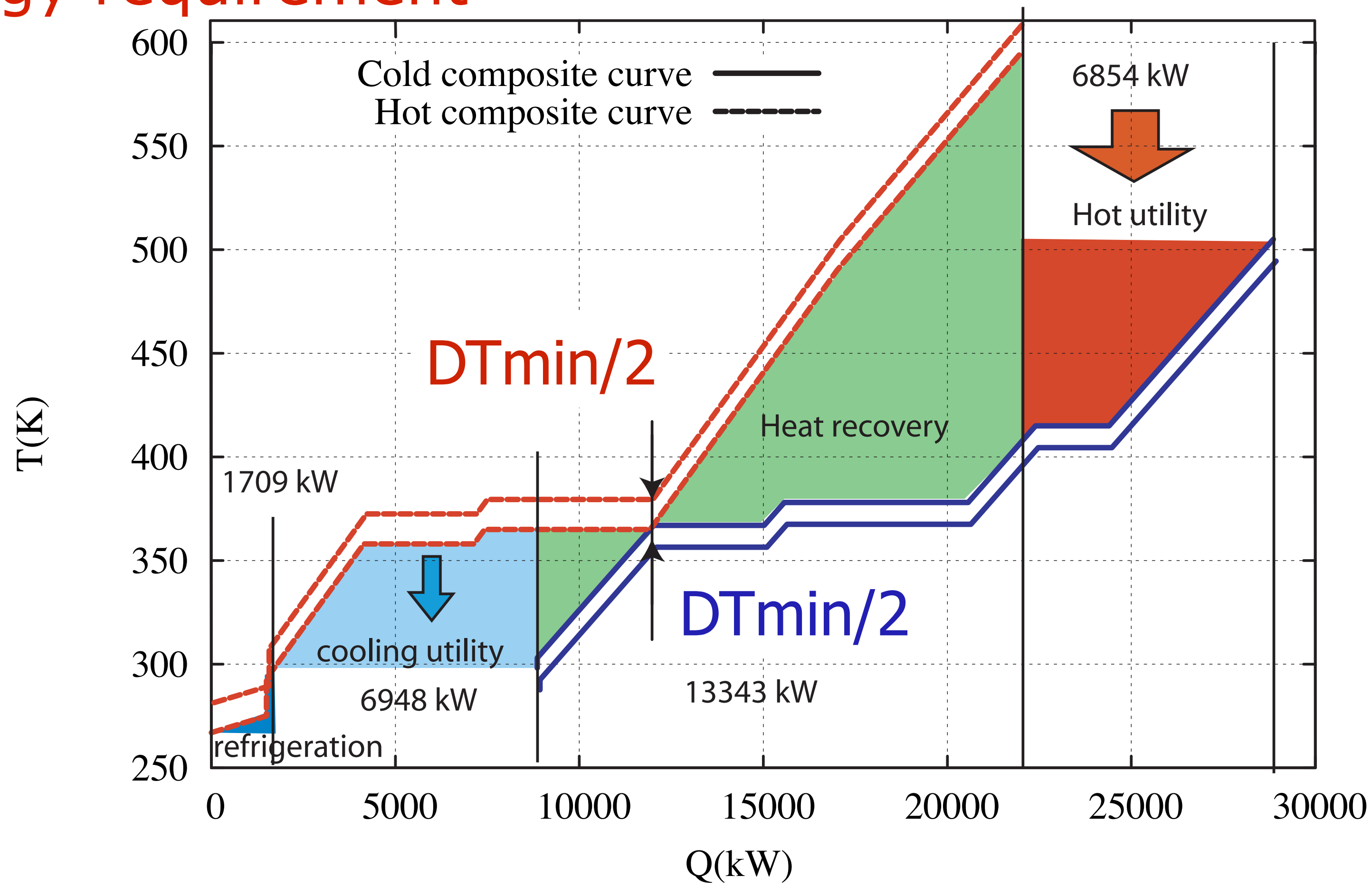
Steam production :1252 kWe

Tank heating : 795 kWe

Heat transfer req. : 100 kWe

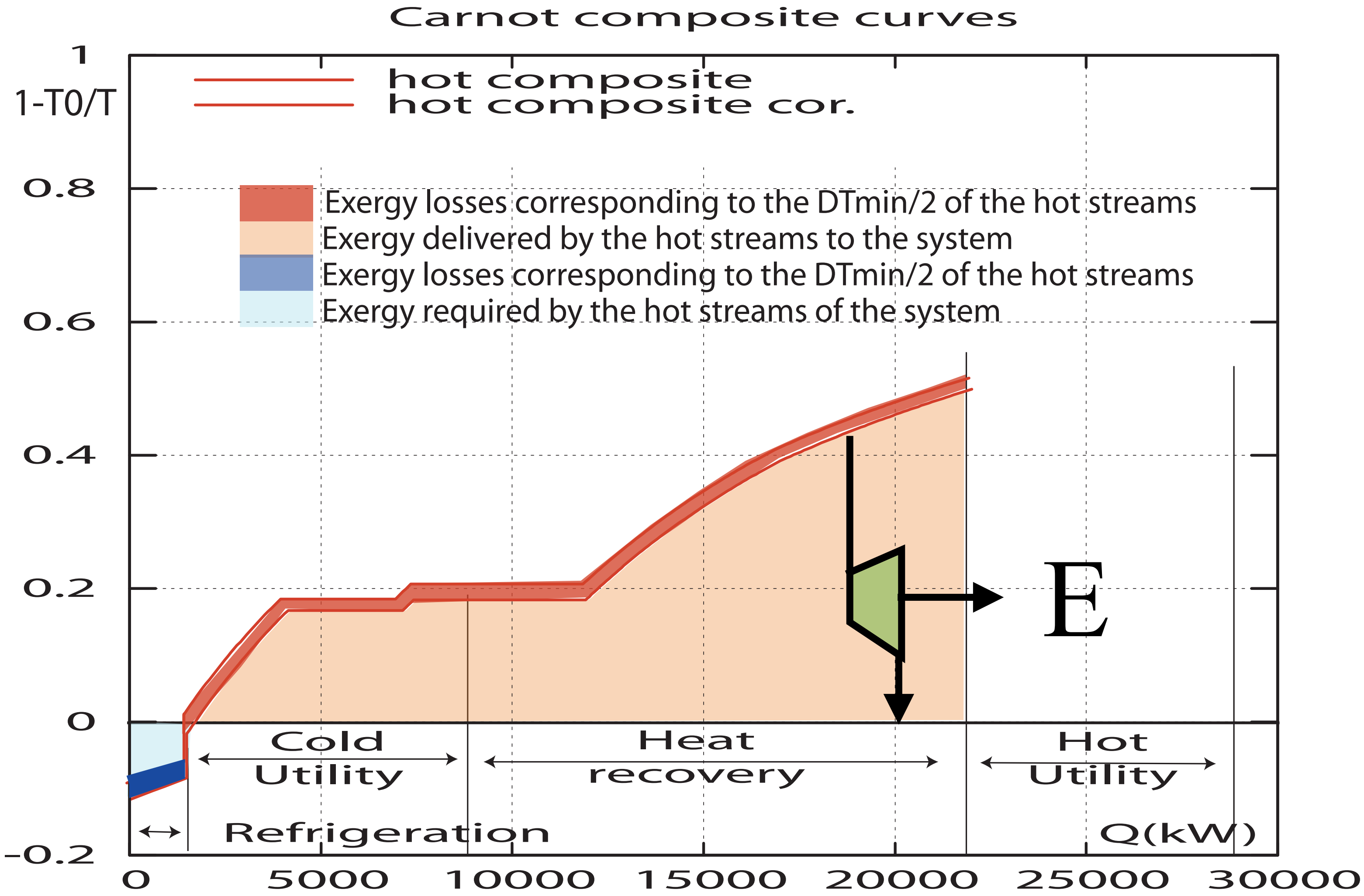


- Hot & cold composite curves
  - Minimum energy requirement
    - Hot
    - Cold
    - Refrigeration
  - Heat recovery



Carnot composite curves of a process

Hot composite curves



Carnot composite curves of the process

Cold composite curves

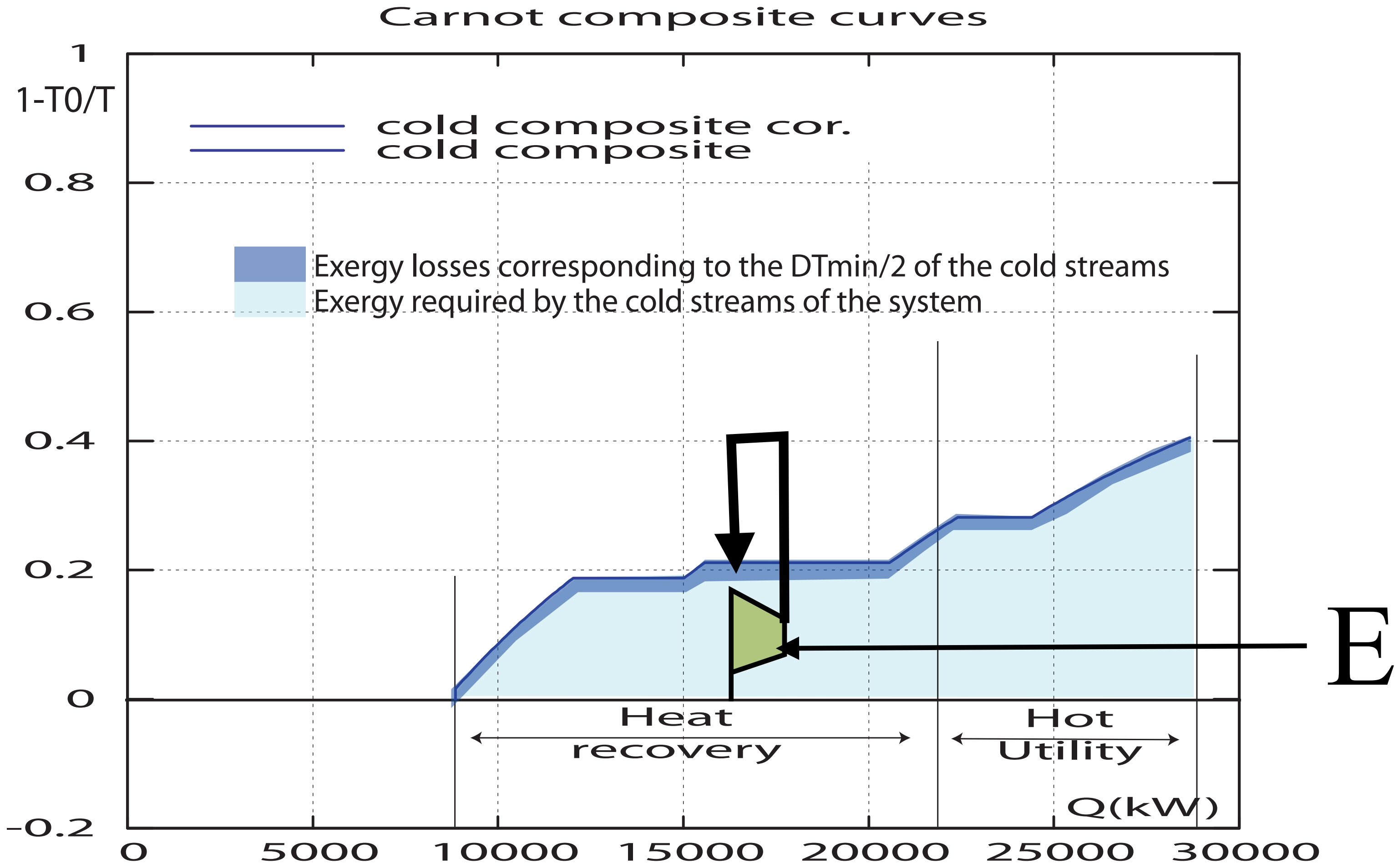
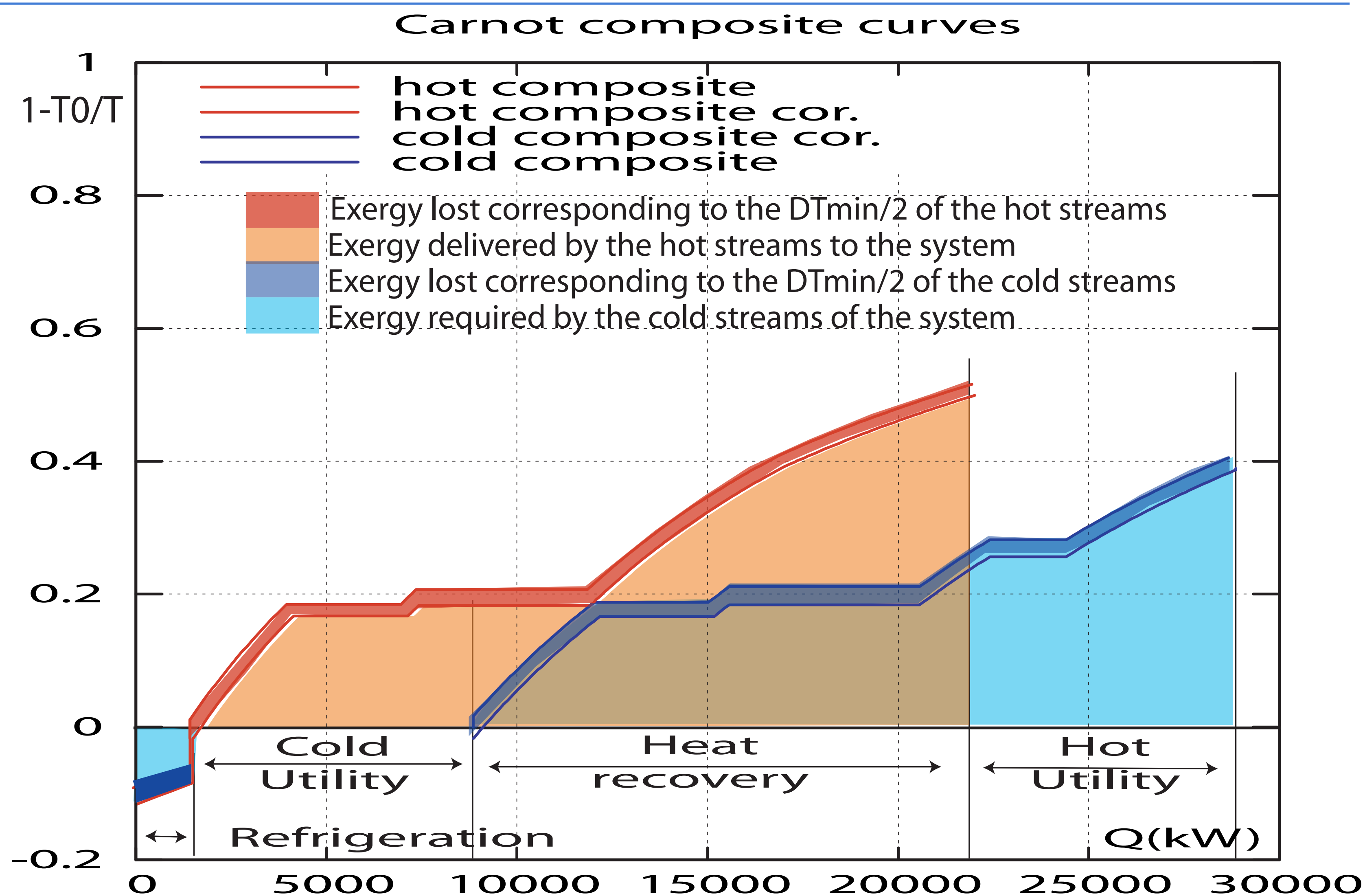


Table 3

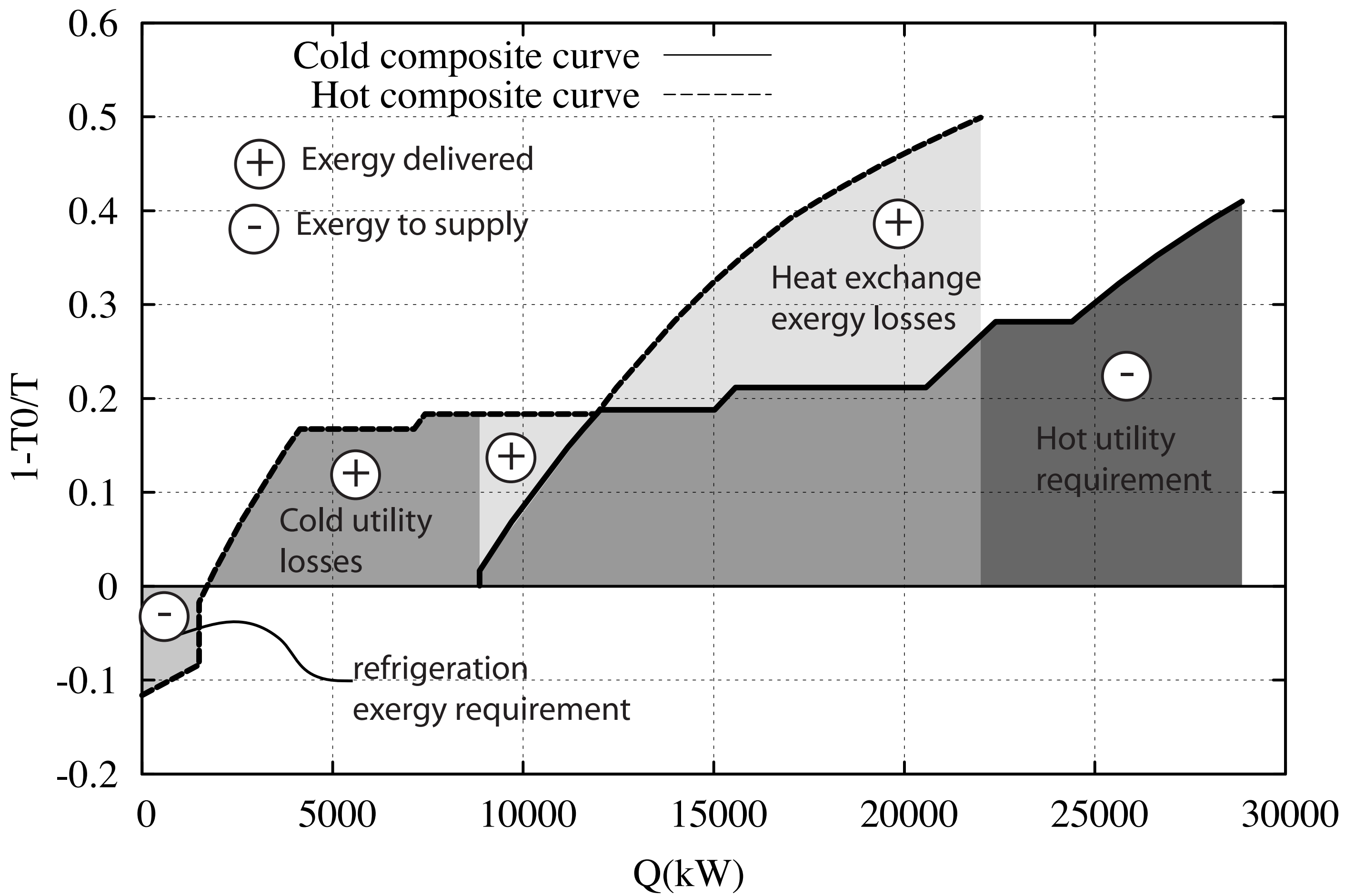
Exergy of the hot and cold process composite curves

	Energy	Exergy Total	Exergy $\Delta T_{min} corrected$	Name
Hot streams [kW]	20291.0	5521.4	5352.4	$\dot{E}q_{hot_a}$
below T_0 [kW]	1709.0	131.5	151.2	$\dot{E}q_{hot_r}$
Cold streams[kW]	20197.0	4599.3	4650.1	$\dot{E}q_{cold_a}$
below T_0 [kW]	0.0	0.0	0.0	$\dot{E}q_{cold_r}$
ΔT_{min} losses [kW]	-		381.2	

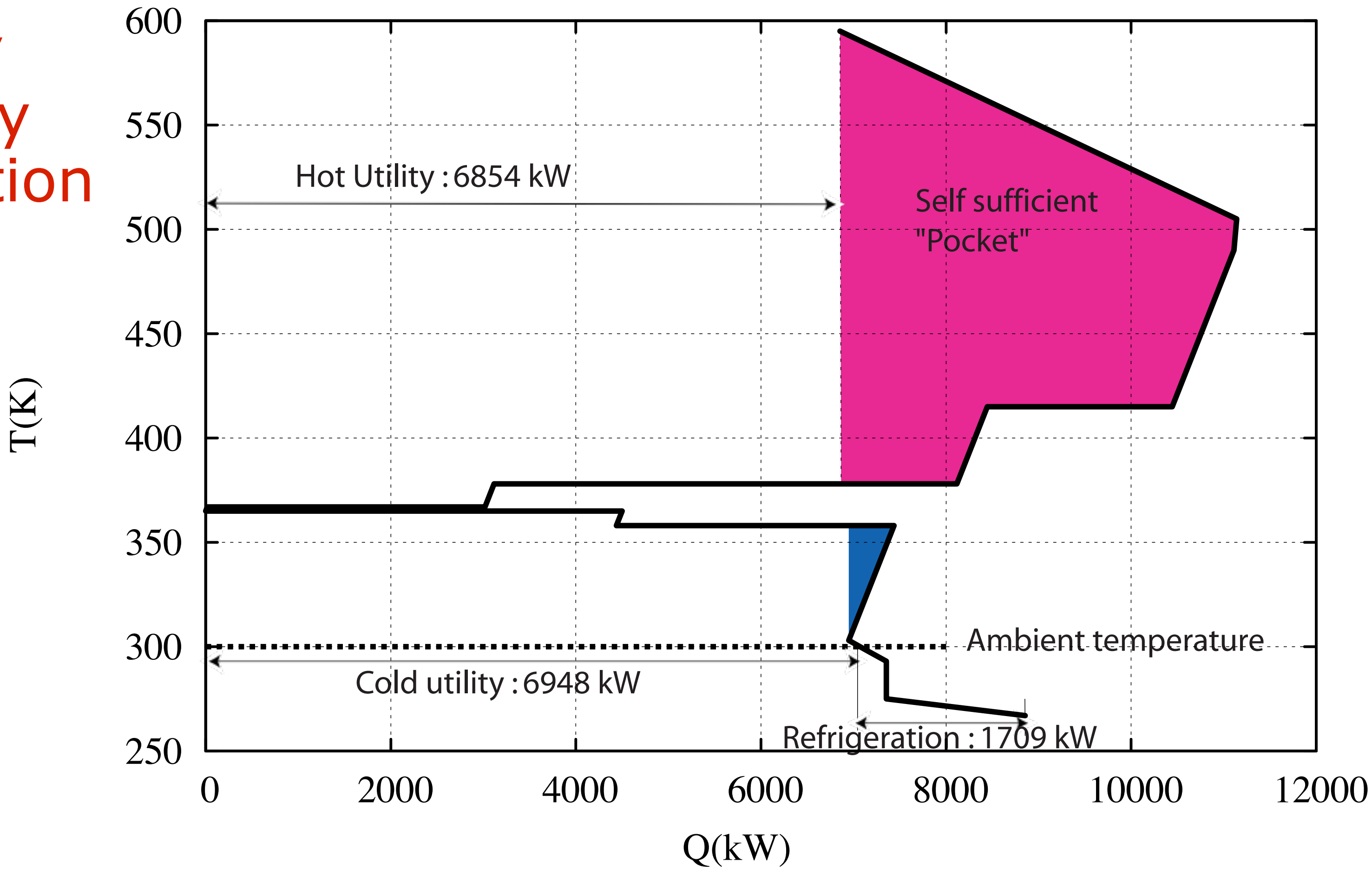
Carnot composite curves



Hot and cold composite

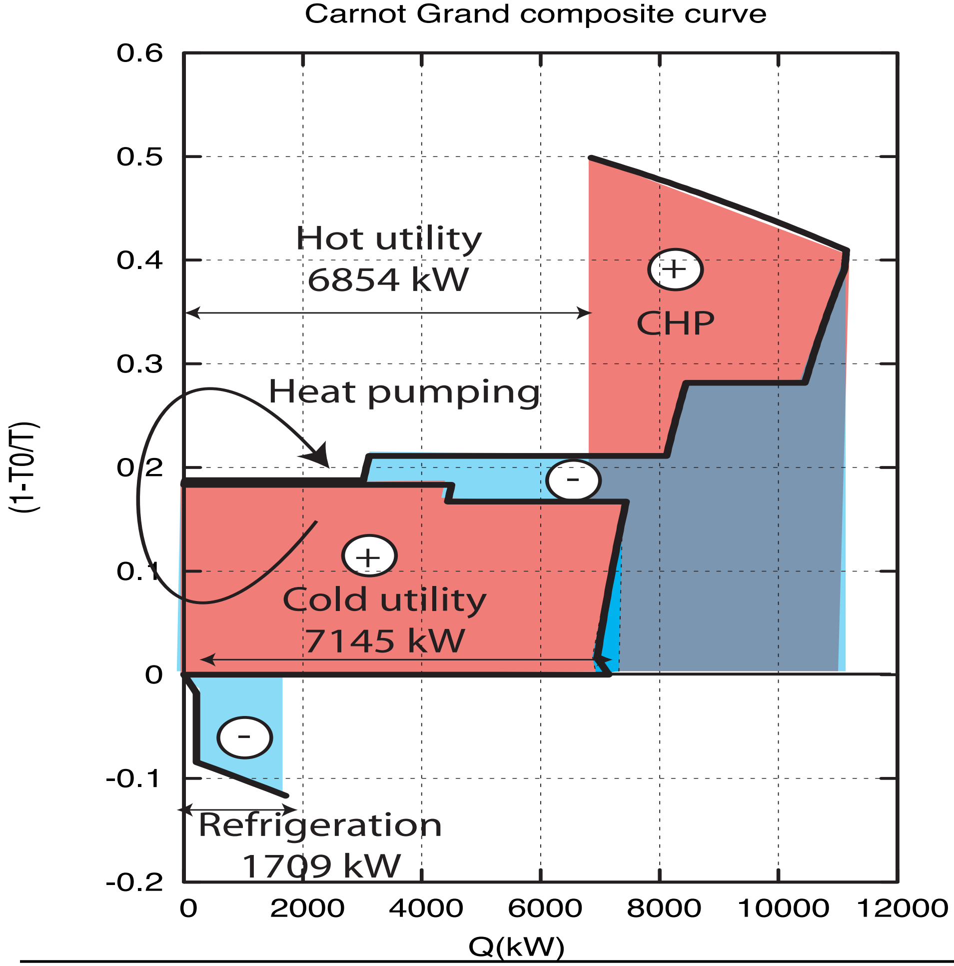


- Grand composite curve
  - ☑ Hot utility
  - ☑ Cold utility
  - ☑ Refrigeration
- CHP
- Cycles



Carnot Grand composite curve

Carnot Grand composite



Exergy requirement

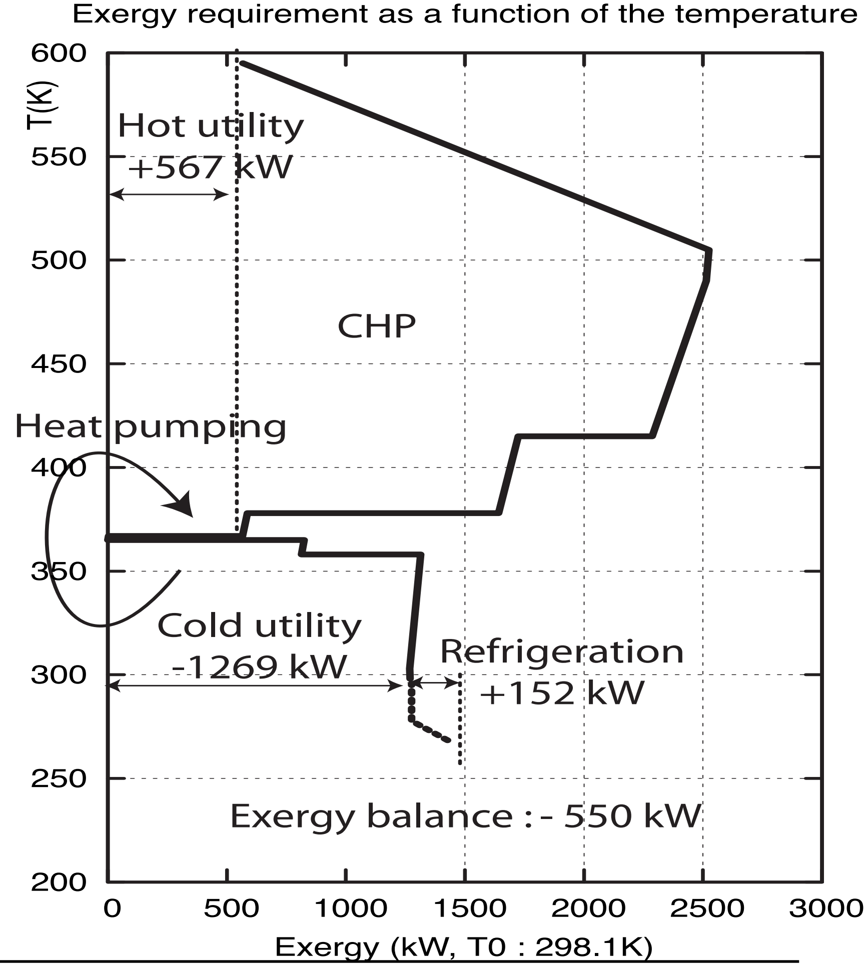
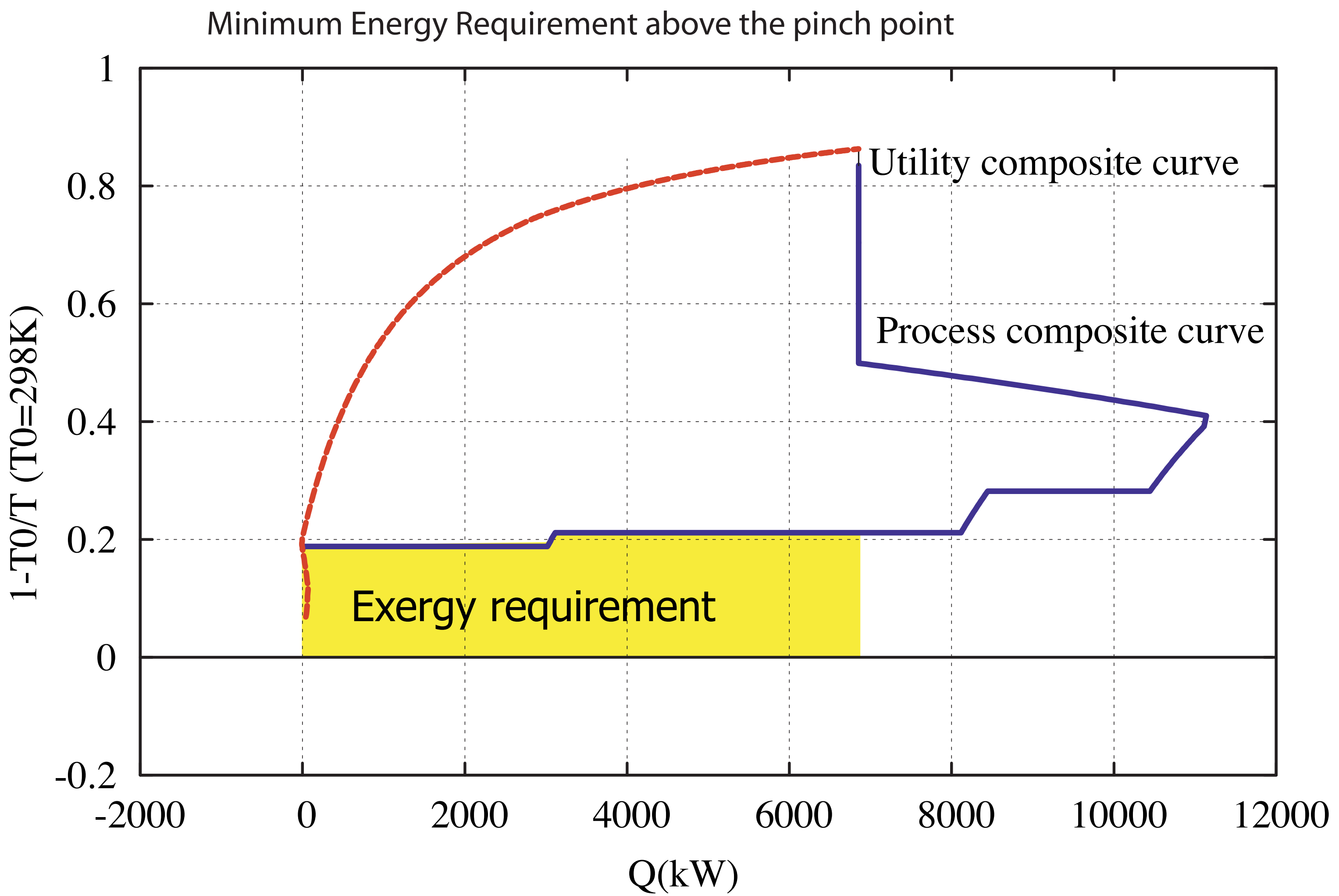


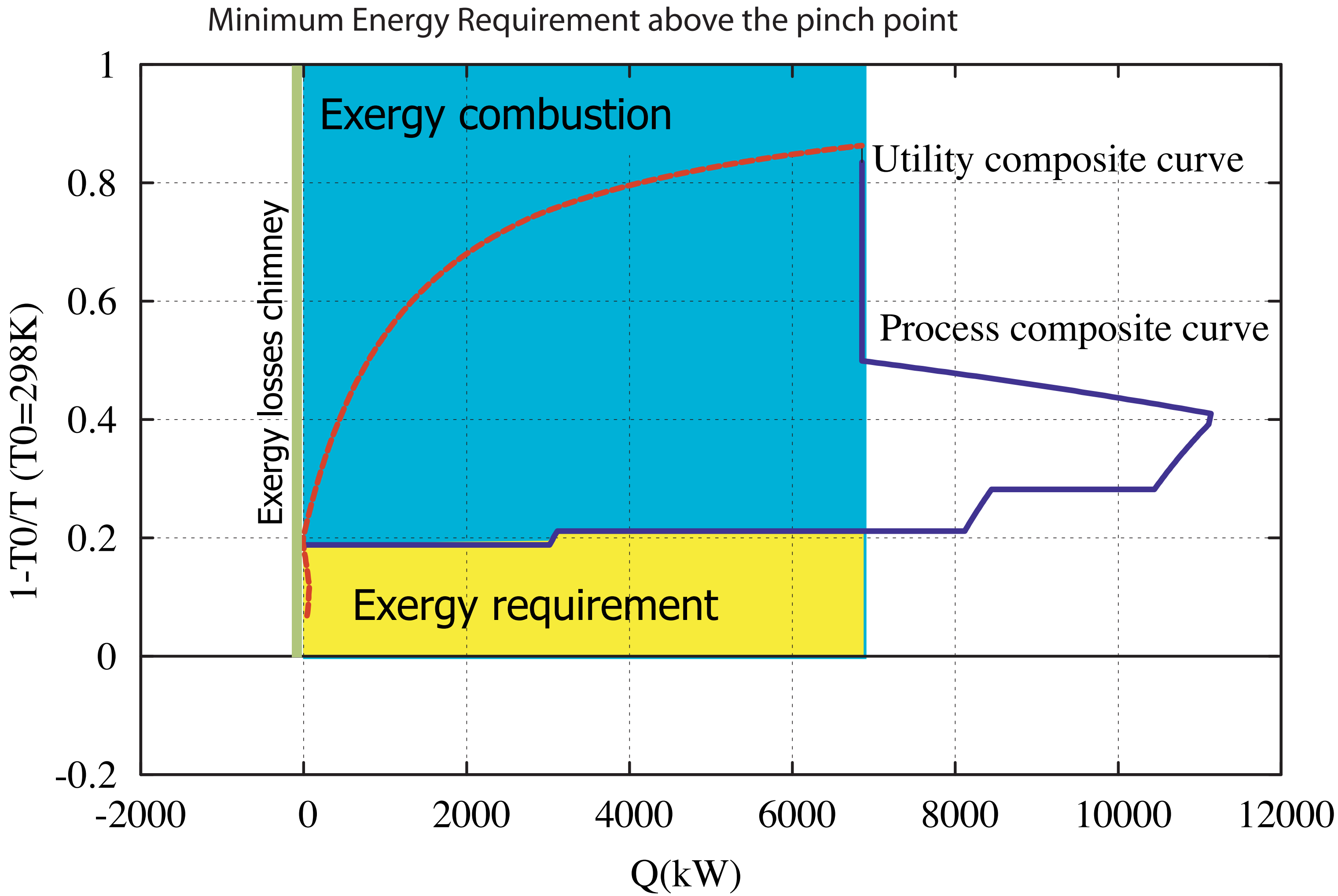
Table 2
Minimum energy and exergy requirements of the process

	Energy	Exergy	Name
Heating [kW]	+6854	+567	$\dot{E}_{heat}$
Cooling [kW]	-7145	- 1269	$\dot{E}_{cool}$
Refrigeration [kW]	+1709	+ 157	$\dot{E}_{frg}$
Balance [kW]		-550	

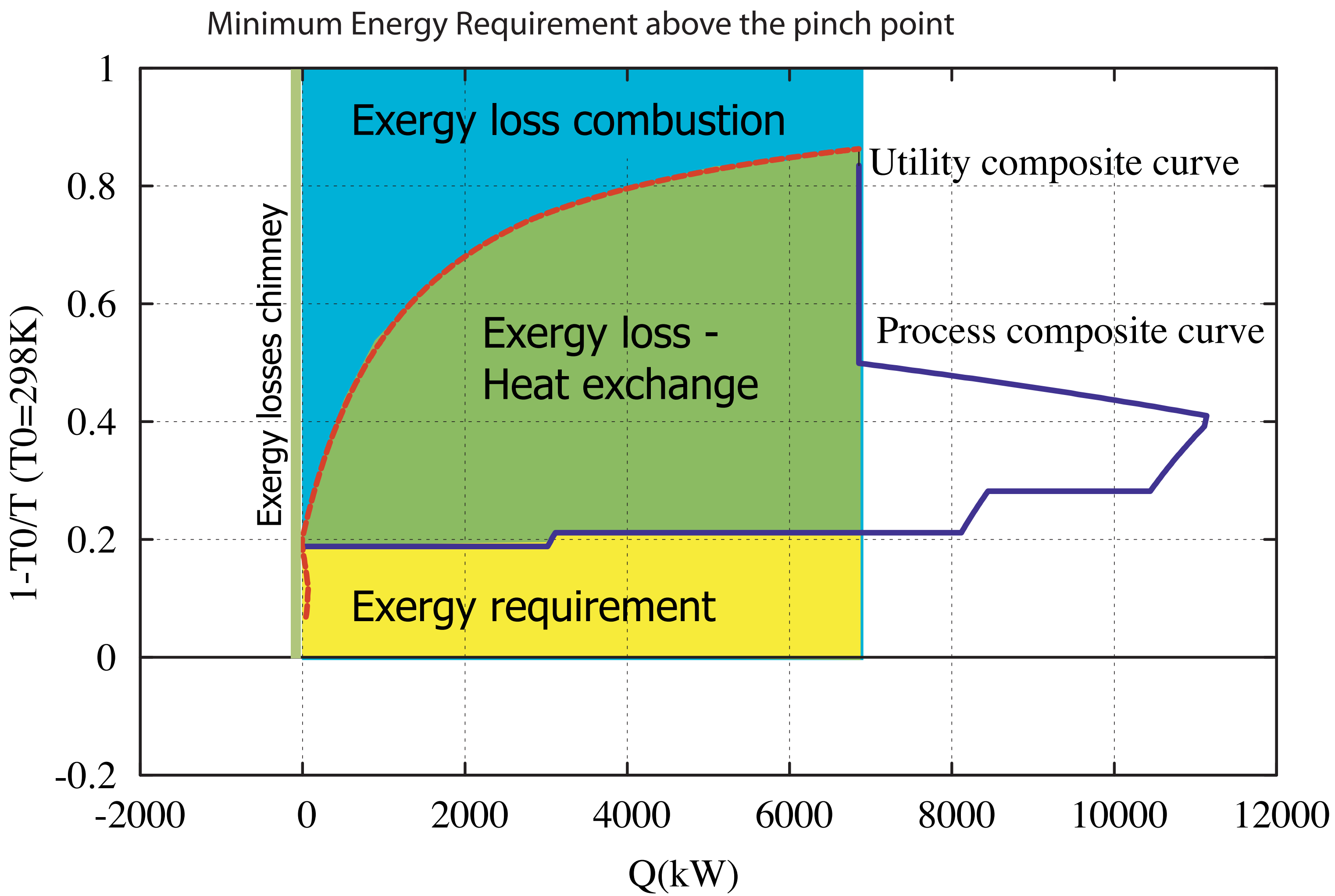
Exergy requirement above the pinch



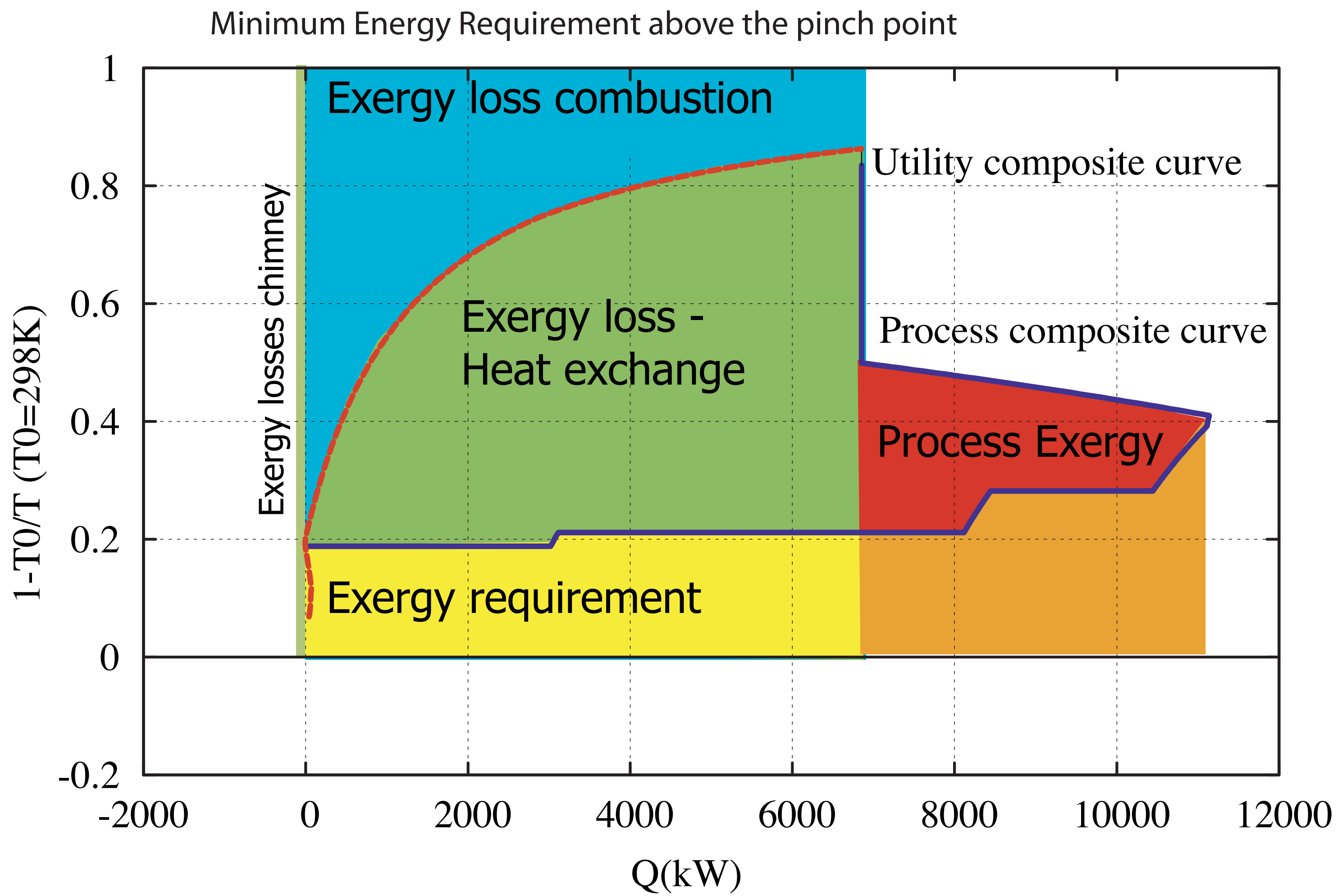
Exergy by combustion



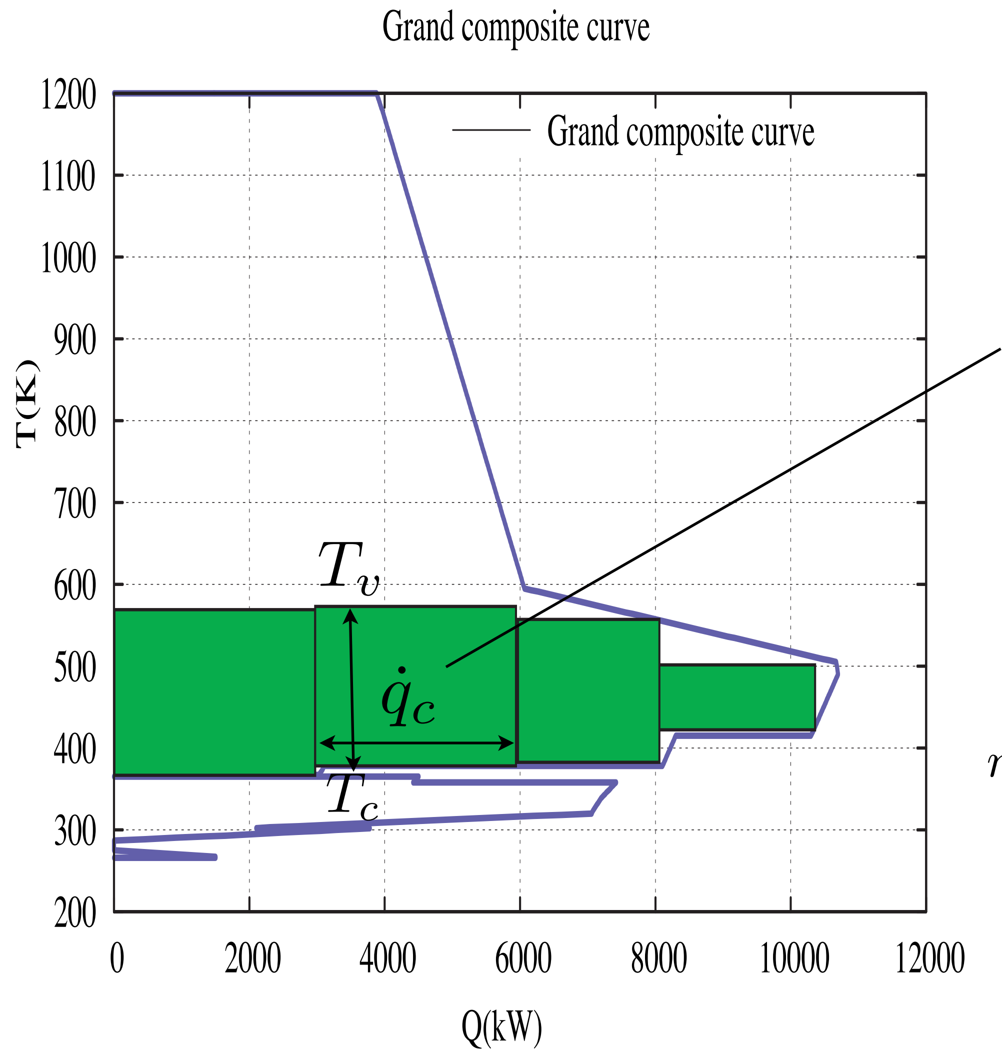
Exergy composite Heat exchange losses



Exergy composite -self-sufficient pockets



CHP : define the steam network



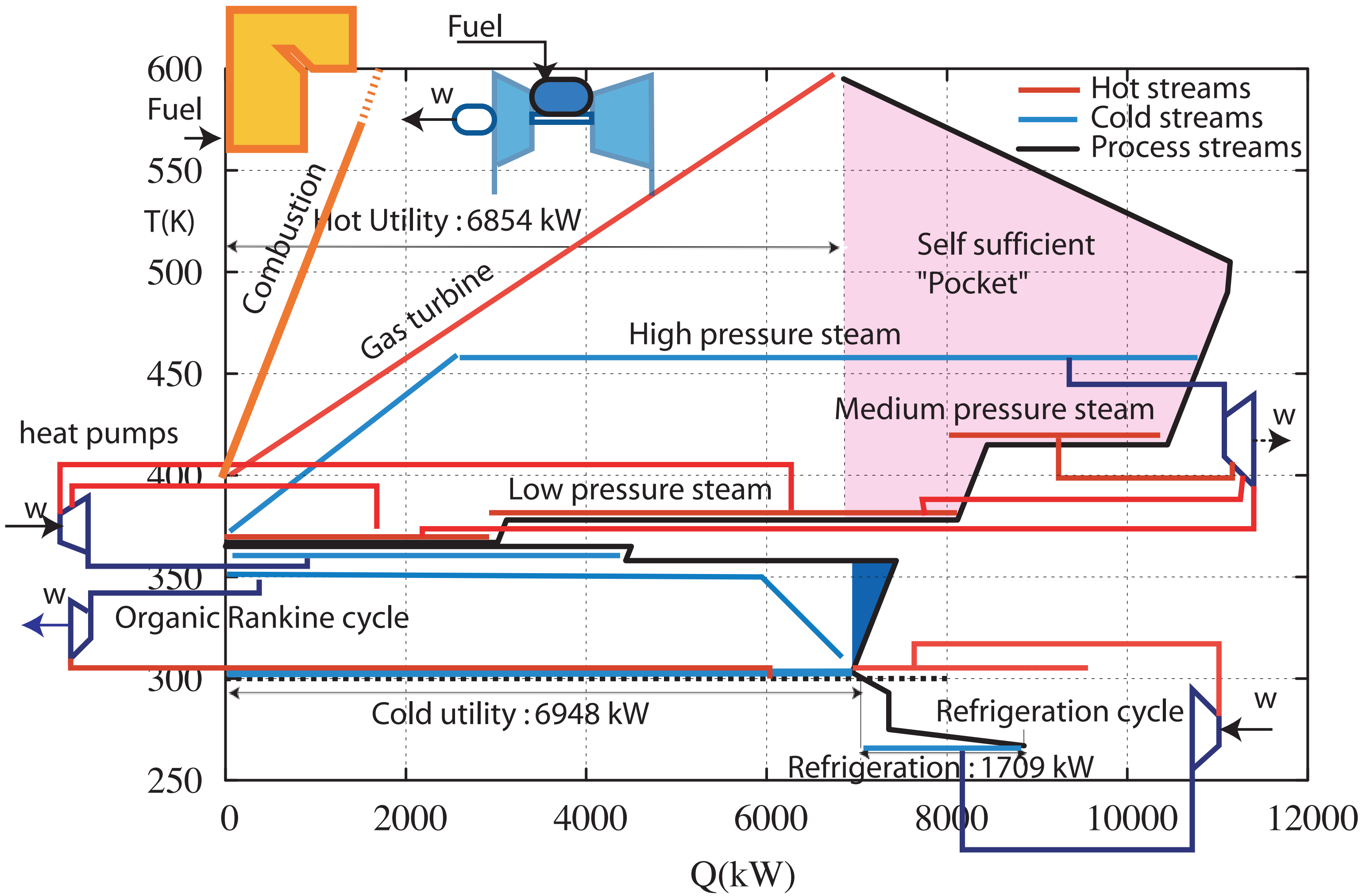
$$\dot{E} = \dot{q}_c \left(\frac{T_v - T_c}{\frac{T_v}{\eta_c} - (T_v - T_c)} \right) = \frac{A}{\frac{T_v}{\eta_c} - (T_v - T_c)}$$

Fuel consumption

$$\dot{m}_{fuel} * LHV_{fuel} = \frac{\dot{Q}_{MER} + \sum_{i=1}^{n_{CHP}} \dot{E}_i}{\eta_{comb}}$$

[1] F. Marechal and B. Kalitventzeff. Identification the optimal pressure levels in steam networks using integrated combined heat and power method. *Chemical Engineering Science*, 52(17):2977–2989, 1997.

Creative engineers ?



Integration of the energy conversion system

Creative engineers ?

Technology w with nominal flow

Hot/cold streams

$$T_{w,i}^{in}, P_{w,i}^{in}, \dot{m}_{w,i}, x_{w,i}$$

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

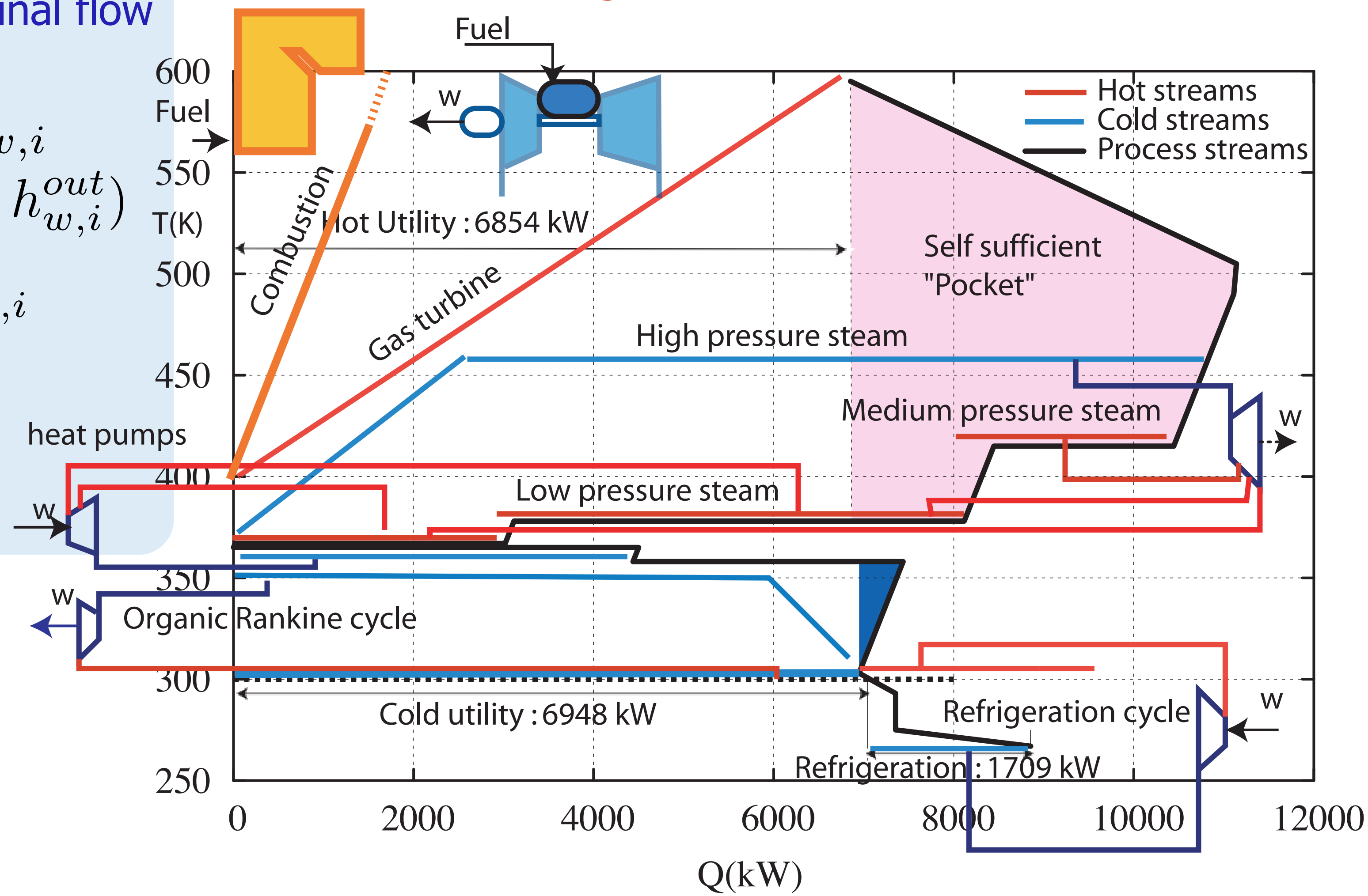
$$T_{w,i}^{out}, P_{w,i}^{out}, \dot{m}_{w,i}, x_{w,i}$$

Mechanical power/electricity

$$e_w$$

Costs

$$C1_w, C2_w, CI1_w, CI2_w$$



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

$$e_w$$

Costs

$$C1_w, C2_w, CI1_w, CI2_w$$

Decision variables

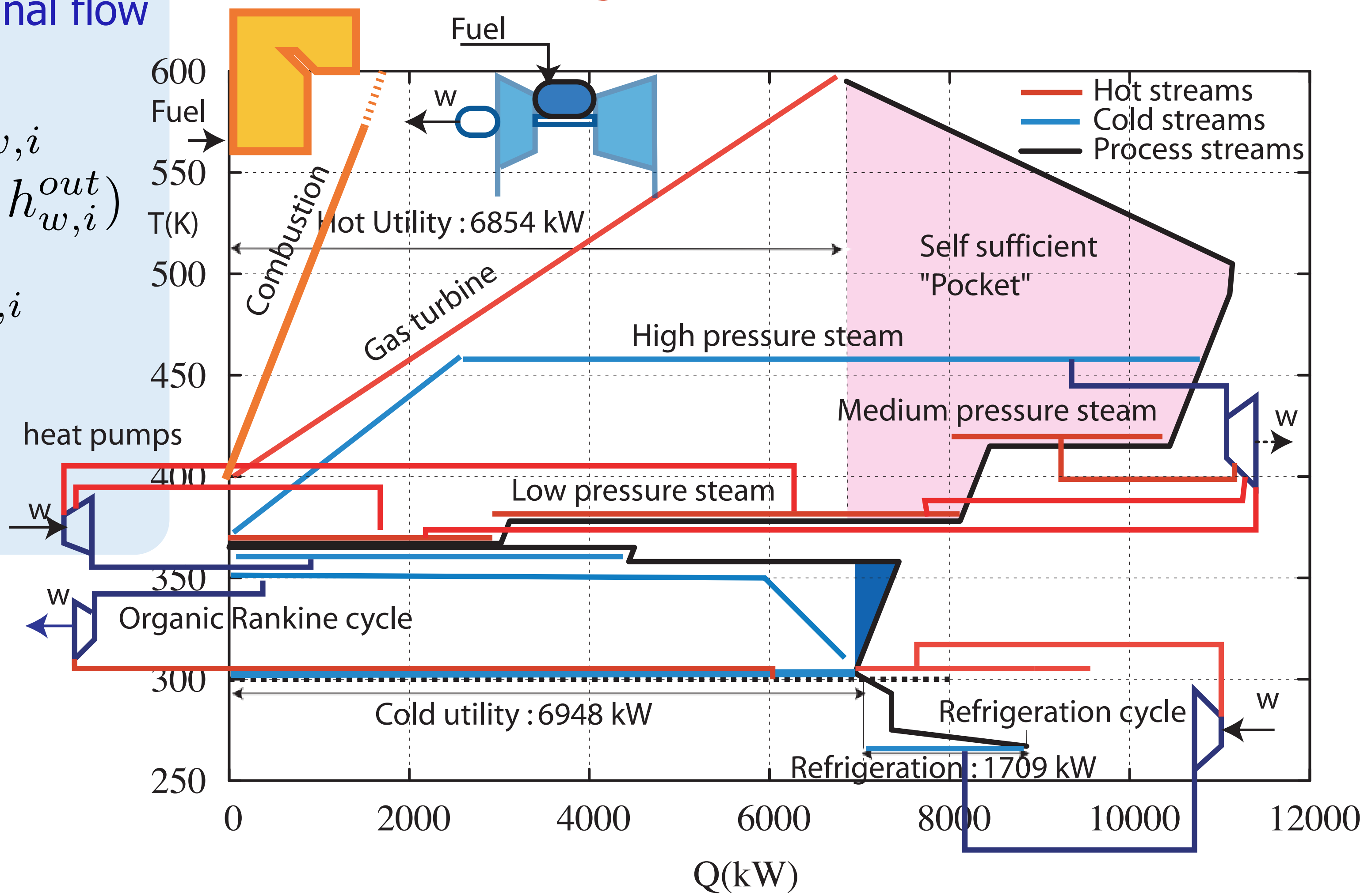
Level of usage of w

$$f_w$$

Buy/use technology w ?

$$y_w$$

Creative engineers ?



MILP formulation

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

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

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

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

Consider exergy losses

- New objective function

$$\min_{\dot{R}_r, y_w, f_w} \sum_{w=1}^{n_w} \dot{L}_w = \sum_{w=1}^{n_w} (f_w * (\dot{E}_w^{+} - \sum_{r=1}^{n_r} (\dot{E}q_{w,r}^{-})_{\Delta T_{min}} - \dot{E}_w^{-}))$$

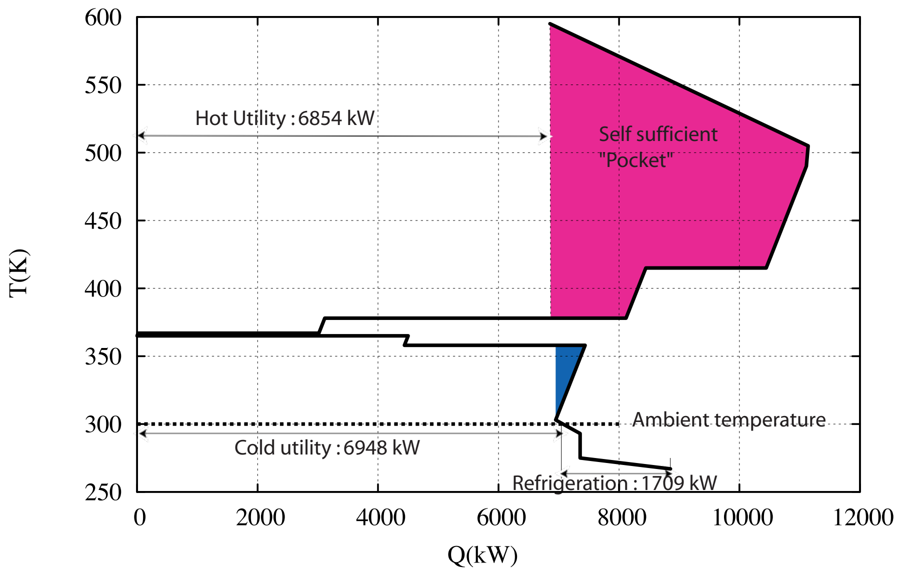
- Thermal exergy : $(\dot{E}q_{w,r}^{-})_{\Delta T_{min}} = \sum_{s=1}^{ns_w} \dot{Q}_{s,r}^{-} * (1 - \frac{T_0 * ln(\frac{T_{r+1}}{T_r})}{T_{r+1} - T_r})$

- Chemical Exergy : $\dot{E}_w^{+} = \sum_{f=1}^{n_{fuel,w}} \dot{M}_{f,w} \Delta k_f^0$

- Work : $\dot{E}_w^{-}$

Maximum energy recovery

	Energy	Exergy
Heating (kW)	+6854	+567
Cooling (kW)	-6948	- 1269
Refrigeration (kW)	+1709	+ 157



Hot utility

Boiler house : NG (44495 kJ/kg)
Air Preheating
Gas turbine : NG (el. eff = 32%)

Steam cycle

Header	P (bar)	T (K)	Comment
HP2	92	793	superheated
HP1	39	707	superheated
HPU	32	510	condensation
MPU	7.66	442	condensation
LPU	4.28	419	condensation
LPU2	2.59	402	condensation
LPU3	1.29	380	condensation
DEA	1.15	377	deaeration

Heat pumps

Fluid R123

	P_{low} (bar)	T_{low} (°K)	P_{high} (bar)	T_{high} (K)	COP -	kWe
Cycle 3	5	354	7.5	371	15	130
Cycle 2	6	361	10	384	12	323
Cycle 0	6	361	7.5	371	28	34

Refrigeration

Refrigerant	R717	Ammonia
Reference flowrate	0.1	kmol/s
Mechanical power	394	kW

	P (bar)	T_{in} (°K)	T_{out} (°K)	Q kW	$\Delta T min/2$ (°K)
Hot str.	12	340	304	2274	2
Cold str.	3	264	264	1880	2

Results

Opt	Fuel kW_{LHV}	GT kWe	CHP kWe	Cooling kW	HP kWe	
1	7071	-	-	8979	-	Comb. + frg
2	10086		2957	9006	-	Comb. + stm + frg
3	16961	5427	2262	9160	-	GT + stm + frg
4	-	-	-	2800	485	hpmp + frg
5	666	-	738	2713	496	hpmp + stm + frg

Results

Opt	Fuel kW_{LHV}	GT kWe	CHP kWe	Cooling kW	HP kWe	
1	7071	-	-	8979	-	Comb. + frg
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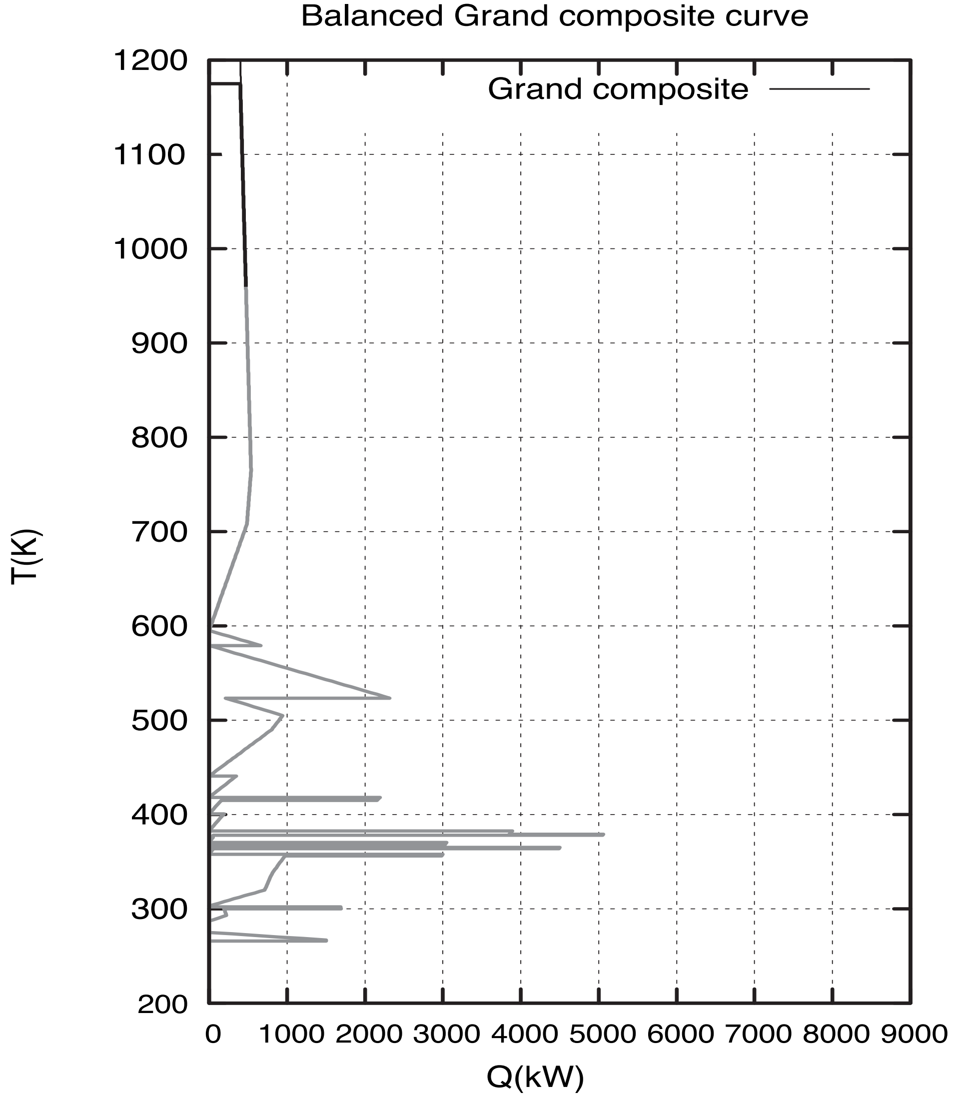
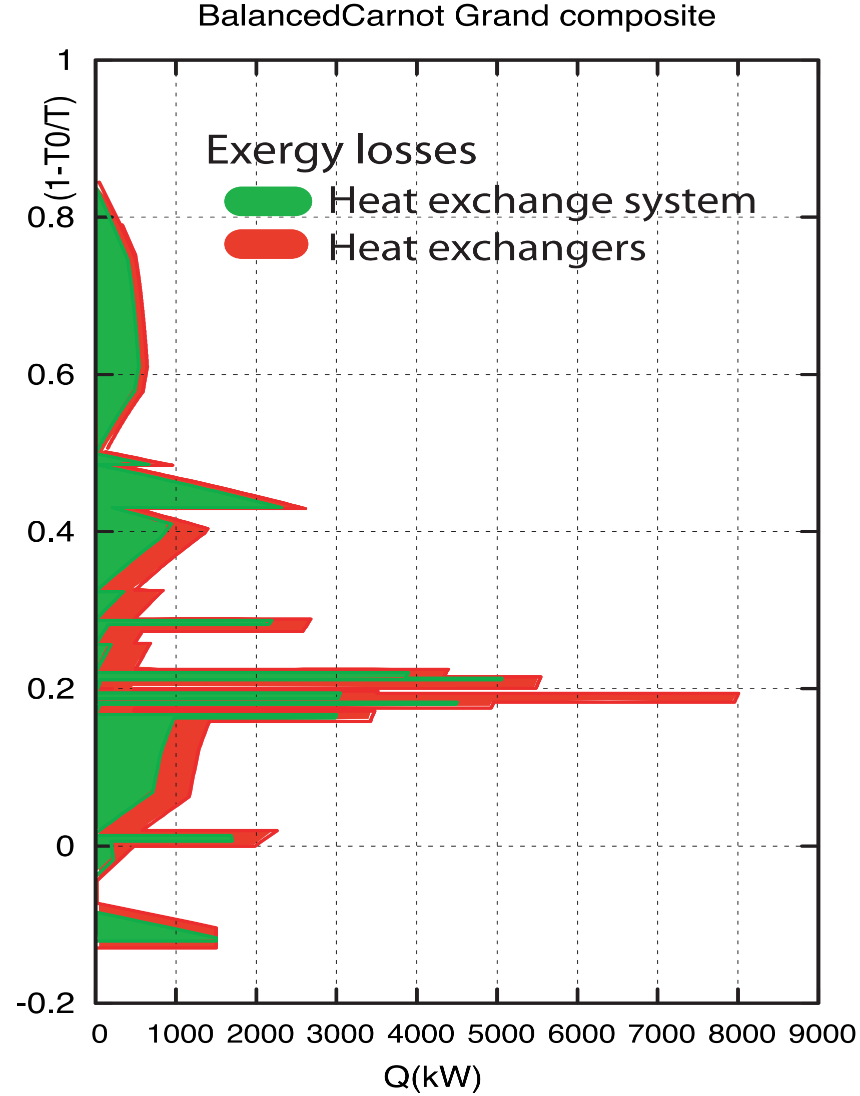
4	-	-	-	2800	485	hpmp + frg
5	666	-	738	2713	496	hpmp + stm + frg

Share between heat pumps

HP1 : 34 kWe
HP2 : 323 kWe
HP3 : 129 kWe

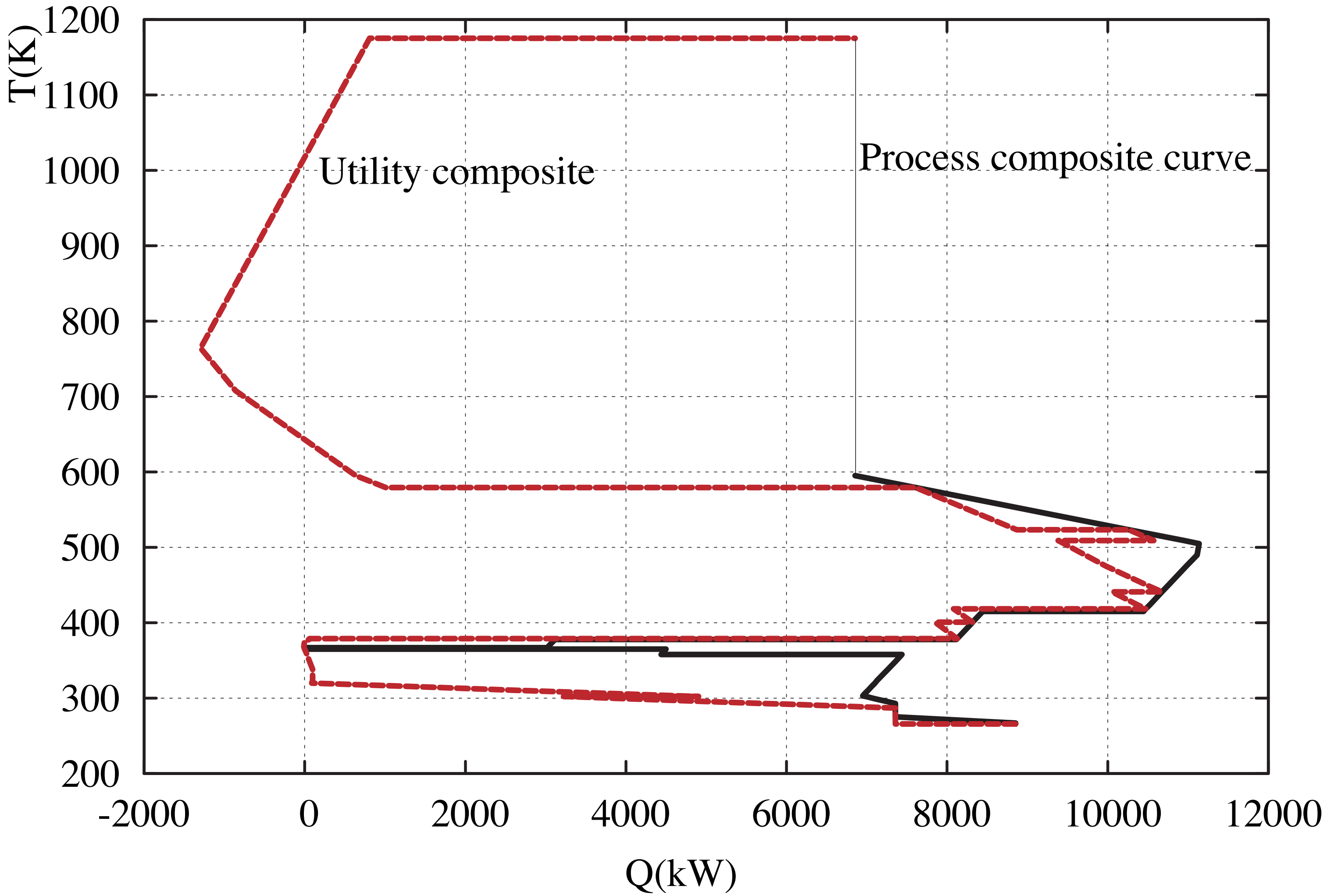
Balanced composite curves (option 5)



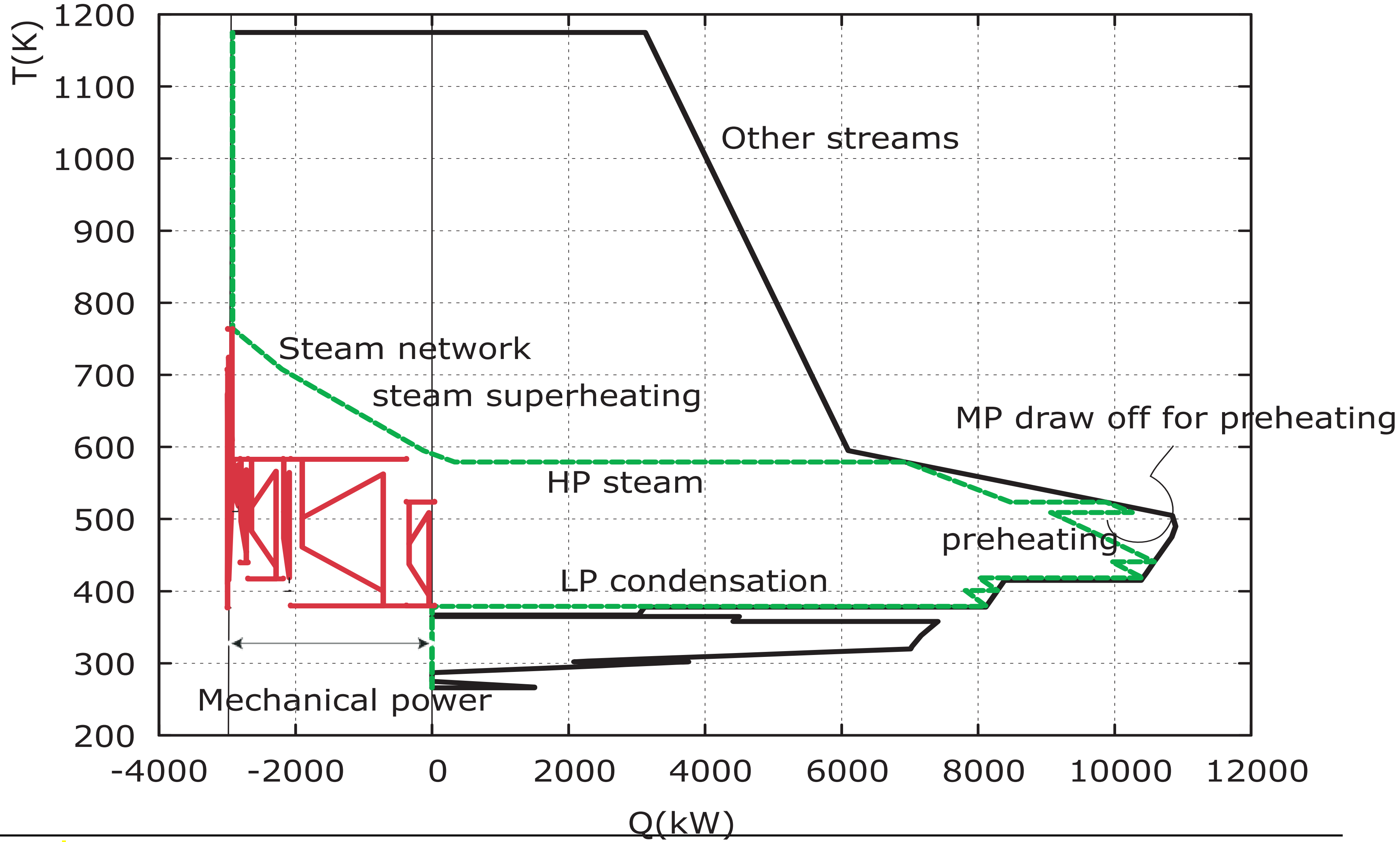


Integrated composite curves

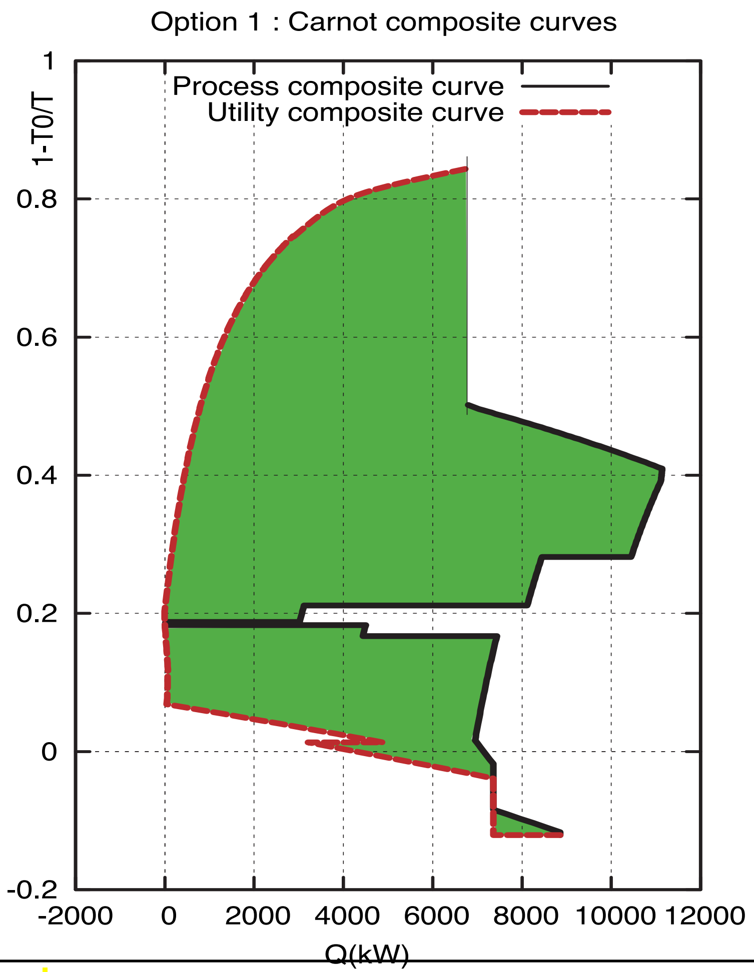
Option 2 : Utility integrated composite curve

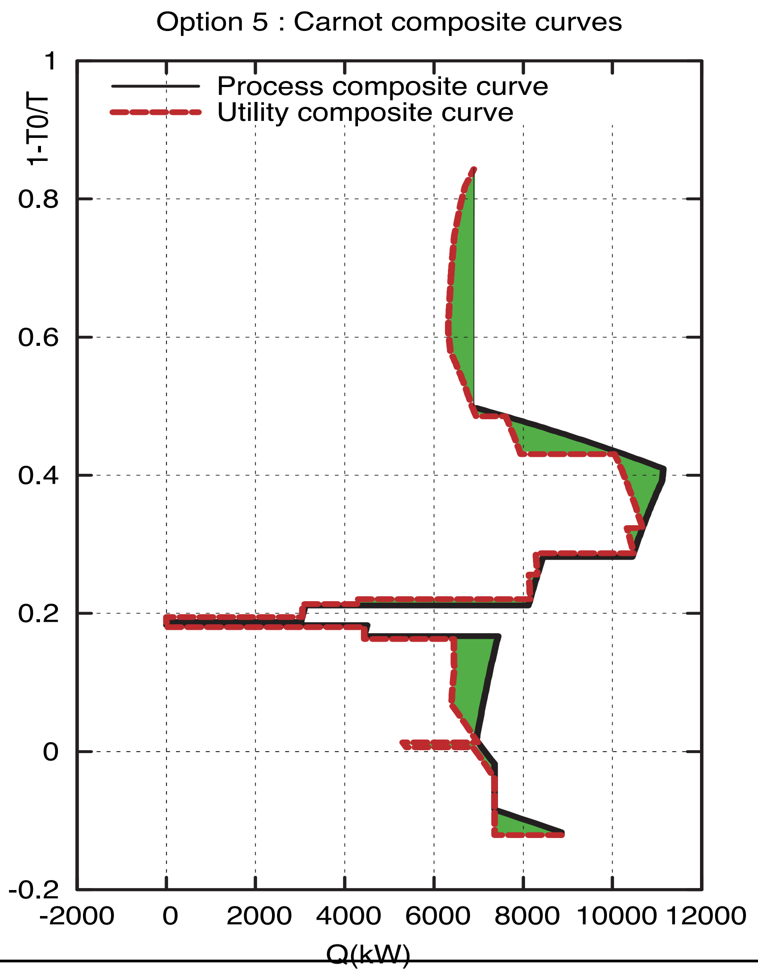


Integrated composite curve : steam network

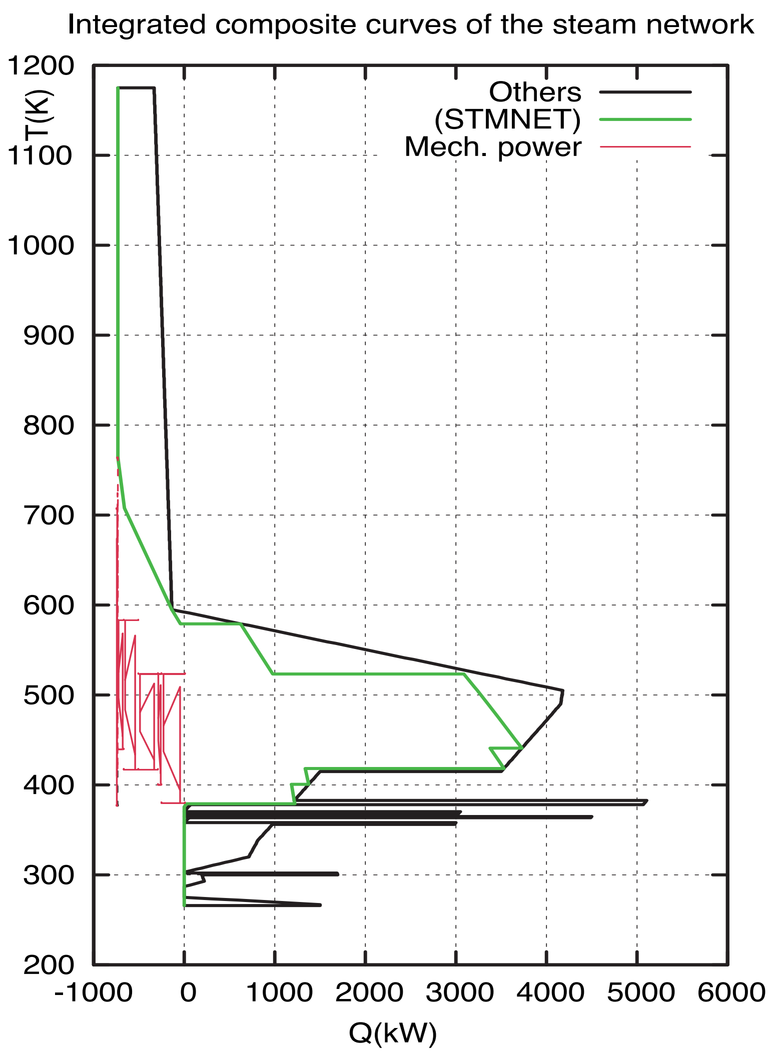


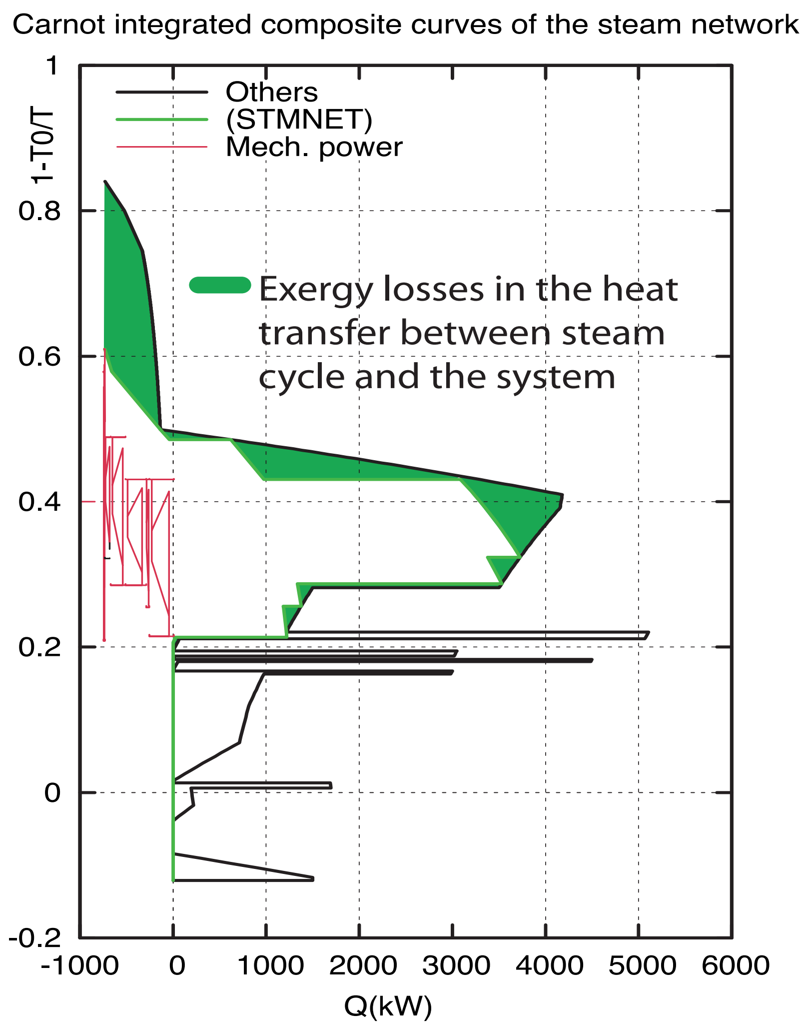
Tricks for creative engineers : reduce the green area !





Carnot integrated composite curves





Comparing results

- Energy efficiency
  - NGCC equivalence of electricity

$$Total1 = \dot{m}_{fuel} * LHV_{fuel} + \frac{(E^+ - E^-)}{\eta_{el}} (= 55\%(NGCC))$$

  - EU mix for electricity

$$Total2 = \dot{m}_{fuel} * LHV_{fuel} + \frac{(E^+ - E^-)}{\eta_{el}} (= 38\%(EUmix))$$

- Exergy efficiency

$$\eta_{ex} = \frac{\dot{E}q_{cold_a} + \dot{E}q_{hot_r} + \dot{E}^-_{grid}}{\dot{E}^+ + \dot{E}q_{cold_r} + \dot{E}q_{hot_a}} \quad \text{with} \quad \dot{E}^+ = \sum_{fuel=1}^{n_{fuels}} \dot{M}^+_{fuel} \Delta k^0_{fuel} + \dot{E}^+_{grid}$$

$$\dot{L} = (1 - \eta_{ex})(\dot{E}^+ + \dot{E}q_{cold_r} + \dot{E}q_{hot_a})$$

Results

$$Total1 = \dot{m}_{fuel} * LHV_{fuel} + \frac{(E^{+} - E^{-})}{\eta_{el}} (= 55\%(NGCC))$$

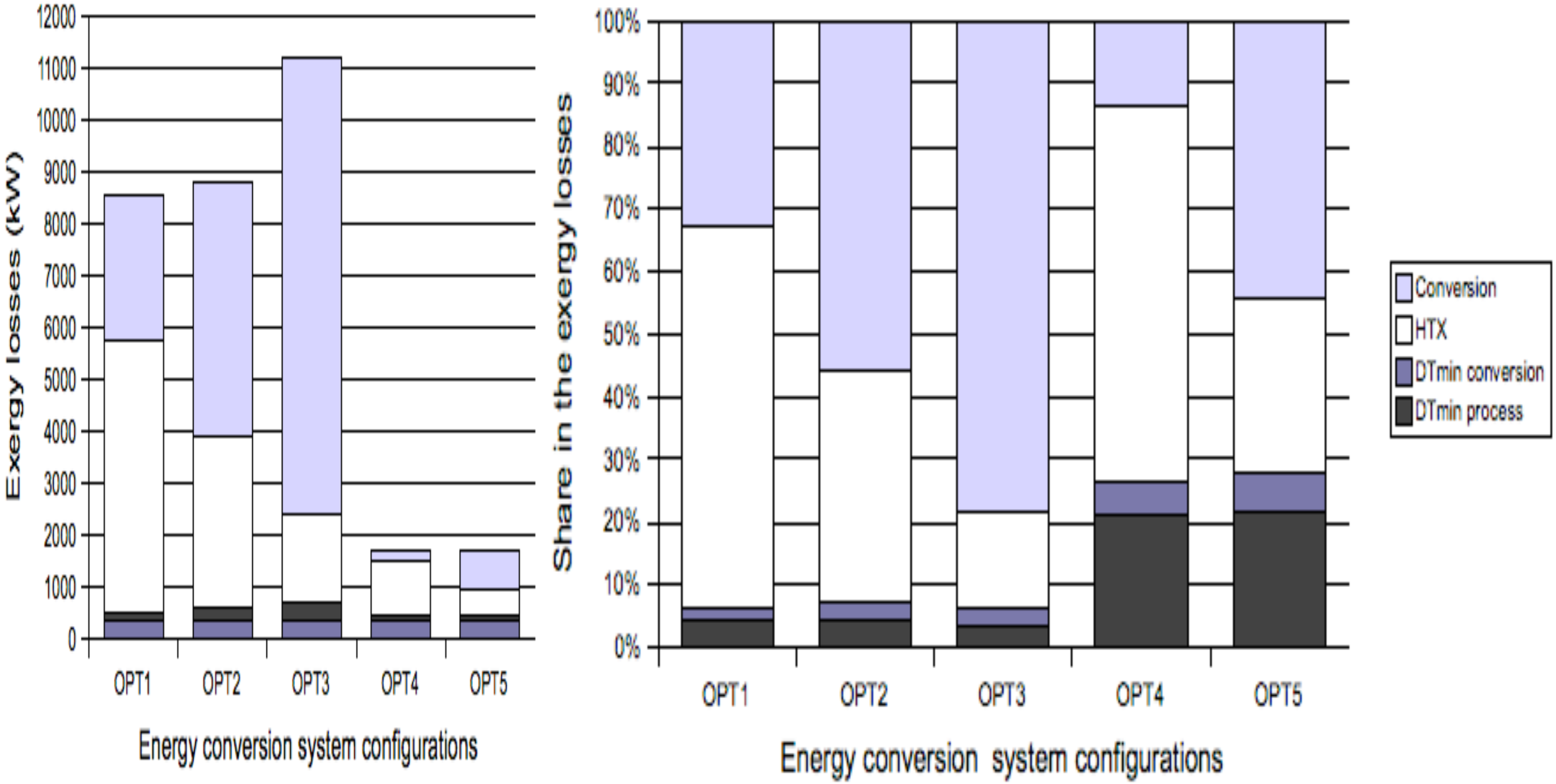
$$Total2 = \dot{m}_{fuel} * LHV_{fuel} + \frac{(E^{+} - E^{-})}{\eta_{el}} (= 38\%(EUmix))$$

Table 9

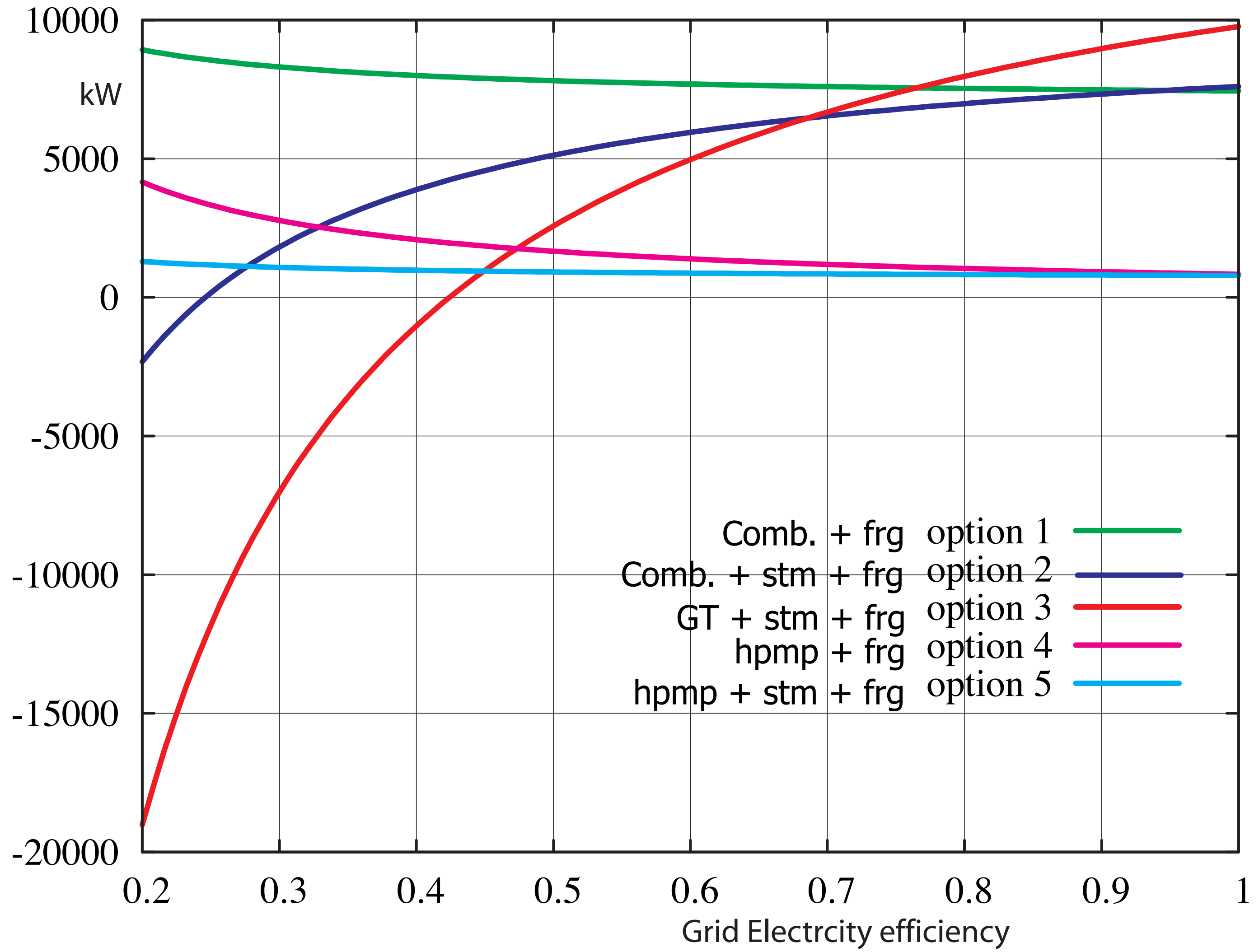
Energy consumption and exergy efficiency of the different options

Option	Fuel $[kW_{LHV}]$	$\dot{E}^{+}_{grid}$ [kWe]	Total 1 $[kW_{LHV}]$	Total 2 $[kW_{LHV}]$	η_{ex} %	Losses [kW]
Comb. + frg	7071.0	371.0	7745.5	8029.7	34.9	8868.0
Comb. + stm + frg	10086.0	-2481.0	5575.1	3675.1	44.5	8830.0
GT + stm + frg	16961.0	-7195.0	3879.2	-1630.7	51.3	11197.2
hpmp + frg	0.0	832.0	1512.7	2149.9	72.4	2408.1
hpmp + stm + frg	666.0	125.0	893.3	989.0	72.6	1831.6

Shares of Exergy losses

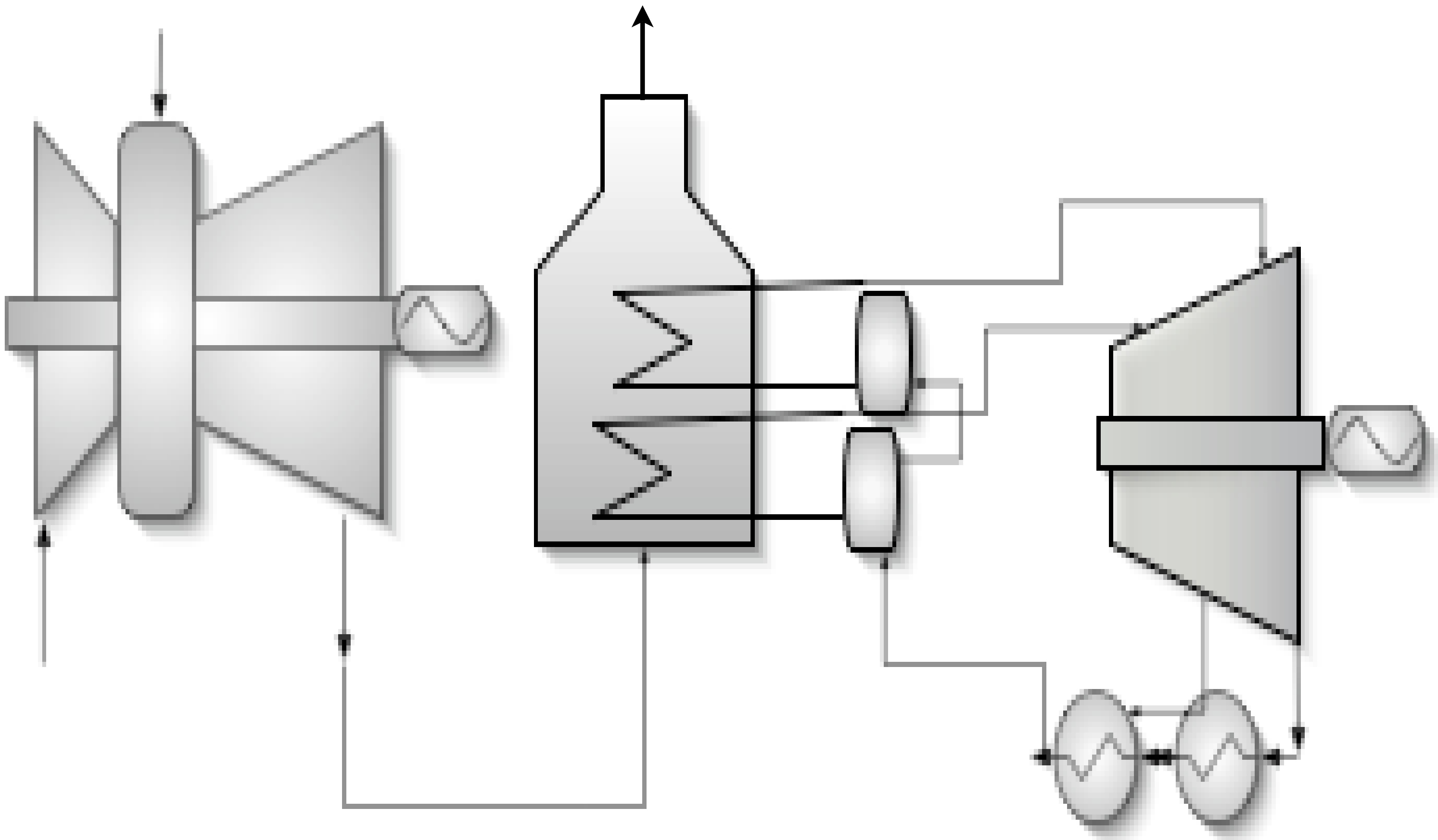


Sensitivity of the grid electricity mix



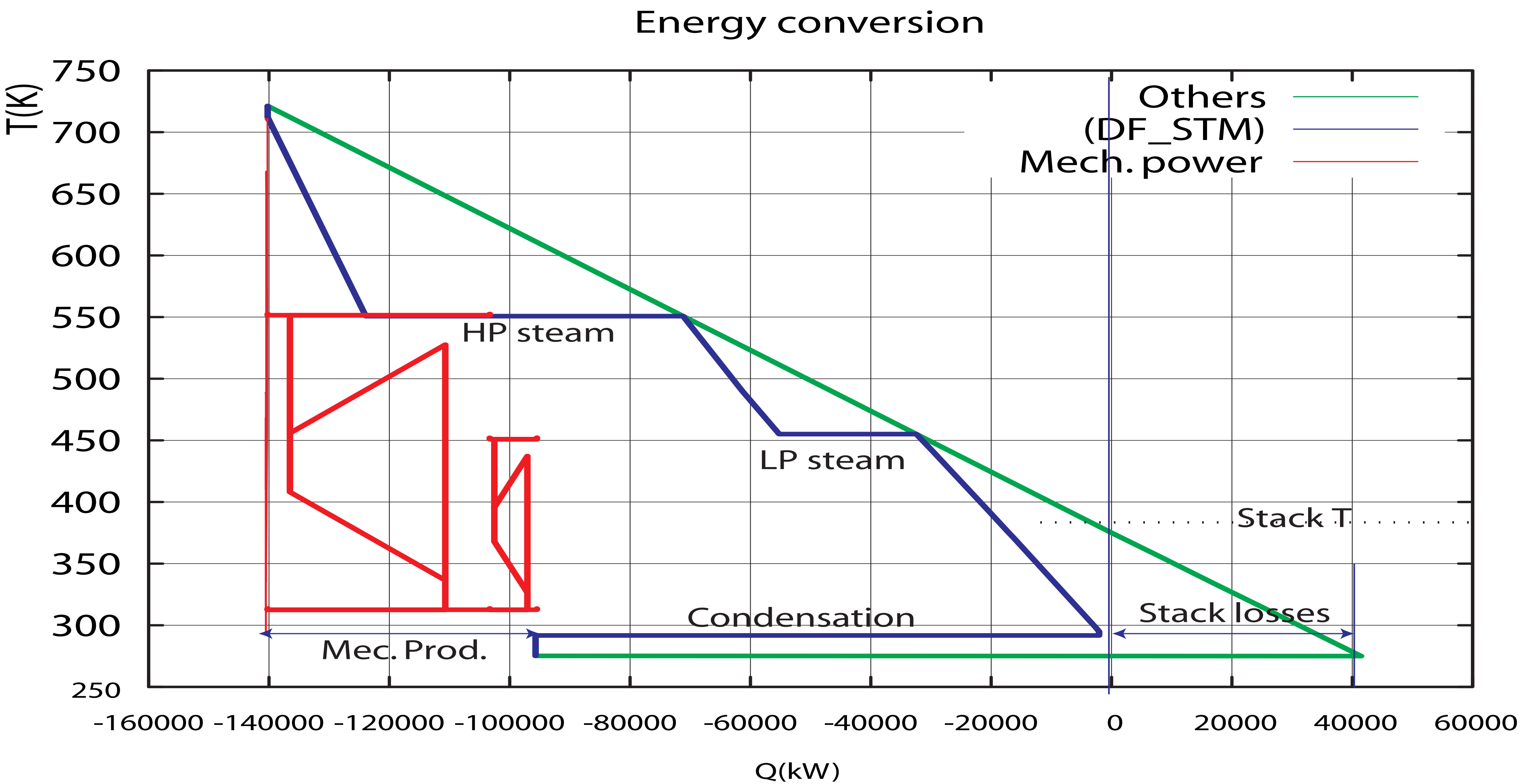
$$\frac{c_{fuel}(€/kJ)}{c^{-}_{grid}(€/kJ_e)}$$

Power plant design



Power plant : steam cycle integration

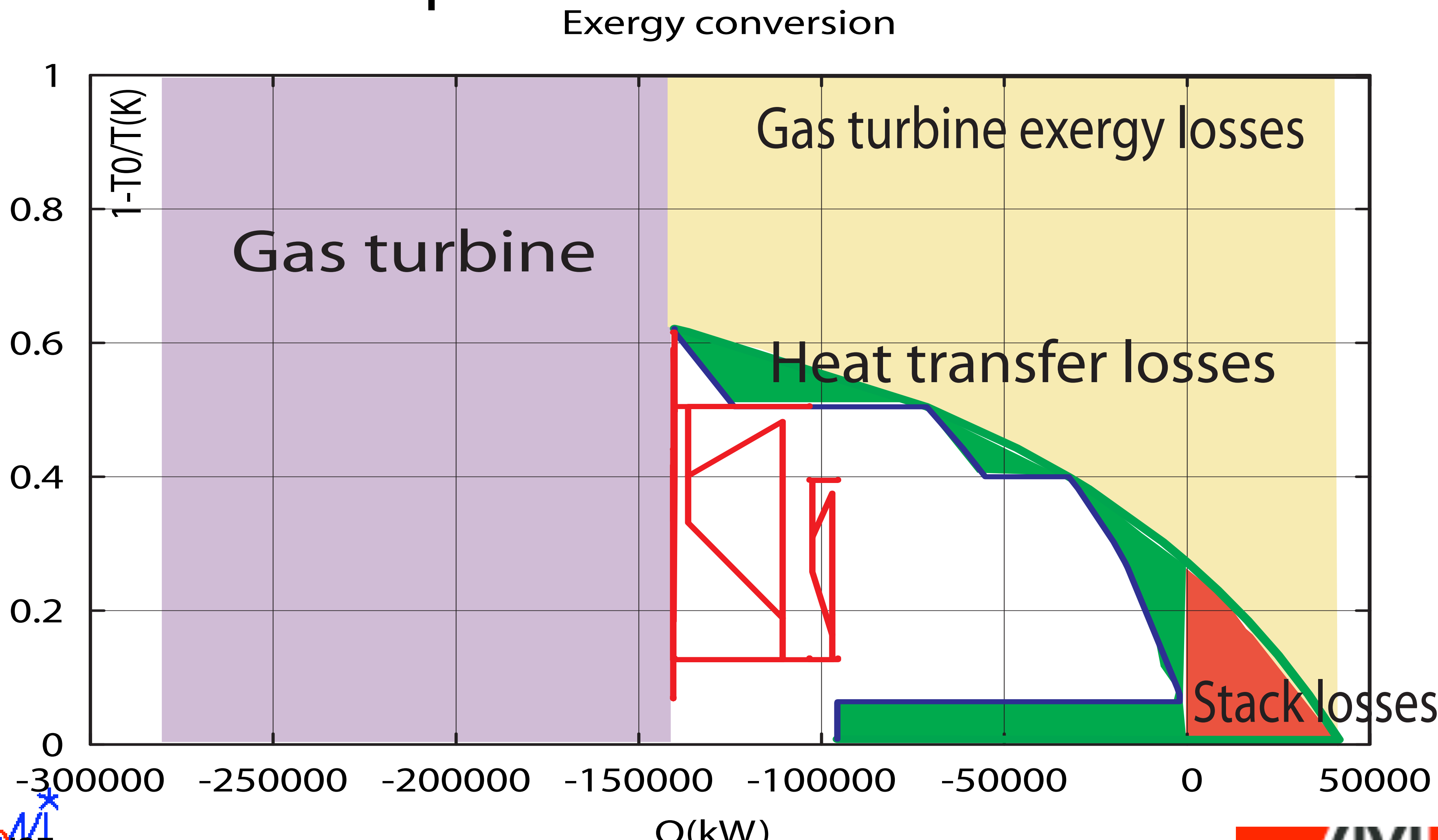
- Integrated composite curves



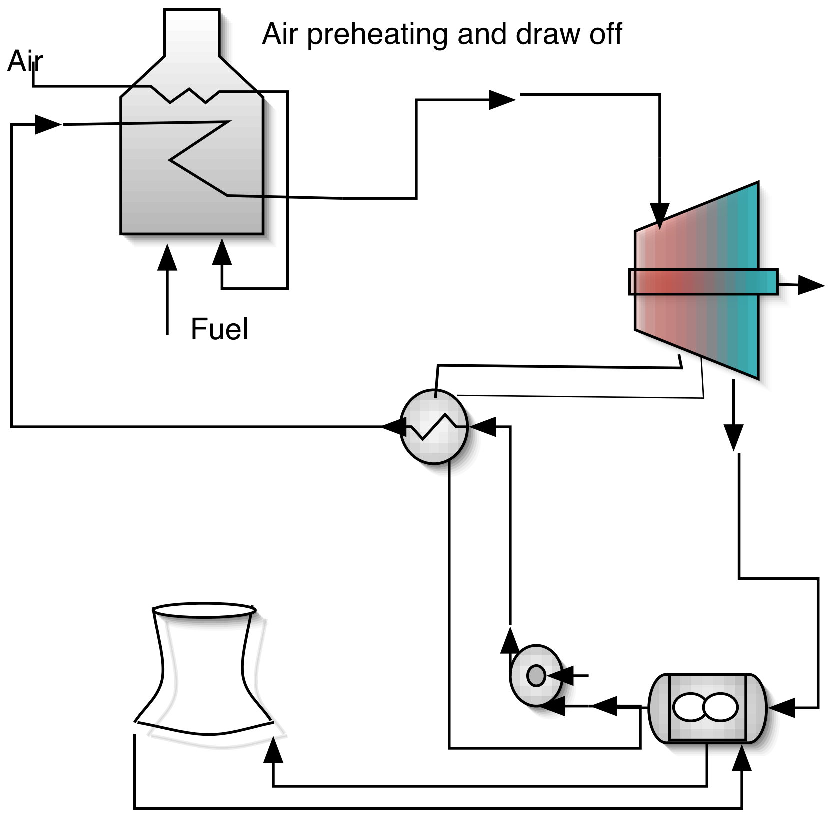
[1] F. Marechal and B. Kalitventzeff. Targeting the minimum cost of energy requirements : a new graphical technique for evaluating the integration of utility systems. *Computers chem. Engng*, 20(Suppl.):S225–S230, 1996.

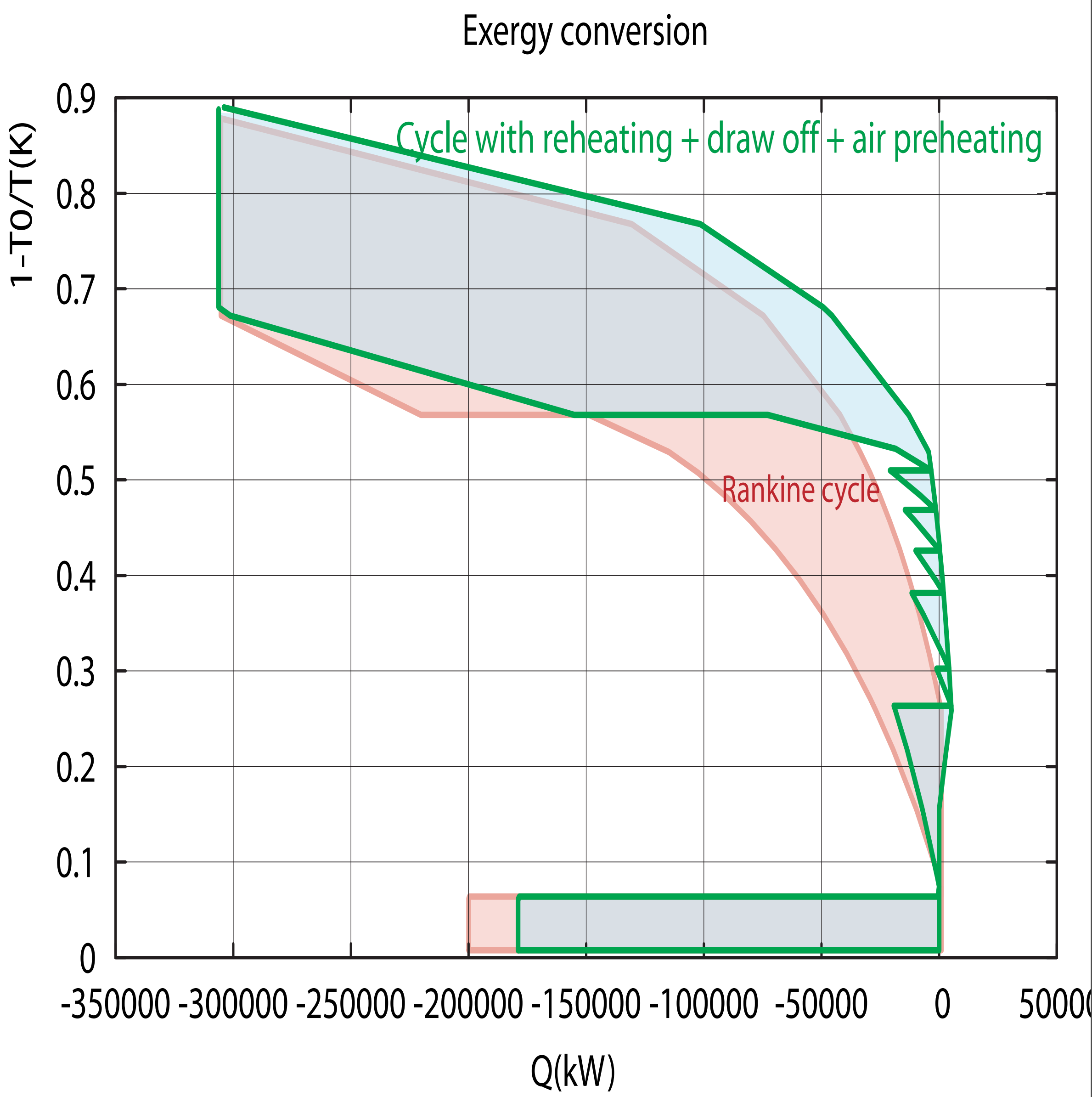
Visualising the integration

- Carnot composite curves

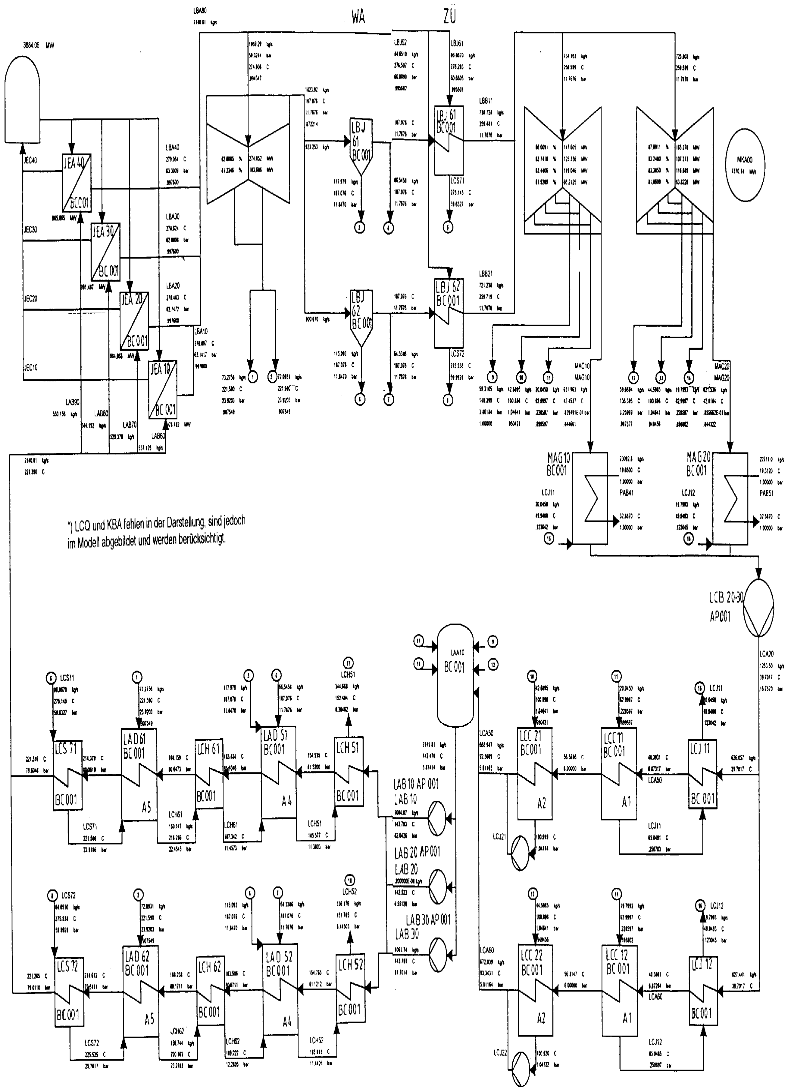


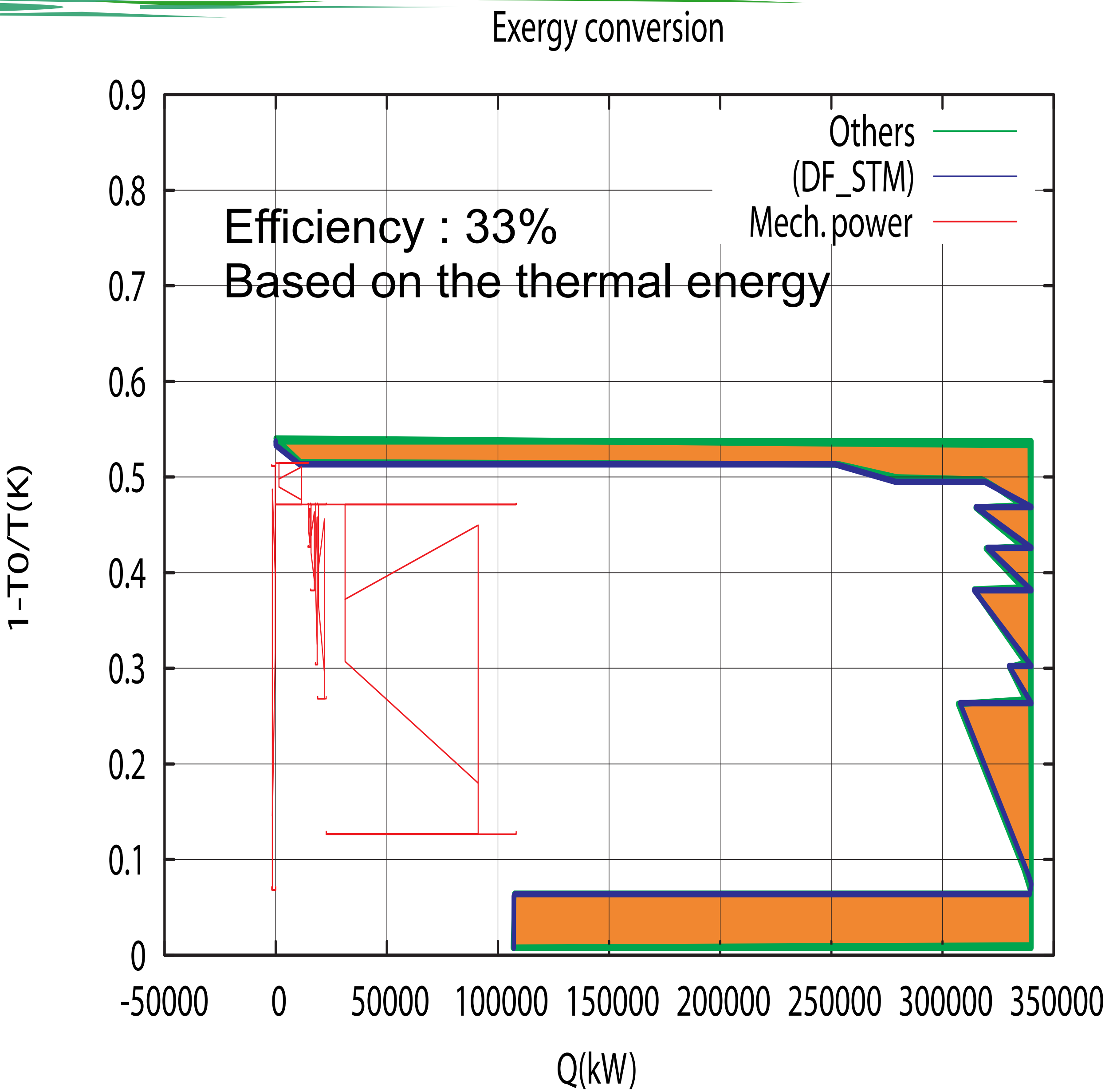
Conventional cycles





Nuclear power plant





Conclusions

- Energy conversion system integration
  - Satisfy the process requirement with minimum ressources
  - Valorise the available process exergy
- Combined exergy - Process integration
  - Analyse the requirements
    - Unit operation analysis : the heat transfer interface
      - heat at the coldest Temp
      - cool at the highest Temp
    - Opportunities for energy conversion integration (Carnot composite)
  - Generate optimal integrated systems
    - MILP method with Exergy objective
  - Evaluate & compare solutions
    - Graphical representations : Carnot composite & area
    - Integrated composite curves