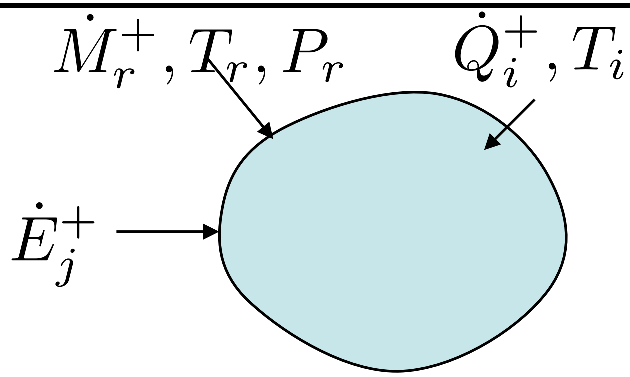
The use of exergy

Open system
without accumulation



Nothing is lost - nothing is created, everything is transformed

First principle: energy balance

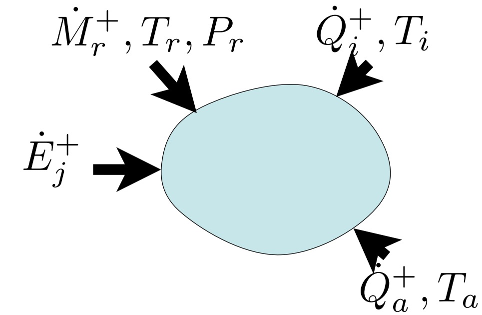
$$\sum_j \dot{E}_j^+ + \sum_i \dot{Q}_i^+ + \sum_r \dot{M}_r^+ h_r(T_r, P_r, X_r) = 0$$

The entropy of an isolated system tends to increase

Second principle: entropy balance

$$dS = \sum_i \frac{\dot{Q}_i^+}{T_i} + \sum_r \dot{M}_r^+ s_r(T_r, P_r, X_r) \geq 0$$

Notion of exergy : Generalisation



1st principle: energy balance

$$\sum_j \dot{E}_j^+ + \sum_i \dot{Q}_i^+ + \sum_r \dot{M}_r^+ h_r(T_r, P_r, X_r) + \dot{Q}_a^+ = 0 \quad \textbf{(1)}$$

2nd principle: entropy balance

$$dS = \sum_i \frac{\dot{Q}_i^+}{T_i} + \sum_r \dot{M}_r^+ s_r(T_r, P_r, X_r) + \frac{\dot{Q}_a^+}{T_a} \geq 0$$

$$\Rightarrow T_a dS = \sum_i \frac{T_a \dot{Q}_i^+}{T_i} + \sum_r \dot{M}_r^+ T_a s_r(T_r, P_r, X_r) + \dot{Q}_a^+ \geq 0 \quad \textbf{(2)}$$

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(1) - (2)

$$\sum_j \dot{E}_j^+ + \sum_i \dot{Q}_i^+ (1 - \frac{T_a}{T_i}) + \sum_r \dot{M}_r^+ (h_r - T_a s_r) \leq 0$$

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then

$$\sum_j \dot{E}_j^- \leq \sum_i \dot{Q}_i^+ (1 - \frac{T_a}{T_i}) + \sum_r \dot{M}_r^+ (h_r - T_a s_r)$$

therefore

$$E_{max}^- = \sum_i \dot{Q}_i^+ (1 - \frac{T_a}{T_i}) + \sum_r \dot{M}_r^+ (h_r - T_a s_r)$$

→ Exergy = max work

$$\dot{L} = \dot{E}_{max}^- - \sum_j \dot{E}_j^- \geq 0$$

→ Exergy loss
=> wrt max work

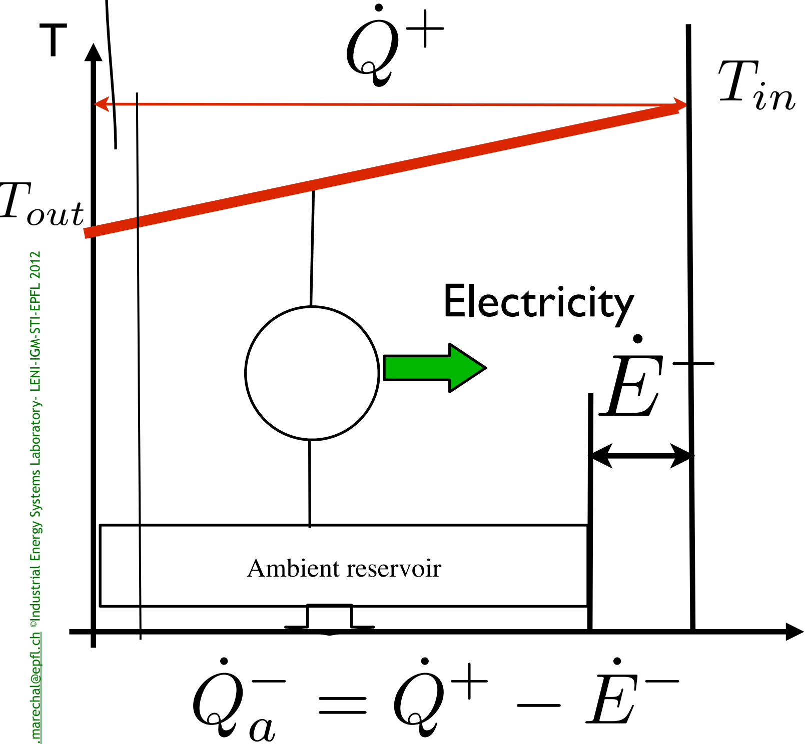
exergy is sometime name availability (of work), exergy loss is the loss of the capacity to produce work, the energy is not lost.

The exergy value of a heat exchange

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

$$\int_{T_{in}}^{T_{out}} d\dot{E}^-_{max} = \dot{M}_h c_{p_h} \int_{T_{in}}^{T_{out}} (1 - \frac{T_a}{T}) dT$$

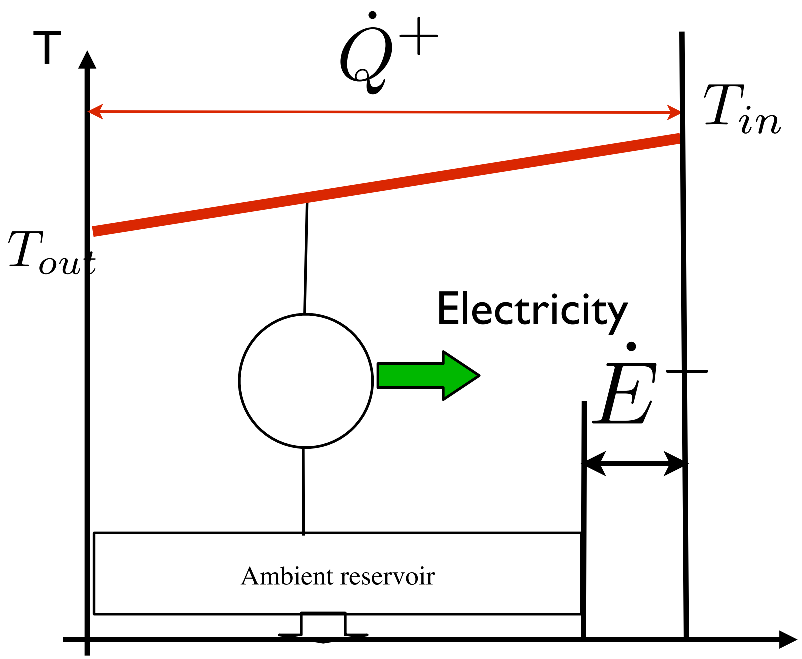
$$\dot{E}^-_{max} = \dot{M}_h c_{p_h} \{(T_{in} - T_{out}) - T_a(ln(T_{in}) - ln(T_{out}))\}$$



$$T_{lm} = \frac{T_{in} - T_{out}}{ln(T_{in}) - ln(T_{out})}$$

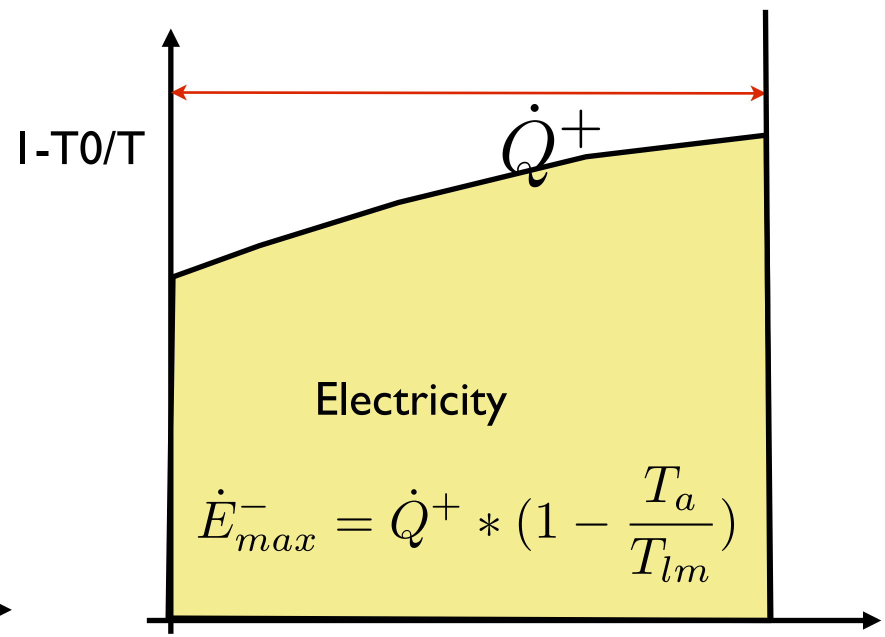
$$\dot{E}^-_{max} = \dot{Q}^+ * (1 - \frac{T_a}{T_{lm}})$$

The exergy value of a heat exchange



$$\dot{Q}_a^- = \dot{Q}^+ - \dot{E}^-$$

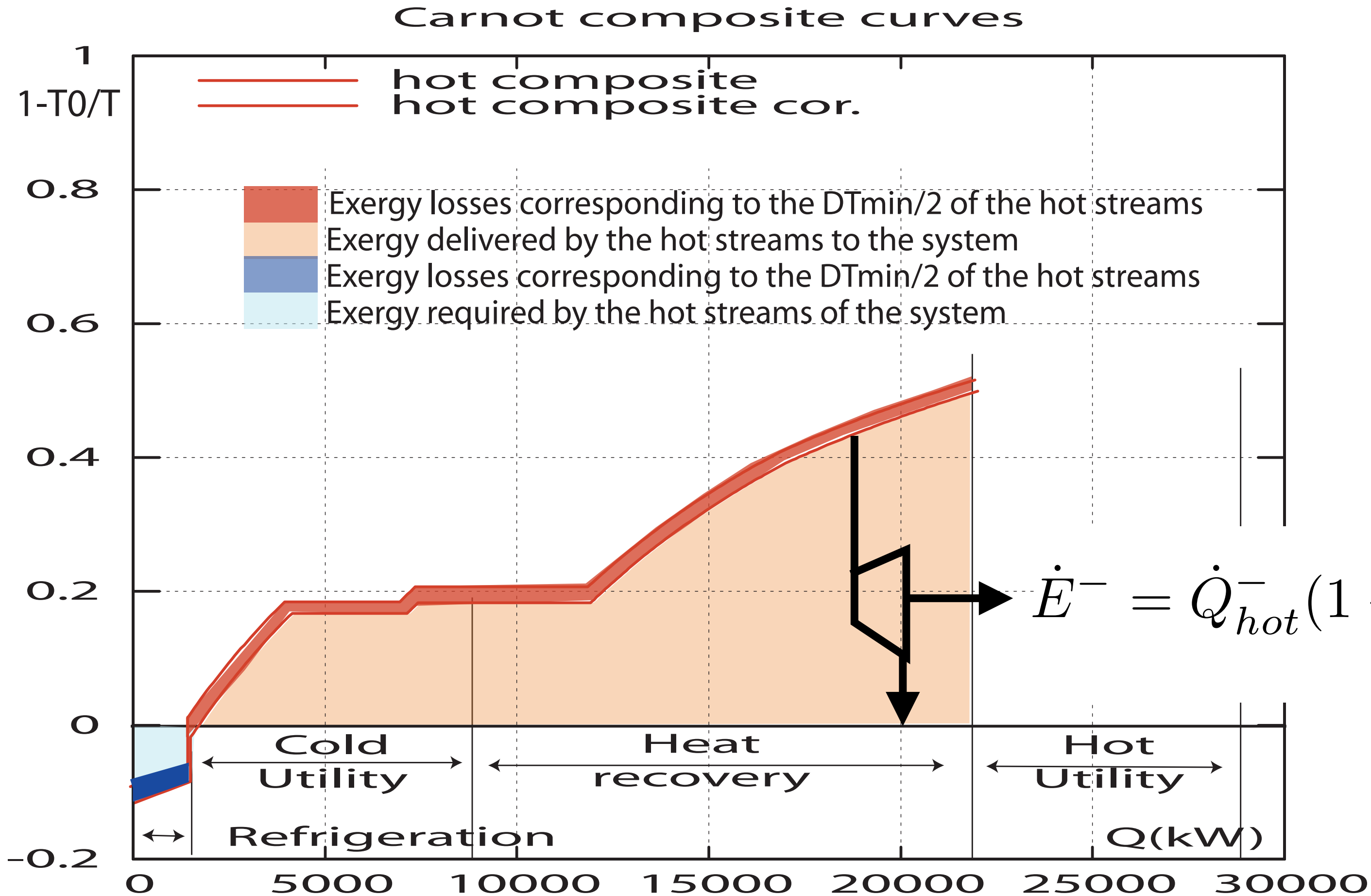
Carnot composite curve



$$T_{lm} = \frac{T_{in} - T_{out}}{ln(T_{in}) - ln(T_{out})}$$

Carnot composite curves of a process

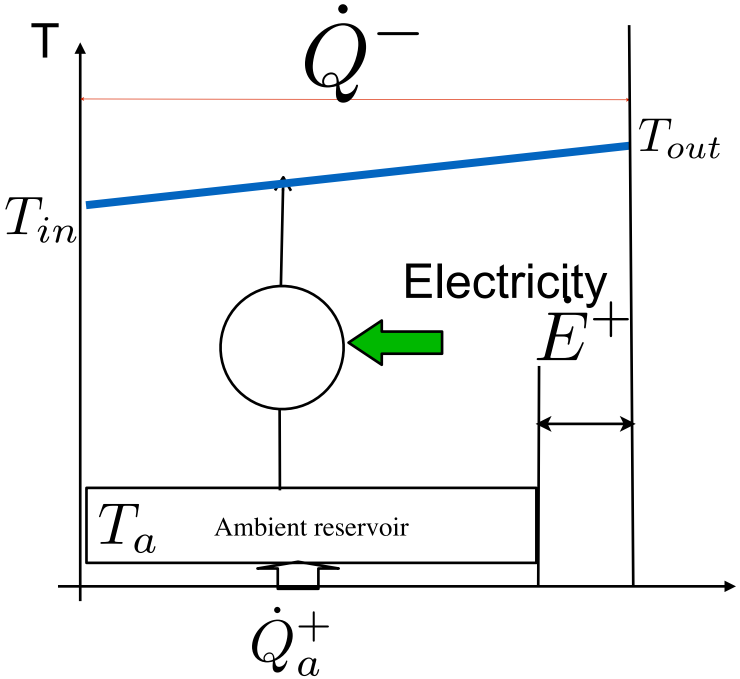
Hot composite curves



$$\dot{E}^{-} = \dot{Q}^{-}_{hot}(1 - \frac{T_a[K]}{T_{lm}[K]})$$

The exergy value of a cold stream

Cold stream : the process requires exergy (if above the ambiance)



Heat from the environment

$$\dot{E}^{+}_{min} = \dot{Q}^{-} * (1 - \frac{T_a}{T_{lm}})$$

$$T_{lm} = \frac{T_{in} - T_{out}}{ln(T_{in}) - ln(T_{out})}$$

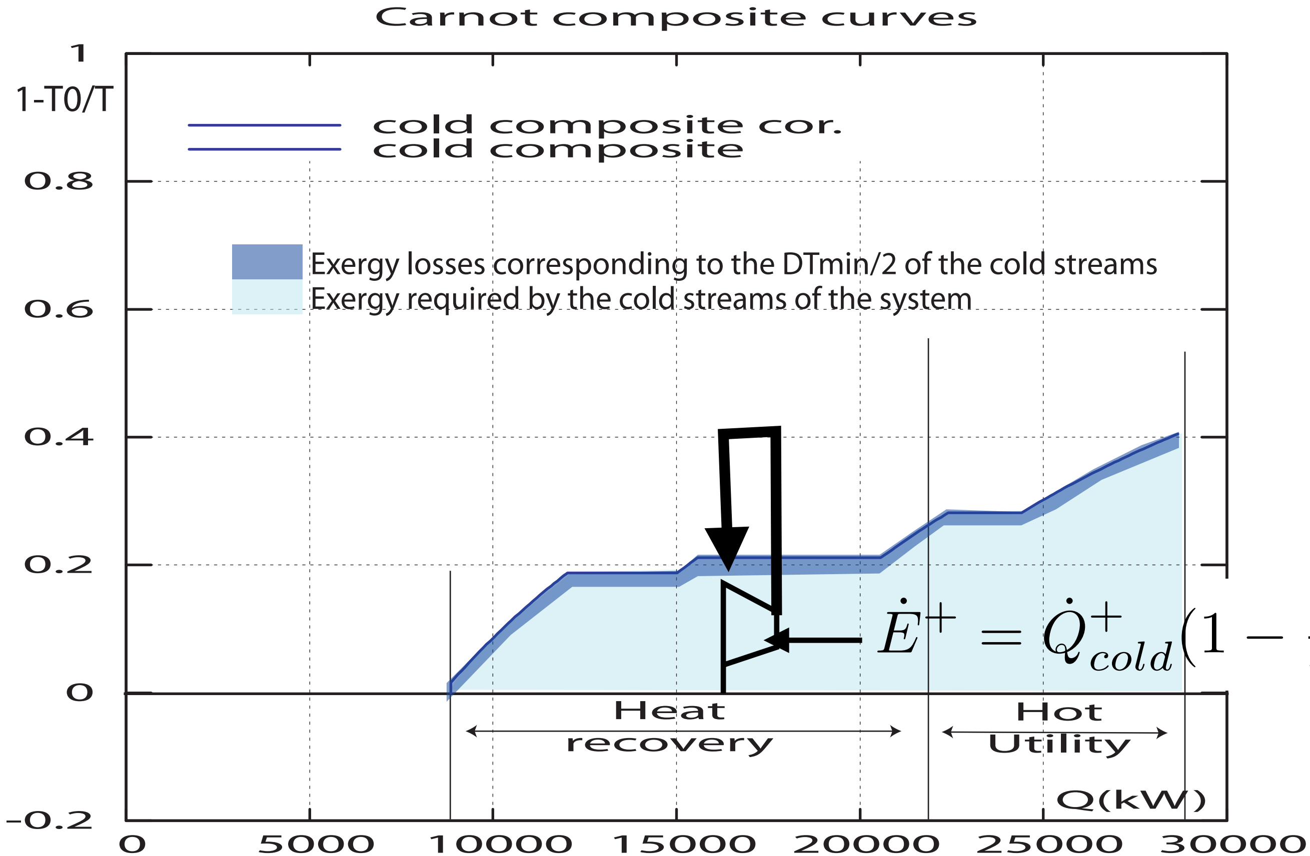
$$\dot{E}^{+} = \frac{\dot{E}^{+}_{min}}{\eta_{Carnot}}$$

$$\eta_{Carnot} \simeq 0.55$$

$$\dot{Q}^{-} = \dot{Q}_a^{+} + \dot{E}^{+}$$

Carnot composite curves of the process

Cold composite curves

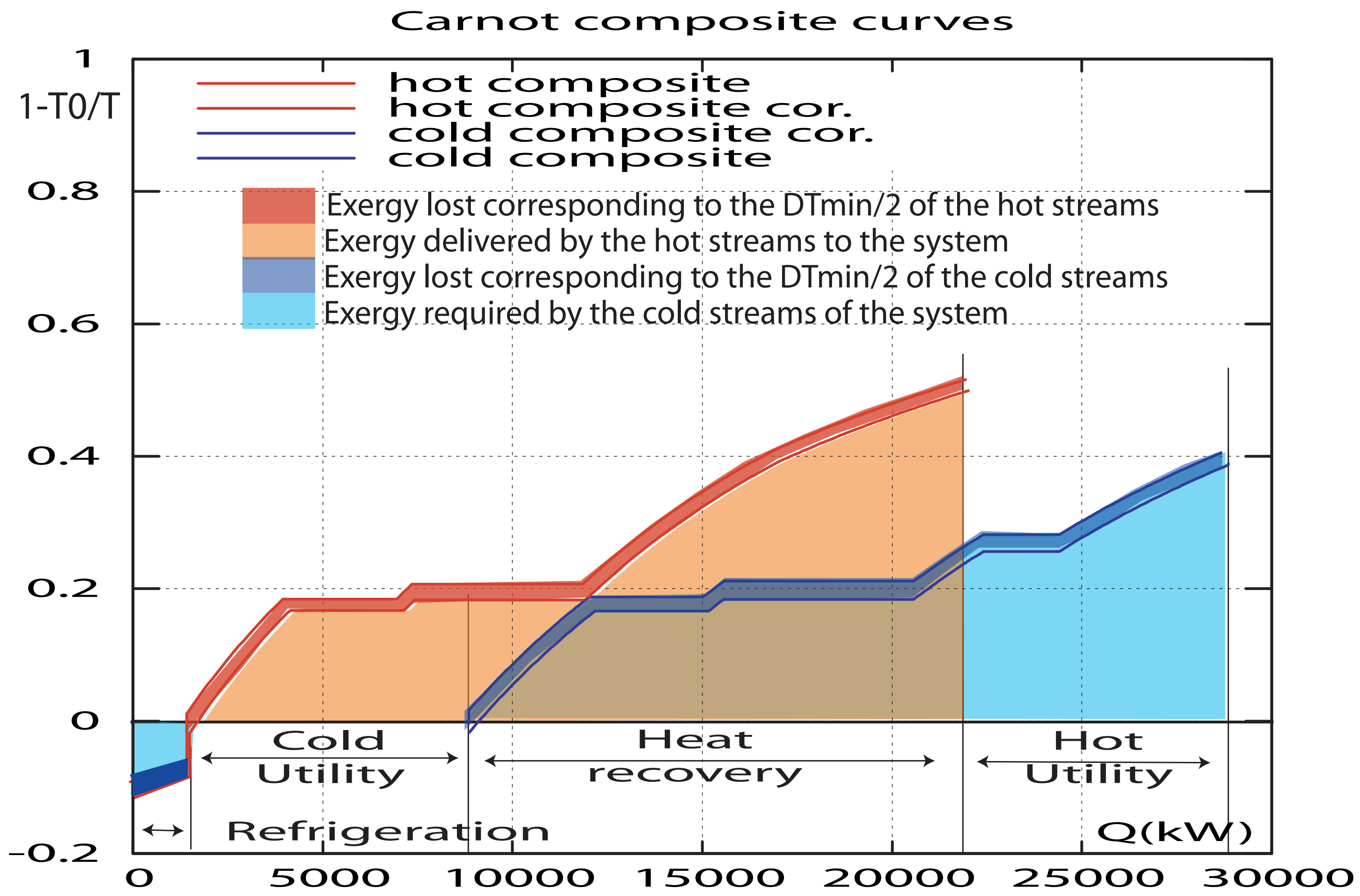


$$\dot{E}^{+} = \dot{Q}^{+}_{cold}(1 - \frac{T_a[K]}{T_{lm}[K]})$$

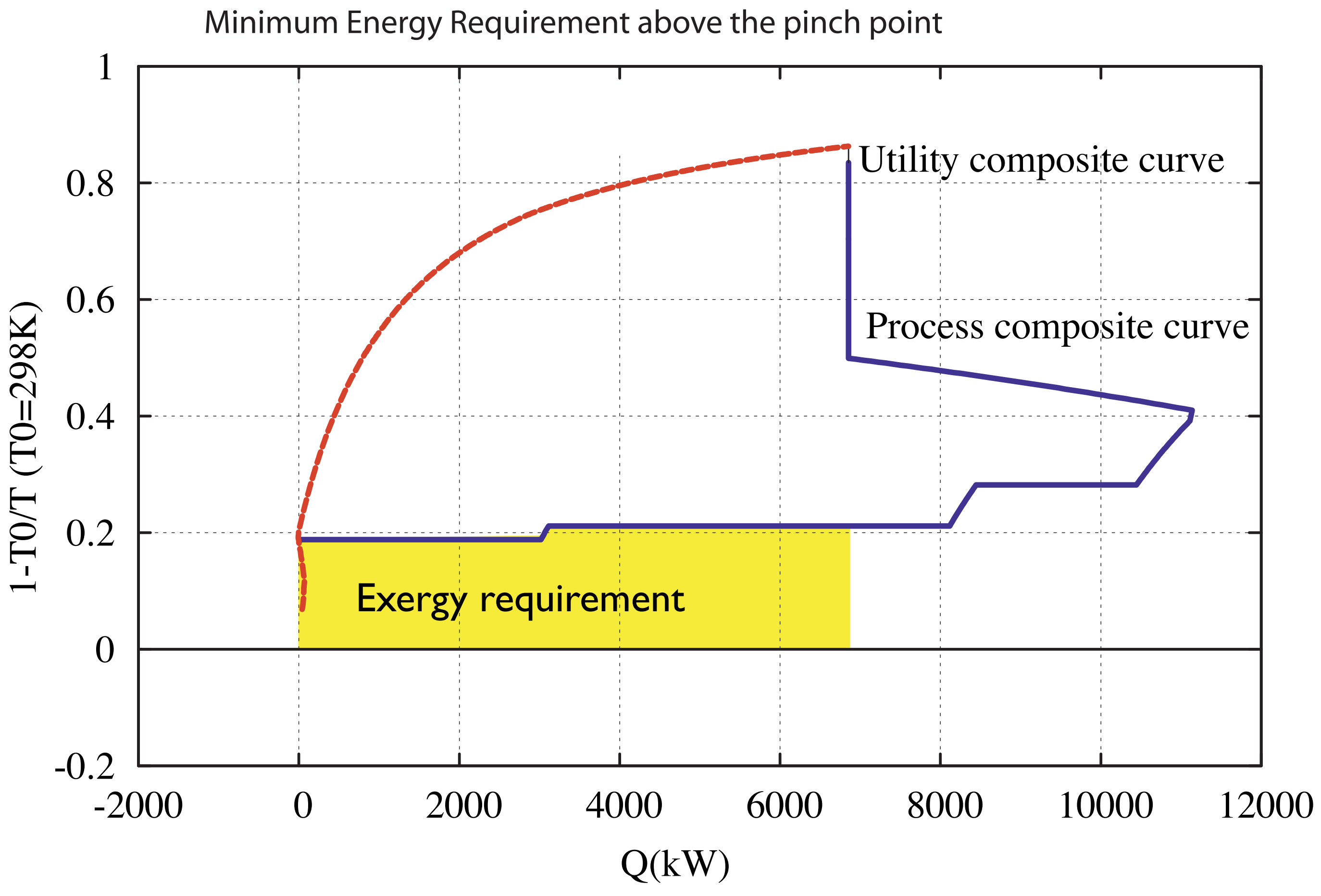
Table 3
Exergy of the hot and cold process composite curves

	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	

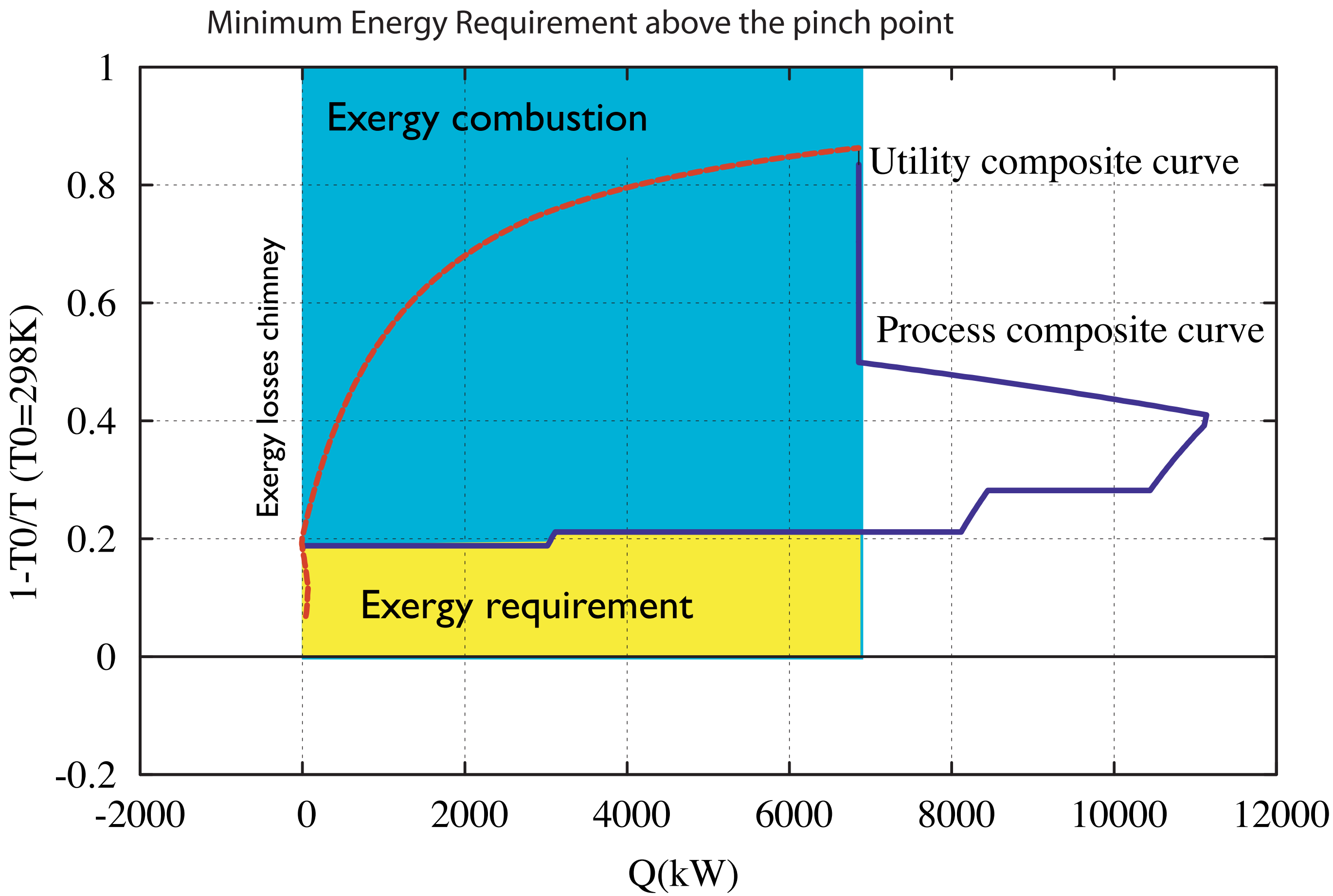
Carnot composite curves



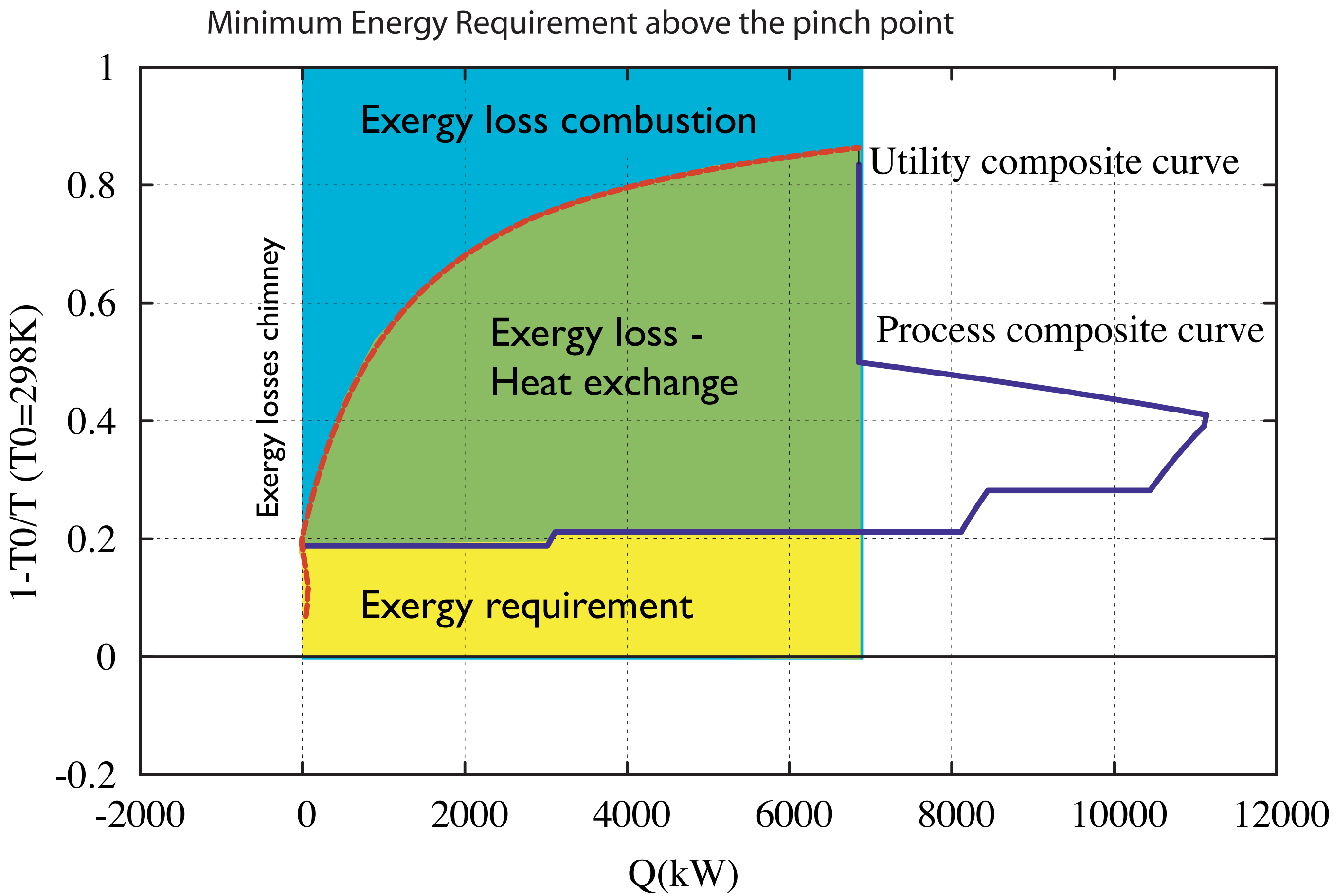
Exergy requirement above the pinch



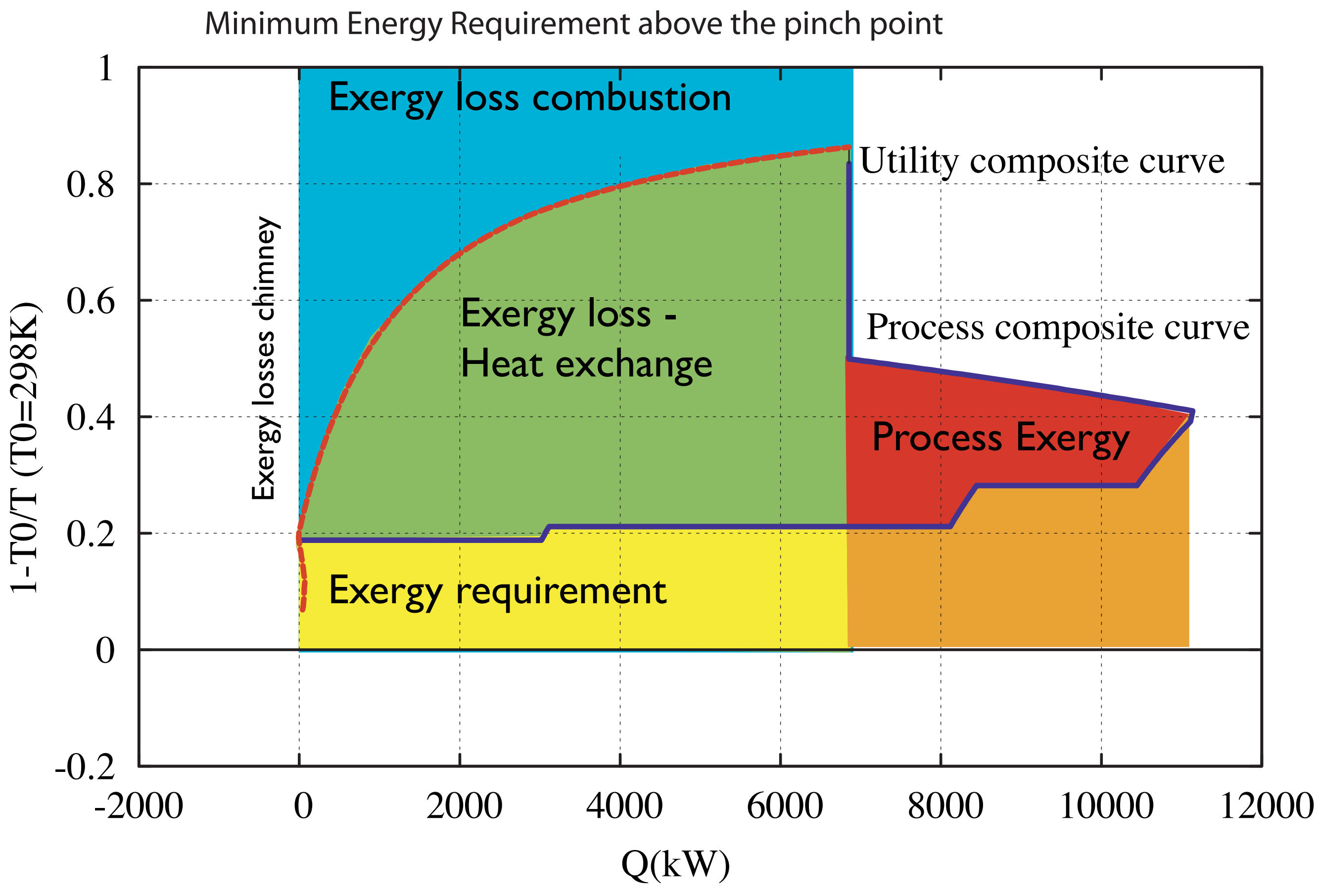
Exergy by combustion



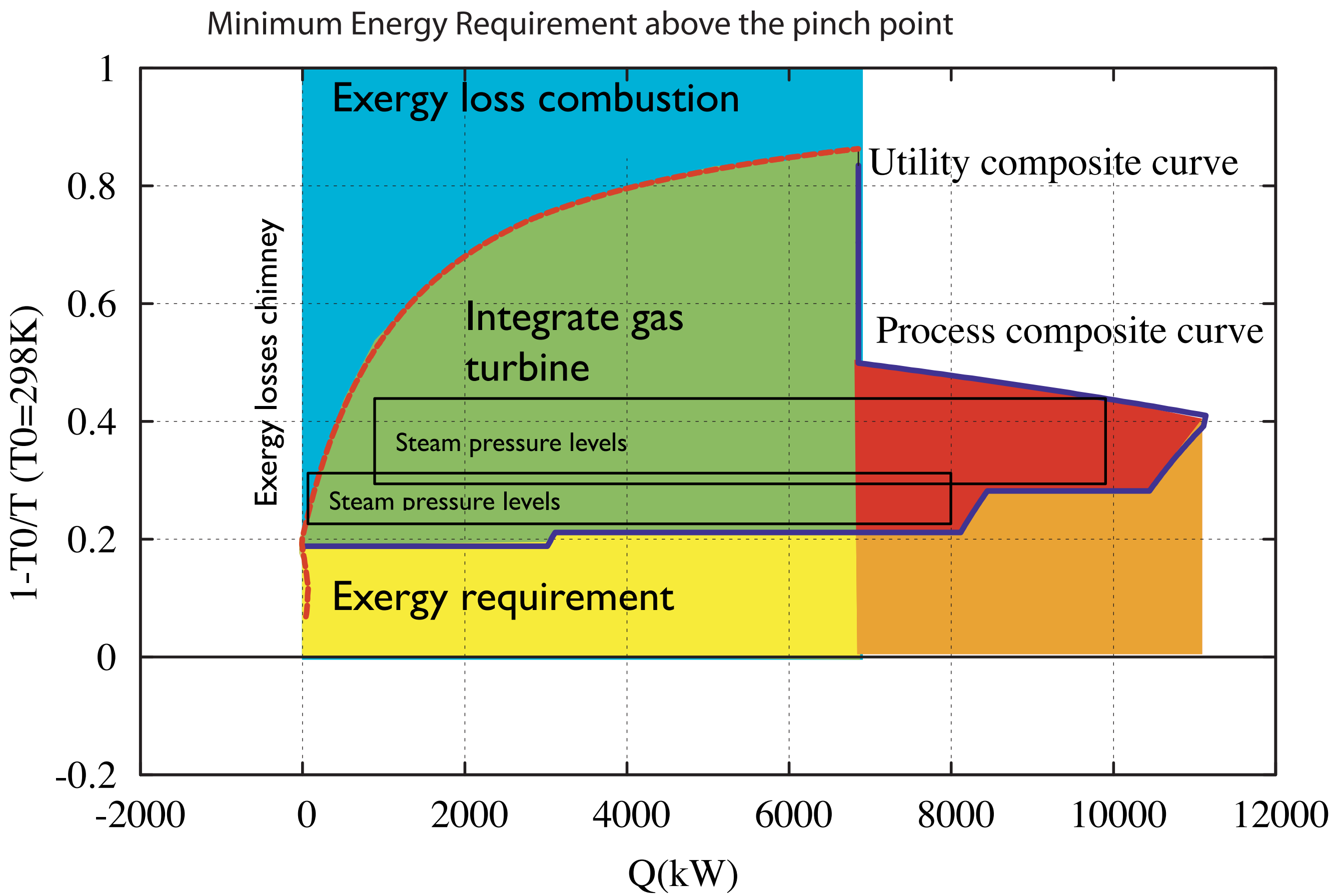
Exergy composite Heat exchange losses



Exergy composite -self-sufficient pockets



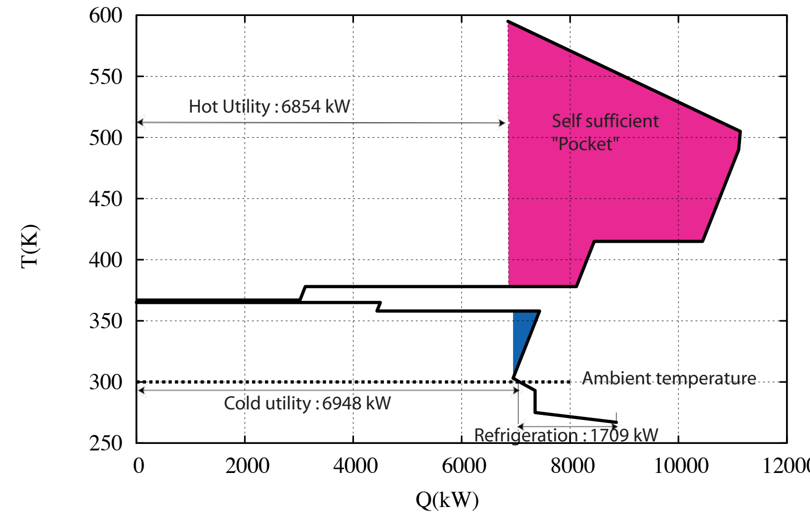
Exergy composite - steam cycle and gas turbine



Application : the engineer creativity

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

Consider exergy losses

- New objective function

$$\underset{\dot{R}_r, y_w, f_w}{Min} \sum_{w=1}^{n_w} \dot{L}_w = \sum_{w=1}^{n_w} (f_w * (\sum_{f=1}^{n_{fuel,w}} \dot{m}_{f,w} \Delta k_f^0 + \dot{e}_w^+ - \sum_{r=1}^{n_r} (\dot{e}q_{w,r}^-)_{\Delta T_{min}} - \dot{e}_w^-))$$

$$(\dot{e}q_{w,r}^-)_{\Delta T_{min}} = \sum_{s=1}^{ns_w} \dot{q}_{s,r}^-(1 - \frac{T_0}{T_{lmr}^*})$$

where T_{lmr}^* is the logarithmic mean temperature of interval r

$T_{lmr}^* = \frac{T_{r+1}^* - T_r^*}{ln(\frac{T_{r+1}^*}{T_r^*})}$ when $T_{r+1}^* \neq T_r^*$ and $T_{lmr}^* = T_r^*$ otherwize

  - Thermal exergy : $\sum_{f=1}^{n_{fuel,w}} \dot{m}_{f,w} \Delta k_f^0$
  - Chemical Exergy : $\dot{e}_w^+$ IN
  - Work : $\dot{e}_w^-$ Out

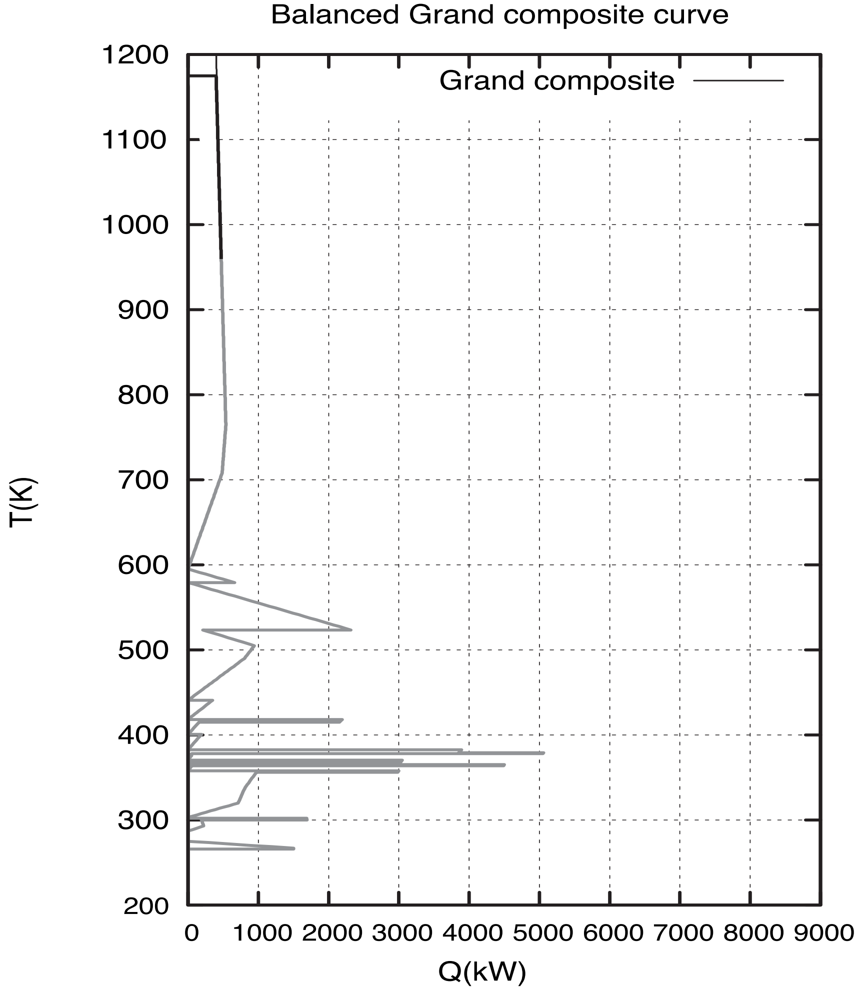
Results

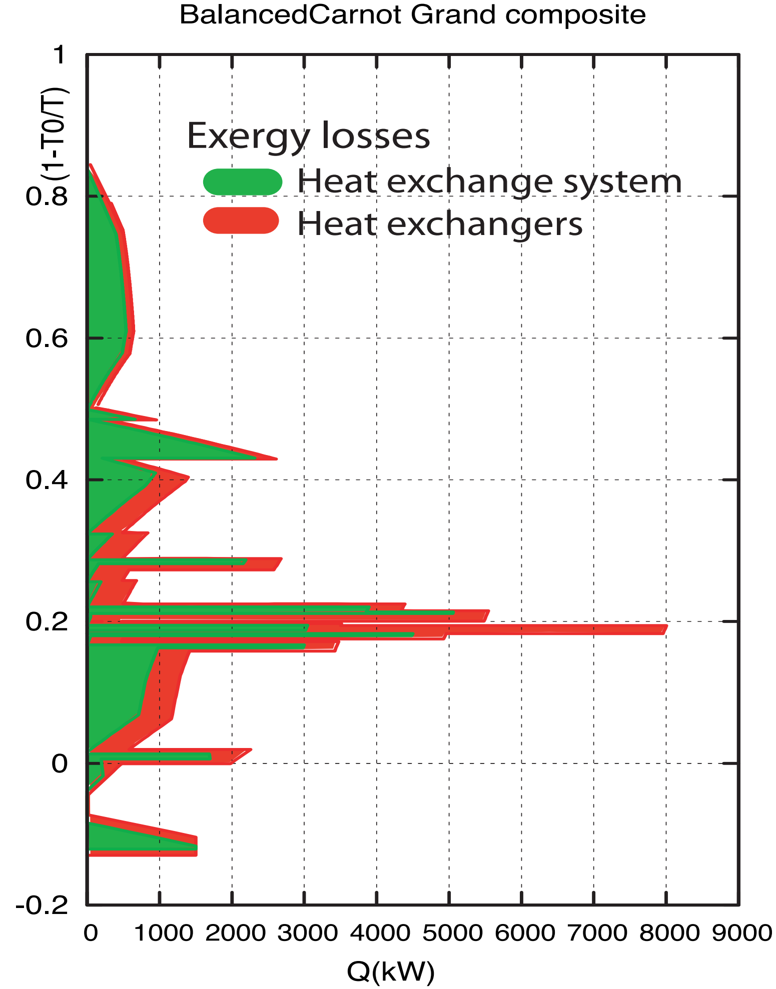
Opt	Fuel kW_{LHV}	GT kWe	CHP kWe	Cooling kW	HP kWe	
1	7071	-	-	8979	-	Comb. + frg
2	10086		2957	9006	-	Comb. + stm + frg
3	16961	5427	2262	9160	-	GT + stm + frg
4	-	-	-	2800	485	hpmp + frg
5	666	-	738	2713	496	hpmp + stm + frg

Share between heat pumps

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

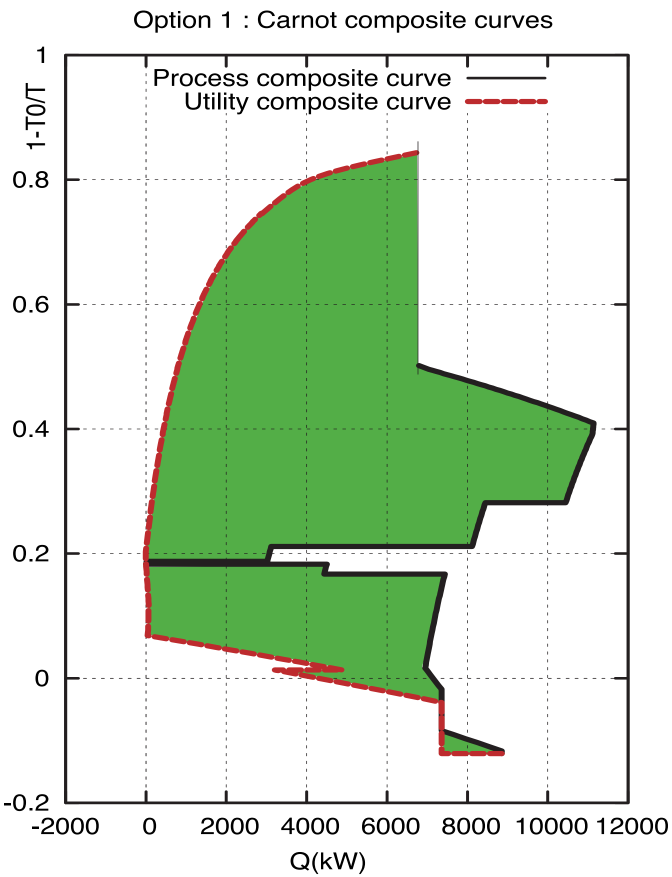
Balanced composite curves (option 5)

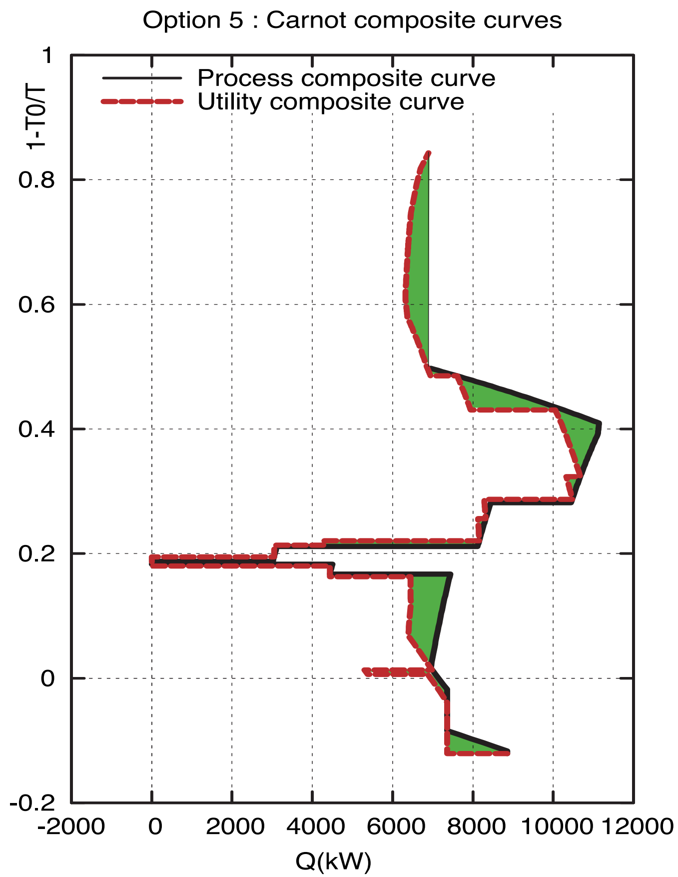




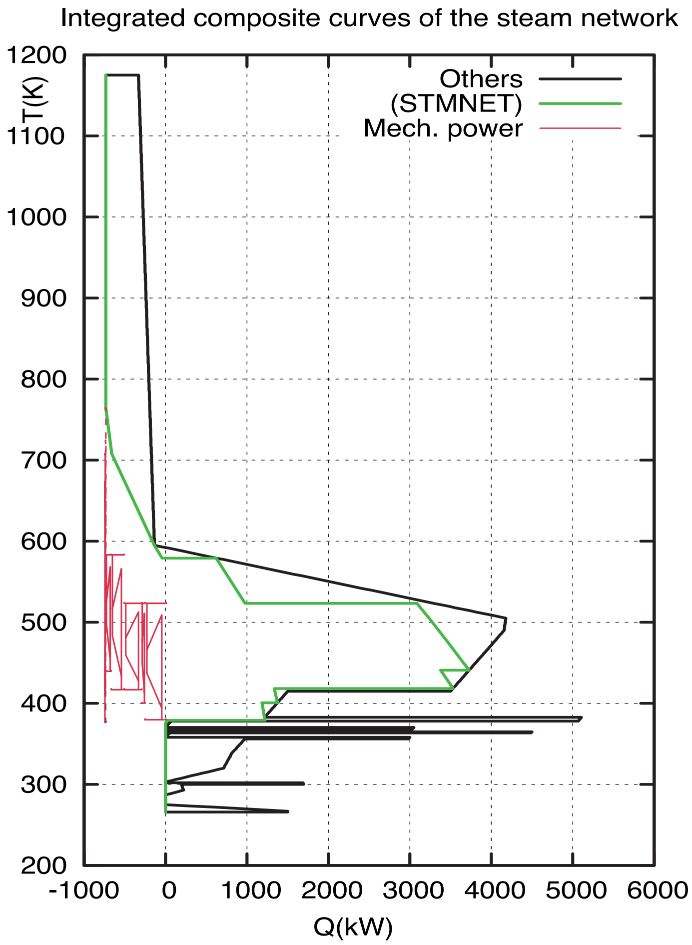
Visualising the results : Carnot efficiency

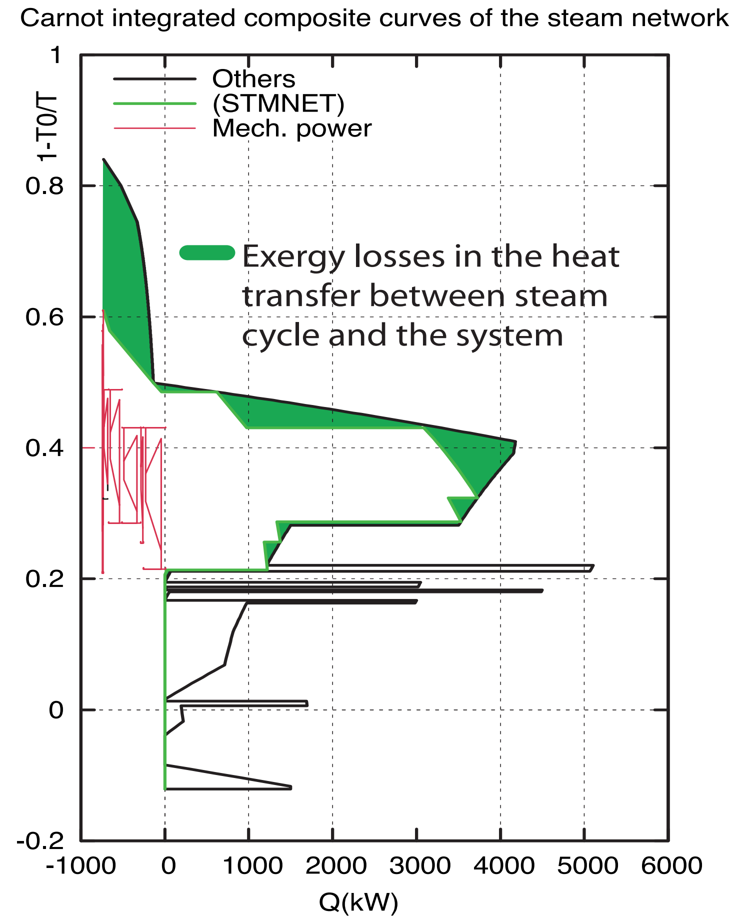
Tricks for creative engineers : reduce the green area !





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

$$\eta_{ex} = \frac{\dot{E}q_{cold_a} + \dot{E}q_{hot_r} + \dot{E}^{-}_{grid}}{\dot{E}^{+} + \dot{E}q_{cold_r} + \dot{E}q_{hot_a}}$$

with

$$\dot{E}^{+} = \sum_{fuel=1}^{n_{fuels}} \dot{M}^{+}_{fuel} \Delta k^{0}_{fuel} + \dot{E}^{+}_{grid}$$

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

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