# On the use of exergy for utility system integration

- Explain the use of the Carnot composite curve
- Explain the role of the exergy analysis for the energy conversion system integration.

# Is the selected set the right one ?

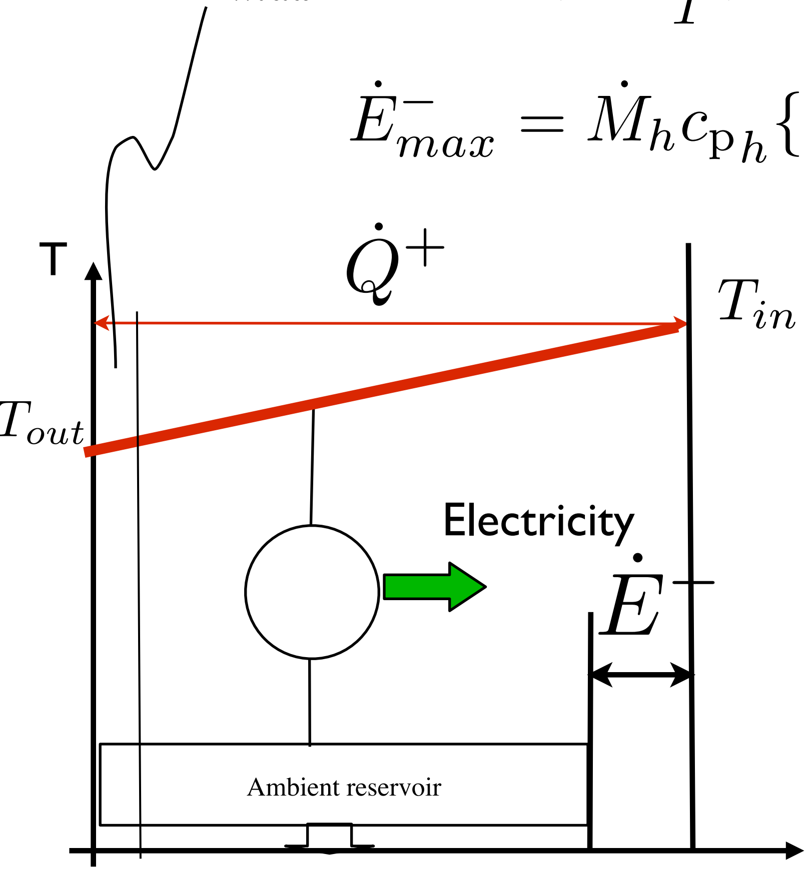
- Analyse the selected utilities
  - flows
  - costs
- Propose new operating conditions
- Propose new set of utility streams

# The exergy value of a heat exchange

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

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

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

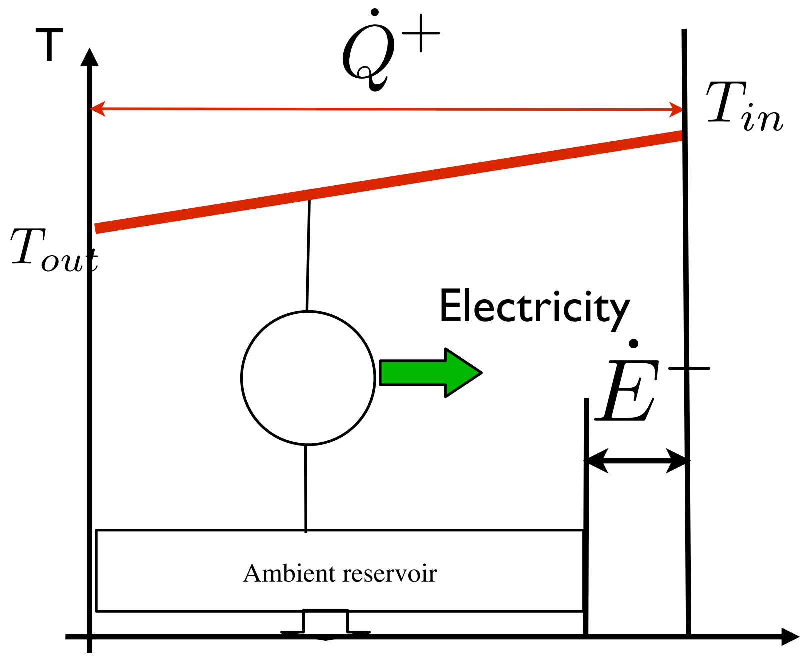



$$T_{lm} = \frac{T_{in} - T_{out}}{ln(T_{in}) - ln(T_{out})}$$

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

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

# The exergy value of a heat exchange

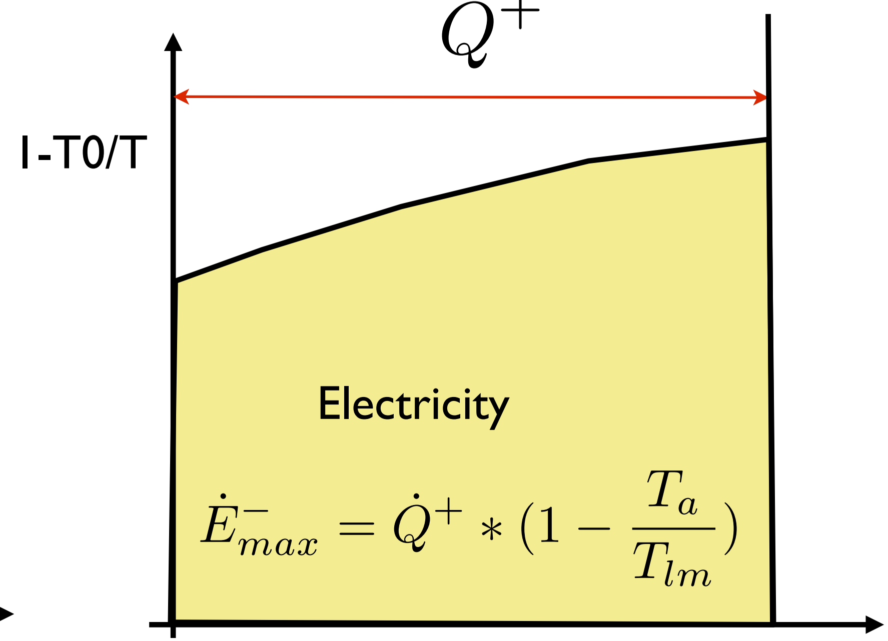



$$\dot{Q}_a^- = \dot{Q}^+ - \dot{E}^-$$

$$\dot{E}^- = \eta_{Carnot} \cdot \dot{E}^-_{max}$$

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

## Carnot composite curve

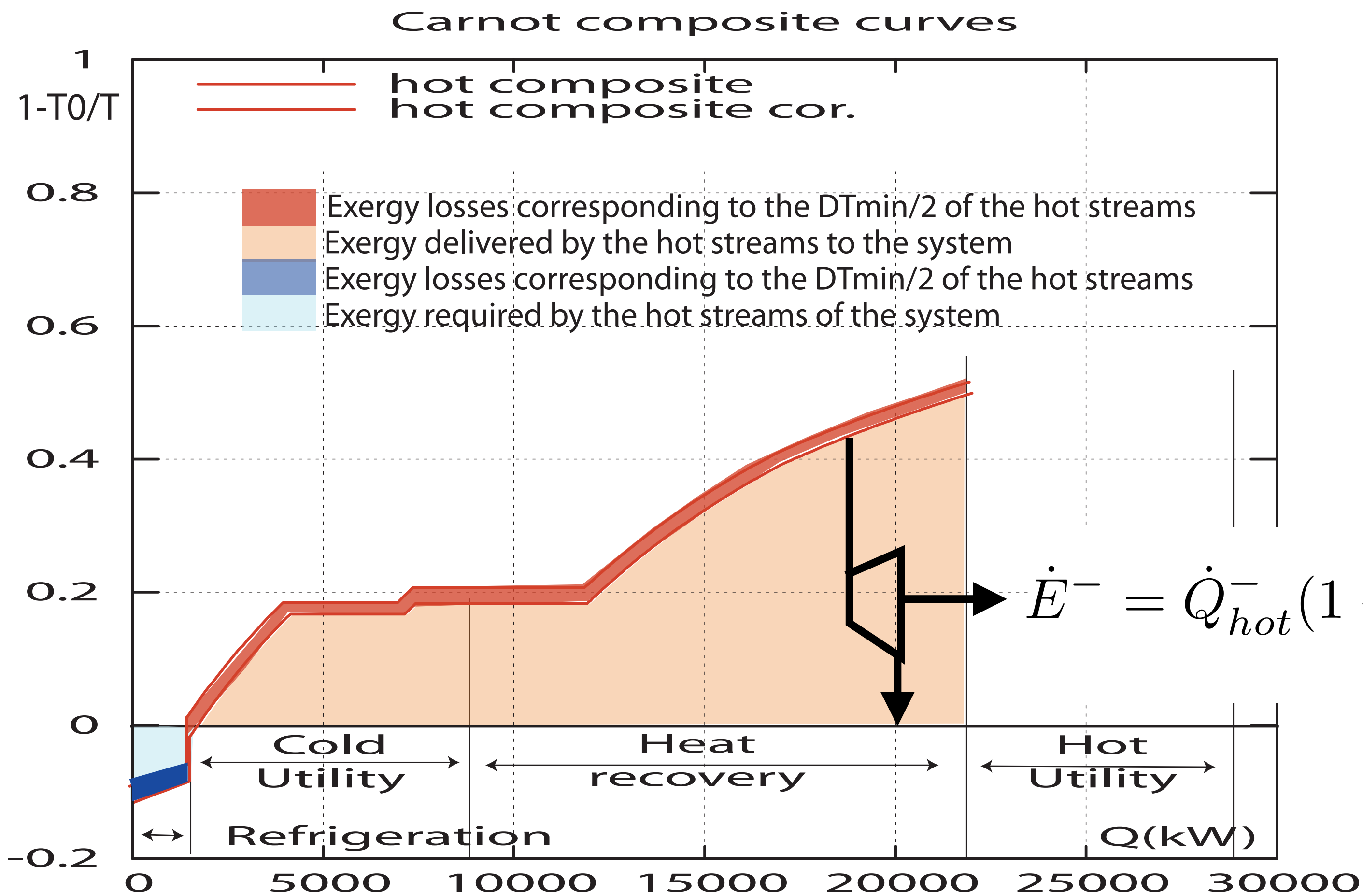



$$T_{lm} = \frac{T_{in} - T_{out}}{ln(T_{in}) - ln(T_{out})}$$

When cp = constant

# Carnot composite curves of a process

## Hot composite curves




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

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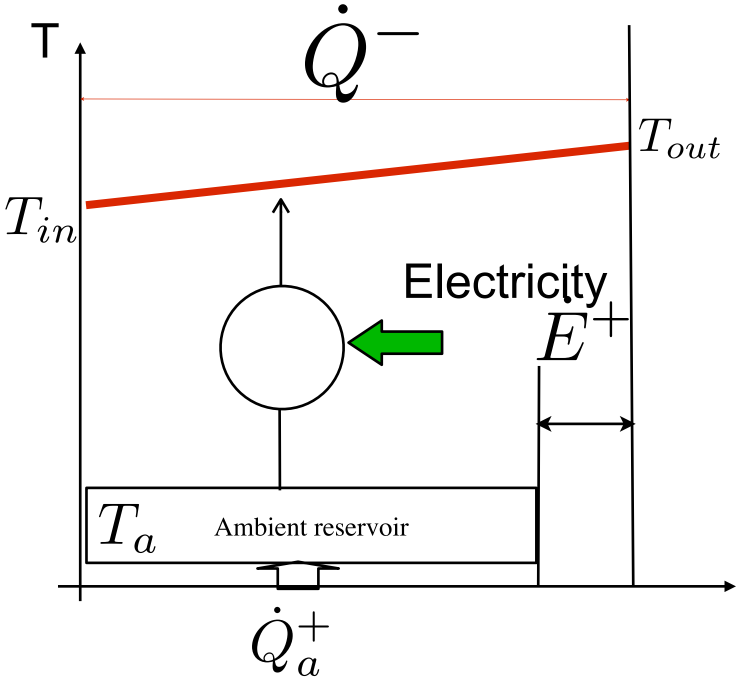
# The exergy value of a heat demand (reversible)




Heat from the environment

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

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

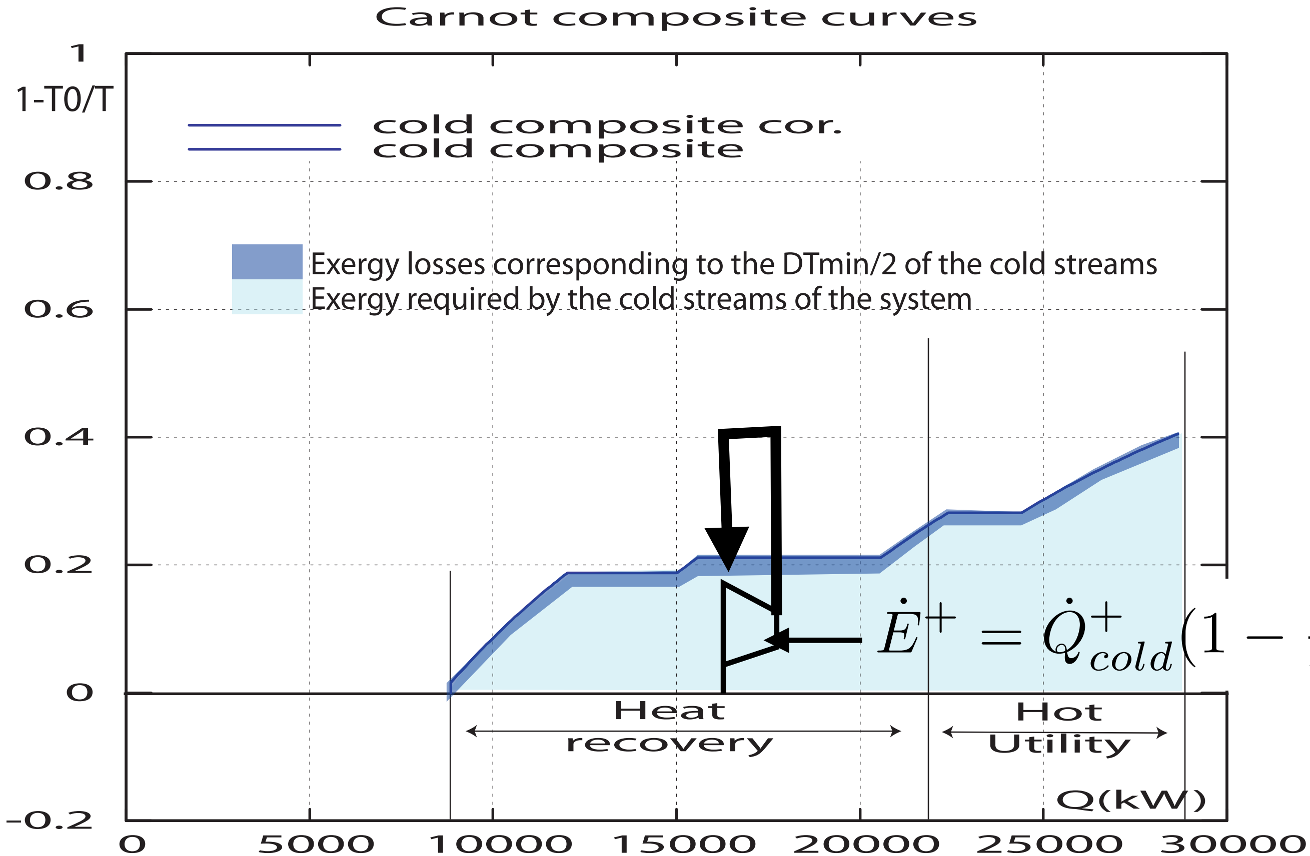
$$\dot{E}^+ = \frac{\dot{E}^+_{min}}{\eta_{Carnot}}$$

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

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

# Carnot composite curves of the process

## Cold composite curves




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

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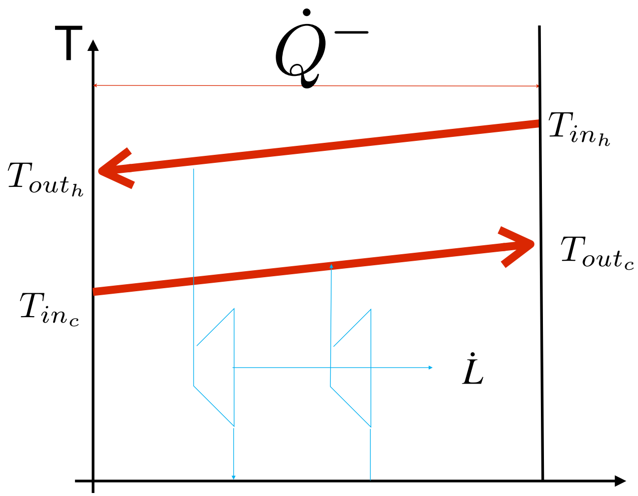
# Heat recovery and exergy

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

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

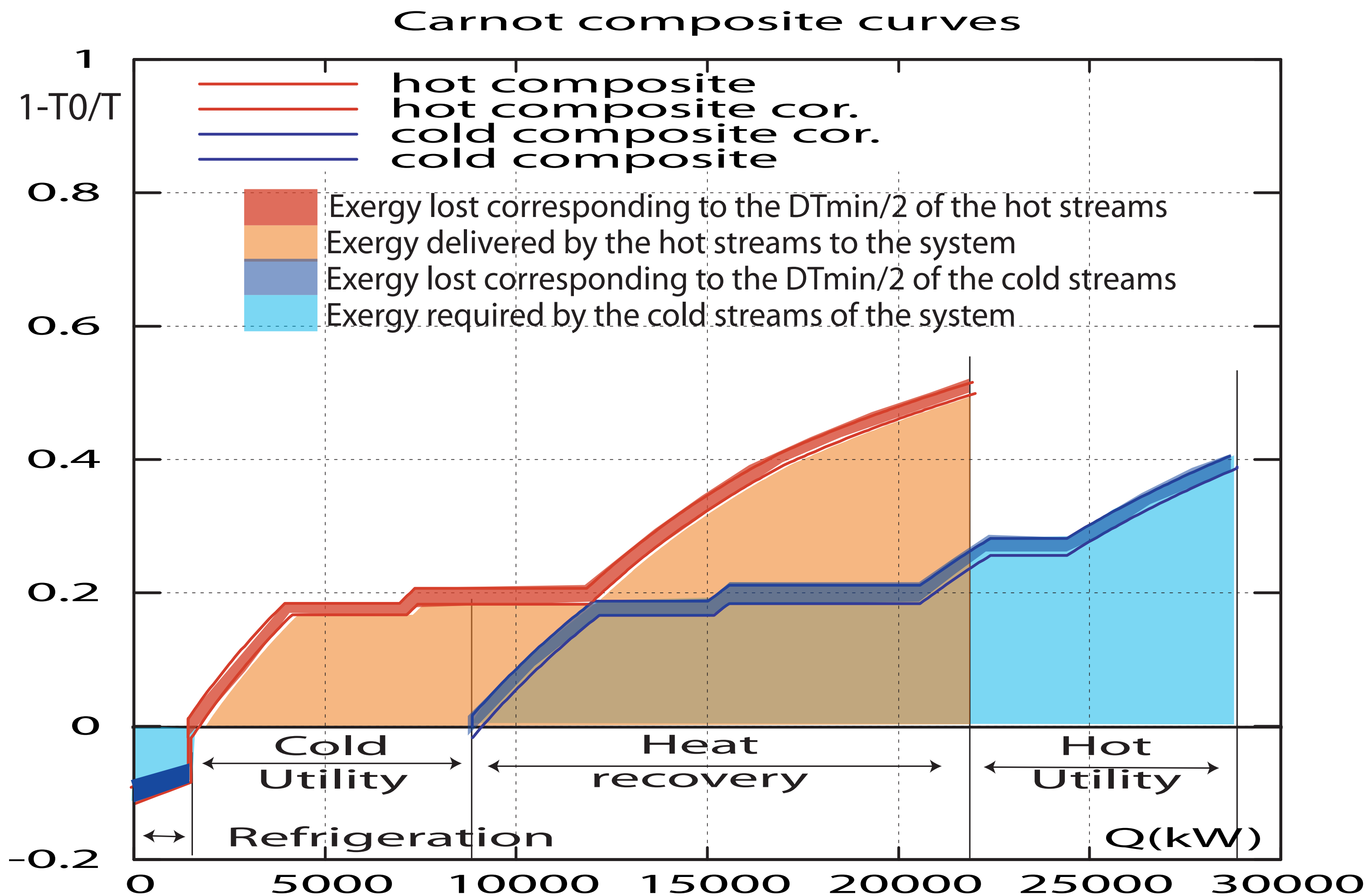
-




$$\dot{L} = \dot{Q}^{-} * (1 - \frac{T_a}{T_{h_{lm}}}) - \dot{Q}^{-} * (1 - \frac{T_a}{T_{c_{lm}}})$$

The exergy lost in the heat exchanger is the amount of work that can not be produced any more (lost) when the heat exchange is realised. It corresponds to the power that could be produced if one installs an infinite number of perfect Rankine cycles between the hot and the cold streams of the heat exchanger

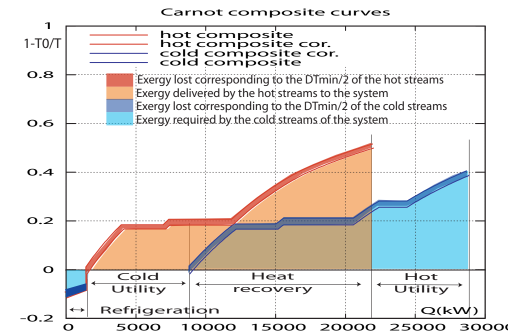
# Carnot composite curves



# Exergy value of the heat transfer in the process

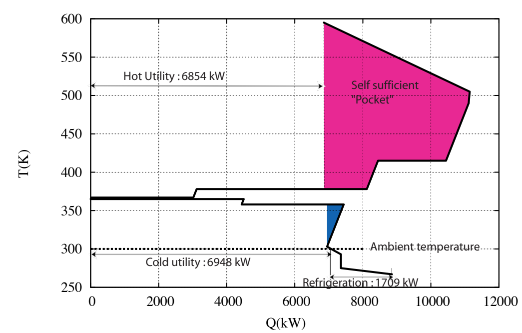
Exergy of the hot and cold process composite curves

| | 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 | - $\dot{E}q_{cold_r}$ |
| $\Delta T_{min}$ losses [kW] | - | | 381.2 | |
| Balance [kW] | 1803.0 | +790.0 | +409.0 | |




## Heat recovery

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

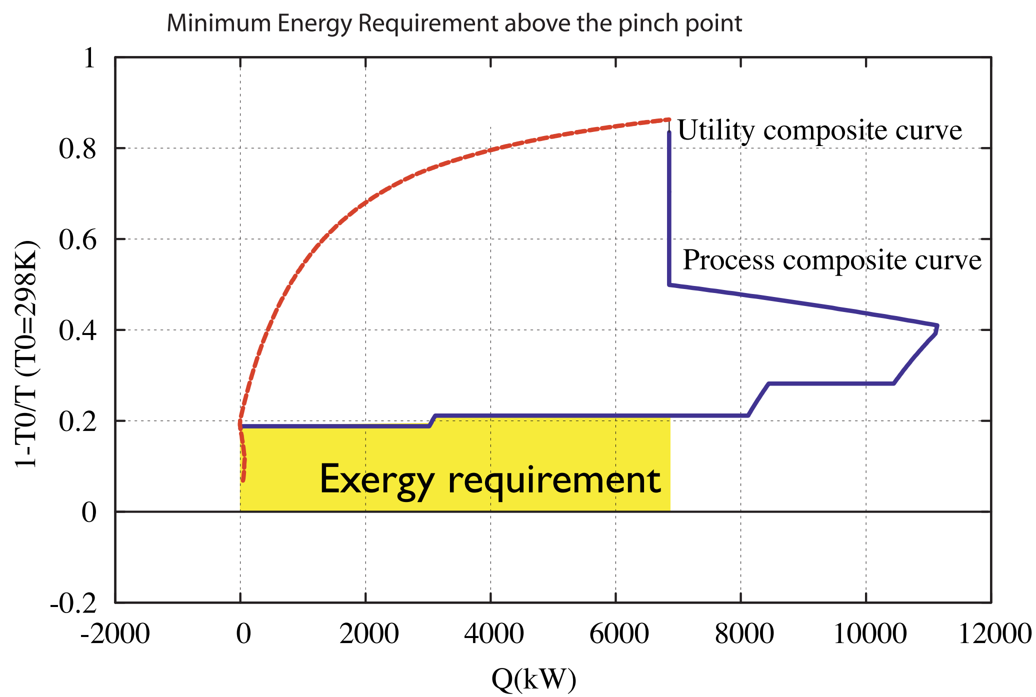




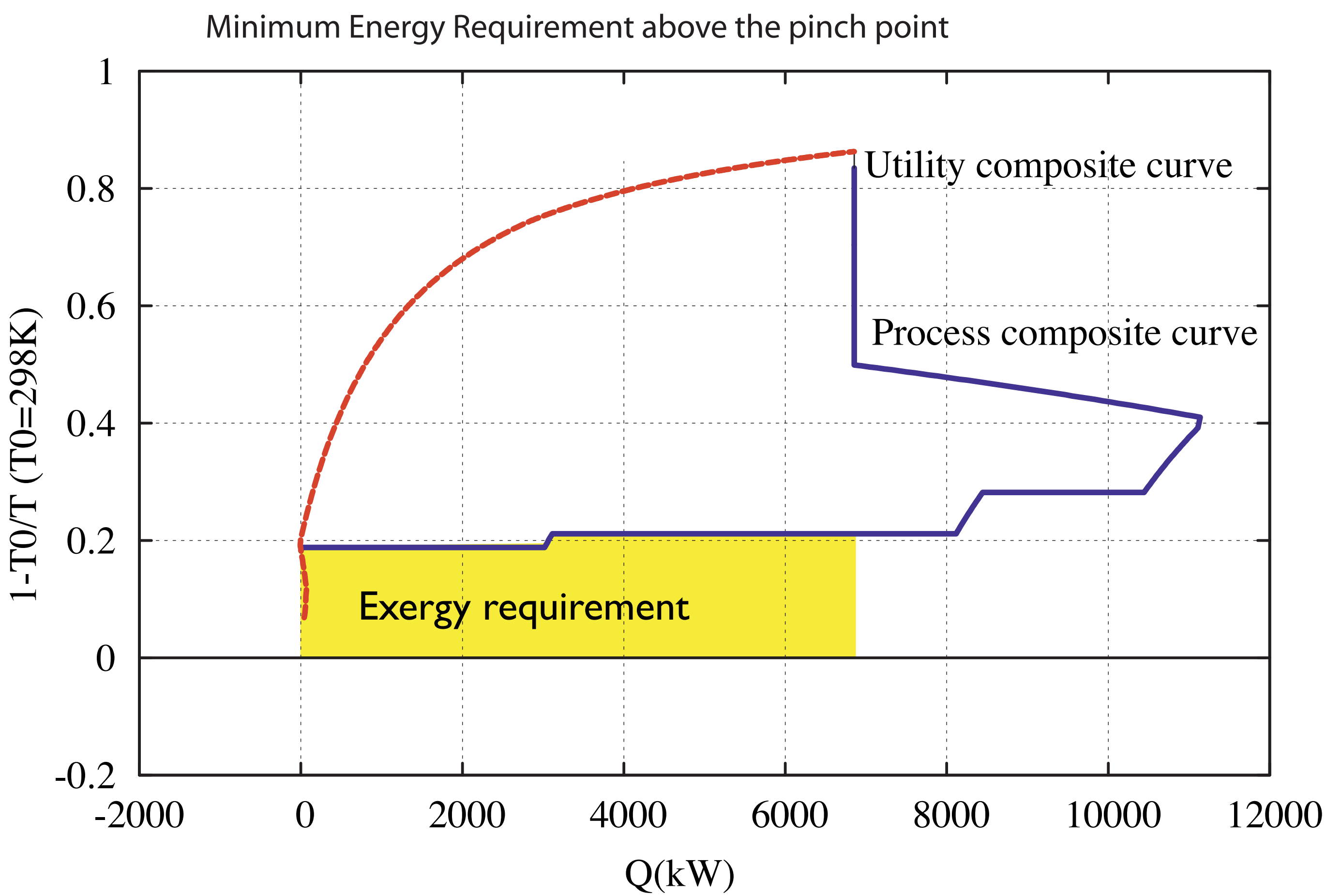
Marechal, François, and Daniel Favrat. "Combined exergy and pinch analysis for the optimal integration of energy conversion technologies." *18th International conference on efficiency, cost, optimization, simulation and environmental impact of energy systems.* 2005.

# Exergy requirement above the pinch

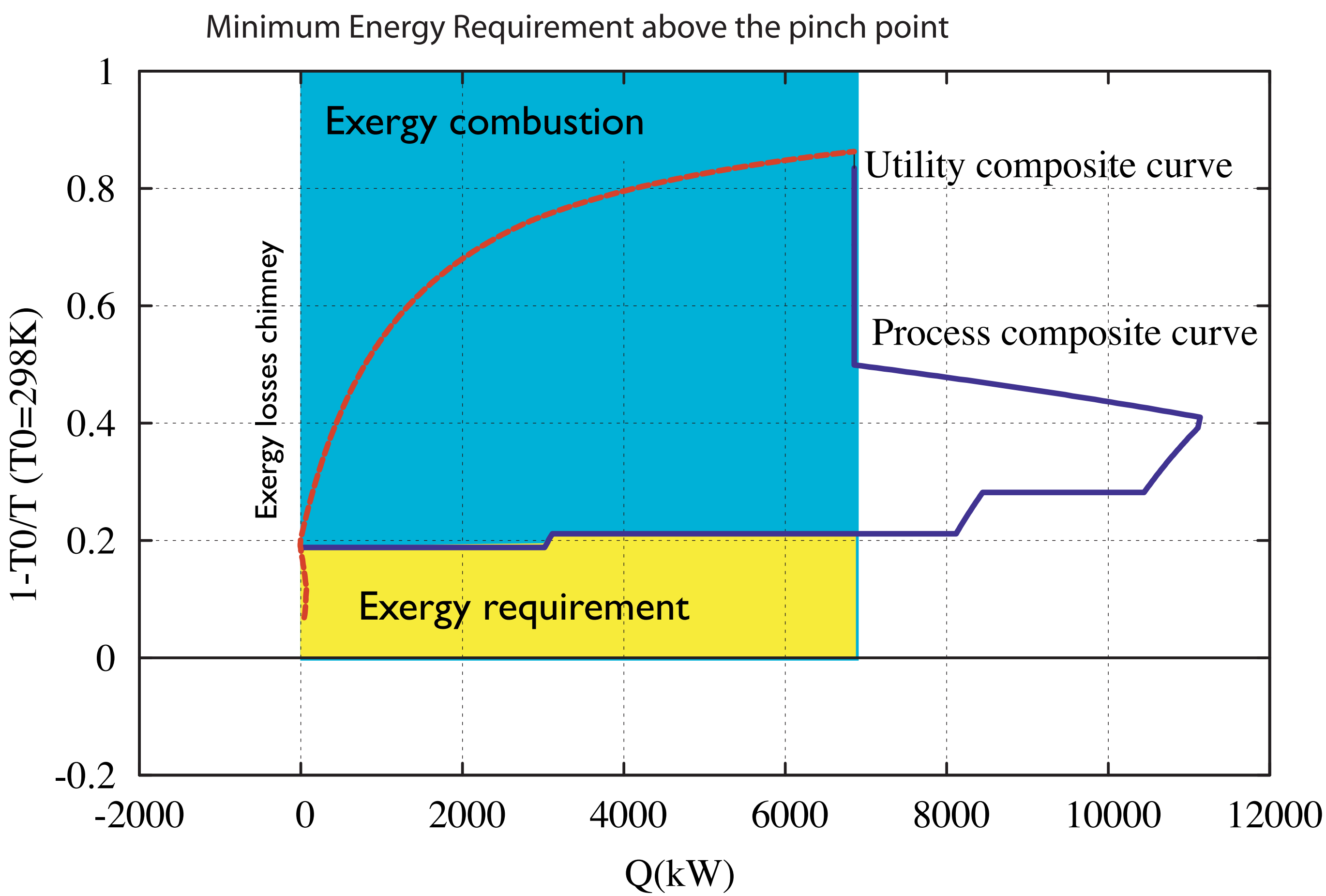
| | Energy | Exergy |
|---|---|---|
| Heating (kW) | +6854 | +567 |
| Cooling (kW) | -6948 | - 1269 |
| Refrigeration (kW) | +1709 | + 157 |



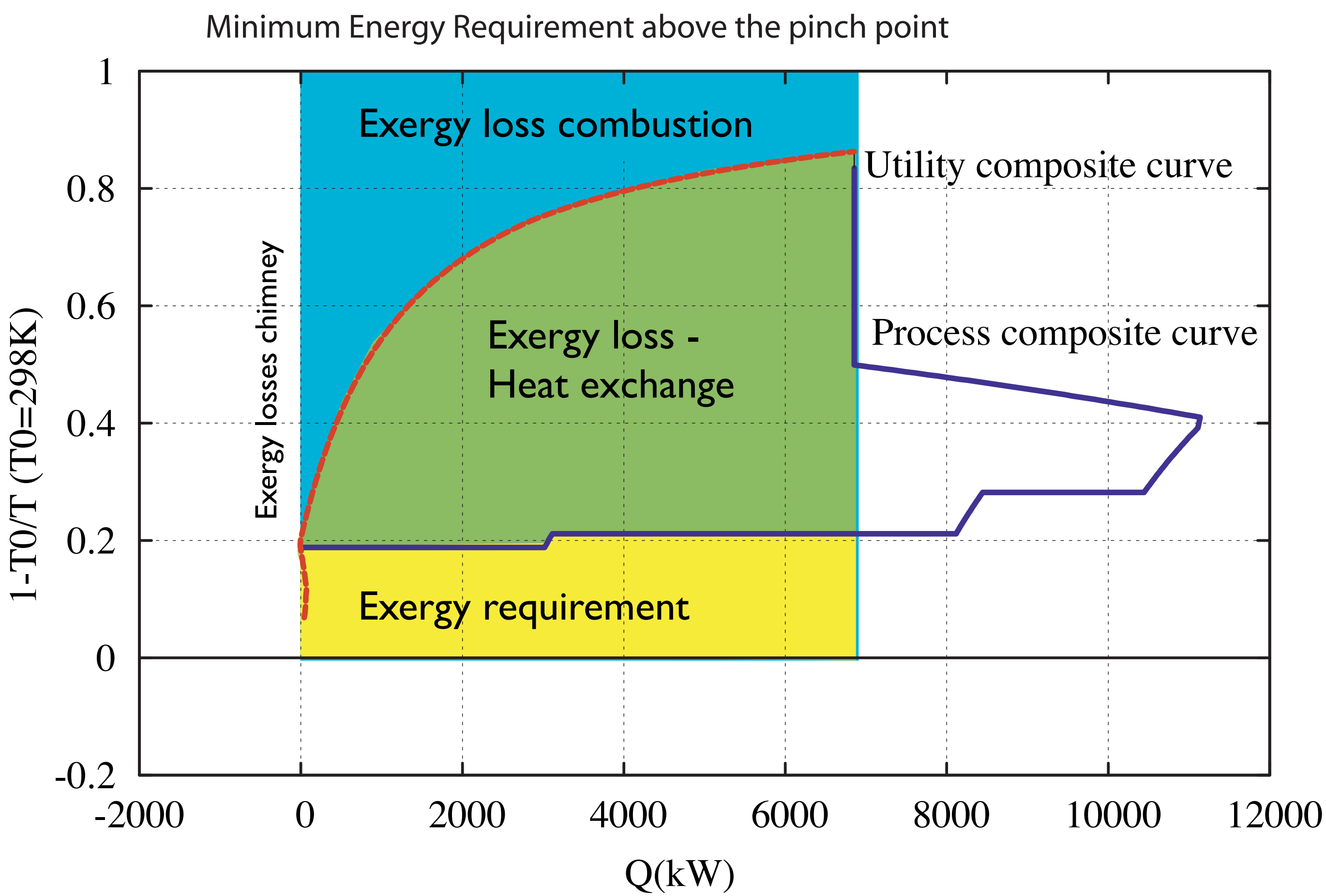
# Exergy requirement above the pinch



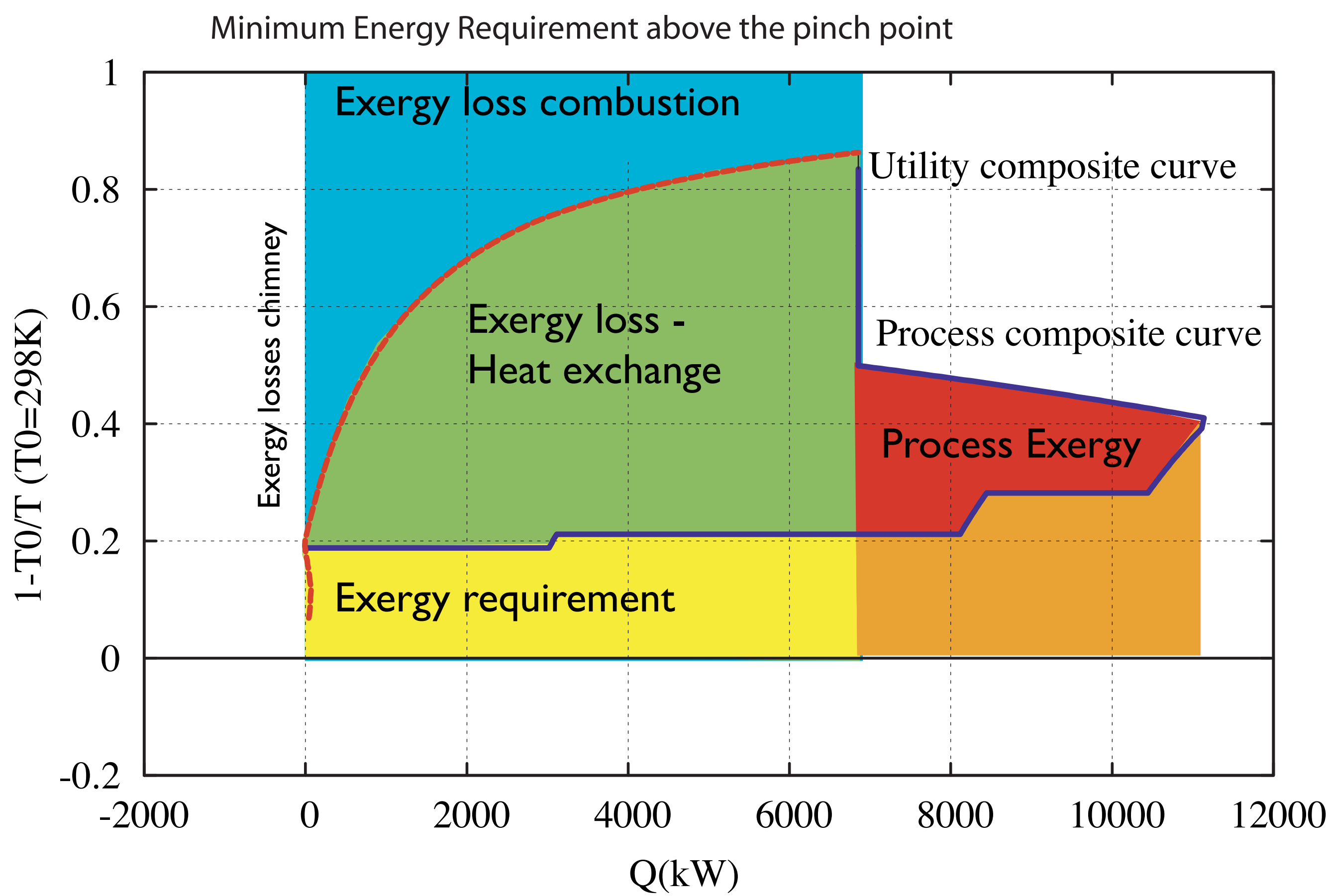
# Exergy by combustion



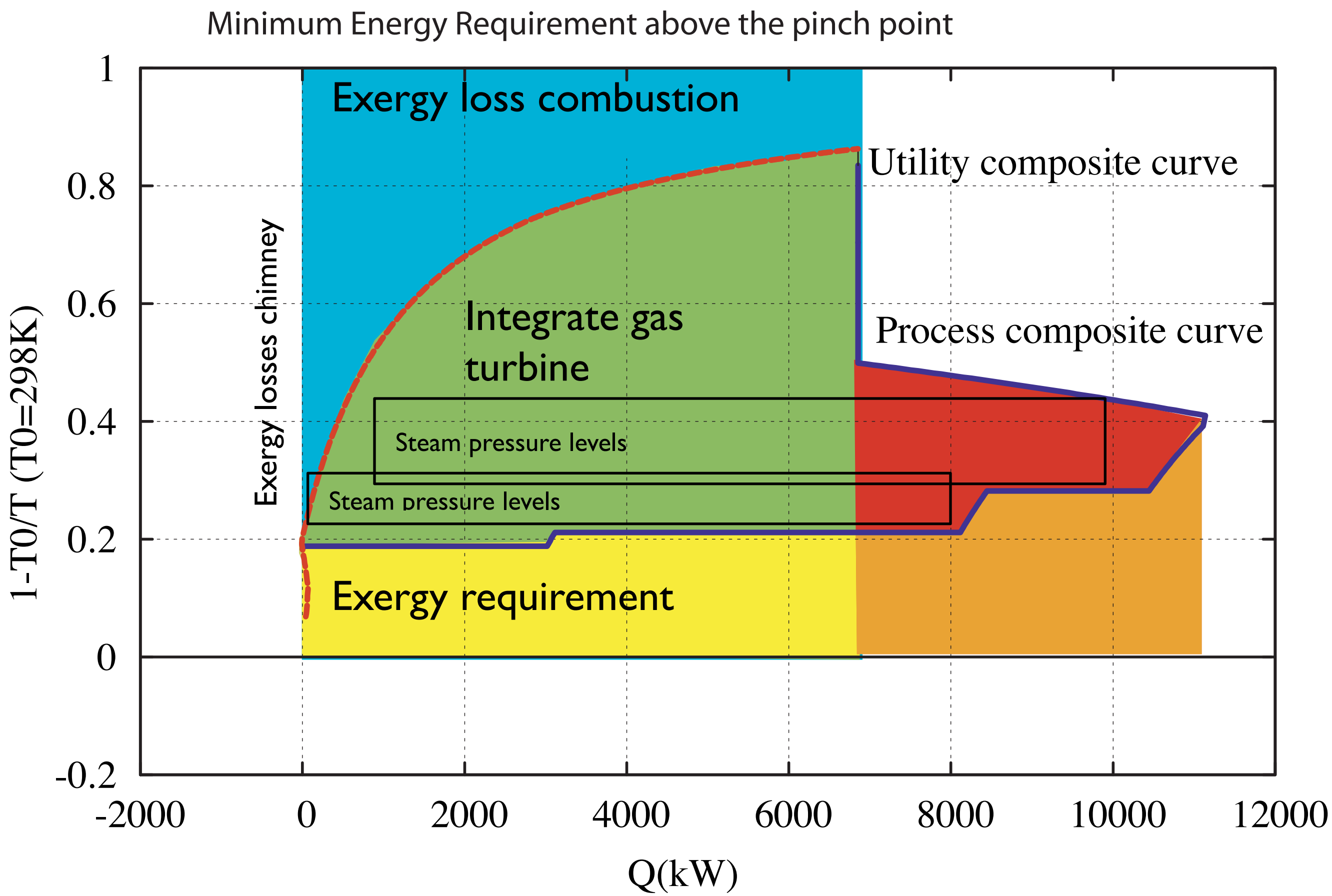
# Exergy composite Heat exchange losses



# Exergy composite -self-sufficient pockets



# Exergy composite - steam cycle and gas turbine

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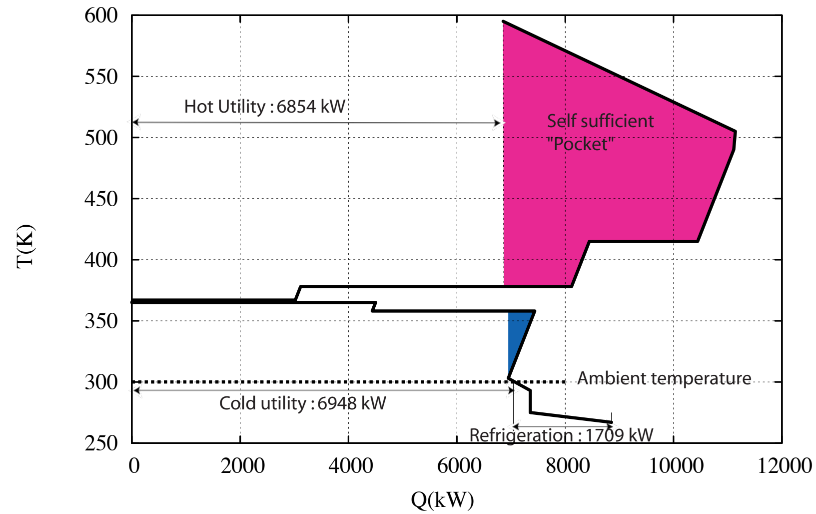
# Application : the engineer creativity

## 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

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

  - Thermal exergy :

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

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

$$\sum_{f=1}^{n_{fuel,w}} \dot{m}_{f,w} \Delta k_f^0$$

  - Chemical Exergy : $\dot{e}_w^+$ IN
  - Work : $\dot{e}_w^-$ Out

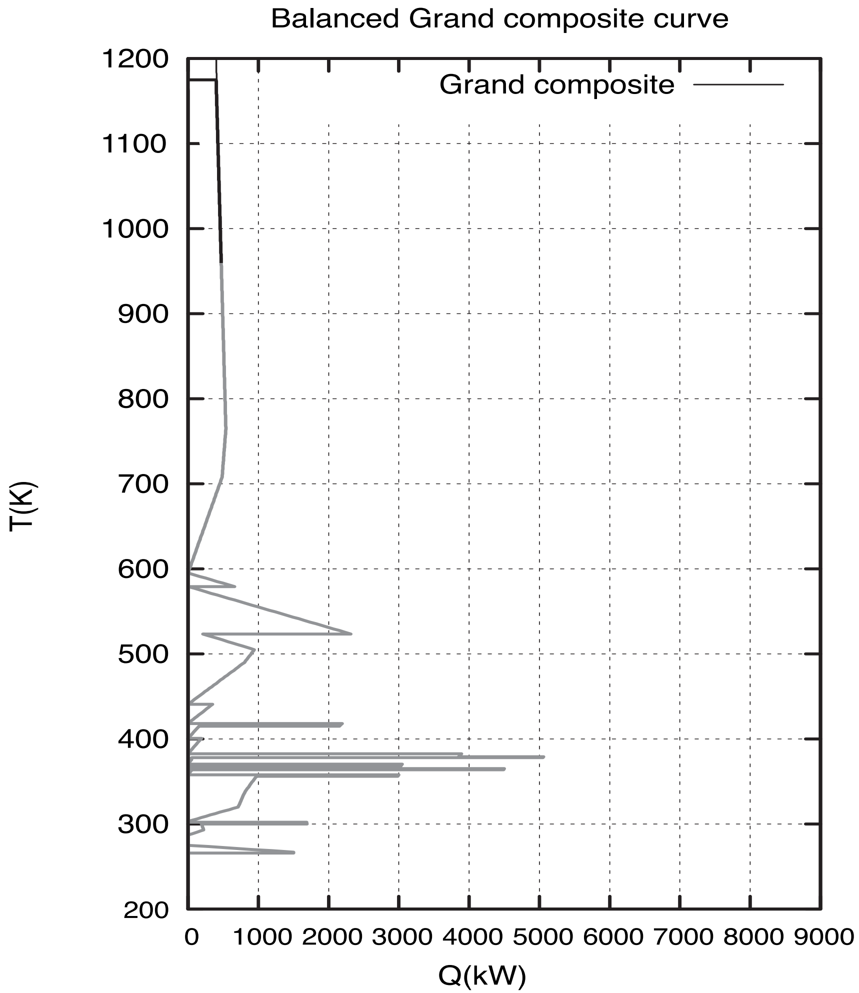
# Results

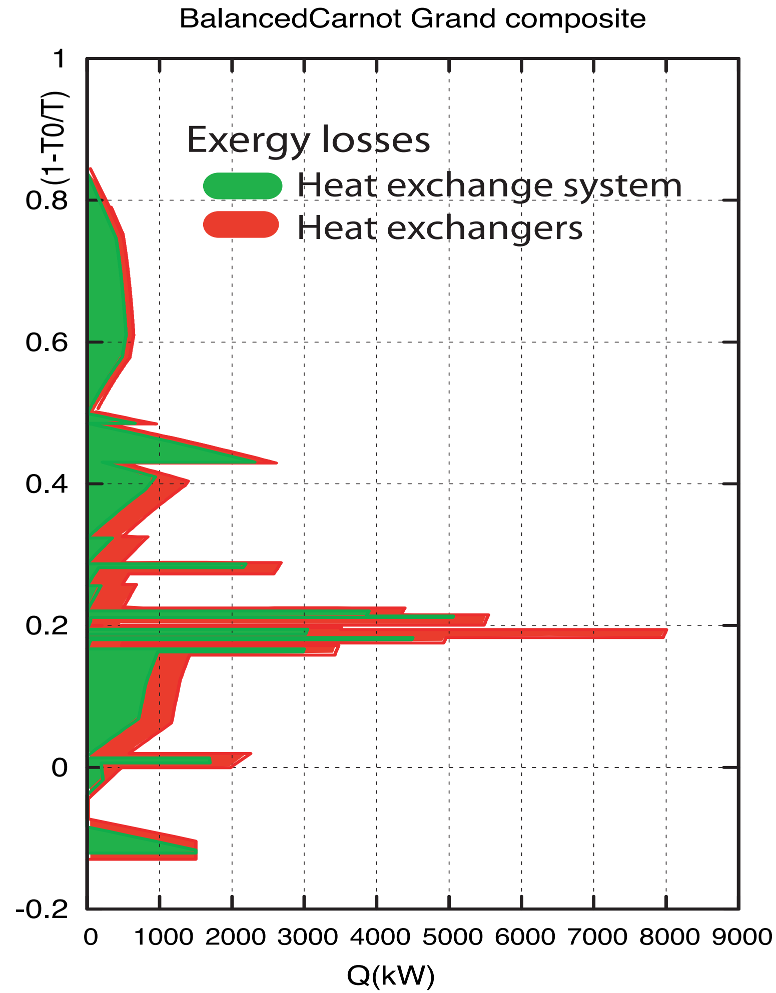
| Opt | Fuel $kW_{LHV}$ | GT kWe | CHP kWe | Cooling kW | HP kWe | |
|---|---|---|---|---|---|---|
| 1 | 7071 | - | - | 8979 | - | Comb. + frg |
| 2 | 10086 | | 2957 | 9006 | - | Comb. + stm + frg |
| 3 | 16961 | 5427 | 2262 | 9160 | - | GT + stm + frg |
| 4 | - | - | - | 2800 | 485 | hpmp + frg |
|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

Share between heat pumps

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

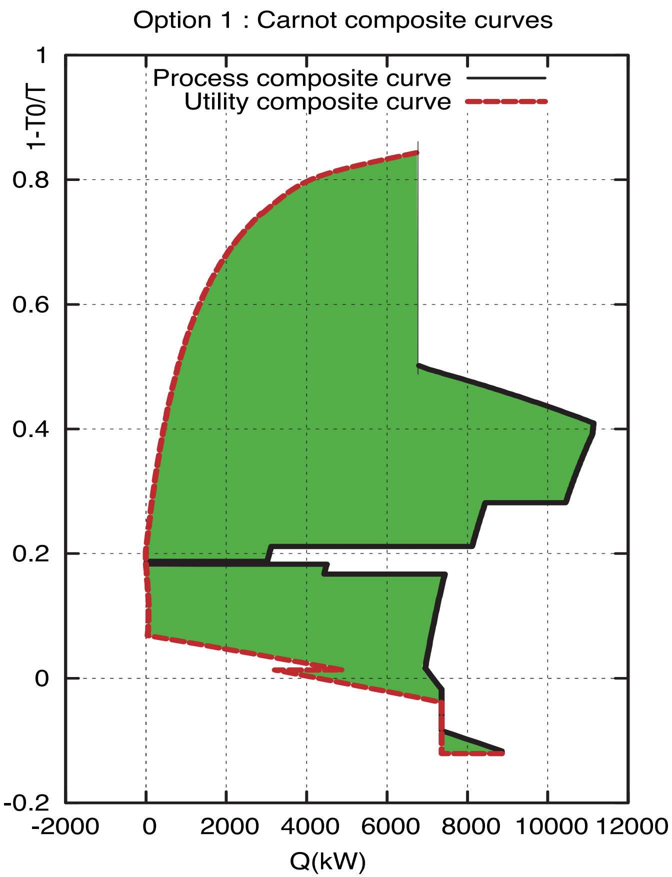
# Balanced composite curves (option 5)

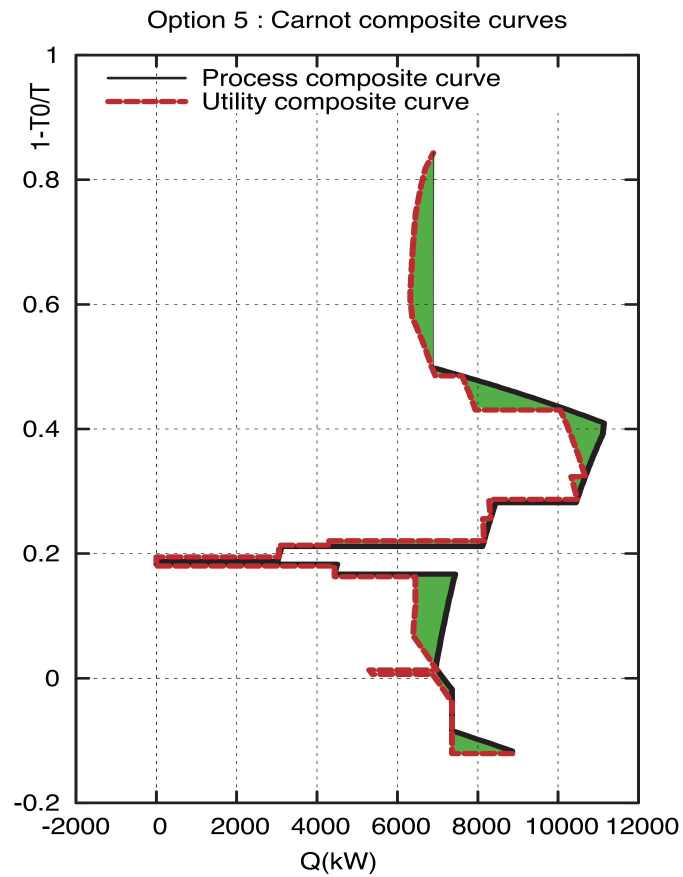


# Visualising the results : Carnot efficiency

Tricks for creative engineers : reduce the green area !



# 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

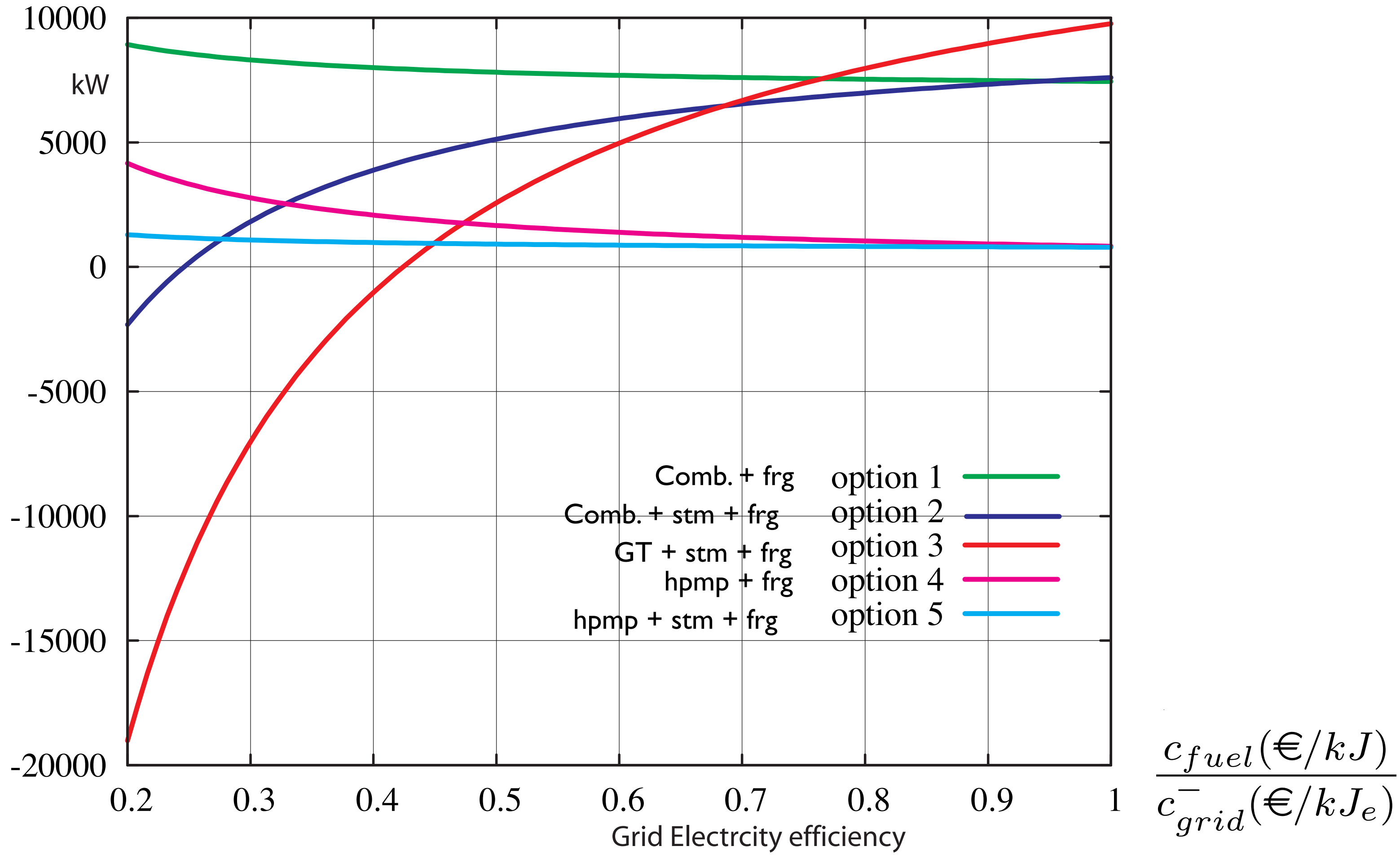
$$Total1 = \dot{m}_{fuel} * LHV_{fuel} + \frac{(E^+ - E^-)}{\eta_{el}}(= 55\%(NGCC))$$

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

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 $[kW_{LHV}]$ | $\eta_{ex}$ % | 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 |

# Sensitivity of the grid electricity mix



# Combined heat and power integration example

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# Energy system analysis

## Conversion system

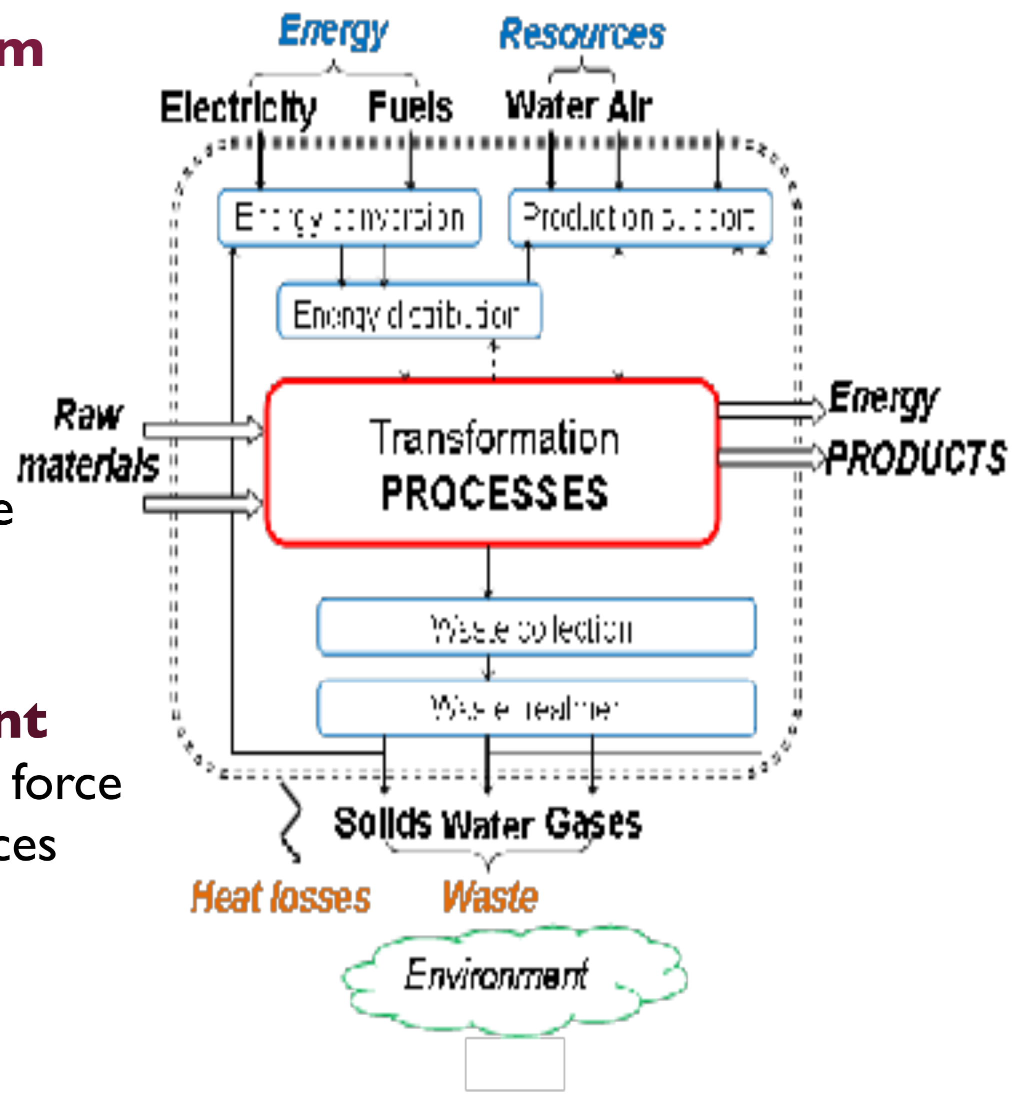
Heat
Electricity
Cooling
Refrigeration

## Production process

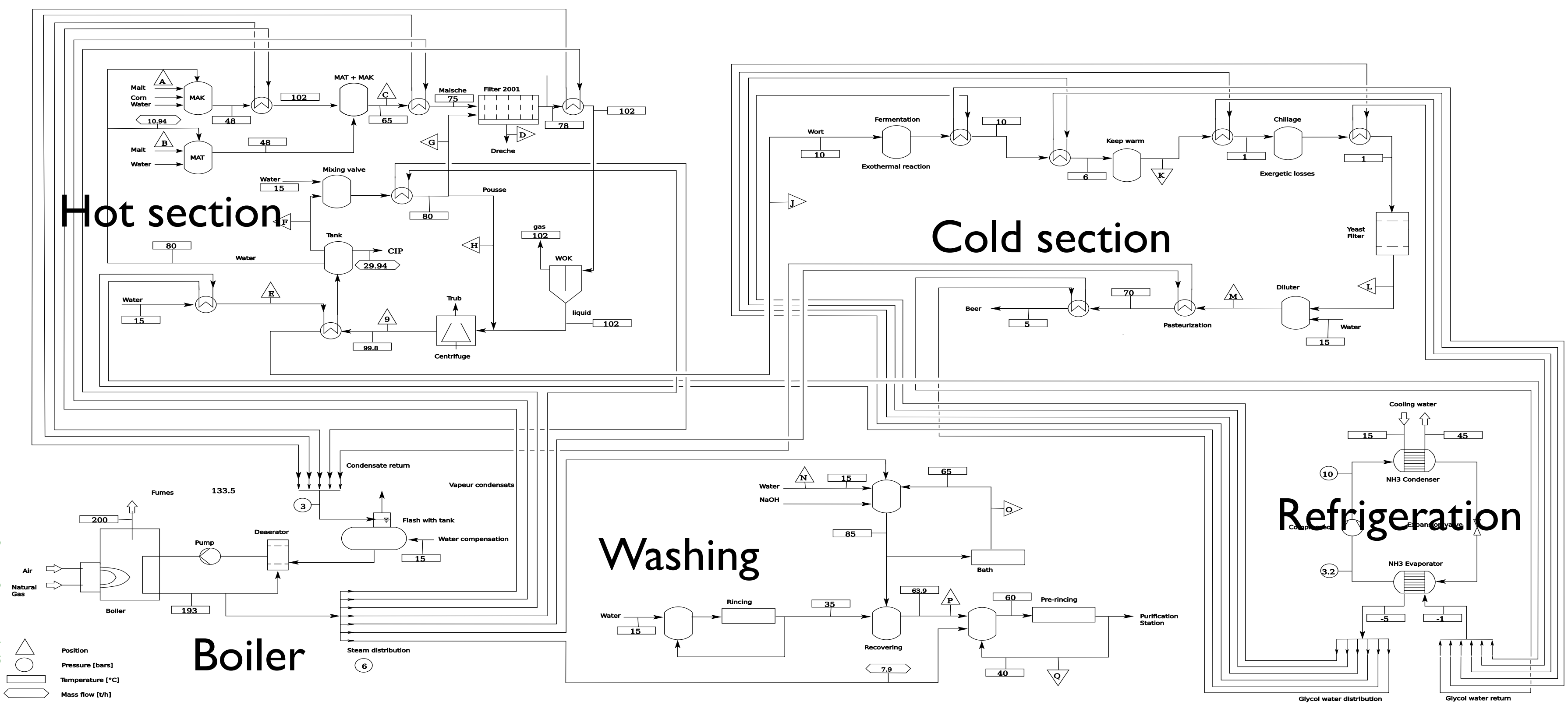
Products from raw materials
Energy is the transformation force
Uses distributed energy
Produces waste

## Waste management

Energy is the driving force
New products/services
Resources
Recycling
- mass
- energy



# Example : Brewing process




| | | |
|---|---:|---|
| Natural gas (steam boiler) | 3133 | kW |
| Steam | 2819.7 | kW |
| Cooling water | 1578.7 | kW |
| Refrigeration | 465 | kWe |
| Steam vented | 455 | kW |

Energy perspective : What you see ?

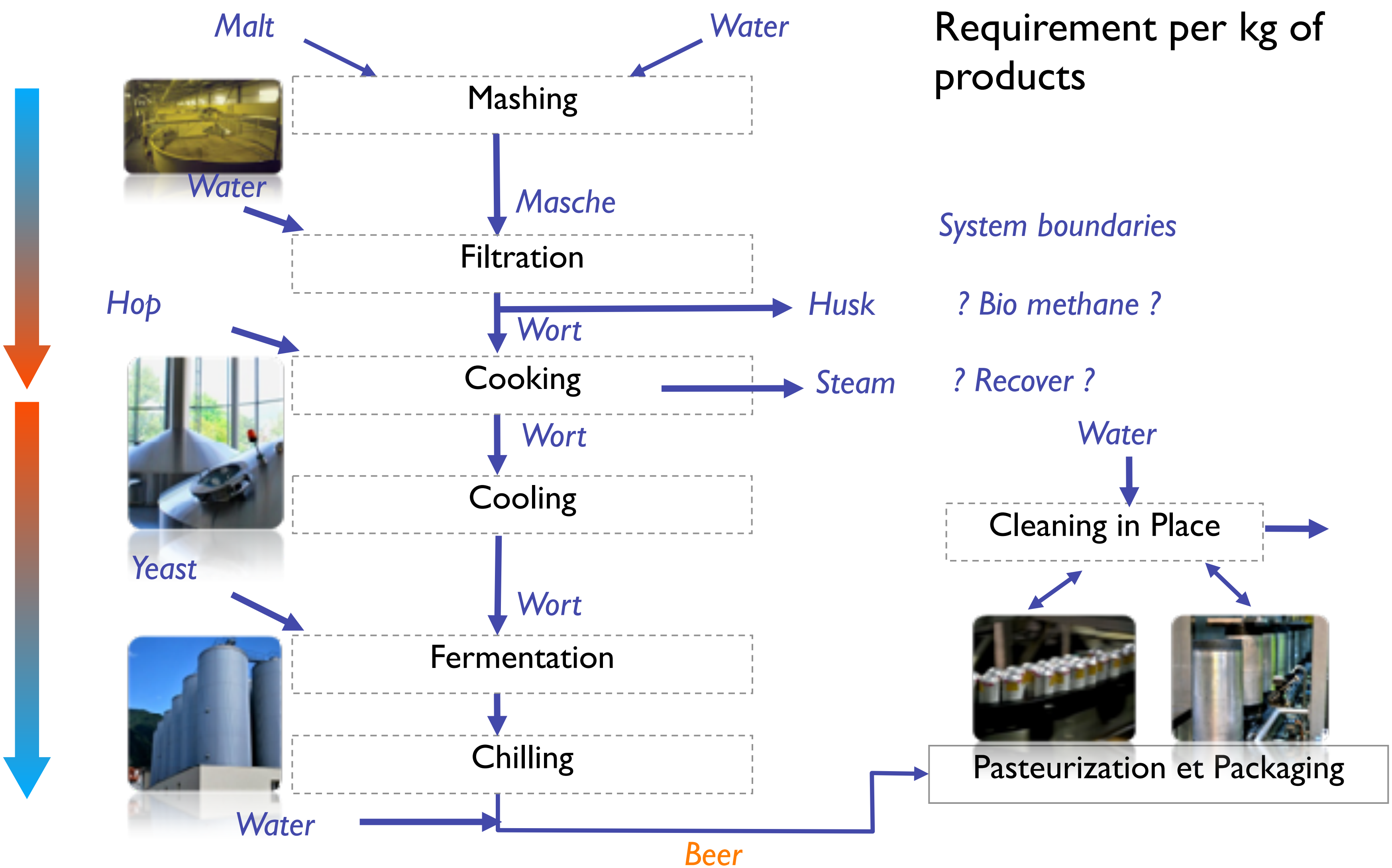
- Energy bill (electricity, gas and water)
- Waste handling
- Maintenance and operation cost
- Environmental regulation

# The cogeneration temptation

- Replace the boiler by an engine
  - GE engine size 2*1250 kWe
    - eff el = 41%
    - eff th = 46 %
- Recover the vented steam
- Export electricity

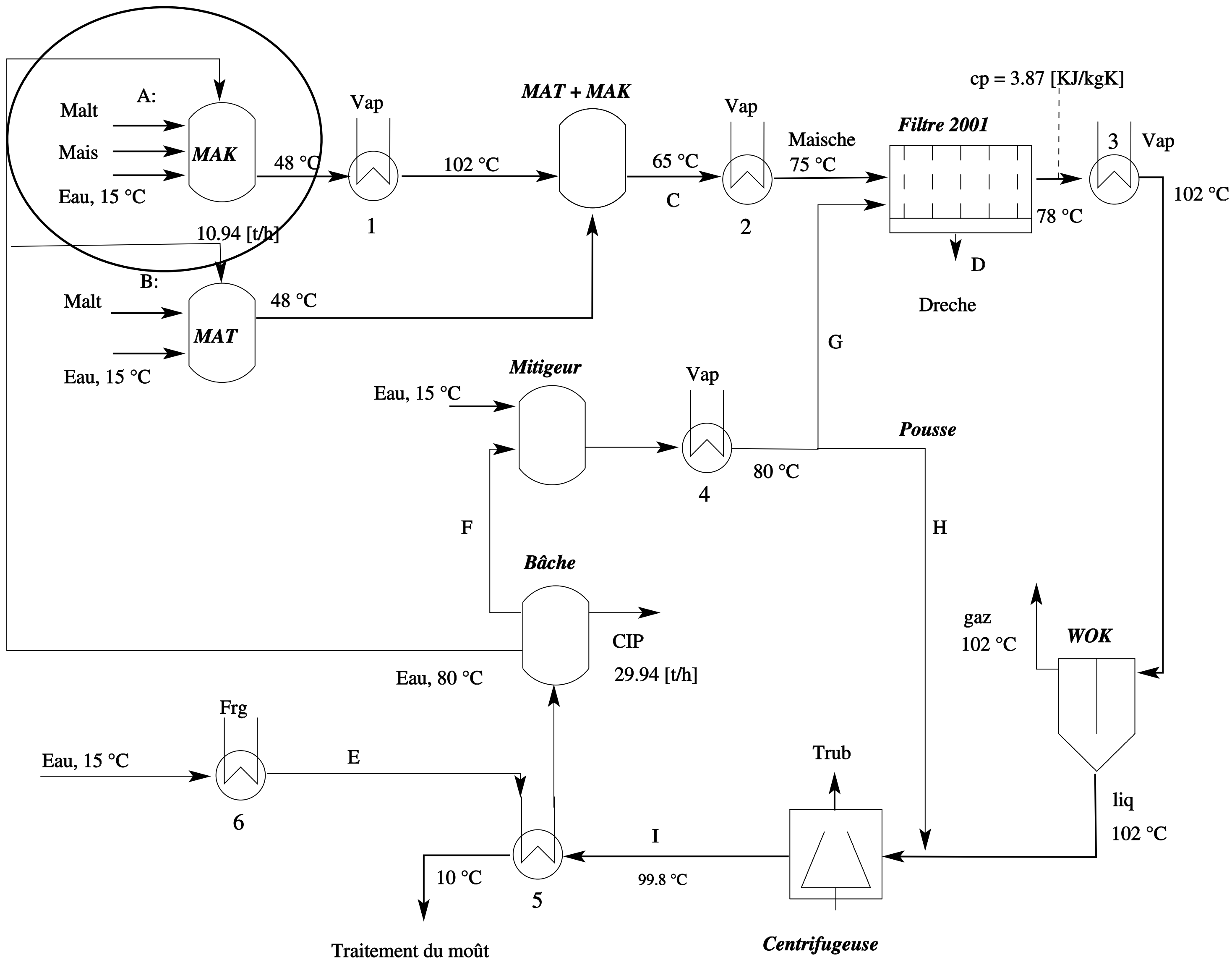
| | | present | cogeneration |
|---|---|---|---|
| Natural gas | kW | 3133 | 6130 |
| Steam | kW | 2820 | |
| Cooling water | kW | 2220 | 2220 |
| Electricity | kWe | 465 | -2048 |
| Steam vented | kW | 455 | 0 |

# do not fall in the trap : Analyse your process requirements



# Hot Section of Brewery : hot water injection

Other examples are given in the lecture notes



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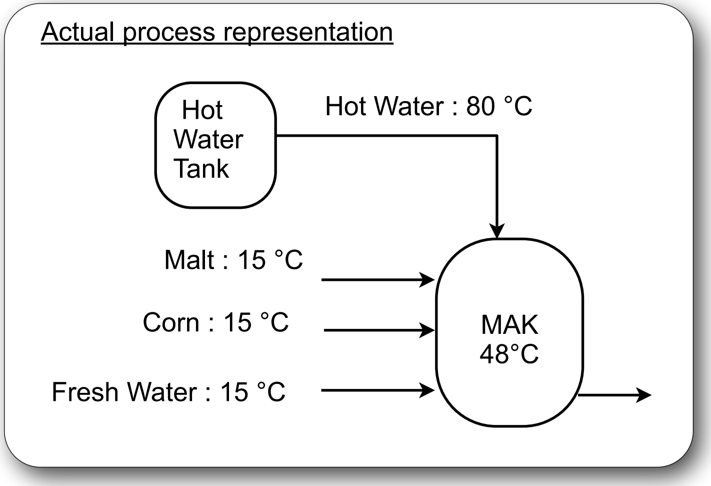
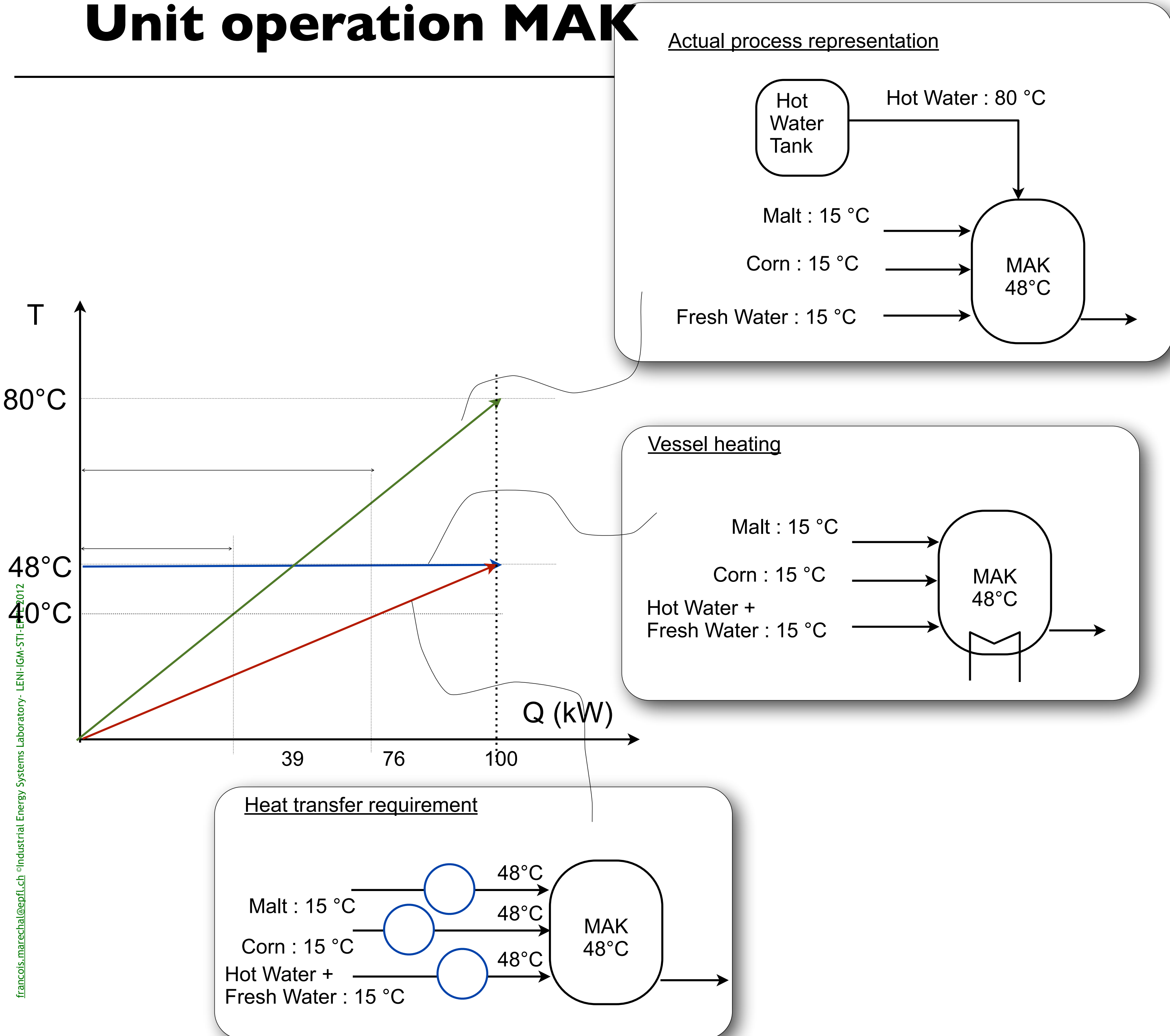
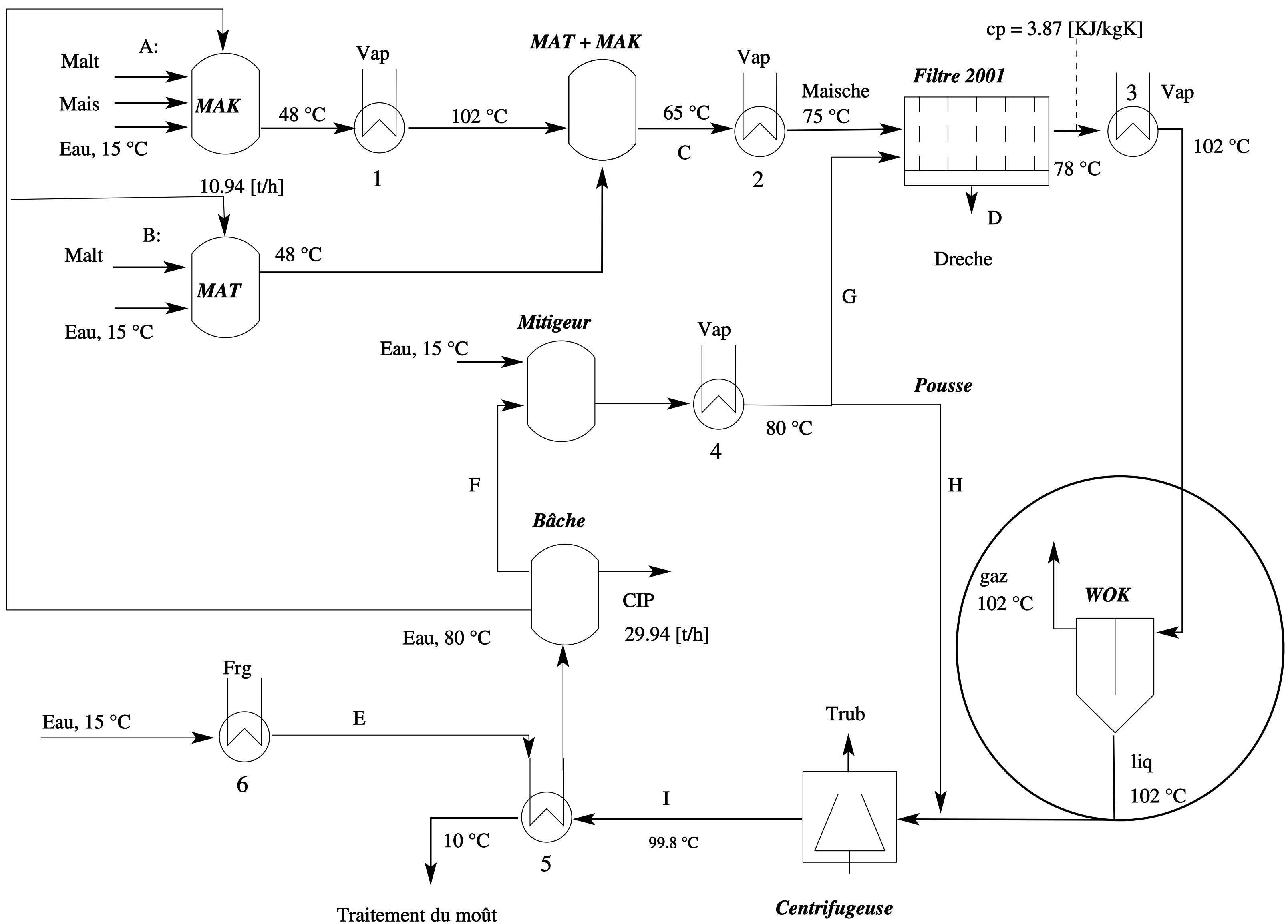
# Unit operation MAK



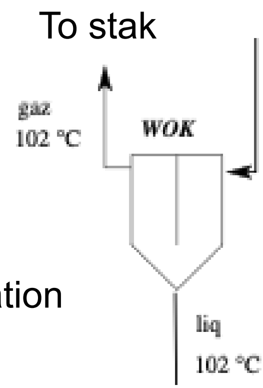
# Unit operation MAK



# Hot Section of Brewery : definition of streams

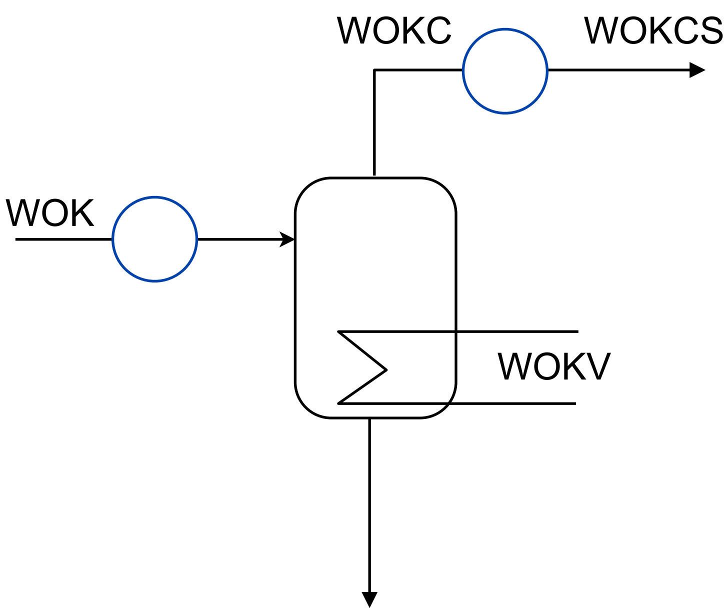


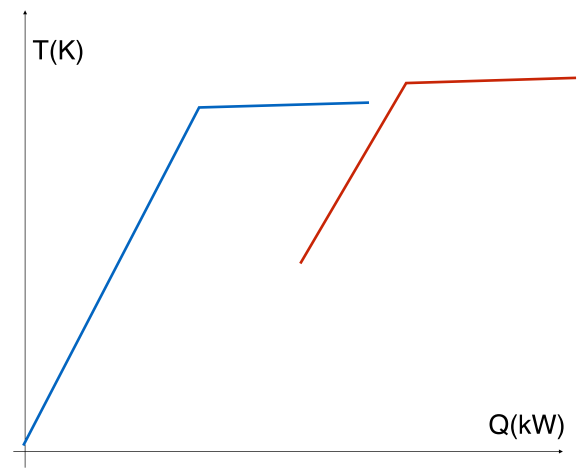
# Recover waste heat lost in the environment



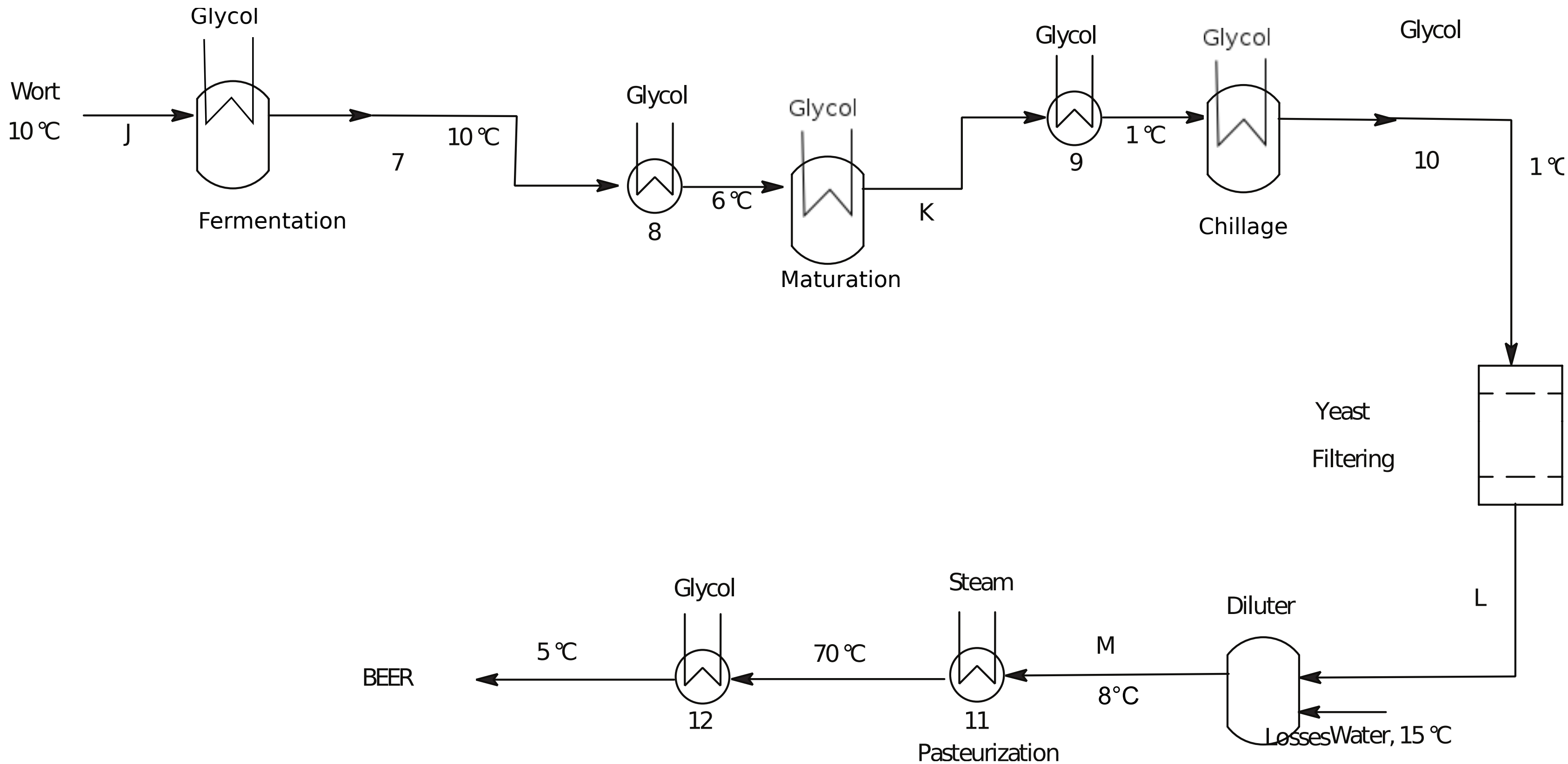

WOK : evaporation

| Nom | Tin [°C] | Tout [°C] | $\dot{M}$ [kg/s] | $\dot{Q}$ [kW] |
|---|---|---|---|---|
| WOK | 78 | 102 | 16.2 | 1504 |
| WOKV | 102 | 102 | - | 4513 |
| WOKC | 95 | 95 | 2.3 | 4513 |
| WOKCS | 95 | 25 | 2.3 | 674 |

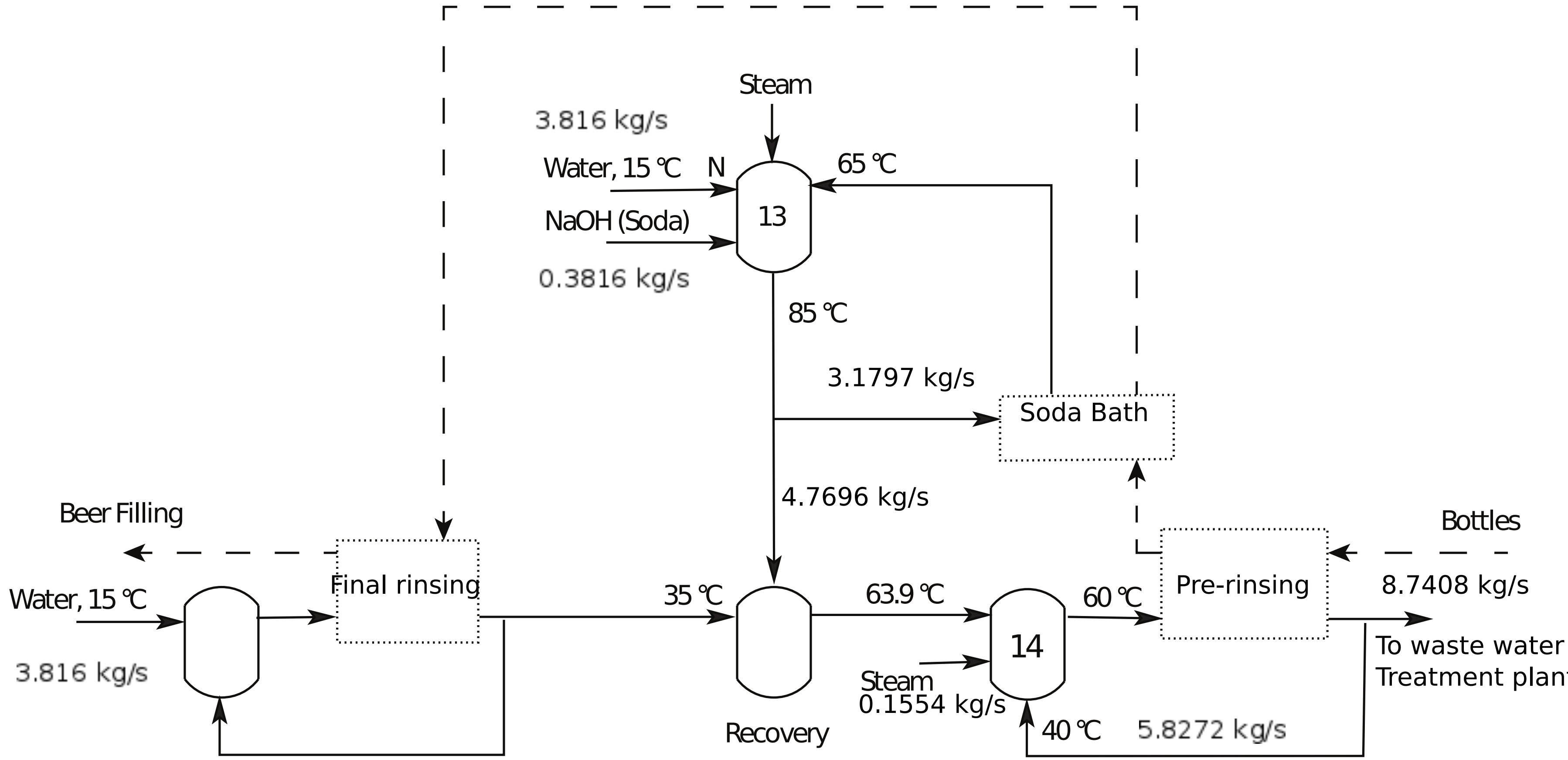


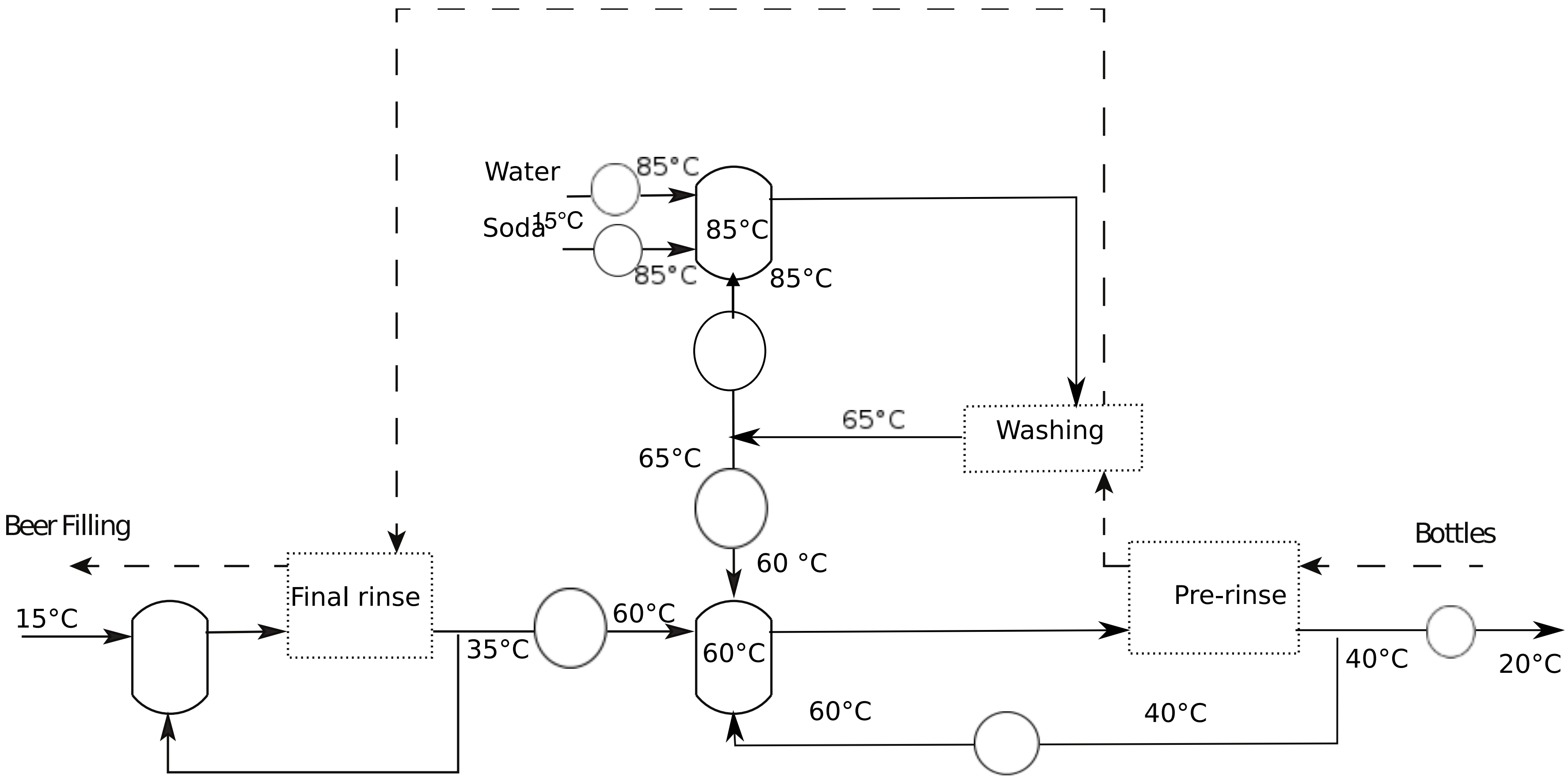
# Cold Section



# Cleaning in place system

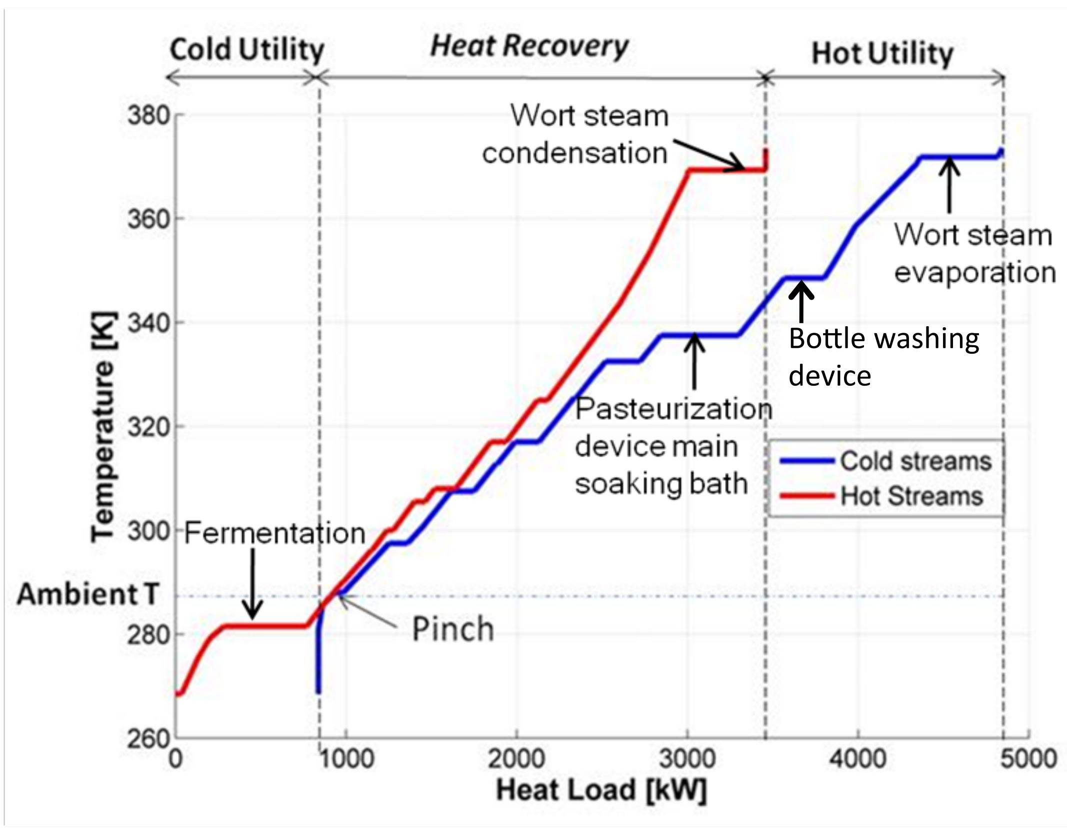


# cleaning in place requirements



# Maximum heat recovery in the system

- Define the heat recovery potential :
  - 2700 kW out of 4000 kW



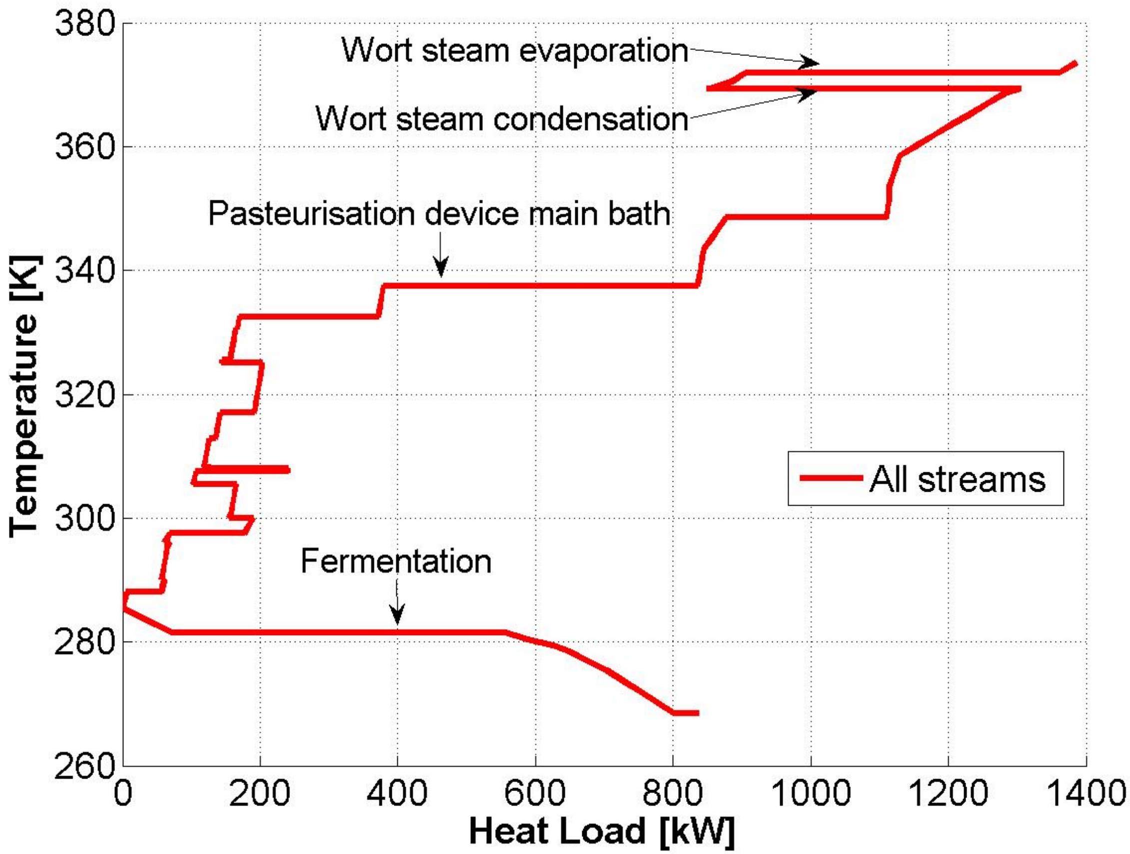

| Utility | MER [kW] | Current [kW] |
|---|---|---|
| Hot utility | 1386 | 2220 |
| Cold utility | - | **16** |
| Refrigeration utility | 837 | **1200** |

Estimated !

Heat recovery leads to 37 % energy savings

# Energy conversion needs

- Heat-temperature profile for the utility system

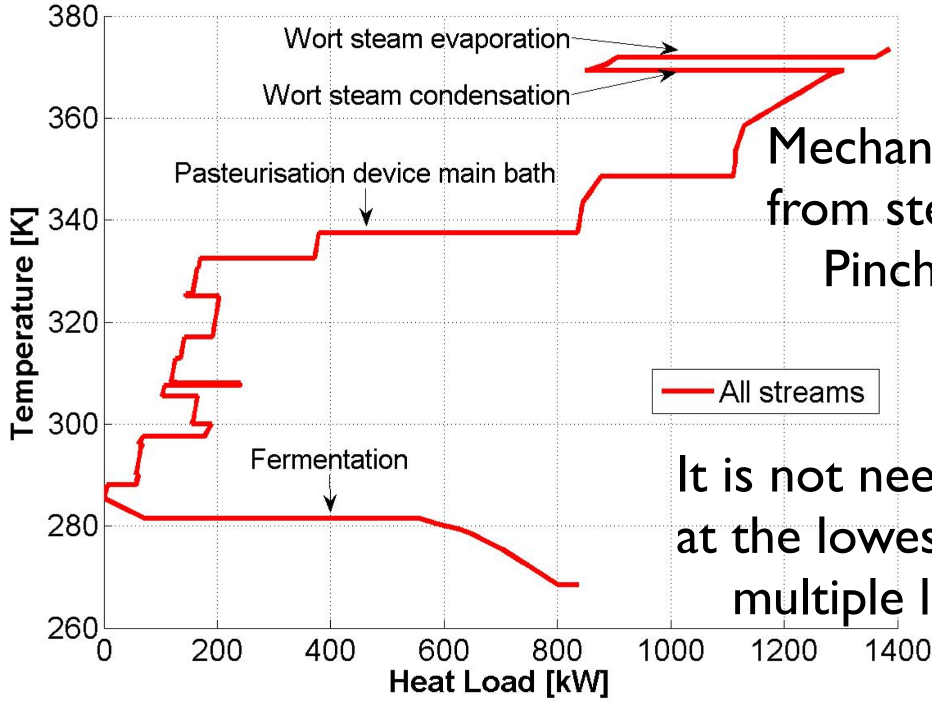


# Energy conversion needs analysis

- What are the options ?

What about heat pumping ?
with refrigeration cycle
Pinch analysis says YES

Cogeneration with engine
check compatibility of temperature for cooling water

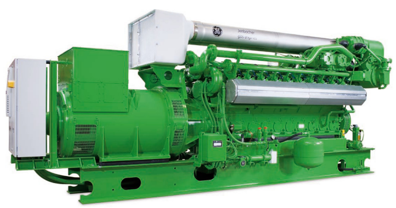



Mechanical vapor recompression from steam recovery ?
Pinch analysis says NO !

It is not needed to refrigerate at the lowest temperature
multiple levels

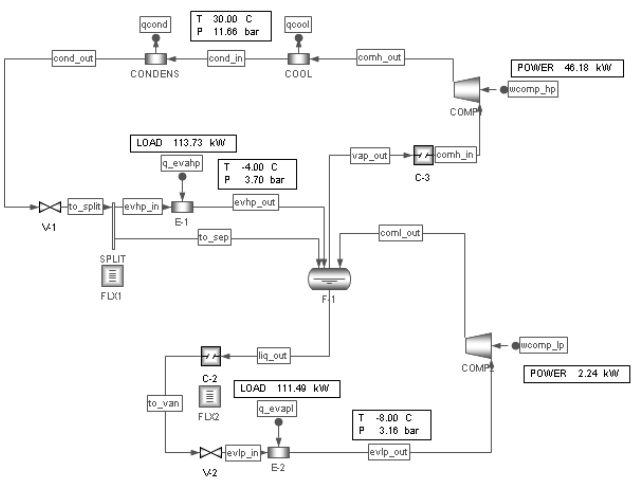
# Energy conversion unit models

| Specification | Symbol | Value | Unit |
|---|---|---|---|
| Fuel | | Natural Gas | |
| Nominal speed | N | 1500 | $min^{-1}$ |
| Effective power | $P_e$ | 1063 | $kW_e$ |
| Mechanical efficiency | $\eta_{mech}$ | 0.408 | - |
| Thermal efficiency | $\eta_{therm}$ | 0.456 | - |
| Exhaust gas temperature (default value) | $T_{gas,out}$ | 470.5 | °C |
| Stack temperature (default value) | $T_{stack}$ | 120 | °C |
| Cooling water inlet temperature (default value) | $T_{wat,in}$ | 87.0 | °C |
| Cooling water outlet temperature (default value) | $T_{wat,out}$ | 79.9 | °C |
| Exhaust gas heat | $\dot{Q}_{th,gases}$ | 537 | kW |
| Cooling water heat | $\dot{Q}_{th,water}$ | 653 | kW |
| Fuel cost | $c_{fuel}$ | 0.01961 | €/s |



GE engine type 3

| Refrigeration cycle | Single-level of evaporation | Two-levels of evaporation | |
|---|---|---|---|
| Ammonia mass flow [kg/s] | 0.2 | 0.1/0.1 | |
| Evaporation temperature [°C] | -8 | -4/-8 | |
| Condensation temperature [°C] | 30 | 30 | |
| Total cooling load [kW] | 225.83 | 223.85 | |
| Compressor power [kW] | 52.71 | 49.78 | |
| Energetic efficiency ε (COP) | 4.28 | 4.65 | *+9%* |
| Exergetic efficiency η ($T_{amb}$=25°C) | 0.53 | 0.54 | *+1%* |

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# Energy conversion system integration

- **Utility system made of a list of optional sub-systems "w"**
  - Mechanical vapor recompression
  - Steam boiler
  - Cogeneration engine
  - Refrigeration cycle (multi levels)
  - Cooling water
- **For each subsystem "w"**
  - Calculate hot and cold streams
    - $q_{w,r}$ : contribution of a stream to the heat cascade interval r if the stream is used
  - Calculate power consumption/production
    - $e_w$ : electricity
  - Calculate fuel consumption => operating cost $C2_w$
  - Investment cost : piecewize linearized function : $CI1_w$,$CI2_w$
- **Unknowns are :**
  - is the sub-system "w" used : **integer** variable $y_w = \{0,1\}$
  - flow in utility sub-system w : **continuous** variable $f_w$ : $fmin_w \leq f_w \leq fmax_w$

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# 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

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

Electricity consumption

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

Electricity production

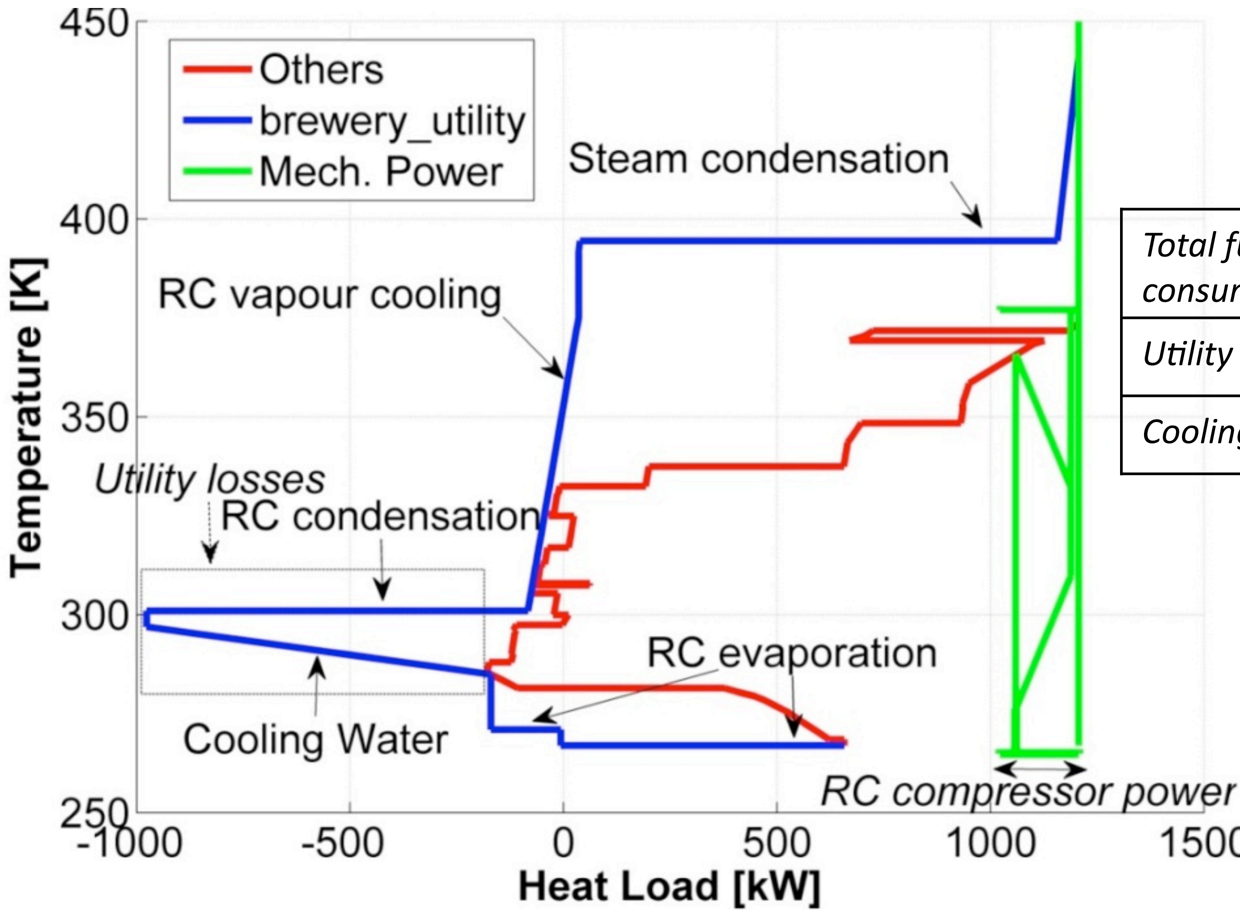
$$\sum_{w=1}^{n_w} f_w e_w + E^+ - E_c - E^- = 0$$

Energy conversion Technology selection

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

# Calculation with the boiler and refrigeration

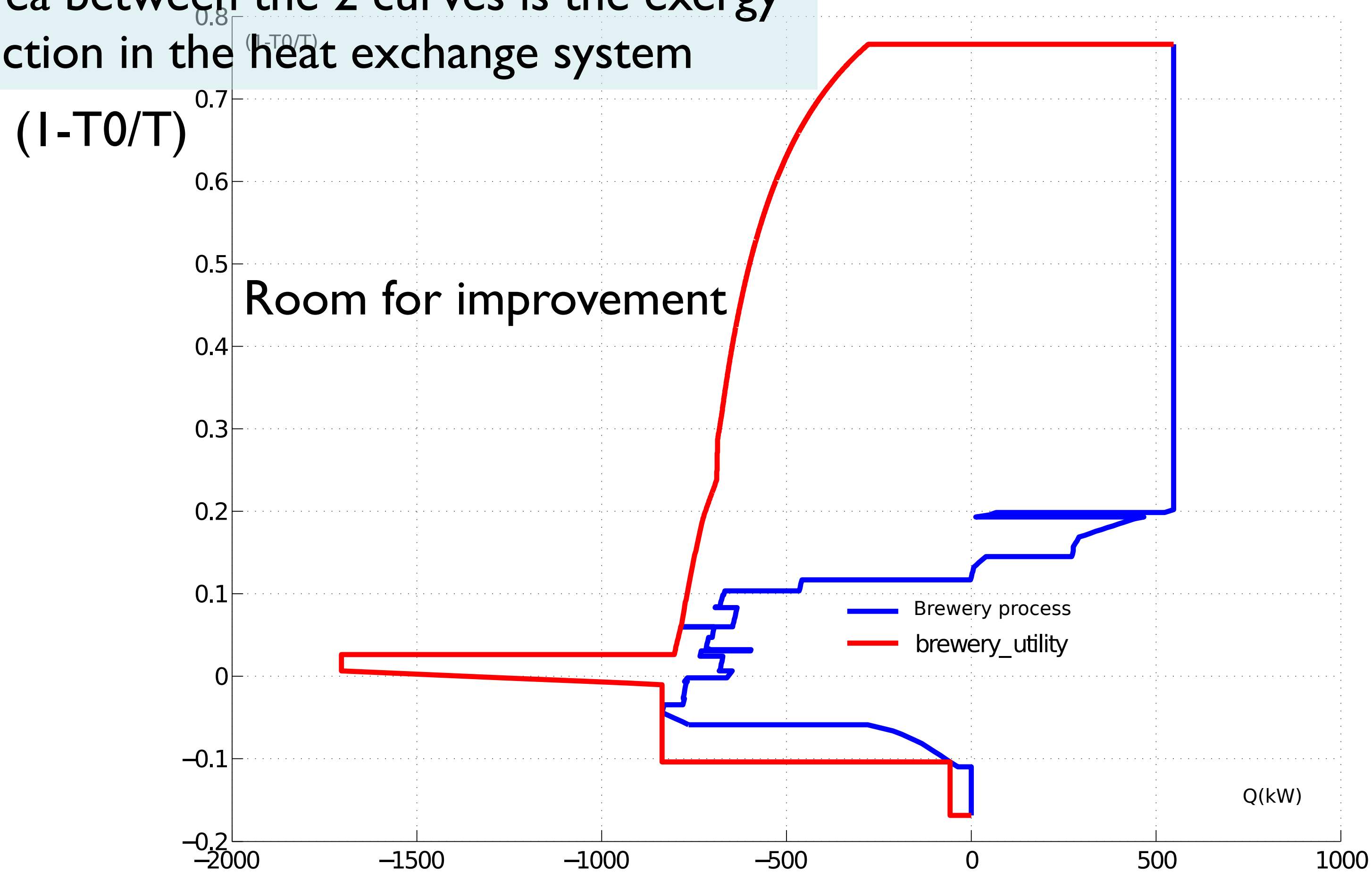
- Integrated curves representation




| | |
|---|---|
| *Total fuel consumption* | *2088 kW* *-33%* |
| *Utility Electricity* | **184 kWe** |
| *Cooling Water* | *17.1 kg/s* |

# The Carnot composite curves and the conversion system

The area between the 2 curves is the exergy destruction in the heat exchange system

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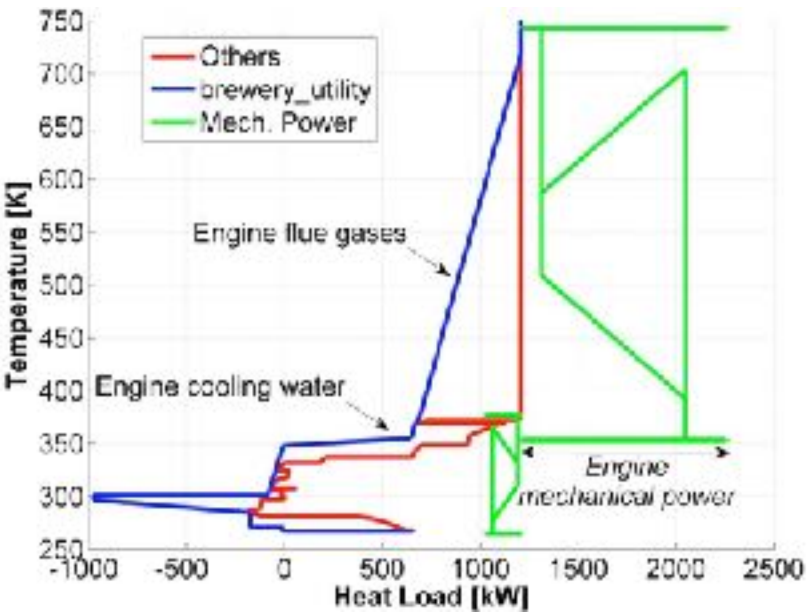
# Integration of the cogeneration engine

- Natural gas CHP system integration




- Increased fuel consumption, but…
- Mechanical power generation

- Heat pumping to lessen heat losses ?

| | |
|---|---|
| *Total fuel consumption* | *3279 kW*<br>*+57%* |
| *Utility Electricity* | **- 863 kWe** |
| *Cooling Water* | *17.1 kg/s* |





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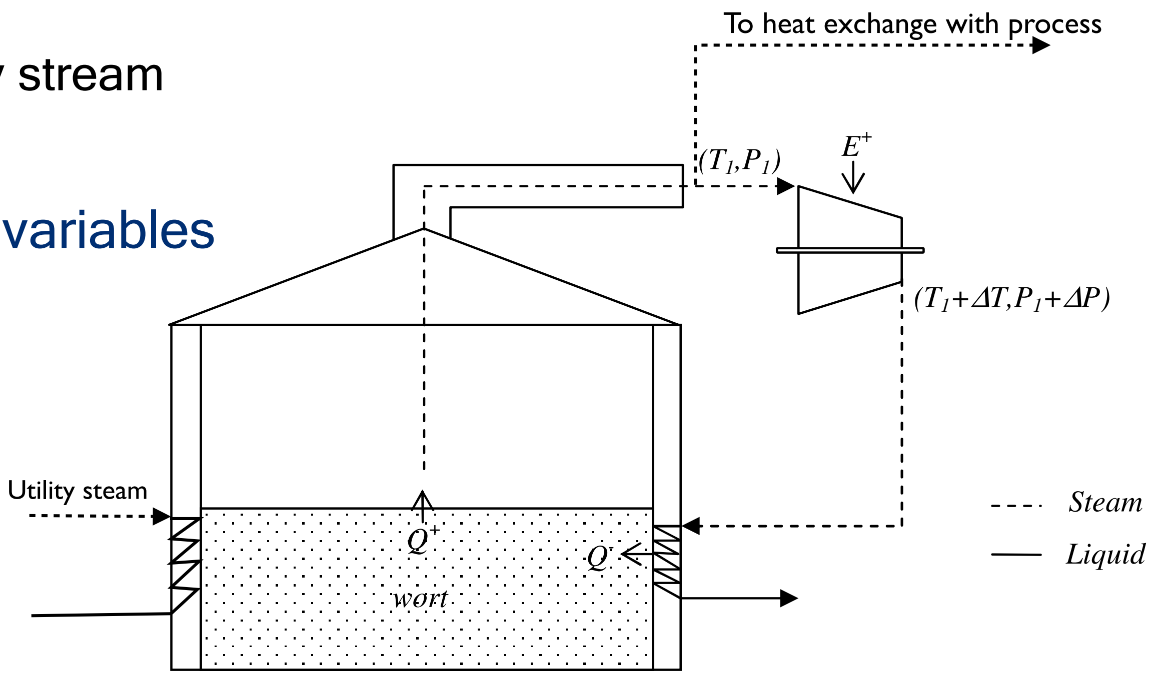
# Heat Pump Integration

- Closed cycle heat pump
  - Refrigeration cycle condensation heat pumped to higher temperature levels

- Mechanical vapour recompression
  - Evaporating wort is directly compressed and delivers heat to the process by condensing
  - Process stream → Utility stream

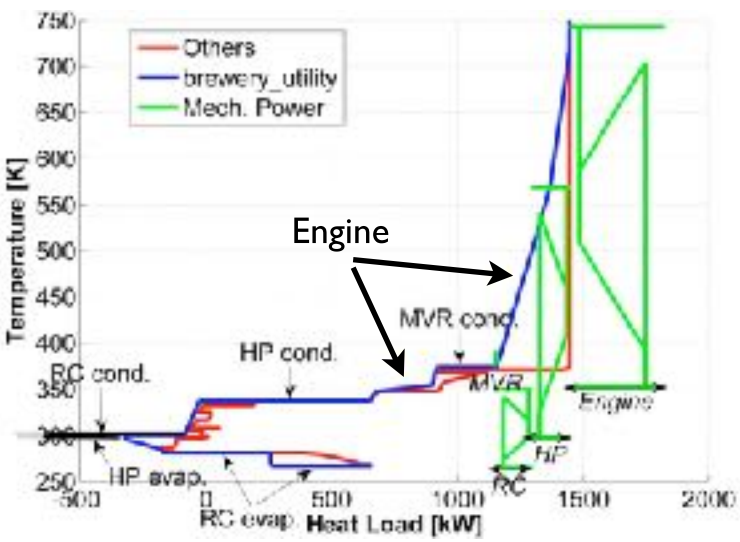
- Cost optimisation design variables
  - Operating temperatures



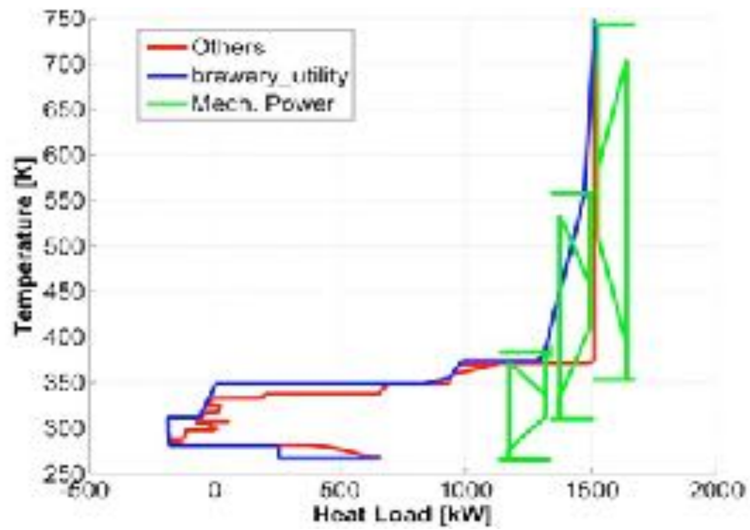
# Heat pump conditions optimisation

- 2 heat pumping conditions

HP1 set up 1 ($T_{cond}$=340K)




HP 2 set up ($T_{cond}$=351K)




| | |
|---|---|
| *Fuel* | *1677 kW* |
| *CHP* | **-374 kWe** |
| *« Heat Pumps »* | **295 kWe** |
| *Cooling Water* | *3.0 kg/s* |

| | |
|---|---|
| *Fuel* | *1140 kW* |
| *CHP* | **-166 kWe** |
| *« Heat Pumps »* | **379 kWe** |
| *Cooling Water* | *0.1 kg/s* |

# Results (Maximum Heat Recovery)

1. Gas Boiler 2.Gas CHP 3.Gas CHP+MVR+HP ($T_{cond}$=66.5°C) 4.Gas CHP+MVR+HP ($T_{cond}$=77.5°C)

| | Unit | 1. | 2. | 3. | 4. |
|---|---|---|---|---|---|
| Natural Gas | kW | 2088 | 3279 | 1677 | 1140 |
| Electricity | $kW_e$ | 184 | -863 | -80 | 212 |
| Water | kg/s | 17.1 | 17.1 | 3.2 | 0.2 |
| Run. Costs FR | k€/yr | 332 | 210 | 205 | 212 |
| Run. Costs GER | k€/yr | 520 | 283 | 312 | 336 |
| TOTAL Costs FR | k€/yr | 332 | 308 | 274 | 274 |
| TOTAL Costs GER | k€/yr | 520 | 380 | 381 | 398 |
| TOTAL $CO_2$ FR* | ton/yr | 2459 | 3544 | 1912 | 1372 |
| TOTAL $CO_2$ GER* | ton/yr | 2987 | 1094 | 1686 | 1976 |

| Energy /Resource | Unit Cost 2007 (Without Taxes) | $CO_2$ Emissions |
|---|---|---|
| France | | |
| Electricity | $0.0541€/kWh_e$ | $55g_{CO2}/kWh_e$ |
| Natural Gas | $0.0271€/kWh_{LHV}$ | $231g_{CO2}/kWh_{LHV}$ |
| Water | $0.00657€/m^3$ | - |
| Germany | | |
| Electricity | $0.0927€/kWh_e$ | $624g_{CO2}/kWh_e$ |
| Natural Gas | $0.0417€/kWh_{LHV}$ | $231g_{CO2}/kWh_{LHV}$ |





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# Bio-Methanation Opportunity

- **Opportunity in breweries: organic waste (husk) bio-methanation**
  - 75 $Nm^3$ $CH_4$/t husk
- **However…**
  - Extra investment (digester), increased electric consumptions (blender, pumps)
  - Heating requirement (Cold stream @ 35 °C)

- **Available : 1660 kW as LHV of $CH_4$**

# MER & Bio-Methanation: Results

1. Gas Boiler 2.Gas CHP 3.Gas CHP+MVR+HP ($T_{cond}$=66.5°C) 4.Gas CHP+MVR+HP ($T_{cond}$=77.5°C)

| | Unit | 1. | 2. | 3. | 4. |
|---|---|---|---|---|---|
| Biogas | kW | 1660 | 1660 | 1660 | 1660 |
| Natural Gas | kW | 664 (2088) | 711 (3279) | 480 (1677) | 200 (1140) |
| Electricity | $kW_e$ | 264 (184) | -924 (-863) | -298 (-80) | -219 (212) |
| Water | kg/s | 17.1 | 17.1 | 3.2 | 0.2 |
| Run. Costs FR | k€/yr | 161 (332) | -31 (210) | -16 (205) | -32 (212) |
| Run. Costs GER | k€/yr | 260 (520) | -280 (283) | -38 (312) | -60 (336) |
| TOTAL Costs FR | k€/yr | 238 (332) | 145 (308) | 124 (274) | 115 (274) |
| TOTAL Costs GER | k€/yr | 338 (520) | -105 (380) | 101 (381) | 88 (398) |
| TOTAL $CO_2$ FR* | ton/yr | 839 (2459) | 566 (3544) | 471 (1912) | 170 (1372) |
| TOTAL $CO_2$ GER* | ton/yr | 1588 (2987) | -2060 (1094) | -377 (1686) | -452 (1976) |

- **Natural gas = -95 %**
- **Electricity = -147 %**

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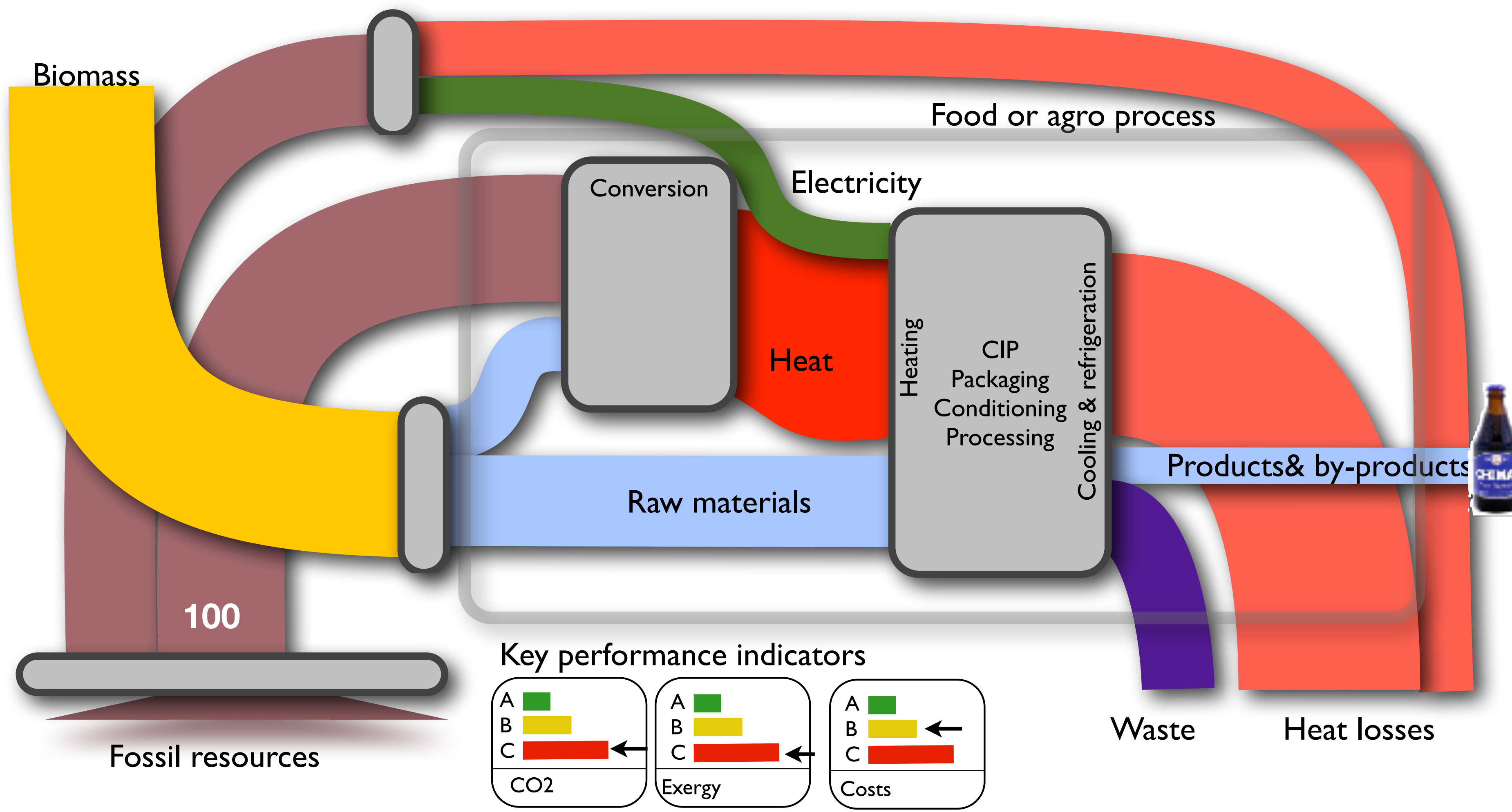
# Conclusions : Before the analysis

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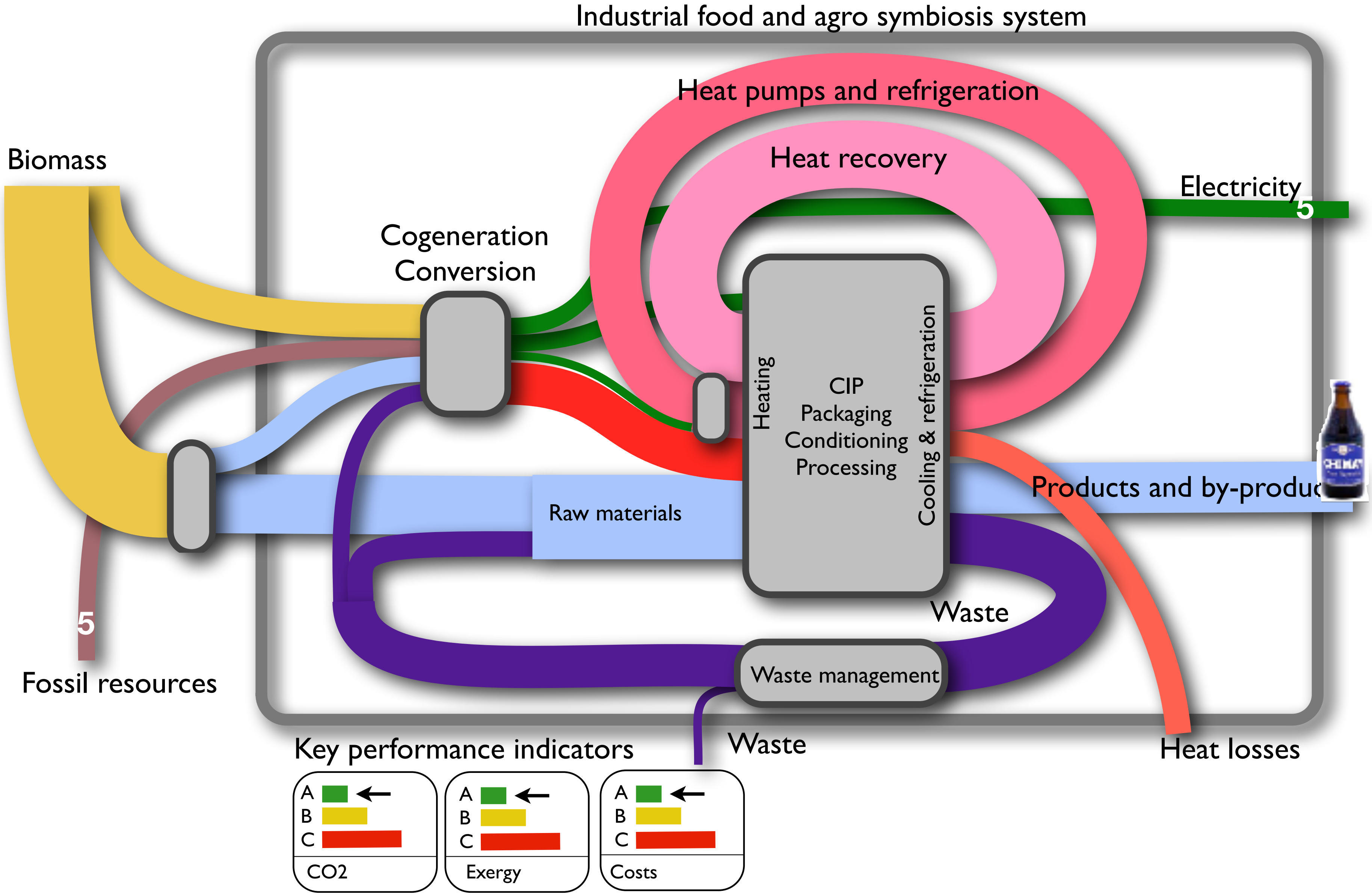
# Conclusion : from process integration perspective



# Conclusions : optimal integration of trigeneration systems

- **Present consumption does not define the energy conversion demand !**
  - buy 1 x 500 kWe unit instead of 2x 1250 kWe unit !
- **Analyze systems requirement : Process efficiency**
  - Consider waste streams that could be recovered
  - Consider heat recovery before energy conversion integration
  - Consider waste streams as resources
- **Integrate the conversion system : Energy conversion efficiency**
  - integrated system (interdependent flows)
  - draw a list of optional sub-systems
  - Optimize the flows (MILP + heat cascade)
- **Thermo-economically compare solutions : do we have money/incentives ?**
  - location/goals dependent
- **Design the system : create confidence in proposed solutions**
  - Consider system operation
  - Opportunities from system control ?





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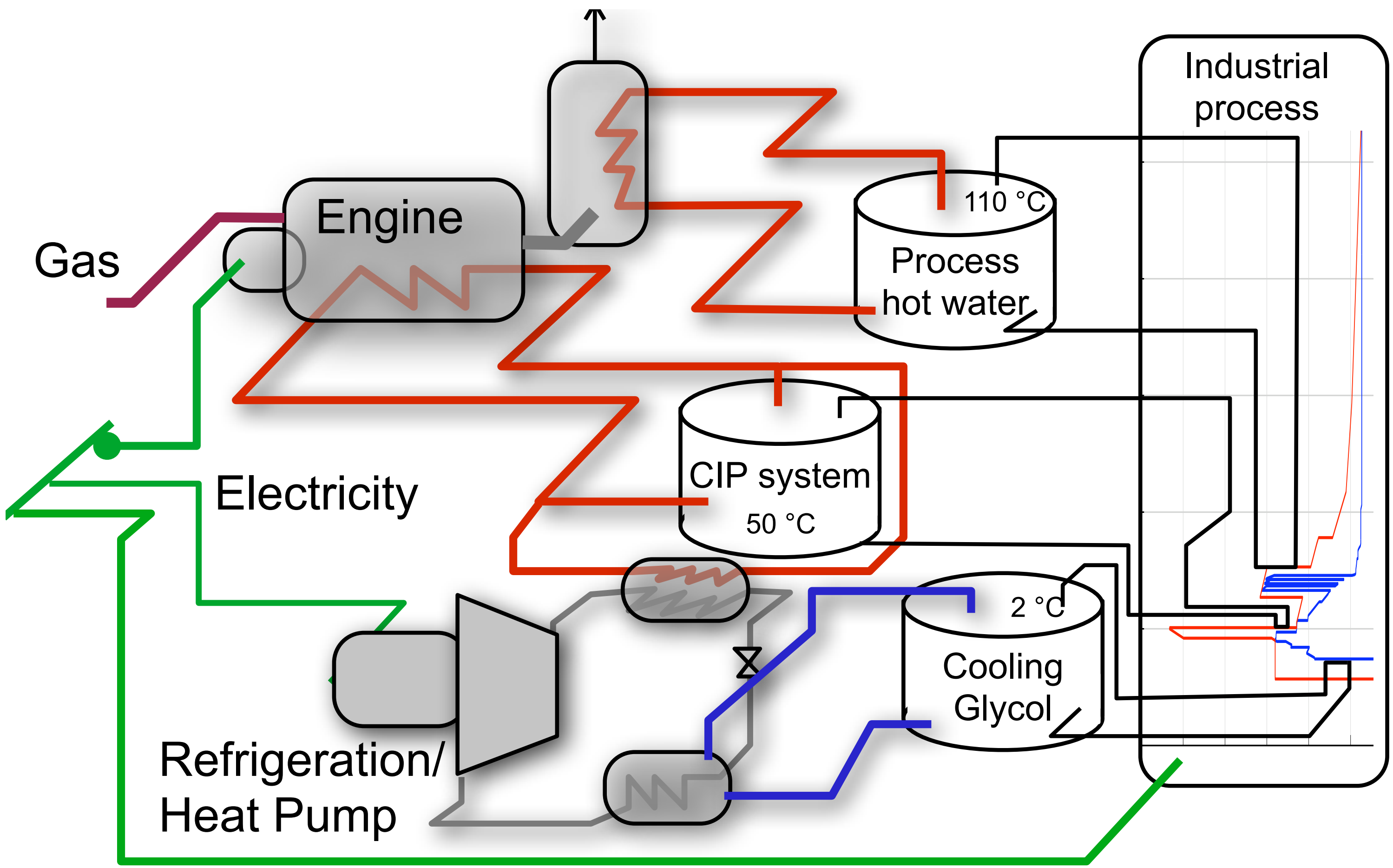
# Restricted matches

# system design + management



- Solar heat integration