IPESE Semester/master projects

Please let your assistant know if you are interested,

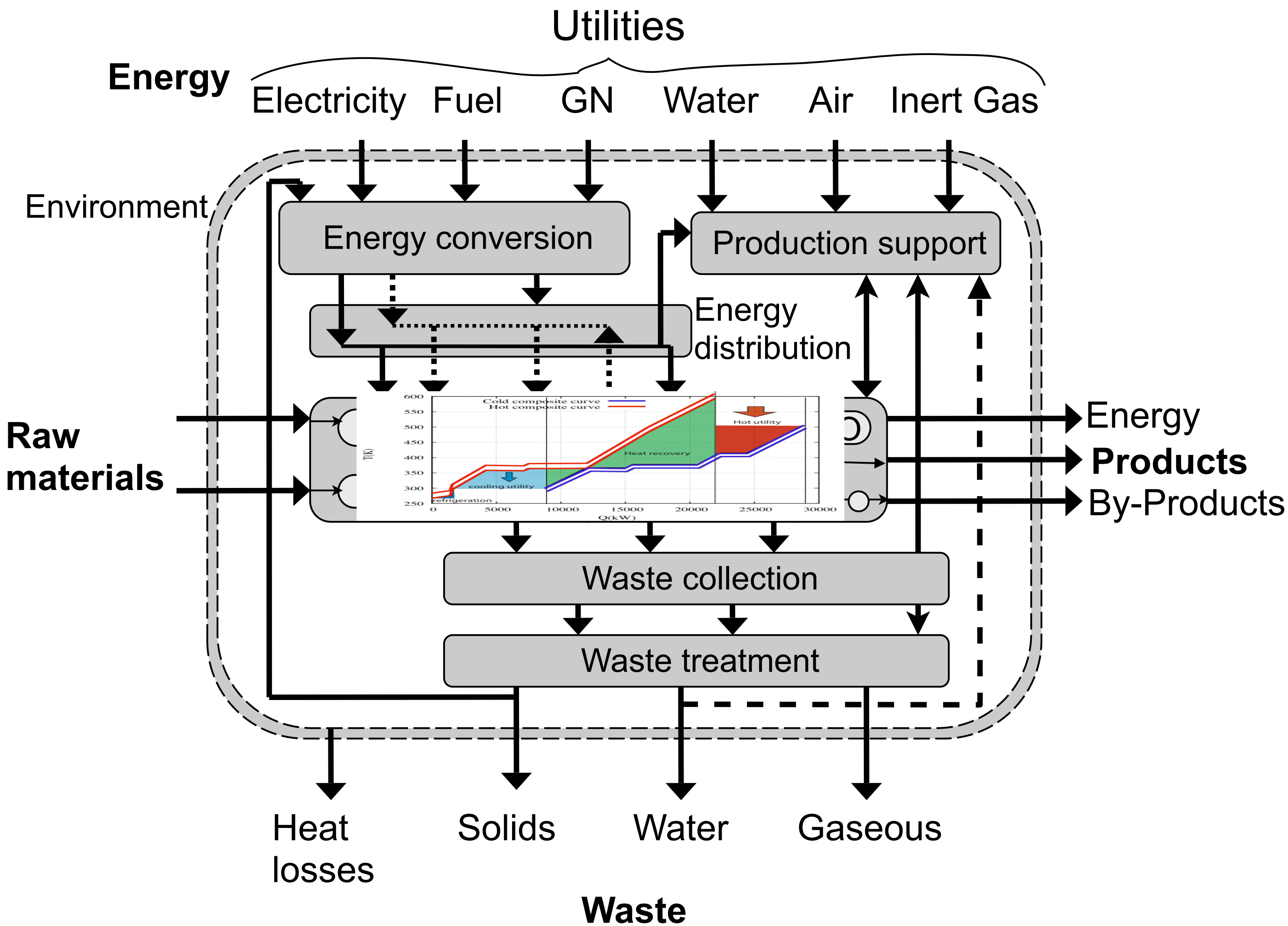
Energy conversion system integration

François Marechal

Where are we ?

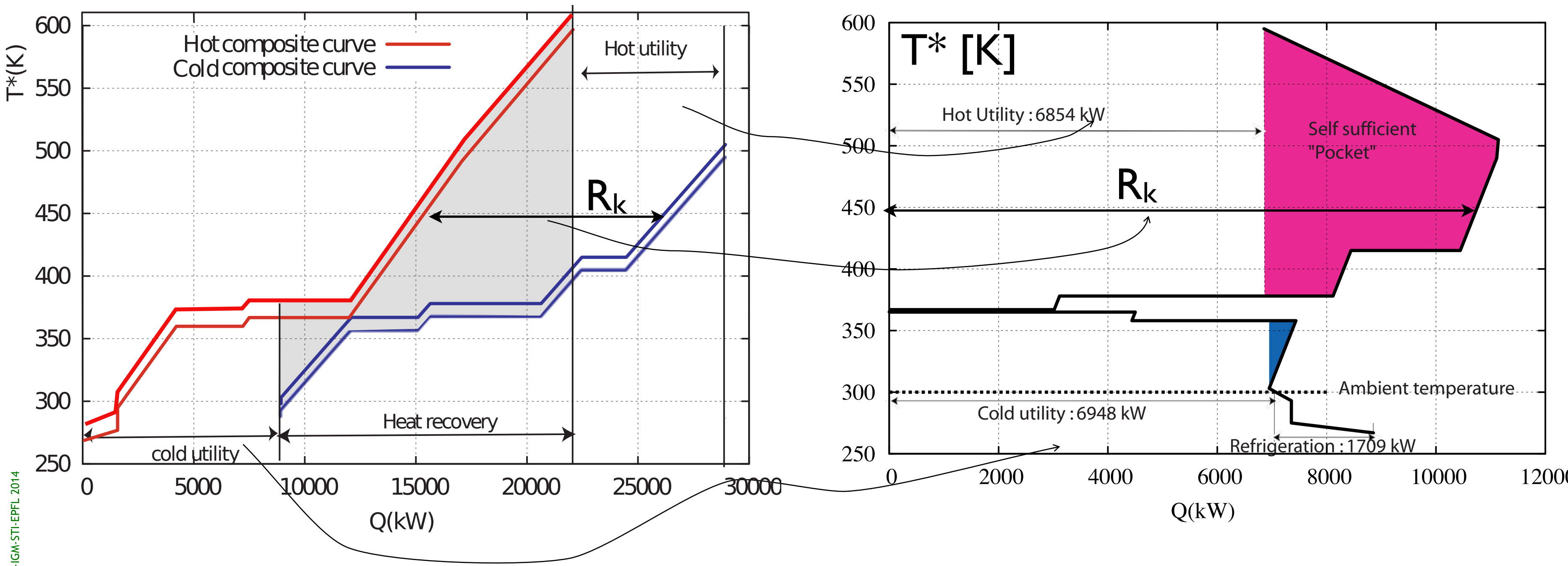
- ✓ Energy efficiency project evaluation
- ✓ DT min
- ✓ Heat recovery
- ✓ Heat exchanger network design
- Integrating the energy conversion units
- Exergy analysis of the energy conversion system
- How can mathematical programming help us
- Evaluate energy efficiency projects

Energy conversion system



Grand composite curve/Heat cascade

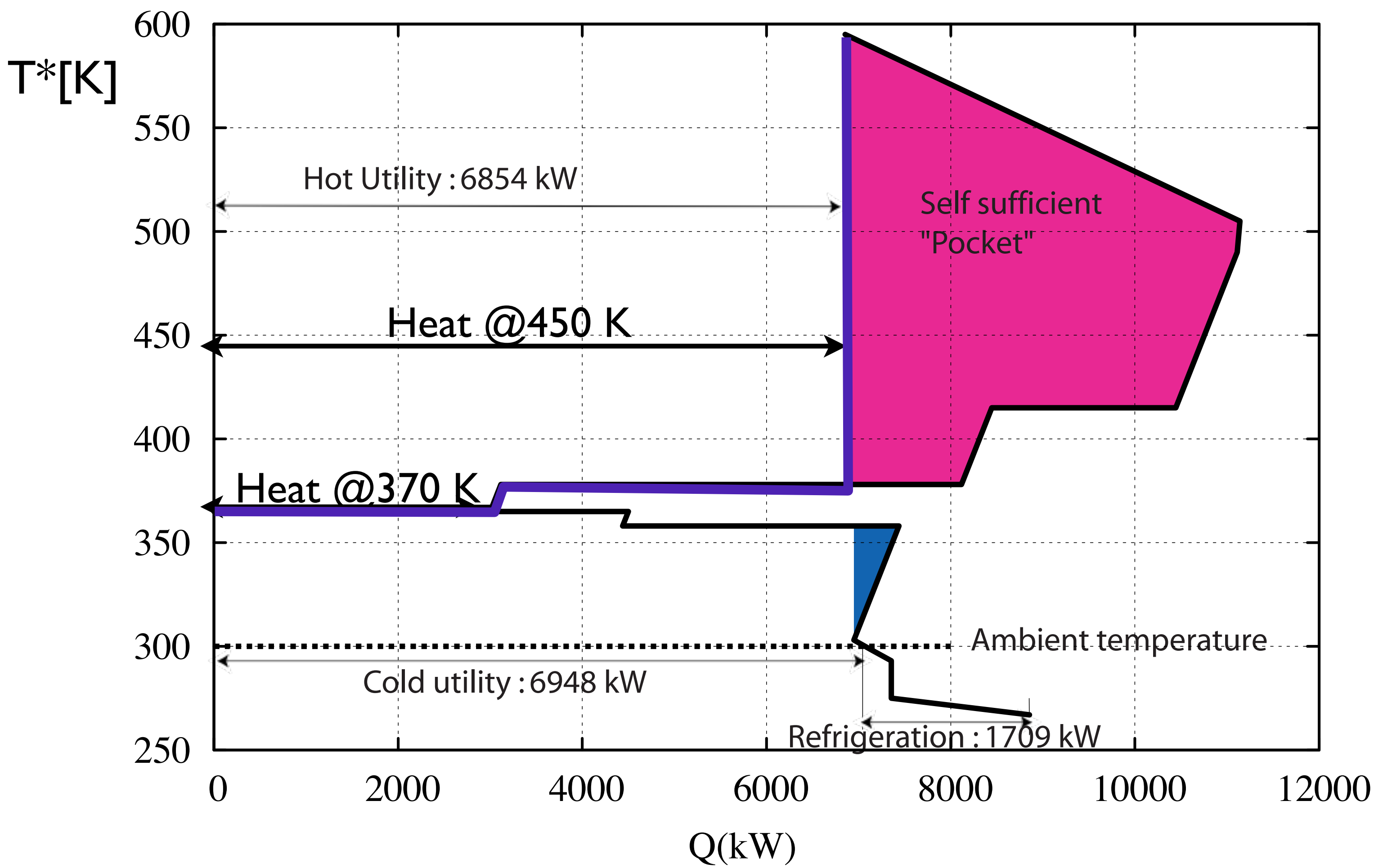
- Corrected temperature domain
- Graphical plot of the heat cascade : [R_r, T^*_r] r=1,n_r



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.

Supplying energy to the process

$$\dot{Q}^{(+)}_{r^{(+)}} = min((\min_r(R_r), \forall r = n_r + 1, ..., r^{(+)}), (\min_r(R_r), \forall r = r^{(-)}, ..., 1))$$



The heat requirement of the process appears as a cold stream to be heated by a hot utility stream whose Q-T* profile should be above the process Grand Composite

Self sufficient zones are eliminated

Grand composite curve => Heat cascade representation

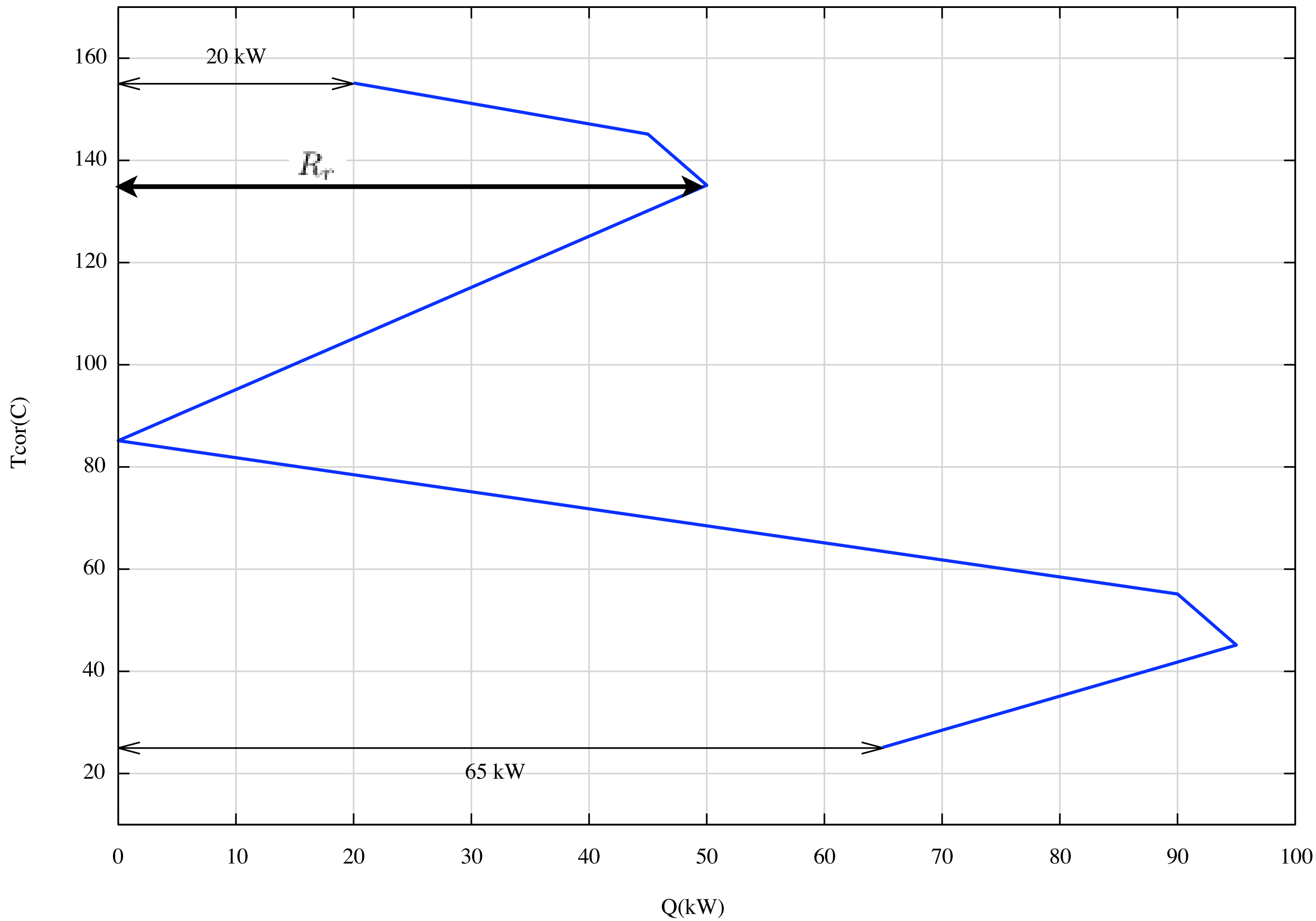
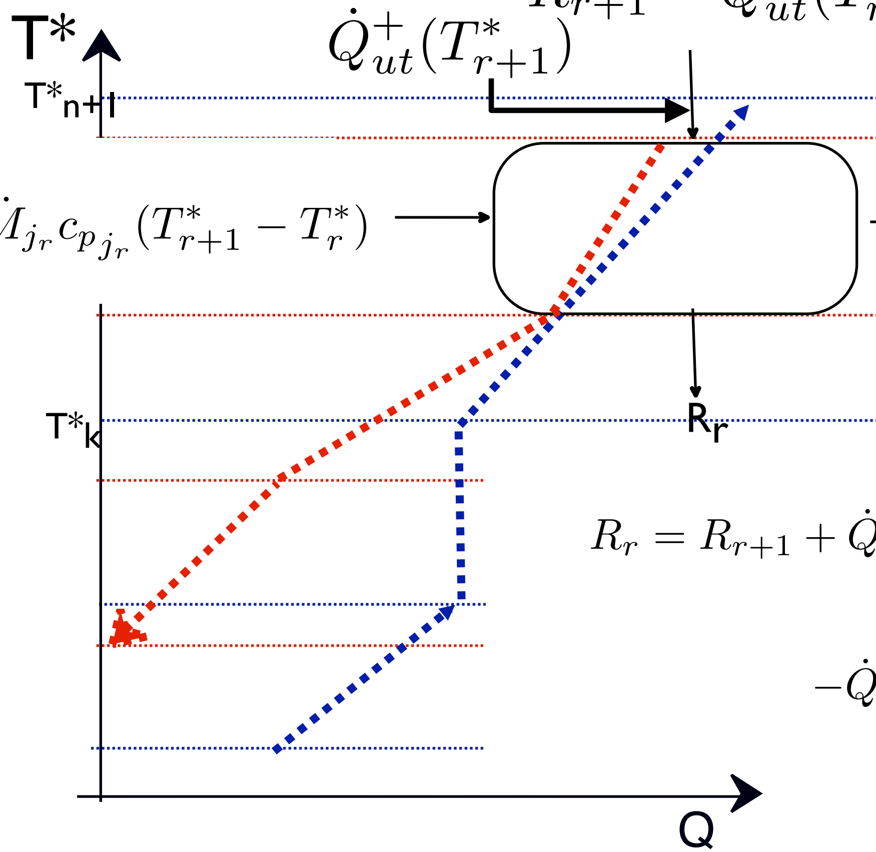


Figure 3: Grand Composite Curve

Adding a utility stream at constant temperature

Heat from the hot streams between T^*_{r+1} et T^*_r

Heat to the cold streams between T_{r+1} and T_r



$$\dot{Q}^+_{ut}(T^*_{r+1})$$

$$R_{r+1} - \dot{Q}^+_{ut}(T^*_{r+1})$$

$$\sum_{j_r=1}^{hot\ streams_r} \dot{M}_{j_r} c_{p_{j_r}} (T^*_{r+1} - T^*_r)$$

$$\sum_{i_r=1}^{cold\ streams_r} \dot{M}_{i_r} c_{p_{i_r}} (T^*_{r+1} - T^*_r)$$

$$R_r = R_{r+1} + \dot{Q}^+_{ut}(T^*_{r+1}) + \sum_{h_r=1}^{n_{HotStreams}} \dot{M}_{h_r} c_{p_{h_r}} (T^*_{r+1} - T^*_r)$$

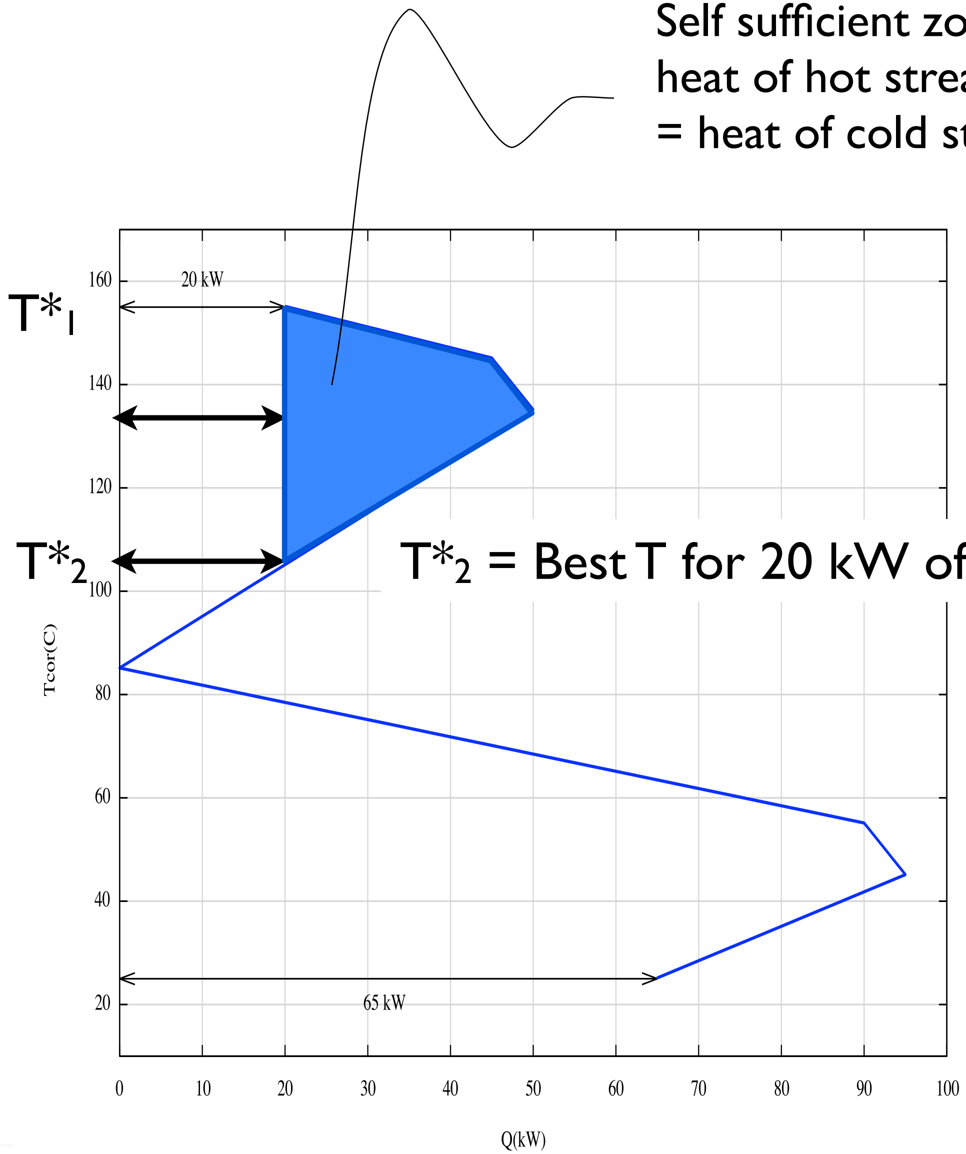
$$- \dot{Q}^-_{ut}(T^*_r) - \sum_{h_r=1}^{n_{ColdStreams}} \dot{M}_{c_r} c_{p_{c_r}} (T^*_{r+1} - T^*_r)$$

$$R_r \geq 0 \qquad \forall r \in \{1..n_r\}$$

$\dot{Q}^+_{ut}(T^*_r)$ max when $R_r = 0$

Exergy value of the utility heat load @ T_r

Self sufficient zone :
heat of hot streams between T^*_1 and T^*_2
= heat of cold streams between T^*_1 and T^*_2



T^*_2 = Best T for 20 kW of Hot utility

Exergy value of Q(T)

$$\dot{E}^{+}_{ut}(T^*_r) = \dot{Q}^{+}_{ut}(T^*_r) \cdot (1 - \frac{T_0}{(T^*_r + \Delta T_{min/2})})$$

$\dot{Q}^{+}_{ut}(T^*_r)$ max when $R_r = 0$

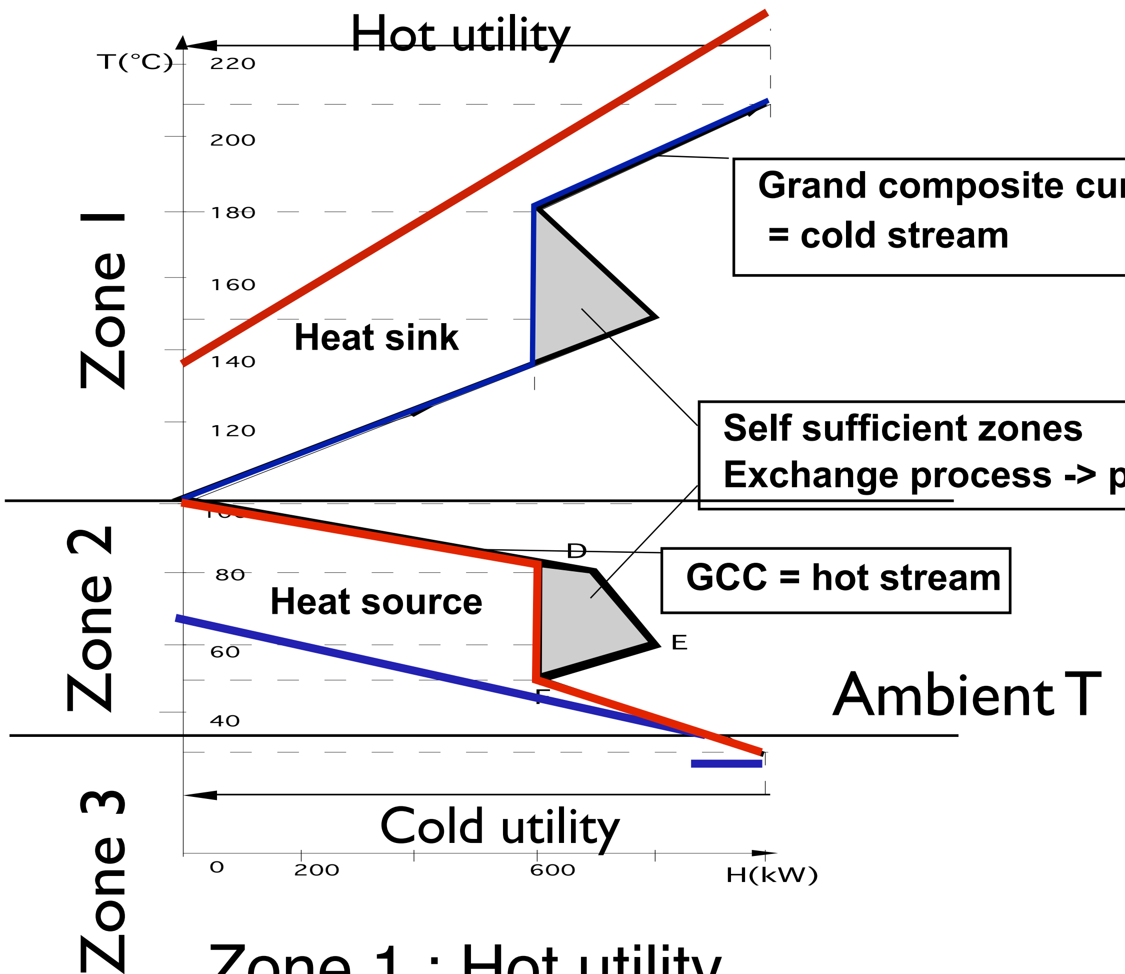
Figure 3: Grand Composite Curve

Question

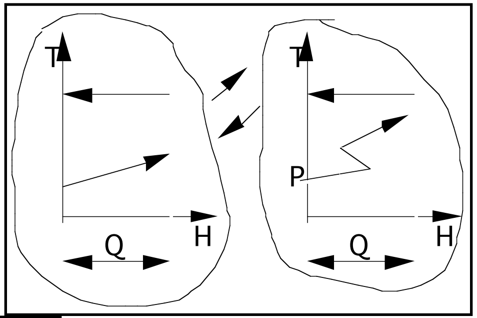
- Explain the use of the grand composite curves to define the energy conversion system of an industrial process.

EPFL

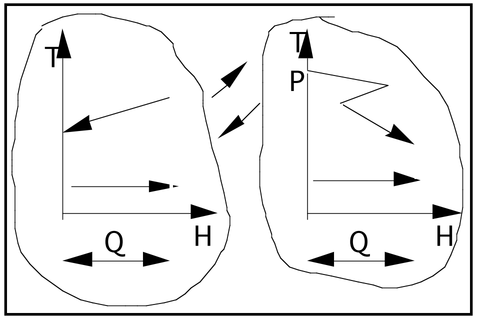
Utility integration principle



Counter current analogy
Hot utility - cold process



Counter current analogy
Hot process - cold utility



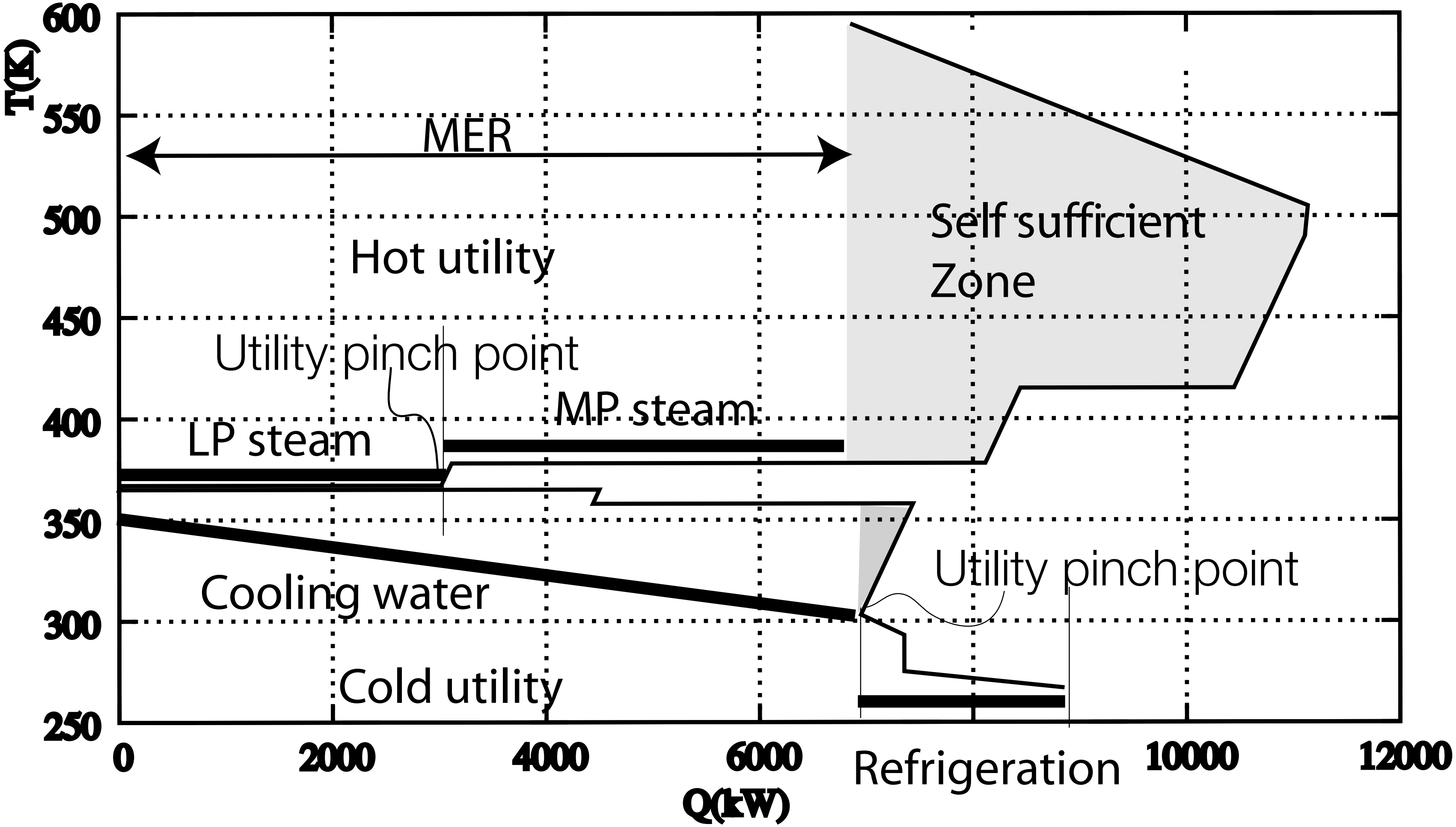
Zone 1 : Hot utility

Zone 2 : Cold utility

Zone 3 : Refrigeration

Multiple utilities

Maximise the use of the cheapest utility



Question

- Explain the integration of combustion and the conditions under which the efficiency can be improved using air preheating.
- Explain how the cost of energy is calculated, and how the fuel flow can be calculated.

Supplying heat by combustion

$C_vH_wS_xO_yN_z$

fuel

air

$$(\frac{v+\frac{w}{4}+z+x-\frac{y}{2}}{0.21})*(1+\lambda_a)*(0.21O_2+0.79N_2)$$

$$vC+vO_2=vCO_2$$

$$wH+\frac{w}{4}O_2=\frac{w}{2}H_2O$$

$$zN+zO_2=zNO_2$$

$$xS+xO_2=xSO_2$$

λ_a : air excess

All the expressions are molar expressions

1 kmol of a compound corresponds to 6,022·10^{26} molecules or atoms (number of Avogadro, universal constant).

If the heat of reaction is used to heat up the combustion gases, the combustion gases reach the adiabatic temperature of combustion

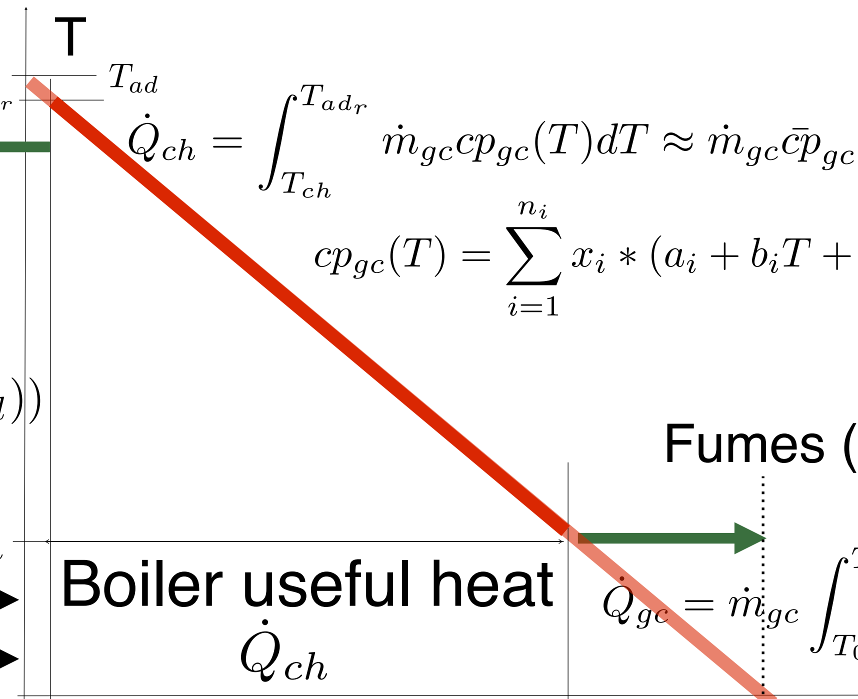
Combustion gases

$$(\frac{v+\frac{w}{4}+z+x-\frac{y}{2}}{0.21})*(1+\lambda_a)*(0.79N_2)+(\frac{v+\frac{w}{4}+z+x-\frac{y}{2}}{0.21})*(\lambda_a)*(0.21O_2)+vCO_2+\frac{w}{2}H_2O+zNO_2$$

Boiler efficiency calculation

Useful heat depends on the temperature of the heat requirement

$$\dot{Q}_{ch} = \dot{Q}_{fuel} + \dot{Q}_{air} - (\dot{Q}_r + \dot{Q}_{gc})$$



Radiative losses (1-2%) $\dot{Q}_r$

$$\dot{Q}_r = \int_{T_{ad_r}}^{T_{ad}} \dot{m}_{gc} cp_{gc}(T)dT \approx 2\% \cdot \int_{T_0}^{T_{ad}} \dot{m}_{gc} cp_{gc}(T)dT$$

$$\dot{Q}_{ch} = \int_{T_{ch}}^{T_{ad_r}} \dot{m}_{gc} cp_{gc}(T)dT \approx \dot{m}_{gc} \bar{cp}_{gc}(T_{ad_r} - T_{ch})$$

$$cp_{gc}(T) = \sum_{i=1}^{n_i} x_i * (a_i + b_i T + c_i T^2 + d_i T^3)$$

$$\dot{Q}_{fuel} = \dot{m}_{fuel}(LHV_{fuel} + \hat{h}_{fuel}(T_{fuel}))$$

$$\hat{h}_{fuel}(T_{fuel}) = \int_{T_0}^{T_{fuel}} cp_{fuel}(T)dT + \alpha_{fuel} \Delta h_{vap}(T_{fuel})$$

Fumes (Chimney)

$$\dot{Q}_{gc} = \dot{m}_{gc} \int_{T_0}^{T_{ch}} cp_{gc}(T)dT$$

Hot gases losses

Fuel

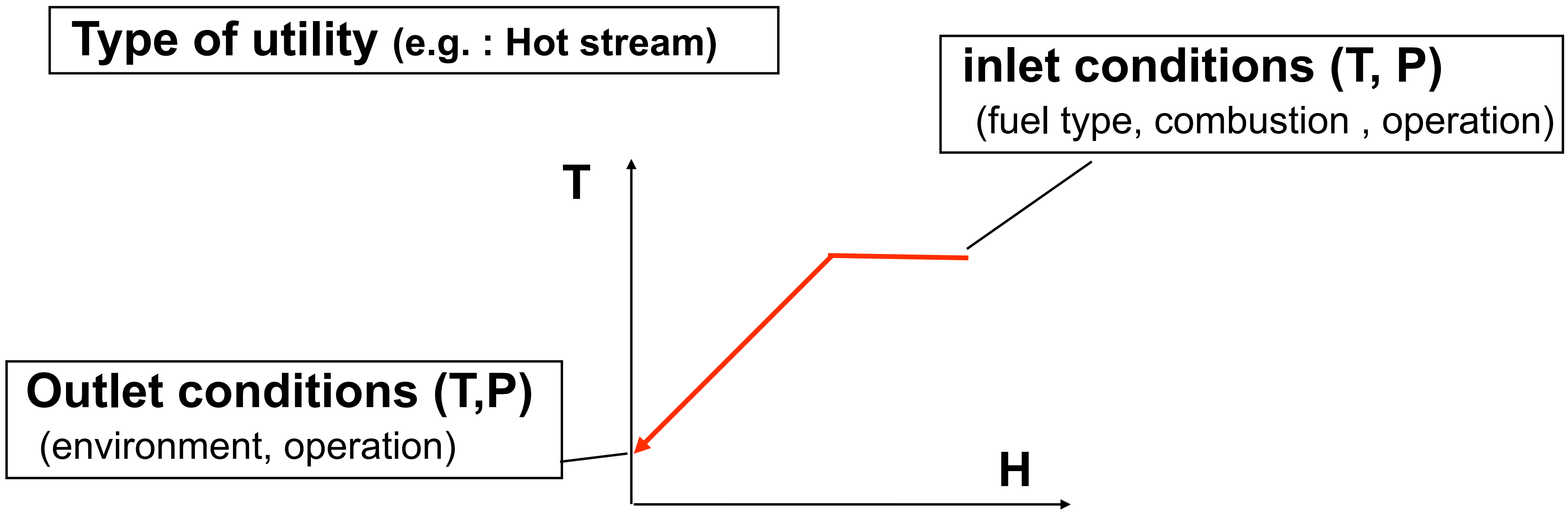
O2 (air)

Air inlet

$$\dot{Q}_{air} = \dot{m}_{air}(\hat{h}_{air}(T_{air}))$$

$$\dot{Q}^+_{air} = \dot{m}^+_{air}(h_{air}(T_{air}) - h_{air}(T_0))$$

Utility stream definition

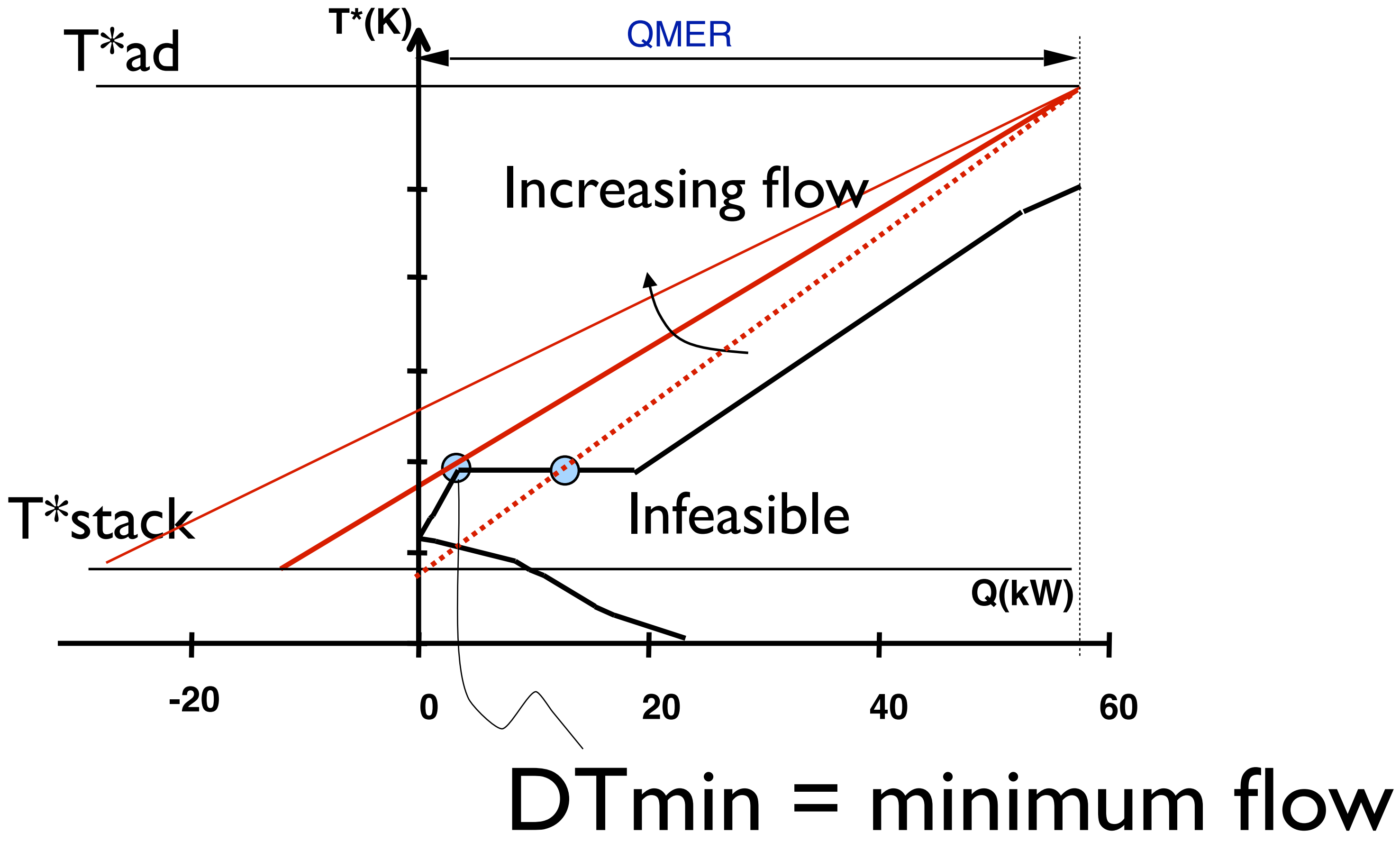


- H-T diagram
- Cost as a function of flowrate
  - Specific Investment [CHF/year/Flowref]
  - Specific Operation [CHF/kg*kg/s/Flowref]*[s/year]

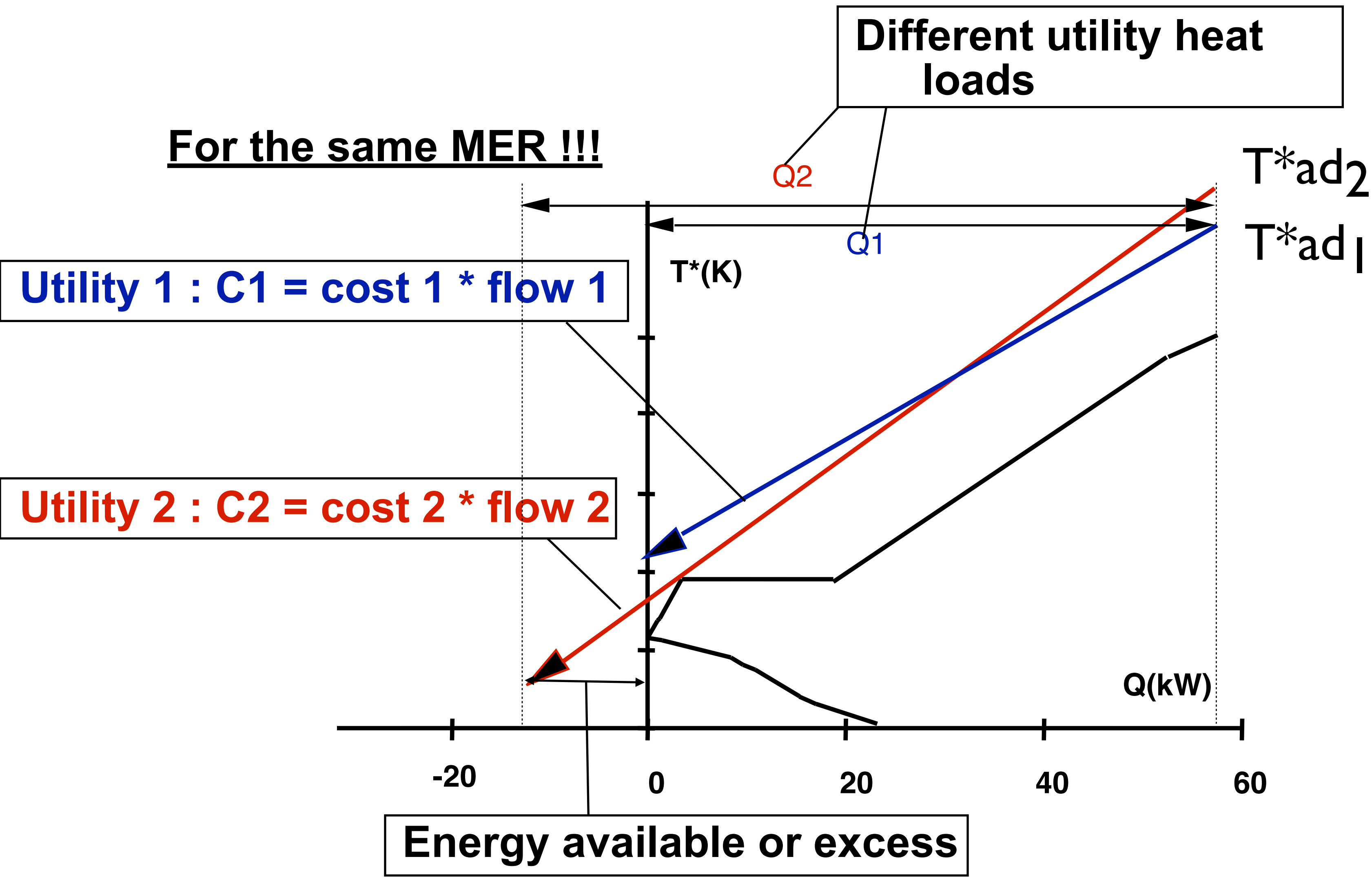
=> **Flow [kg/s = mult* Flowref] to be determined to satisfy the requirements at Minimum Costs.**

Utility flow definition

Utility cost : C(CHF/s) = cost(CHF/kg) * flow(kg/s)



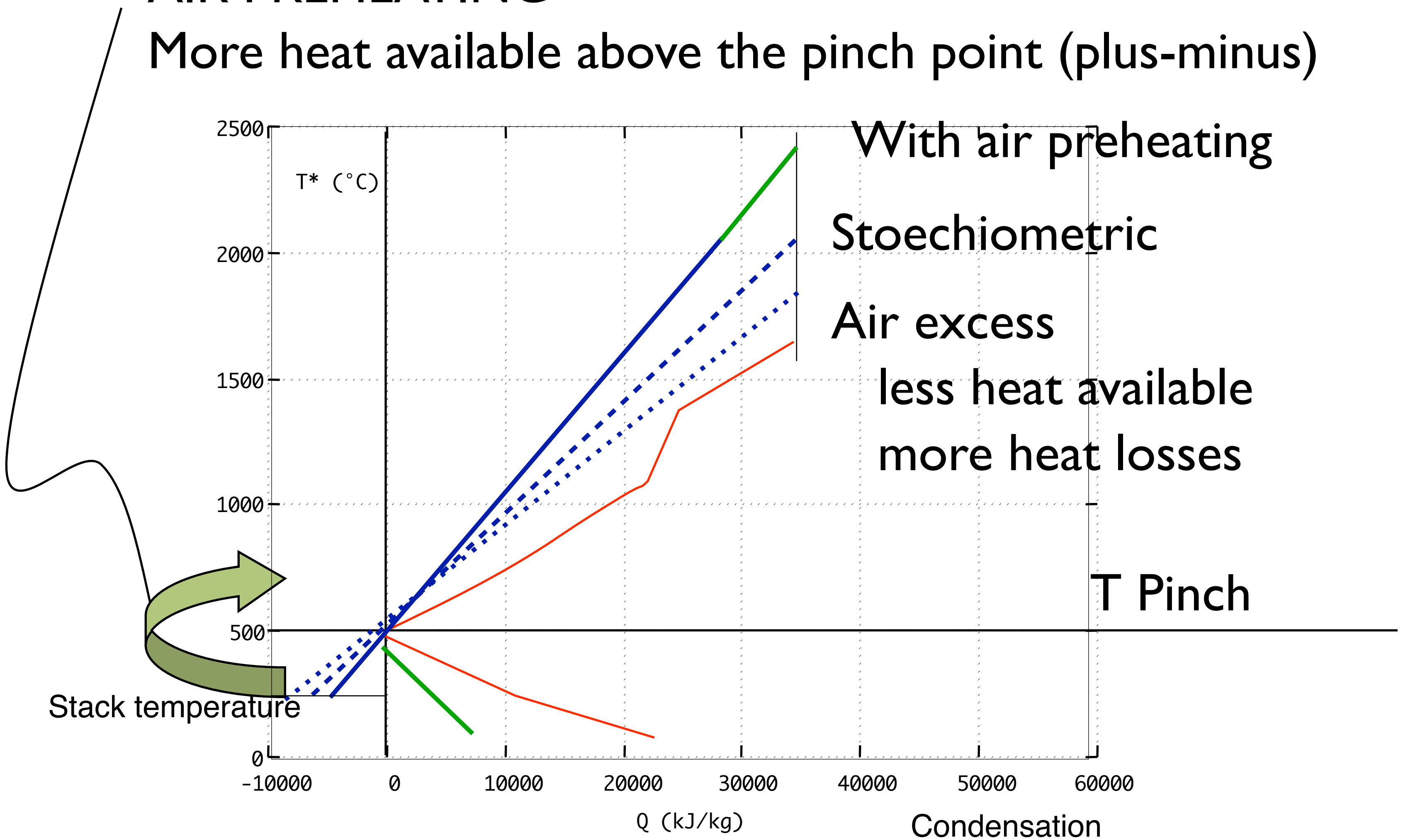
Different fuels



COMBUSTION INTEGRATION : Plus-Minus

AIR PREHEATING

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

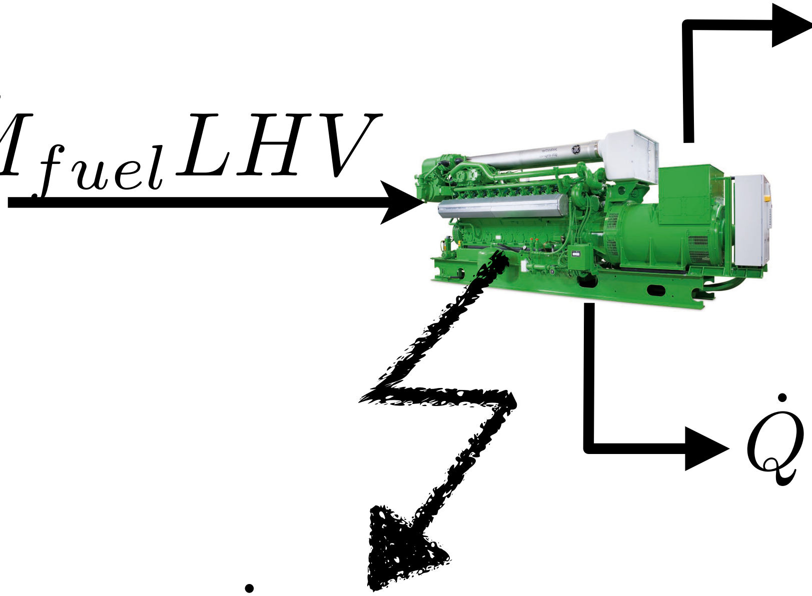


Question

- Explain the principle of the integration of a combined heat and power production unit.

Cogeneration system : Energy Balance

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



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

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

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

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

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

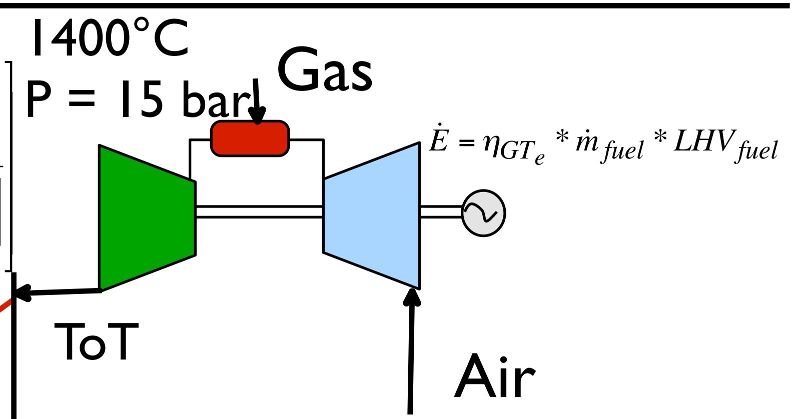
The benefit of the system mainly depends on the negociated prices for Electricity (net balance to be considered) and heat

Importance of the operating time : t

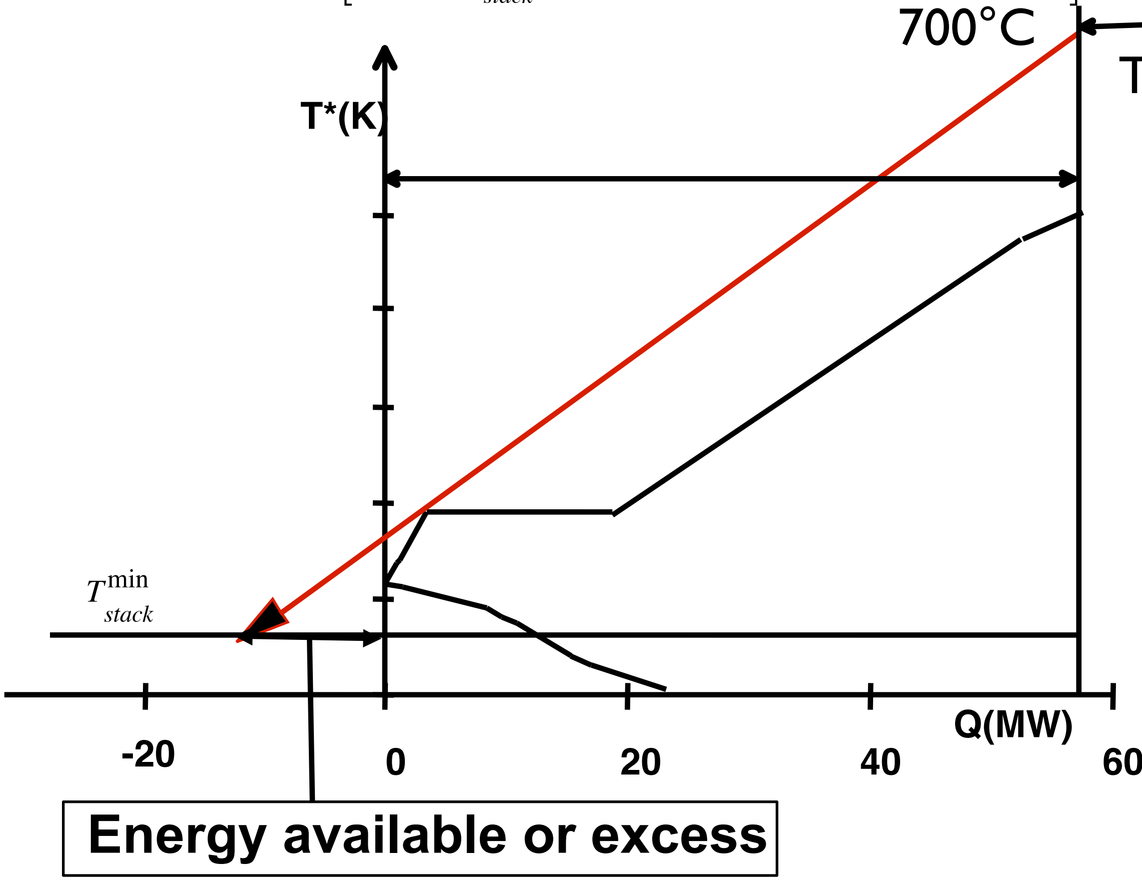
EPFL

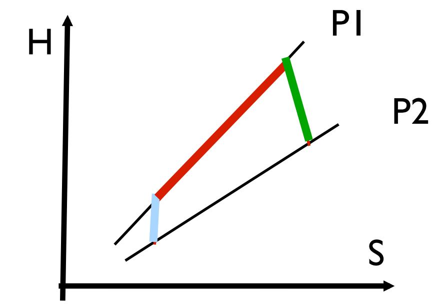
Cogeneration : gas turbines

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



$$\dot E = \eta_{GT_e} * \dot m_{fuel} * LHV_{fuel}$$





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

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

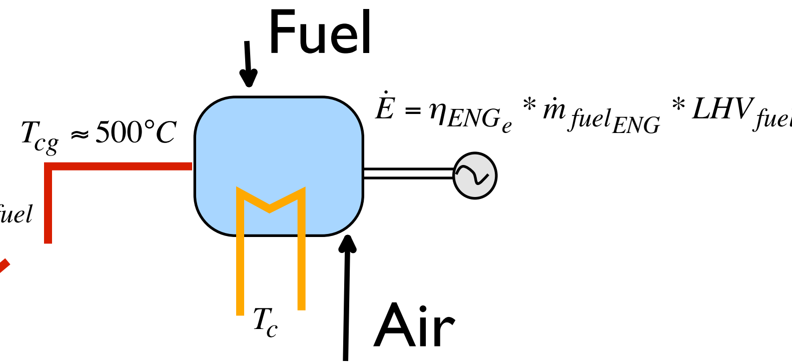
=> 120°C

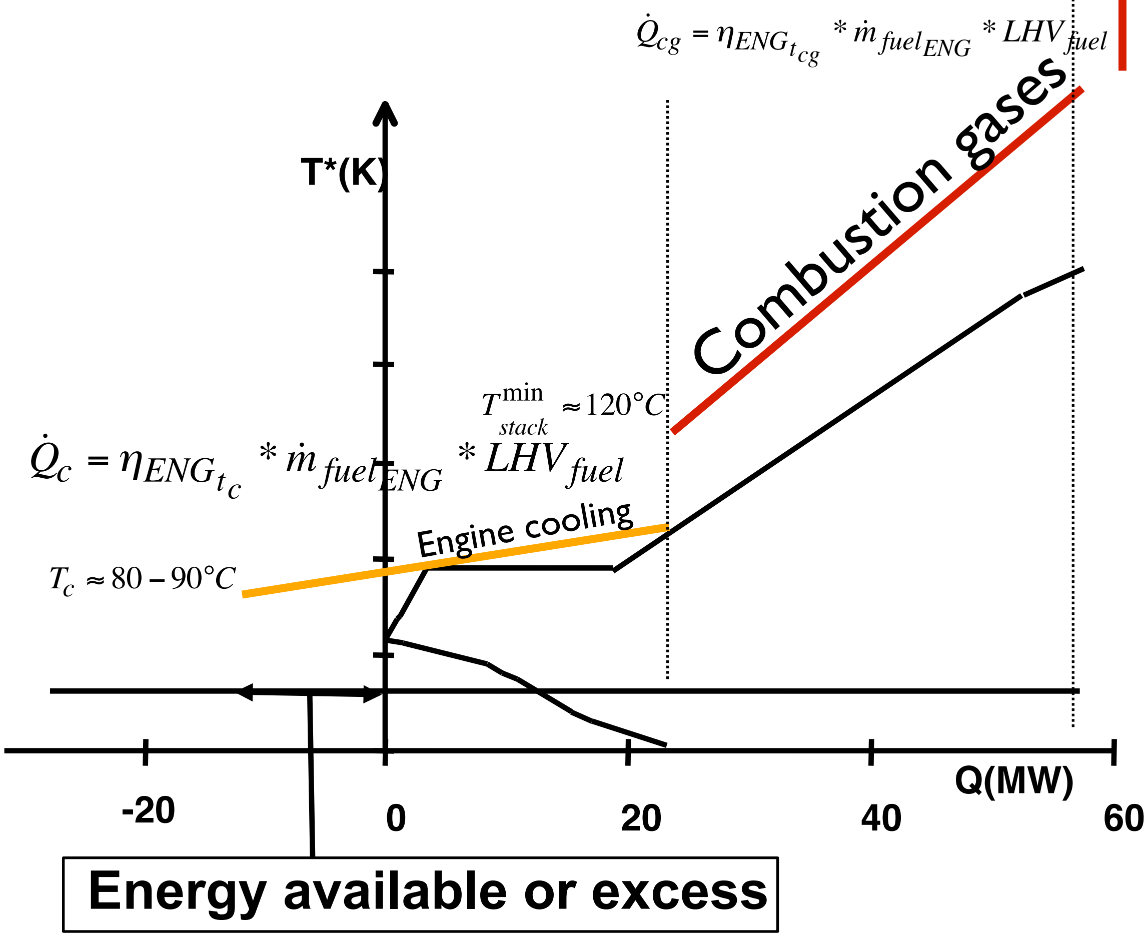
$$\eta_{GT} = 85\%$$

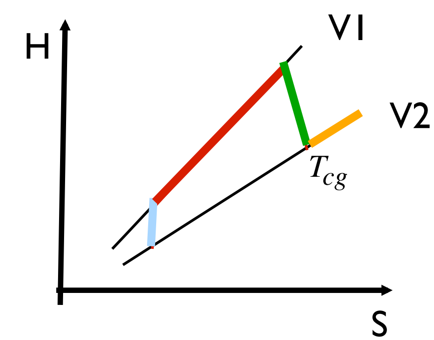
CAPEX = 1000 - 2500 CHF/kWe
Size = 50000 - 1000 kWe

Cogeneration engines

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







$$\eta_e = 35\%$$

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

$$\eta_{t_{cg}} = 25\% \quad \Rightarrow 120°C$$

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

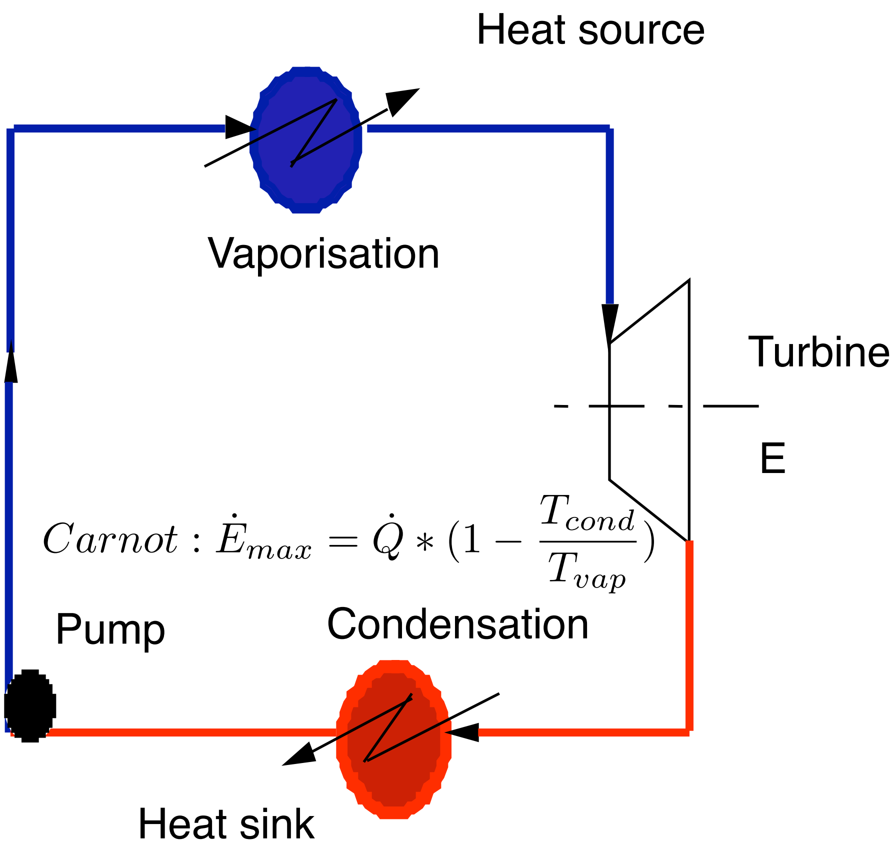
EPFL

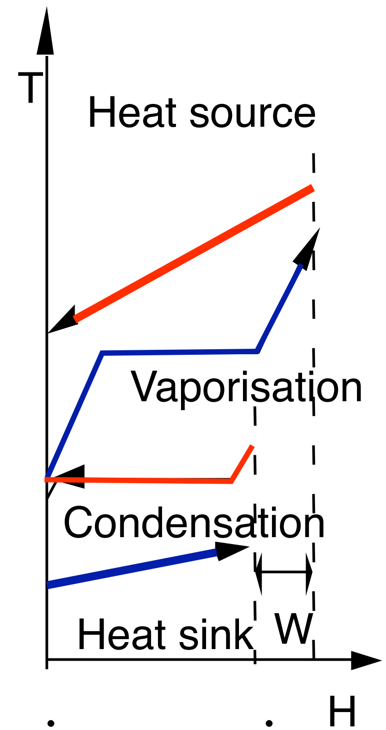
Combined heat and power

Example : Rankine cycle

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

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



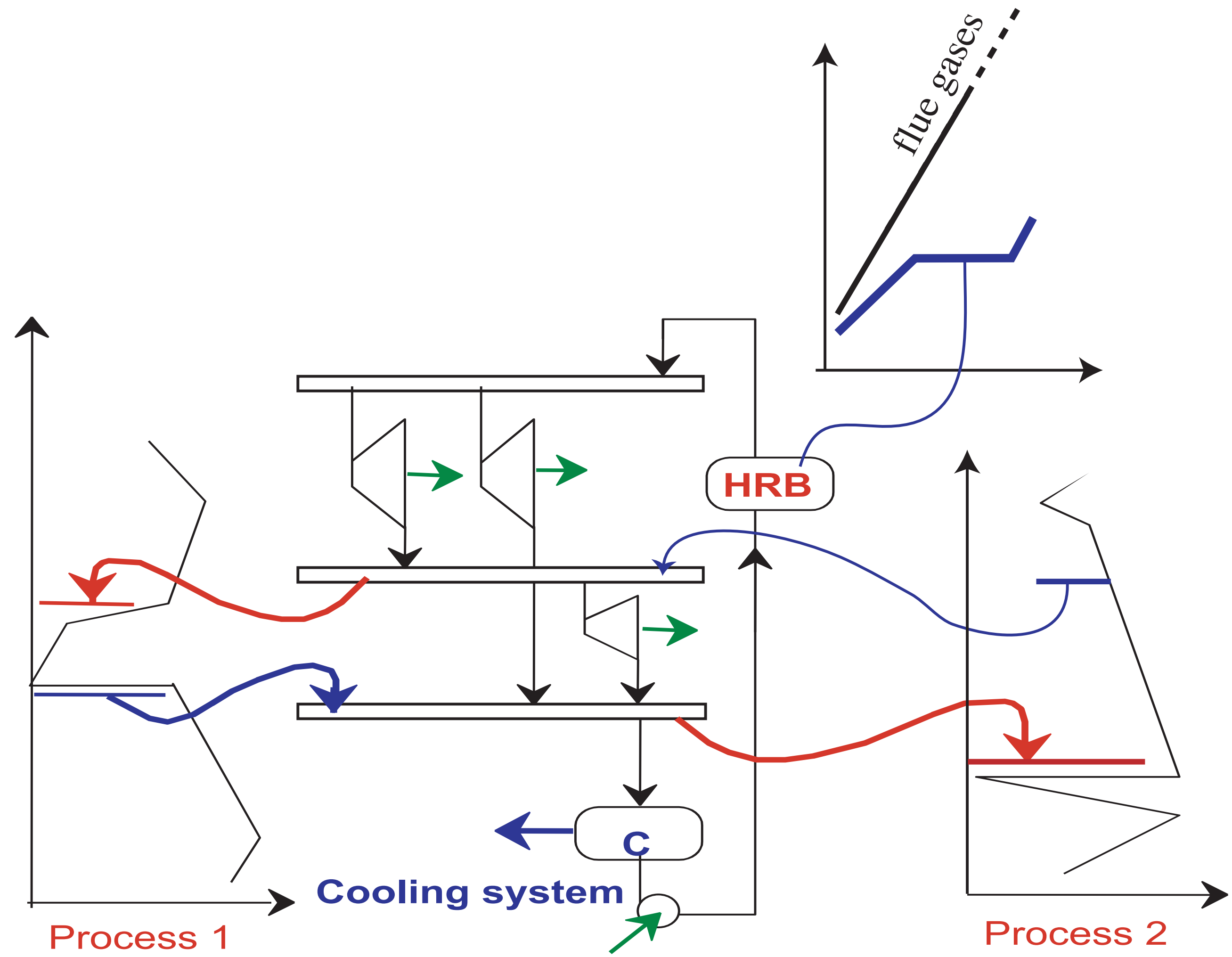


$$\dot{Q}_{low} = \dot{Q}_{hot} - \dot{E}$$

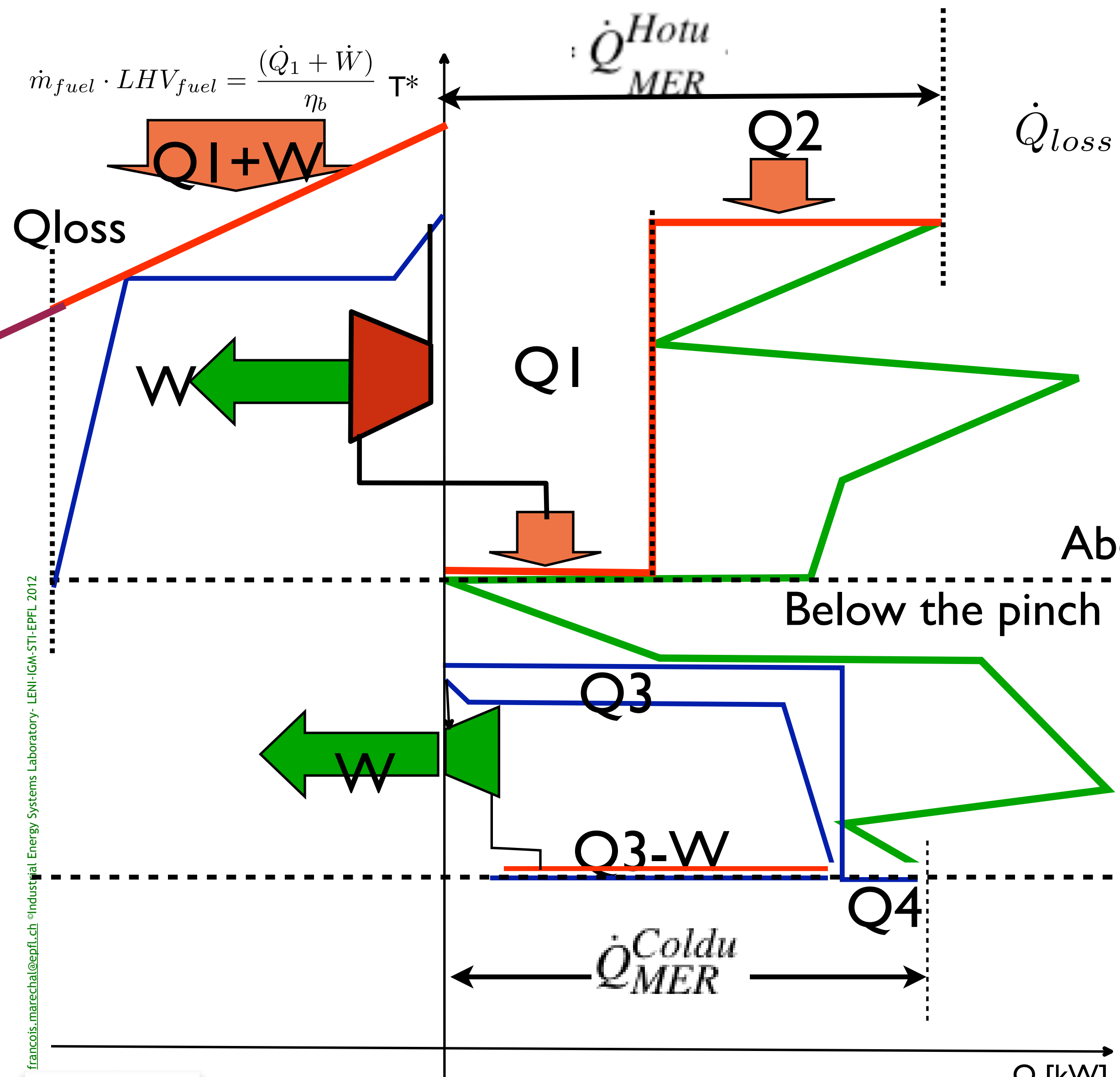
Carnot Factor between the high (source) and the low (sink) temperature of the source can be used to approximate the mechanical power production. The 0.55 efficiency with respect to Carnot is a good aproximation. Mean temperatures are logarithmic mean temperatures.

EPFL

Steam network integration



Combined heat and power



New Hot Utility

$$\dot{Q}_{loss} + \dot{Q}_1 + \dot{W} + \dot{Q}_2 = \dot{Q}^{Hotu}_{MER} + \dot{W}$$

Marginal efficiency

$$\eta_e = \frac{\dot{W}}{\frac{\Delta \dot{Q}}{\eta_b}} = \frac{\dot{W}}{\frac{\dot{W}}{\eta_b}} = \eta_b$$

Above the pinch

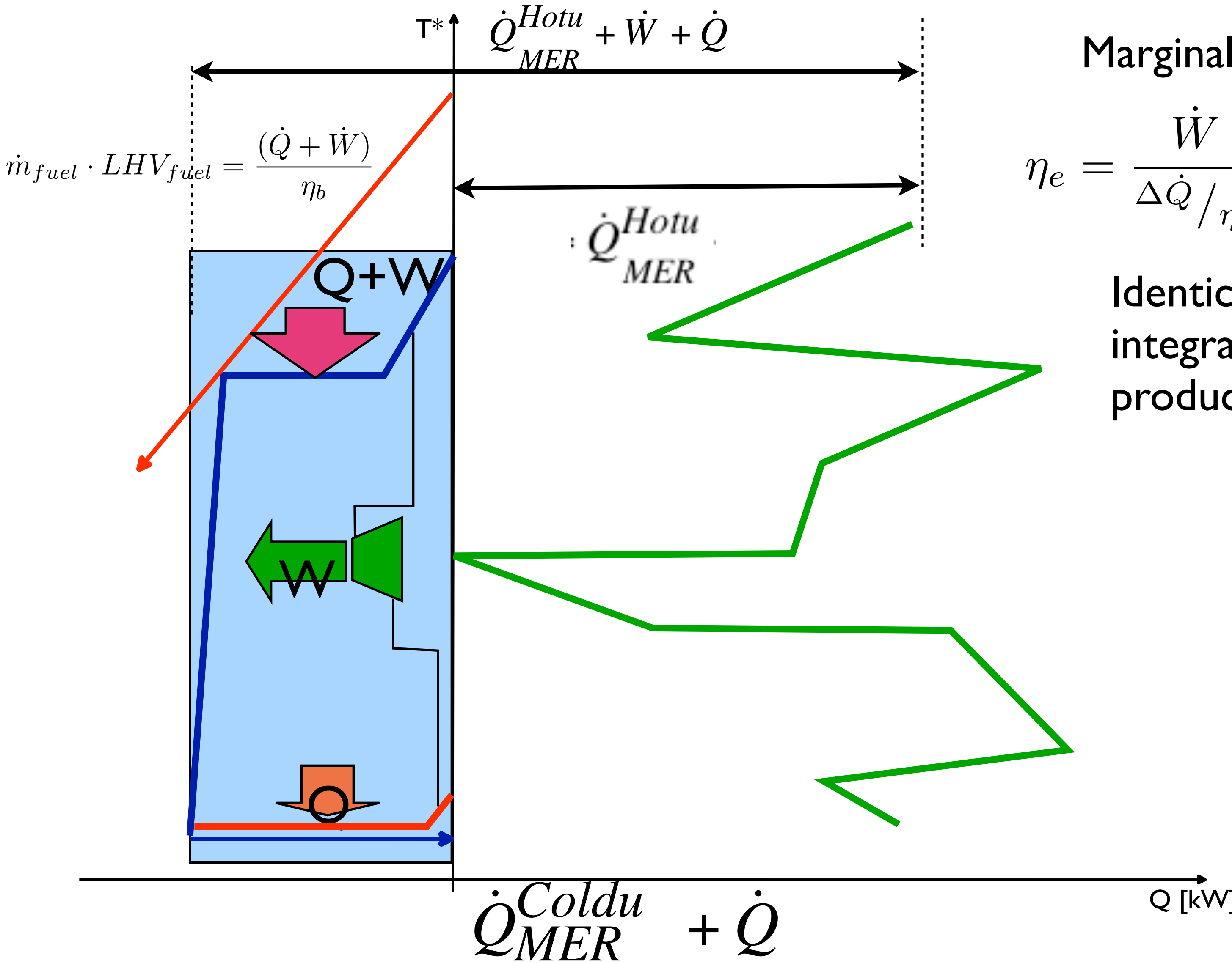
New Cold Utility

$$\dot{Q}_3 - W + \dot{Q}_4 = \dot{Q}^{Coldu}_{MER} - \dot{W}$$

$$\dot{W}(T) = \eta_{Carnot} \cdot \dot{Q}(T) \cdot (1 - \frac{T_0}{T})$$

Ambient temperature

Combined heat and power



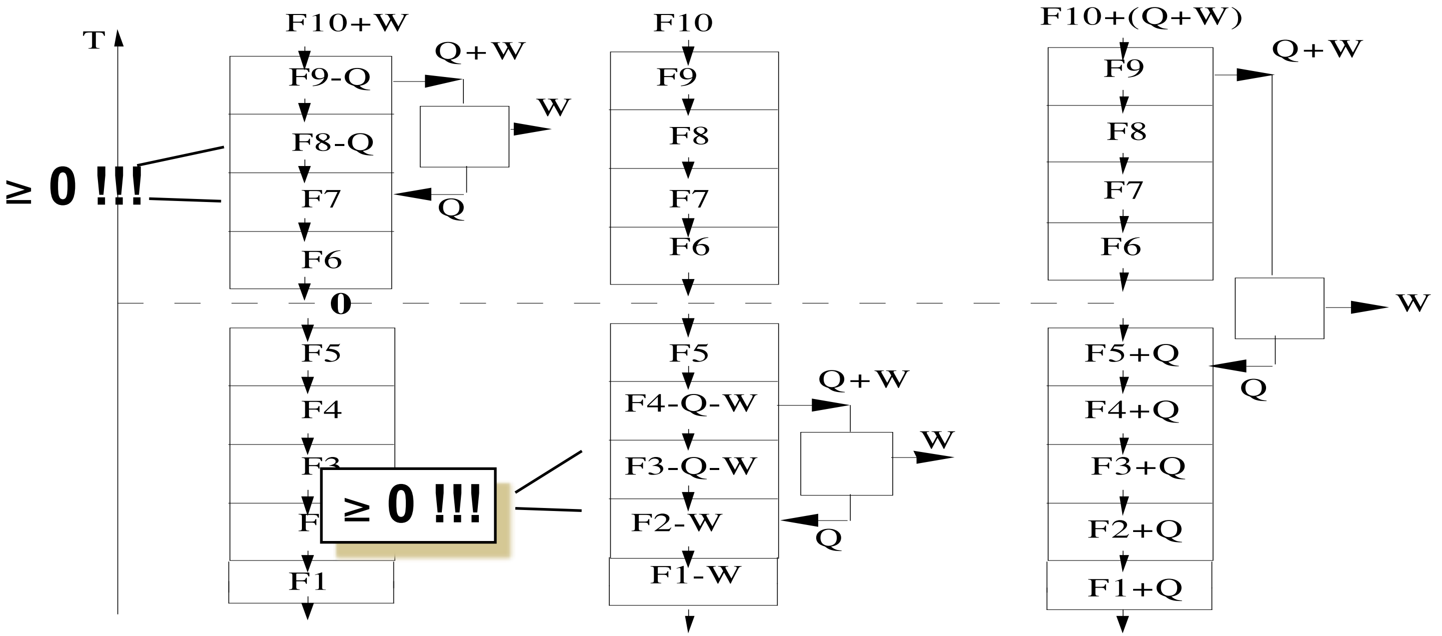
Marginal efficiency

$$\eta_e = \frac{\dot{W}}{\Delta\dot{Q}/\eta_b} = \frac{\dot{W}}{\frac{(\dot{Q}+\dot{W})}{\eta_b}}$$

Identical to non integrated power production

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



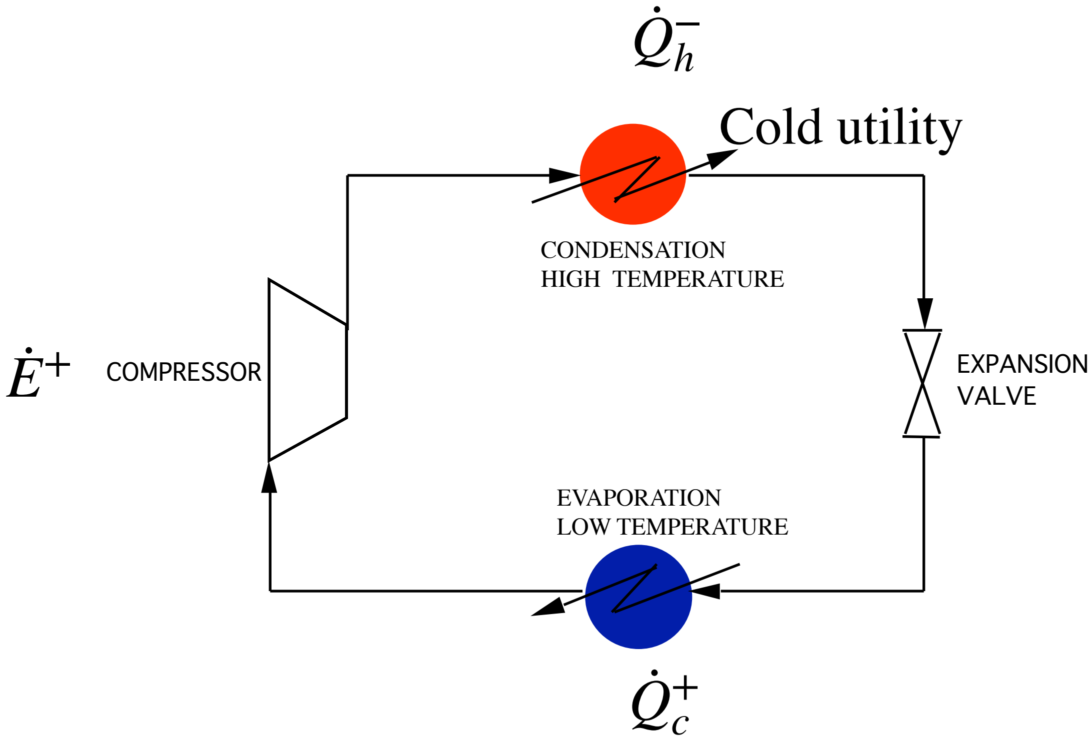
The pinch constraints limit the CHP production

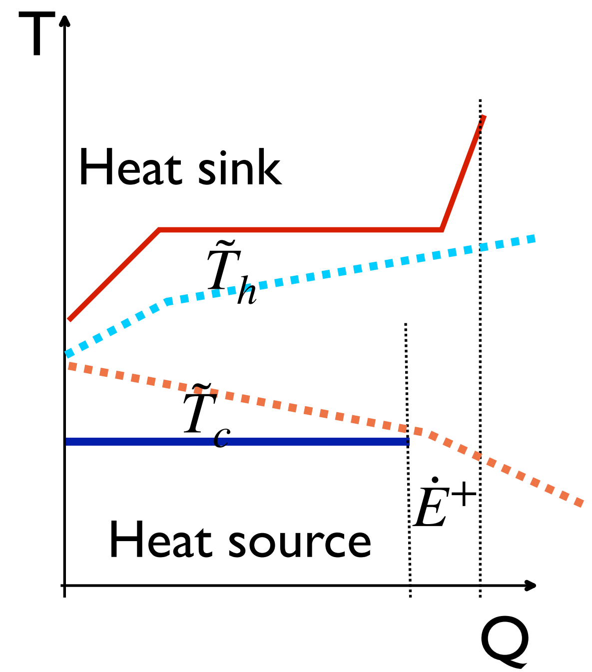
The cogeneration unit integrates a hot and a cold stream in the heat cascade. The flow will therefore be limited by the activation of a utility pinch point. This pinch point will define the maximum combined production of heat and electricity for the selected system.

- Explain the calculation of the investment and the benefits that result from a combined heat power production unit.

- Explain the conditions of integration of heat pumping systems.

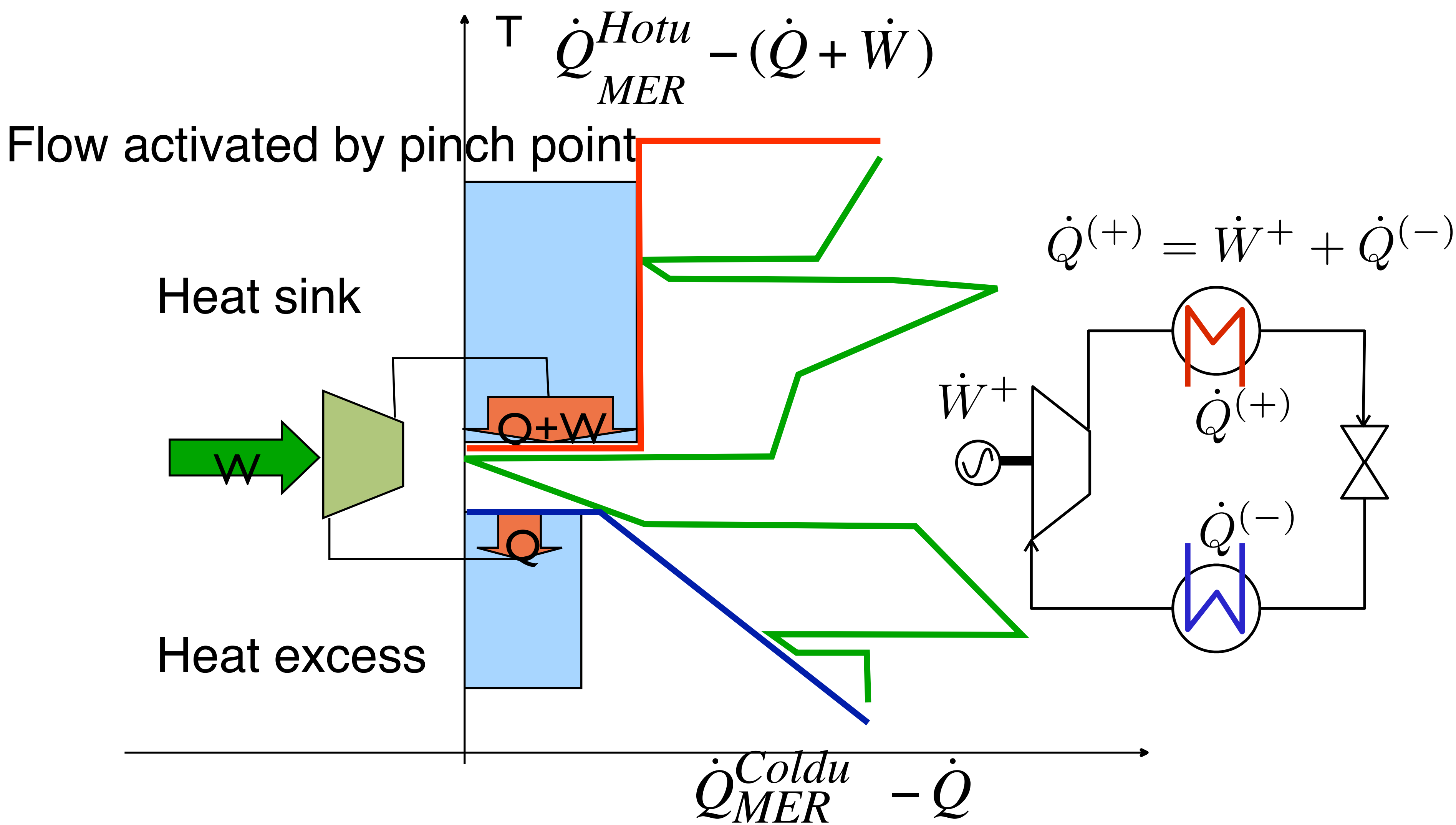
Heat pump and refrigeration



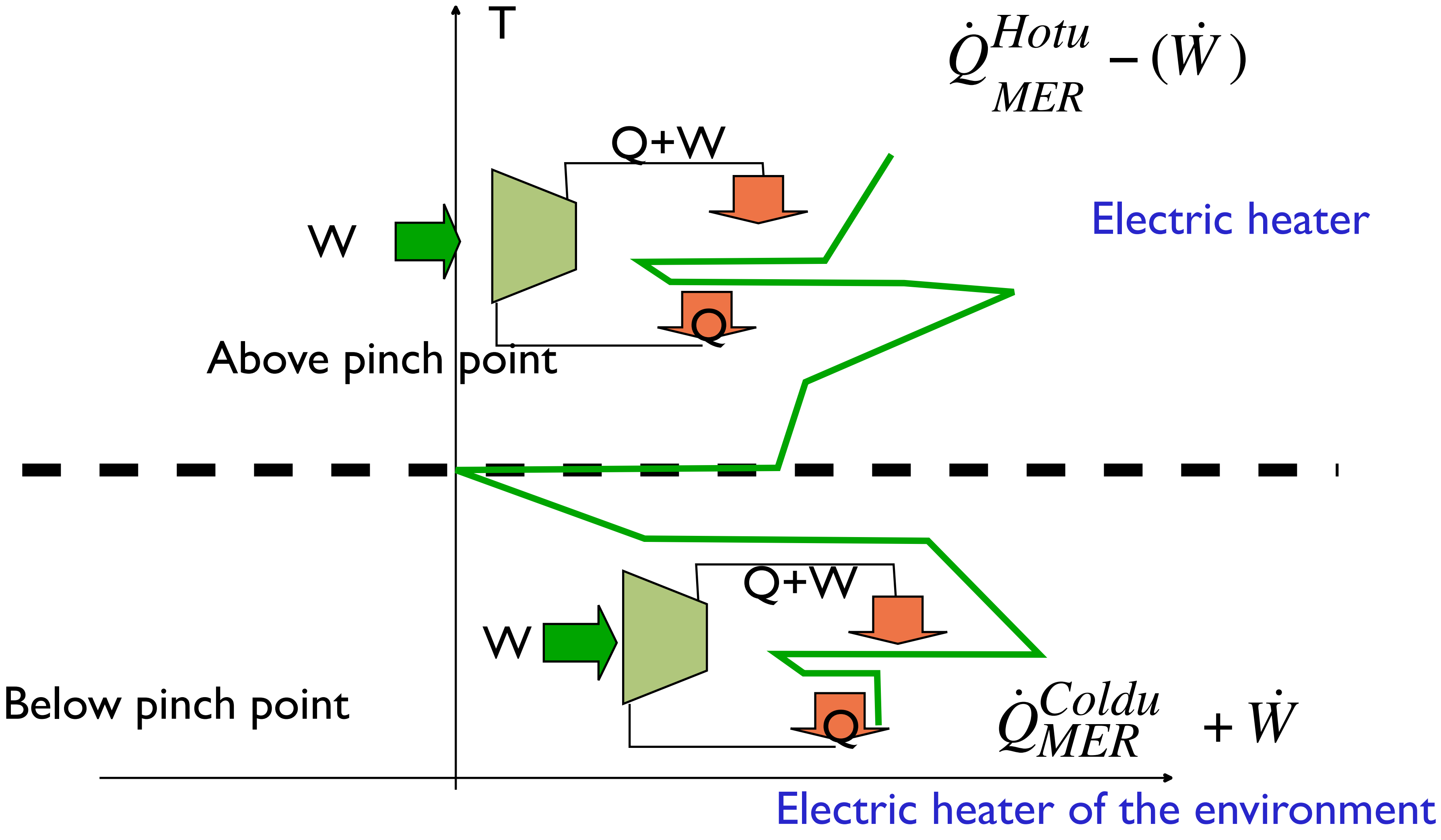


$$COP = \frac{\dot{Q}_h^-}{\dot{E}^+} = \frac{1}{\eta_{Carnot}} \cdot \frac{\tilde{T}_h}{\tilde{T}_h - \tilde{T}_c}$$

Heat pumping always from below to above the pinch



Miss placed heat pumps : above or below the pinch

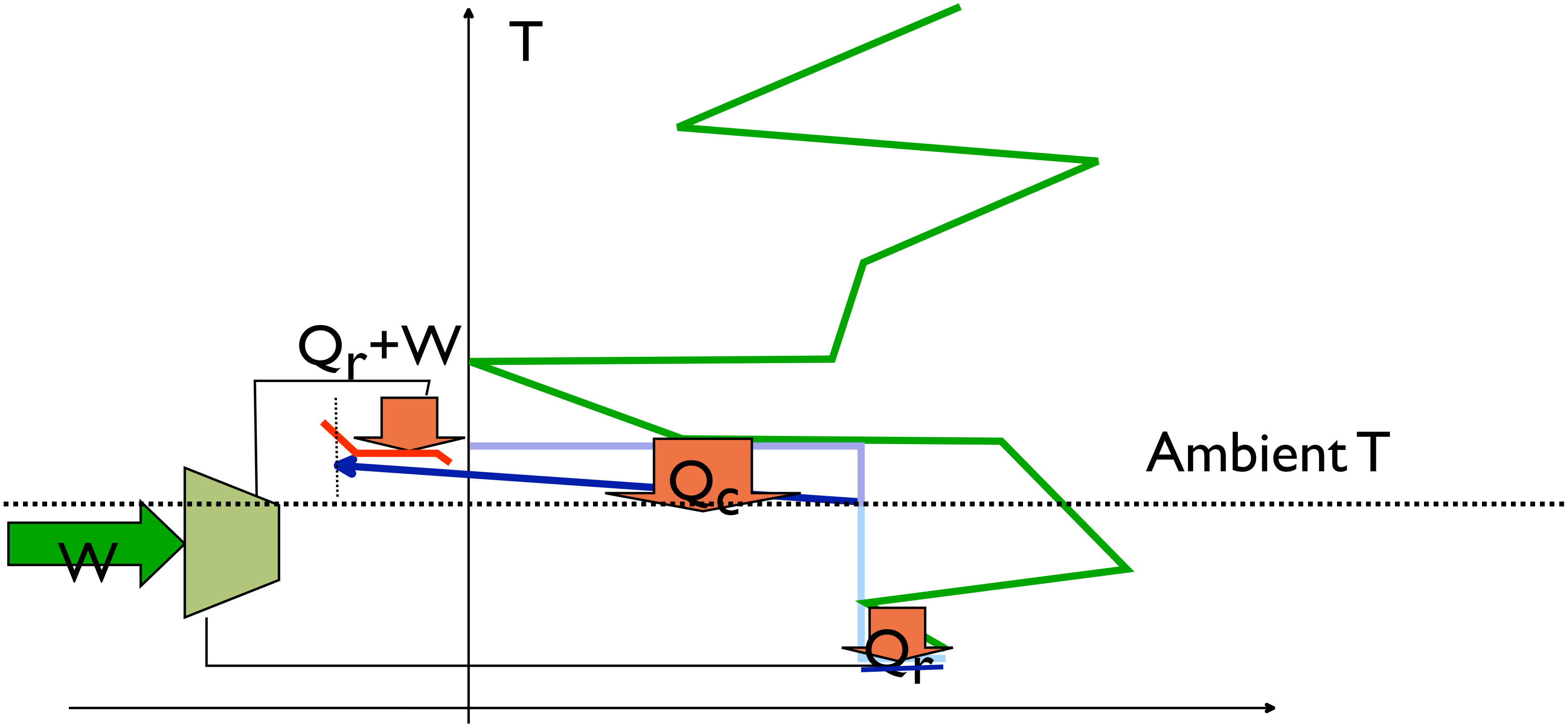


EPFL

Question

- Explain the integration of a refrigeration system in an industrial process.
- Explain how to calculate the investment and explain how to calculate the cost of the refrigeration service supply

Refrigeration

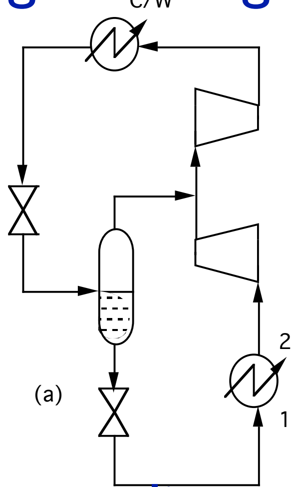


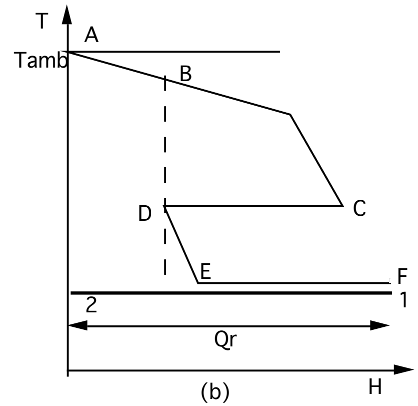
$$\dot{Q}_c + \dot{Q}_r + \dot{W} = \dot{Q}_{MER}^{Coldu} + \dot{W}$$

Increasing the flow of the cold water

Refrigeration cycle integration

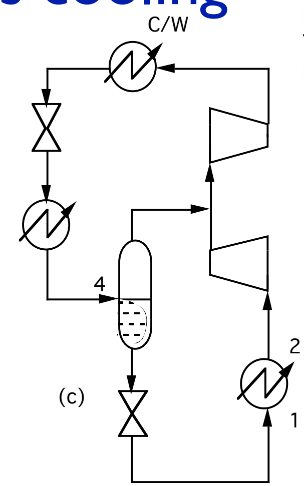
Single stage cooling

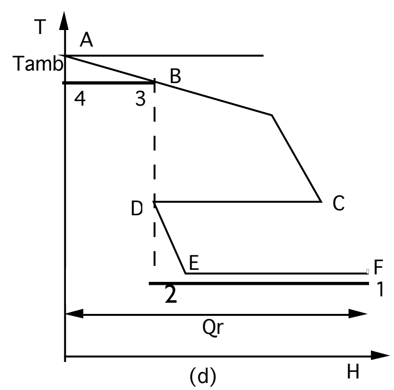




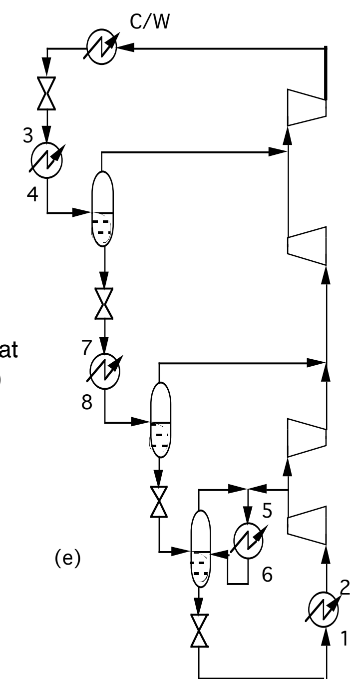
Two stages with intermediate cooling (system integration)
Two stages allows to not recompress a fluid that is already vapour in the intermediate pressure)

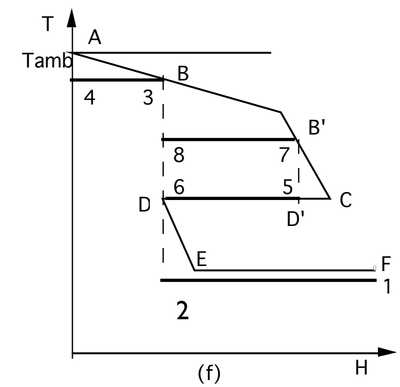
Two stages cooling





Three stages cooling + condensation



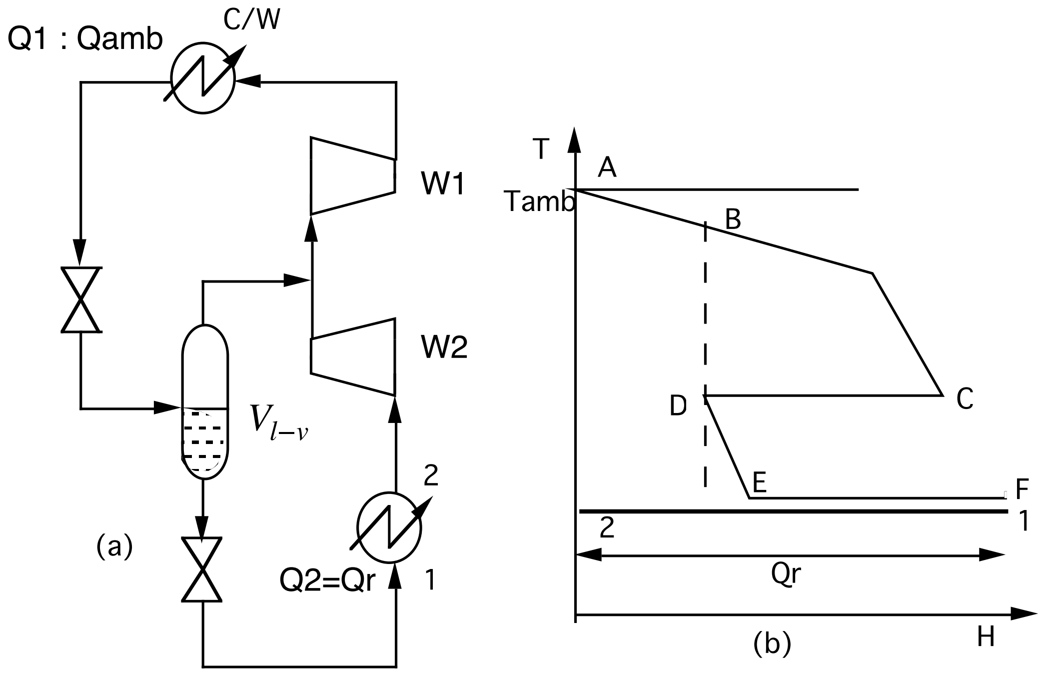


The 3 stages presented has the equivalent of a heat pump at D-C level that allow to use cooling at higher temperature (B') and therefore with lower compression cost.

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

Estimating the cost

Flows are defined activation by heat cascade pinch points



Investment of equipments [CHF/year]

Cost of electricity [CHF/year]

$$\frac{\frac{1}{\tau} \cdot (k1_{l-v} \cdot V_{l-v}{}^{k2_{l-v}} + k1_e \cdot \dot{Q}_1{}^{k2_e} + k1_e \cdot \dot{Q}_2{}^{k2_e} + k1_c \cdot \dot{W}_1{}^{k2_c} + k1_c \cdot \dot{W}_1{}^{k2_c}) + c_{elec} \cdot t_{op} \cdot (\dot{W}_1 + \dot{W}_2)}{\dot{Q}_2 \cdot t_{op}} in[CHF/kWh]$$

Cold services delivered in [kWh/year]