The plus and minus principle

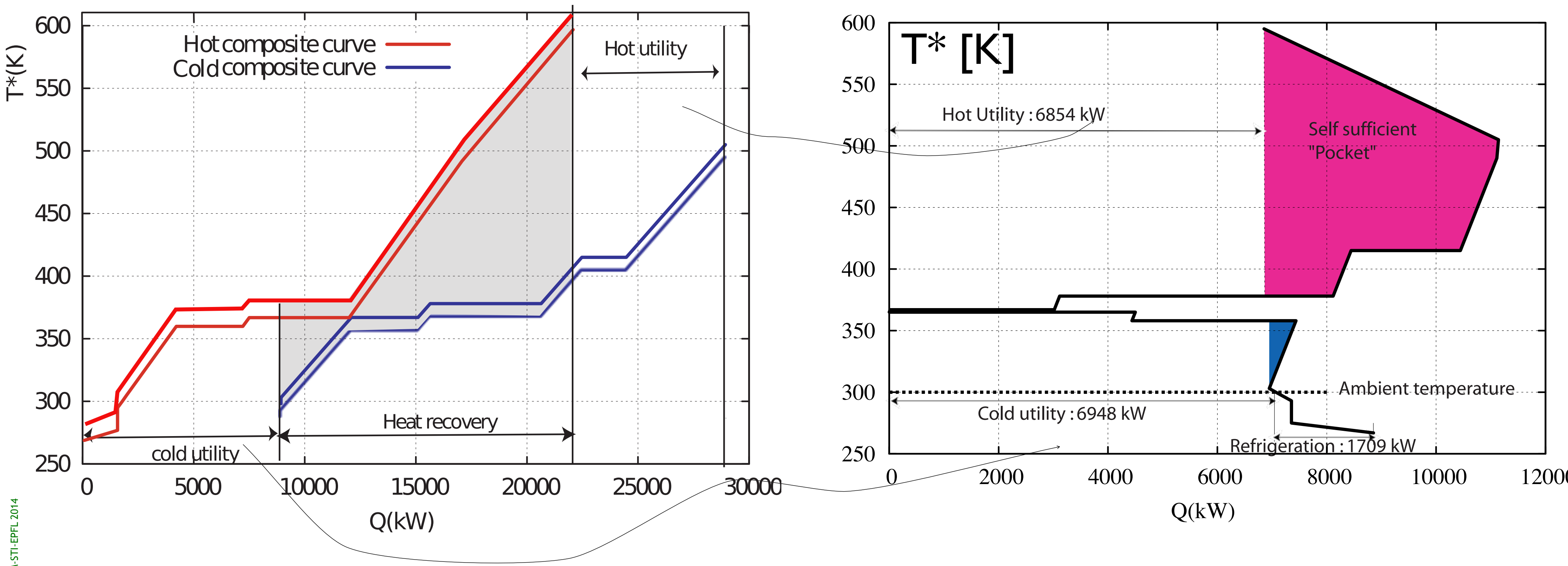
How to maximise the heat recovery potential of a process

Prof François Marechal

EPFL

Grand composite curve/Heat cascade

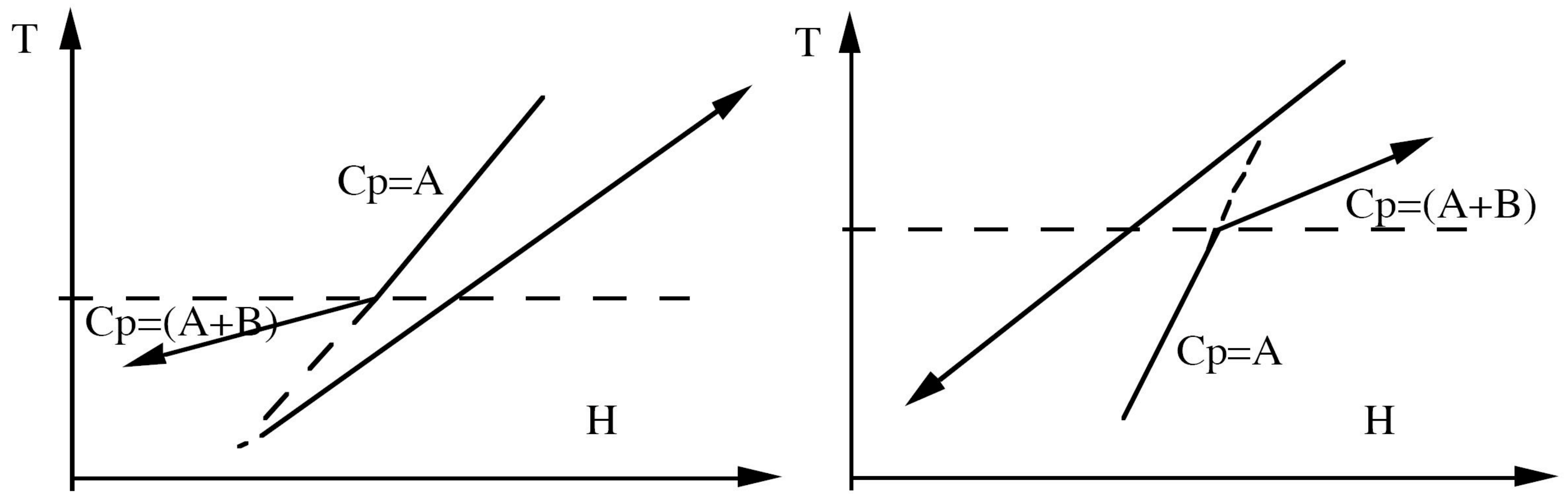
- Heat recovery limited by the Pinch Point
    - Temperature difference = DTmin assumption



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.

Who is creating a pinch point ?

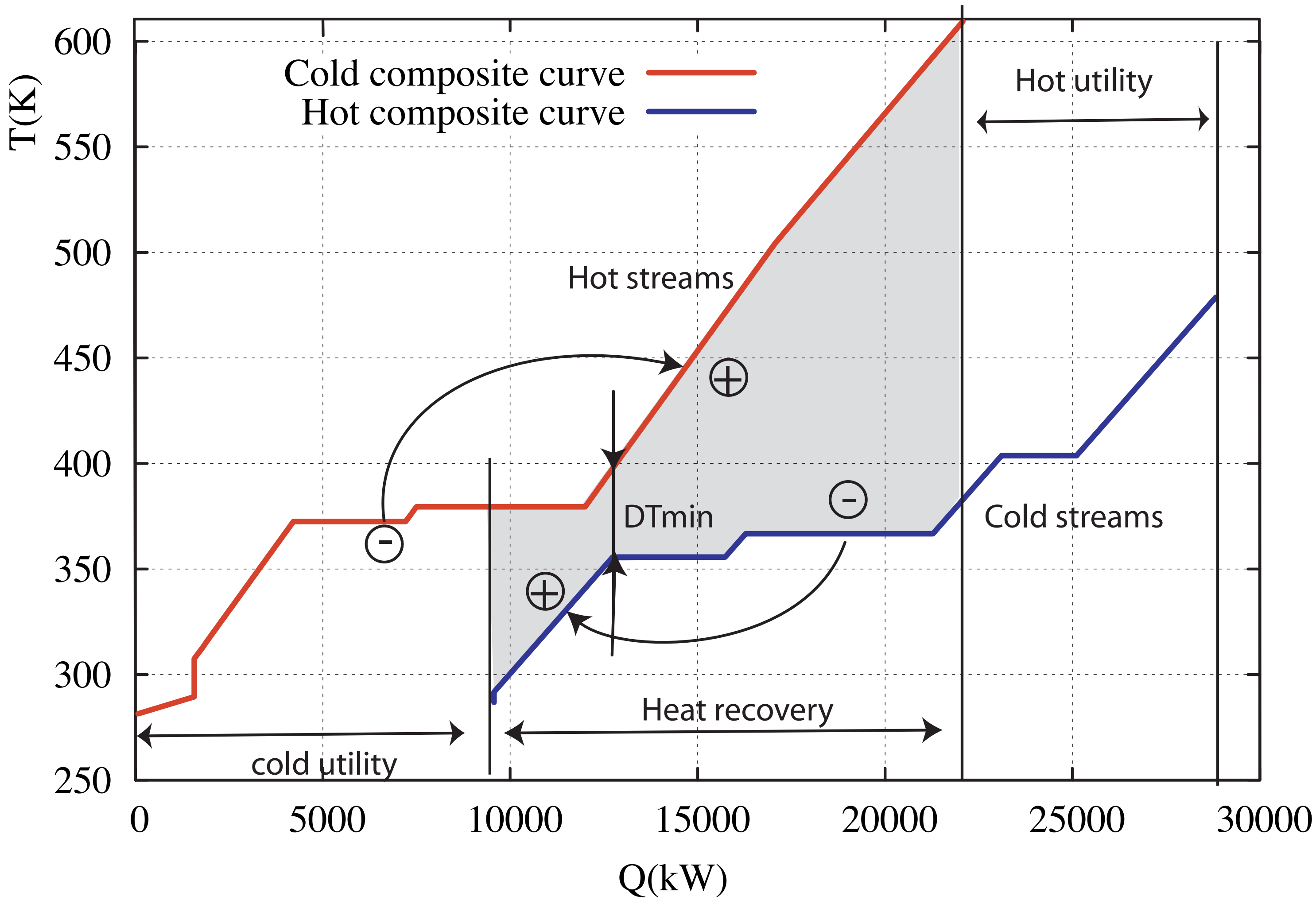
- Pinch are always created by inlet conditions of a stream (or a change of slope, when the H-T profile is not linear)



(a) Hot streams (b) Cold streams

Plus - Minus principle : Around the pinch temperature

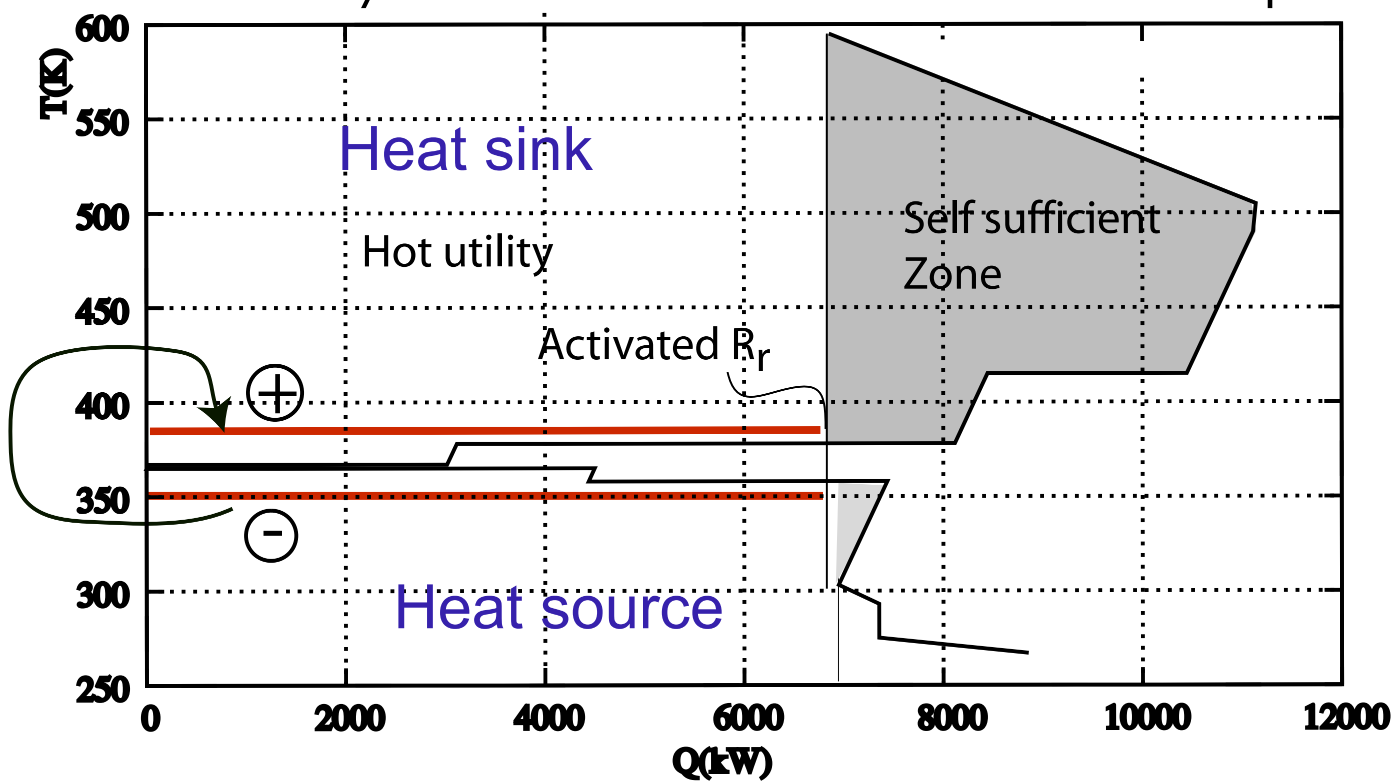
Transfer hot streams from below to above the pinch : to allow them supply heat to the cold streams above the pinch where there is a heat deficit



Transfer cold streams from above to below the pinch : to allow them recover heat from the excess of heat in the hot streams below the pinch

Grand composite analysis (Heat cascade)

- The overall balance is not changed !
  - Hot streams from below to above the pinch
  - Cold streams from above to below
  - $\dot{Q}$ limited by the creation of a new pinth point



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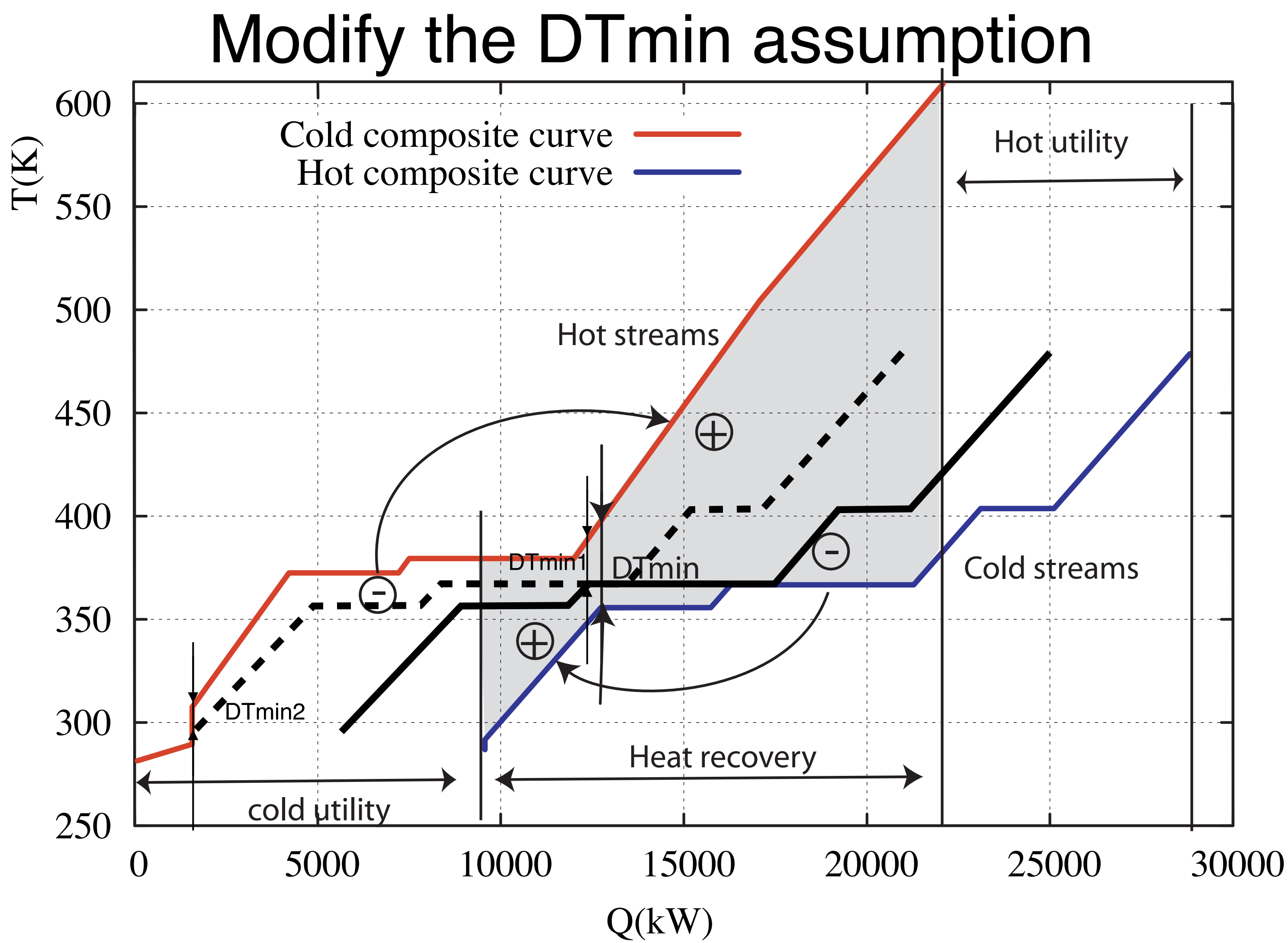
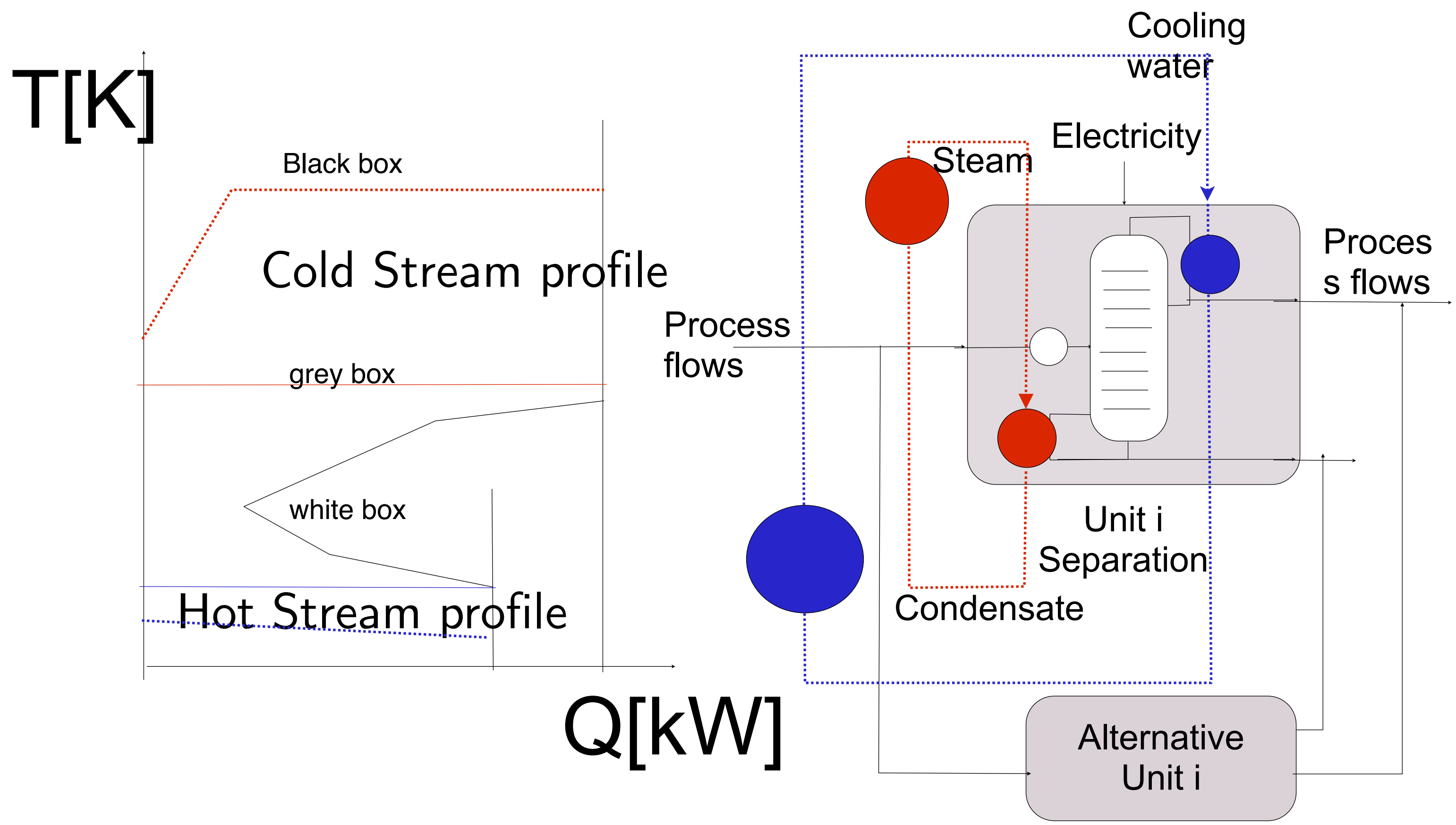
Plus - Minus principle : around the pinch

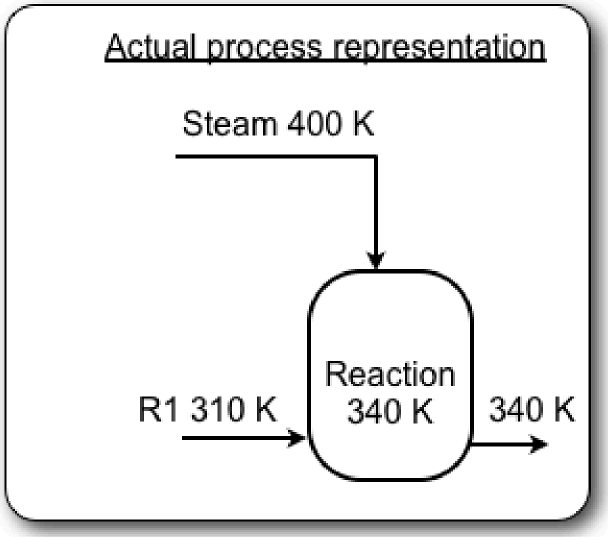


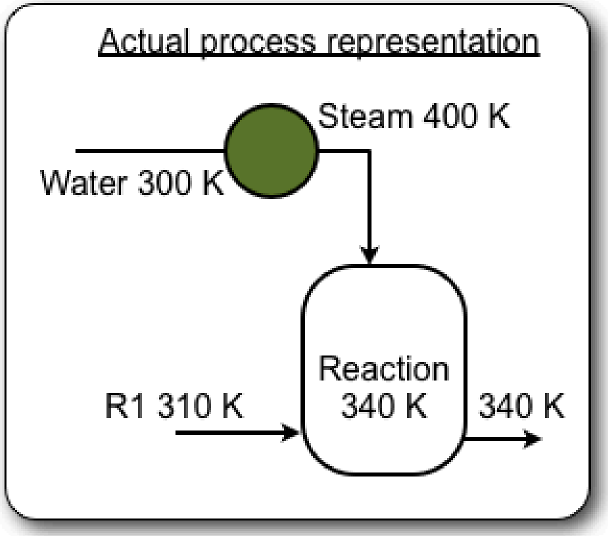
Unit Operation energetics : Heat transfer Interfaces

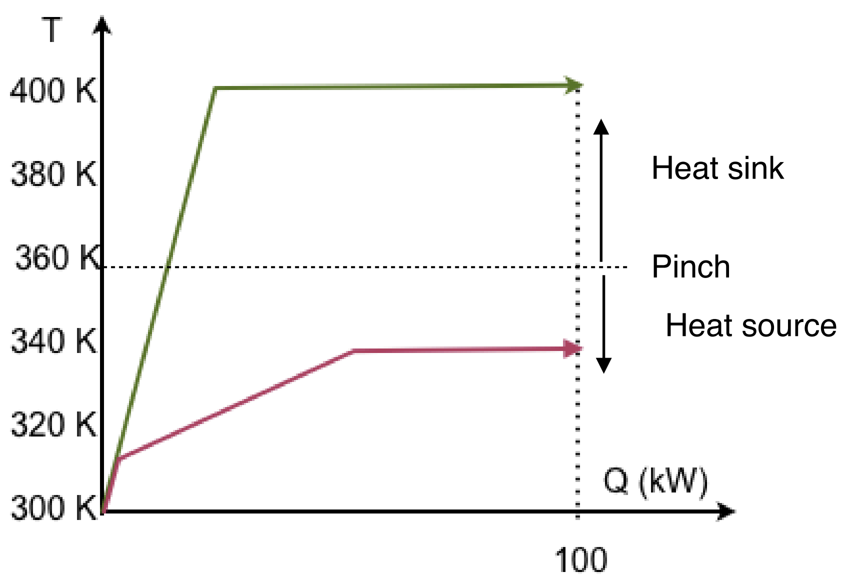
- **Same unit operation : different heating and cooling profiles**

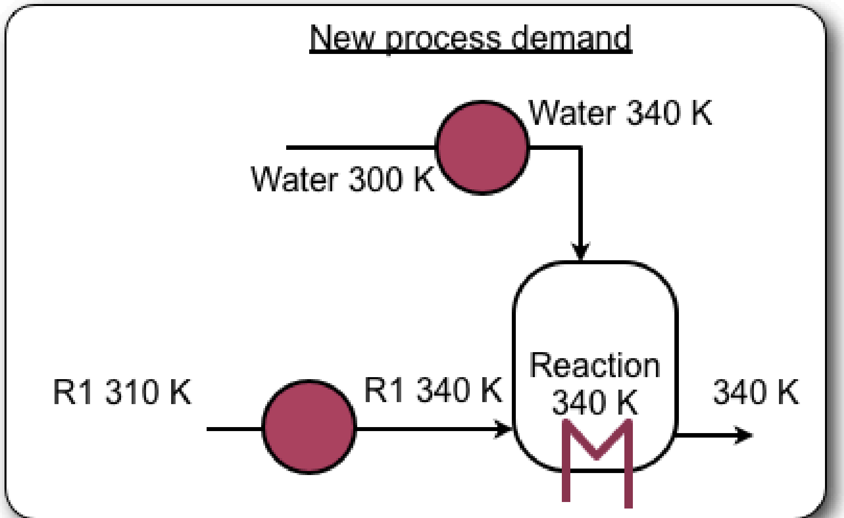


Changing the process demand interface





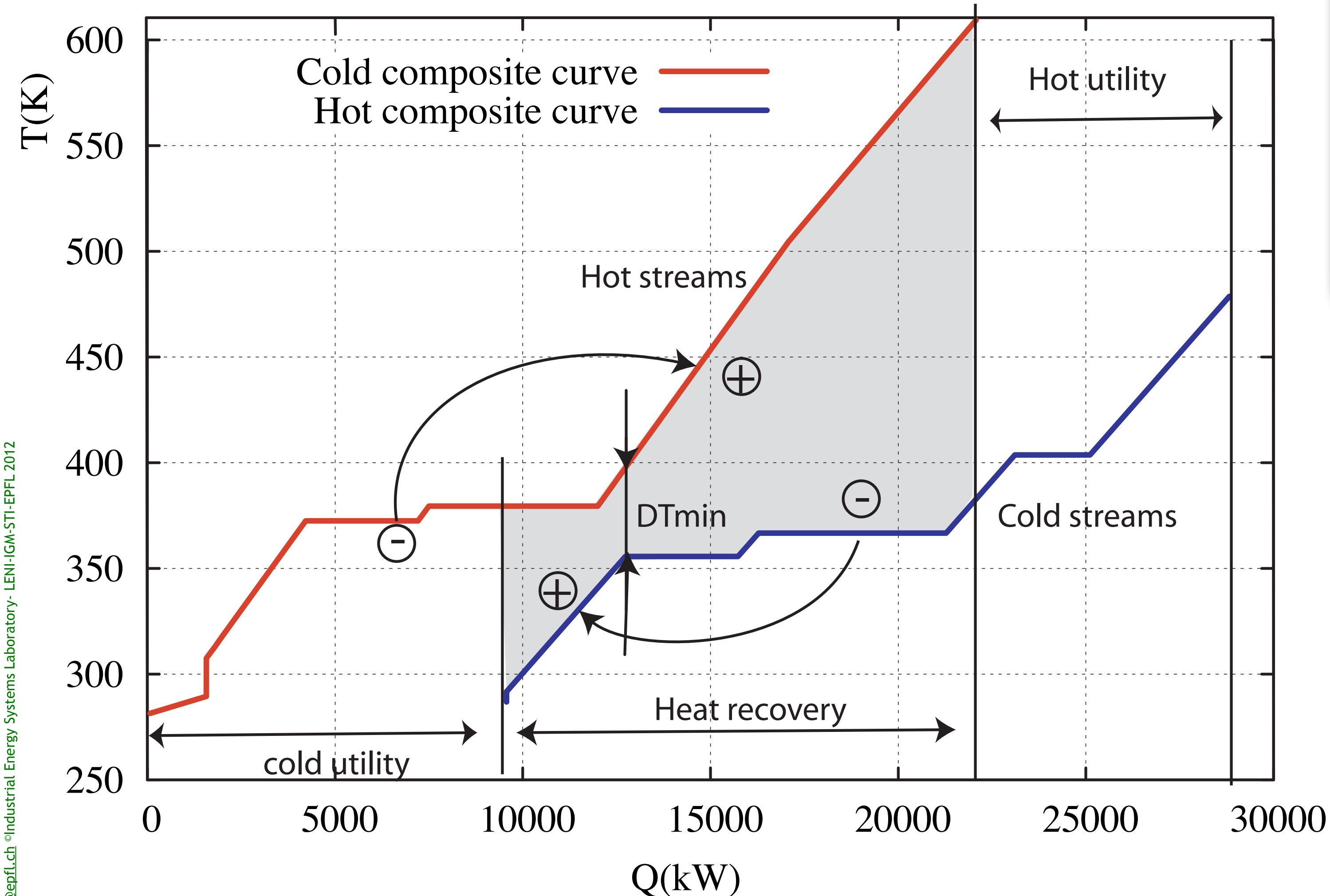


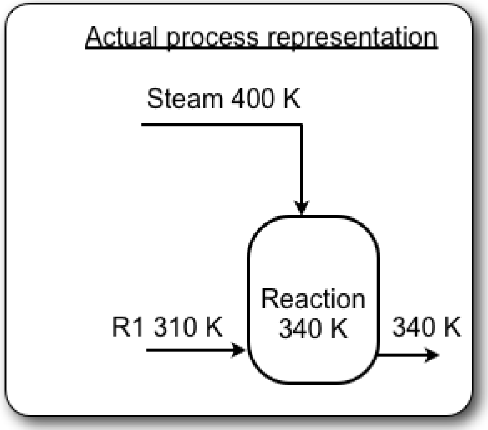


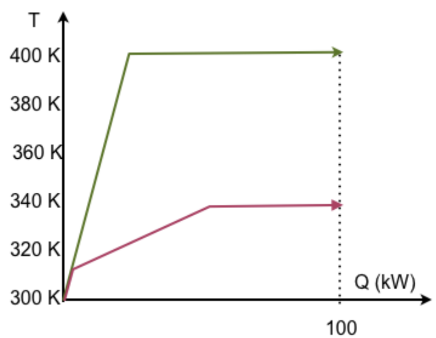
Changing the process demand profile allows to change the temperature at which the heat is asked or made available by a process operation

Plus - Minus principle : change the heat requirement

Transfer hot streams from below to above the pinch : to allow them supply heat to the cold streams above the pinch where there is a heat deficit



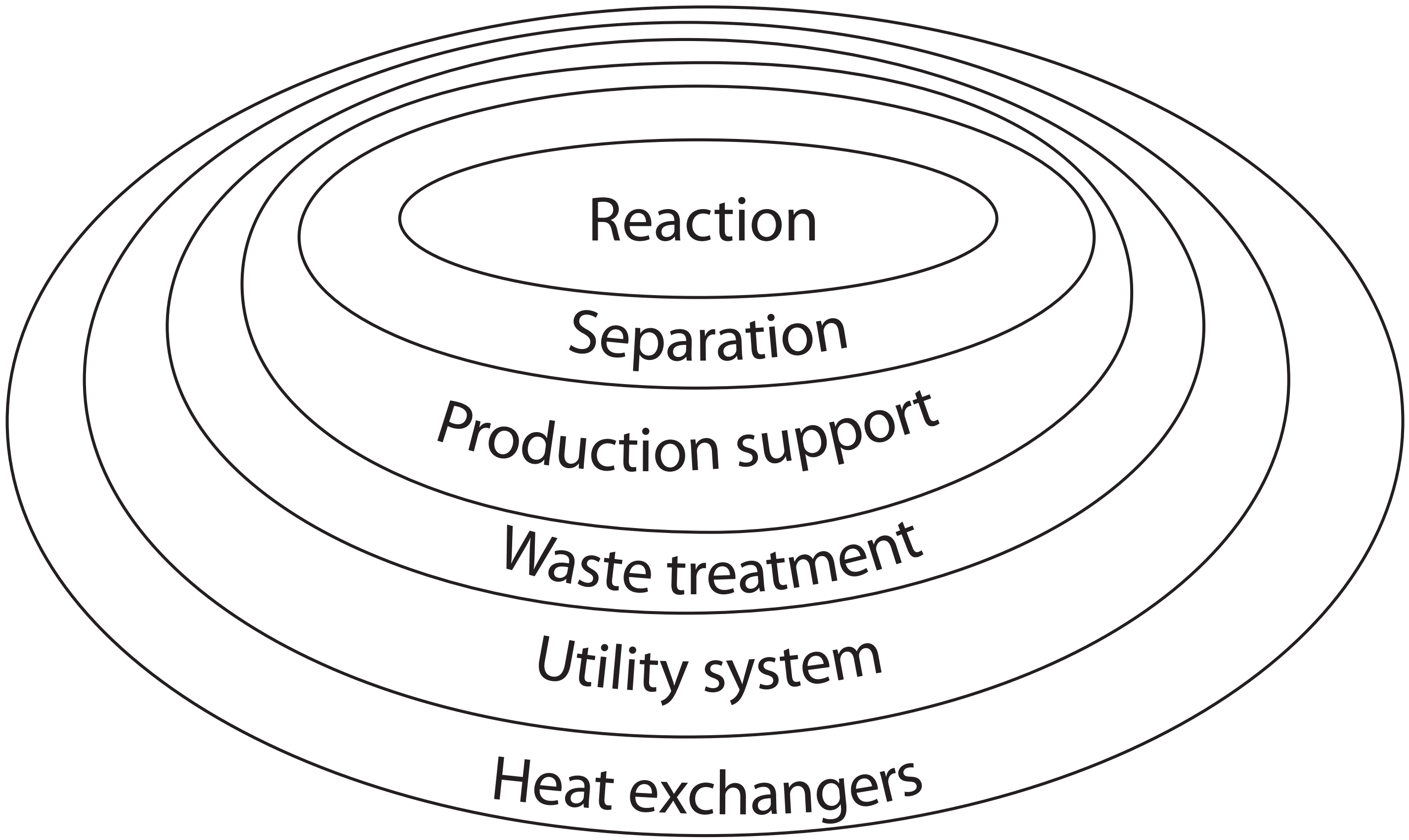




Transfer cold streams from above to below the pinch : to allow them recover heat from the excess of heat in the hot streams below the pinch

Onion diagram

- Hierarchy in the process unit operations

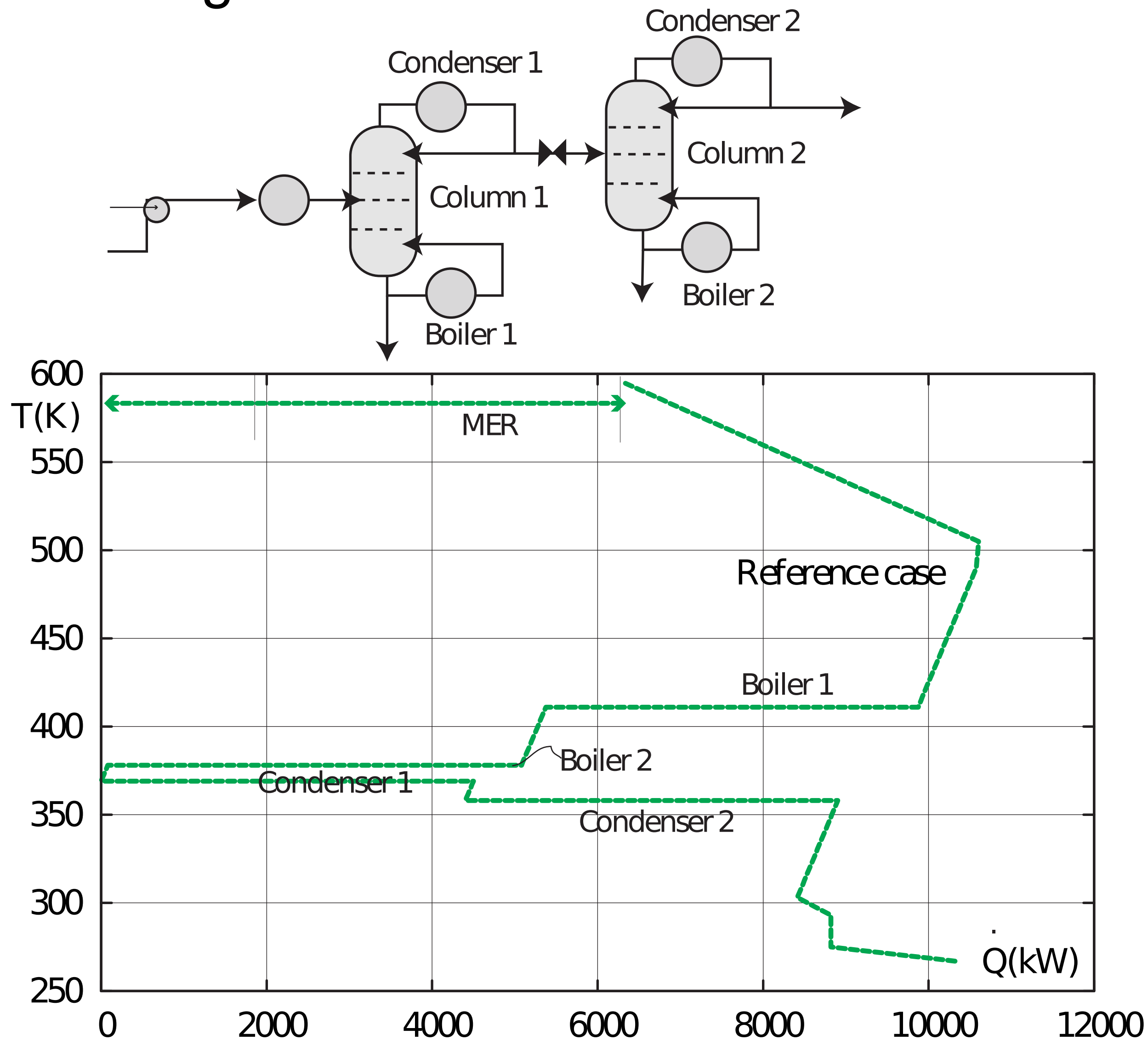


Modifying the process integration opportunities

- **Modify the process units heat transfer interface**
- **Modify the process units operating conditions**
  - to increase the heat recovery potential
  - e.g. change the operating pressure of a unit
- **Externally change the temperature of the requirement**
  - Heat pumping/ expansion

Changing the operating conditions

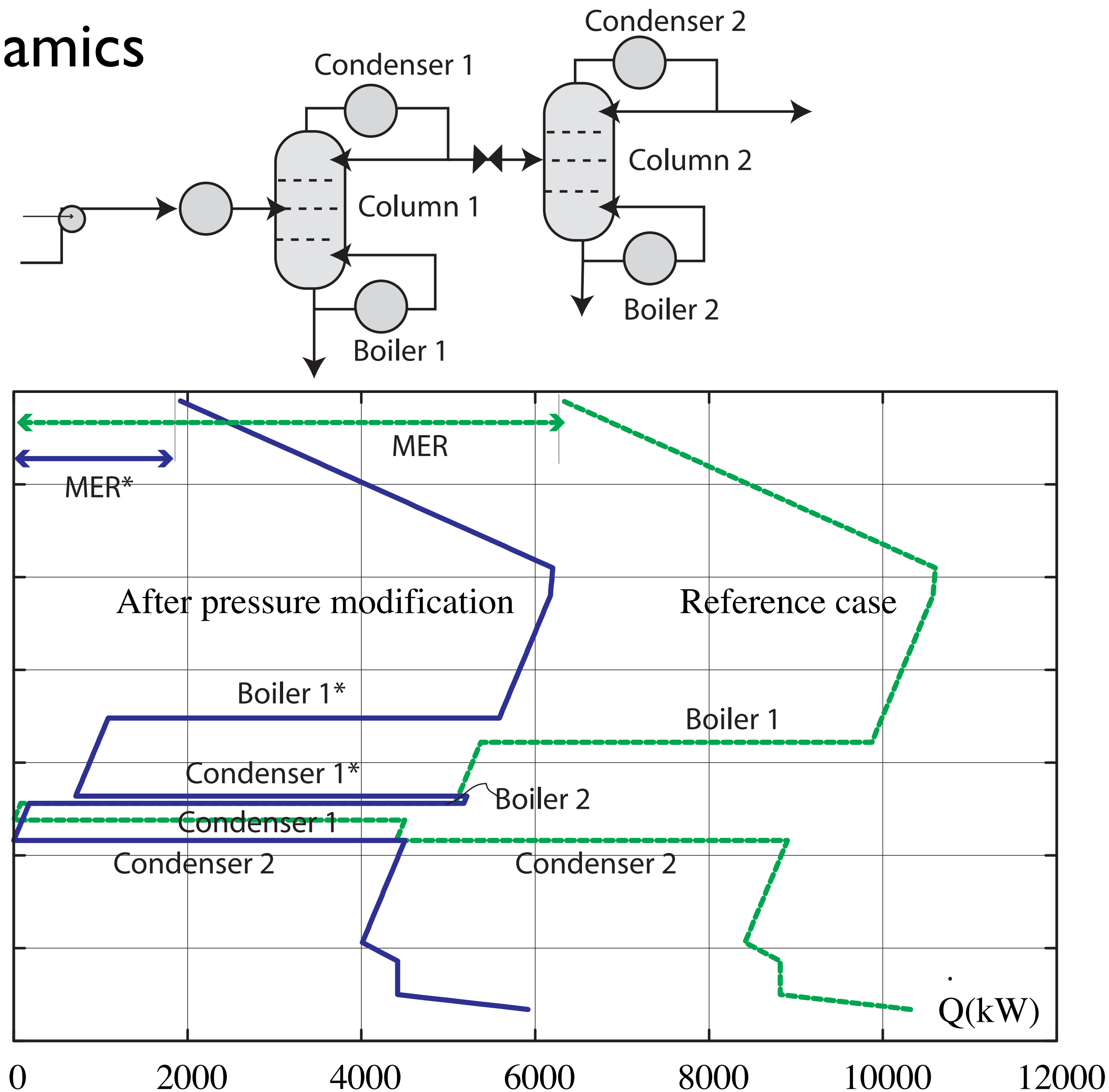
Heat integration of two distillation columns



Column1 operates at P1 - Column 2 operates at P2 < P1

Example : two columns integration : pressure change

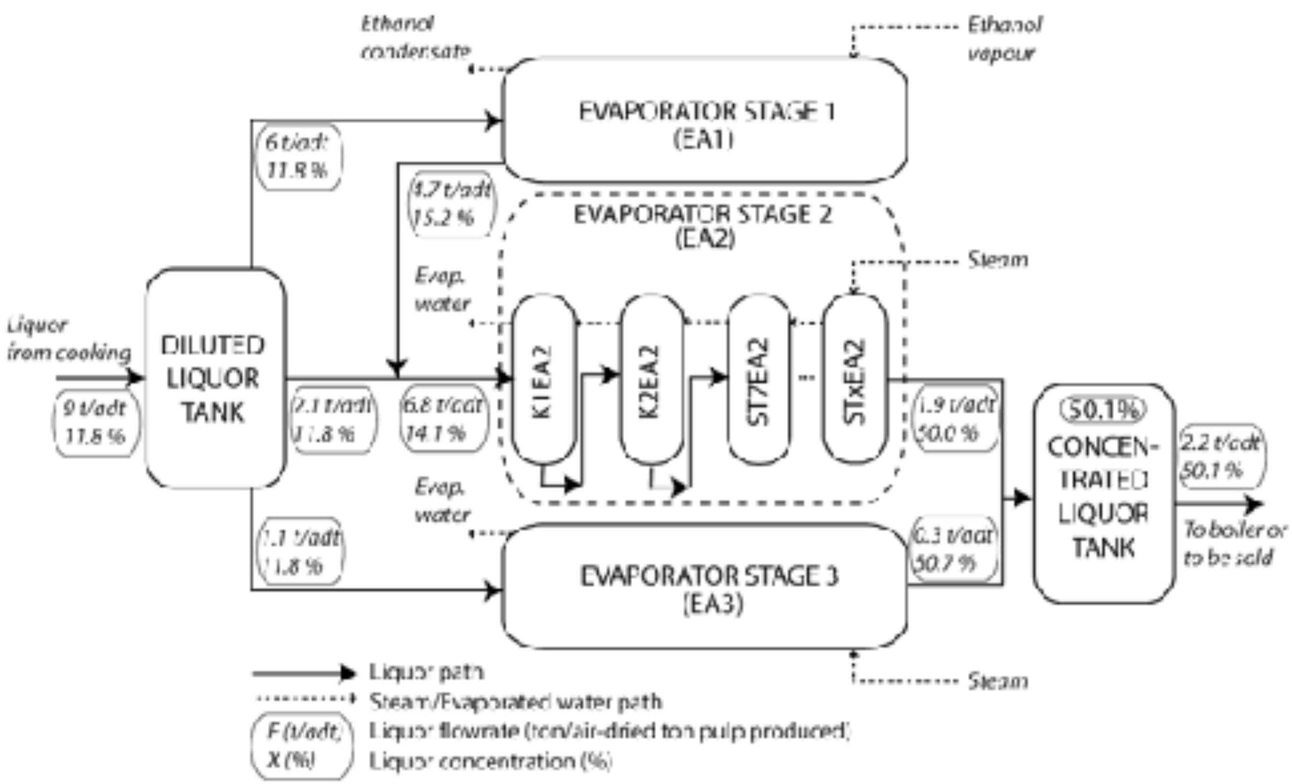
- Increase pressure of column 1 using a pump
- verify column hydrodynamics



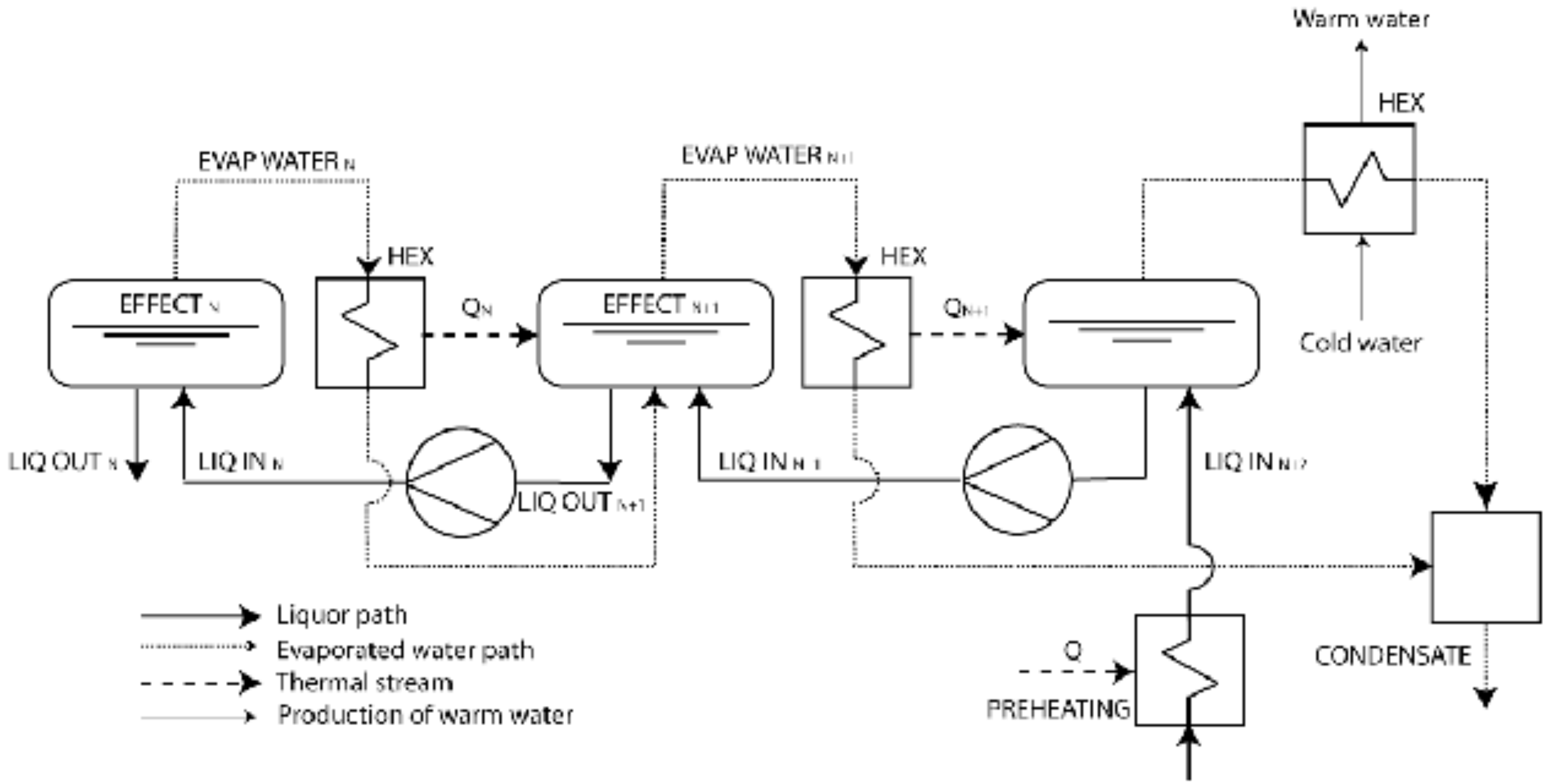
* The heat of condensation in the condenser is higher when pressure is increased
* Choose the pressure so that the condenser 1 temperature is higher then the boiler 2 temperature

Example 2 : the multi-effect evaporator

- Multi effect evaporators are used to
  - Concentrate liquid streams
  - are large steam consumers
  - food and pulp and paper industry



From the actual model of evaporators…



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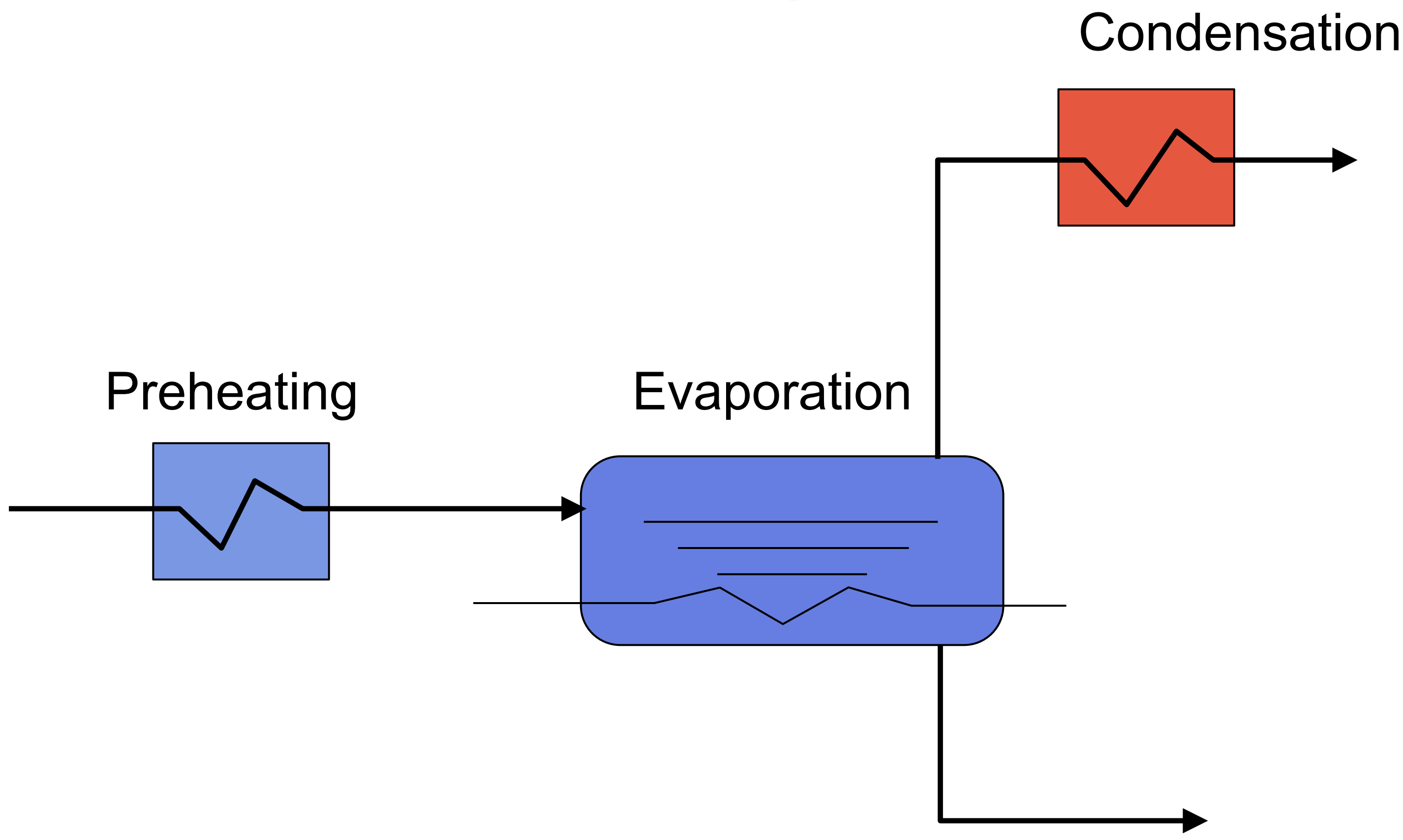
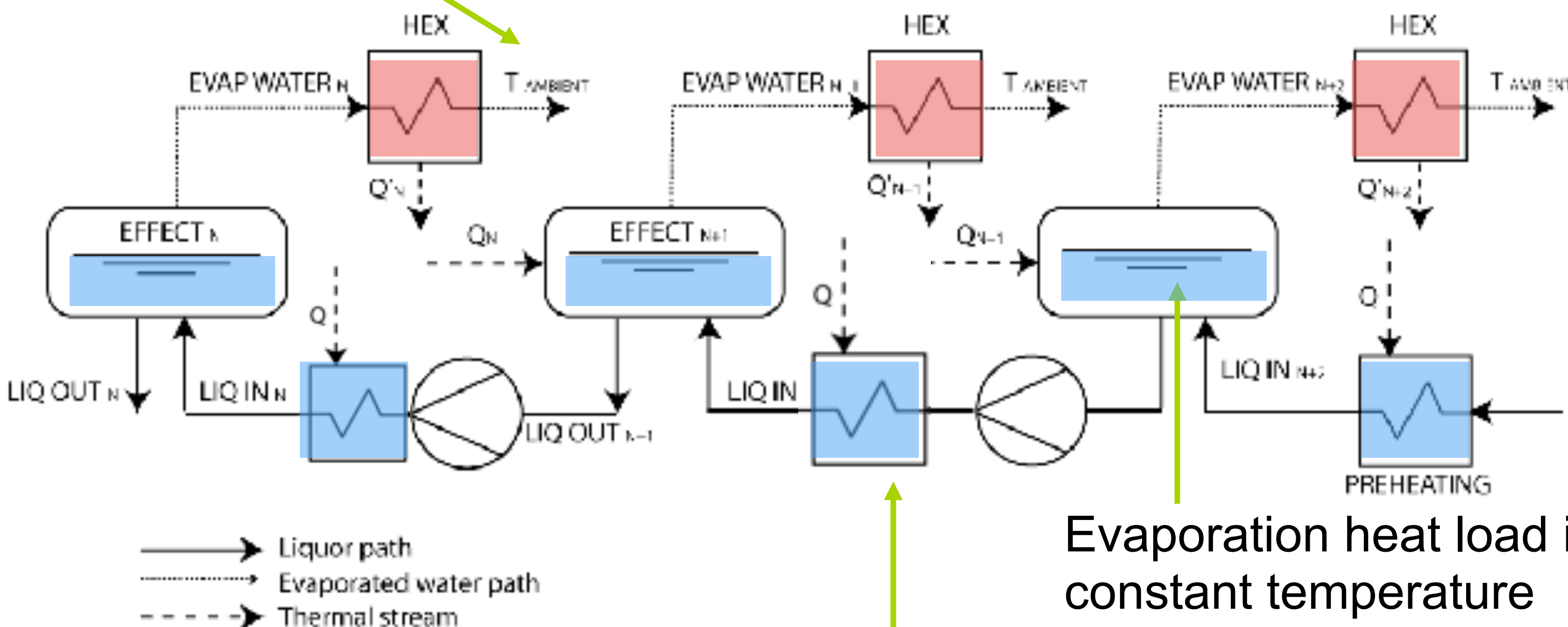
Single effect modeling

- Understanding the unit operation



...to the simplified model of evaporators

The evaporated water leaving each effect is cooled down to ambient temperature → Amount of heat recovered

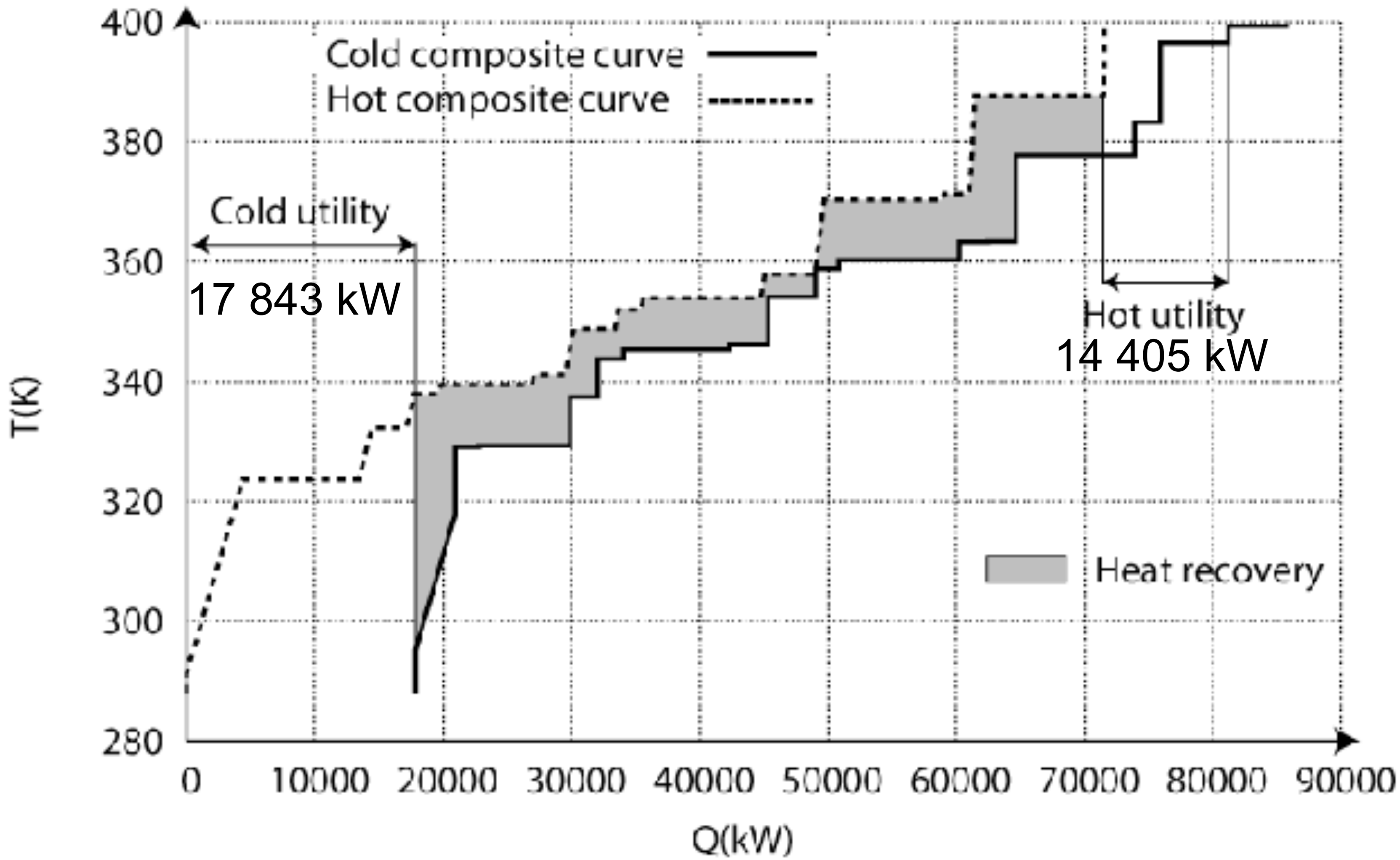


Evaporation heat load is at constant temperature

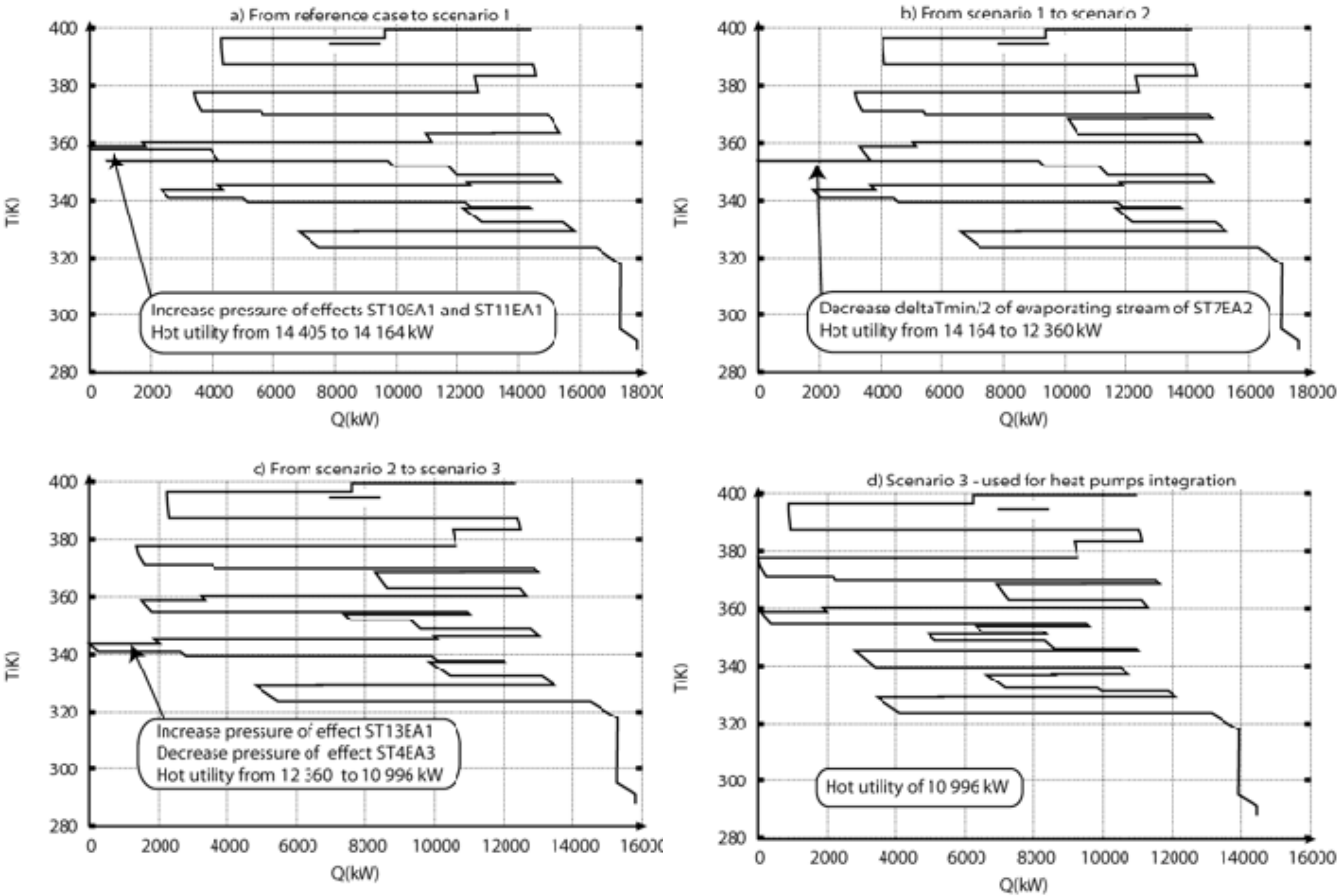
Preheating is possible between effects

Actual process requirement

- Multi-effect system for one concentration



Applying plus-minus principles



Note that the effect is limited by the activation of an other pinch point

Comparison of energy saving scenarios

	Scenario 0	Scenario 1	Scenario 2	Scenario 3
Pinch point (corr temp) (K)	359	354	344	378
Hot utility requirement (kW)	14 405	14 164	12 360	10 996
Cold utility requirement (kW)	17 843	17 616	15 813	14 447
Hot utility cost (k€ /y)	1245	1224	1068	950
Cold utility cost (k€ /y)	154	152	137	125
Cost total utilities (k€ /y)	1399	1376	1205	1075
Total HEX area (m^2)	3875	4058	5286	6176
NminMER	16	16	16	16
HEX area (m^2)	242	254	330	386
Cost total HEX area (k€)	603	633	749	763
Cost total HEX area/y (k€ /y)	70.43	73.95	87.55	88.99

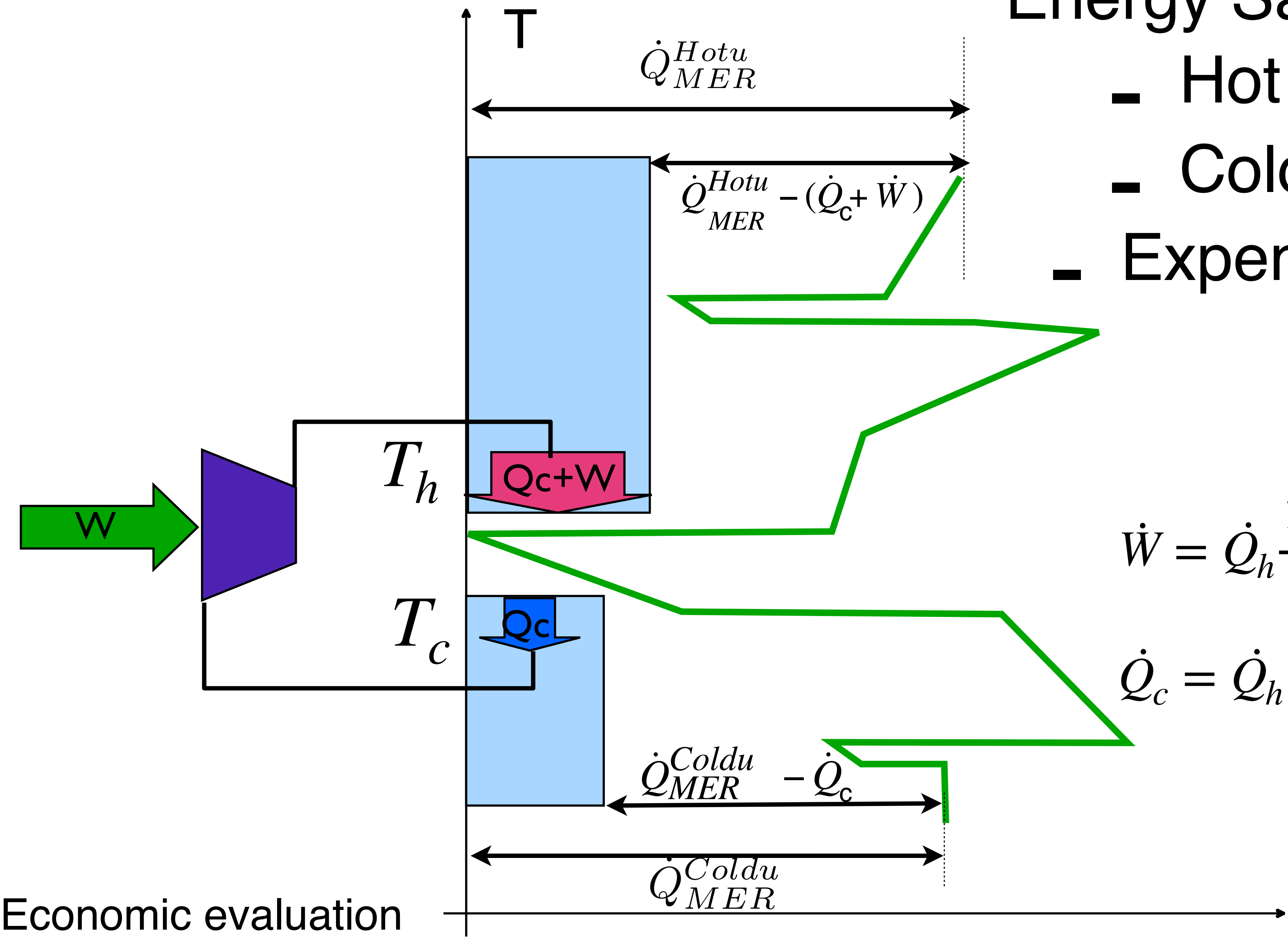
Comparison of energy saving scenarios

	Scenario 0	Scenario 1	Scenario 2	Scenario 3
Comparison with the reference case				
Utility demand (%)	-	-1.5	-12.6	-21.1
Cost total utilities (%)	-	-1.6	-13.9	-23.2
Total HEX area (%)	-	+4.7	+36.4	+59.4
Cost total HEX area year (%)	-	+5.0	+24.3	+26.4

As the curves are closer one from the other, the heat recovery area and the associated investment cost is going to increase

Heat pumping

A heat pump is using mechanical power to change the temperature of a fluid.



Energy Savings:

- Hot: $\dot{Q}_c + \dot{W}$
- Cold : $\dot{Q}_c$
- Expenses : $\dot{W}$

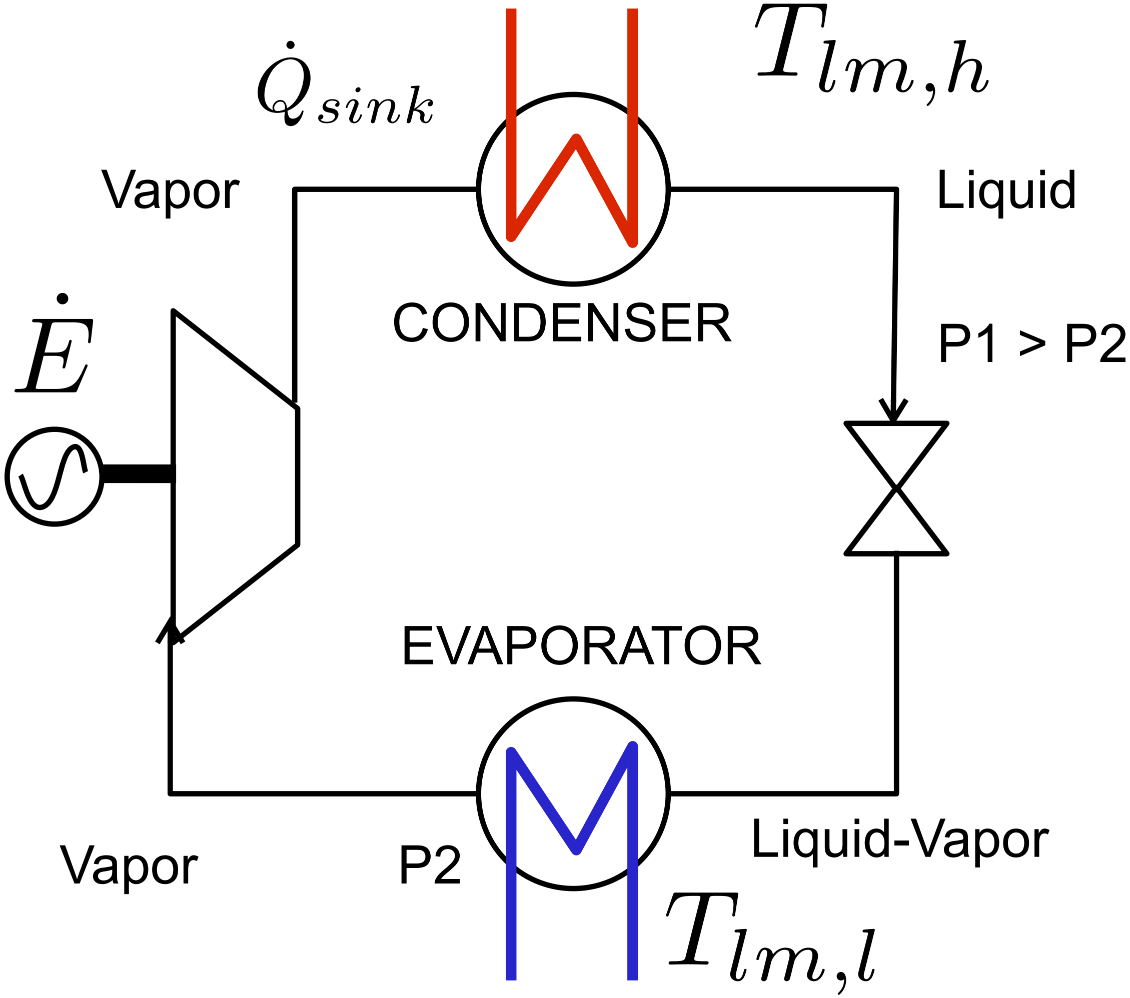
$$\dot{W} = \dot{Q}_h \frac{T_h - T_c}{T_h} \frac{1}{\eta_{COP}}$$

$$\dot{Q}_c = \dot{Q}_h - \dot{W}$$

Economic evaluation

$$((\dot{Q}_c + \dot{W}) \,.\, c_{hot} + \dot{Q}_c \,.\, c_{cold} - \dot{W} \,.\, c_{el}) \,.\, t_{op} - \frac{1}{\tau} I_{heatpump}(\dot{Q}_h, \dot{W}, \dot{Q}_c)$$

Heat pump efficiency



$$\dot{Q}_{source} = \dot{Q}_{sink} - \dot{E}$$

$$COP = \frac{\dot{Q}_{sink}}{\dot{E}}$$

$$COP = \eta_{COP} COP_{th}$$

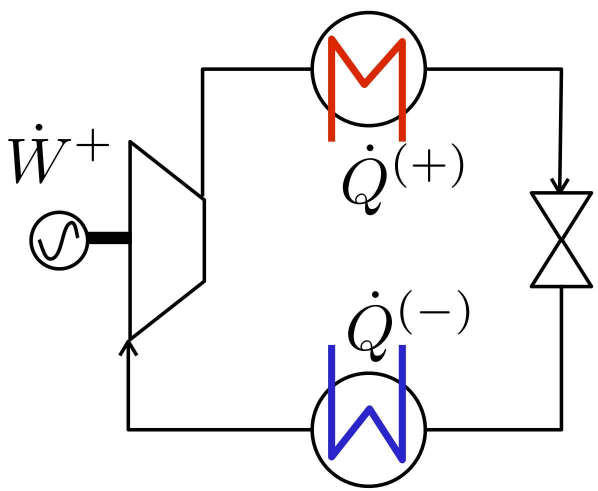
$$COP_{th} = \frac{T_{lm,h}}{T_{lm,h} - T_{lm,l}}$$

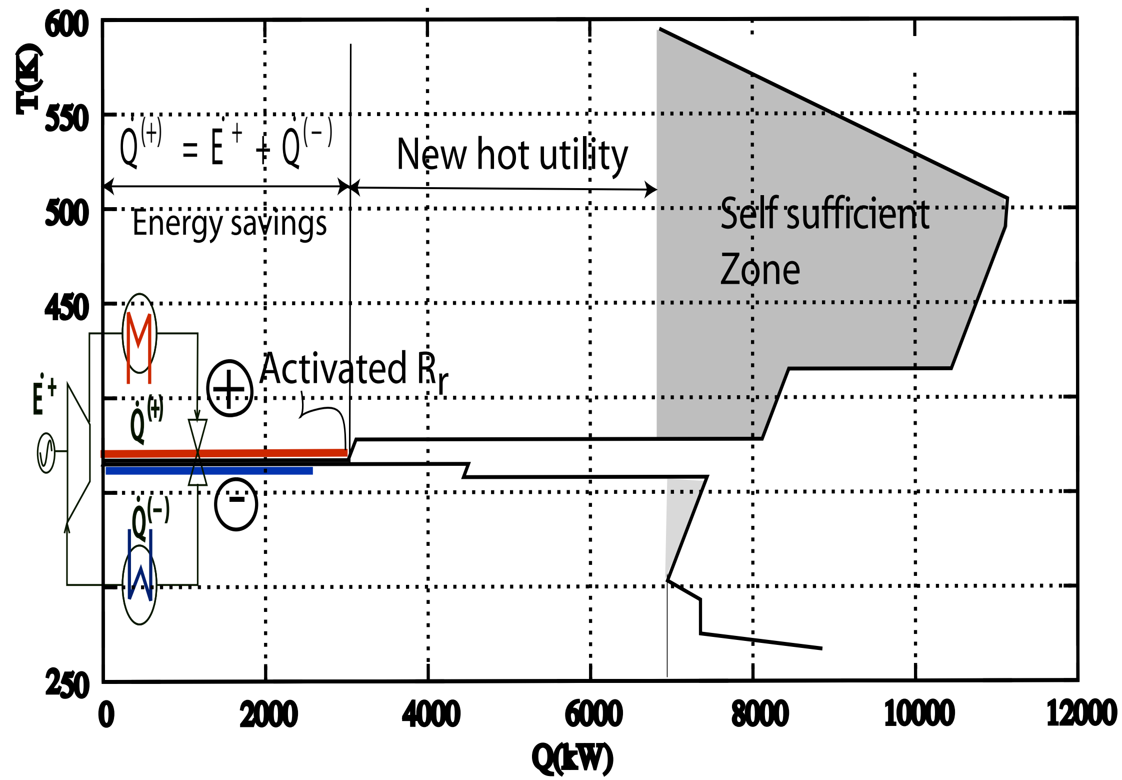
$$\eta_{COP} = 50\%$$

Heat pump integration

- Optimise pressures => Heat pump efficiency
- Optimise the flows => pinch point activation

$$\dot{Q}^{(+)} = \dot{W}^{+} + \dot{Q}^{(-)}$$





$$\dot{W}^{+} = \dot{Q}^{+}\frac{T_h - T_c}{T_h}\frac{1}{\eta_{Carnot}}$$

$$COP = \frac{\dot{Q}^{+}}{\dot{W}^{+}} \quad >> 3$$

$$\eta_{Carnot} = 50\%$$

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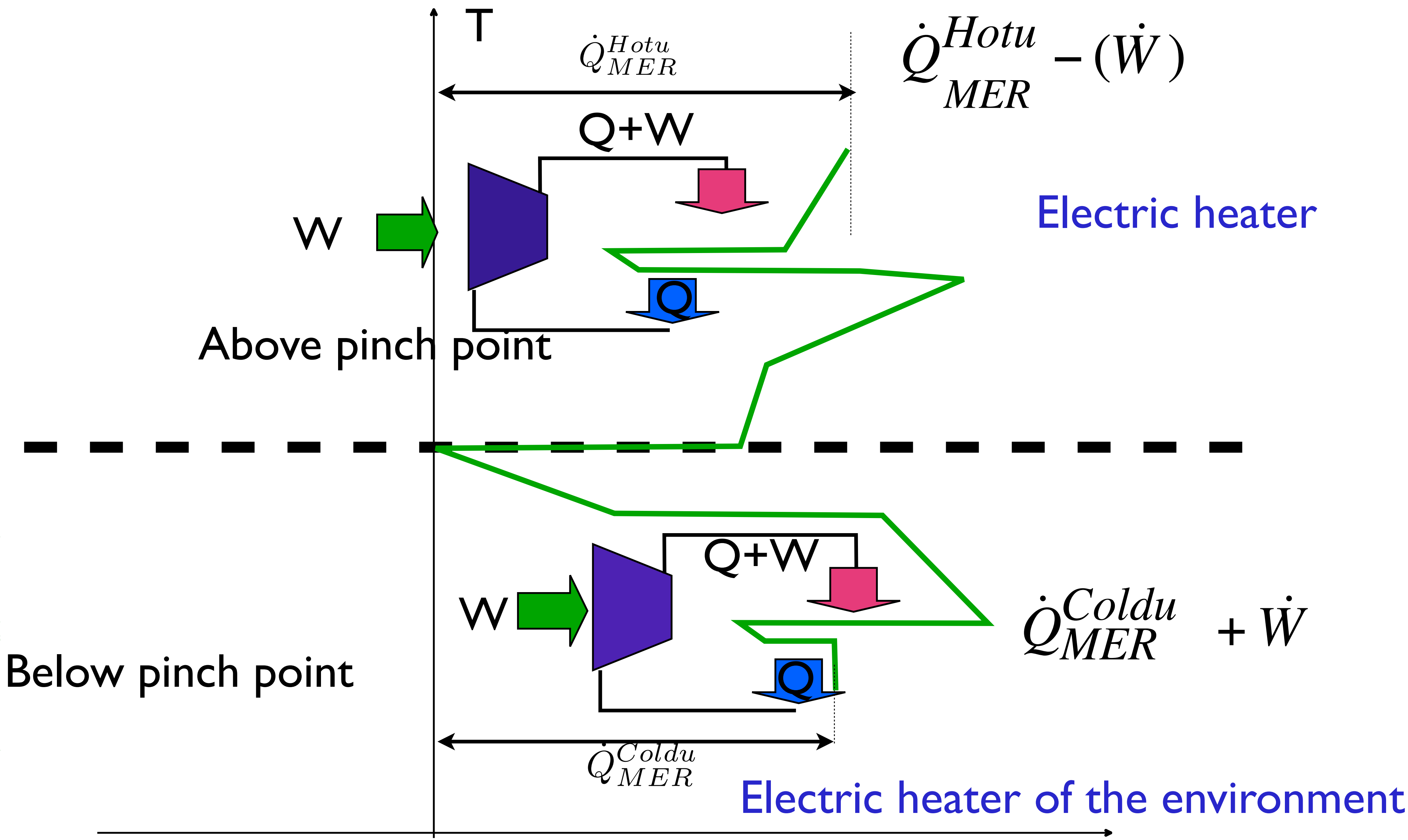
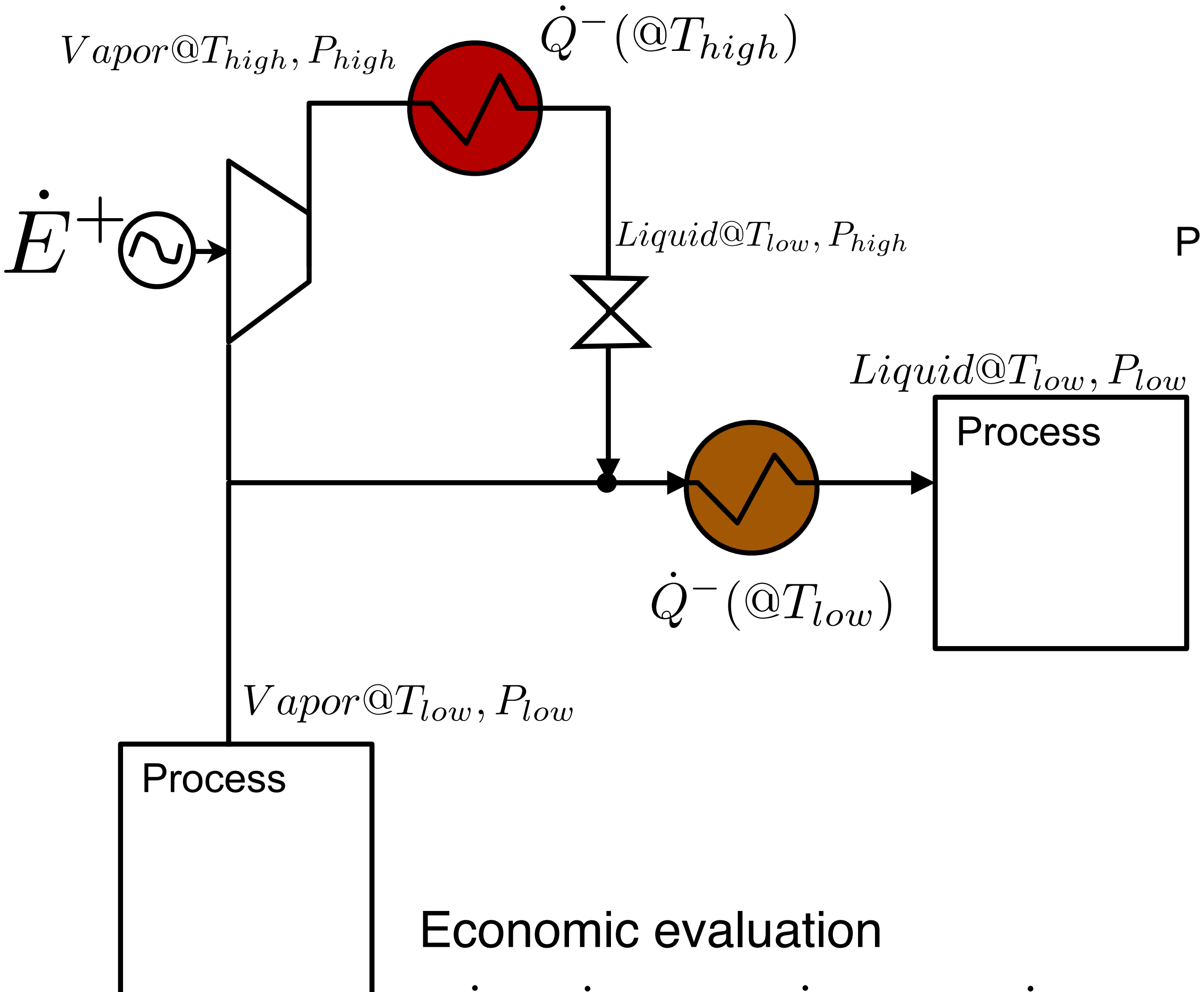
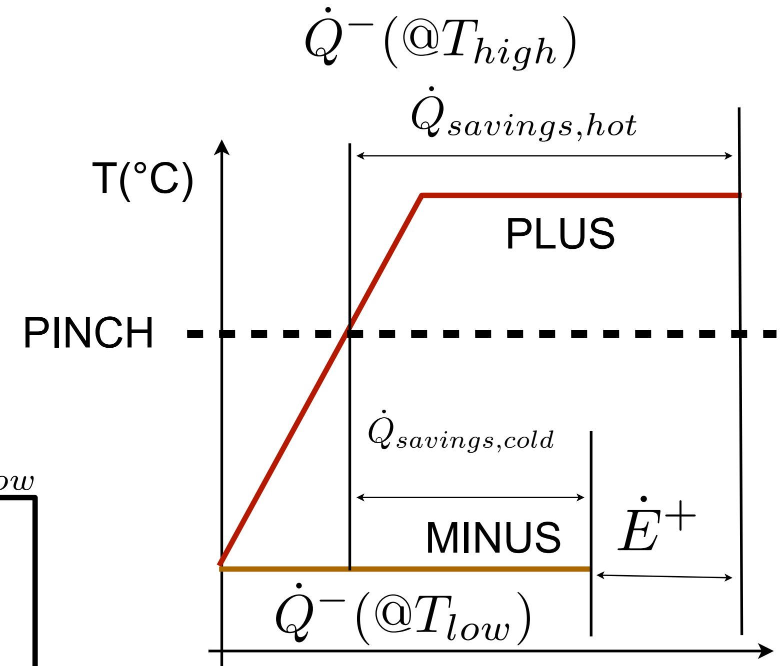
Miss placed heat pumps



Mechanical Vapour Recompression

- Electricity is the price to pay





$$\dot{Q}_{savings,hot} = \dot{Q}_{savings,cold} + \dot{E}^+$$

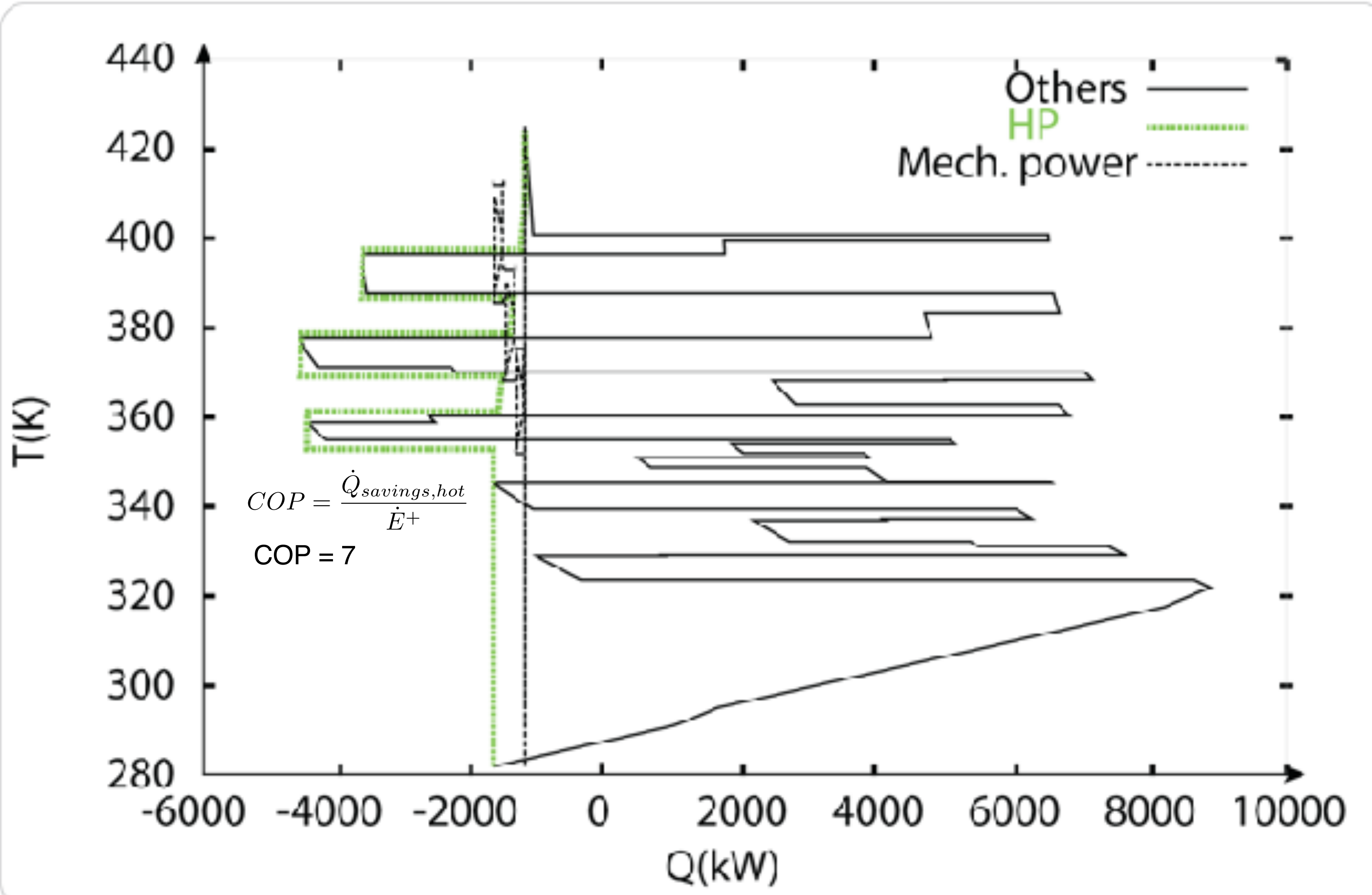
$$COP = \frac{\dot{Q}_{savings,hot}}{\dot{E}^+}$$

Economic evaluation

$$((\dot{Q}_c + \dot{W}) \, . \, c_{hot} + \dot{Q}_c \, . \, c_{cold} - \dot{W} \, . \, c_{el}) \, . \, t_{op} - \frac{1}{\tau} I_{heatpump}(\dot{Q}_h, \dot{W}, \dot{Q}_c)$$

multiple heat pumps integration

- Multi -effect evaporator case



$$COP = \frac{\dot{Q}_{savings,hot}}{\dot{E}^{+}}$$

COP = 7

Energy saving options

Operating, investment and total costs and savings for heat pump integration scenario

	OC* (k€/y)	ΔOC (k€/y)	IC (k€)	ΔIC (k€)	ΔIC/y (k€/y)	TC (k€/y)	Savings (k€/y)	Savings (%)
1 Original scenario	2807	0	4452	0	0	2807	0	0
2 Process improvements	2143	-664	5019	592	69	2212	595	12.2
3 Improved scenario + HP	1647	-1160	7007	2555	376	2023	784	27.2

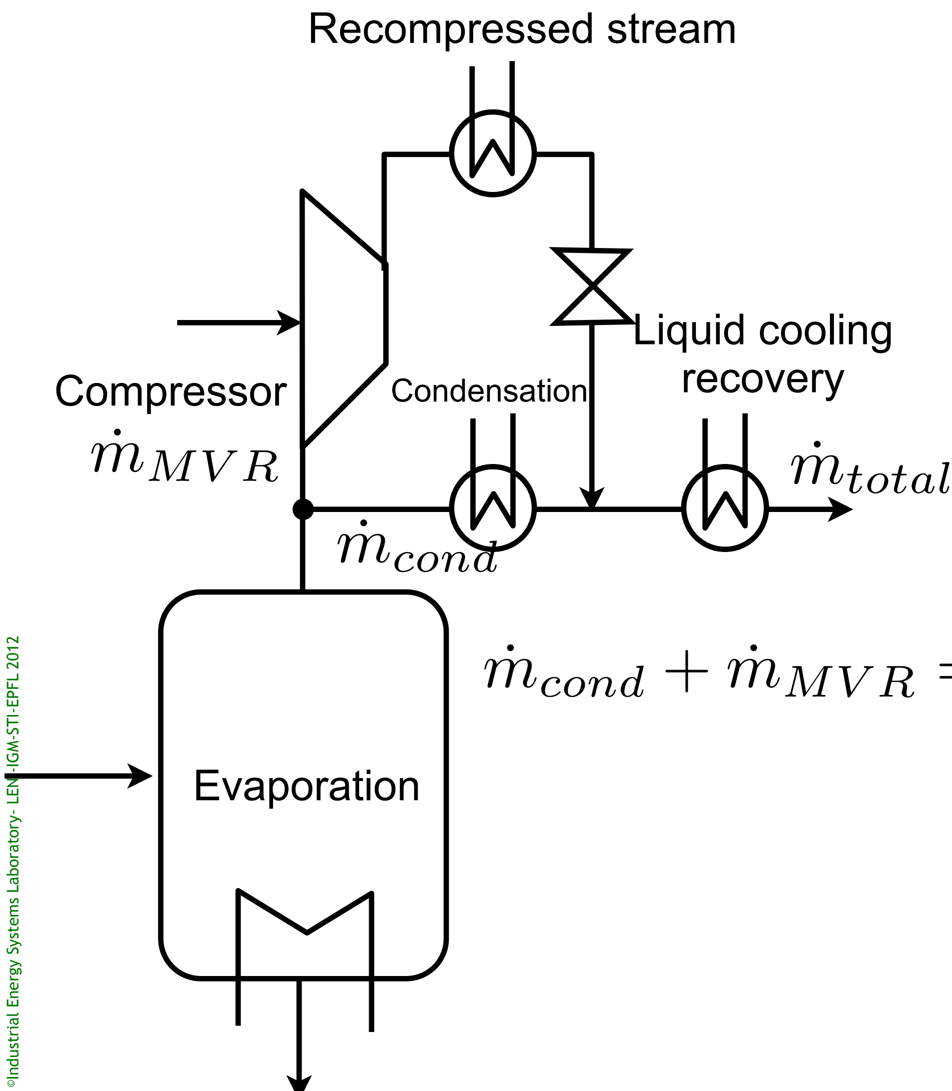
* OC: operating cost, ΔOC: operating cost reduction, IC: investment cost, ΔIC: investment cost reduction, ΔIC/y: annualized investment cost, TC: total cost

ENERGY SAVING OPTIONS

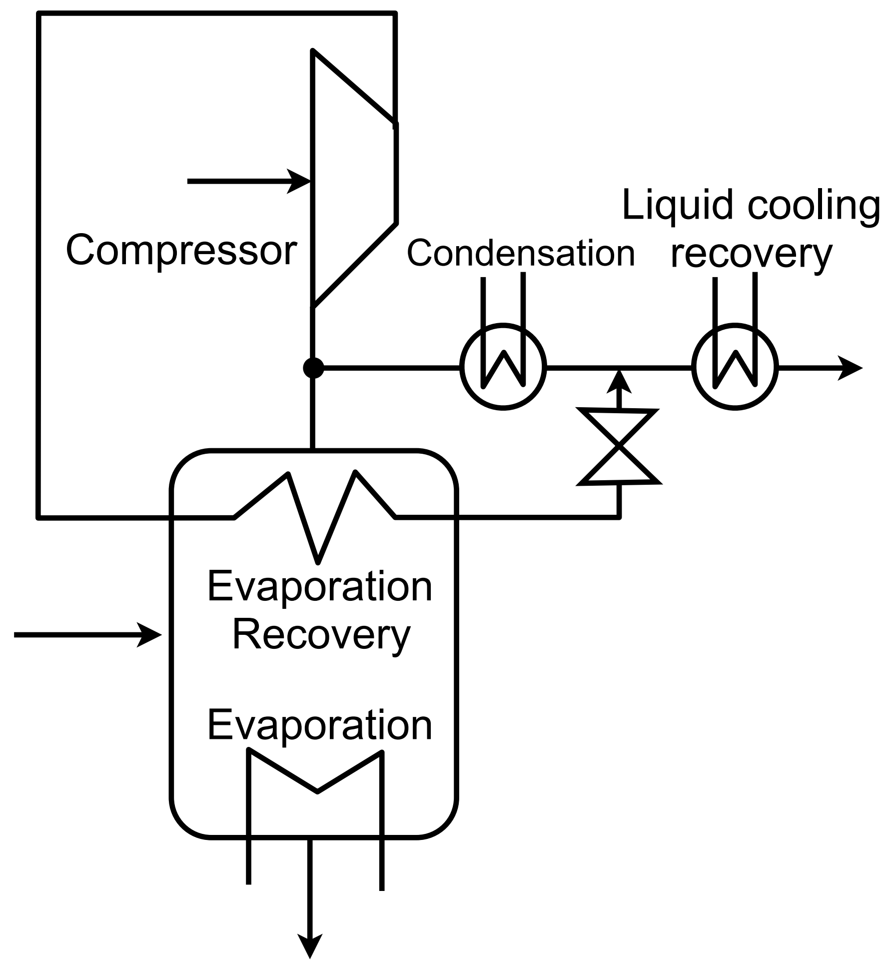
1. Heat exchange integration
2. Process improvements (decrease ΔTmin and increase/decrease pressures of evaporation effects)
3. Heat pump (HP) integration

- Reduction of the minimum energy requirement by 20%
- Reduction of the utility cost by 23%

correct integration : Partial flows possible



$$\dot{m}_{cond} + \dot{m}_{MVR} = \dot{m}_{total}$$

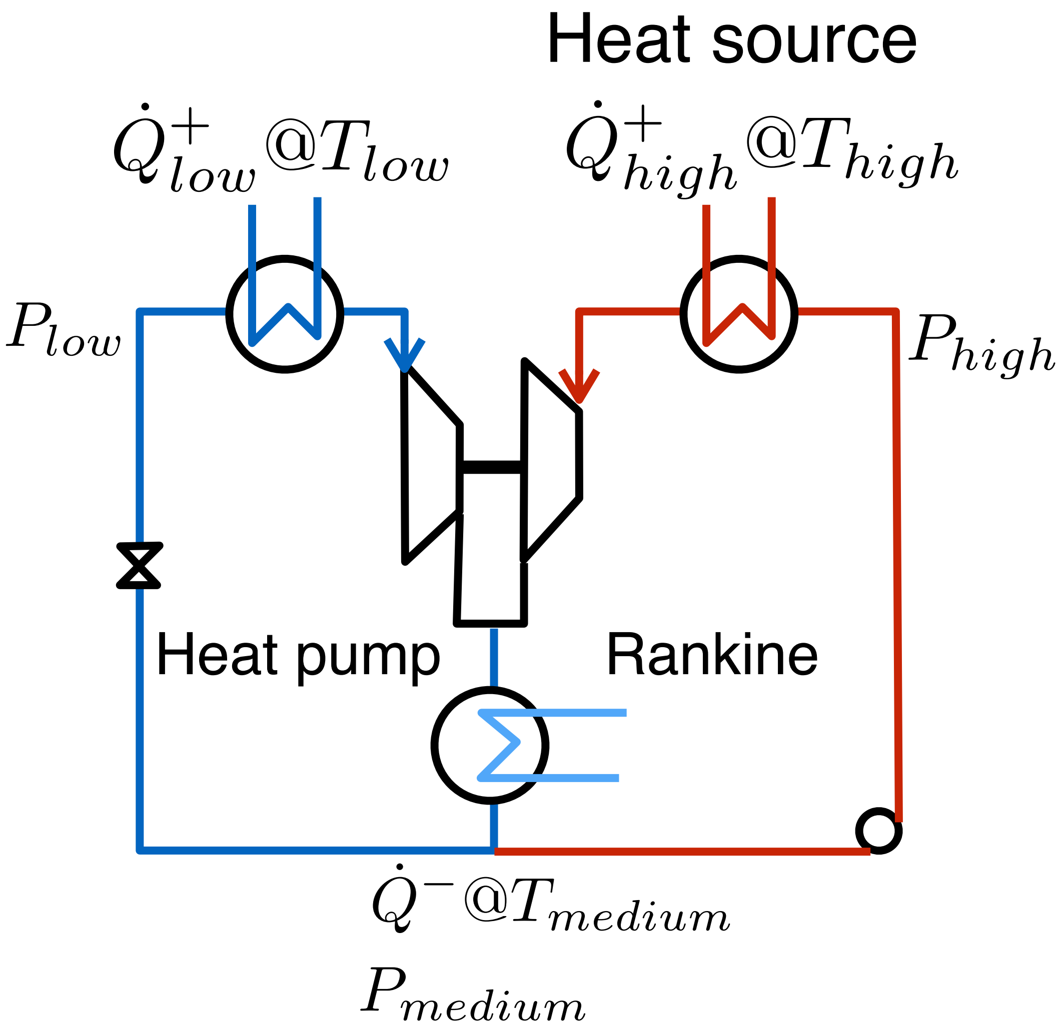


Process requirements

In practice

if only part of the heat load is useful, then it is always possible to compress only part of the flow in order to reduce the compression power

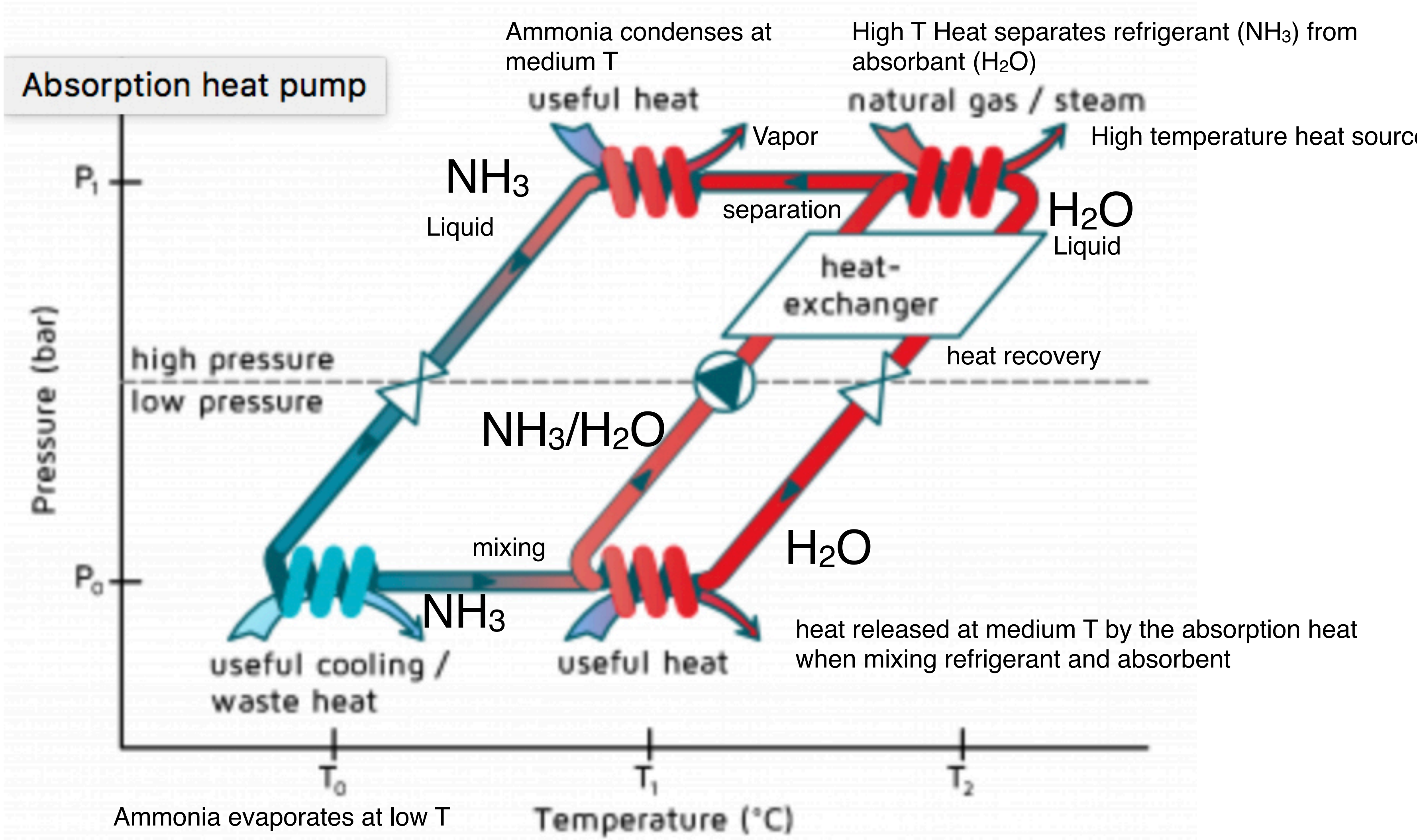
Tri-thermal cycle : driver = heat source



$$COP = \frac{\dot{Q}^-}{\dot{Q}^+_{high}} \simeq 1.7$$

The heat source is used to drive a Rankine cycle that in turns drives a compressor of a heat pump that is taking the heat from the process and delivering it in a condenser that is shared by the heat pump and the Rankine cycle and that is delivering useful heat to the process.

Absorption heat pumps : Thermally driven



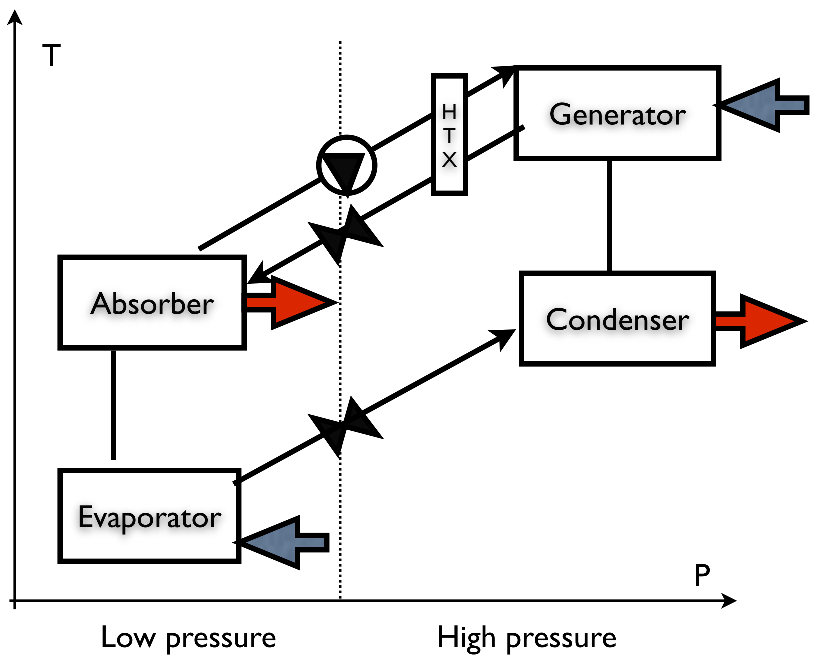
Fluids : mixtures

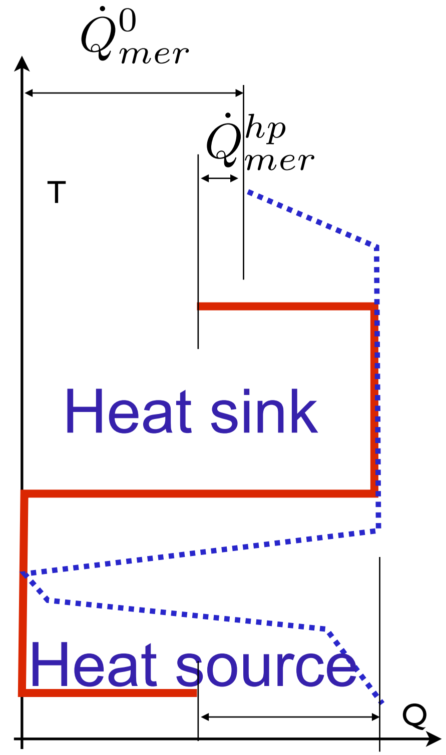
NH_3 (refrigerant) / H_2O (absorbent)

LiBr (refrigerant) / H_2O (absorbent)

http://industrialheatpumps.nl

Absorption heat pump





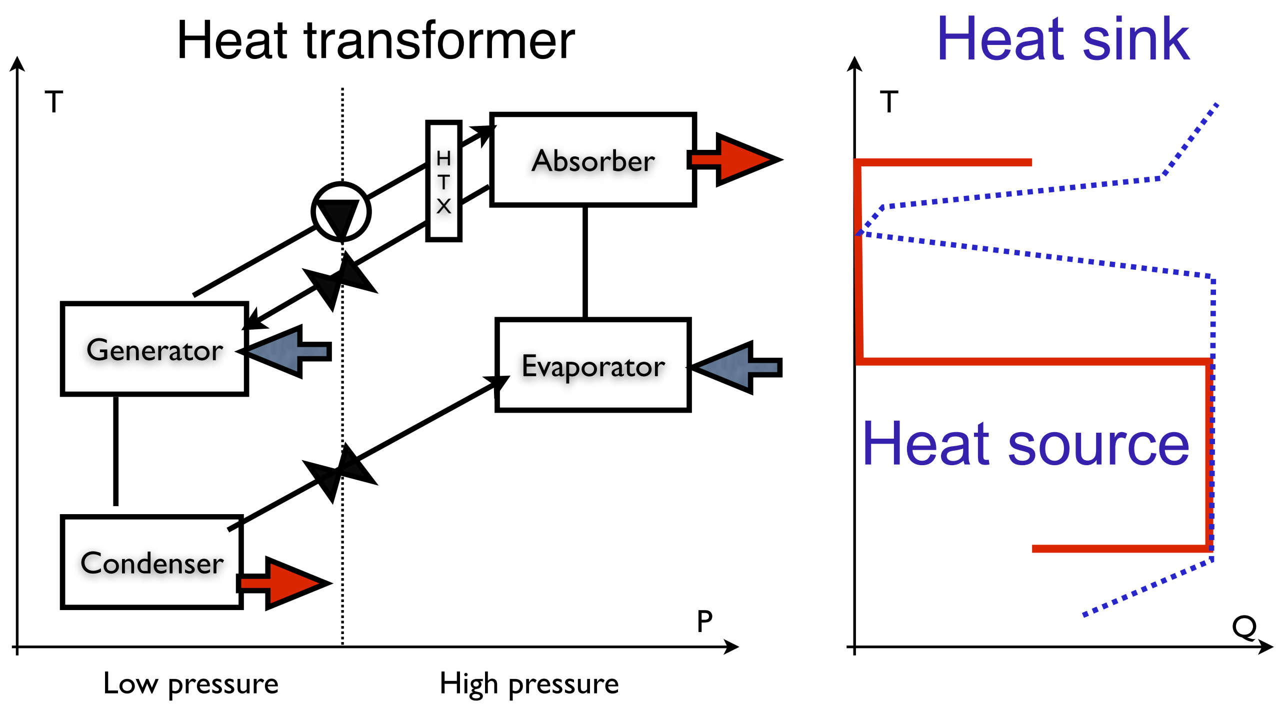
$$\dot{Q}^{hp}_{c,mer} = \dot{Q}^{0}_{c,mer} - (\dot{Q}^{0}_{mer} - \dot{Q}^{hp}_{mer})$$

$$\dot{Q}_{heat} = \dot{Q}_{HotSource} + \dot{Q}_{ColdSource}$$

$$COP = \frac{\dot{Q}_{heat}}{\dot{Q}_{HotSource}}$$

Typical COP = 1.7

Heat transformers



Conclusions : Plus-Minus Principle

- Around pinch point
  - hot streams from below to above
  - cold streams from above to below
- Actions
  - Change DTmin (accept smaller DTmin to transfer a cold stream below the pinch)
  - Change Temperature profile of the heat transfer interfaces of process unit operations
  - Change the operating conditions (P,T) of unit operation
  - Using mechanical power to change the temperature
  - Use heat pumps

Conclusions : Heat pump placement

- Around pinch points
  - from a heat source $T^{(-)}$
    - Exergy source => highest temperatures
  - to a heat sink $T^{(+)}$
    - Exergy sink => lowest temperatures

$$\dot{W}^+ = \dot{Q}^{(-)} \frac{(T^{(+)} - T^{(-)})}{T^{(-)} \eta_{Carnot}} \qquad COP = \frac{\dot{Q}^+}{\dot{W}^+} \gg 3$$

- Optimize heat pump performance
  - select the fluids (best is the process stream)
  - choose the temperatures => pressure
- Flow limitation by pinch point activation
- Multiple heat pumping unit integration

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