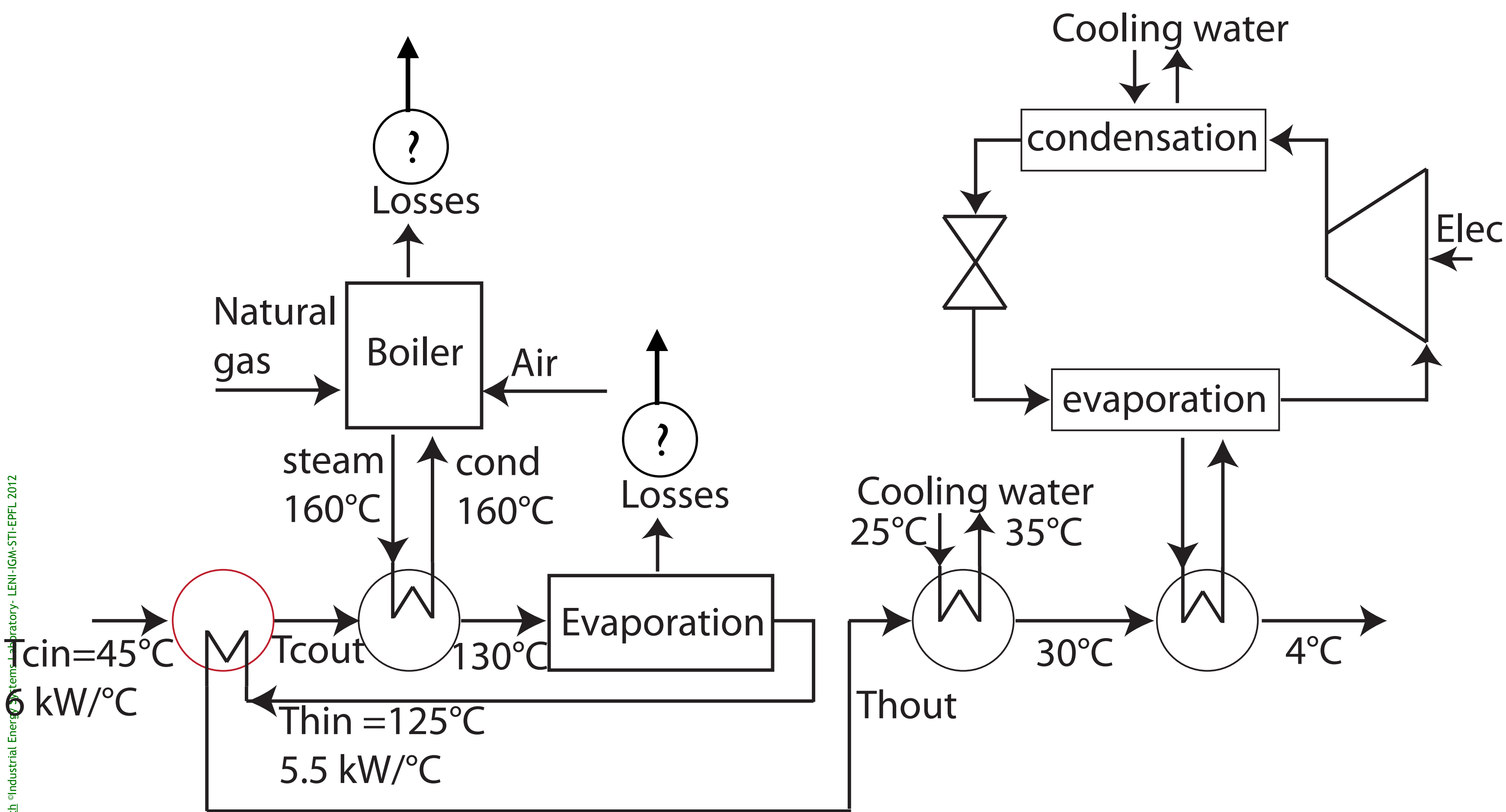
Process integration

Targeting the maximum heat recovery in a process

Prof François Maréchal
IPESE-IGM-EPFL
Industrial Process and Energy Systems Engineering

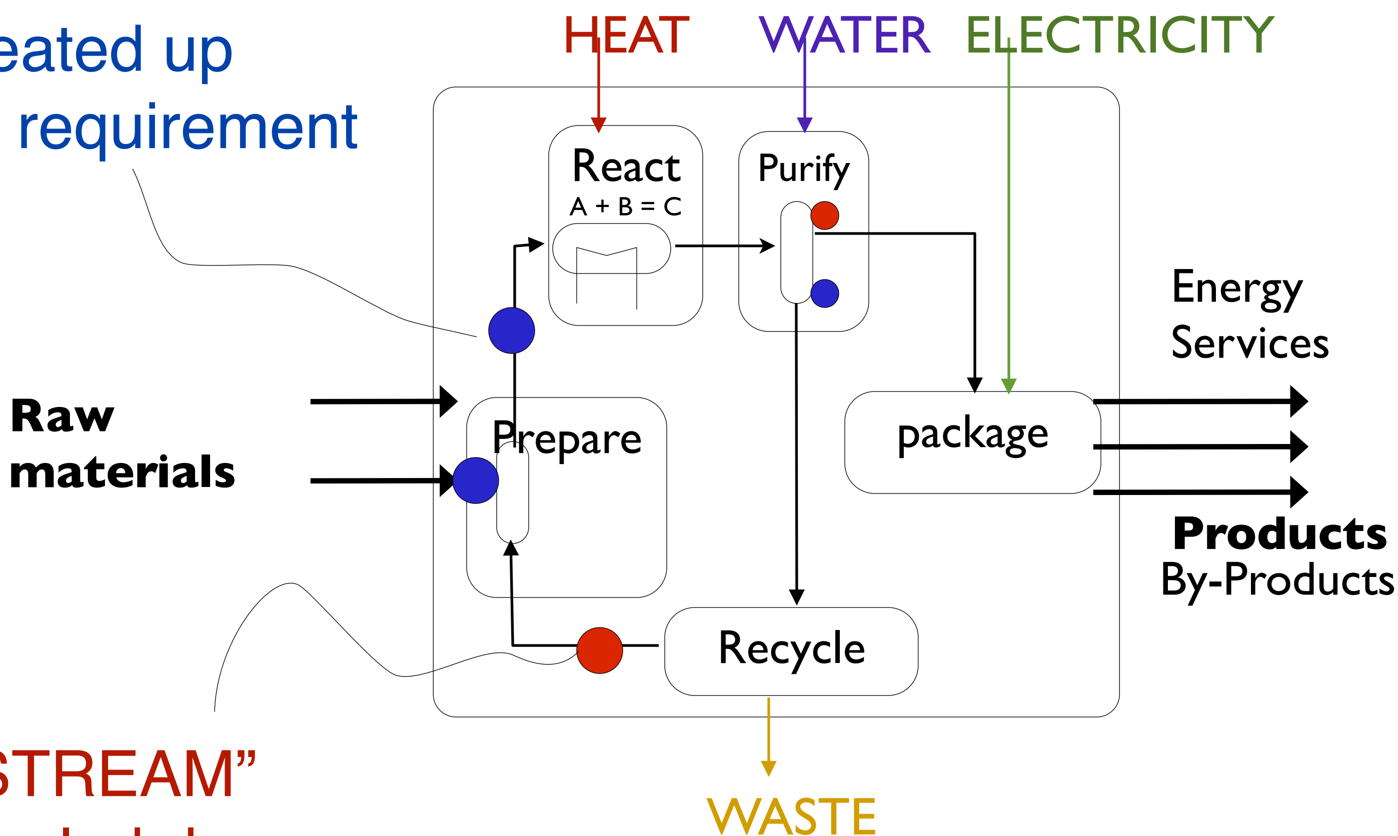
EPFL

Heat recovery by adding a heat exchanger



Generalisation heat exchanges requirements

COLD "STREAM"
to be heated up
heating requirement



HOT "STREAM"
to be cooled down
cooling requirement

Identify the heat transfer requirements

Heat load

Target State

- Environment
- to process unit operation

$$\dot{Q} = -\dot{m}_c \int_{T_{in,c}}^{T_{out,c}} cp_c dT \simeq \dot{m}_c cp_c (T_{in,c} - T_{out,c})$$

Inlet State

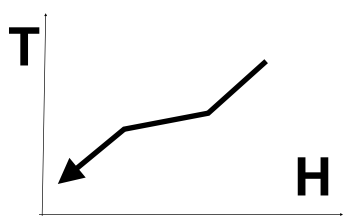
- Environment
- from process unit operation

Hot Streams

---> To be cooled down

Examples

- Distillation condenser
- Exothermic reactor
- Fumes
- Steam condenser
- Hot stream of a refrigeration cycle



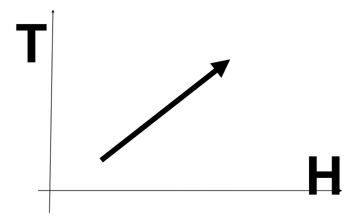
Heat/temperature profile

Cold Streams

---> To be heated up

Examples

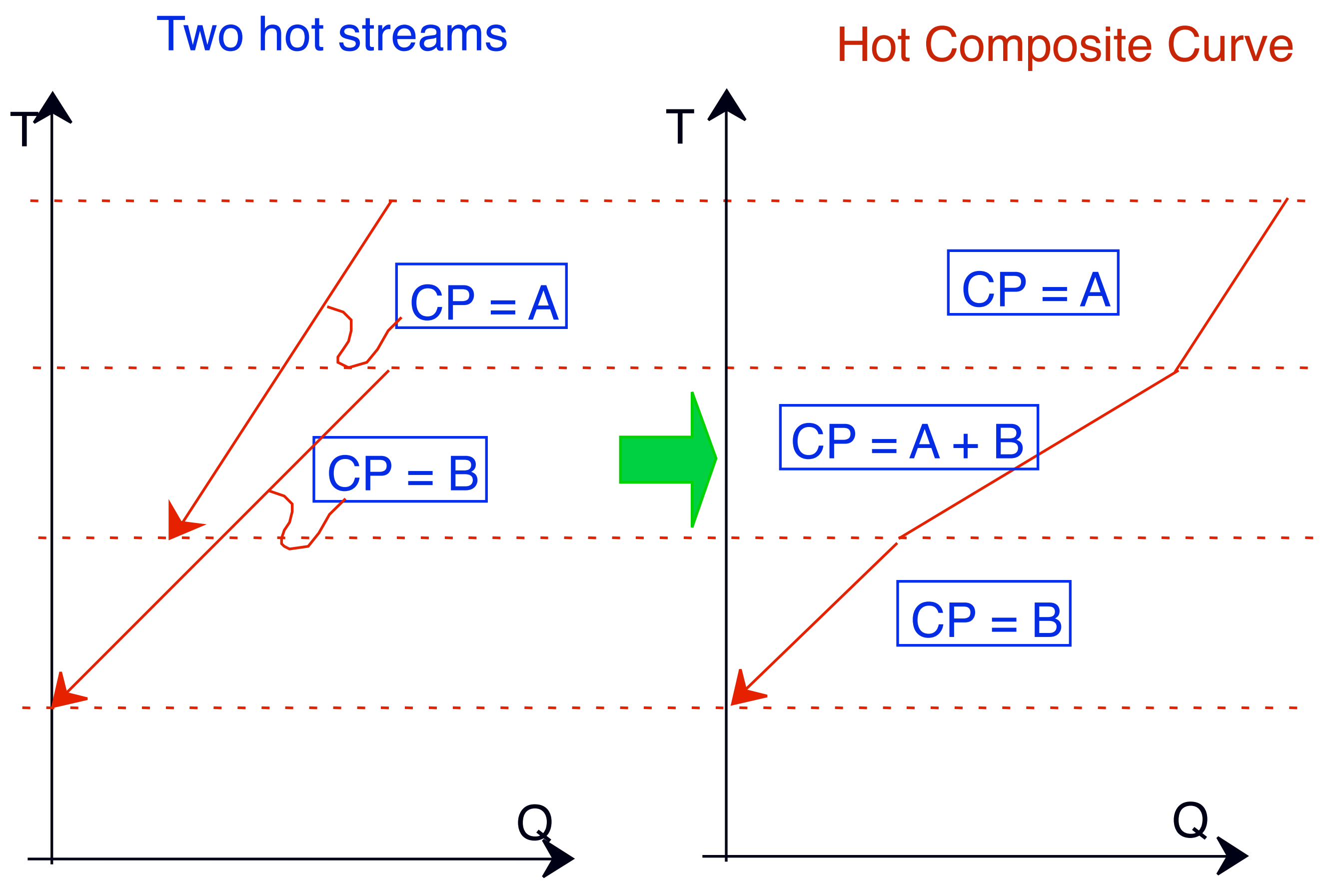
- Distillation boilers
- Reactants Preheating
- Cooling water
- Steam production
- Cold stream of a refrigeration cycle



Heat/temperature profile

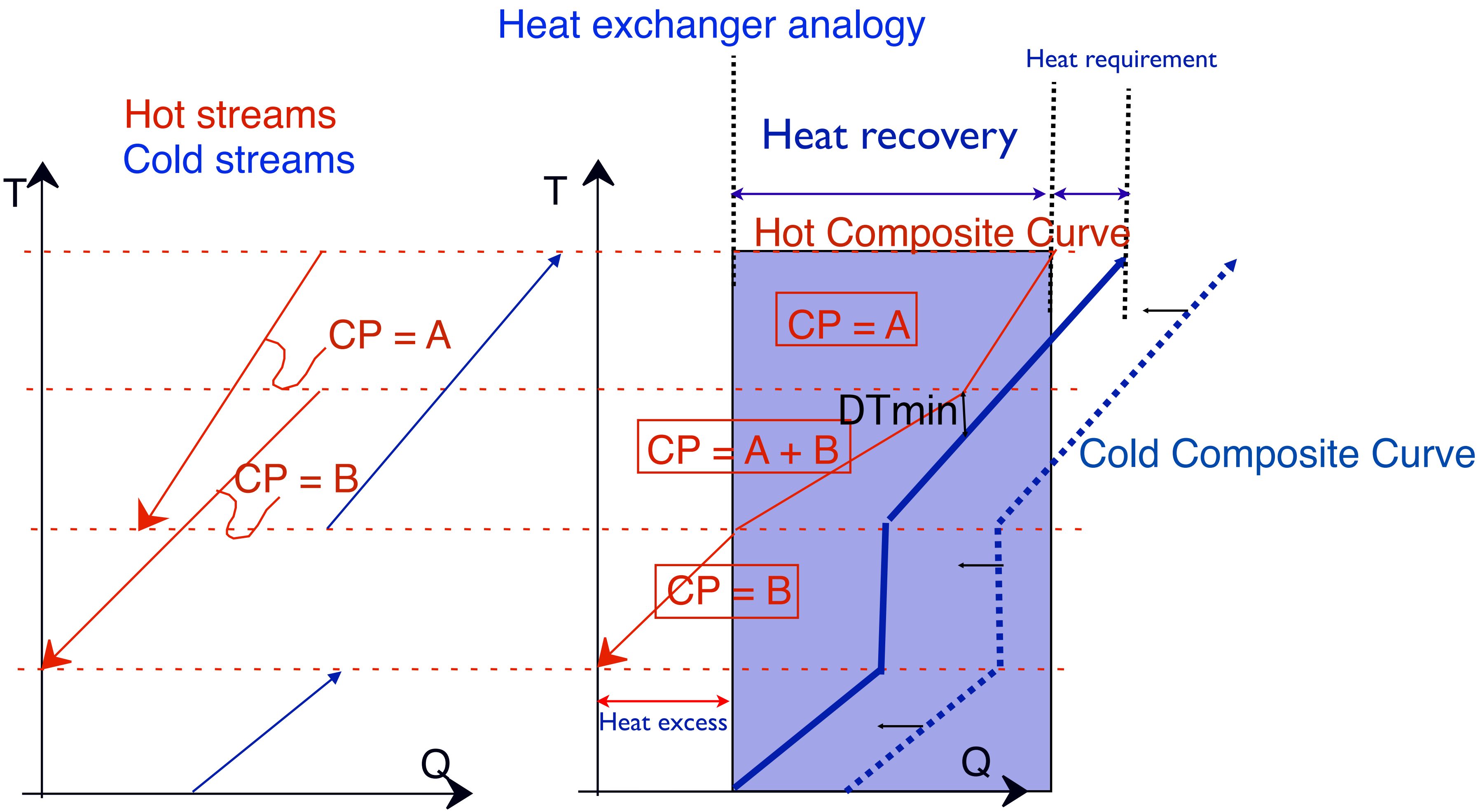
Composite curves

The heat-temperature profile of the heat available in the hot streams as a function of the temperature



This is the integral of the heat made available for the heat exchange in the system. This is like if there would be a centrale heat exchange system t would receive all the hot streams in a single heat exchanger therefore creating a non constant heat temperature profile.

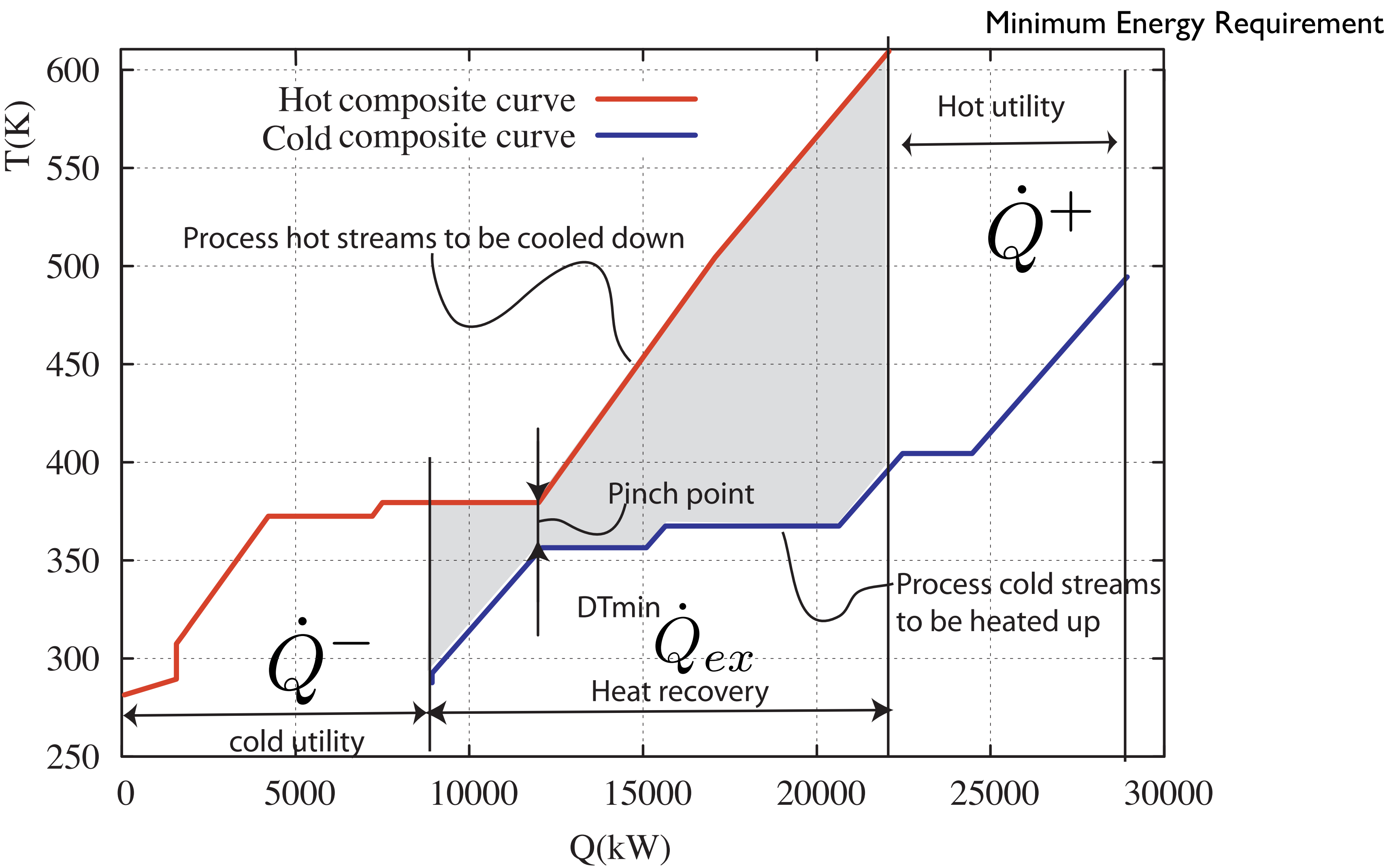
Composite curves and pinch point



Heat excess and Heat by energy balance from the hot and cold streams needs

We consider that the global cold stream (cold composite) can receive heat from the cold global hot stream (hot composite), provided that the temperature of the hot stream is higher enough than the temperature of the cold streams. The theory of the counter current heat recovery between two streams is valid and allows to maximise the heat recovery between the hot and the cold streams in the system, independently of the system size and of the number of streams considered.

Hot and cold composite curves



When the pinch point is activated, we can identify the heat recovery between hot and cold streams. By balance the heat supplied from outside (named hot utility) is the heat needed by the cold streams minus the heat recovery. For the hot streams the heat to be released outside the system (named the cold utility) is the total heat available in the hot streams from which we deduce the heat recovery.

Maximum Heat Recovery

- Heat Balances

$$\text{Heat from the hot streams : } \dot{Q}^+_{hot} = \sum_{i=1}^{n_{hot}} \dot{Q}^+_i$$

$$\text{Heat to the cold streams : } \dot{Q}^-_{cold} = \sum_{j=1}^{n_{cold}} \dot{Q}^-_j$$

- Pinch point constraint
  - DTmin Value
- Results

Minimum heat requirement as hot utility: $\dot{Q}^+$

Maximum heat recovery in heat exchangers :

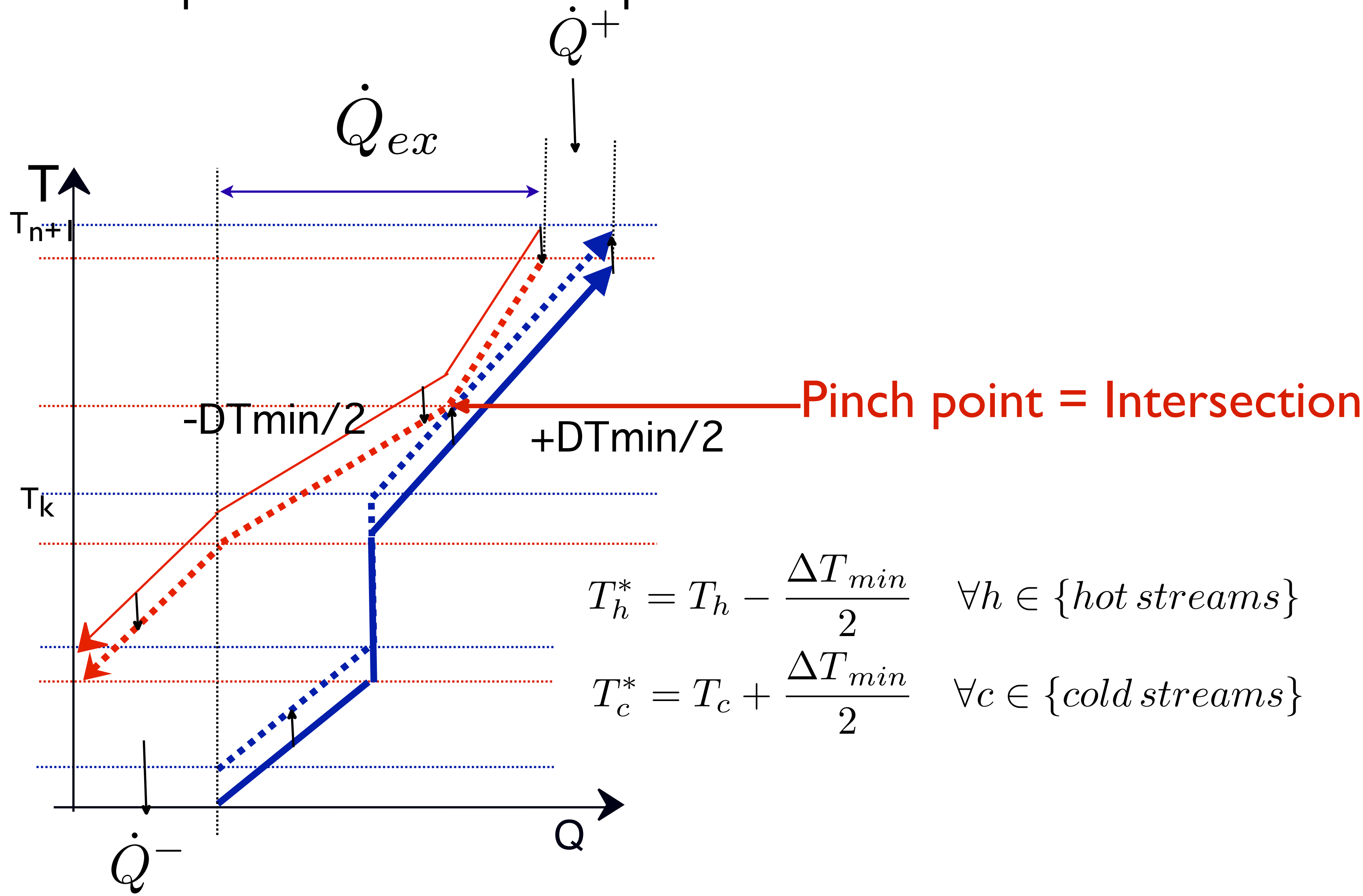
$$\dot{Q}_{ex} = \dot{Q}^-_{cold} - \dot{Q}^+ = \dot{Q}^+_{hot} - \dot{Q}^-$$

Minimum cooling requirement as cold utility:

$$\dot{Q}^- = \dot{Q}^+ + \dot{Q}^+_{hot} - \dot{Q}^-_{cold}$$

Calculation of the minimum energy requirement

Corrected Temperatures or shifted temperatures



$$T_h^* = T_h - \frac{\Delta T_{min}}{2} \quad \forall h \in \{hot\ streams\}$$

$$T_c^* = T_c + \frac{\Delta T_{min}}{2} \quad \forall c \in \{cold\ streams\}$$

An intersection of two curves can be easier to calculate than a vertical distance between two curves. In the corrected or shifted temperature domain (this is a change in the scale), the two curves are intersecting. In the corrected temperature domain, when a hot stream has a corrected temperature higher than the corrected temperature of a cold stream, it can exchange his heat in an economically acceptable way (as calculated with the DTmin assumption).

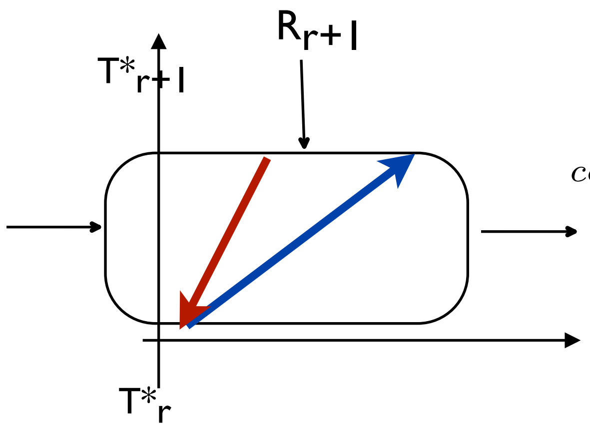
Heat balance in one corrected temperature interval

Change in the scale : Corrected temperatures !

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

Heat to the cold streams between T^*_{r+1} and T^*_r

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



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

Heat deficit

From the definition of the corrected temperature and the heat availability, there is less heat available in the hot streams than in the amount needed in the cold streams : the total amount of heat of the hot streams can be recovered. The heat required to balance the need of the cold streams has to come from higher temperatures.

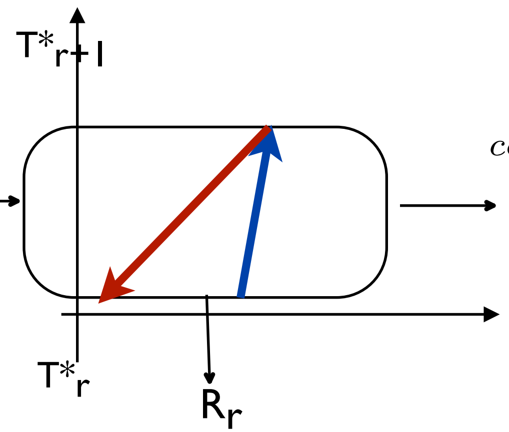
Heat balance in one corrected temperature interval

Change in the scale : Corrected temperatures !

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

Heat to the cold streams between T^*_{r+1} and T^*_r

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



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

Heat Surplus

From the definition of the corrected temperature and the heat availability, there is more heat available in the hot streams than the amount needed by the cold streams : the total amount of heat of the cold stream can be supplied and there is a surplus is available for the streams with lower temperatures (lower temperature intervals)

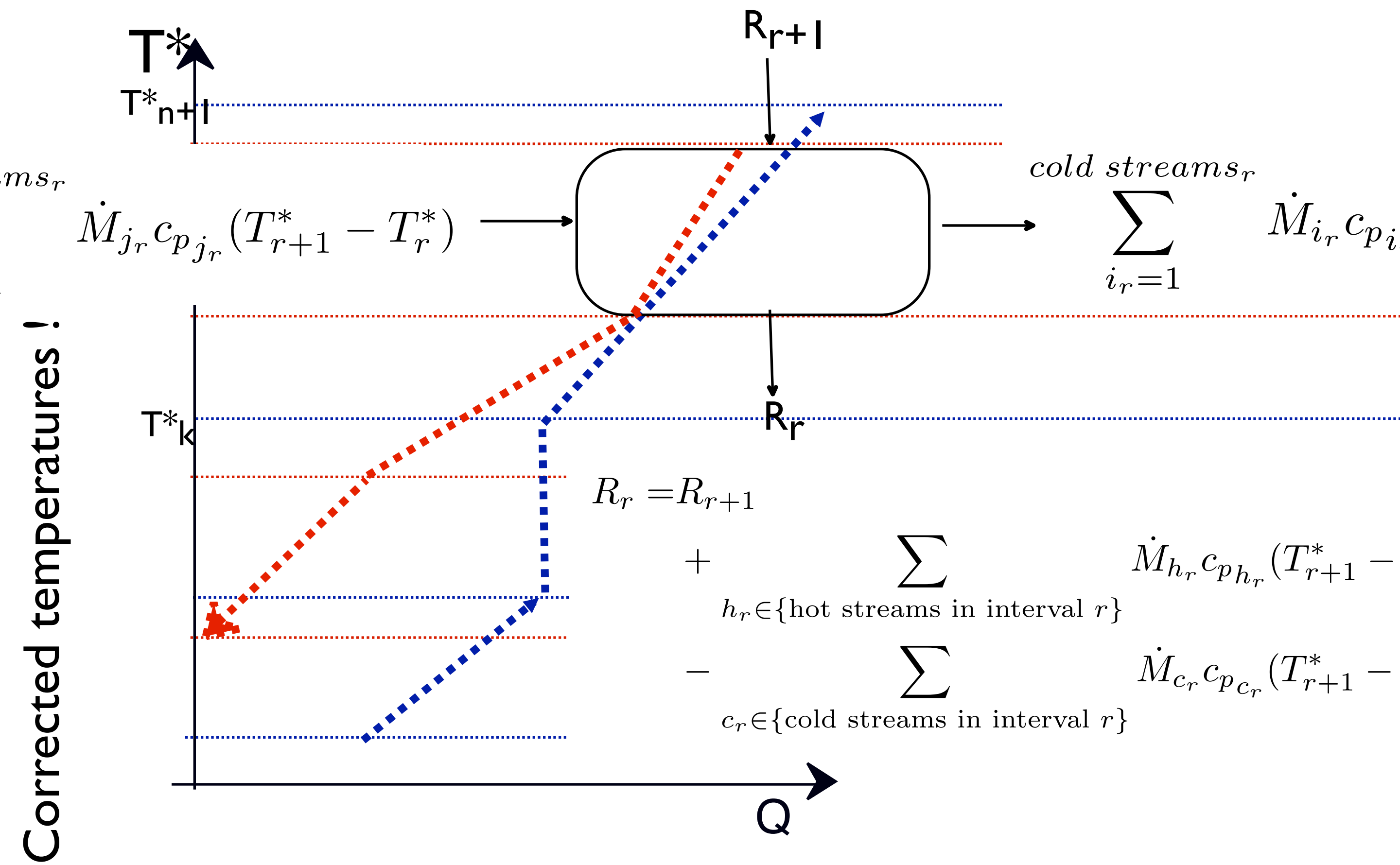
Heat balance in one corrected temperature interval

EPFL

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

Heat to the cold streams between T^*_{r+1} and T^*_r

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



$$R_r = R_{r+1} + \sum_{h_r \in \{\text{hot streams in interval } r\}} \dot{M}_{h_r} c_{p_{h_r}} (T^*_{r+1} - T^*_r) - \sum_{c_r \in \{\text{cold streams in interval } r\}} \dot{M}_{c_r} c_{p_{c_r}} (T^*_{r+1} - T^*_r) \quad \forall r = 1, ..., n_r$$

Heat cascade : [R_r, T^*_r] , $R_r \geq 0$

The flow from higher temperatures to lower temperatures in the corrected temperature domain is defined as being the heat cascade. It is the amount of heat that flows from higher temperatures to lower temperatures. This flow needs to be greater than zero.

Problem table method : solving the problem by hand

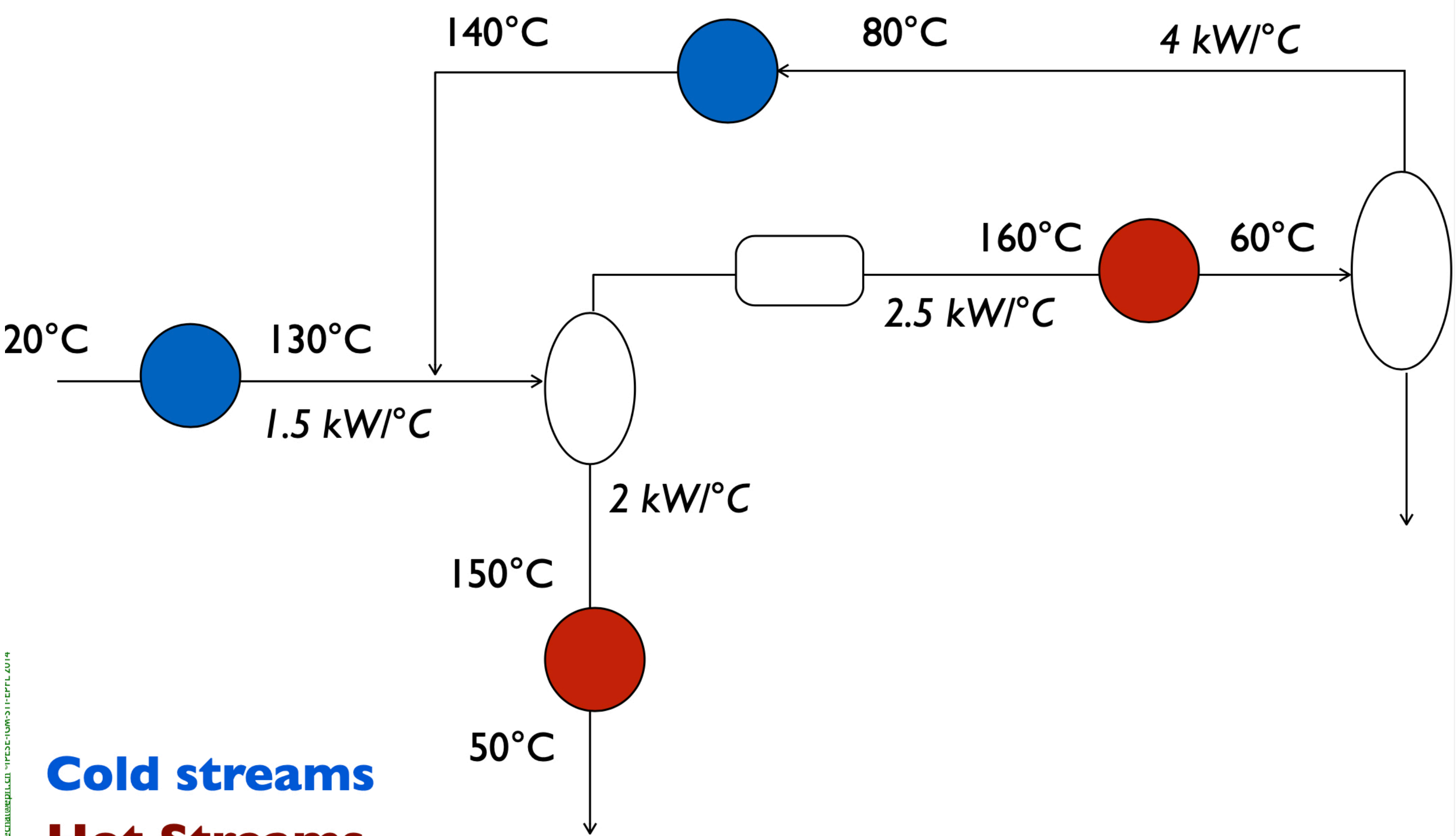
1. Define the hot and the cold streams
2. Divide the enthalpy-temperature profile into linear segments
3. Compute the ordered list of corrected temperatures
4. Compute the temperature difference $\Delta T_r = T^*_{r+1} - T^*_r$
5. For each temperature interval r compute :
   $(\sum_{h_r} \dot{M}_{h_r} c_{p_{h_r}} - \sum_{c_r} \dot{M}_{c_r} c_{p_{c_r}})\Delta T_r$
   $h_r \in \{\text{hot stream segments in interval } r\}$
   $c_r \in \{\text{cold stream segments in interval } r\}$.
6. Assume $R_{n_r+1} = 0$
7. From eq. 9, compute R_r sucessively for $r = n_r, ..., 1$
8. Compute $R_{min} = min_{r=1,...,n_r+1}(R_r)$
9. Set $R_{n_r+1} = -R_{min}$
10. Recompute $R_r = R_r + R_{n_r+1}$ for $r = 1, ..., n_r$ using eq. 9

$$\begin{aligned} R_r = & R_{r+1} \\ & + \sum_{h_r \in \{\text{hot streams in interval } r\}} \dot{M}_{h_r} c_{p_{h_r}} (T^*_{r+1} - T^*_r) \\ & - \sum_{c_r \in \{\text{cold streams in interval } r\}} \dot{M}_{c_r} c_{p_{c_r}} (T^*_{r+1} - T^*_r) \end{aligned} \quad \forall r = 1, ..., n_r \qquad (9)$$

IPESE INDUSTRIAL PROCESS AND

EPFL

Example



Cold streams

Hot Streams

Streams definition

	T_{in} [C]	T_{out} [C]	$\dot{M}cp$ [kW/C]	$\dot{Q}$ [kW]	α $[kW/C/m^2]$
A	20	130	-1.5	-165.0	0.5
B	80	140	-4.0	-240.0	0.5
C	160	60	+2.5	250.0	0.5
D	150	50	+2.0	200.0	0.5

Table 1: Streams definition

Application : I corrected temperatures

	T_{in} [C]	T^*_{in} [C]	T_{out} [C]	T^*_{out} [C]	$\dot{M}cp$ [kW/C]	$\dot{Q}$ [kW]
A	20		130		-1.5	-165.0
		25		135		
B	80		140		-4.0	-240.0
		85		145		
C	160		60		+2.5	+250.0
		155		55		
D	150		50		+2.0	+200.0
		145		45		

Table 2: Corrected temperatures

Problem table application

T^*	
155	
145	
135	
85	
55	
45	
25	

Table 3: Problem Table Method

Problem table application DT calculations

T^*	ΔT	
155		
	10	
145		
	10	
135		
	50	
85		
	30	
55		
	10	
45		
	20	
25		

Table 3: Problem Table Method

Problem table application streams contributions

T^*	ΔT	A	B	C	D
155					
	10			+2.5	
145					
	10		-4.0	+2.5	+2.0
135					
	50	-1.5	-4.0	+2.5	+2.0
85					
	30	-1.5		+2.5	+2.0
55					
	10	-1.5			+2.0
45					
	20	-1.5			
25					

Table 3: Problem Table Method

Problem table application Mcp balance

T^*	ΔT	A	B	C	D	$\sum \dot{M}cp$
155						
	10			+2.5		+2.5
145						
	10		-4.0	+2.5	+2.0	+0.5
135						
	50	-1.5	-4.0	+2.5	+2.0	-1.0
85						
	30	-1.5		+2.5	+2.0	+3.0
55						
	10	-1.5			+2.0	+0.5
45						
	20	-1.5				-1.5
25						

Table 3: Problem Table Method

Problem table application Heat load contributions

T^*	ΔT	A	B	C	D	$\sum \dot{M}cp$	$\Delta \dot{Q}$
155							
	10			+2.5		+2.5	+25.0
145							
	10		-4.0	+2.5	+2.0	+0.5	+5.0
135							
	50	-1.5	-4.0	+2.5	+2.0	-1.0	-50.0
85							
	30	-1.5		+2.5	+2.0	+3.0	+90.0
55							
	10	-1.5			+2.0	+0.5	+5.0
45							
	20	-1.5				-1.5	-30.0
25							

Table 3: Problem Table Method

Problem table application Heat cascade 0

T^*	ΔT	A	B	C	D	$\sum \dot{M}cp$	$\Delta\dot{Q}$	$\dot{R}_r^0$
155								+0.0
	10			+2.5		+2.5	+25.0	
145								+25.0
	10		-4.0	+2.5	+2.0	+0.5	+5.0	
135								+30.0
	50	-1.5	-4.0	+2.5	+2.0	-1.0	-50.0	
85								**-20.0**
	30	-1.5		+2.5	+2.0	+3.0	+90.0	
55								+70.0
	10	-1.5			+2.0	+0.5	+5.0	
45								+75.0
	20	-1.5				-1.5	-30.0	
25								+45.0

Table 3: Problem Table Method

Problem table application Heat cascade

T^*	ΔT	A	B	C	D	$\sum \dot{M}cp$	$\Delta\dot{Q}$	$\dot{R}_r^0$	$\dot{R}_r$
155								+0.0	**+20.0**
	10			+2.5		+2.5	+25.0		
145								+25.0	+45.0
	10		-4.0	+2.5	+2.0	+0.5	+5.0		
135								+30.0	+50.0
	50	-1.5	-4.0	+2.5	+2.0	-1.0	-50.0		
85								**-20.0**	**0.0**
	30	-1.5		+2.5	+2.0	+3.0	+90.0		
55								+70.0	+90.0
	10	-1.5			+2.0	+0.5	+5.0		
45								+75.0	+95.0
	20	-1.5				-1.5	-30.0		
25								+45.0	**+65.0**

Table 3: Problem Table Method

Hot and cold composite curves

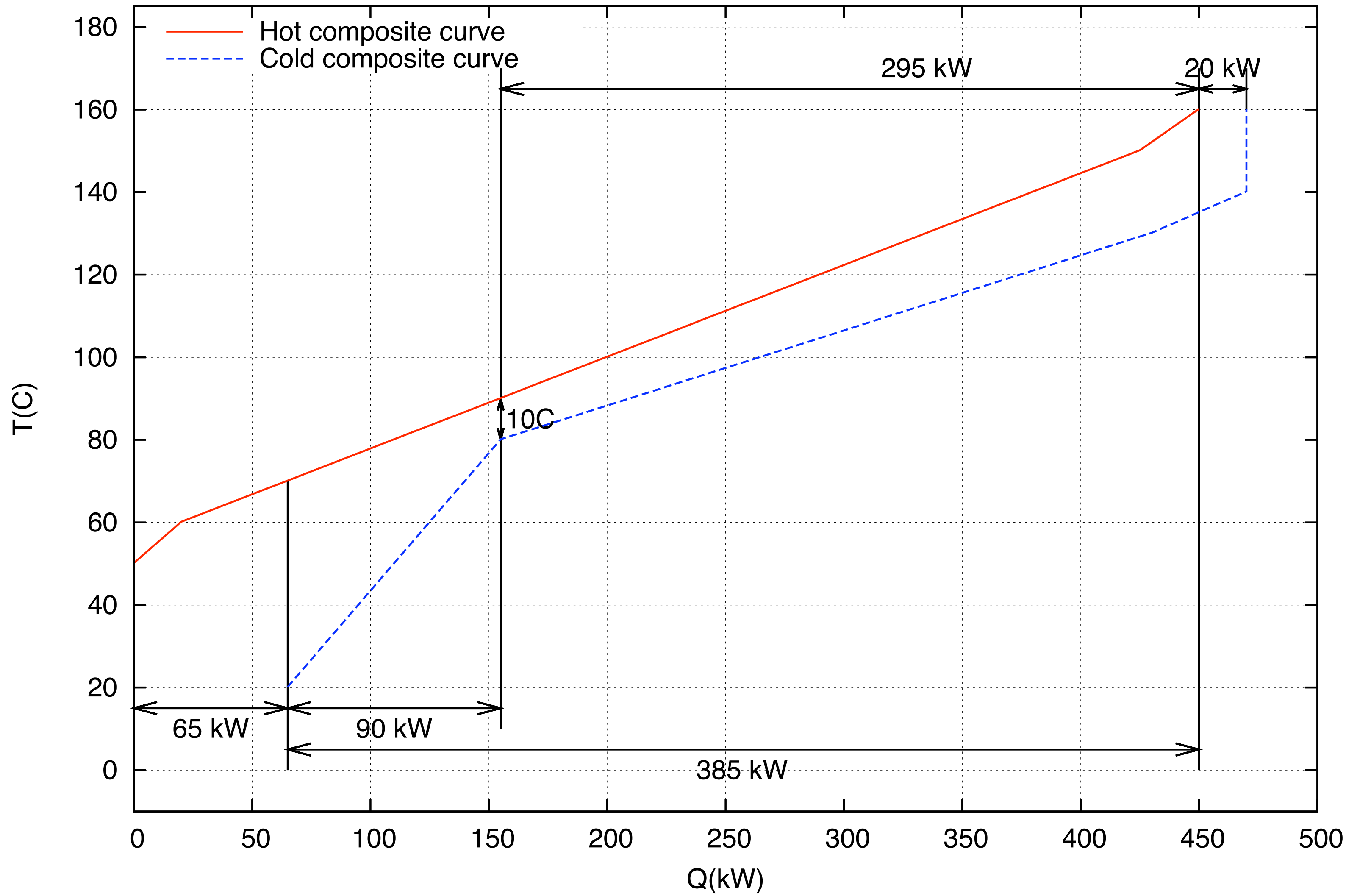


Figure 2: Hot and Cold Composite Curves

Grand composite curve => Heat cascade representation

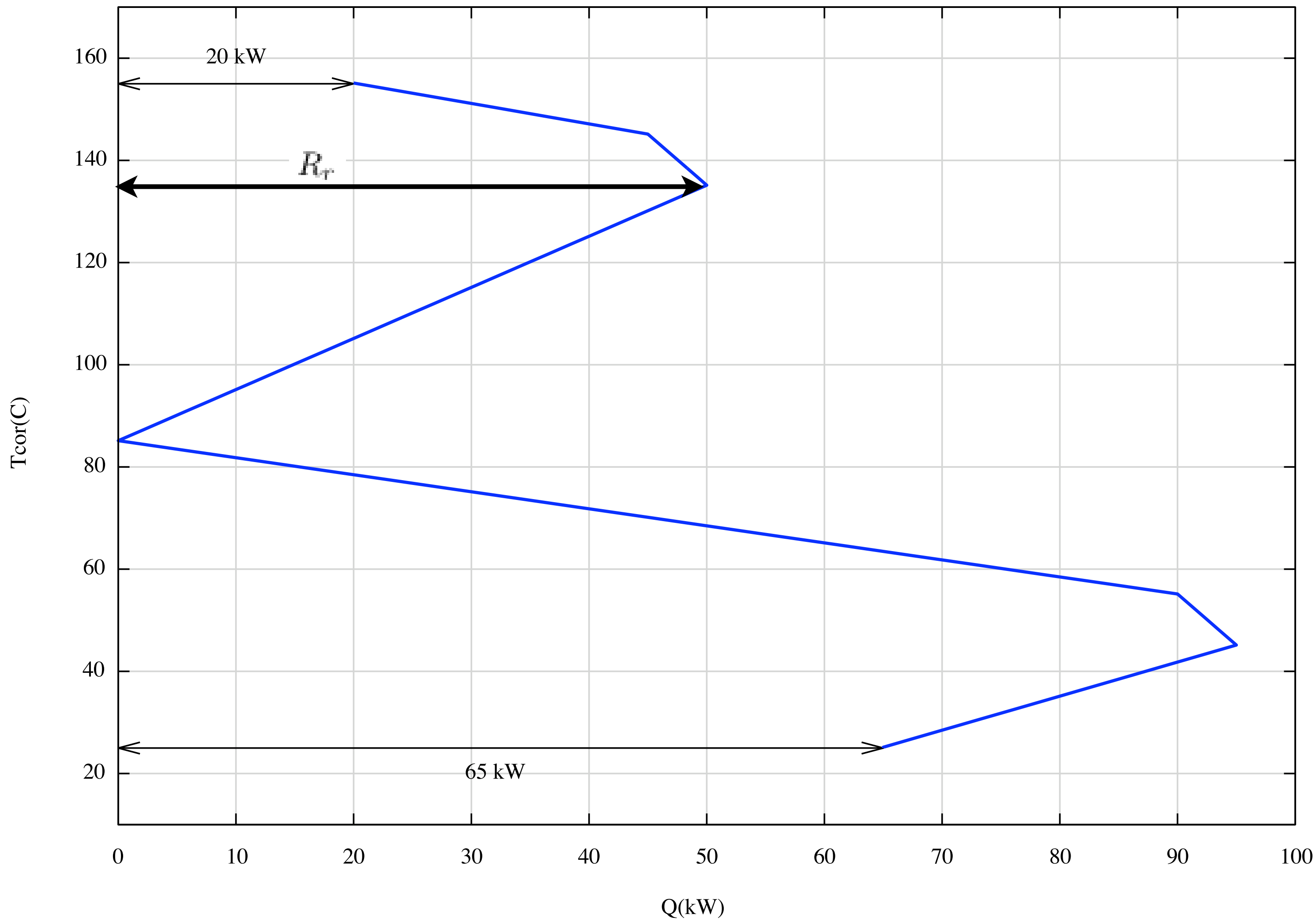


Figure 3: Grand Composite Curve

Heat cascade

EPFL

$$\min_{R_r} \dot{Q}^+ = R_{n_r+1}$$

subject to heat balance of the temperature intervals :

$$\begin{aligned} R_r =& R_{r+1} \\ &+ \sum_{h_r \in \{\text{hot streams in interval } r\}} \dot{M}_{h_r} c_{p_{h_r}} (T^*_{r+1} - T^*_r) \\ &- \sum_{c_r \in \{\text{cold streams in interval } r\}} \dot{M}_{c_r} c_{p_{c_r}} (T^*_{r+1} - T^*_r) \end{aligned} \quad \forall r = 1, ..., n_r$$

and the heat cascade feasibility

$$R_r \geq 0 \quad \forall r = 1, ..., n_r + 1$$

$$T^*_h = T_h - \frac{\Delta T_{min}}{2} \quad \forall h \in \{hot\, streams\}$$

$$T^*_c = T_c + \frac{\Delta T_{min}}{2} \quad \forall c \in \{cold\, streams\}$$

The fact that we look for the minimum of heat input is going to tell us that one of the inequality contraints (Rr≥0) will be activated. The place where the constraint is activated is defined as being the pinch point.

Alternative definition

$$\dot{Q}^{+} = -\min_{s}(0, R_s^*), \forall s \in \{\text{hot and cold stream segments}\}$$

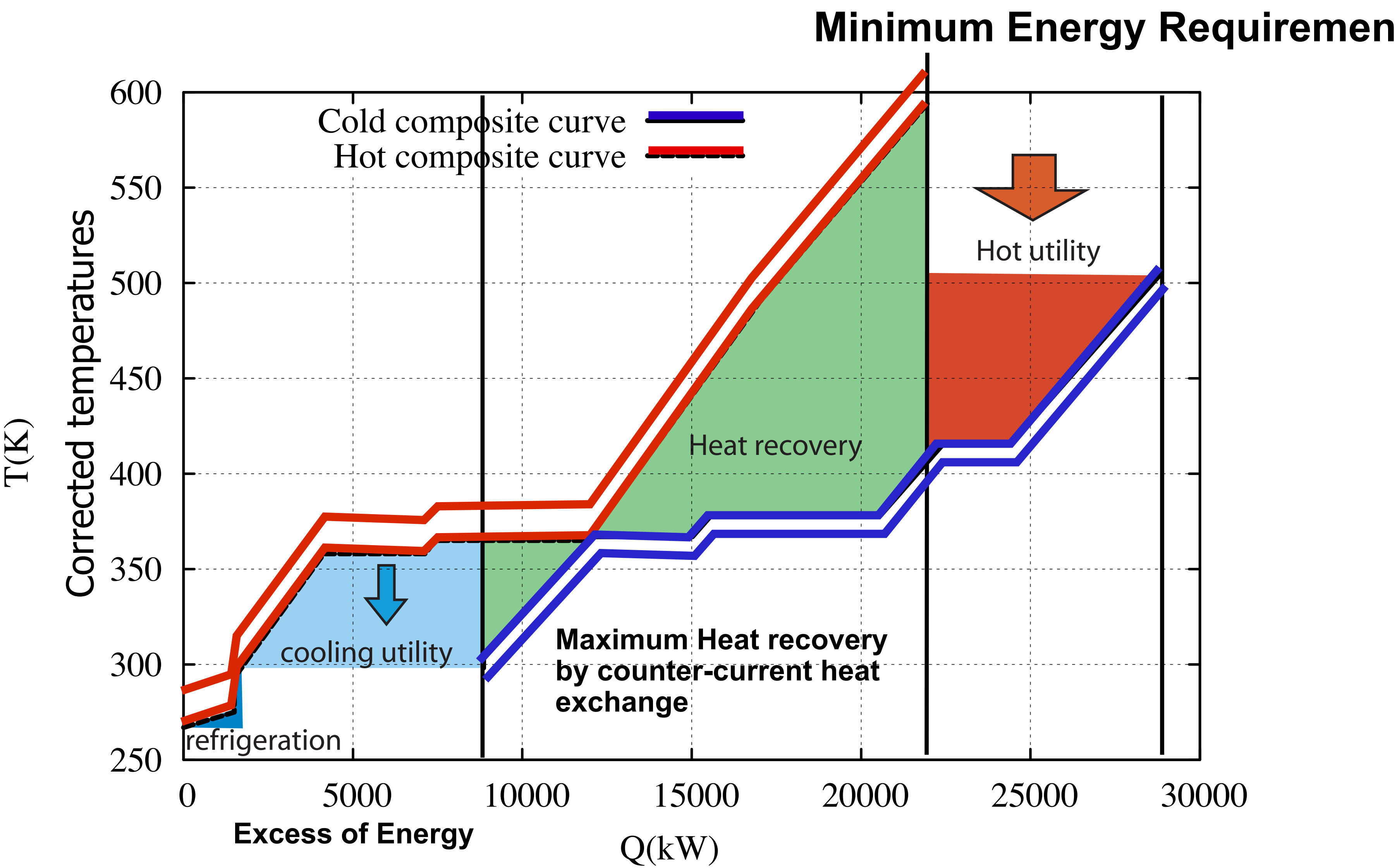
$$R_s^* = \sum_h \dot{M}_h c_{p_h} (max(T_s^*, T_{h,in}^*) - max(T_s^*, T_{h,target}^*))$$

$$- \sum_c \dot{M}_c c_{p_c} (max(T_s^*, T_{c,target}^*) - max(T_s^*, T_{c,in}^*))$$

$$h \in \{\text{hot stream segments}\}, c \in \{\text{cold stream segments}\}$$

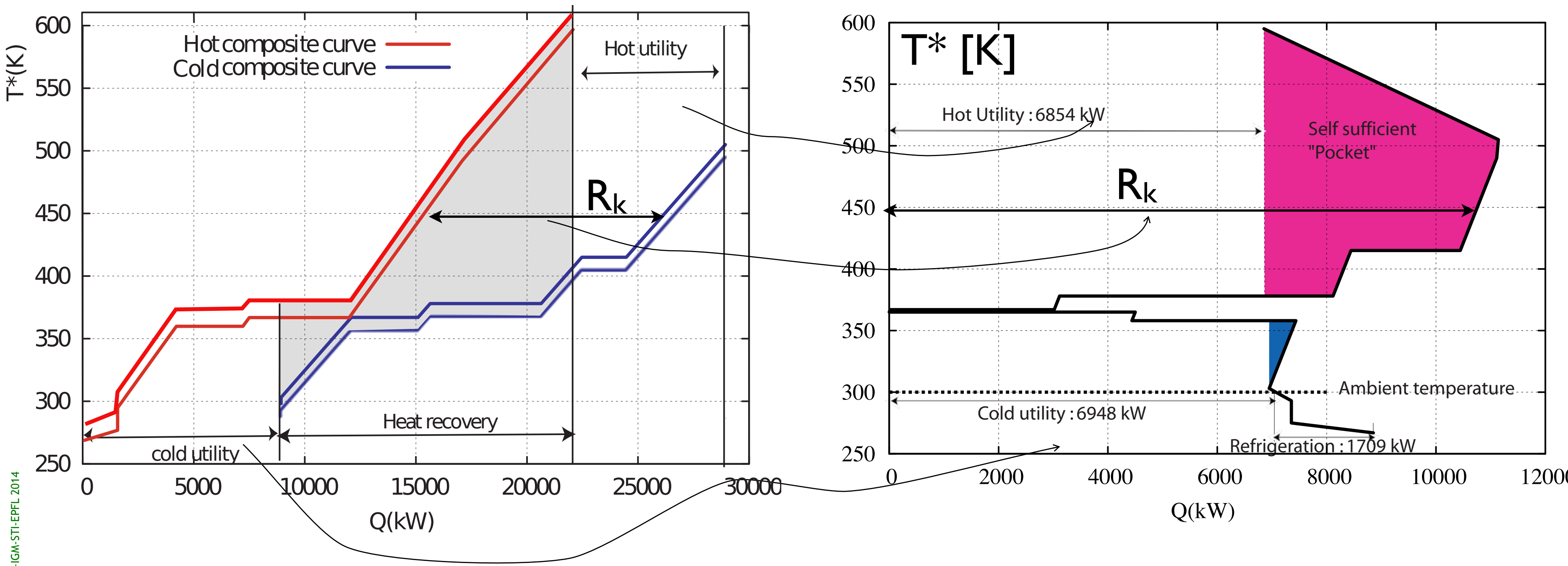
$$\dot{Q}^{-} = \dot{Q}^{+} + \sum_h \dot{Q}_h - \sum_c \dot{Q}_c$$

Maximum heat recovery Target



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.

Conclusions

- **Hot and cold streams for the overall system**
  - Composite curves
- **From the DTmin assumptions**
  - Maximum heat recovery
  - Minimum hot&cold utility
  - Energy savings
- **Algorithm for calculating maximum heat recovery**
  - Problem table
  - Corrected temperature
  - Heat cascade => Grand composite curve

Consistency check

- Energy balance :

$$\sum_{i=1}^{n_{in}} \dot{m}_i^+ \cdot h_i^*(T_i, P_i, X_i) + \sum_{u=1}^{n_u} \dot{E}_u^+ + \sum_{h=1}^{n_h} \dot{Q}_h - (\sum_{o=1}^{n_{out}} \dot{m}_o^- \cdot h_o^*(T_o, P_o, X_o) + \sum_{u=1}^{n_u} \dot{E}_u^- + \sum_{c=1}^{n_c} \dot{Q}_c) - \dot{Q}_{loss}^- = 0$$

with

(subscript + refers positive when entering, - positive when leaving)

$\dot{m}_i^+$ input flows

$h_i^*(T_i, P_i, X_i)$ enthalpy of stream i at temperature, pressure and composition of the stream including the enthalpy of formation

$\dot{E}_u^+$ electricity (work) used by the unit u

$\dot{Q}_h$ heat delivered by the hot streams including the hot utility

$\dot{Q}_c$ heat need by the cold streams including the cold utility

$\dot{Q}_{loss}^-$ heat losses in the system (radiated to outside) : **not the error !**

n_{out} streams leaving the system : includes products, by-products and waste (including gas emissions released in the environment)

it is important to realise that all the streams handled by the process are in a pipe, a tank or a transfer line before leaving the process

n_{in} streams entering the process : includes raw materials but also flows from the environment that are used by the process (like air, water). Those streams enter the process in a transfer line, a pipe or a storage (truck ?)