ETH zürich

epse ENERGY & PROCESS SYSTEMS ENGINEERING

# Introduction to Modeling and Optimization of Sustainable Energy Systems:

## Heat integration

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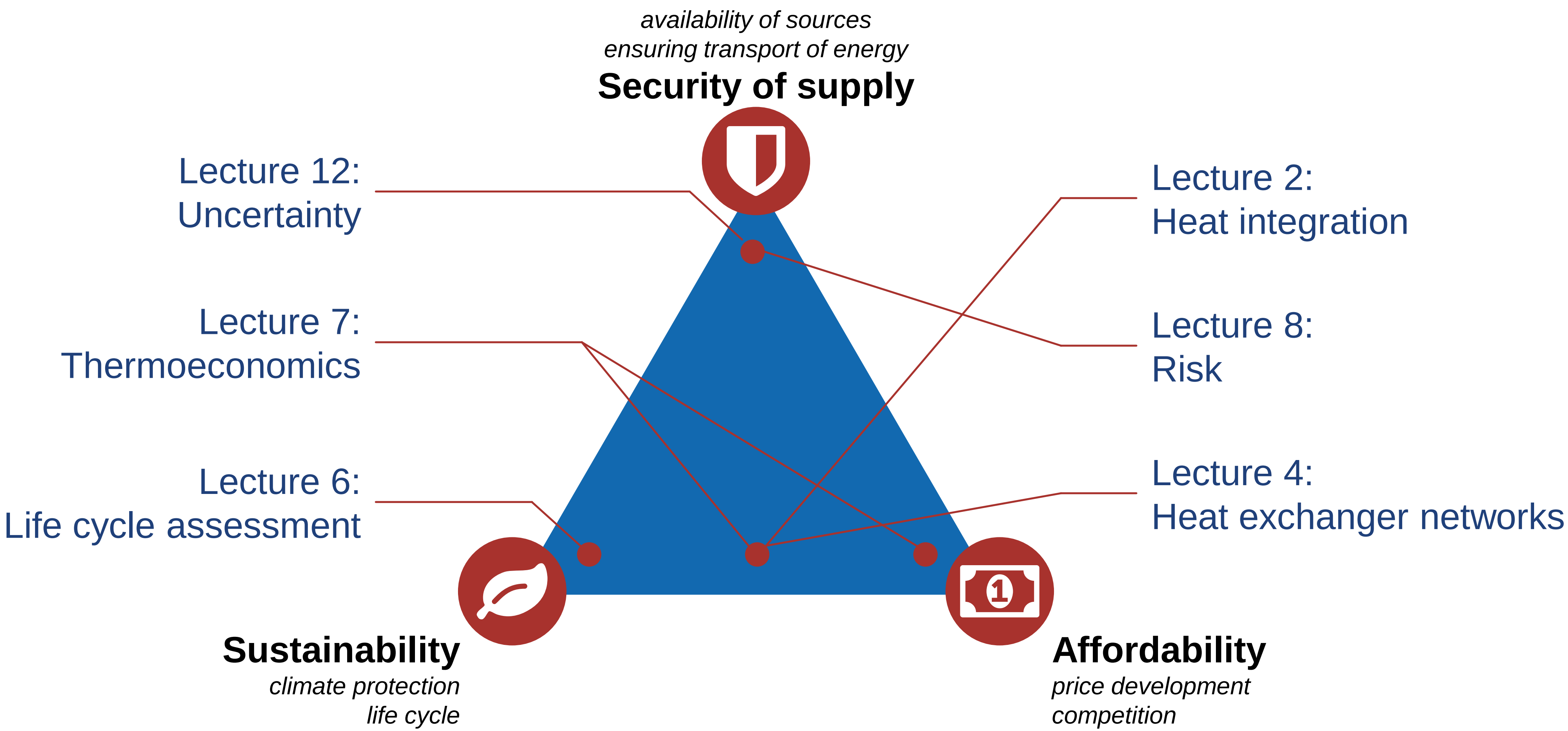
*Energy and Process Systems Engineering*

D MAVT

# Since the last lecture, you are able to…

- ✓ explain the **scope of this course**
- ✓ explain **your participation** in this course
- ✓ recognize tradeoffs in the **energy trilemma**
- ✓ classify **mathematical models**

# Course content in the energy trilemma




***Methods & Models:***

Lecture 3 & 5: Optimization

Lecture 9: Conversion

Lecture 10: Storage

Lecture 11: Transport

# Mathematical model types
Summary

increasing complexity →

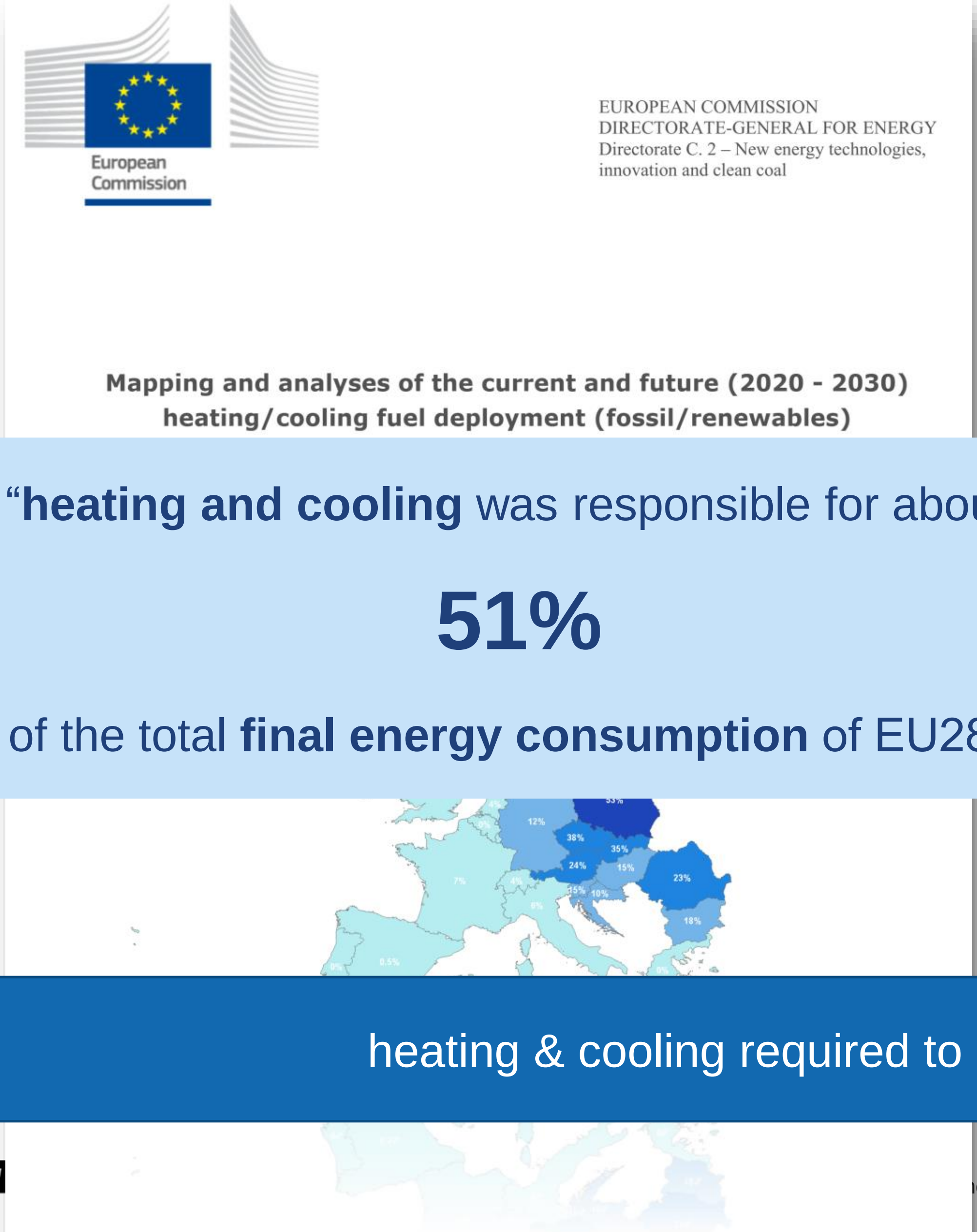
| | | |
|---|---|---|
| dimension | 0D | 1D, 2D, 3D |
| time | static | dynamic |
| variables | continuous | discrete |
| equations | linear | nonlinear |
| predictability | deterministic | stochastic |

**There is no single “right” model! The choice of model type depends on the problem at hand!**

# After this lecture, you will be able to…

- explain the idea underlying **the heat integration problem**
- apply the **pinch rules** to heat integration problems.
- thermodynamically analyze **heat exchangers** with the **pinch method**.
- integrate external utilities by using the grand composite curve
- interpret **heat integration as optimization problem**

# Heating & cooling demands

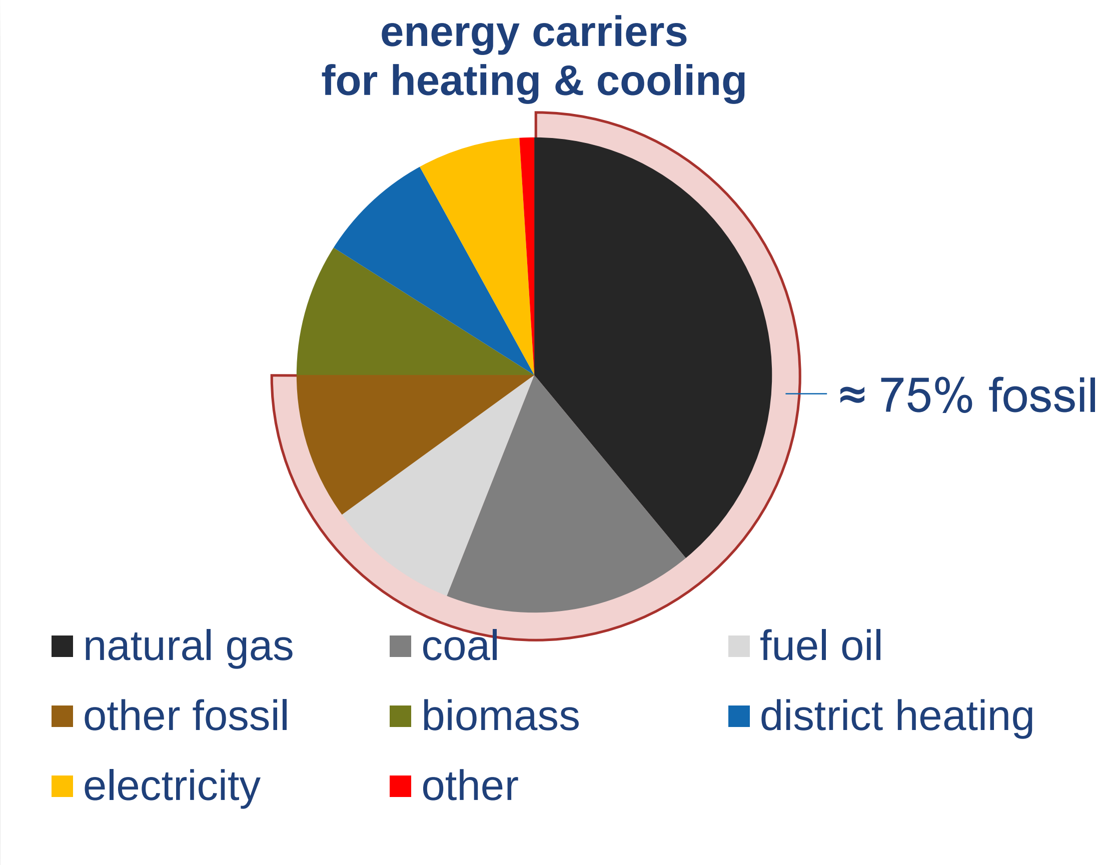

EUROPEAN COMMISSION
DIRECTORATE-GENERAL FOR ENERGY
Directorate C. 2 – New energy technologies, innovation and clean coal

Mapping and analyses of the current and future (2020 - 2030) heating/cooling fuel deployment (fossil/renewables)

“**heating and cooling** was responsible for about

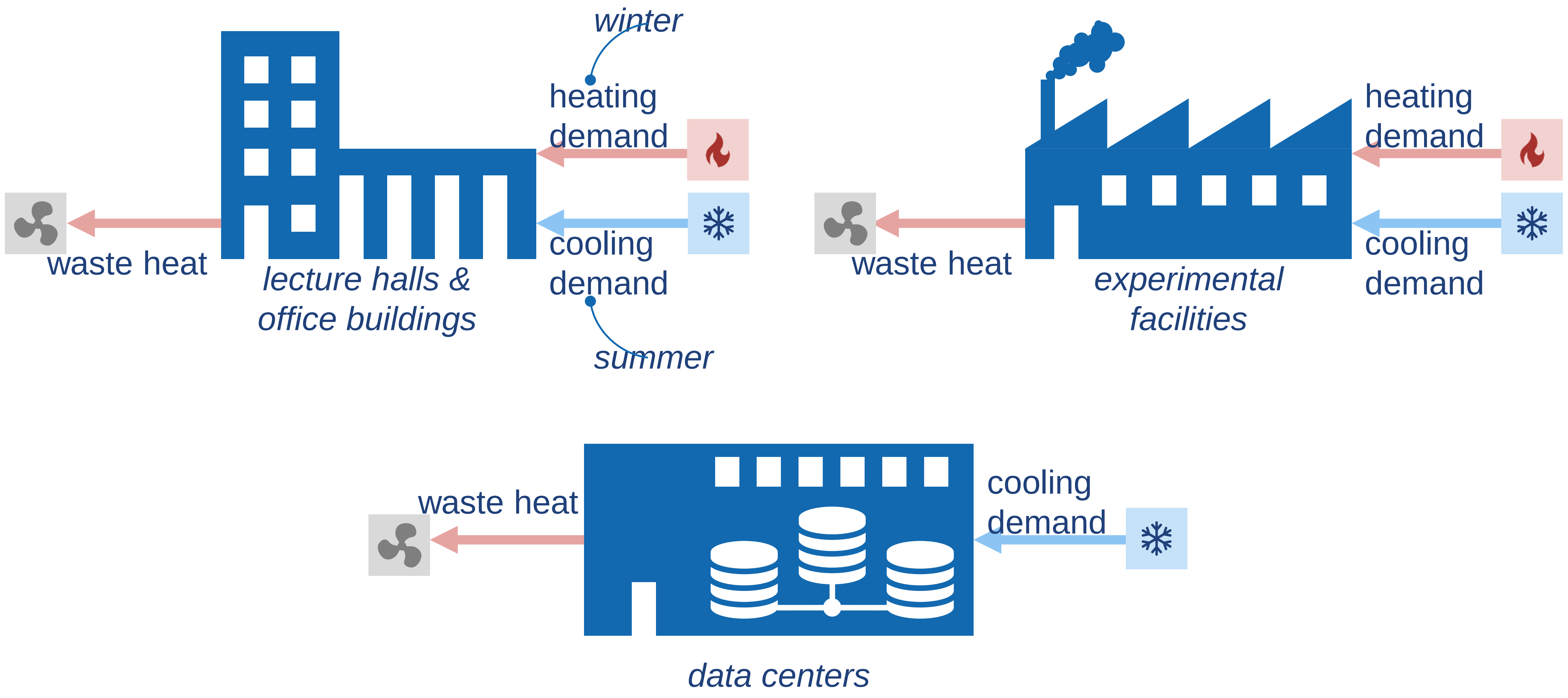
**51%**

of the total **final energy consumption** of EU28“

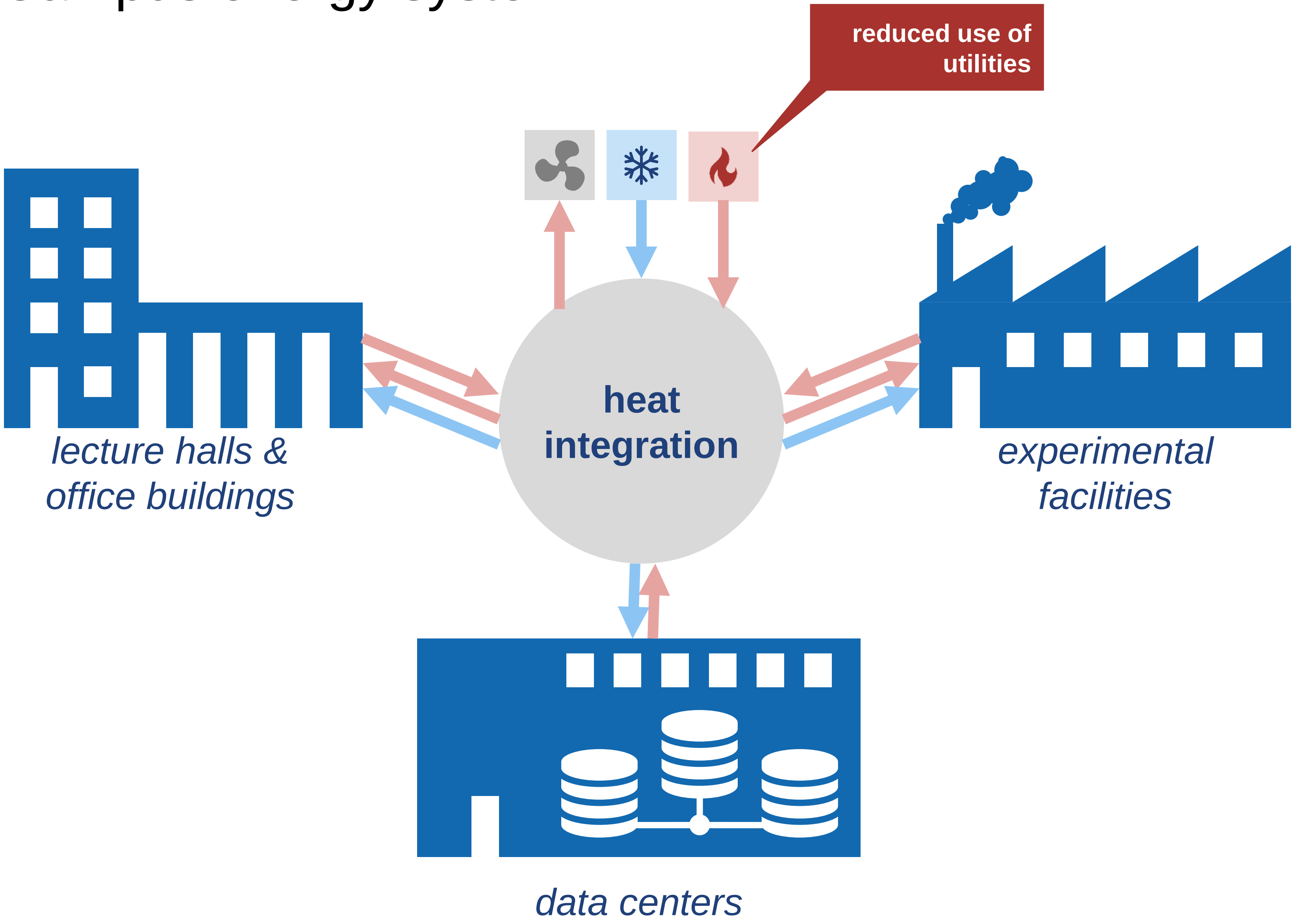


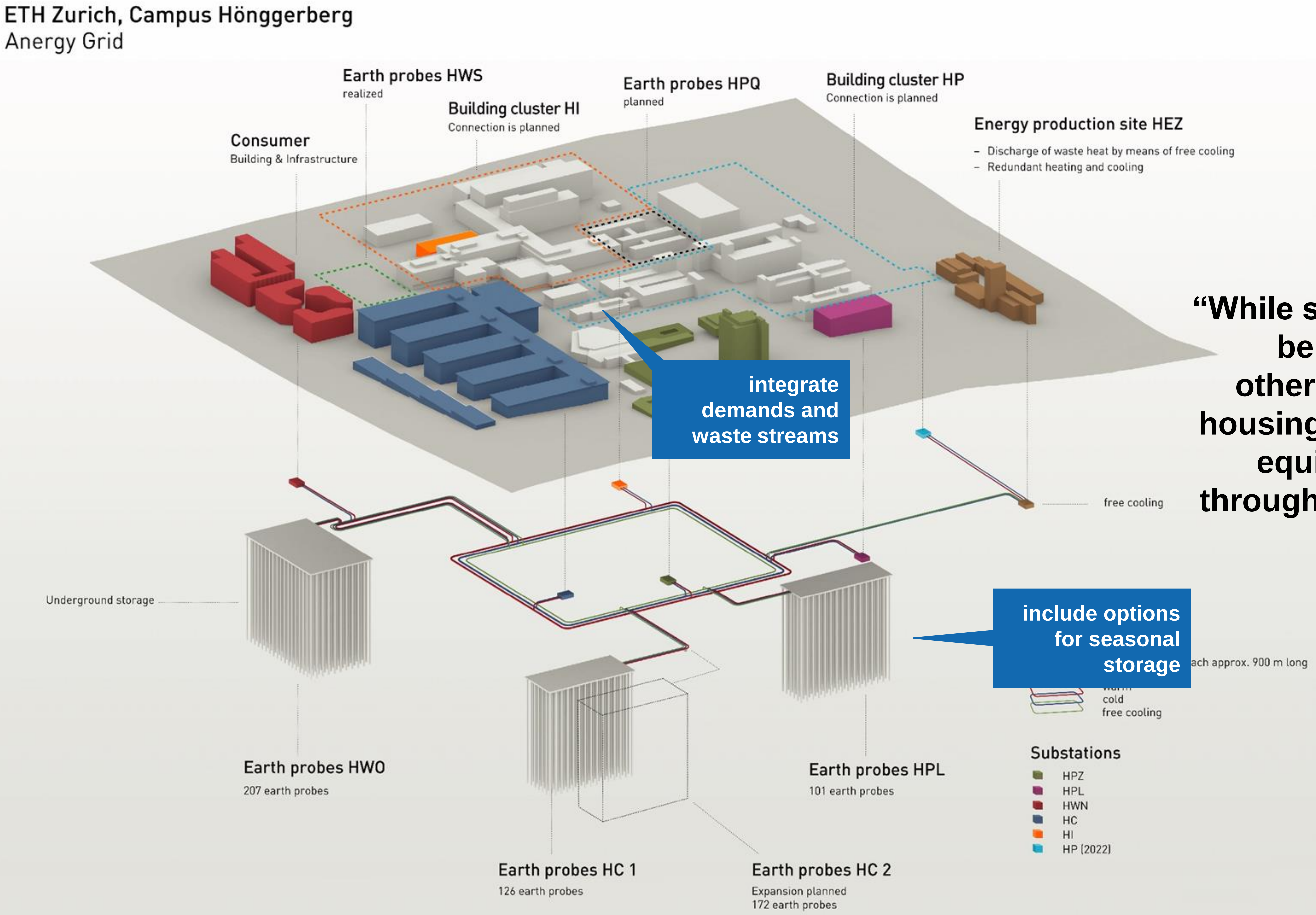

heating & cooling required to achieve a sustainable energy system.

# Example: Campus energy system

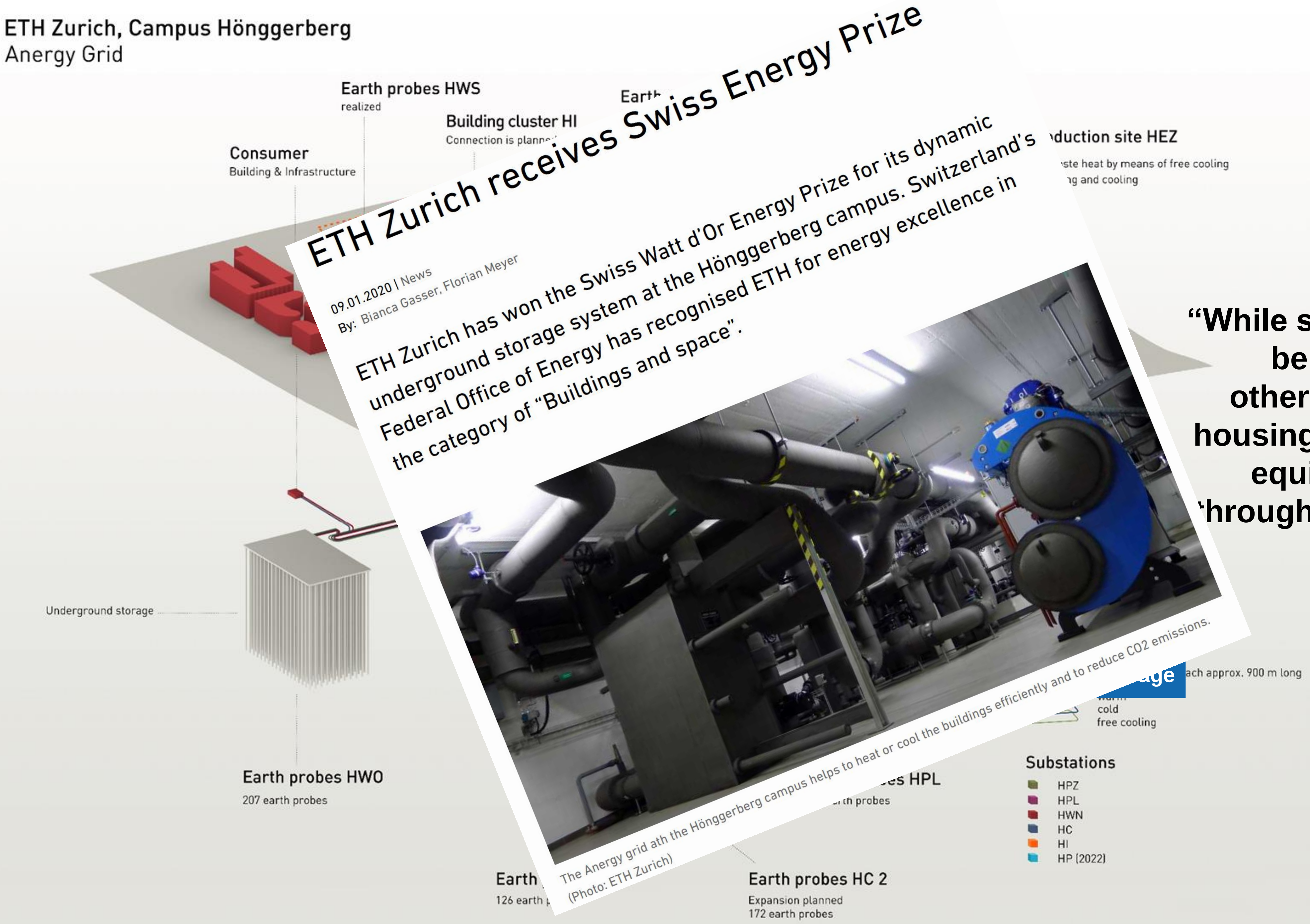


# Example: Campus energy system






**"While some buildings have to be heated in winter, others – especially those housing servers or laboratory equipment – emit heat throughout the year and need to be cooled."**




# ETH Zurich receives Swiss Energy Prize

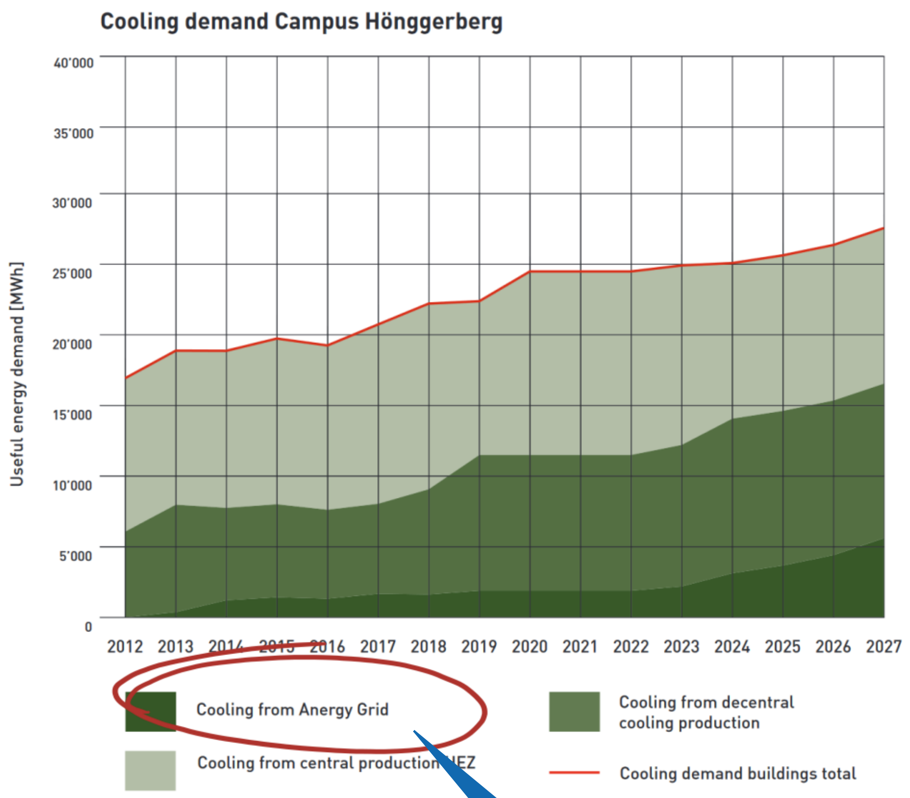
09.01.2020 | News
By: Bianca Gasser, Florian Meyer

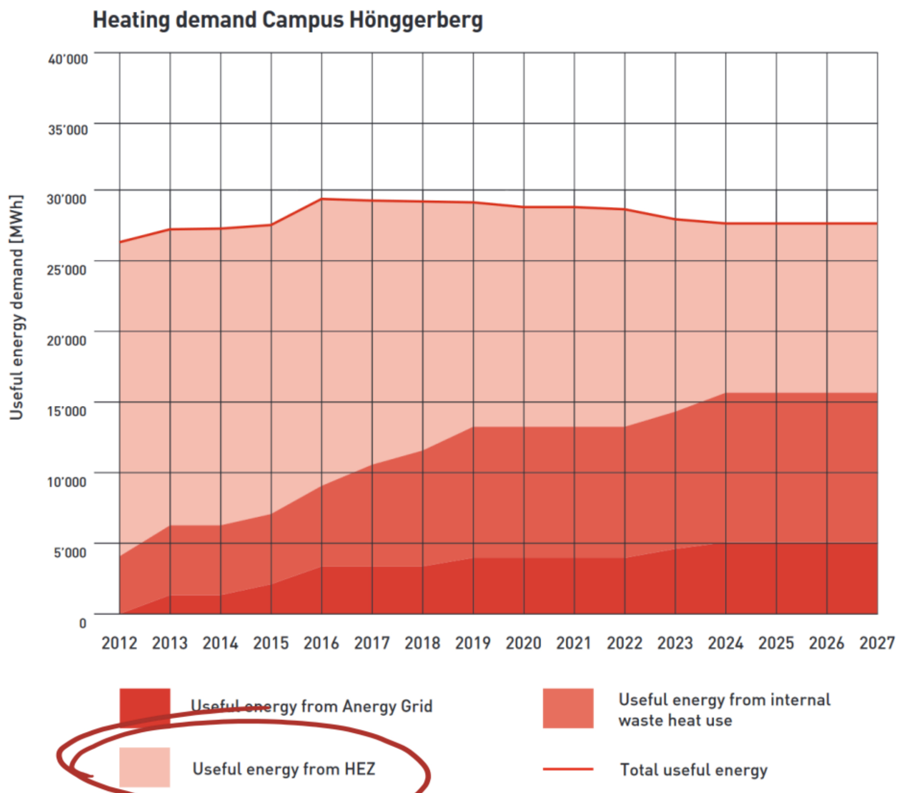
ETH Zurich has won the Swiss Watt d'Or Energy Prize for its dynamic underground storage system at the Hönggerberg campus. Switzerland's Federal Office of Energy has recognised ETH for energy excellence in the category of "Buildings and space".

The Anergy grid ath the Hönggerberg campus helps to heat or cool the buildings efficiently and to reduce CO2 emissions. (Photo: ETH Zurich)

**"While some buildings have to be heated in winter, others – especially those housing servers or laboratory equipment – emit heat throughout the year and need to be cooled."**

# Example: AnergyGrid




heat integration expected
to reduce the
net cooling demand

expected falling fossil
heating production
despite stable demand

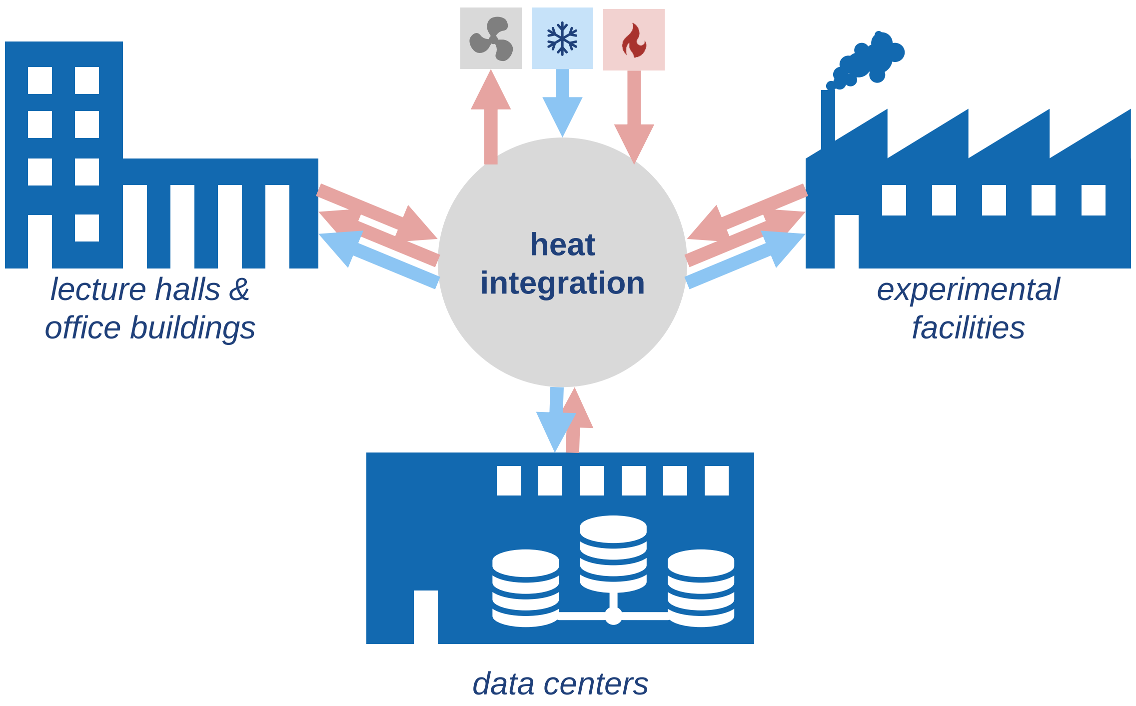
# The heat integration problem

Given multiple hot streams that need cooling

and multiple cold streams that need heating,

and considering the cost of external heating & cooling utilities,

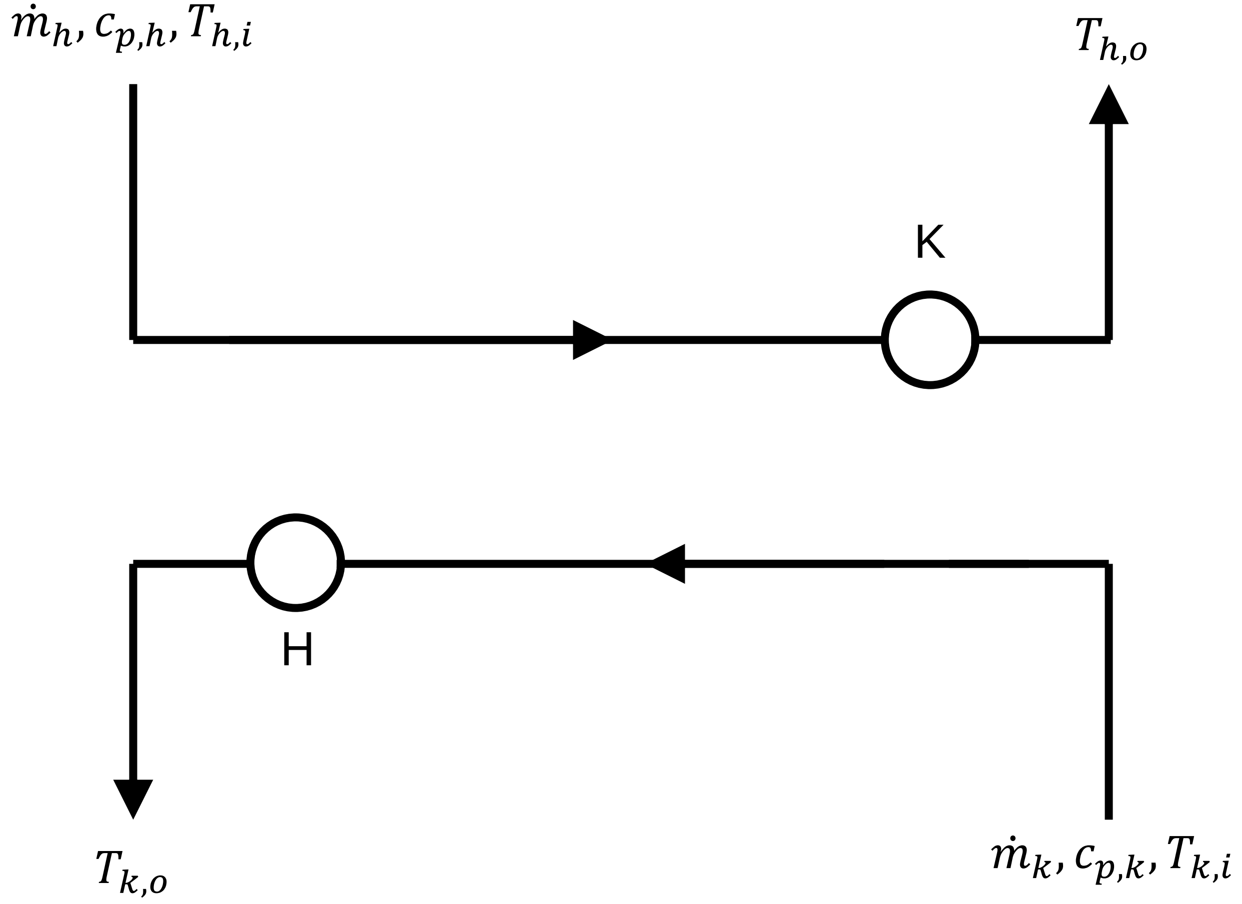
**how to optimally combine (integrate) heating & cooling demands to minimize cost?**



# After this lecture, you will be able to…

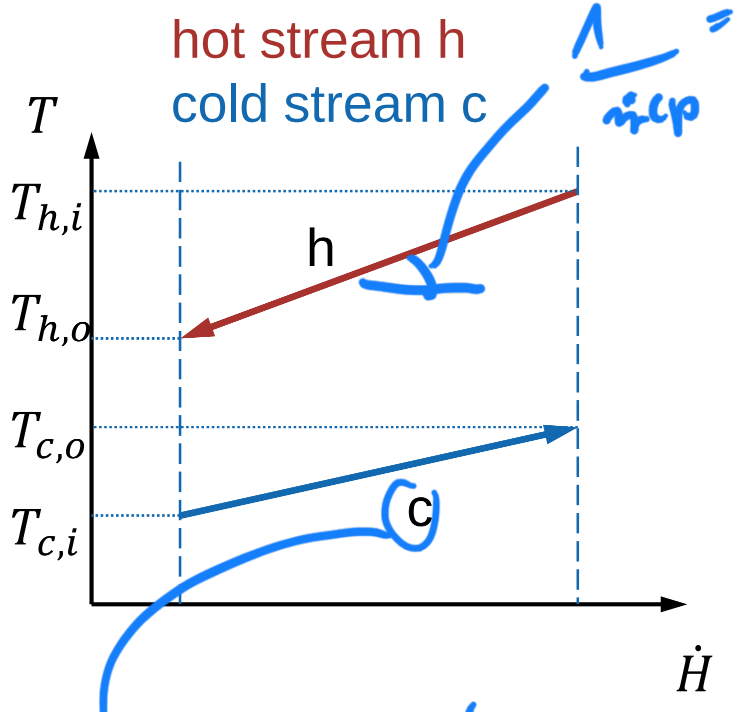
- ✓ explain the idea underlying **the heat integration problem**
- apply the **pinch rules** to heat integration problems.
- thermodynamically analyze **heat exchangers** with the **pinch method**.
- integrate external utilities by using the grand composite curve
- interpret **heat integration as optimization problem**

# The basic heat integration problem: 1 hot & 1 cold stream



# t,H-diagram of heat transfer

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




$\frac{1}{\dot{m}c_p} = \frac{1}{\dot{C}_p}$

Larger heat capacity!

(than hot one)

**Energy balance of steady-state heat exchangers**

(no losses, no external energies)

$$\dot{Q}_i = \dot{m} \cdot \left(h_{i,out} - h_{i,in}\right)$$

$$\approx \dot{m}_i \cdot c_{p,i} \cdot \left(T_{i,out} - T_{i,in}\right)$$

$$T_{i,out} = T_{i,in} + \frac{\dot{Q}_i}{\dot{m}_i \cdot c_{p,i}}$$

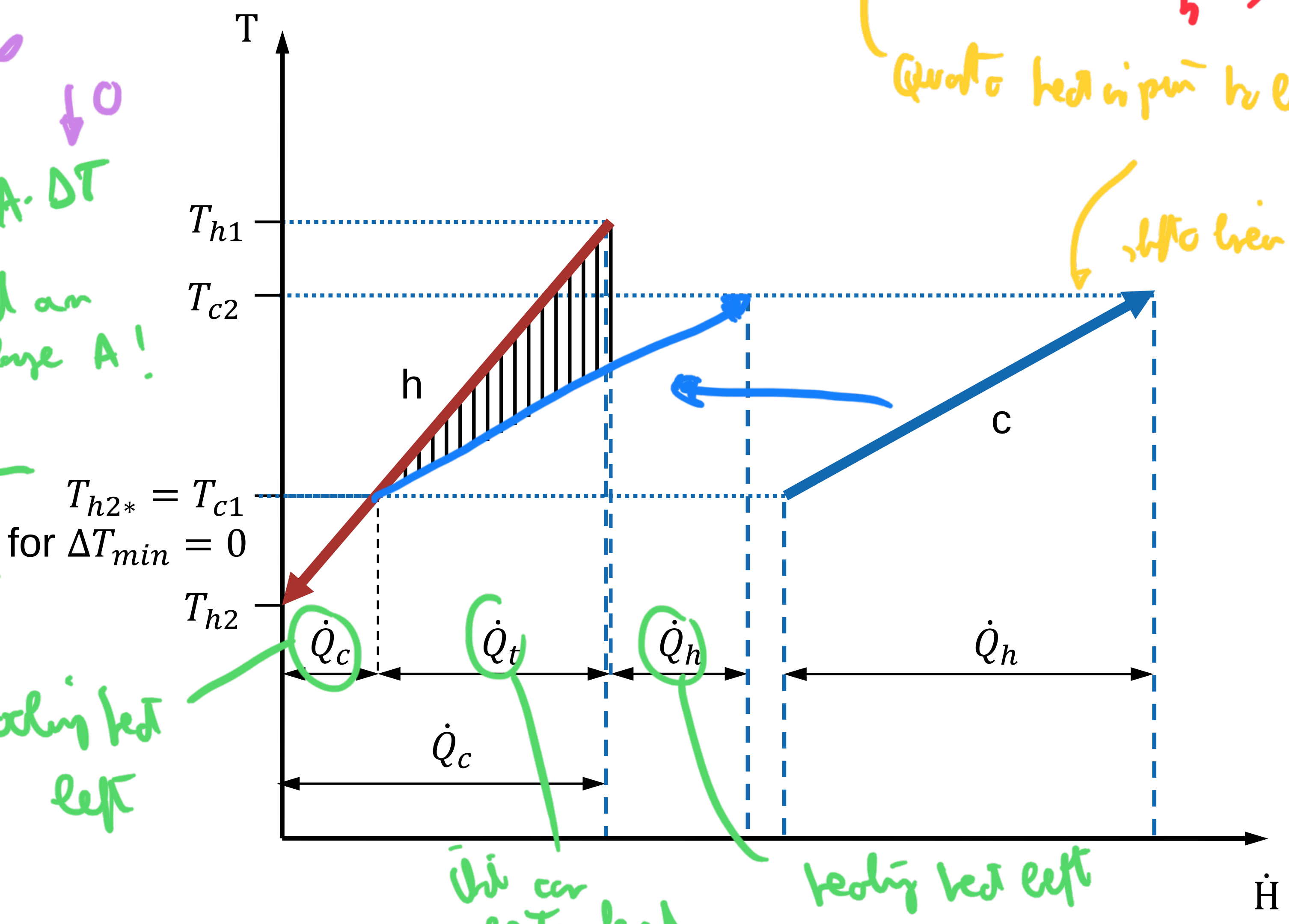
parameter

# Heat integration idea in the t,H-diagram

1st law $\dot{Q}_h > \dot{Q}_c$

2nd law $T_h \geq T_c$

Quantify heat input to ensure?




shift to lower c

$\dot{Q} = \alpha A \cdot \Delta T$

we need an extremely large A!

cooling heat left

this can be transferred

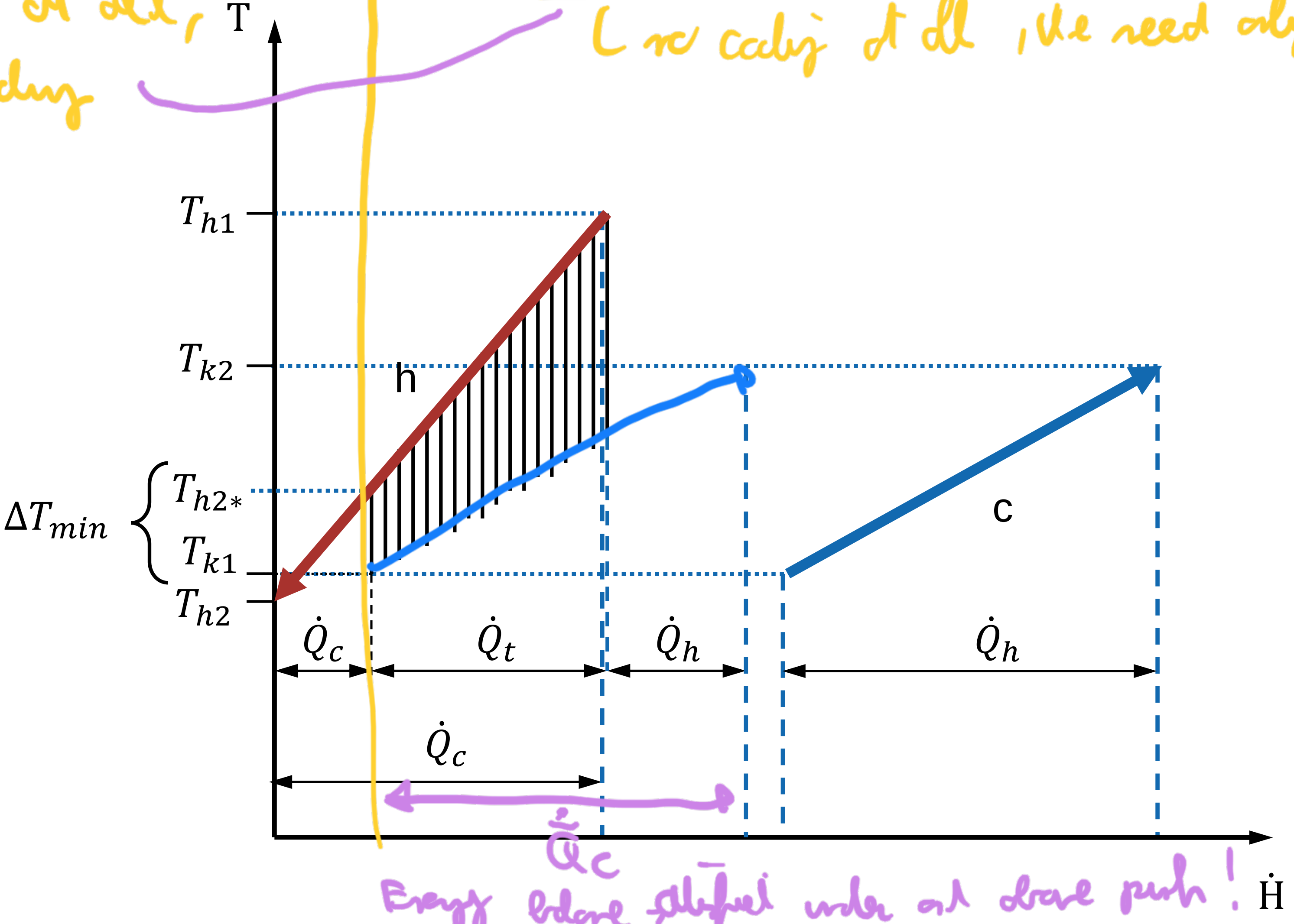
heating heat left

# Changes in state in the t,H-diagram

relax (push) above

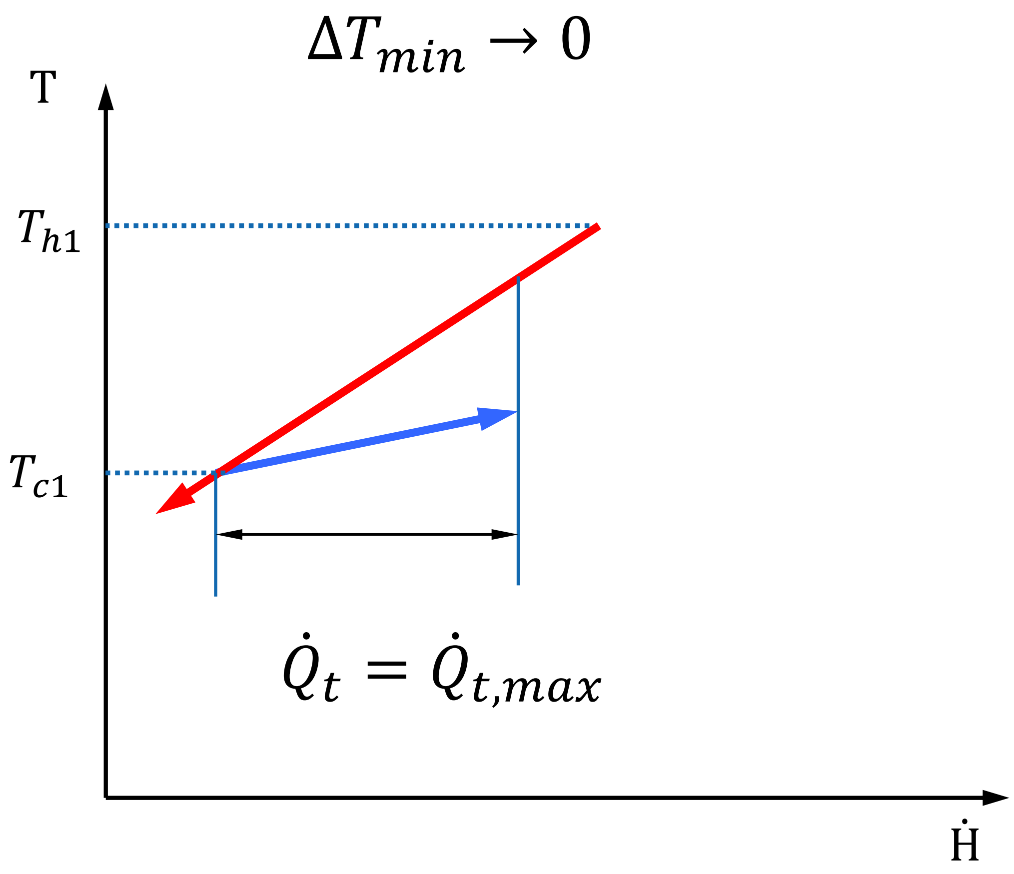
no heating at all, only cooling

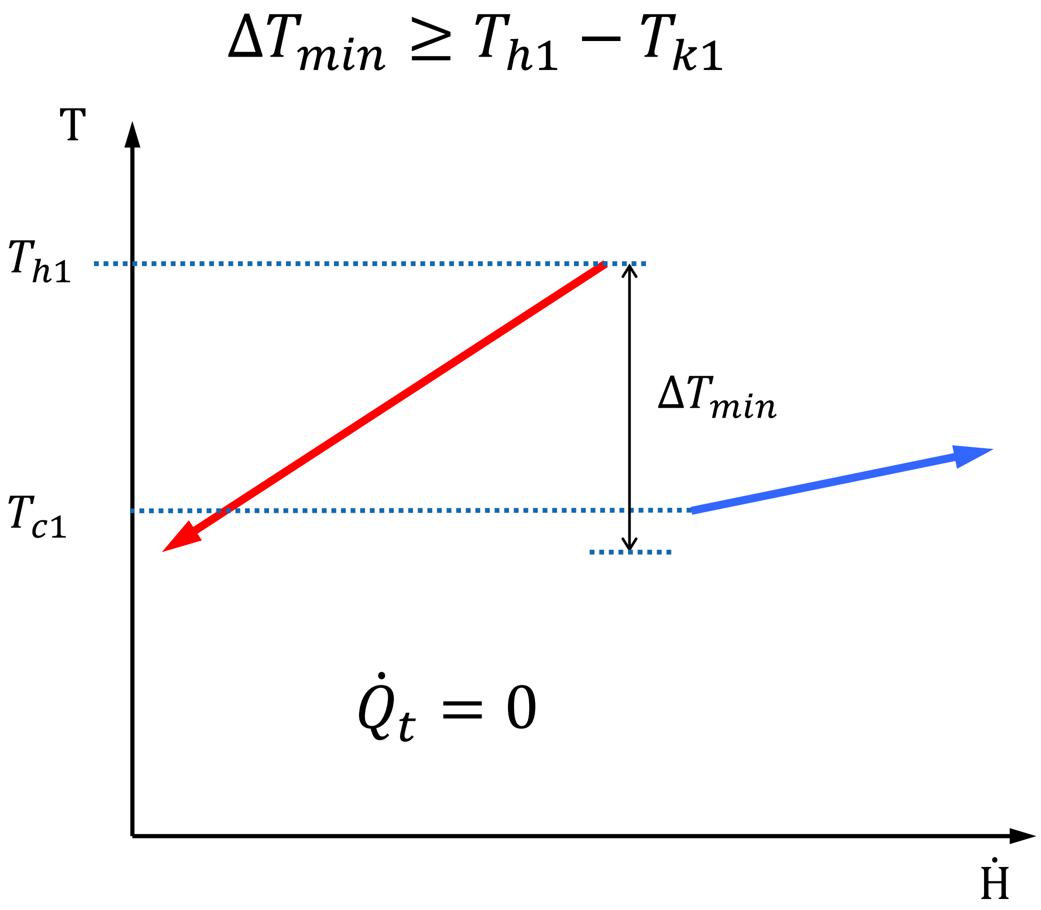
[ no cooling at all, we need only to heat!



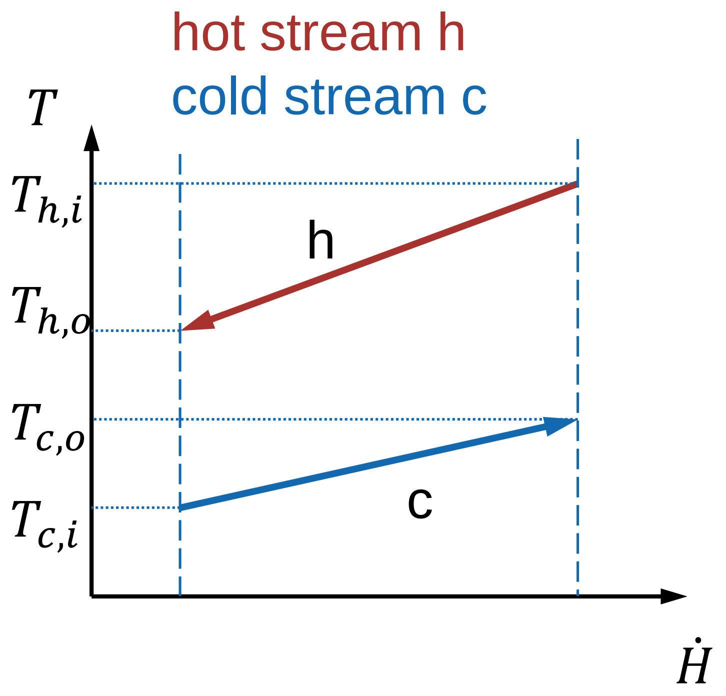

Energy balance satisfied under all above push!

# Limit cases of heat integration



# Exergy losses during heat transfer




Entropy production

**Exergy loss**

a) Pressure loss

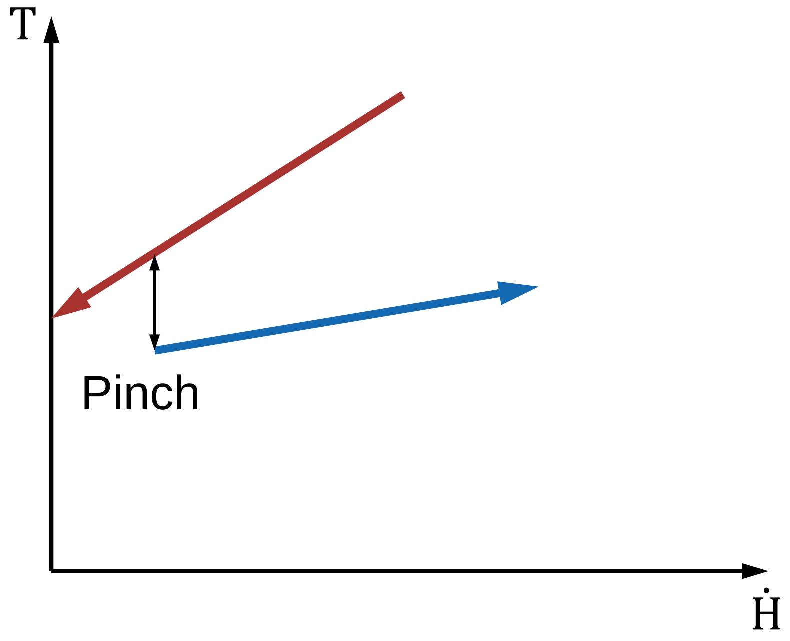
$$ds_{dp}^{irr} = -\frac{\nu}{T}dp$$

b) Heat transfer

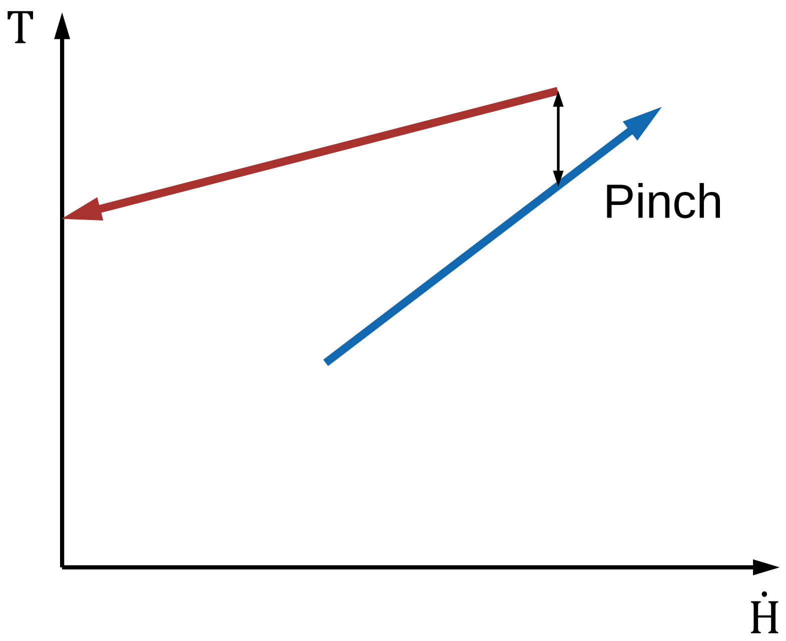
$$ds_{\Delta}^{irr} = dq_{12}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) = dq_{12}\left(\frac{T_1 - T_2}{T_1 T_2}\right)$$

# Position of the "pinch" vs heat capacity flows: counter-current flow

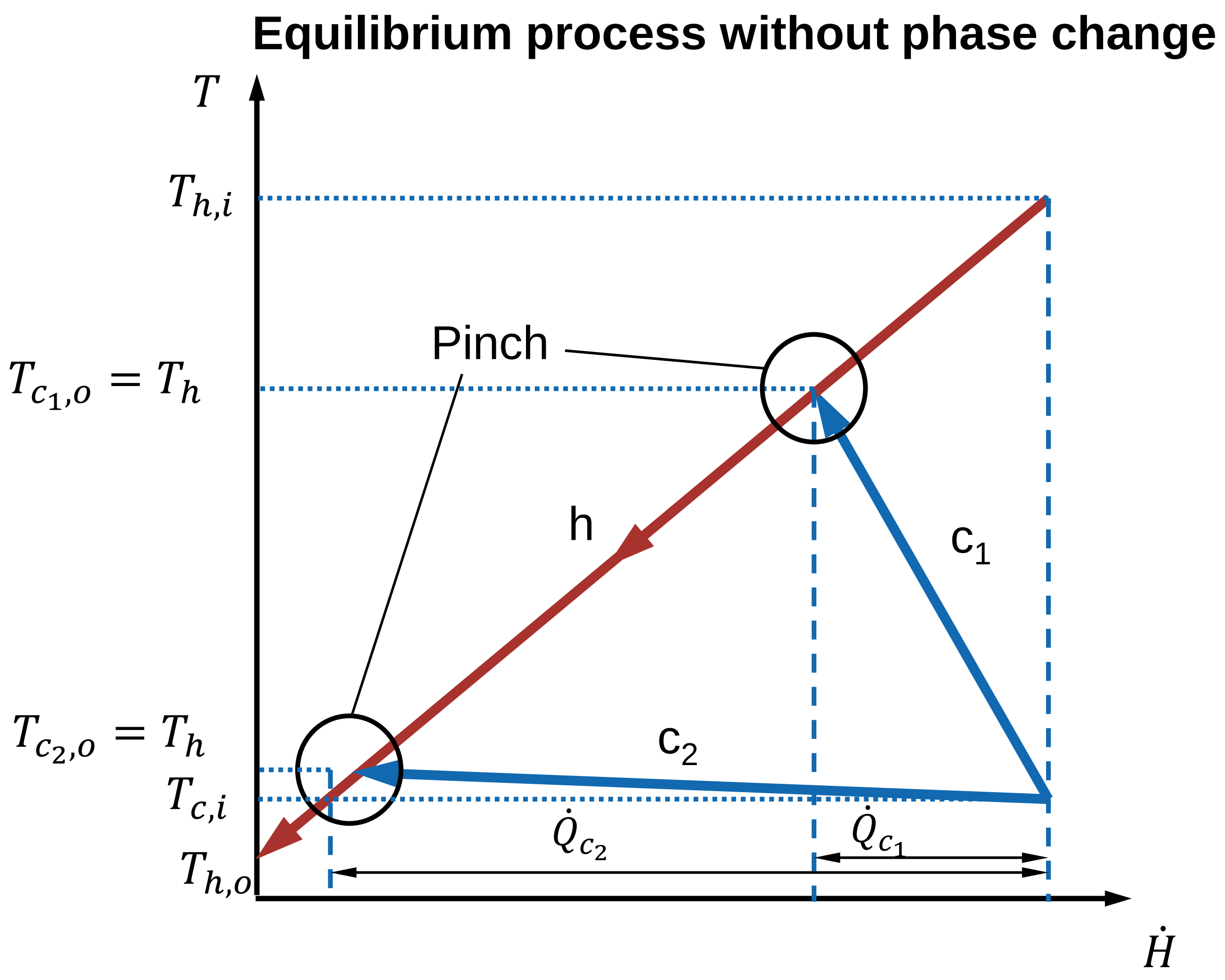
$\dot{C}_{p,h} < \dot{C}_{p,c}$




$\dot{C}_{p,h} > \dot{C}_{p,c}$



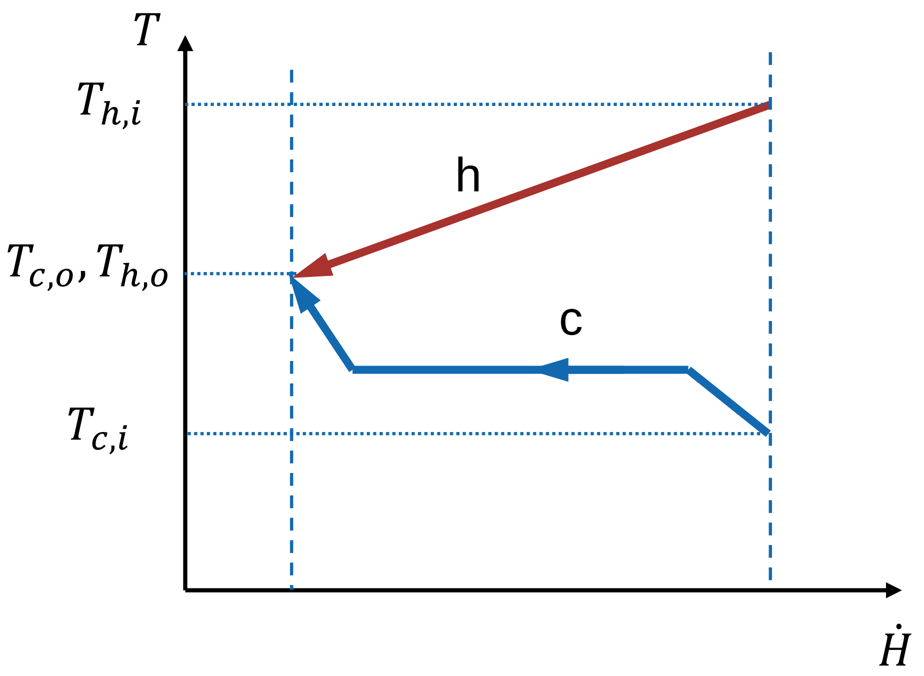
# t,H-diagram: parallel-flow heat exchanger



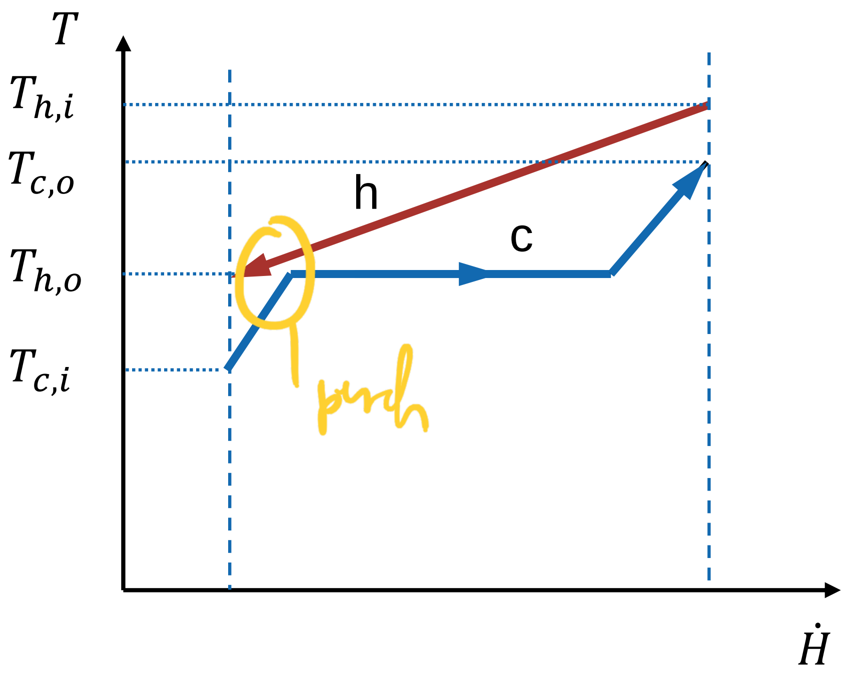

$$\left(\dot{m} \cdot c_p\right)_{c_1} < \left(\dot{m} \cdot c_p\right)_h \quad ; \quad \left(\dot{m} \cdot c_p\right)_{c_2} > \left(\dot{m} \cdot c_p\right)_h$$

# t,H-Diagram: Phase change

## Parallel flow



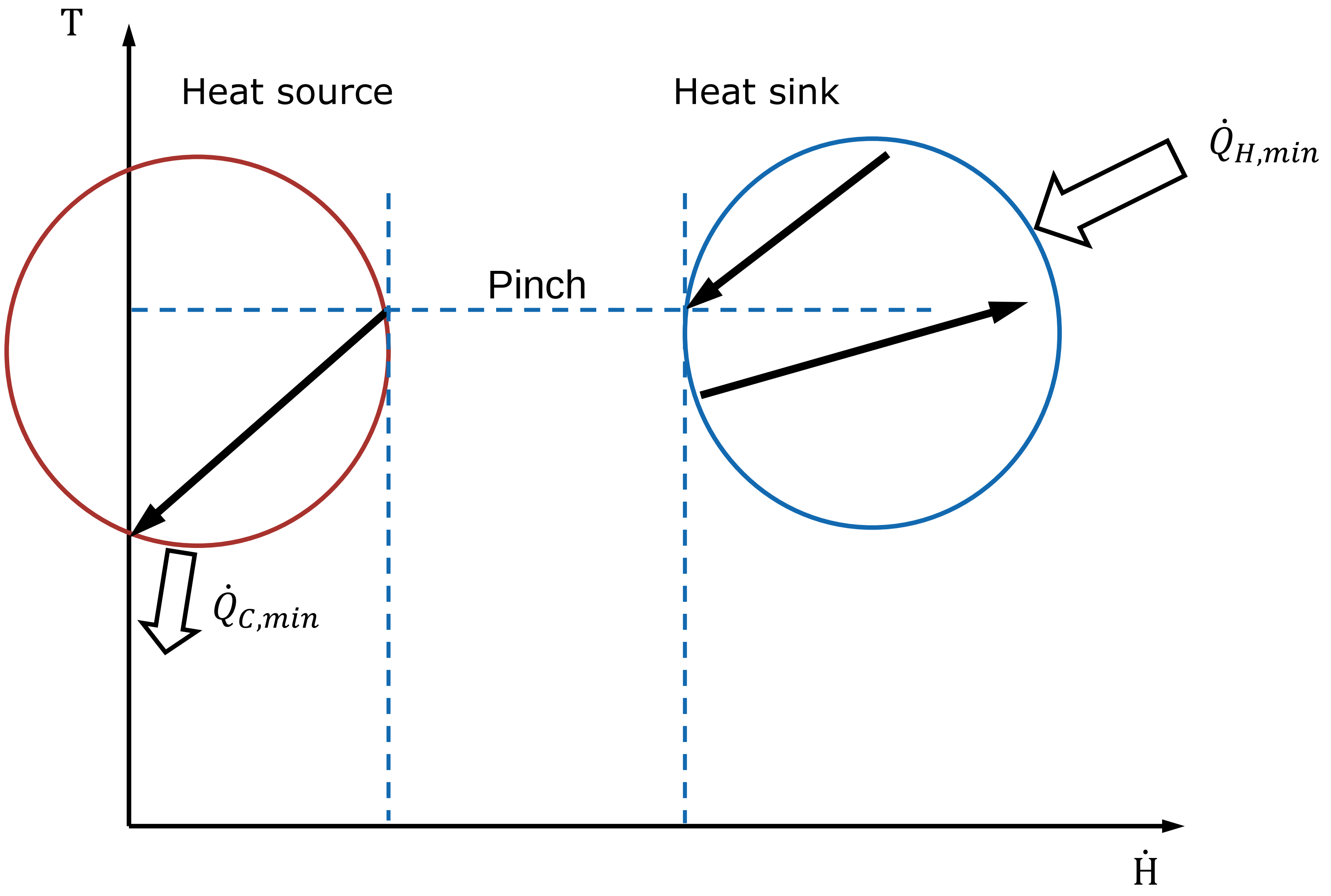

## Counter flow



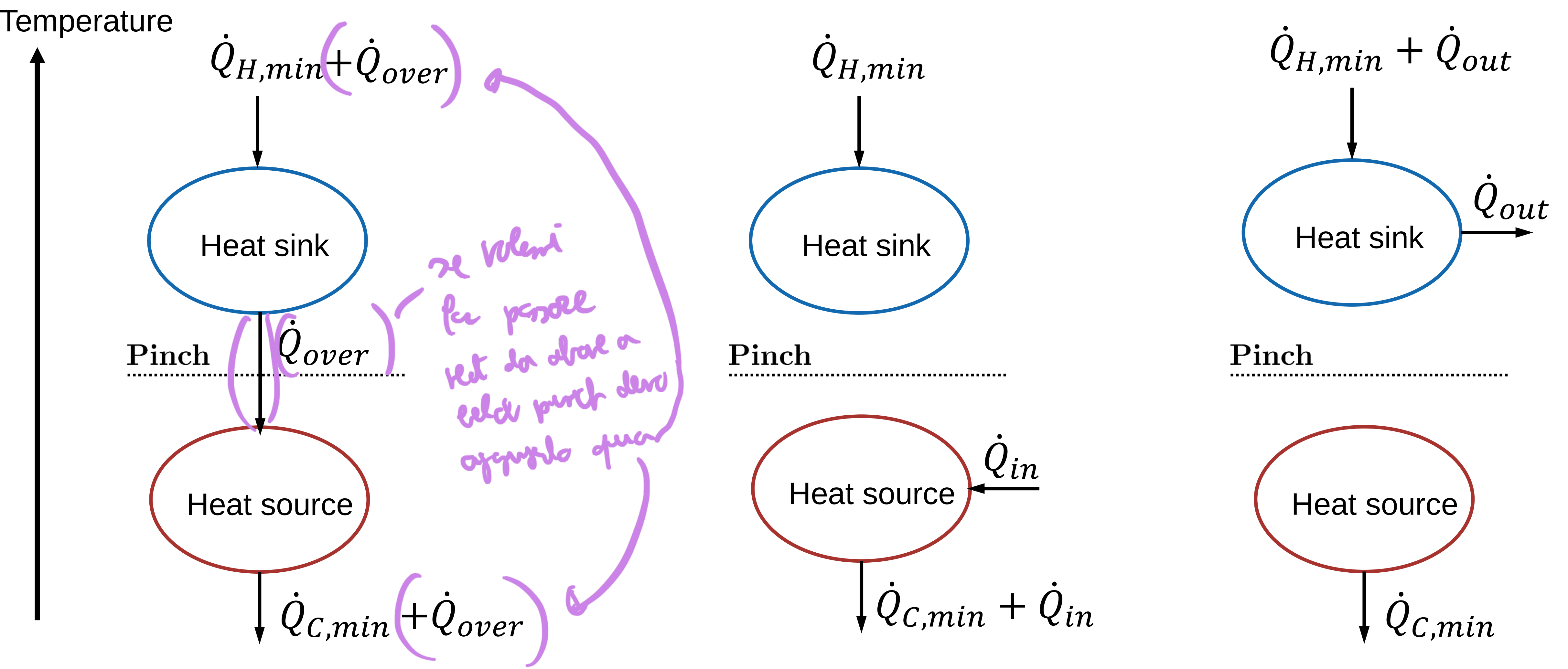

- Parallel flow: pinch always at the end of the heat exchanger
- Counter-flow: pinch could occur at both ends – and also in the heat exchanger

where $c_p$ changes

# Split process: subsystem Heat source/sink



# Illustration of the three "pinch" rules




No heat from above the pinch to below

Heating only above the pinch

Cooling only below the pinch

# After this lecture, you will be able to…

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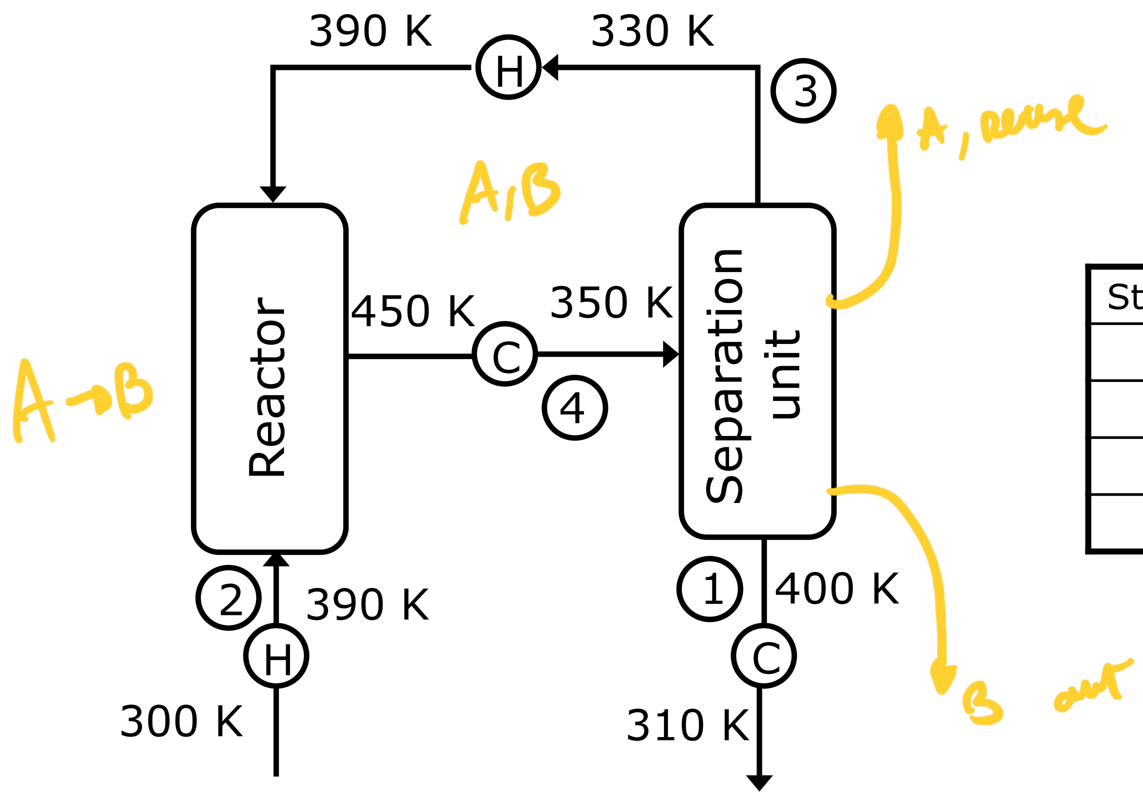
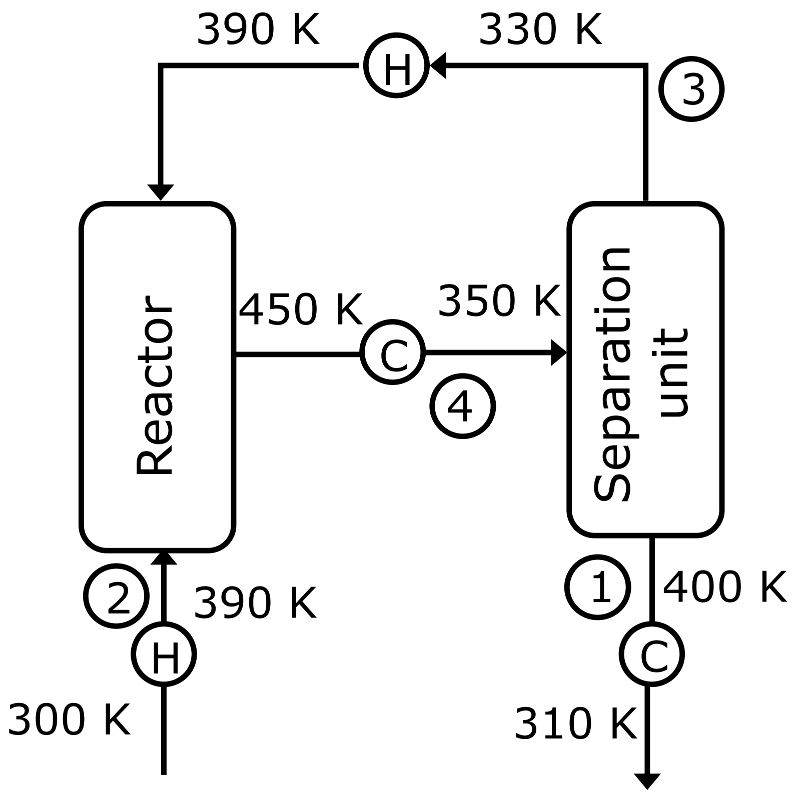
# Hot and cold streams Process example




Stream table

| Stream-No. | $T_{in}$ [K] | $T_{out}$ [K] | $\dot{C}_p$ [kW/K] |
|---|---|---|---|
| 1(h) | 400 | 310 | 2 |
| 2(c) | 300 | 390 | 1.8 |
| 3(c) | 330 | 370 | 4 |
| 4(h) | 450 | 350 | 1 |

# Hot and cold streams Process example




| Stream-No. | $T_{in}$ [K] | $T_{out}$ [K] | $\dot{C}_p$ [kW/K] |
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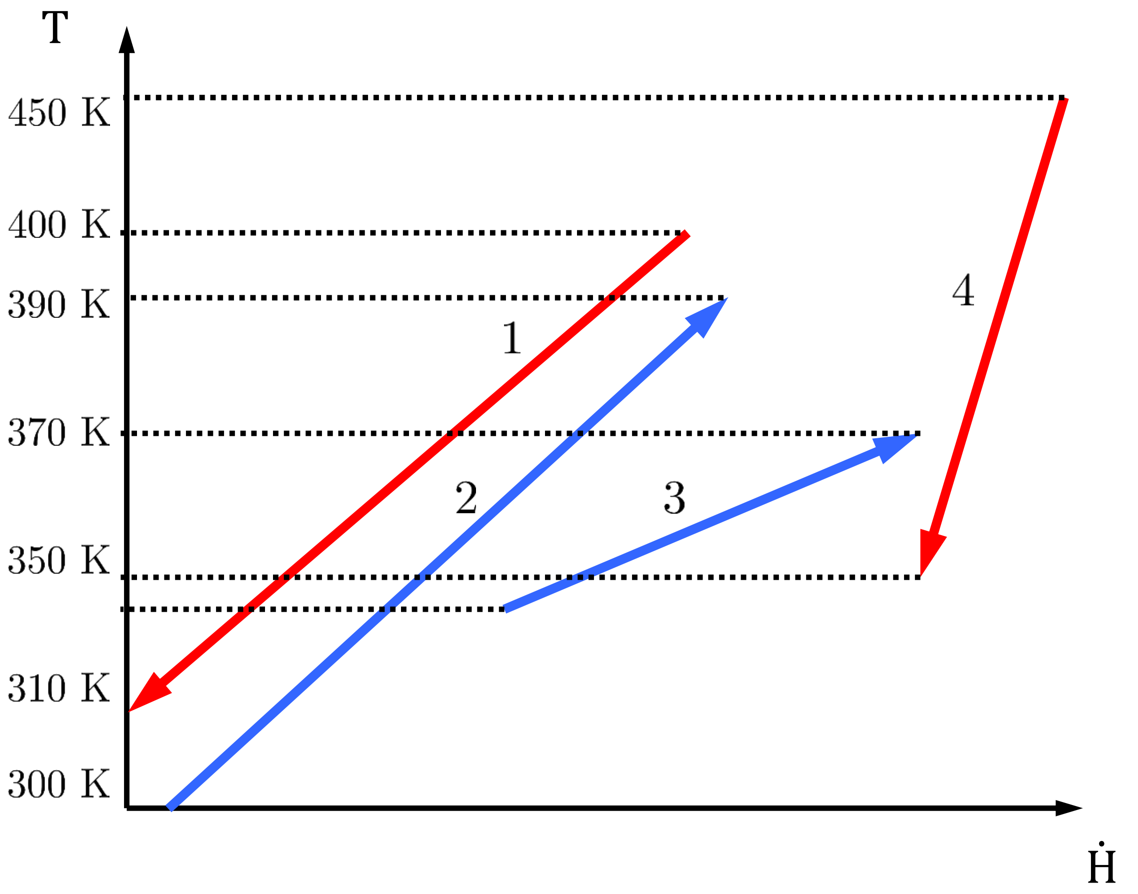
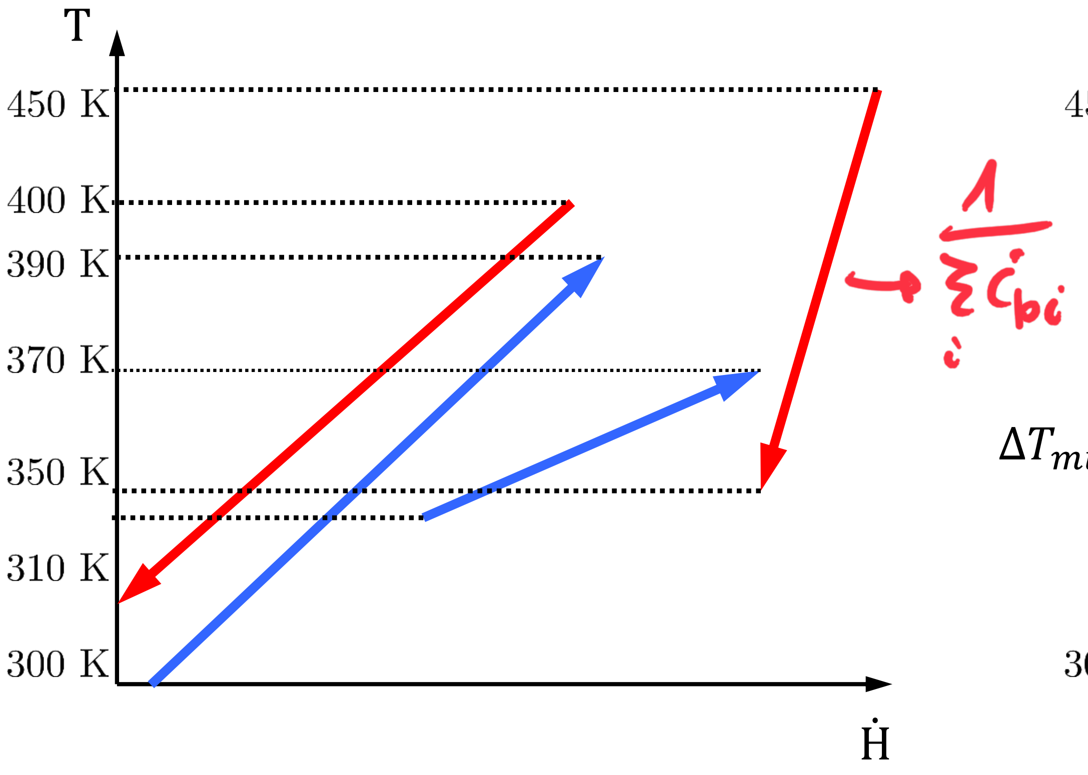
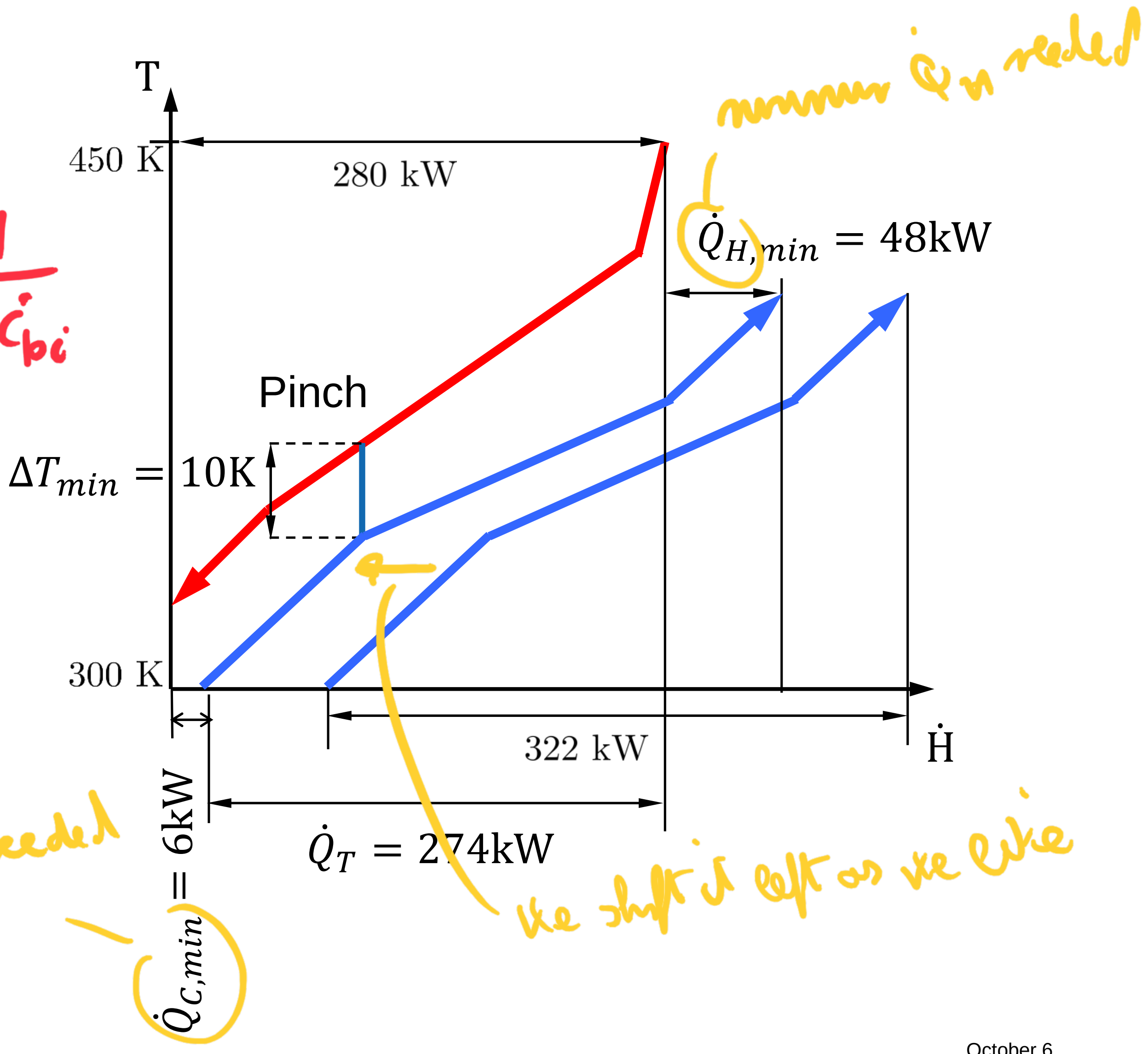


# Example process as **composite curves** in t,H-diagram



# Stream table with shifted inlet and outlet temperatures of the streams

| Stream -No. | $T_{in}$ [K] | $T_{out}$ [K] | $\dot{C}_p$ [kW/K] |
|---|---|---|---|
| 1(h) | 400 | 310 | 2 |
| 2(c) | 300 | 390 | 1,8 |
| 3(c) | 330 | 370 | 4 |
| 4(h) | 450 | 350 | 1 |

10K

[illegible]

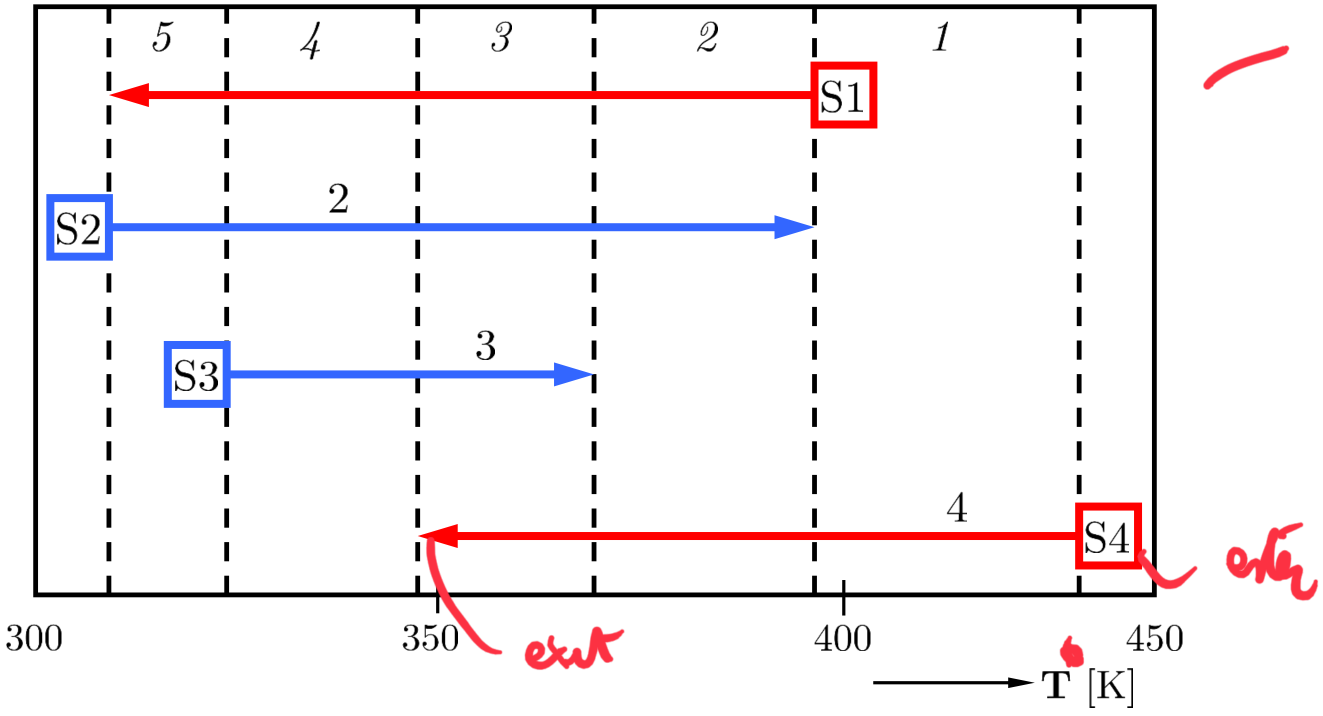
$$T_h^* = T_h - \frac{\Delta T_{min}}{2}$$

$$T_c^* = T_c + \frac{\Delta T_{min}}{2}$$

$$\Rightarrow \Delta T^*_{\mathrm{min}} = 0$$

| Stream -No. | $T_{in}^*$ [K] | $T_{out}^*$ [K] | $\dot{C}_p$ [kW/K] |
|---|---|---|---|
| 1(h) | 395 | 305 | 2 |
| 2(c) | 305 | 395 | 1,8 |
| 3(c) | 335 | 375 | 4 |
| 4(h) | 445 | 345 | 1 |

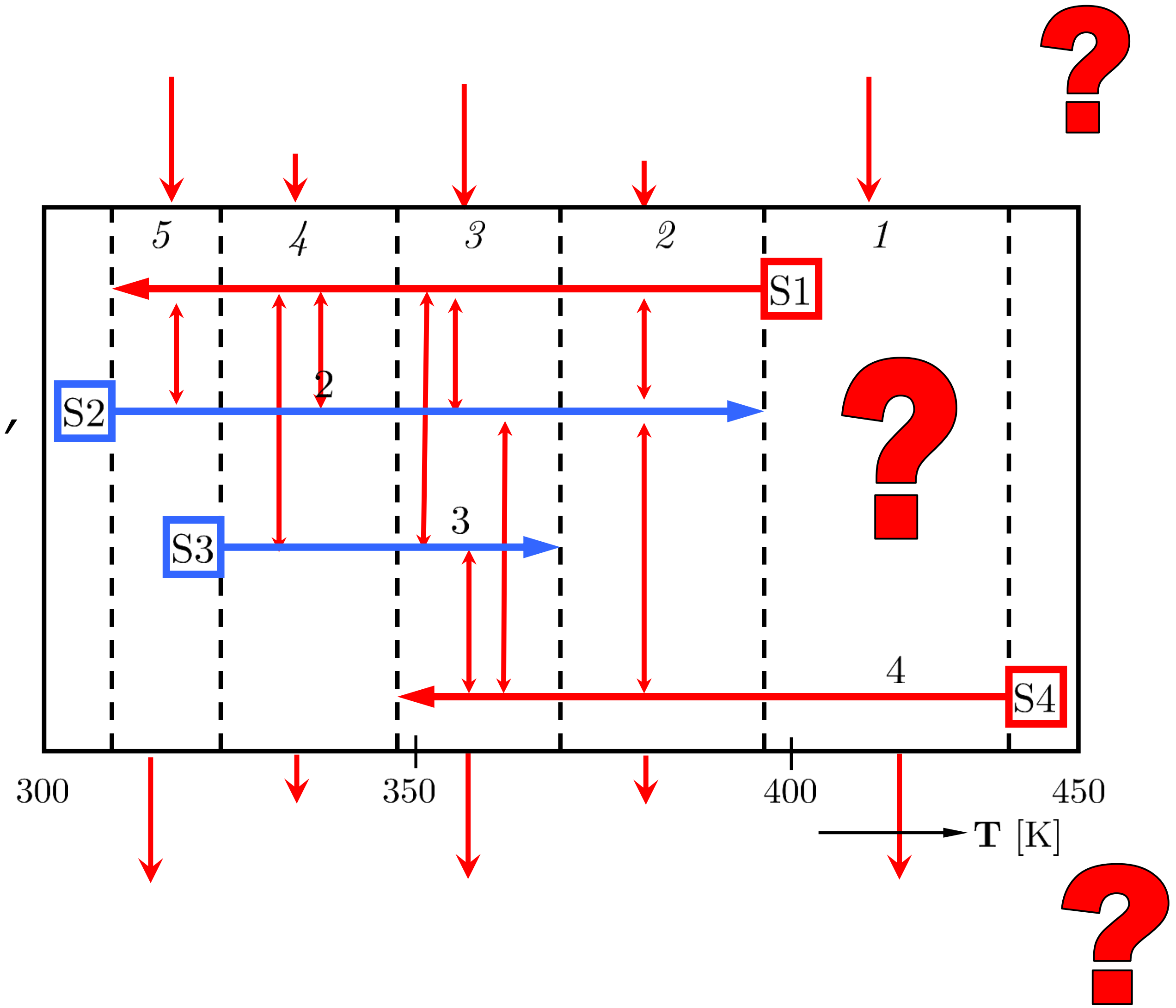
# Stream diagram with shifted inlet and outlet temperatures of the streams




in/out of stream or
change slope

| Stream -No. | $T_{in}^*$ [K] | $T_{out}^*$ [K] | $\dot{C}_p$ [kW/K] |
|---|---|---|---|
| 1(h) | 395 | 305 | 2 |
| 2(c) | 305 | 395 | 1,8 |
| 3(c) | 335 | 375 | 4 |
| 4(h) | 445 | 345 | 1 |

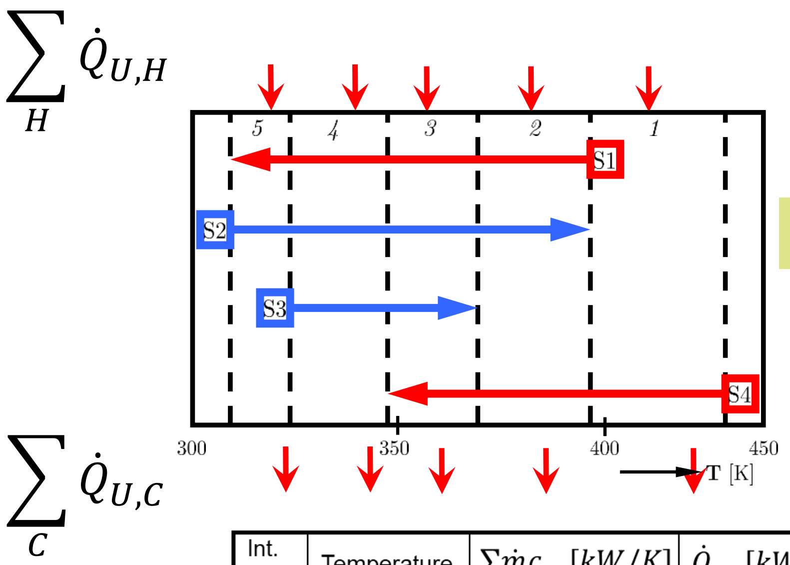
# Heat integration between streams




**Heat integration**

*h hot streams (1, 4) and c cold streams (2, 3)*

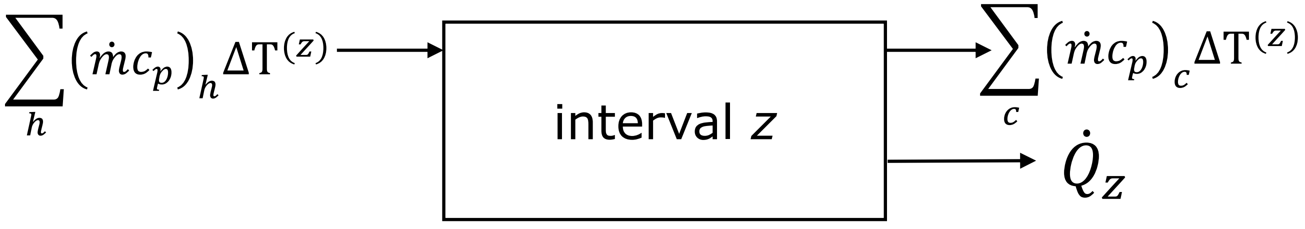
# Energy balances




| Int. No. | Temperature | $\sum \dot{m}c_p \; [kW/K]$ | $\dot{Q}_z \; [kW]$ |
|---|---|---|---|
| | 445 K | | |
| 1 | | +1.0 | +50 |
| | 395 K | | |
| 2 | | +1.2 | +24 |
| | 375 K | | |
| 3 | | -2.8 | -84 |
| | 345 K | | |
| 4 | | -3.8 | -38 |
| | 335 K | | |
| 5 | | +0,2 | +6 |
| | 305 K | | |

*Energy balances ∀ intervals z:*

hot/cold streams




„Heat Generation"

accesible heat!

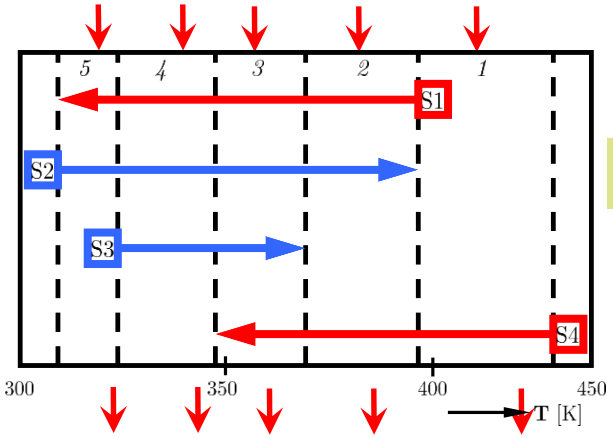
$$0 = \sum_h (\dot{m}c_p)_h \Delta T^{(z)} - \sum_c (\dot{m}c_p)_c \Delta T^{(z)} - \dot{Q}_z$$

$$\Leftrightarrow \dot{Q}_z = \sum_h (\dot{m}c_p)_h \Delta T^{(z)} - \sum_c (\dot{m}c_p)_c \Delta T^{(z)}$$

$$= \Delta T^{(z)} \left[ \sum_h (\dot{m}c_p)_h - \sum_c (\dot{m}c_p)_c \right]$$

# Energy balances

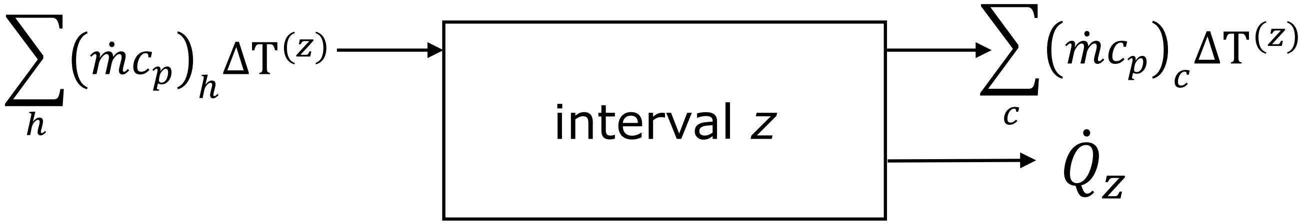
$$\sum_H \dot{Q}_{U,H}$$




$$\sum_C \dot{Q}_{U,C}$$

hot/cold streams

*Energy balances* $\forall$ *intervals* $z$:

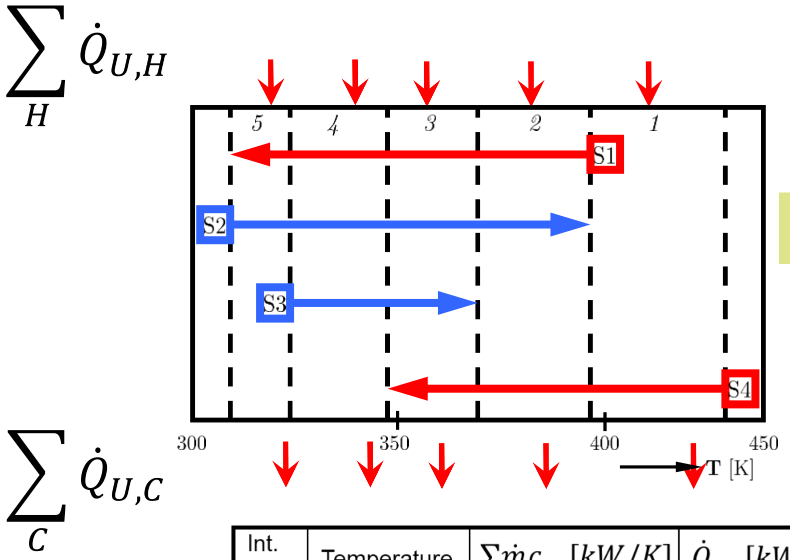



| Int. No. | Temperature | $\sum \dot{m}c_p$ $[kW/K]$ | $\dot{Q}_z$ $[kW]$ |
|---|---|---|---|
| | 445 K | | |
| 1 | | +1.0 | +50 |
| | 395 K | | |
| 2 | | +1.2 | +24 |
| | 375 K | | |
| 3 | | -2.8 | -84 |
| | 345 K | | |
| 4 | | -3.8 | -38 |
| | 335 K | | |
| 5 | | +0,2 | +6 |
| | 305 K | | |

se c'è un ⊕ quello in eccesso lo passo dove c'è ⊖

Heat integration from higher to lower temperatures

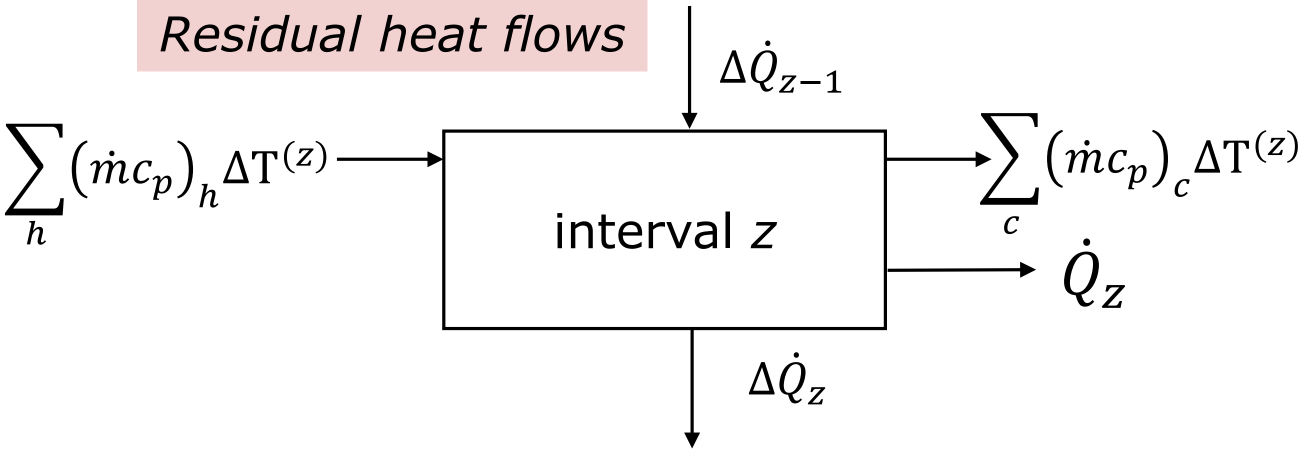
# Energy balances




hot/cold streams

*Energy balances ∀ intervals z:*

Residual heat flows



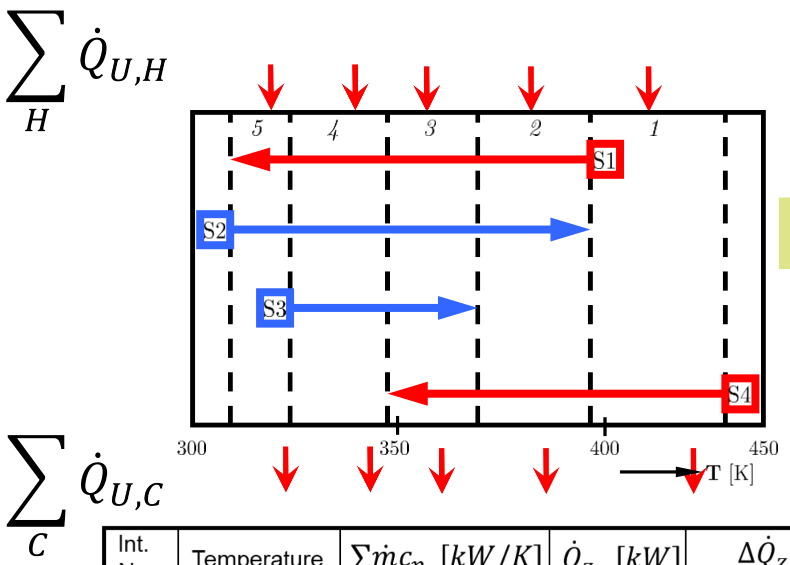

| Int. No. | Temperature | $\sum \dot{m}c_p\ [kW/K]$ | $\dot{Q}_z\ [kW]$ | $\Delta\dot{Q}_z$ |
|---|---|---|---|---|
| | | | | +0 [kW] |
| | 445 K | | | |
| 1 | | +1.0 | +50 | +50 [kW] |
| | 395 K | | | |
| 2 | | +1.2 | +24 | +74 [kW] |
| | 375 K | | | |
| 3 | | -2.8 | -84 | -10 [kW] |
| | 345 K | | | |
| 4 | | -3.8 | -38 | -48 [kW] |
| | 335 K | | | |
| 5 | | +0,2 | +6 | -42 [kW] |
| | 305 K | | | |

$$\min_z \Delta\dot{Q}_z$$

$$0 = \sum_h (\dot{m}c_p)_h \Delta T^{(z)} - \sum_c (\dot{m}c_p)_c \Delta T^{(z)} - \Delta\dot{Q}_z + \Delta\dot{Q}_{z-1}$$

$$\Delta\dot{Q}_{z=0} = 0;$$

# Energy balances

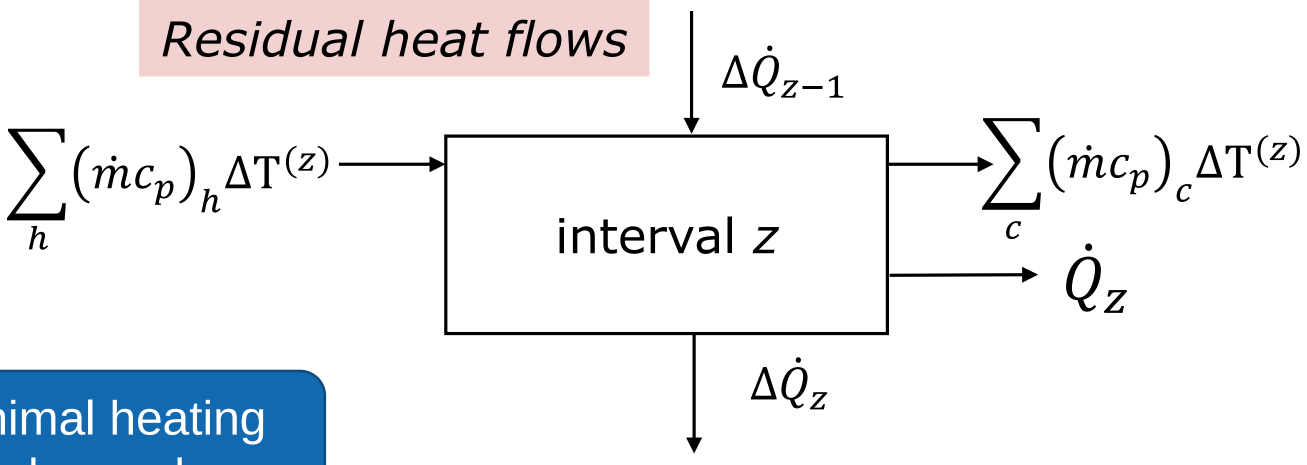



hot/cold streams

| Int. No. | Temperature | $\sum \dot{m}c_p$ $[kW/K]$ | $\dot{Q}_z$ $[kW]$ | $\Delta\dot{Q}_z$ | $\Delta\dot{Q}_z^*$ |
|---|---|---|---|---|---|
| | | | | +0 [kW] | +48 [kW] |
| | 445 K | | | | |
| 1 | | +1.0 | +50 | +50 [kW] | +98 [kW] |
| | 395 K | | | | |
| 2 | | +1.2 | +24 | +74 [kW] | +122 [kW] |
| | 375 K | | | | |
| 3 | | -2.8 | -84 | -10 [kW] | +38 [kW] |
| | 345 K | | | | |
| 4 | | -3.8 | -38 | -48 [kW] | +0 [kW] |
| | 335 K | | | | |
| 5 | | +0,2 | +6 | -42 [kW] | +6 [kW] |
| | 305 K | | | | |

pinch!

*Energy balances* $\forall$ *intervals* $z$:




Minimal heating demand

$$0 = \sum_h (\dot{m}c_p)_h \Delta T^{(z)} - \sum_c (\dot{m}c_p)_c \Delta T^{(z)} - \Delta\dot{Q}_z^* + \Delta\dot{Q}_{z-1}^*$$

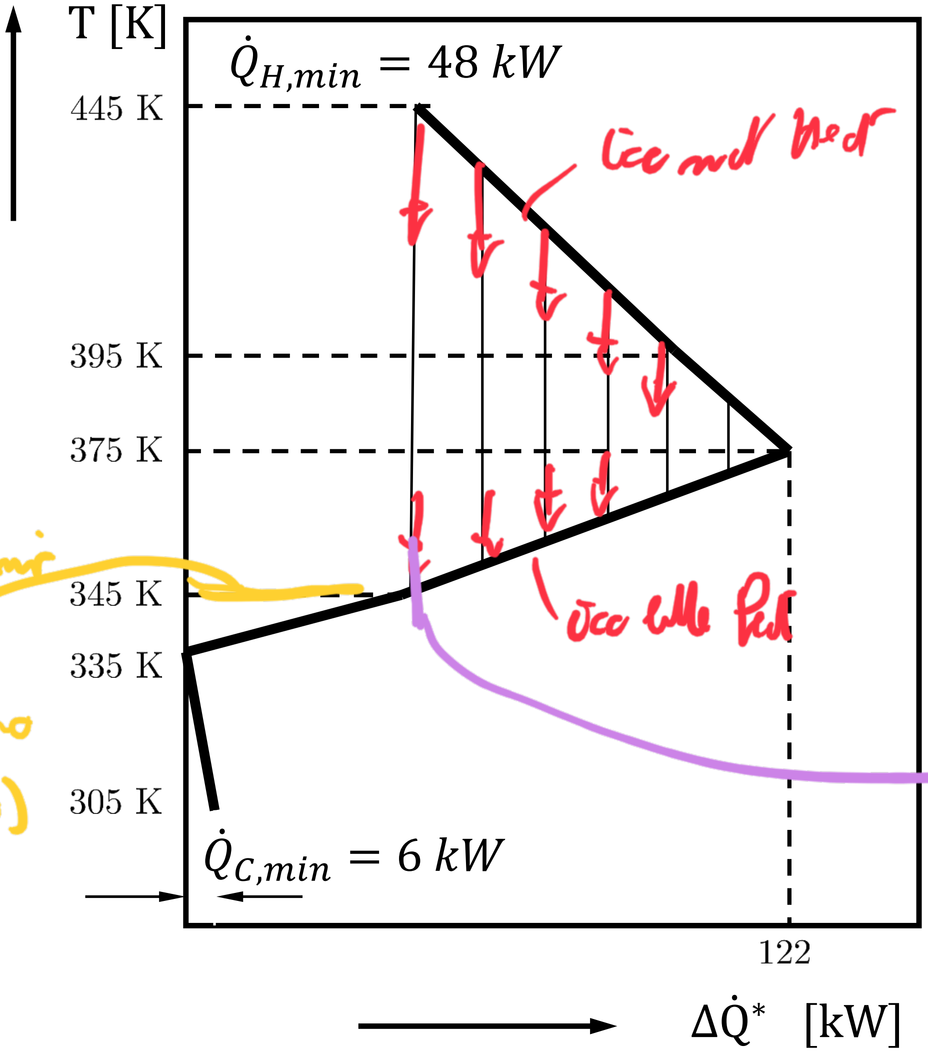
$$\Delta\dot{Q}_{z=0}^* = \min_z \Delta\dot{Q}_z;$$

Minimal cooling demand

# Heat cascade for the example process

| Int. No. | Temperature | $\sum \dot{m} c_p \ [kW/K]$ | $\dot{Q}_z \ [kW]$ | $\Delta \dot{Q}_z$ | $\Delta \dot{Q}_z^*$ |
|---|---|---|---|---|---|
| | | | | +0 [kW] | $-\Delta \dot{Q}_{z,min} =$ +48 [kW] |
| | 445 K | | | | |
| 1 | | 50 × +1.0 = | +50 | +50 [kW] | + = +98 [kW] |
| | 395 K | | | | |
| 2 | | +1.2 | +24 | +74 [kW] | +122 [kW] |
| | 375 K | | | | |
| 3 | | -2.8 | -84 | -10 [kW] | +38 [kW] |
| | 345 K | | | | |
| 4 | | -3.8 | -38 | -48 [kW] $\Delta \dot{Q}_{z,min}$ | +0 [kW] |
| | 335 K | | | | |
| 5 | | +0,2 | +6 | -42 [kW] | +6 [kW] |
| | 305 K | | | | |

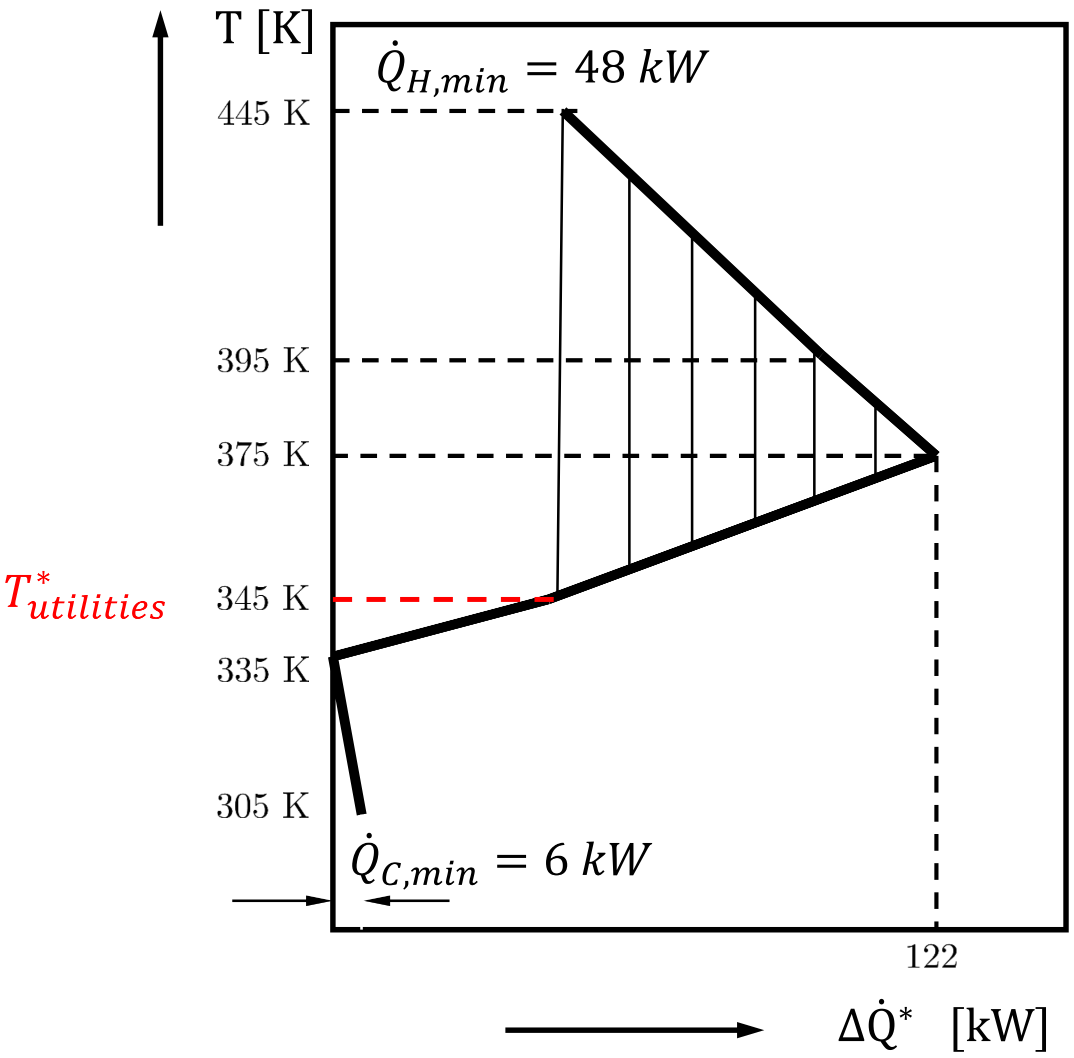
# Grand composite curve of the example process



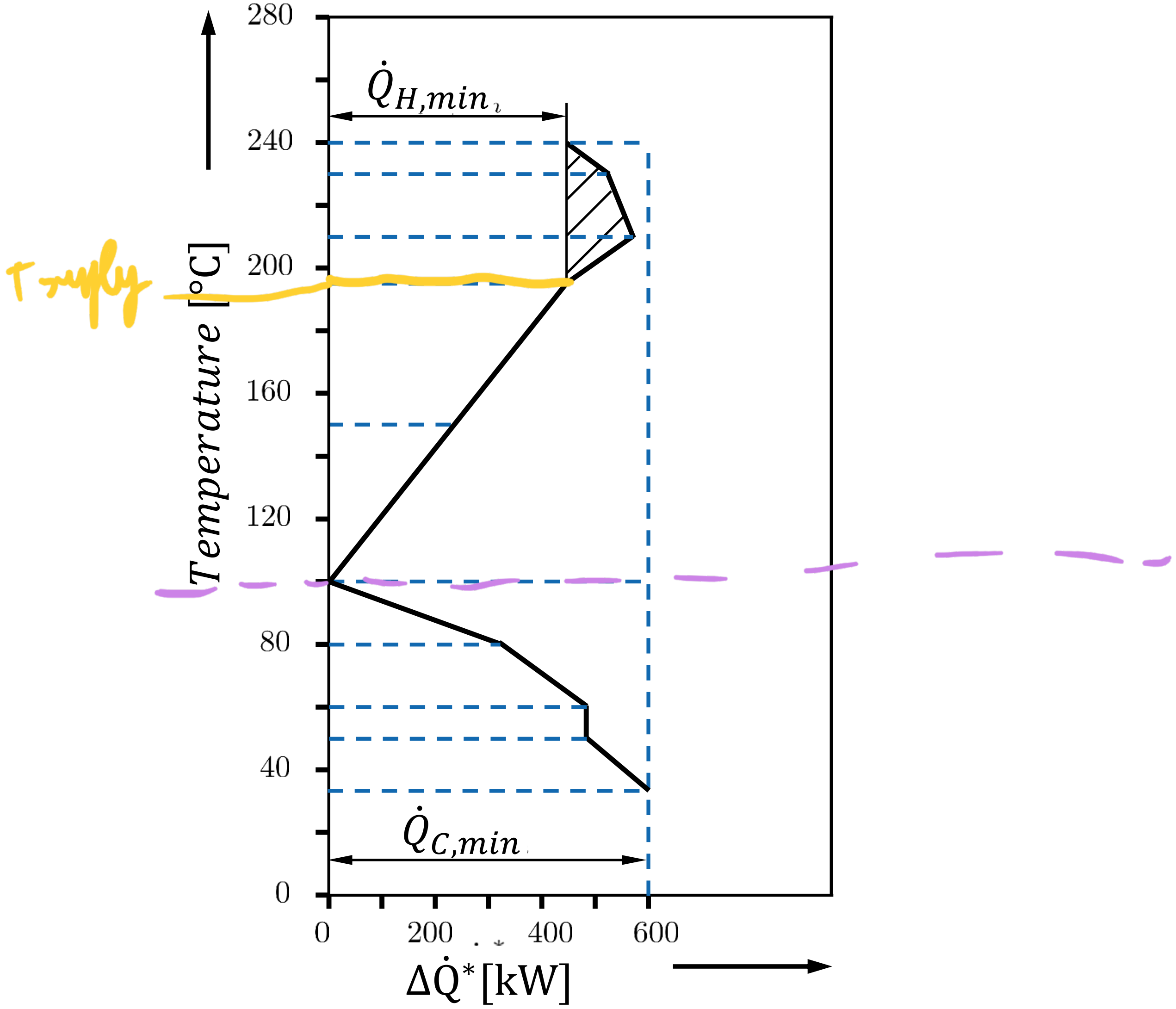
# After this lecture, you will be able to…

- ✓ explain the idea underlying **the heat integration problem**
- ✓ apply the **pinch rules** to heat integration problems.
- ✓ thermodynamically analyze **heat exchangers** with the **pinch method**.
- ▪ integrate external utilities by using the grand composite curve
- ▪ interpret **heat integration as optimization problem**

# Grand composite curve of the example process

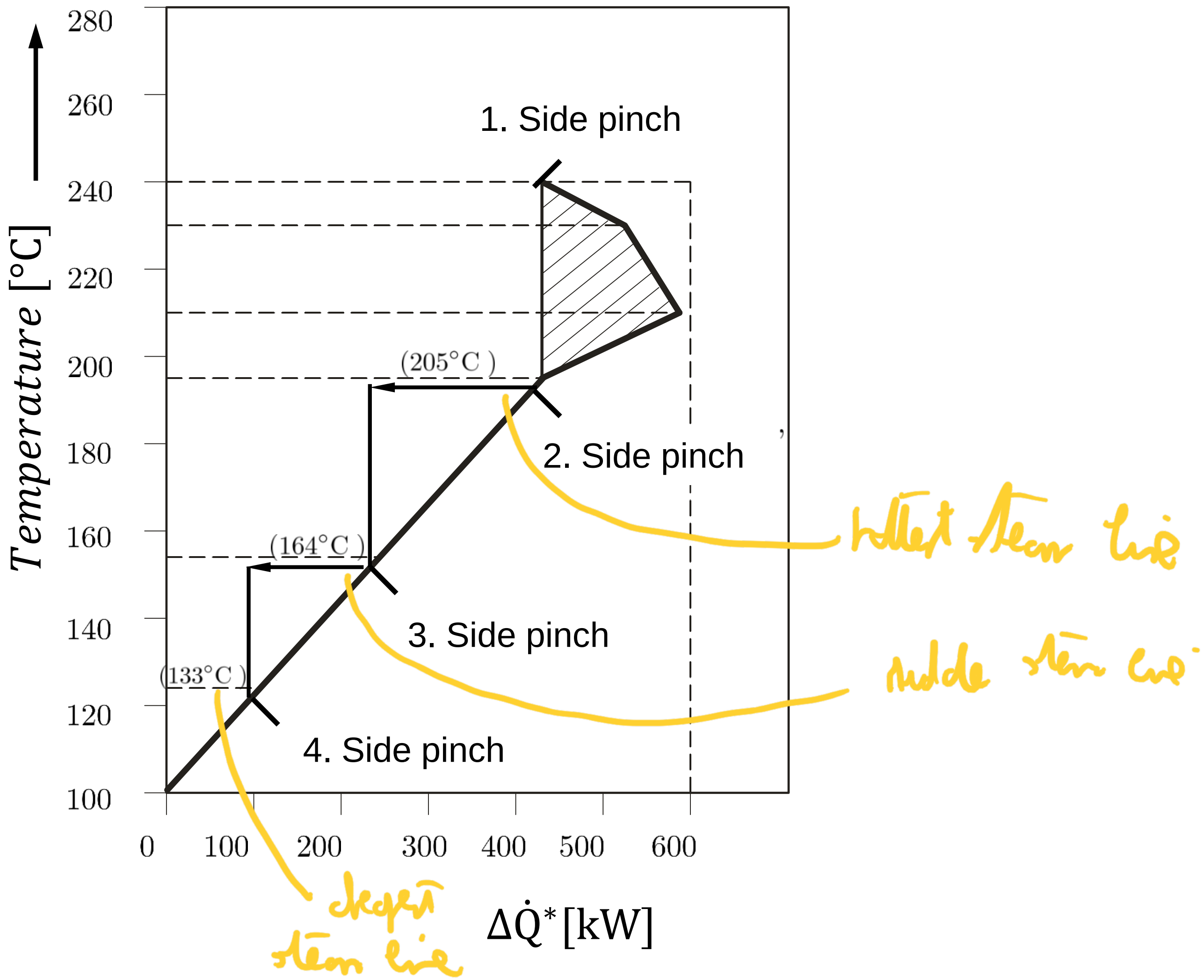


# Grand composite curve of a process $(\Delta T)_{min}$=20K



# Upper part of the grand composite curve with steam

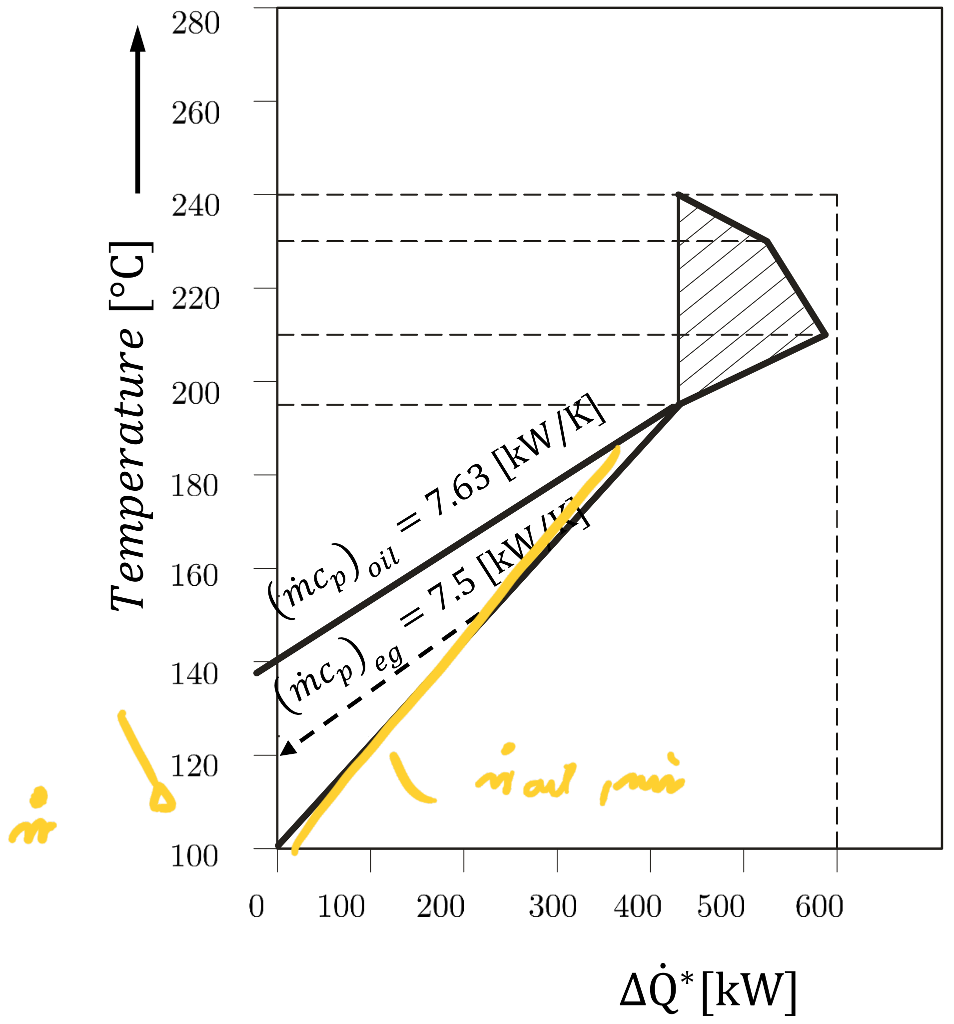
Heating with steam on three pressure stages $(\Delta T)_{min}$=20K



# Upper part of the grand composite curve with thermal oil or exhaust gas

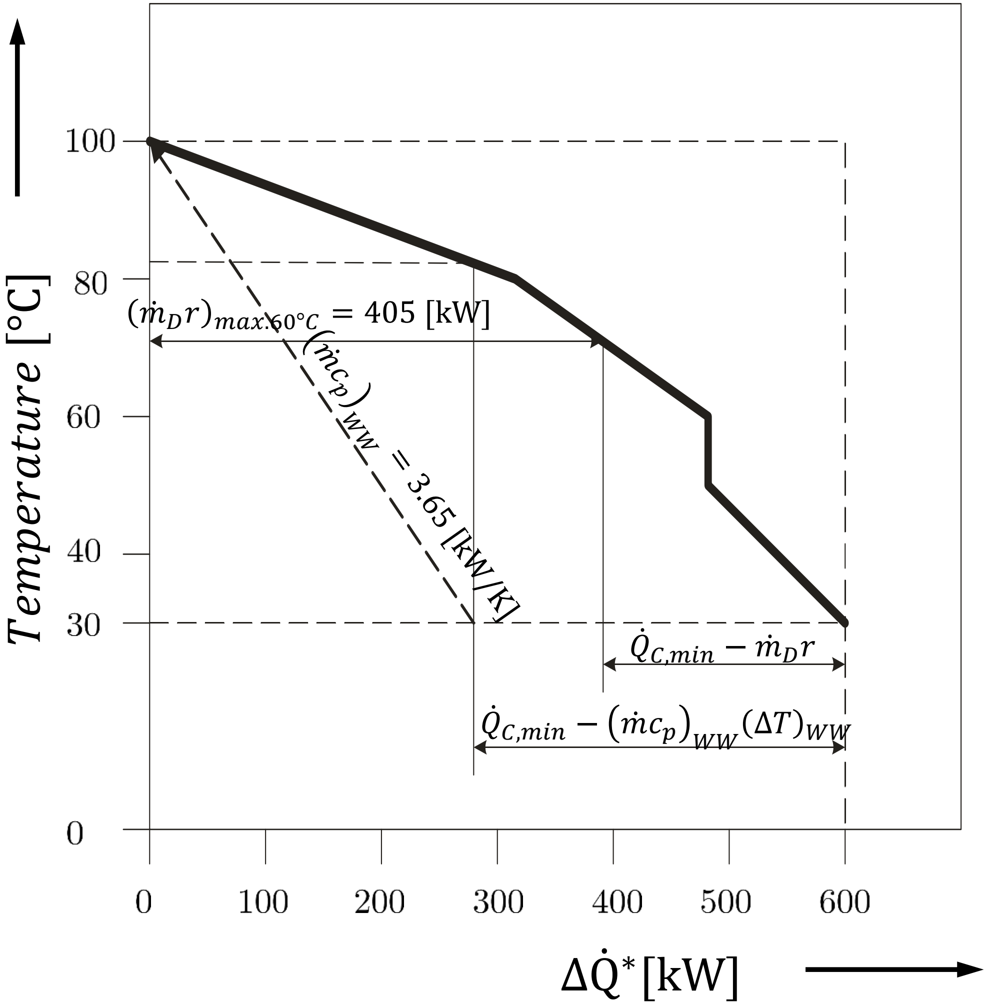
Heating by thermal oil or hot exhaust gas, $(\Delta T)_{min}$=20K

$\dot{Q}$ oil = $(\dot{m}c_p)_{oil}$ $\Delta T$



# Lower part of the grand composite curve

## Use of waste heat for steam or warm water production



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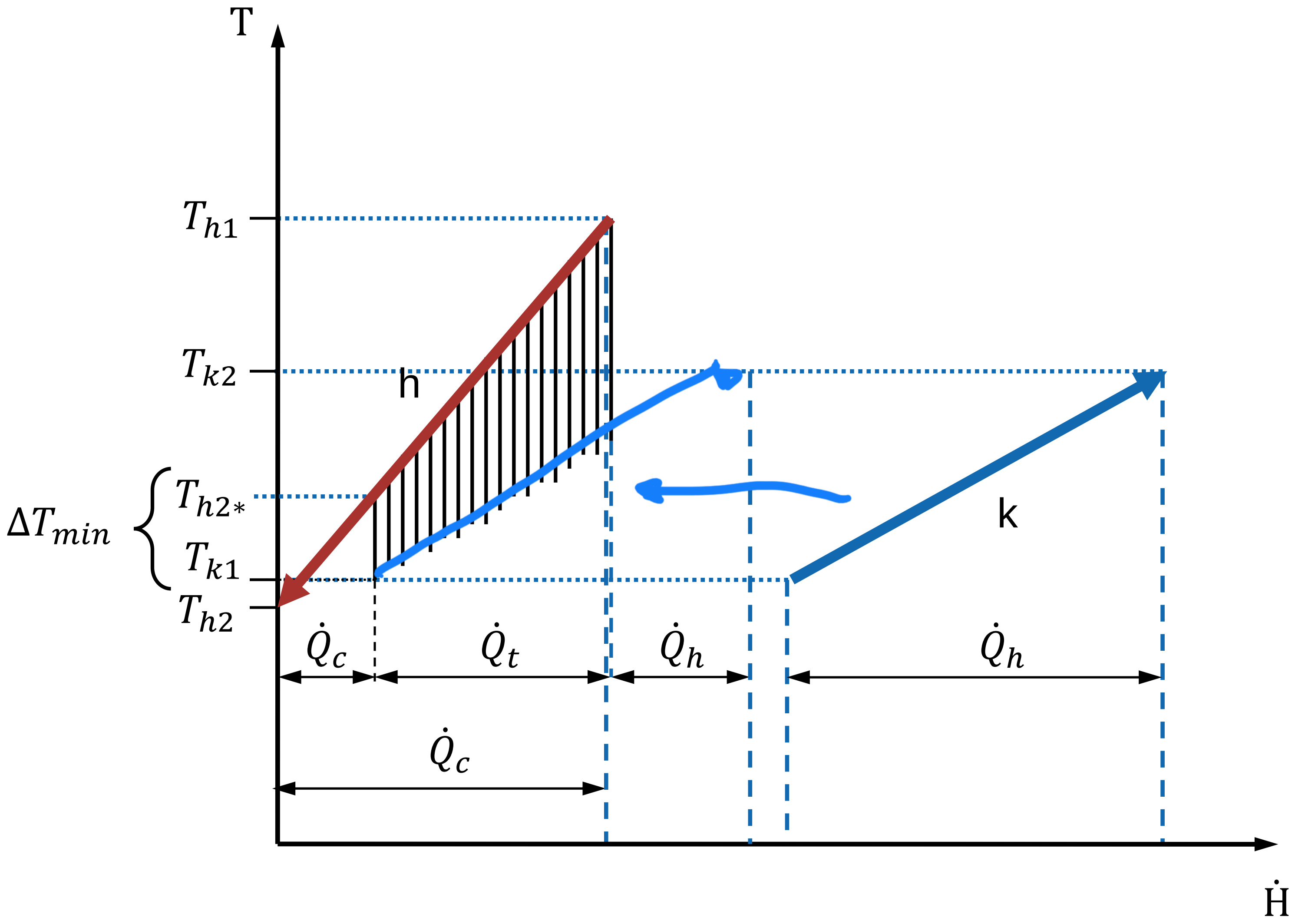
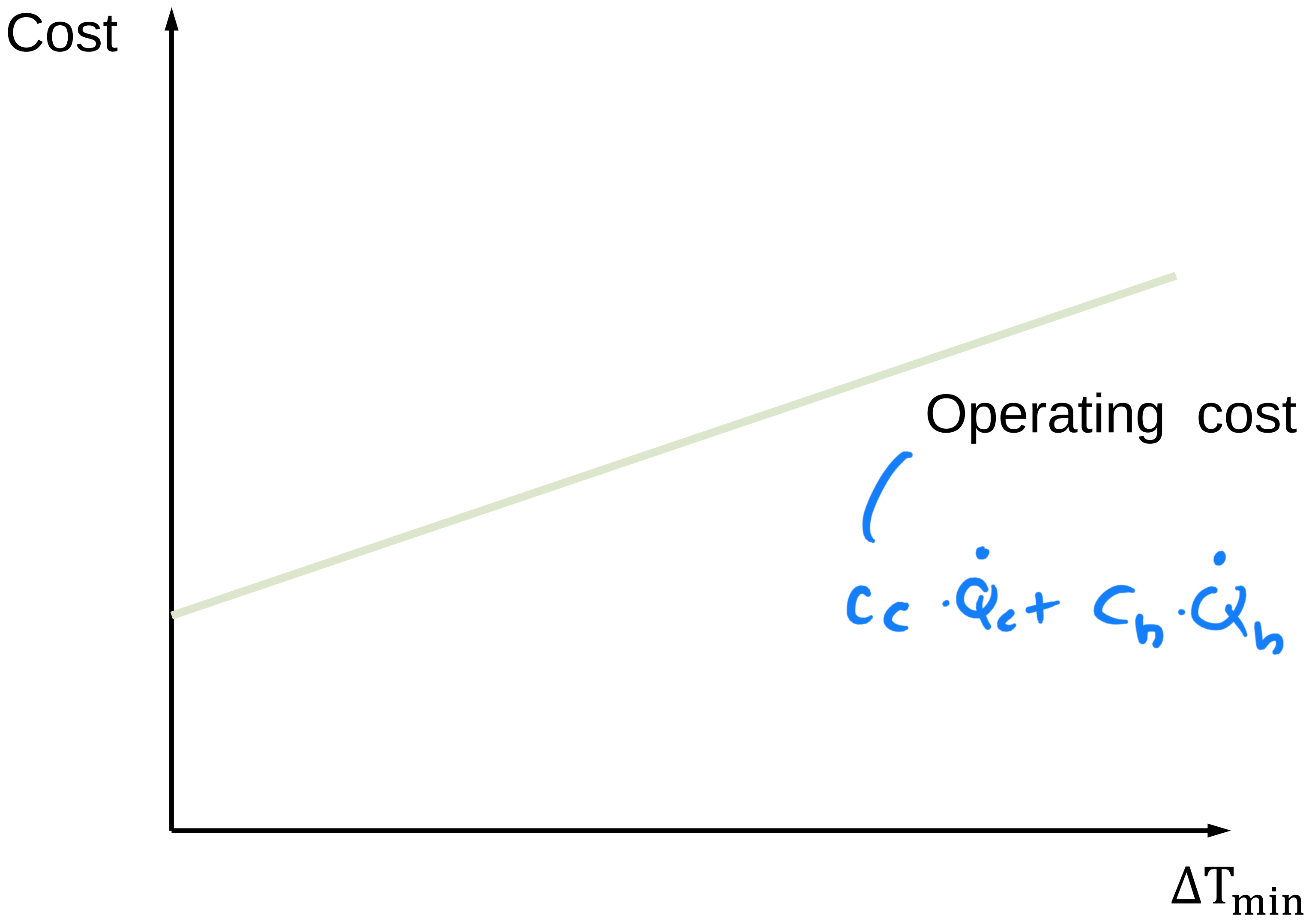
- ▪ interpret **heat integration as optimization problem**

# Changes in state in the t,H-diagram



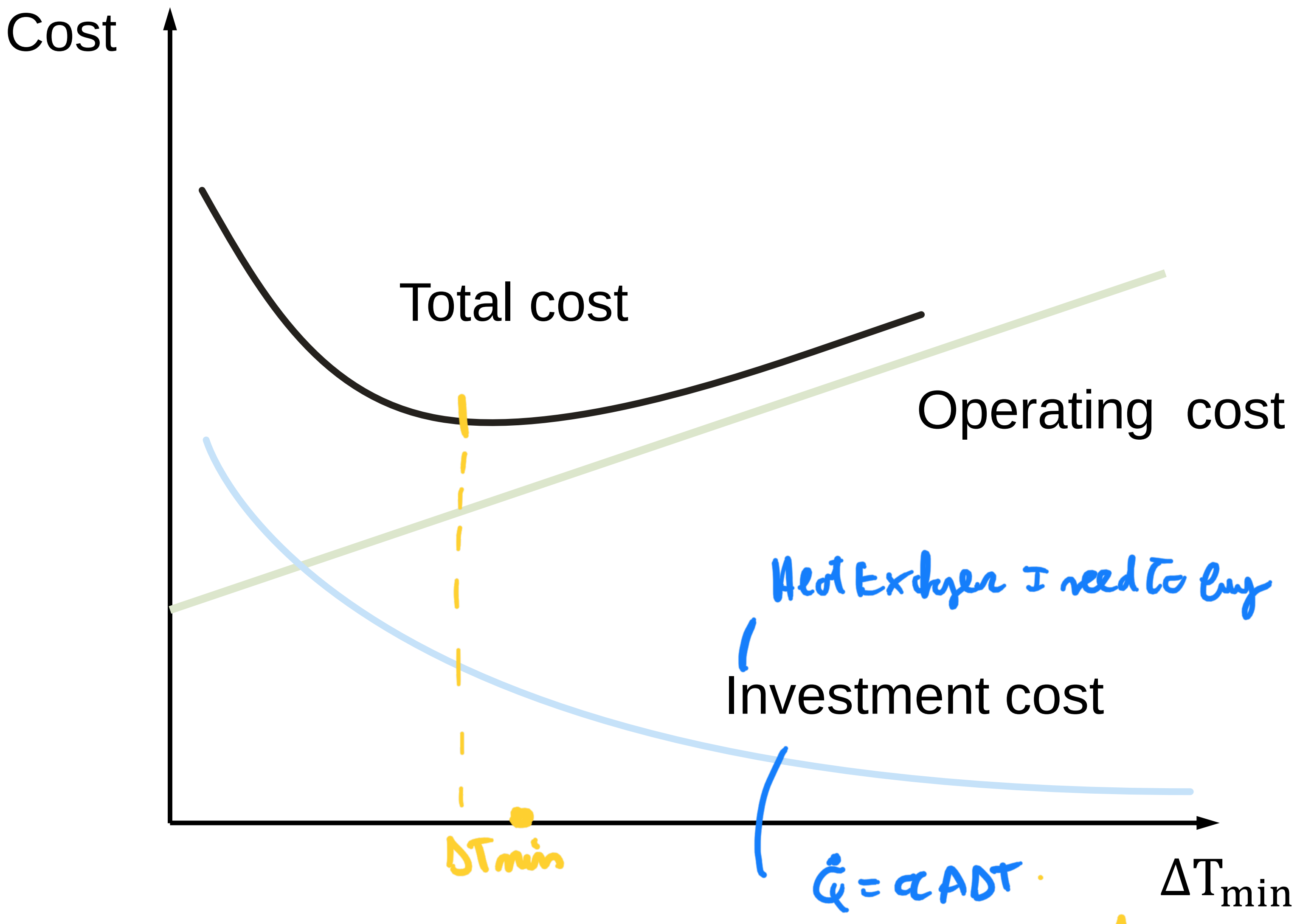
# Total Cost vs. $\Delta T_{min}$

total costs = investment costs + operation costs



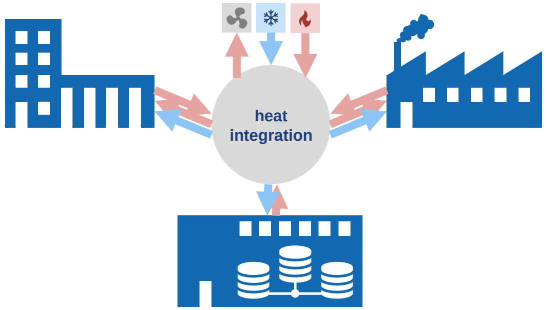
# Total Cost vs. $\Delta T_{min}$

total costs = investment costs + operation costs




cost ~ A ~ $\frac{1}{\Delta T}$

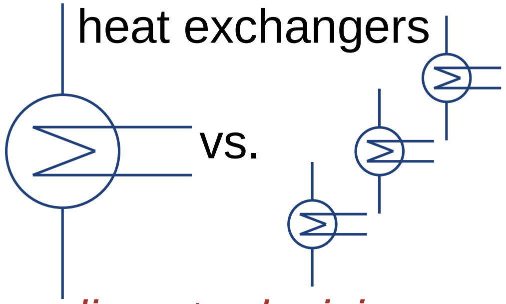
# Heat integration: Cost optimization




total costs = investment costs + operation costs

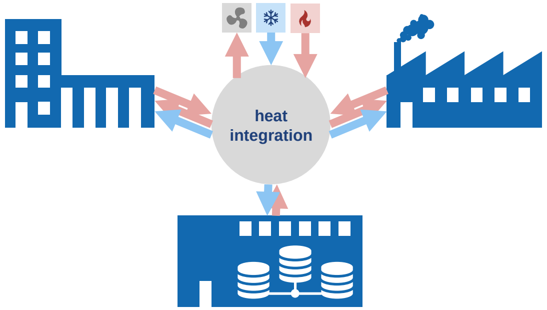
how many and where?

heat exchangers



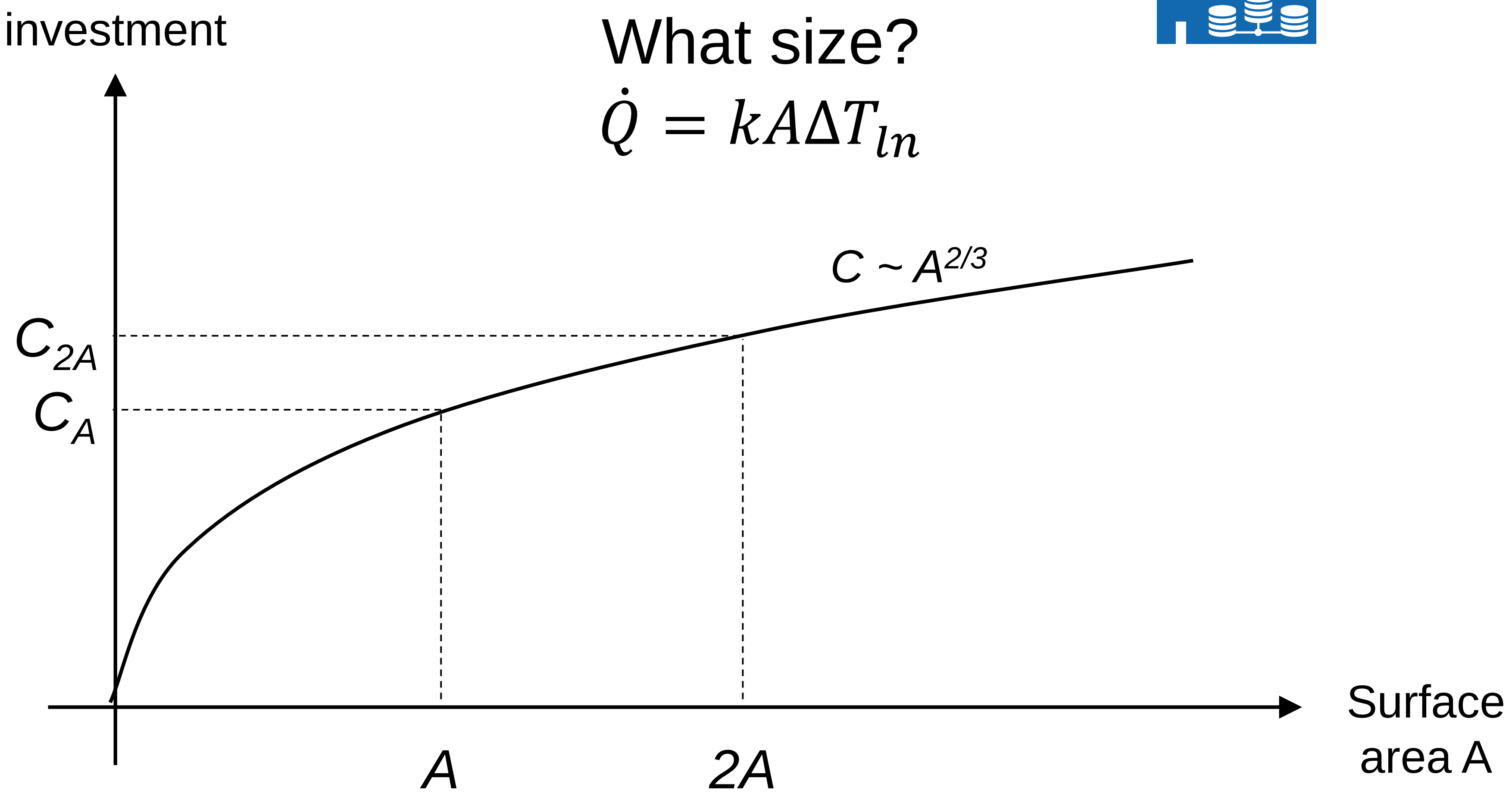

*discrete decisions*

# Heat integration: Cost optimization
## Investment cost




What size?

$$\dot{Q} = kA\Delta T_{ln}$$



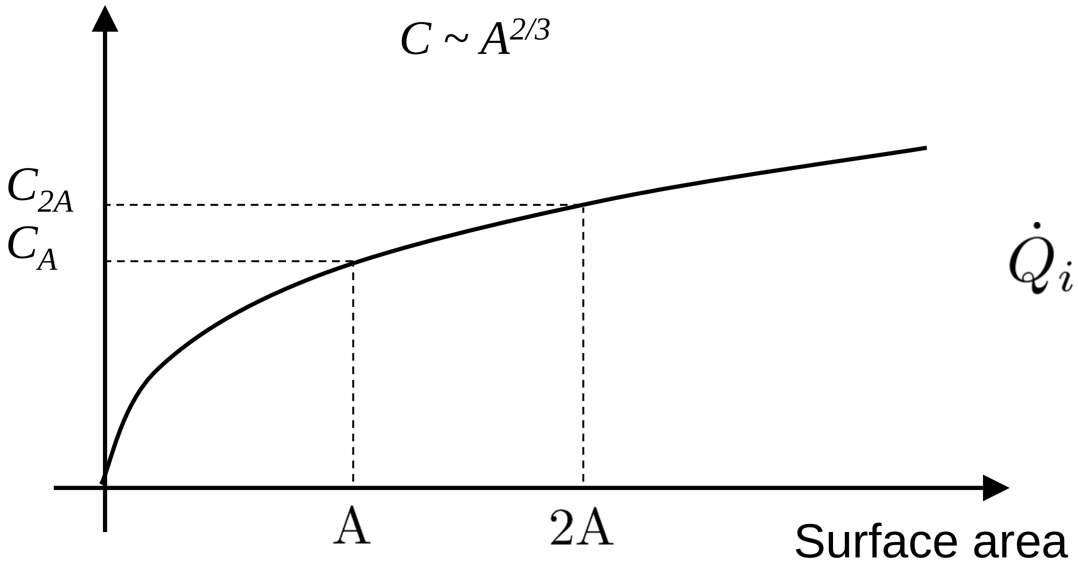

*concave (nonlinear) investment cost*

# Cost-optimized heat exchanger networks

Total costs = operating costs + capital costs

→ minimum operating costs ≈ given by pinch methodology

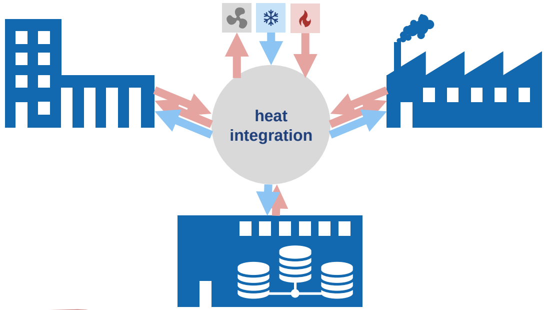
→ minimum capital costs :




$$\dot{Q}_i = k_i A_i \Delta T_{\ln,i}$$

*„ better few large than many small heat exchangers!"*

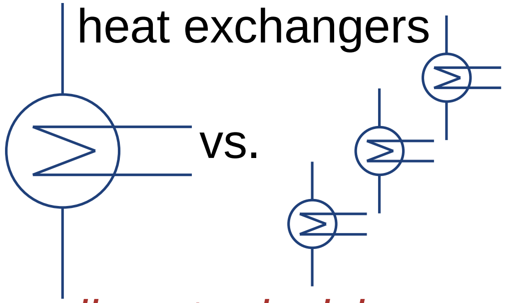
# Heat integration: Cost optimization




total costs = investment costs + operation costs

how many and where?

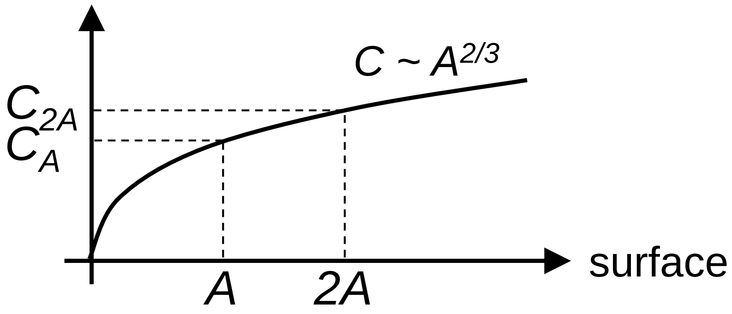
heat exchangers




*discrete decisions*

what size?

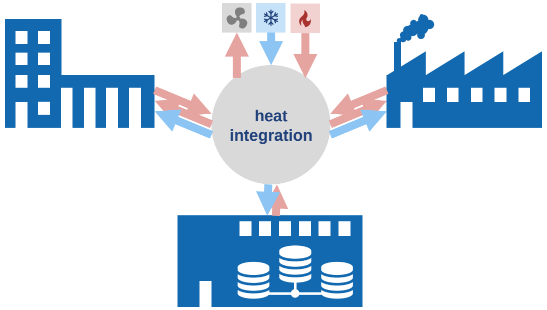
investment $\dot{Q} = kA\Delta T_{ln}$

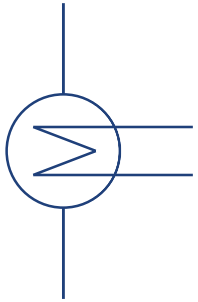



*concave (nonlinear) investment cost*

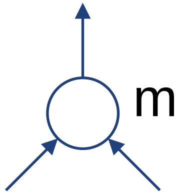
How much utility supply needed?
How much heat transfer?

# Heat integration
# How much utility supply & heat transfer?



heat exchanger



mixing & splitting

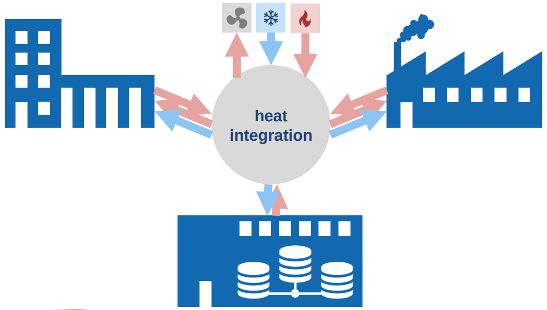
$$\dot{Q} = \dot{m} \int_{T_{in}}^{T_{out}} c_p(T)dT$$

$$\dot{m}_1 \int_{T_0}^{T_1} c_p(T)dT + \dot{m}_2 \int_{T_0}^{T_2} c_p(T)dT$$
$$= \dot{m}_{mix} \int_{T_0}^{T_{mix}} c_p(T)dT$$

*nonlinear*

*nonlinear*

# Heat integration – What to consider?
# An economic perspective

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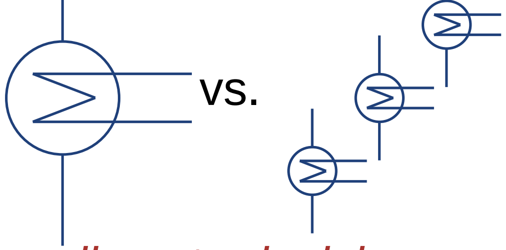
how many and where?

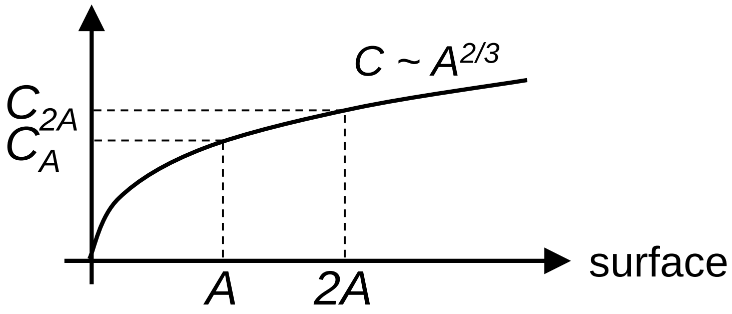
heat exchangers




*discrete decisions*

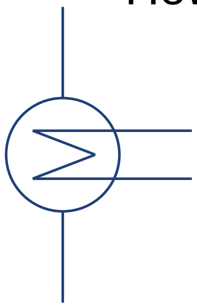
what size?

investment $\dot{Q} = kA\Delta T_{ln}$




*concave (nonlinear) investment cost*

How much utility supply needed?
How much heat transfer?



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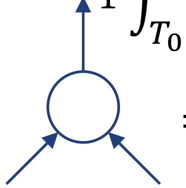

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$$= \dot{m}_{mix} \int_{T_0}^{T_{mix}} c_p(T)dT$$

*nonlinear*

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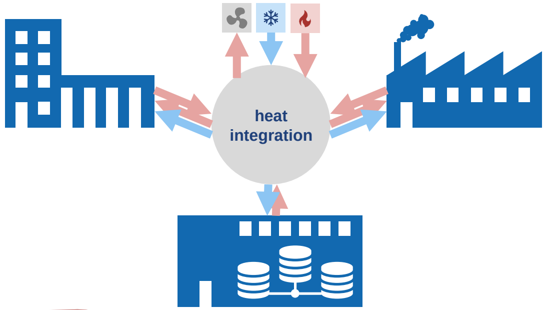
# An economic perspective

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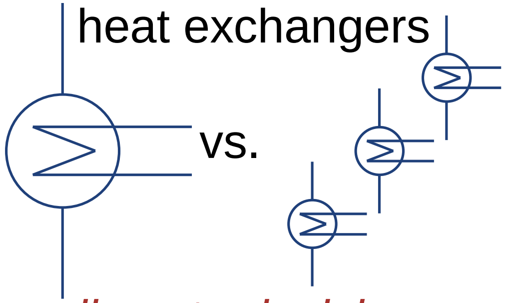


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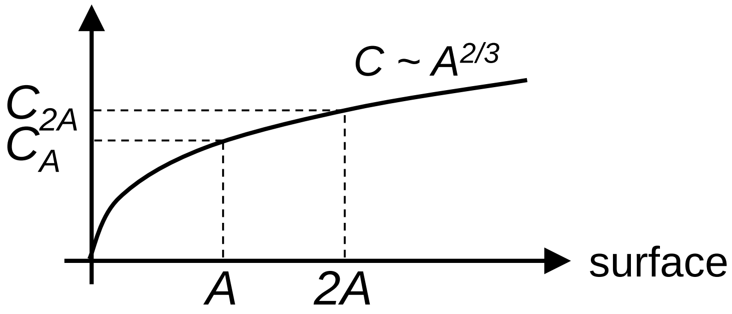


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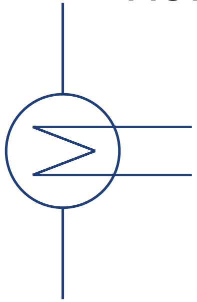

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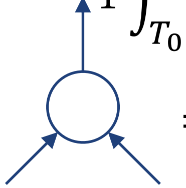
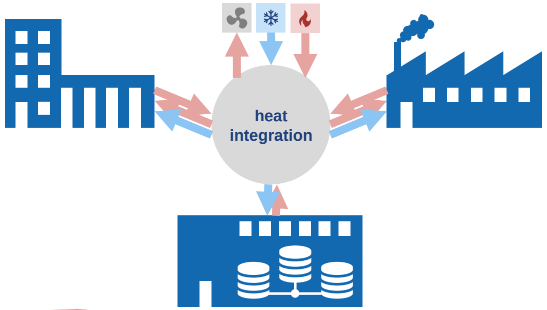


$$\dot{m}_1 \int_{T_0}^{T_1} c_p(T)dT + \dot{m}_2 \int_{T_0}^{T_2} c_p(T)dT = \dot{m}_{mix} \int_{T_0}^{T_{mix}} c_p(T)dT$$

*nonlinear*

# Heat integration – What to consider?
# An economic perspective

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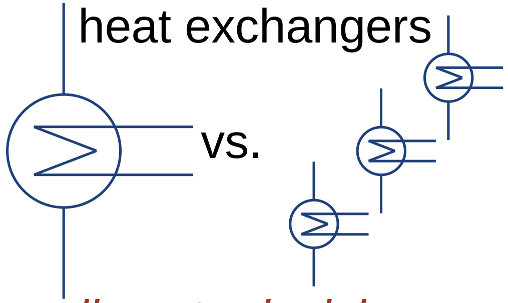


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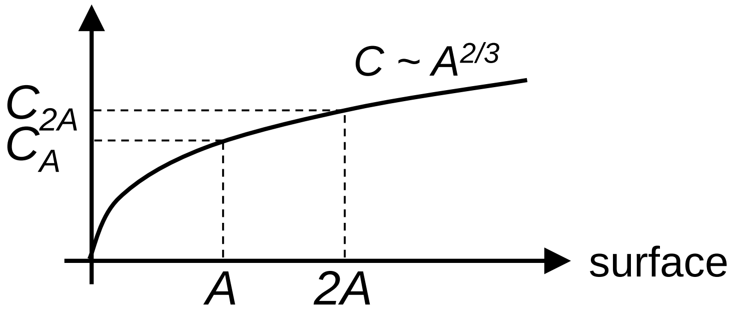


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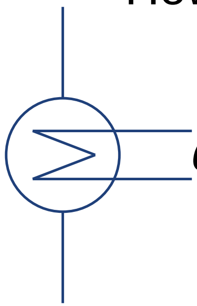
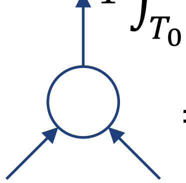


$$\dot{Q}_i \approx \dot{m}_i \cdot c_{p,i} \cdot (T_{i,out} - T_{i,in})$$

**assume constant**



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*linear*

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