eurammon Natural Refrigeration Award 2020

Lecture event, October 9, 2020

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refrigerants delivered by mother nature

Programme and Presentations

8:30 – 8:40	Welcome and Introduction of the Award Winners Monika Witt - TH. WITT Kältemaschinenfabrik GmbH, eurammon Vice Chair
8:40 – 9:10	Winner 1st place - Benjamin Zühlsdorf DTU Technical University of Denmark "High-performance heat pump systems - Enhancing performance and range of heat pump systems for industry and district heating"
9:10 – 9:40	Winner 2nd place - Maaike Leichsenring Delft University of Technology, Netherlands "Flow visualization of downward condensing ammonia in a gasketed plate heat exchanger"
9:40 –10:10	Winner 3rd place - Fabio Giunta KTH – Royal Institute of Technology, Sweden "Techno-economic assessment of CO_2 refrigeration systems with geothermal integration, a field measurements and modelling analysis"
10:10 – 10:30	Q&A session and closing remarks Andrew Stockman, Managing Director for Europe and the Middle East at EVAPCO Europe Group and eurammon executive board

The future is Natural!

The smartest decision is to leapfrog other refrigerant options and turn to the natural choices…

DANISH
TECHNOLOGICAL
INSTITUTE

DTU

eurammon Natural Refrigeration Award 2020
High-performance heat pump systems
Enhancing performance and range of heat pump systems for industry and district heating

Webinar, October 9, 2020 – Benjamin Zühlsdorf, Technical University of Denmark

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Agenda

- Zeotropic working fluids in heat pumps
  - Motivation and potential
  - Screening procedure
  - Optimization of cycle and working fluid
  - Summary and outlook

- [High-temperature heat pumps]

ThermCyc
Efficient use of low-temperature heat sources

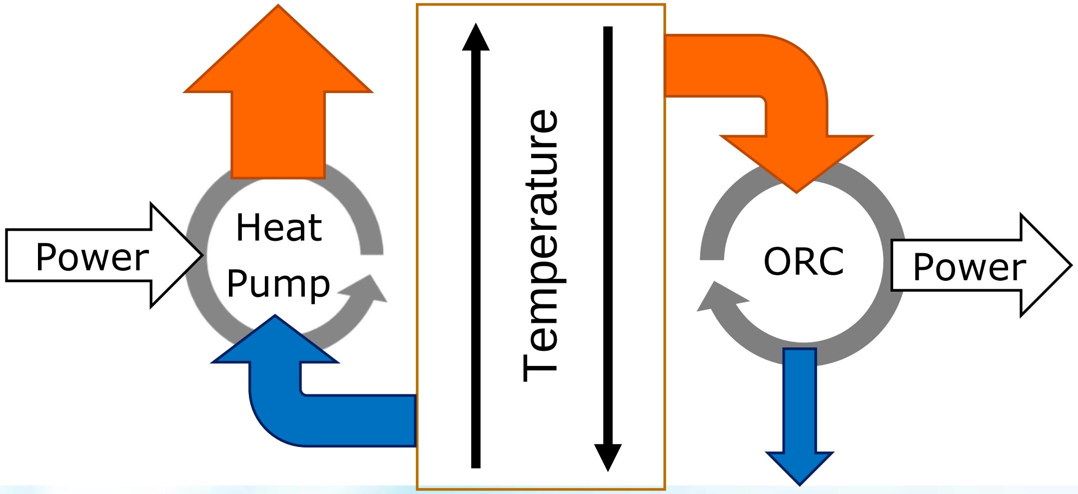
March 2014 – February 2019

Hypothesis:

Low-temperature heat sources represent a favorable energy source.

There is a great potential to enhance their utilization by:

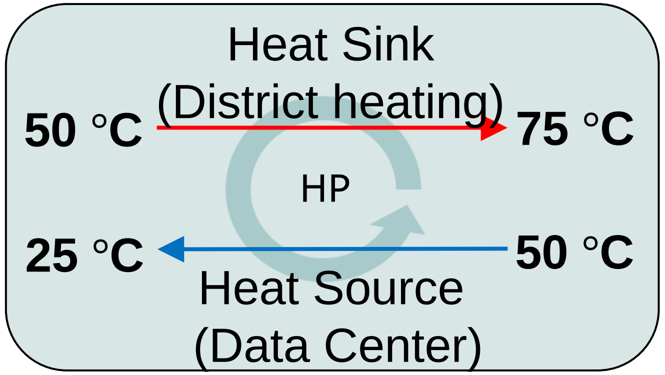
- Novel cycle layouts
- Utilization of working fluid mixtures
- Improved component design



Project Partners

http://www.thermcyc.mek.dtu.dk/

Motivation and potential
Use of zeotropic working fluid mixtures

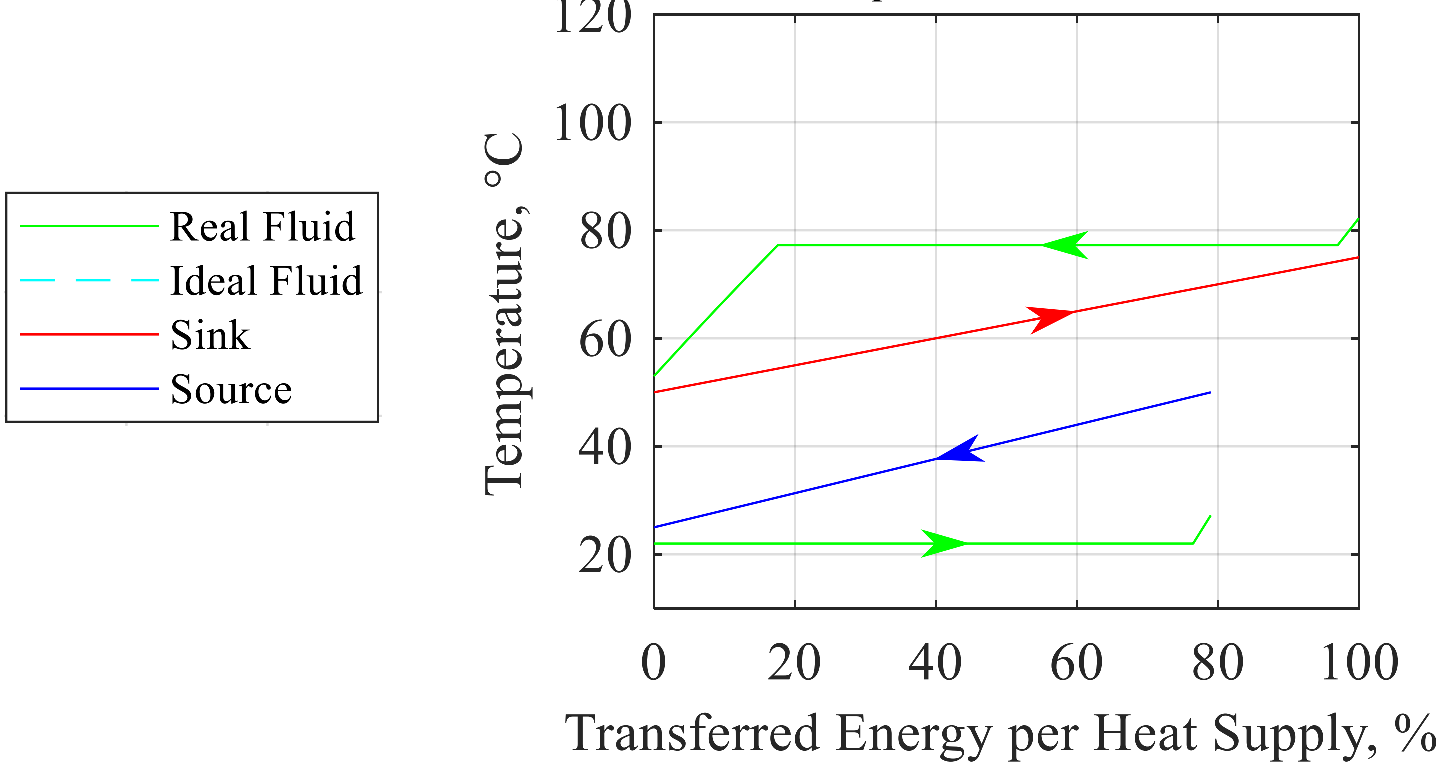


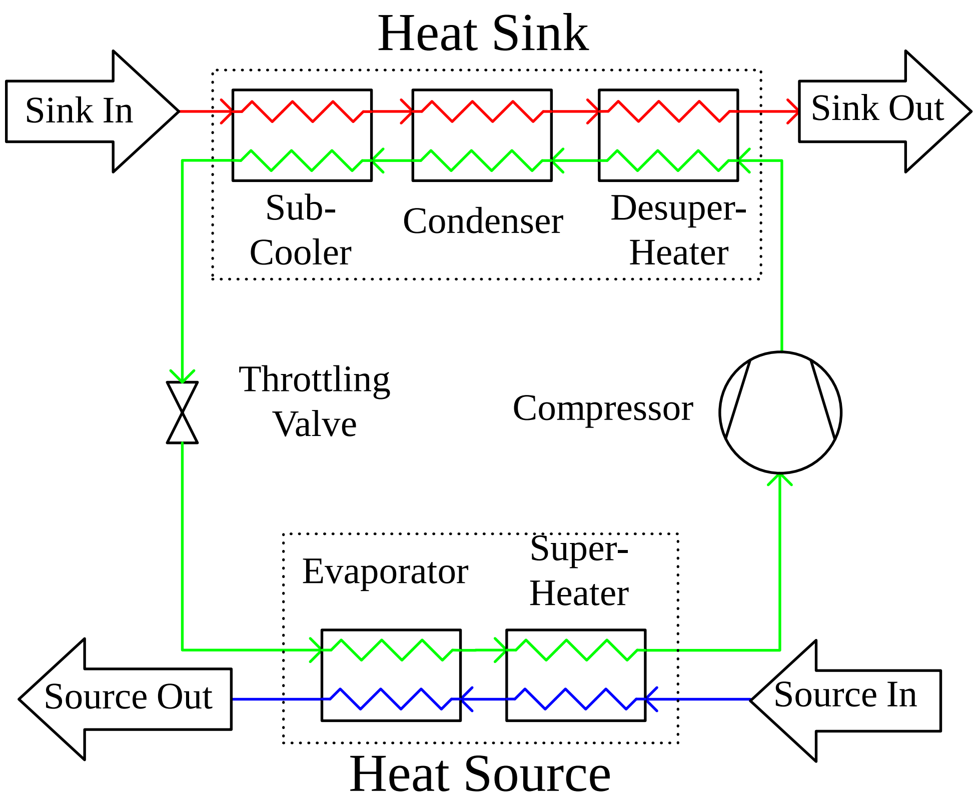
Motivation and potential
Use of zeotropic working fluid mixtures

50 °C → 75 °C
25 °C ← 50 °C

Butane

COP = 4.52, p_{evap} = 2.21 bar, p_{cond} = 9.53





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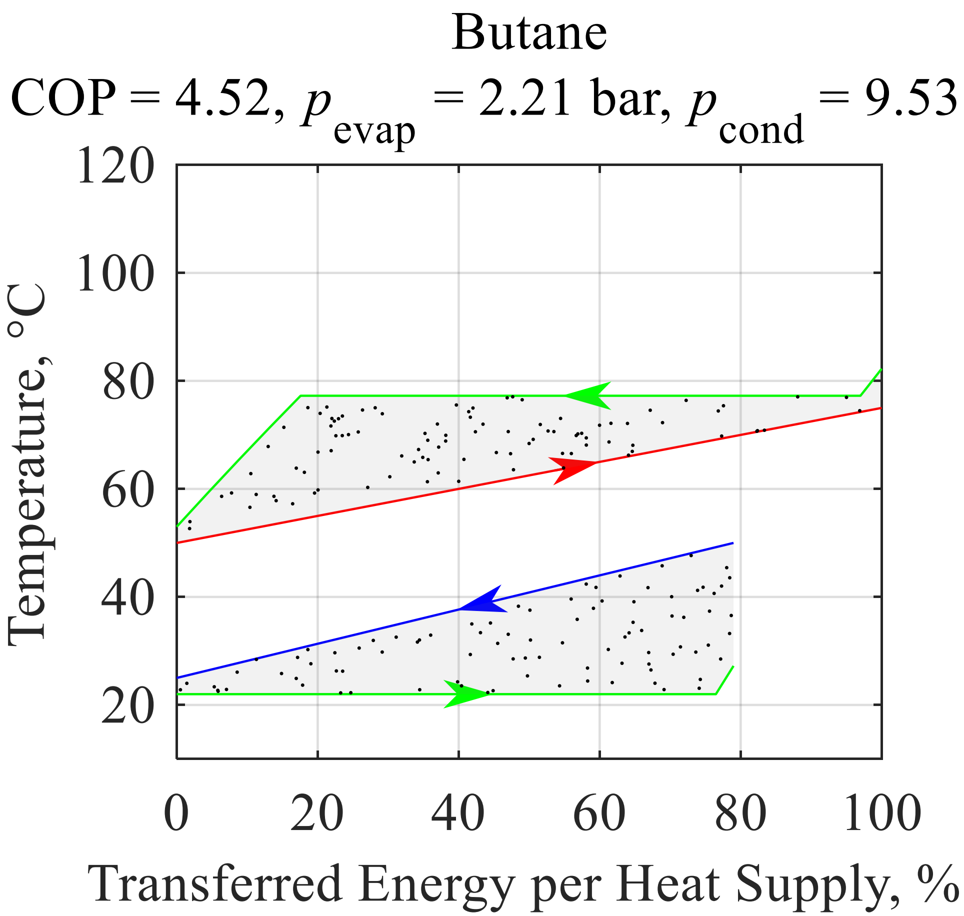
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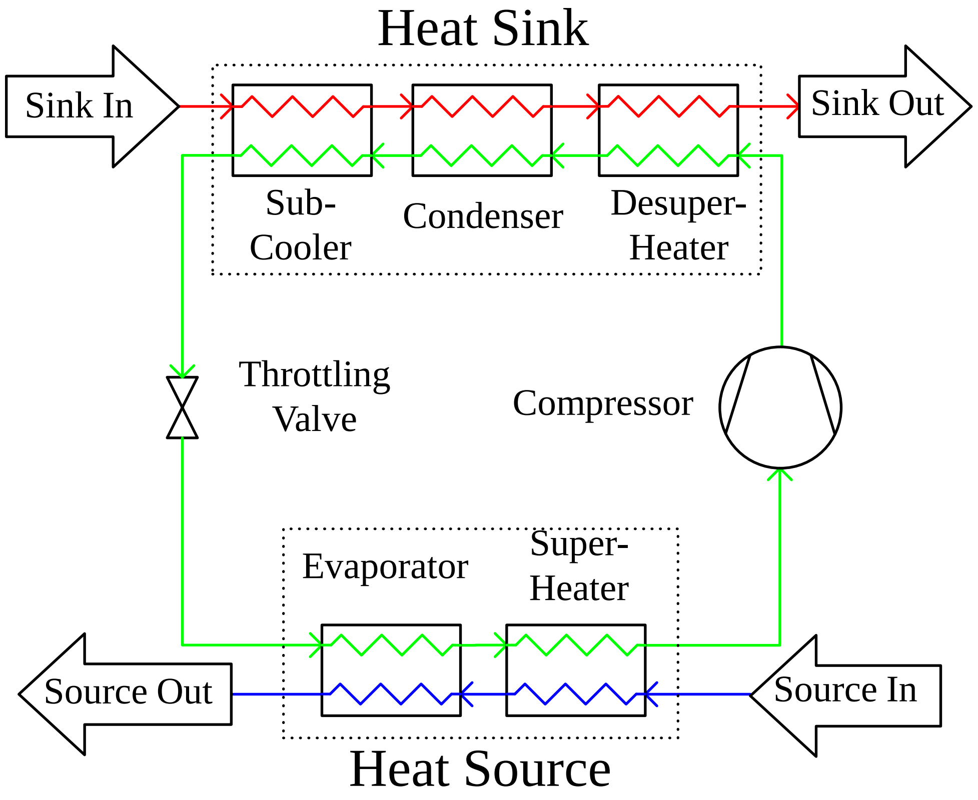

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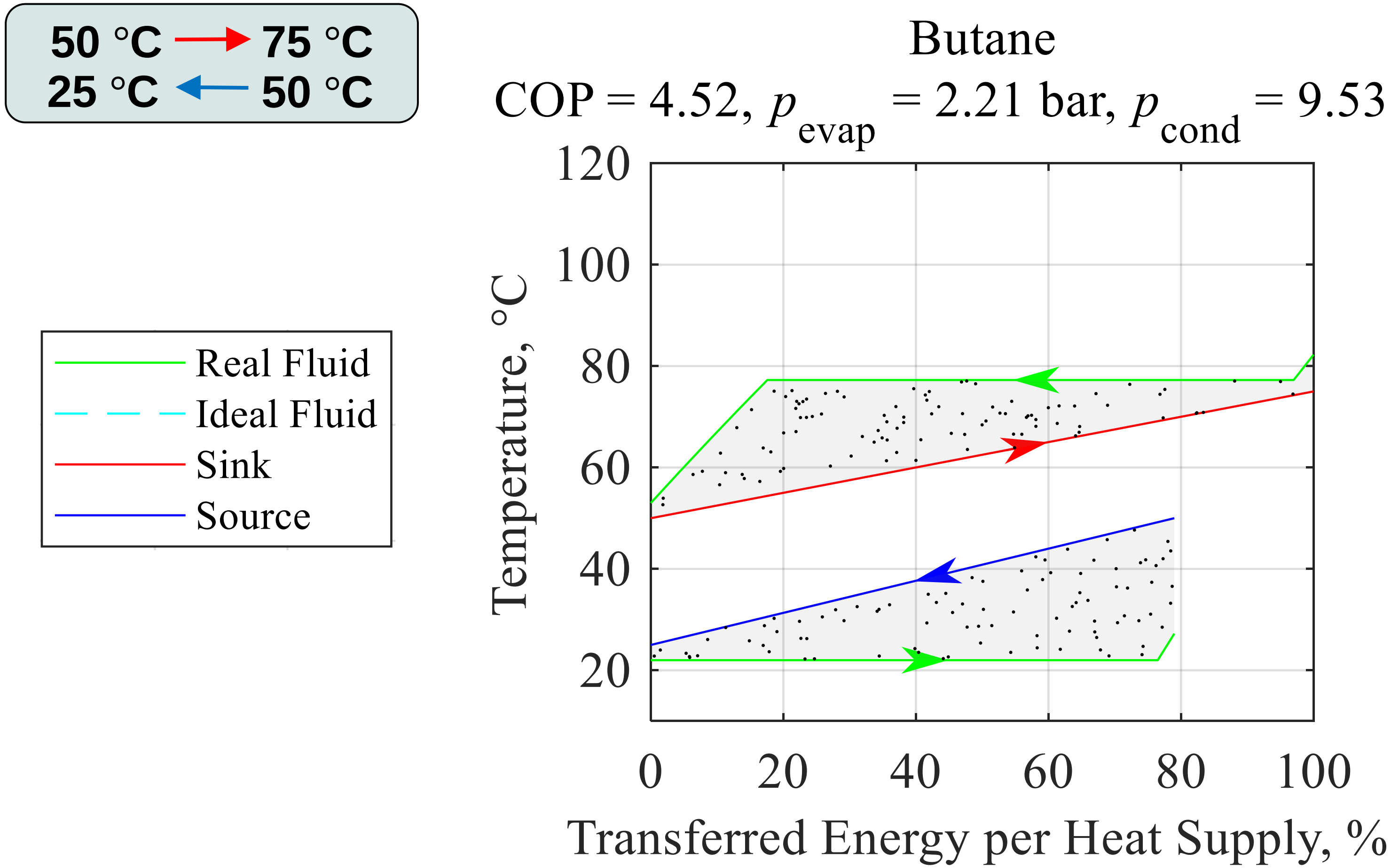

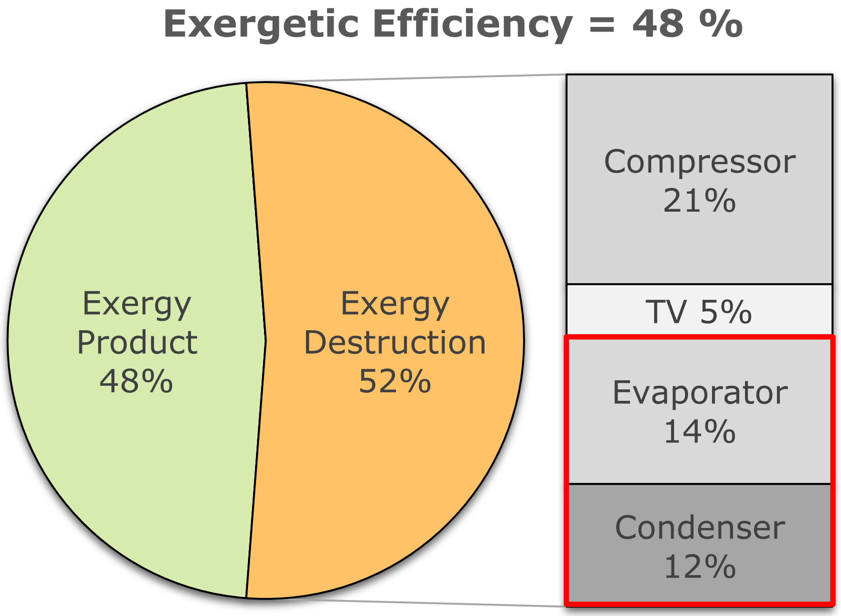

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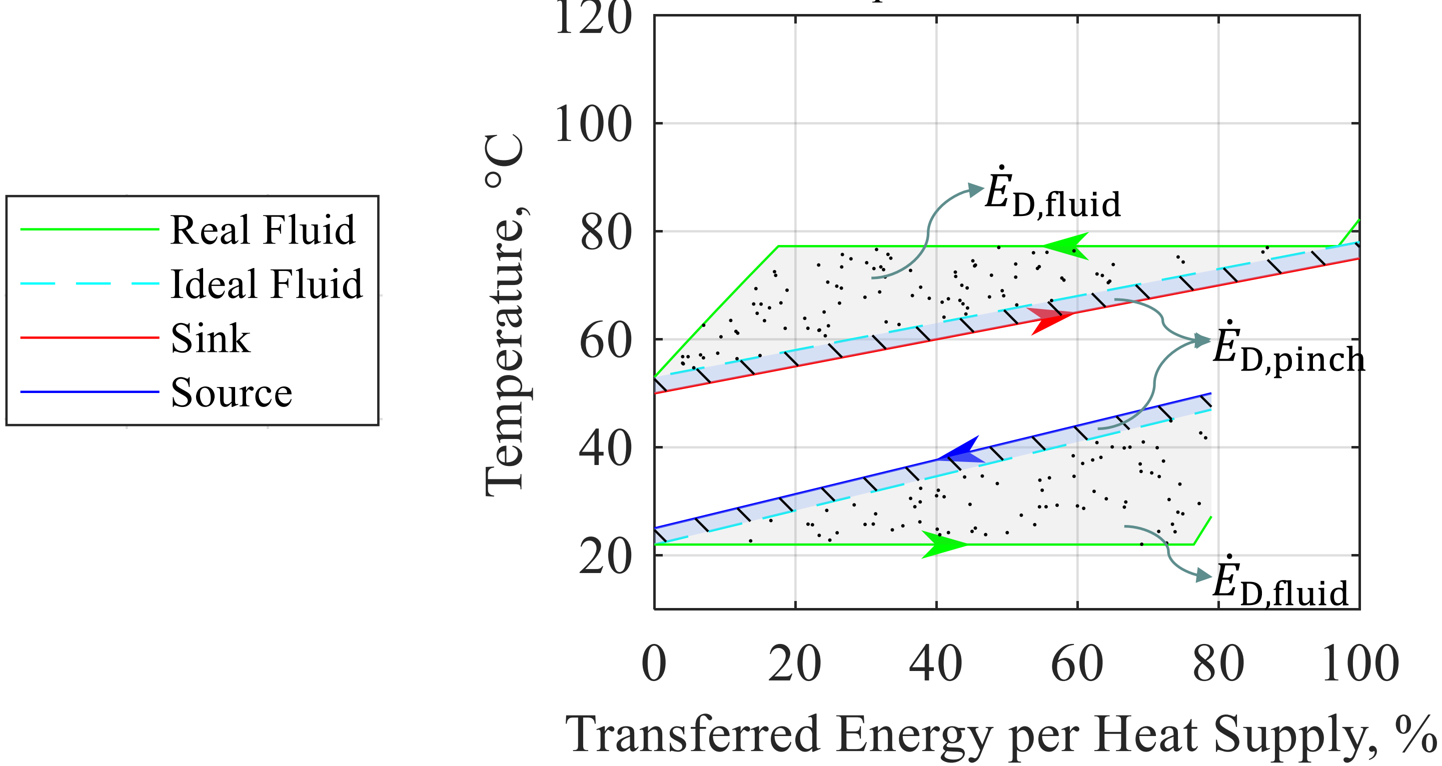
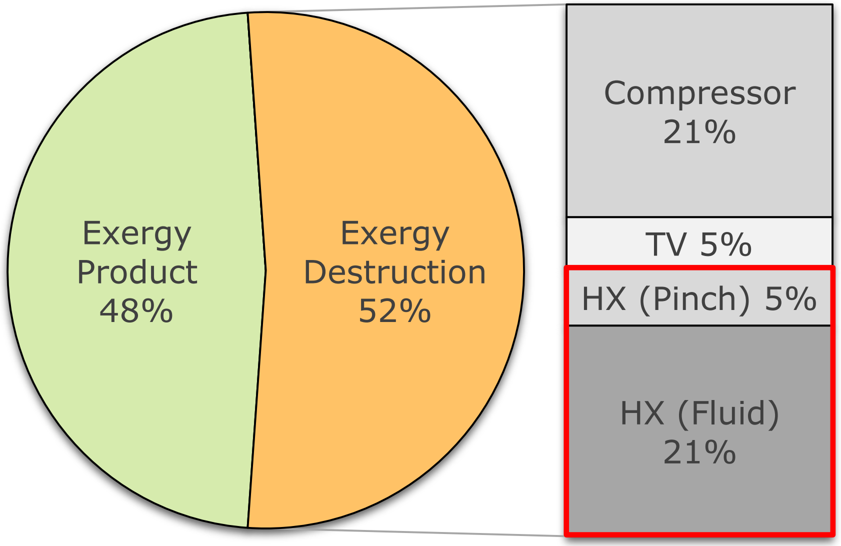


Exergetic Efficiency = 48 %



Motivation and potential
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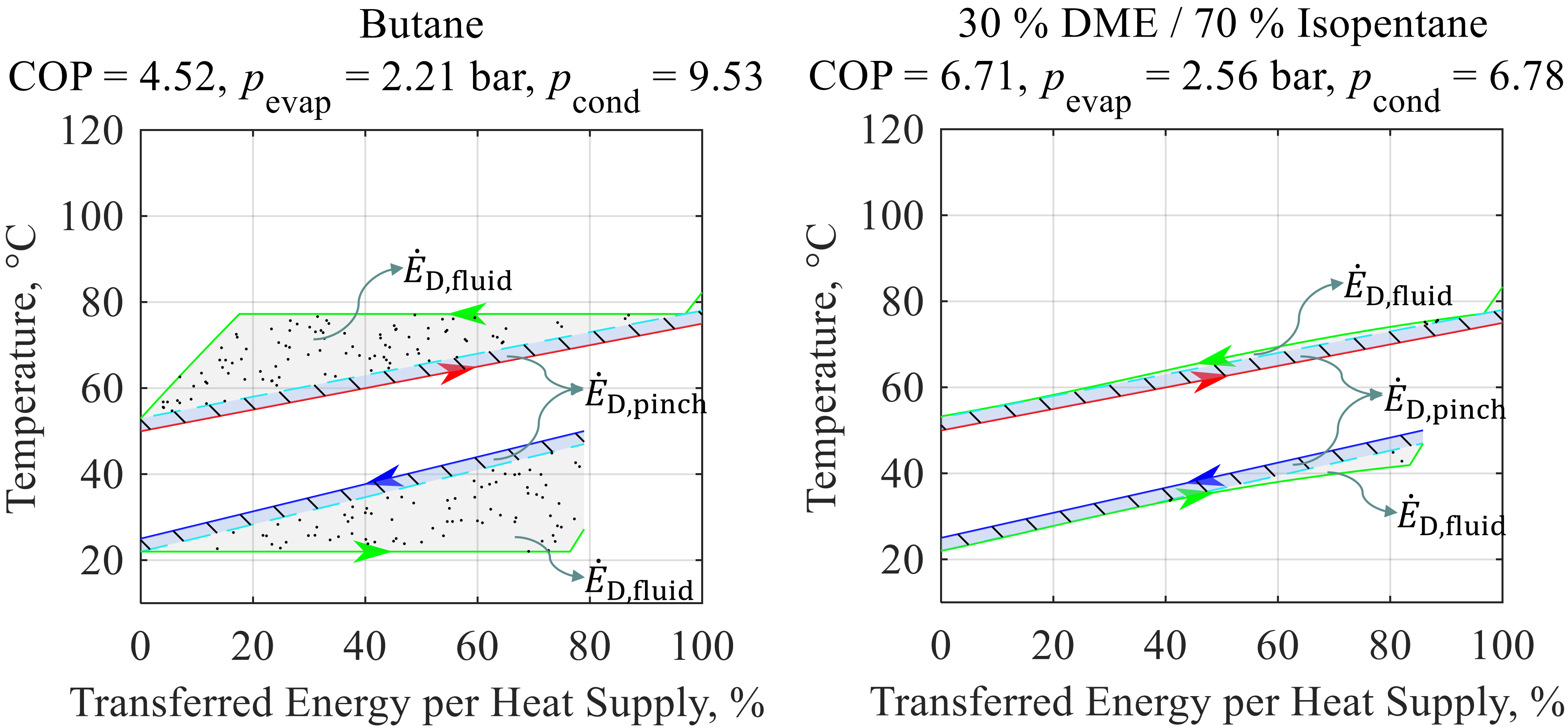
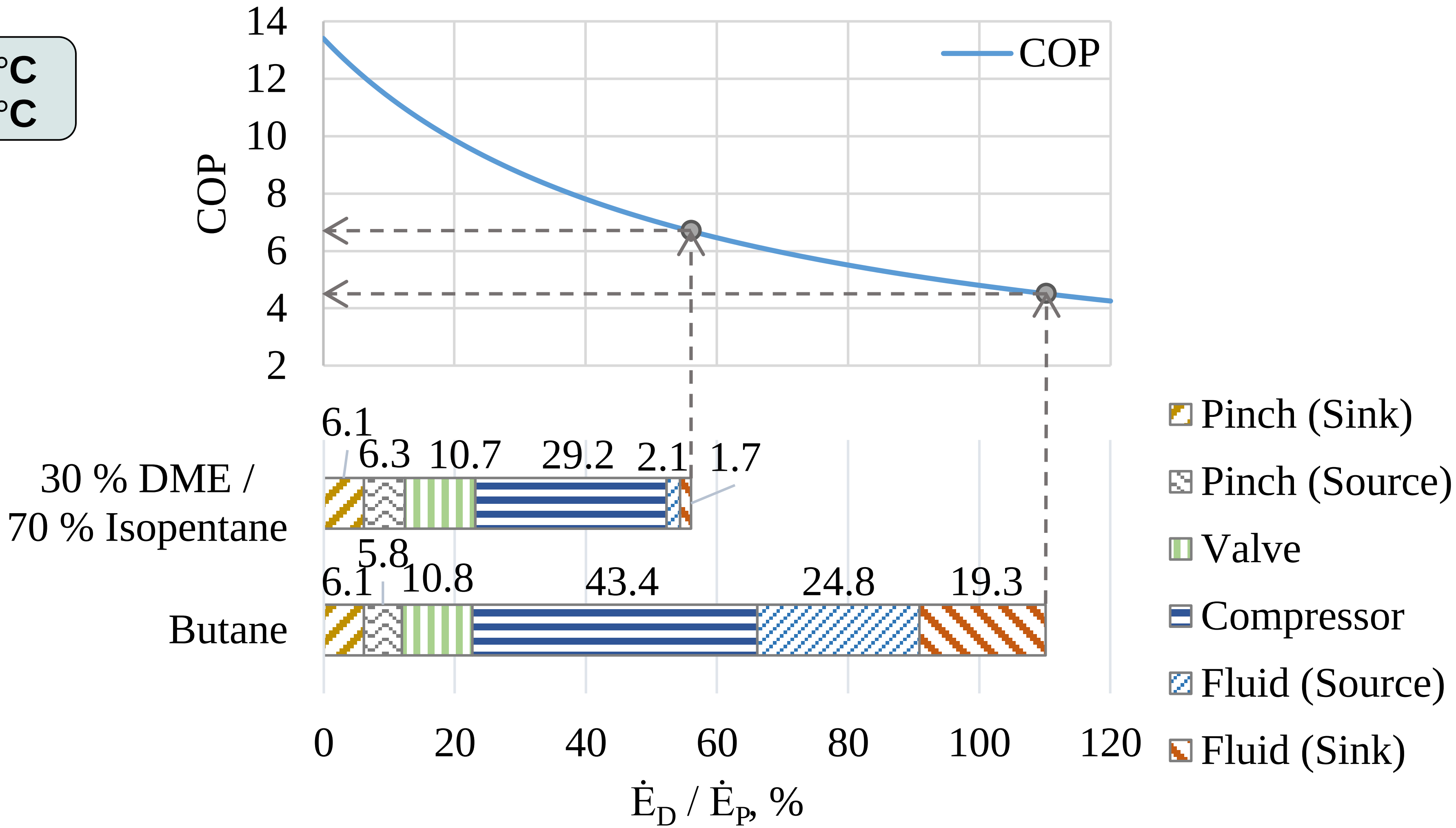

Butane
COP = 4.52, p_{evap} = 2.21 bar, p_{cond} = 9.53

30 % DME / 70 % Isopentane
COP = 6.71, p_{evap} = 2.56 bar, p_{cond} = 6.78

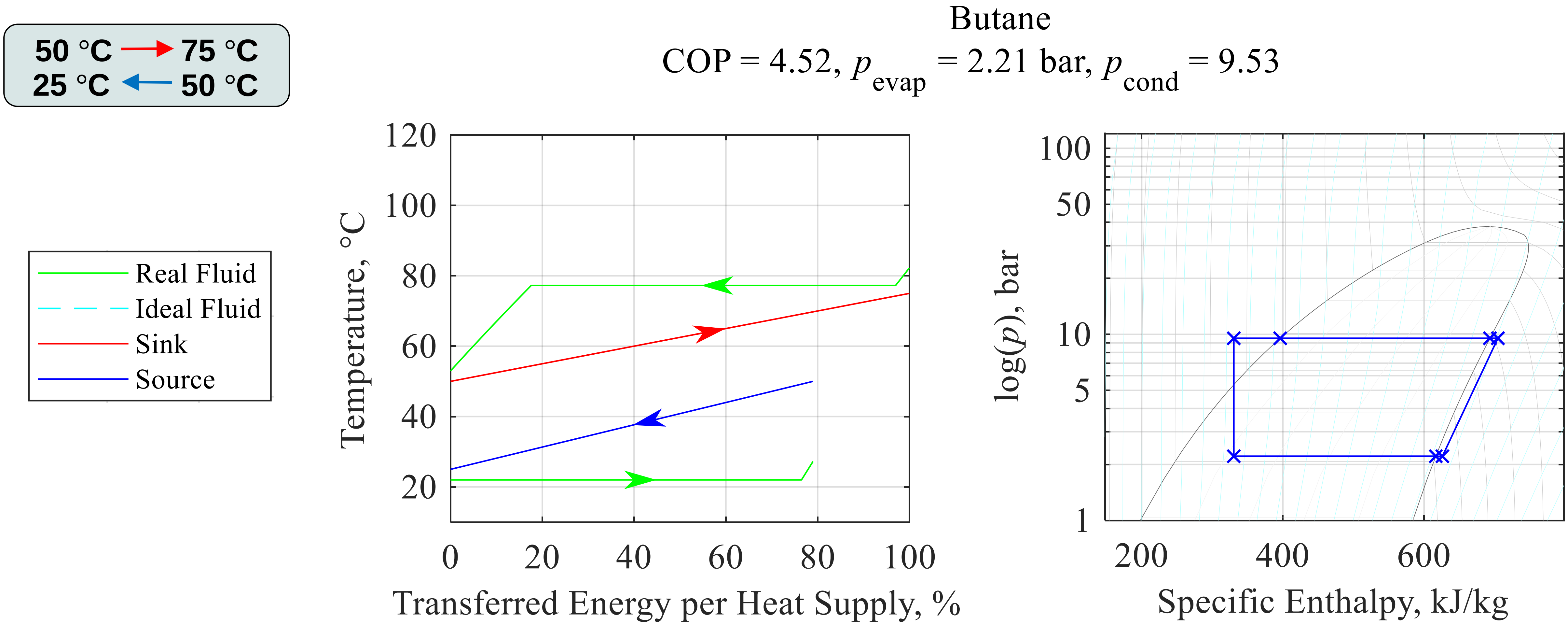
Motivation and potential
Relating exergy destruction and COP

50 °C → 75 °C
25 °C ← 50 °C



Screening procedure
Case study: Data Center to District heating

50 °C → 75 °C
25 °C ← 50 °C



Screening procedure
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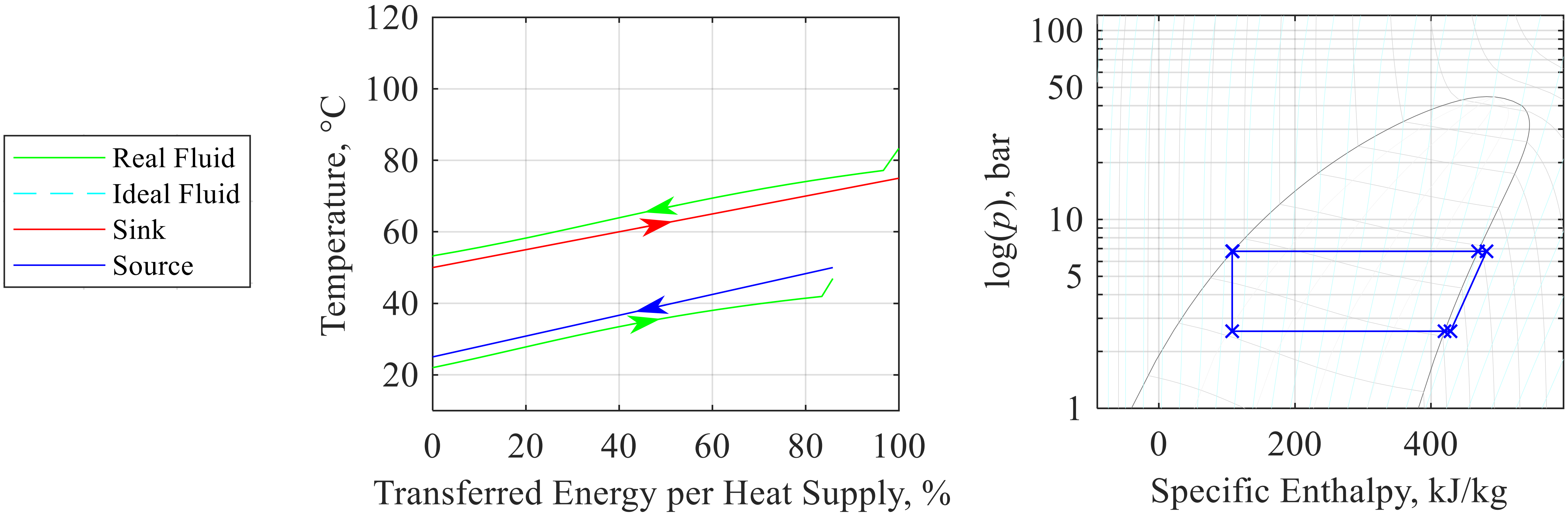
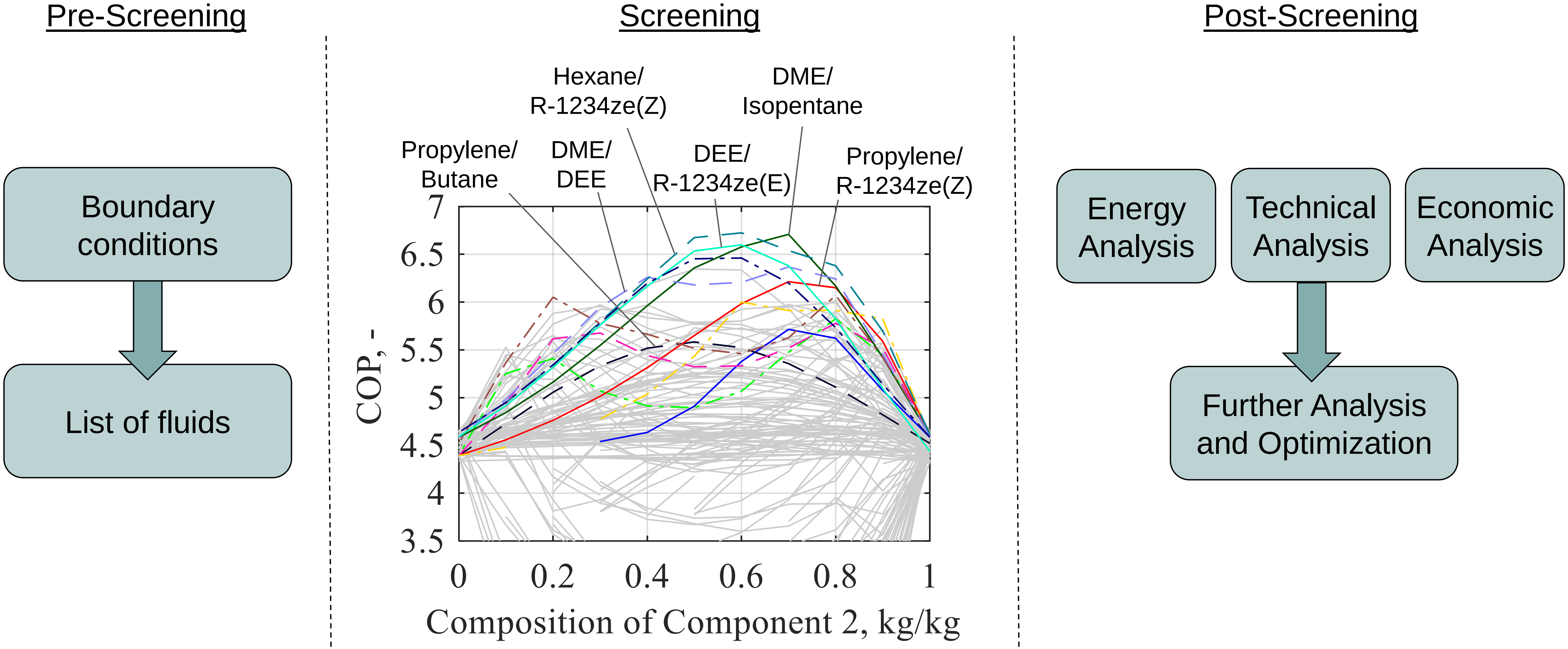


Screening procedure
How to find promising mixtures?



Pre-Screening

Boundary conditions

List of fluids

Screening

Post-Screening

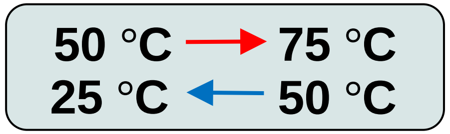
Energy Analysis

Technical Analysis

Economic Analysis

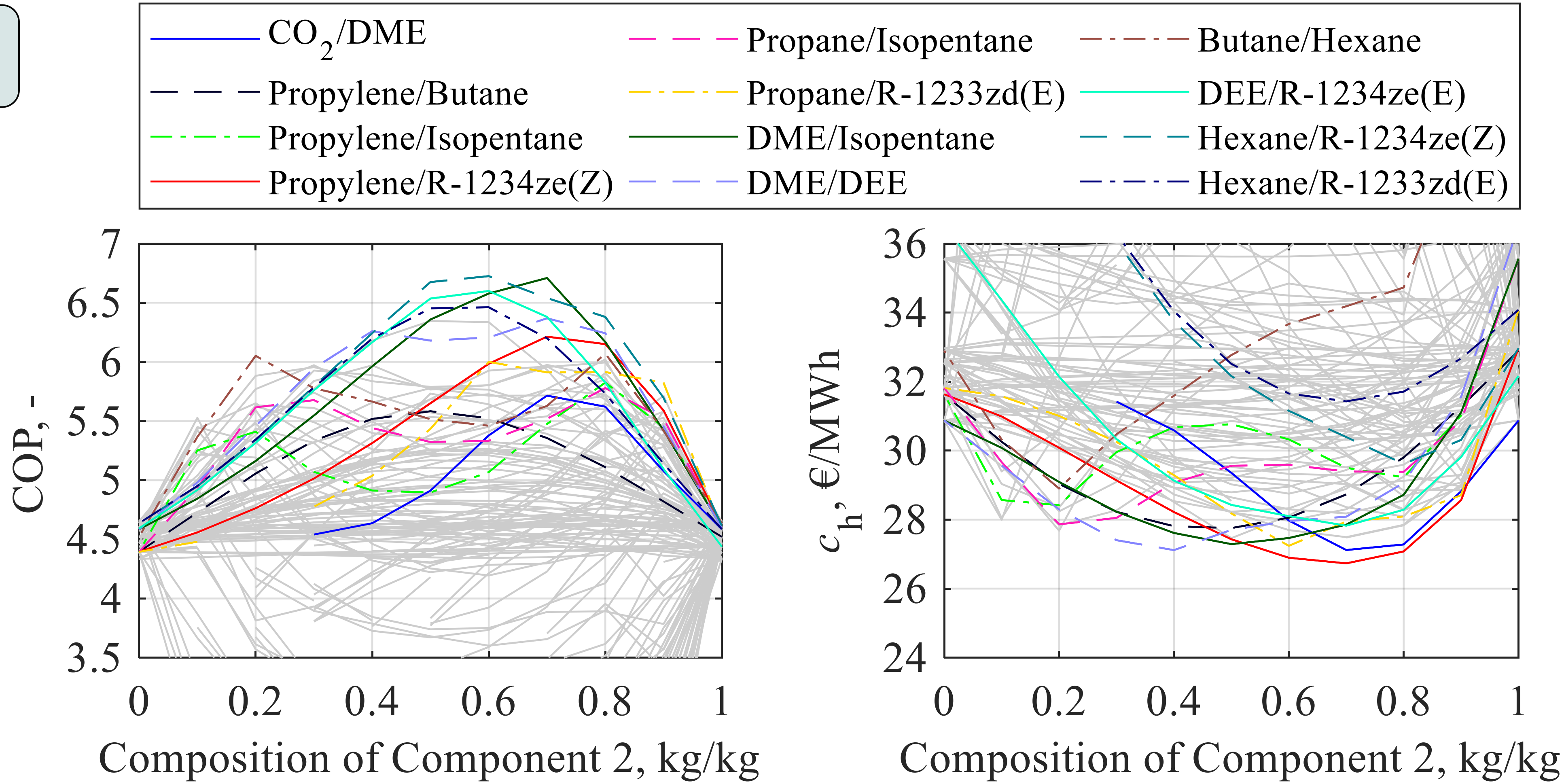
Further Analysis and Optimization

Screening procedure
Case study: Data Center to District heating

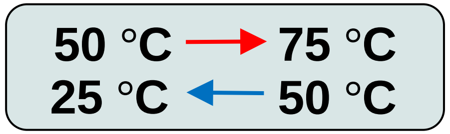


COP: + 35 %

c_h: - 11 %

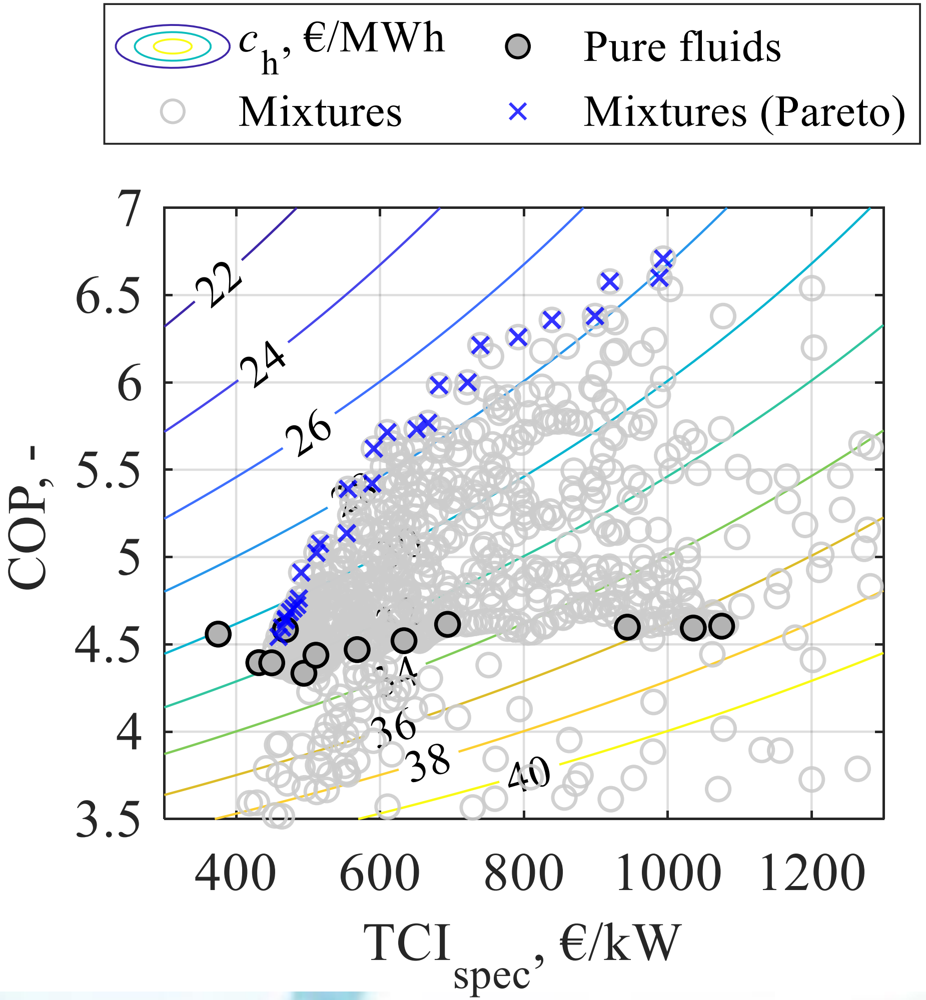


Screening procedure
Case study: Data Center to District heating



50 °C → 75 °C
25 °C ← 50 °C

- Pure fluids:
  - COP around 4.5
  - Lower c_h mainly due to lower TCI_{spec}
- Mixtures:
  - Higher TCI_{spec} allows for higher COP
  - Increase in COP compensates higher TCI_{spec}



Screening procedure
Underlying assumptions for comparisons

50 °C → 75 °C
25 °C ← 50 °C

a) Fixed Pinch

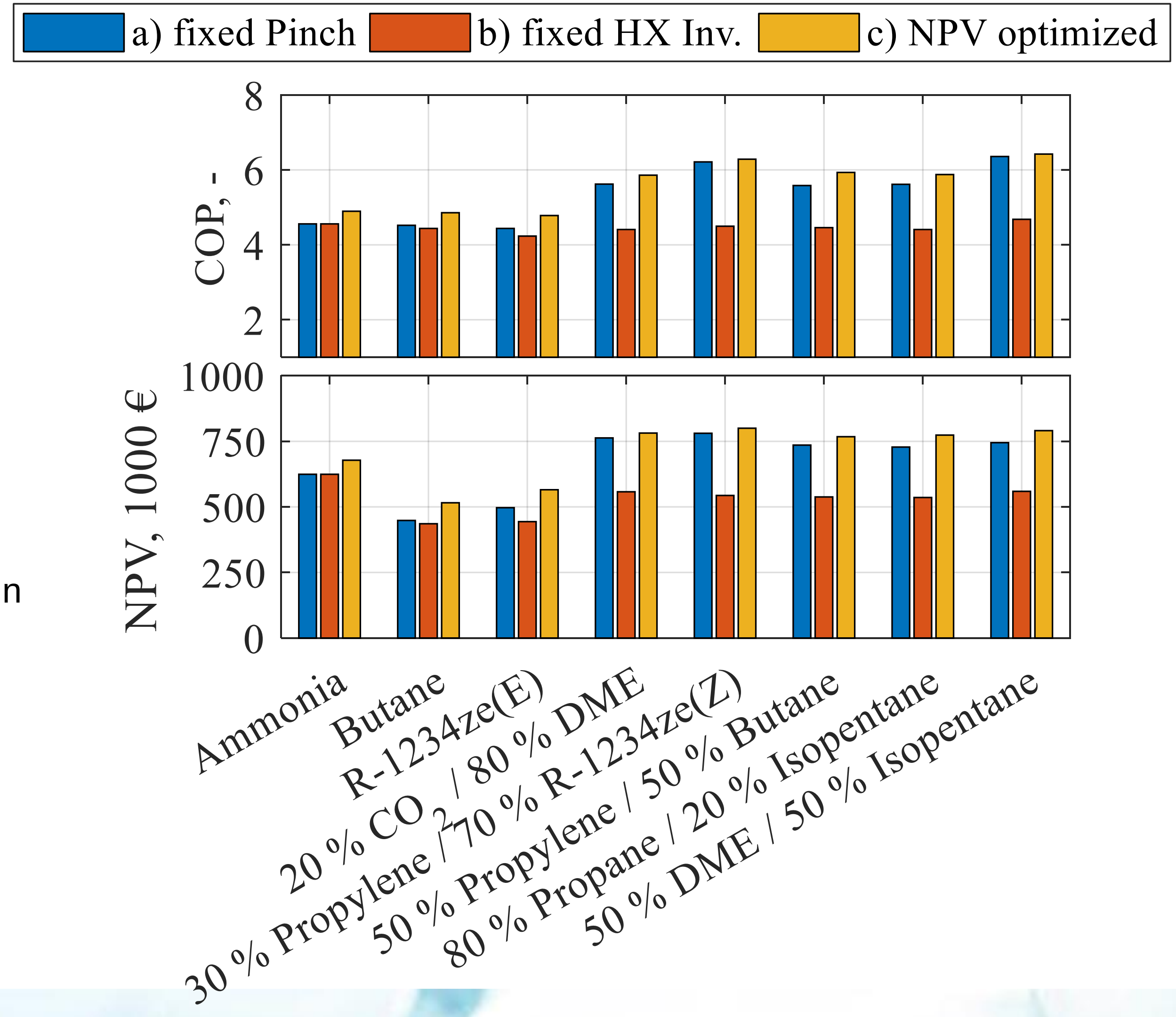
- Simple design approach for each fluid
- Requires design experience
- Yields economically fair results

b) Fixed HX Investment

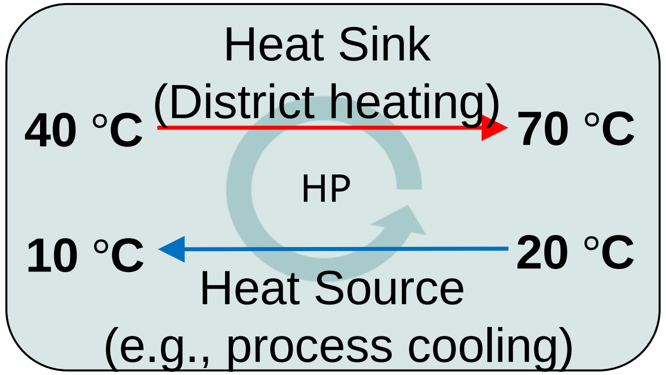
- Total investment in HX area fixed to result from ammonia in a)
- Distribution to source/sink of area optimized
- Results were biased by choice of area/investment

c) Optimized area w.r.t. NPV

- Investment in HX area optimized w.r.t. NPV
- Numerically more demanding

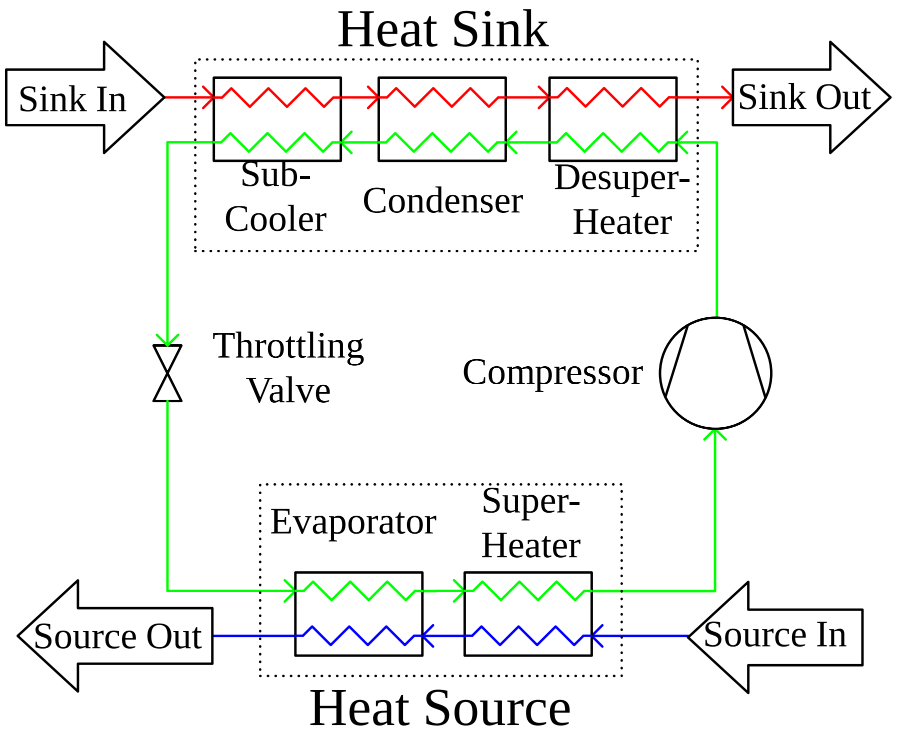


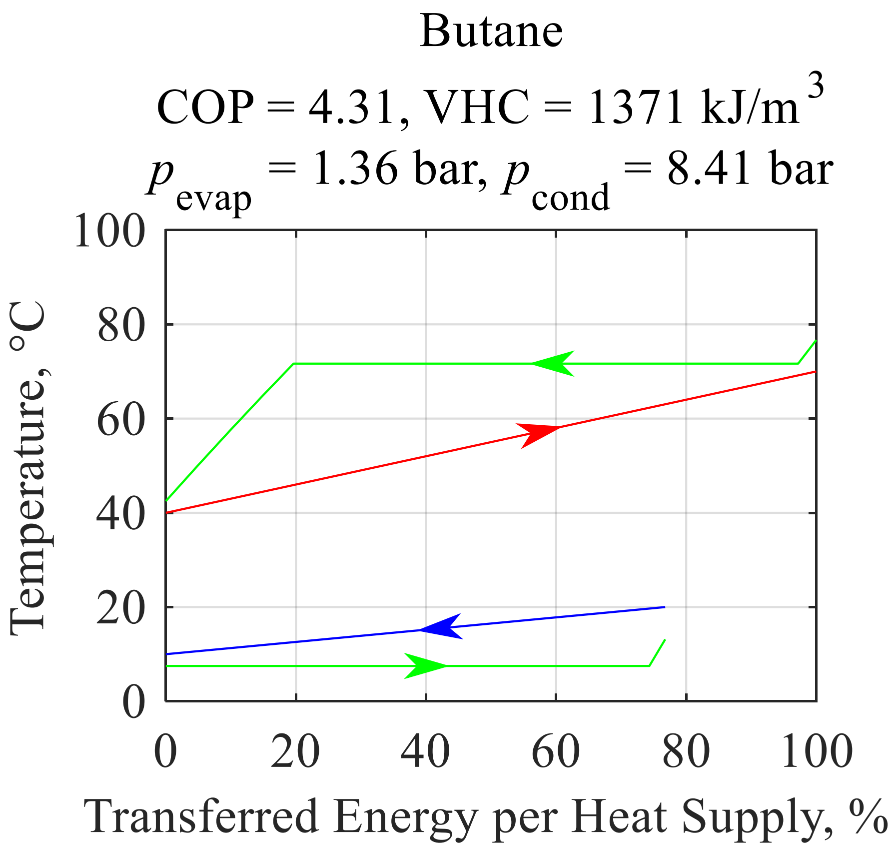
Optimization of cycle and working fluid
Standard cycle


Heat Sink
(District heating)
40 °C
70 °C
HP
10 °C
20 °C
Heat Source
(e.g., process cooling)

Optimization of cycle and working fluid
Standard cycle

40 °C → 70 °C
10 °C ← 20 °C



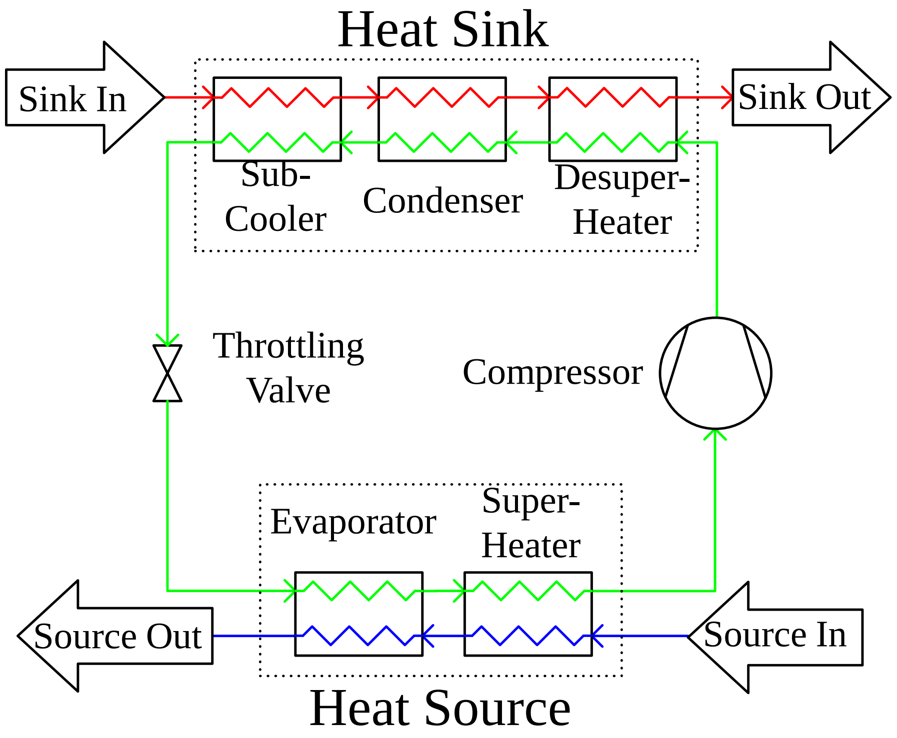

Butane

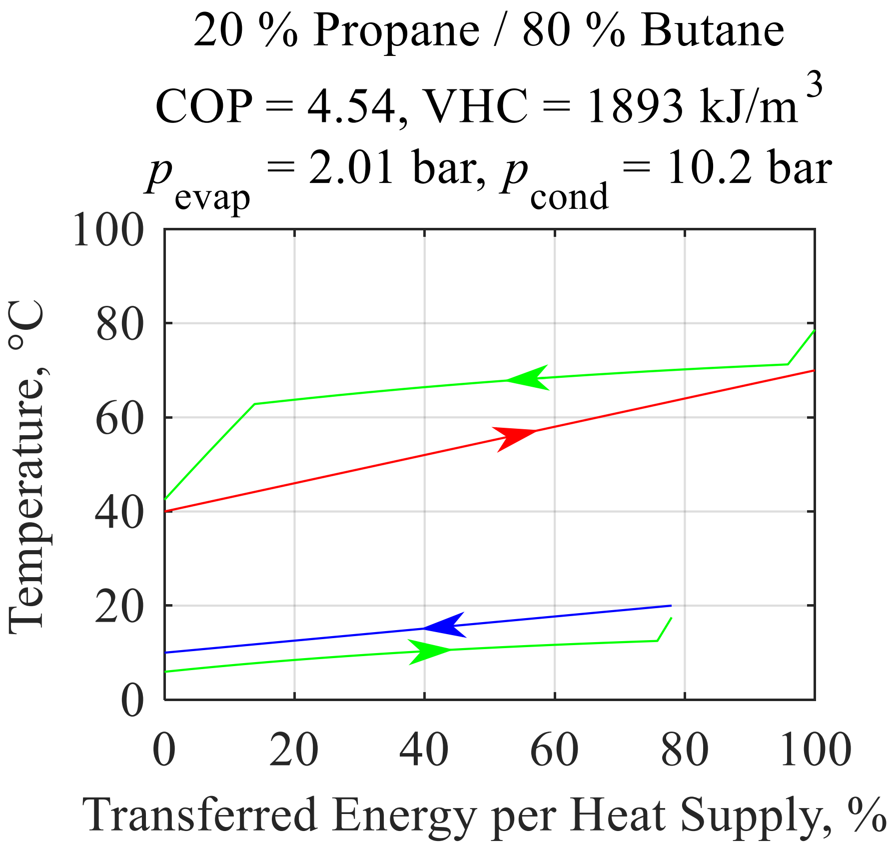
COP = 4.31, VHC = 1371 kJ/m^3

p_{evap} = 1.36 bar, p_{cond} = 8.41 bar

Optimization of cycle and working fluid
Standard cycle

40 °C → 70 °C
10 °C ← 20 °C



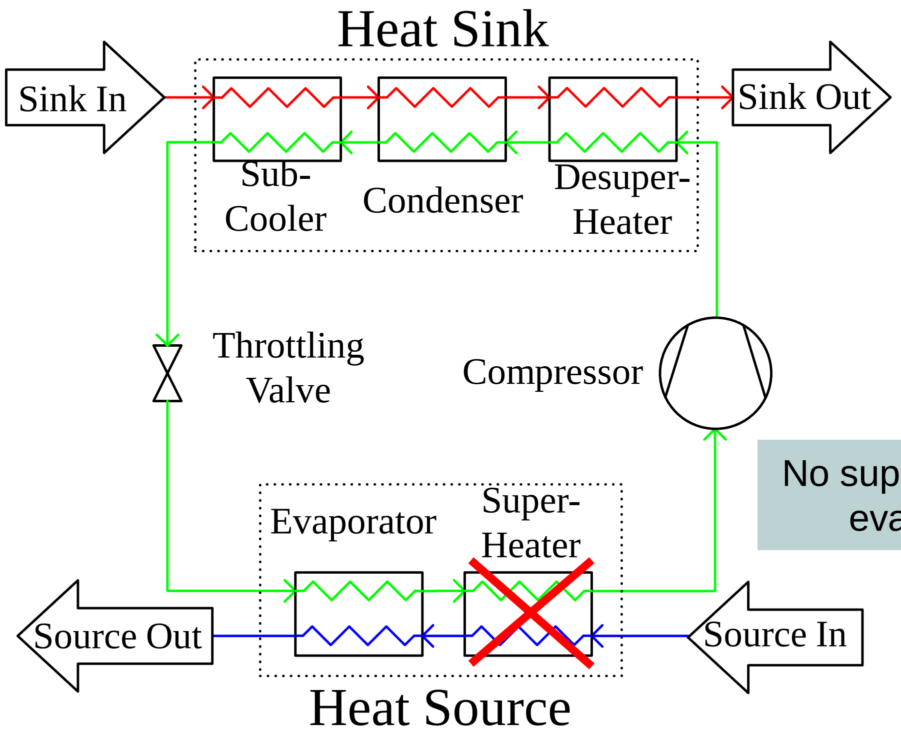

20 % Propane / 80 % Butane

COP = 4.54, VHC = 1893 kJ/m^3

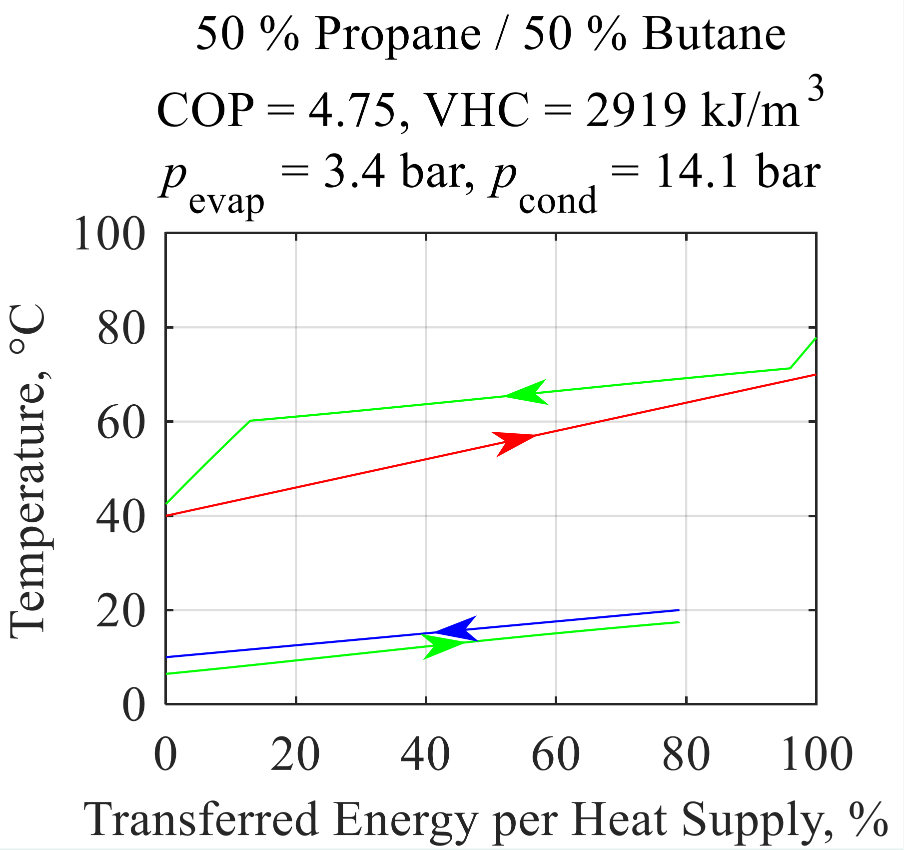
p_{evap} = 2.01 bar, p_{cond} = 10.2 bar

Optimization of cycle and working fluid
Standard cycle

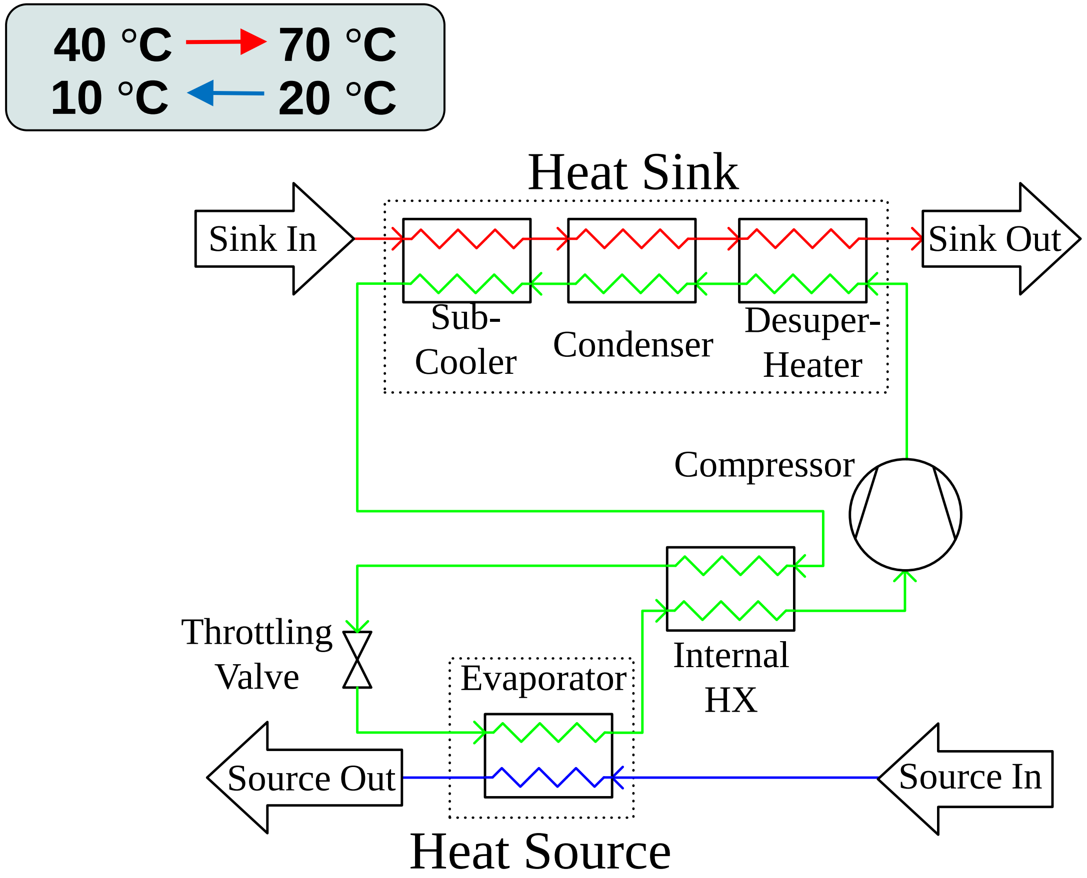
40 °C → 70 °C
10 °C ← 20 °C

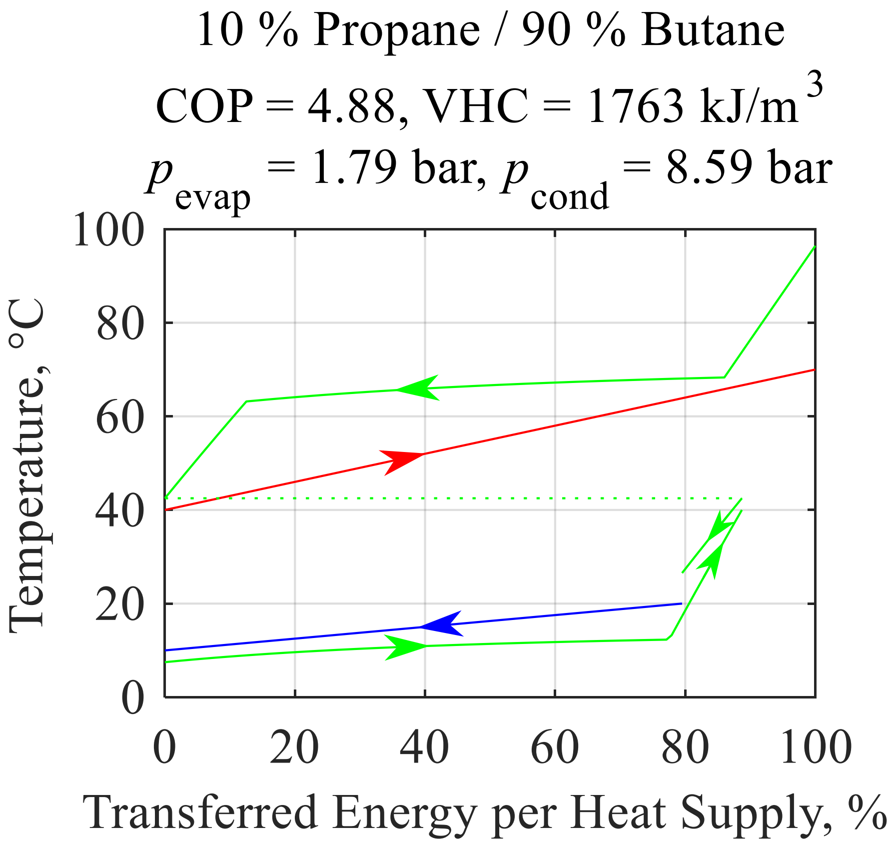


No superheating in evaporator



Optimization of cycle and working fluid
Internal Heat Exchanger cycle





Optimization of cycle and working fluid
Internal Heat Exchanger cycle

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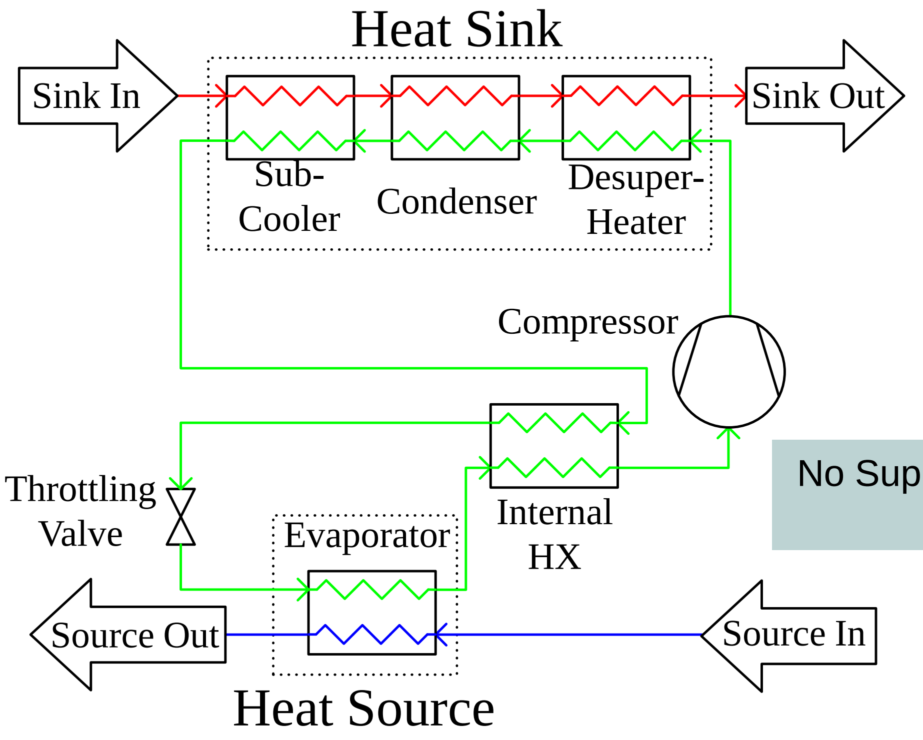
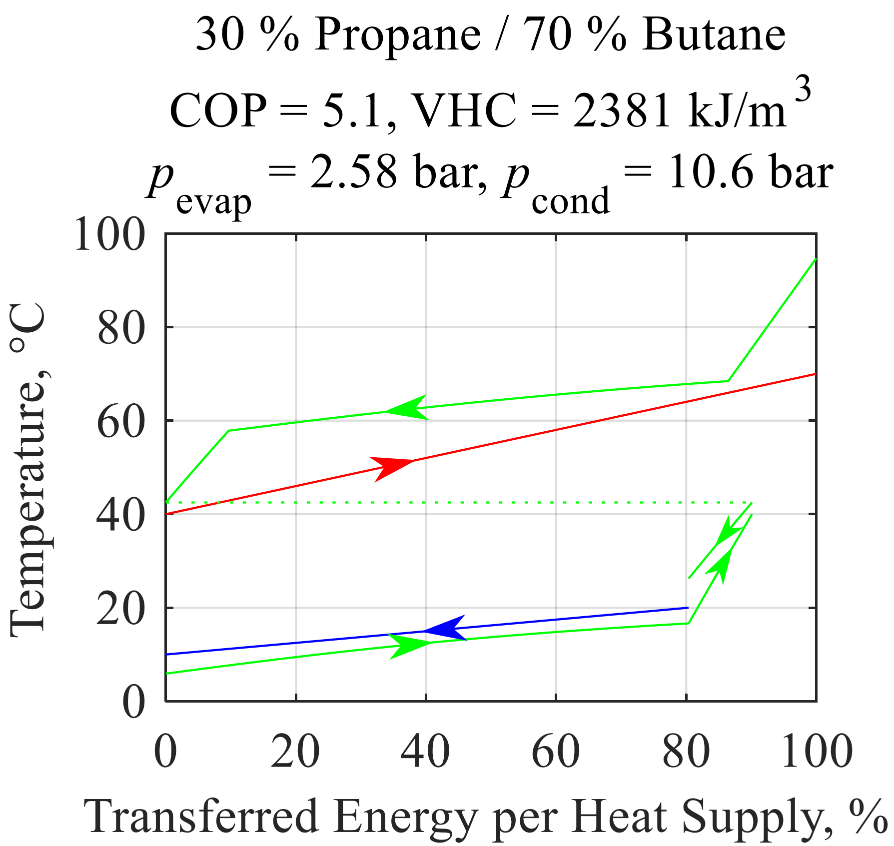
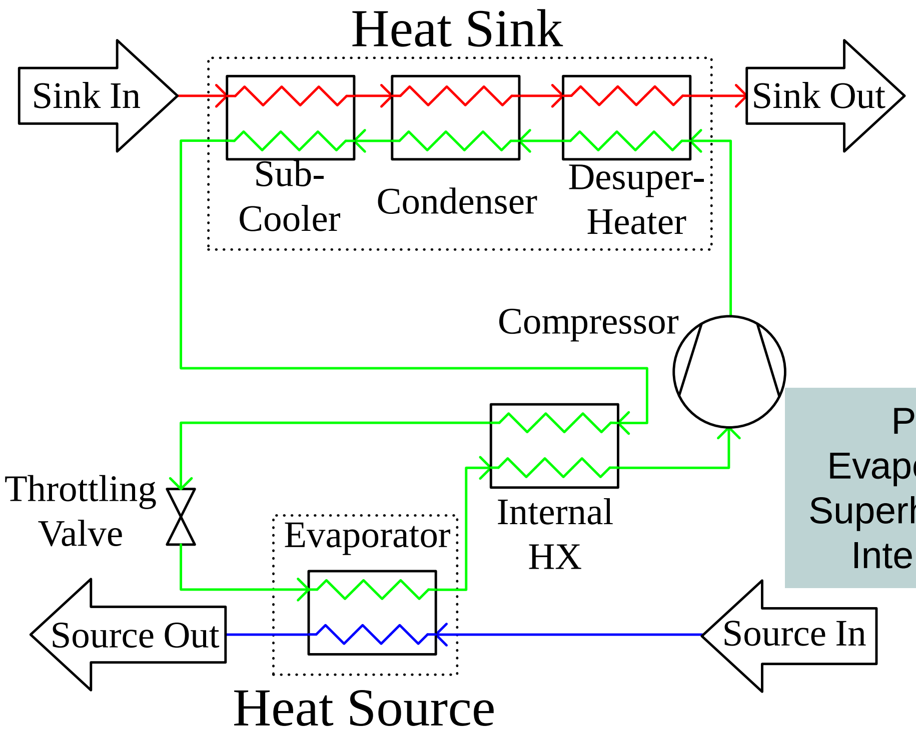


No Superheating in IHX

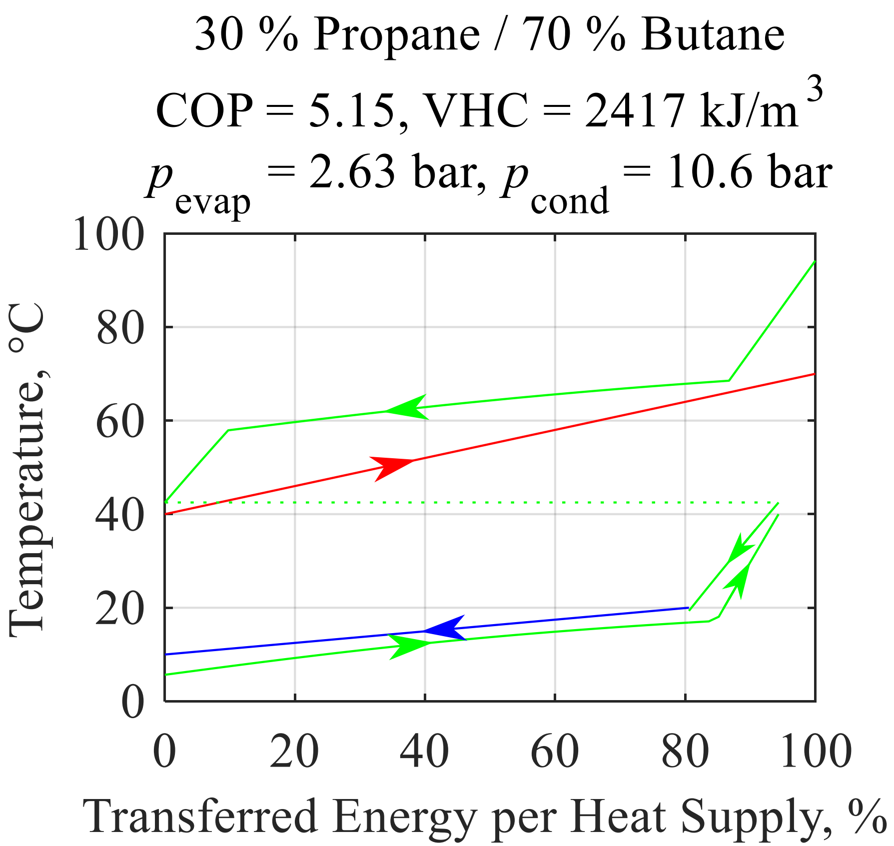


Optimization of cycle and working fluid
Internal Heat Exchanger cycle

40 °C → 70 °C
10 °C ← 20 °C

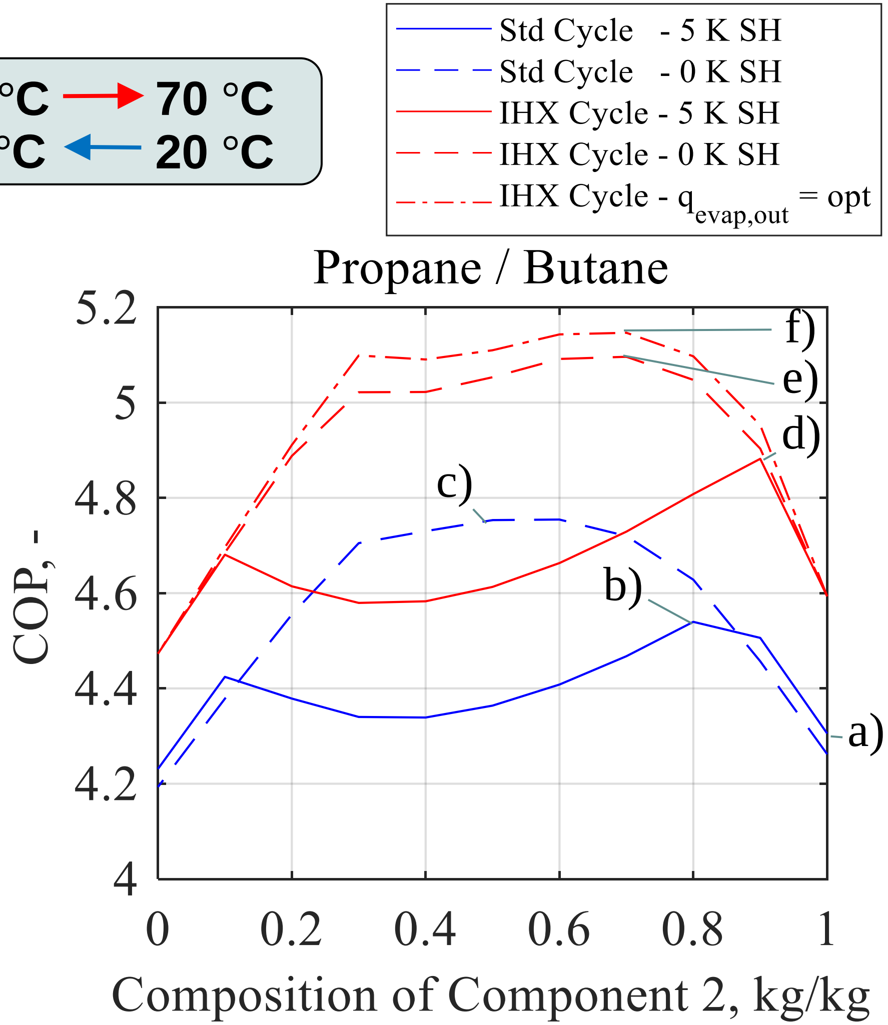


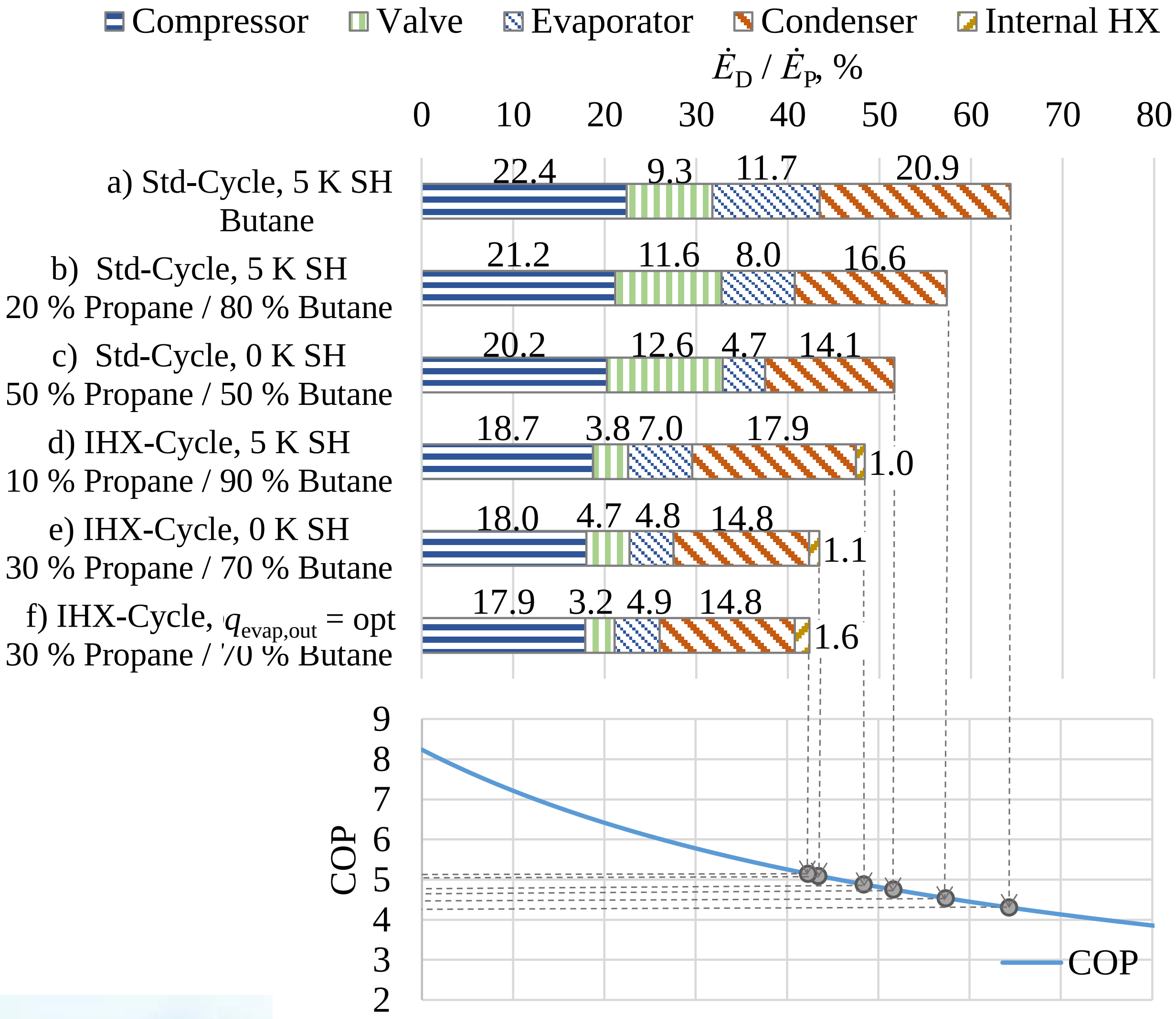
Partial Evaporation & Superheating in Internal HX



Optimization of cycle and working fluid
Overview results

40 °C → 70 °C
10 °C ← 20 °C





Zeotropic working fluids in heat pumps
Summary and outlook

- Heat pump applications often show temperature glides (contrary to refrigeration systems)

- Conclusions:
  - Large potential for zeotropic working fluid mixtures
    - COP increases >30 %
    - Higher COP can compensate additional investment
  - Temperature glide matching possible
    - Glide match on source side has dominating impact
    - Further influence from e.g., compression & expansion
  - Screening required for identifying promising fluids
  - Cycle layout
    - Considerable increases possible using standard cycle
    - Further improvements obtainable by cycle optimization (e.g., IHX, reduction of superheating, …)

- Challenges
  - Design procedure following the screening procedure
  - Experimental validation of these procedures

Thank you for your attention!

DANISH TECHNOLOGICAL INSTITUTE

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Flow visualization of downward condensing ammonia inside a gasketed plate heat exchanger

Webinar, October 9, 2020
Maaike Leichsenring

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Content

Introduction

OTEC – by means of Ammonia

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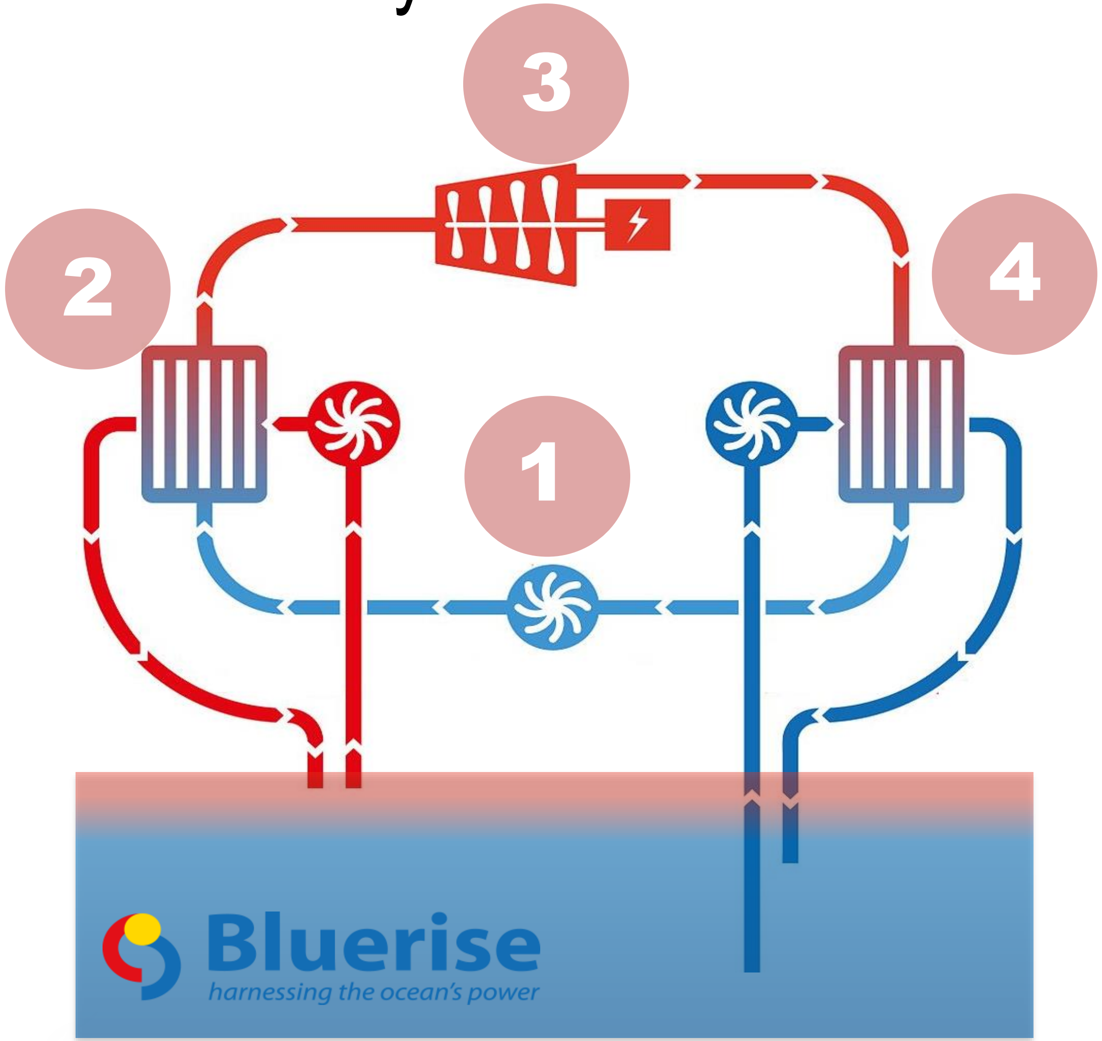
OTEC – by means of Ammonia



OTEC

***O**cean **T**hermal **E**nergy **C**onversion*
- Renewable
- Natural Refrigerant

NH_3

Ammonia
- Zero **GWP** & **ODP**
- High availability

PHE

***P**late **H**eat **E**xchanger*
- Condensing ammonia

Introduction

Plate heat exchangers (PHEs)

Benefits

- Favourable heat transfer coefficients
- Compactness
- Design flexibility
- Thermal effectiveness

Challenge

- Two-phase behaviour not yet fully understood
- Over- and underestimating heat transfer and pressure drop correlations

Faulty design

Expected

Flow patterns influence the performance

Better predictions of **flow patterns** enhance the accuracy of performance calculations

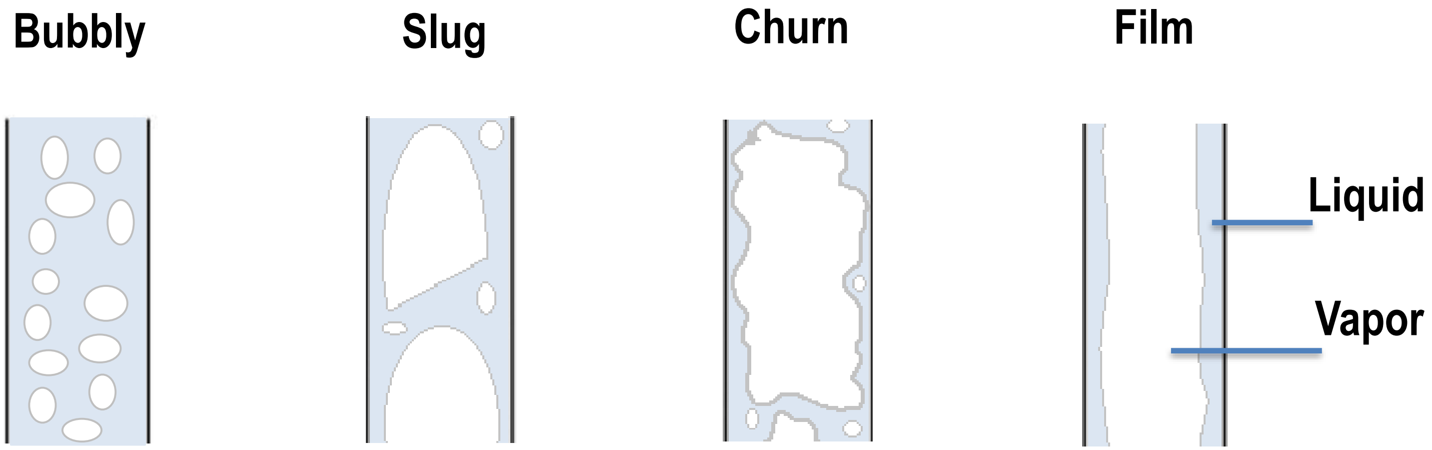
Introduction

Flow patterns

Geometric configuration of vapor and liquid

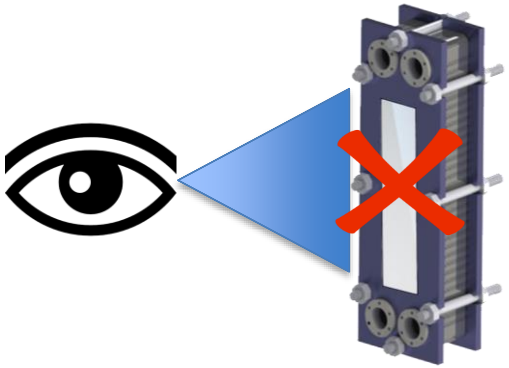
4 main flow patterns

Occurring flow pattern in the PHE generally **unknown**



Introduction

Research question



Scientific knowledge gap
No information is available on flow patterns of **condensing ammonia** in corrugated PHE's

Faulty design

Main research question
'Which flow patterns are dominant inside the PHE condenser and how do they relate to its performance?'

NH_3

Approach
Performing flow visualization experiments and data analysis

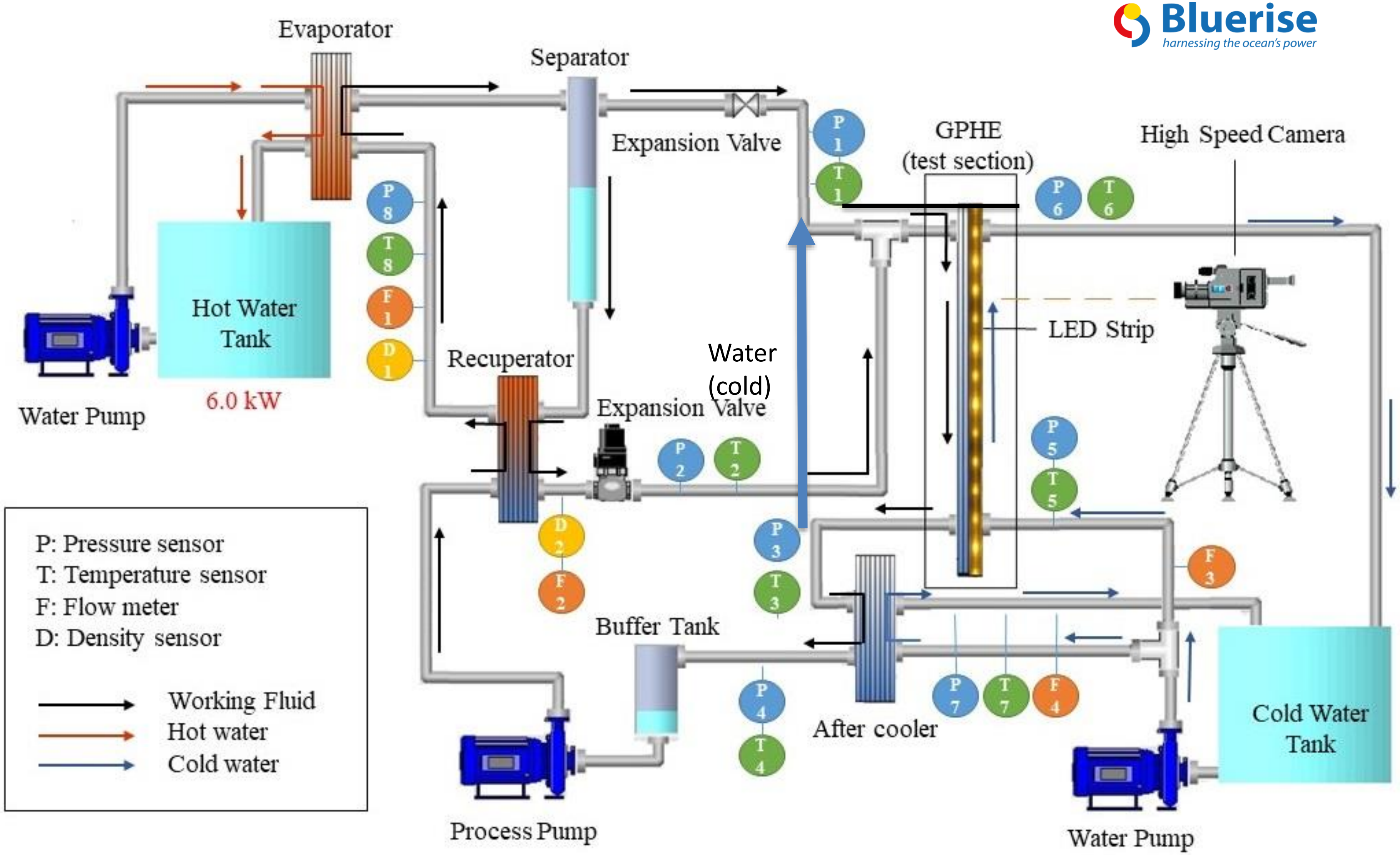
Safety Glasses

Experimental setup

Test section

Experimental setup

Test section



Experimental setup

Test section

Visualization section

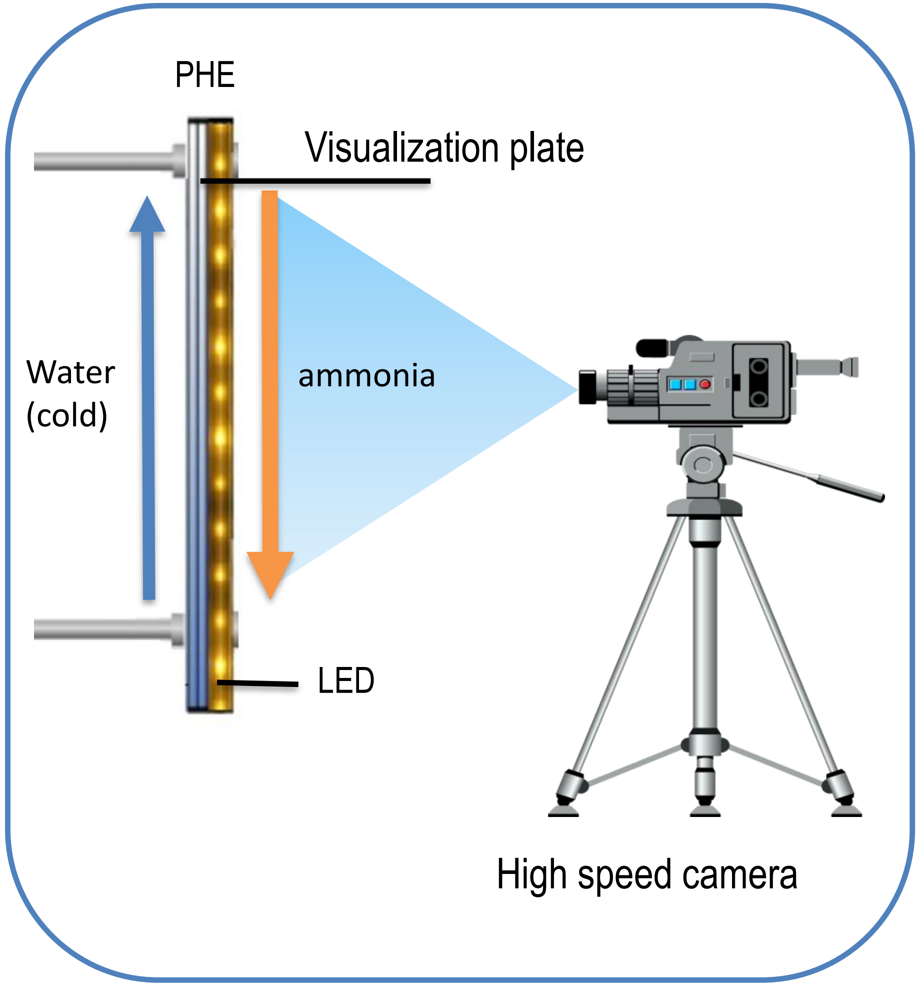
- Plate heat exchanger
- LED illumination
- 3000 fps camera
- **Visualization plate**

100W small scale setup

- Organic Rankine Cycle
- Pure ammonia
- OTEC purposes

Similar components to
Refrigeration cycle

Bluerise
harnessing the ocean's power



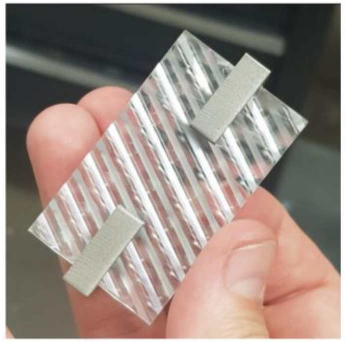
Experimental setup

Material selection

- Chemical resistance charts
- Actual chemical resistance

Contradicting ✗

Chemical resistance tests
  - Transparent materials
  - Liquid ammonia
  - Four days



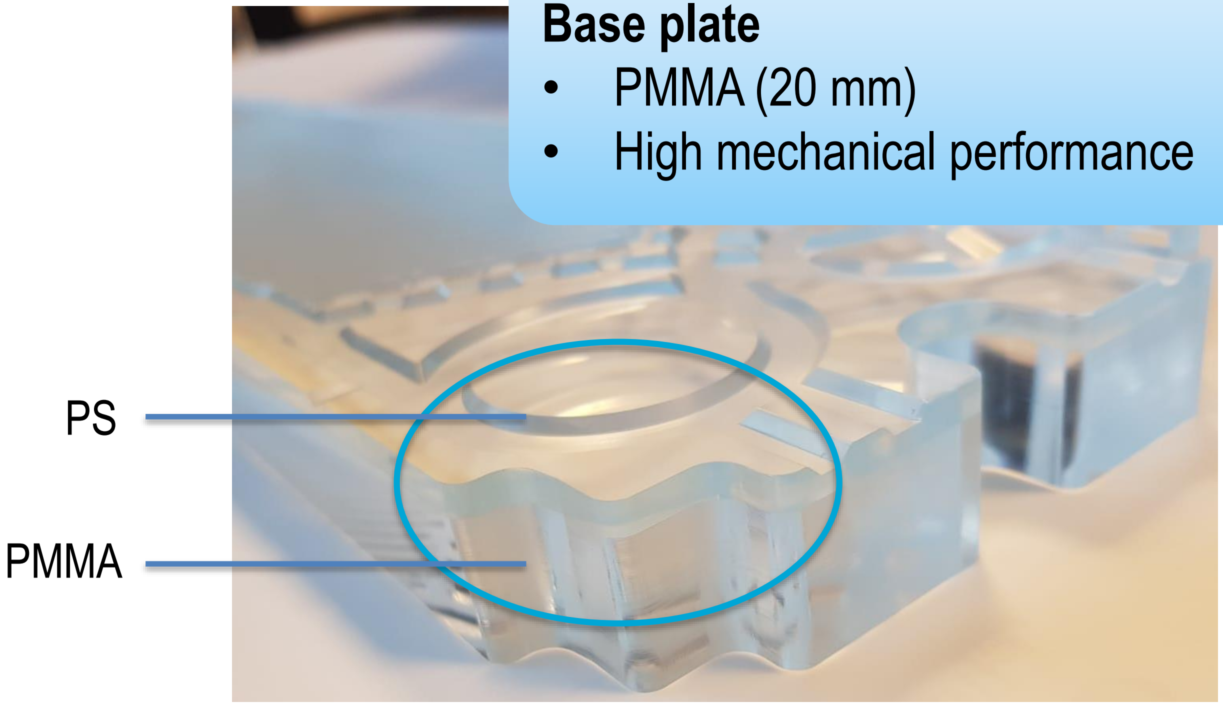
Requirements visualization plate	Glass	PS	/	PMMA
Chemically resistant to ammonia	☑	☑	☑	✗
High mechanical performance	✗	✗	☑	☑
Transparent	☑	☑	☑	☑
Easy to machine	✗	☑	☑	☑

Experimental setup

Final setup

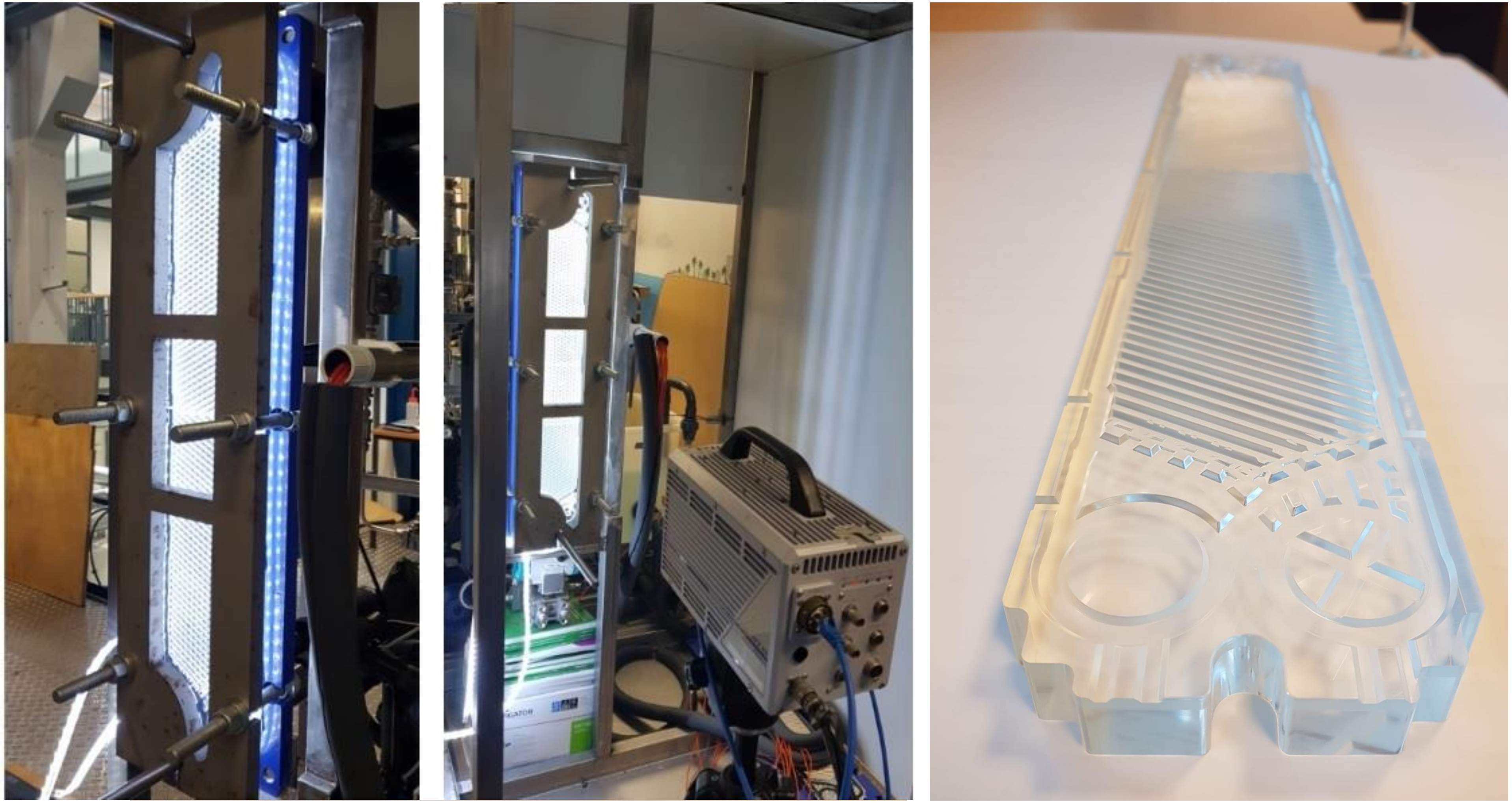
Top layer
- Corrugated PS layer (4.75 mm)
- Chemically resistant

Base plate
- PMMA (20 mm)
- High mechanical performance



Experimental setup

Final setup



Visualization experiments

Test conditions

refrigerants delivered by mother nature

Visualization experiments

Test conditions

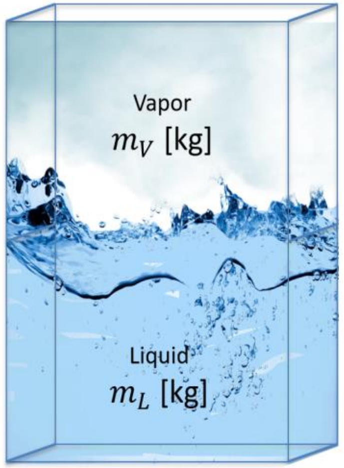
Varying parameters G, x

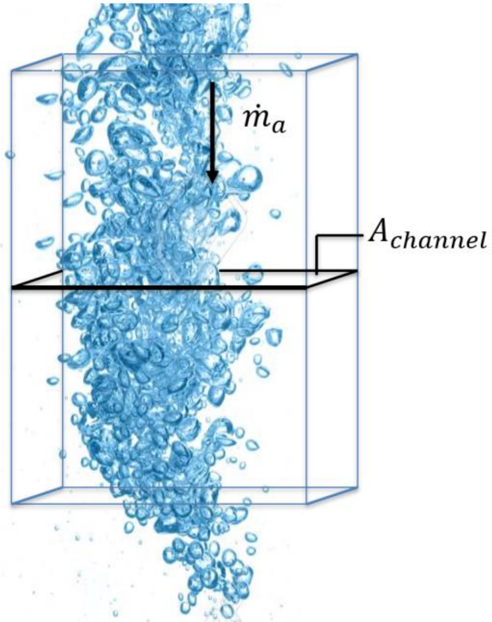
Vapor quality

$$x = \frac{m_V}{m_V + m_L} \quad [-]$$

Mass flux

$$G = \frac{\dot{m}_a}{A_{channel}} \quad [\mathrm{kgm^{-2}s^{-1}}]$$

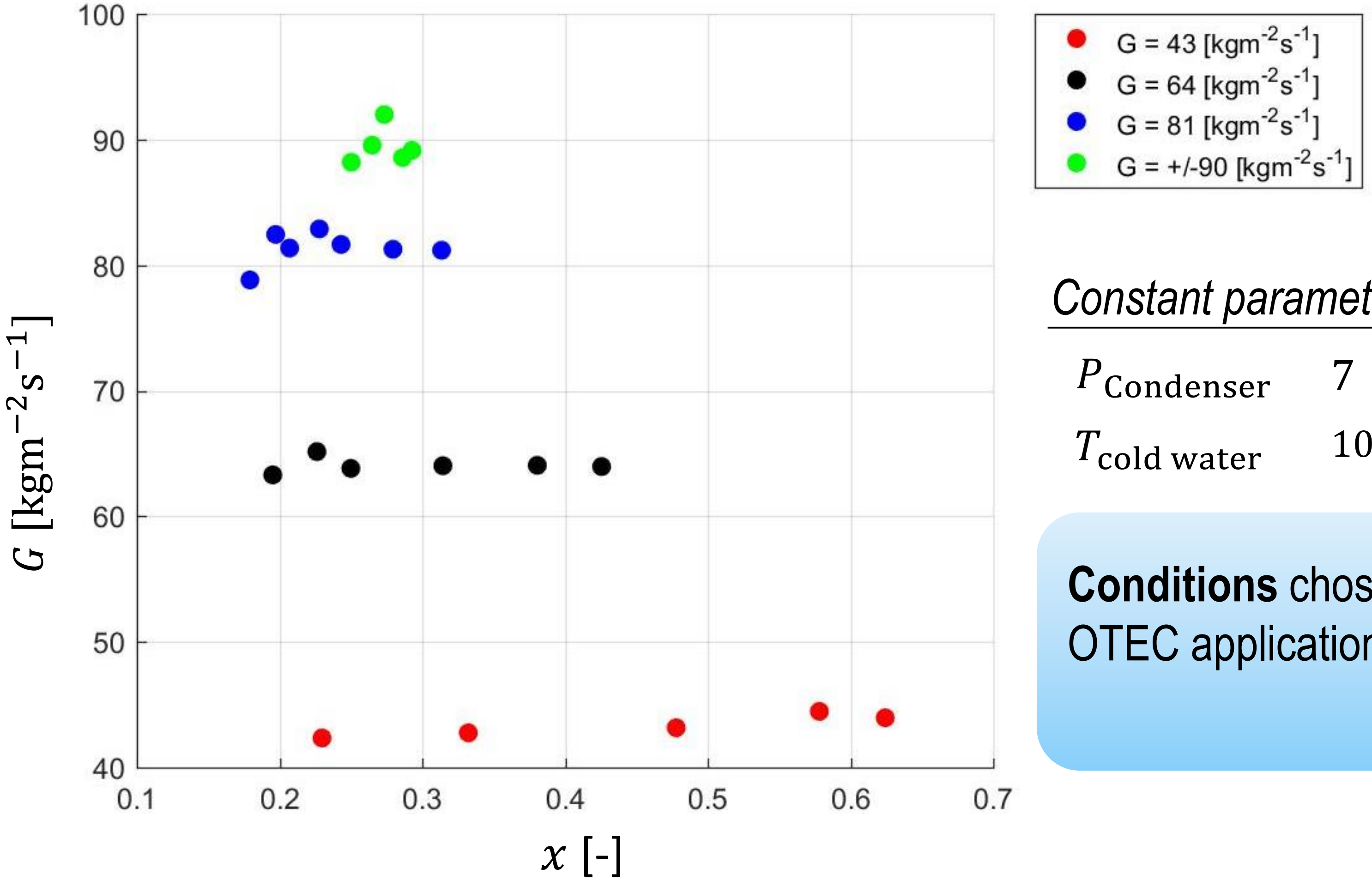




Visualization experiments

Test conditions

Varying parameters G, x



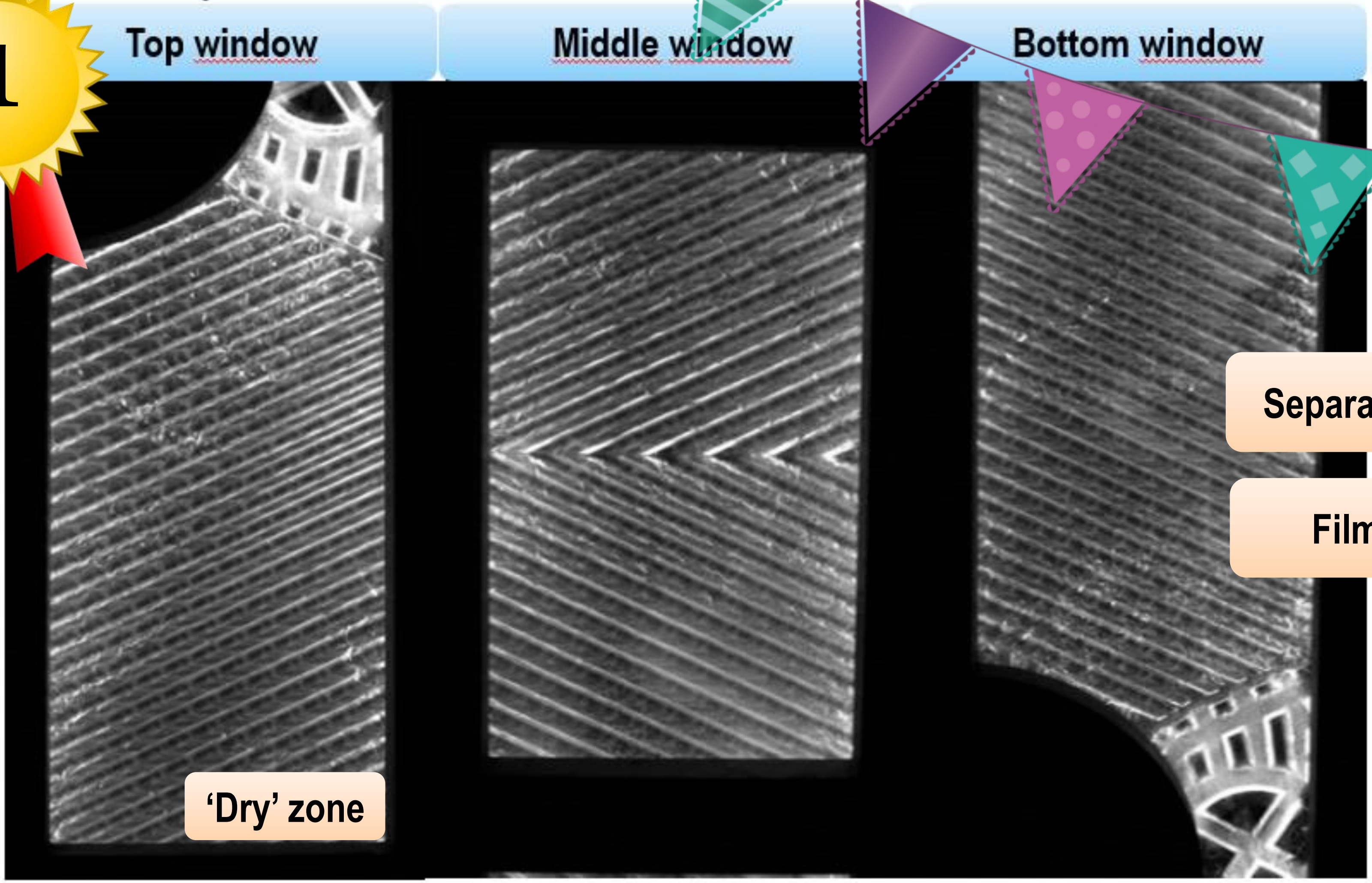
Constant parameters

$P_{\text{Condenser}}$	7	[bar]
$T_{\text{cold water}}$	10	[°C]

Conditions chosen for OTEC applications

Visualization experiments

Flow path & flow pattern



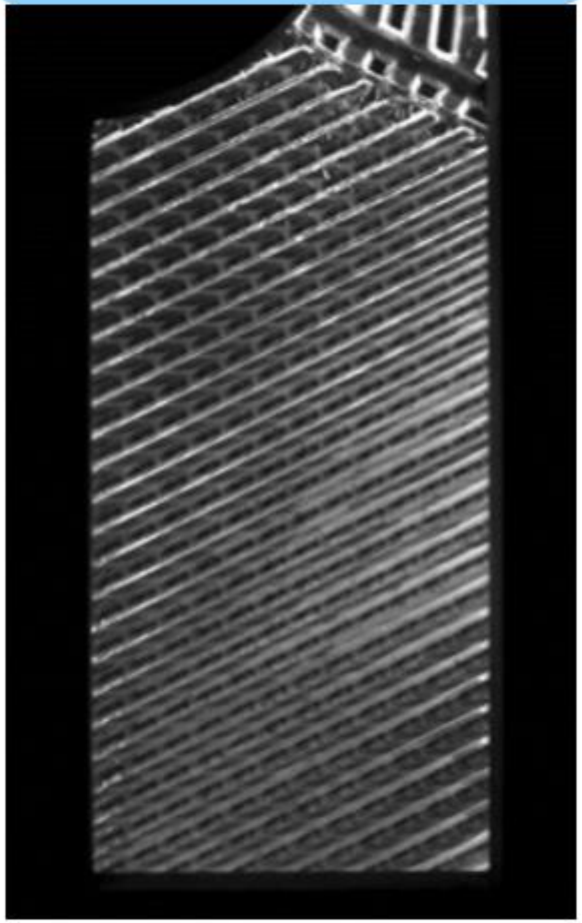
Separated flow

Film flow

Visualization experiments

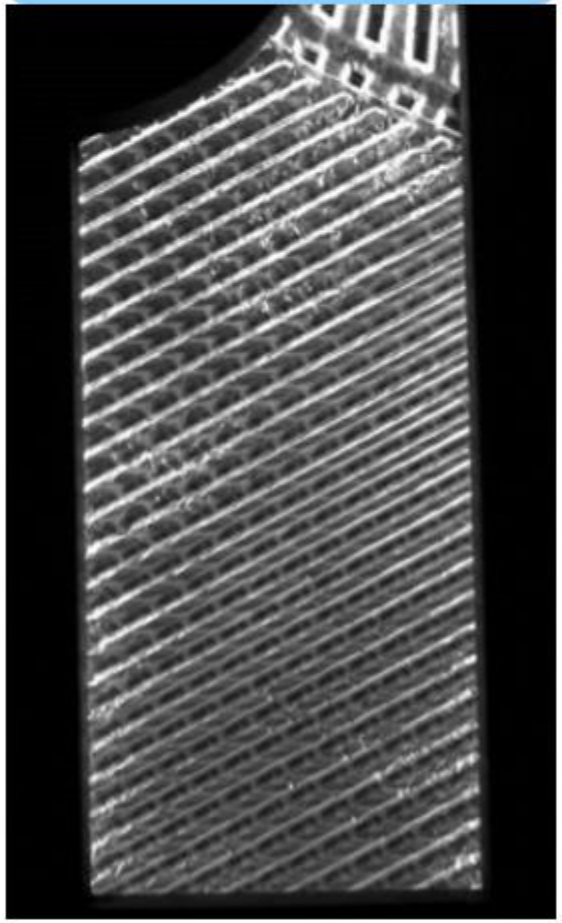
Flow path & flow pattern

Partial film flow



$43 \leq G \leq 64$ $[\mathrm{kgm^{-2}s^{-1}}]$

Film flow



$64 > G \geq 91$ $[\mathrm{kgm^{-2}s^{-1}}]$

Separated flow

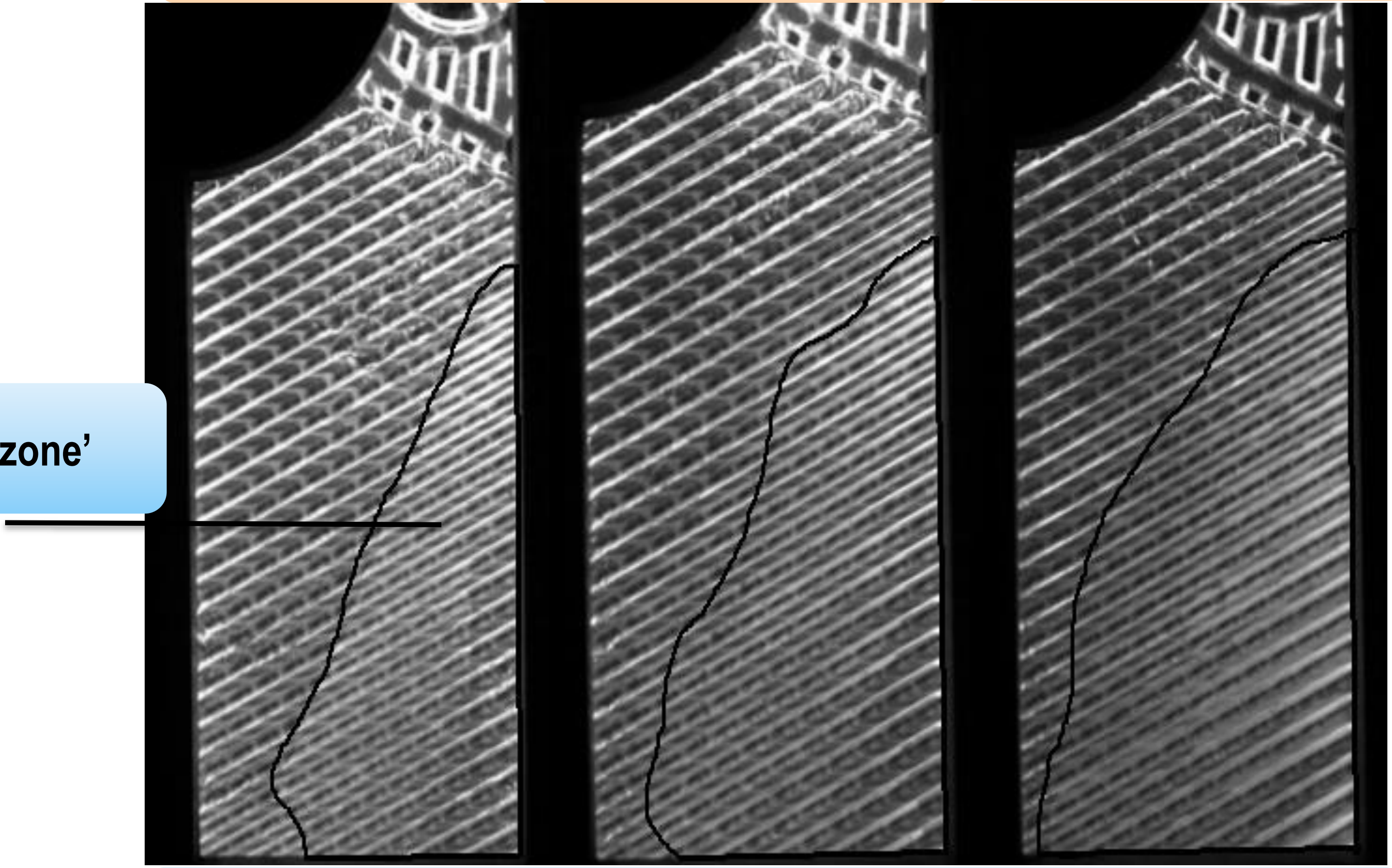
Film flow

Visualization experiments

Influence of G

$G = 43 [\mathrm{kg m^{-2} s^{-1}}]$

$x = 0.22$ $x = 0.48$ $x = 0.62$



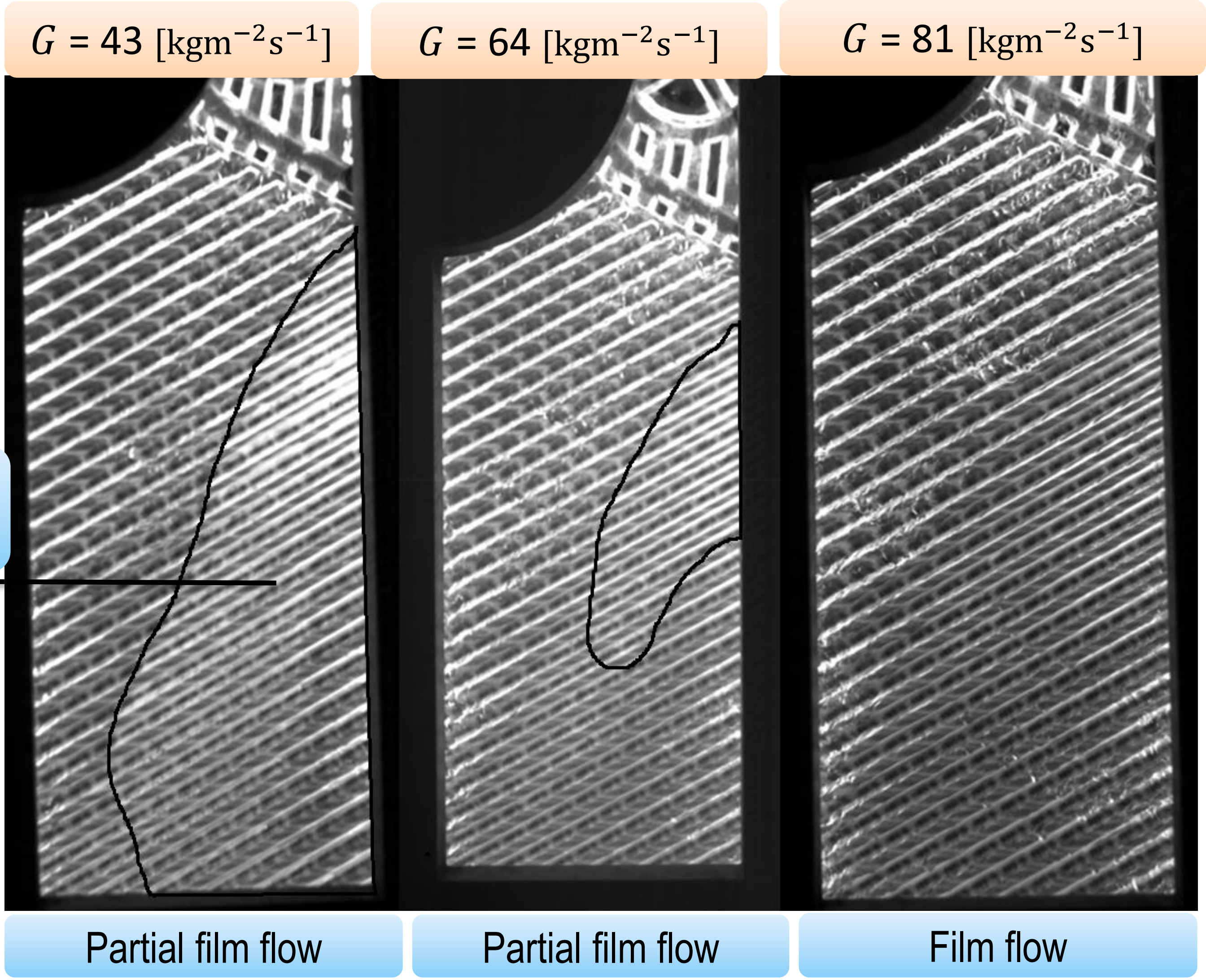
'Dry zone'

Partial film flow

Visualization experiments

Influence of x

$x = 0.3$ [–]



Data analysis

Dry zone fraction

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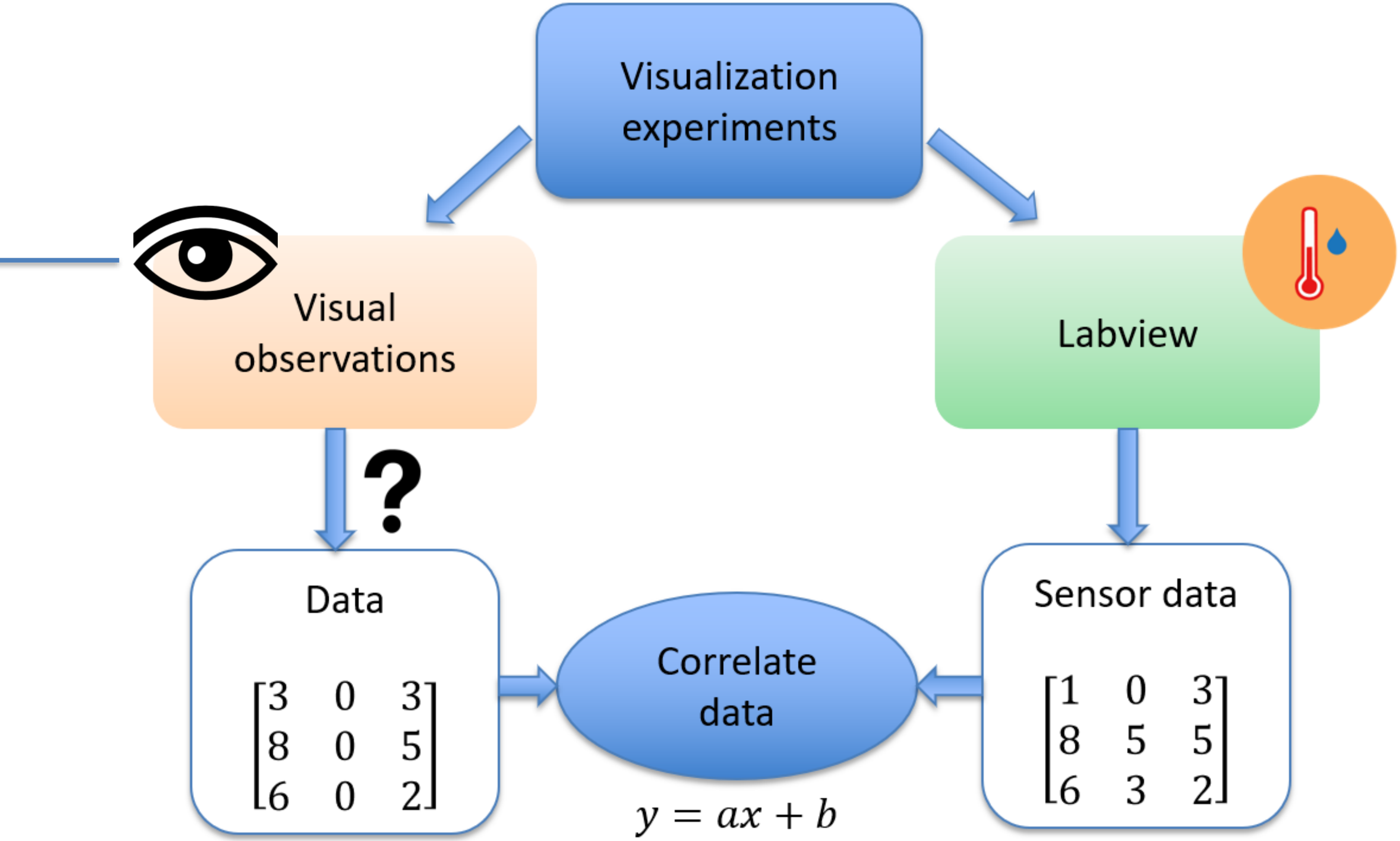
Data analysis

Dry zone fraction



Visualization experiments

Visual observations

Labview

?

Data

$$\begin{bmatrix} 3 & 0 & 3 \\ 8 & 0 & 5 \\ 6 & 0 & 2 \end{bmatrix}$$

Correlate data

$$y = ax + b$$

Sensor data

$$\begin{bmatrix} 1 & 0 & 3 \\ 8 & 5 & 5 \\ 6 & 3 & 2 \end{bmatrix}$$

Data analysis

Dry zone fraction

$\epsilon_A = \ ...\% \ ?$

Dry-zone fraction

$$\epsilon_A = \frac{A_{dry}}{\mathrm{A_{plate}}} \ \%$$

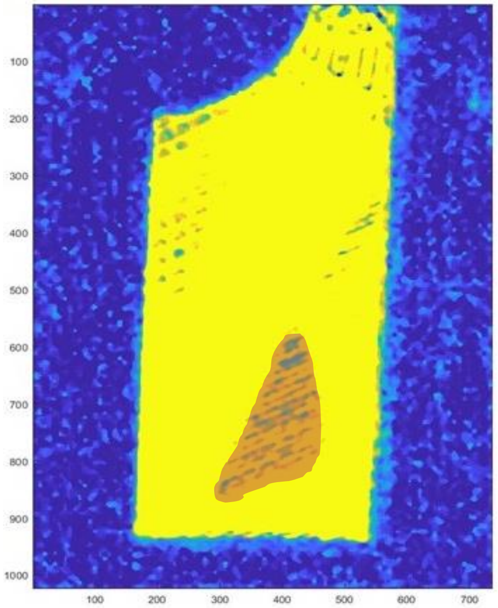
Matlab image processing

Assumptions

- **Dynamic** Fluid $= f(t)$
- **Static** dry area $\neq f(t)$

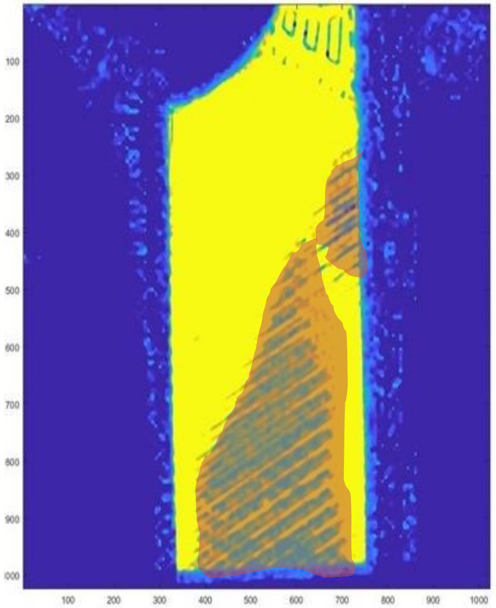
G = 64 $[\mathrm{kgm^{-2}s^{-1}}]$

x = 0.2 [-]



G = 43 $[\mathrm{kgm^{-2}s^{-1}}]$

x = 0.3 [-]



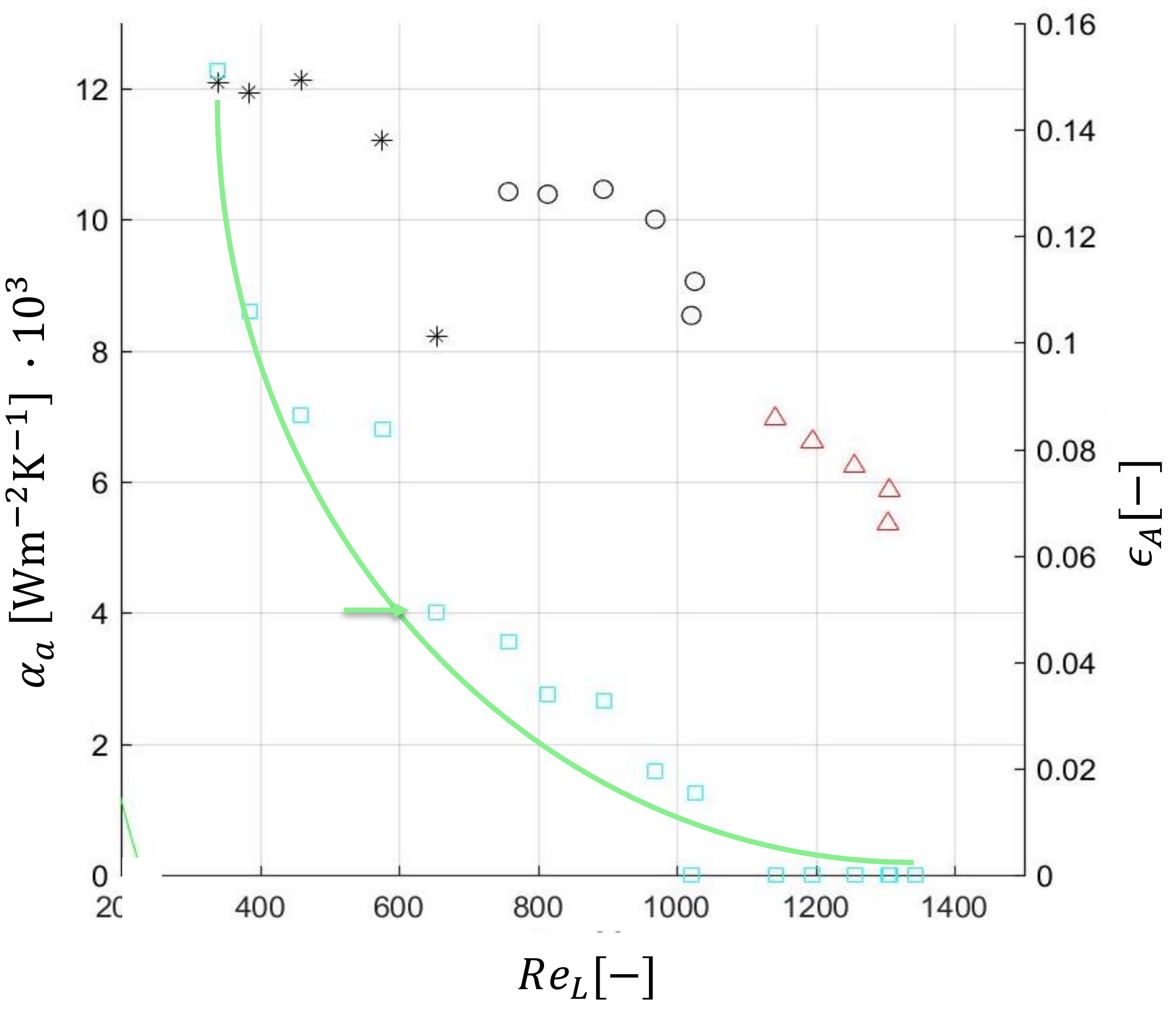
Conclusion

ϵ_A increases with x

ϵ_A decreases with G

Data analysis

Heat transfer vs. flow pattern



— ϵ_A trendline

☐ ϵ_A Matlab data points

○ ✱ HTCs partial film flow

△ HTCs film flow

Conclusion

Partial film flow and film flow show **different** heat transfer characteristics

Partial film flow is **preferred** flow pattern w.r.t. heat transfer

Data analysis

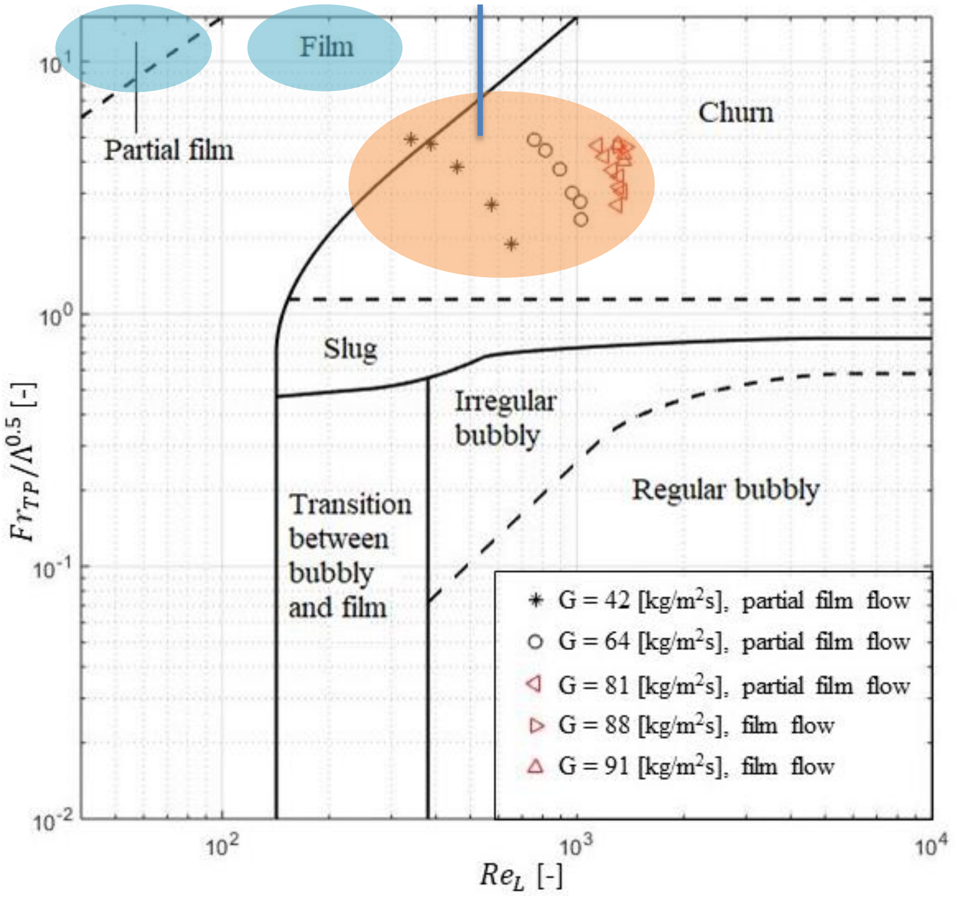
Flow pattern maps (FPMs)

FPMs:
- Prediction tools
- Describe which flow pattern is expected

General FPM by Tao et al. (2018):
- vertical downward PHEs
- Mainly air-water
- Expected applicable **for ammonia**

Experimental results do not agree with FPM

Experimental results



Data analysis

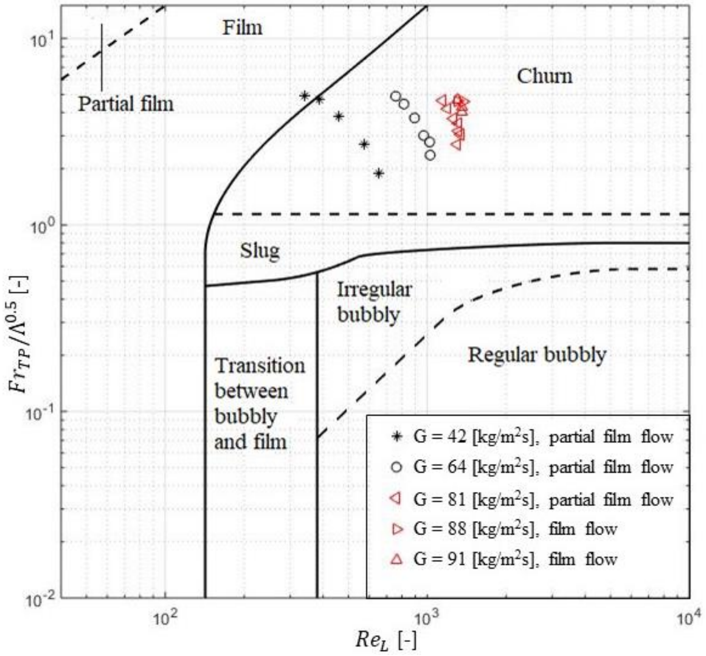
Flow pattern maps (FPMs)

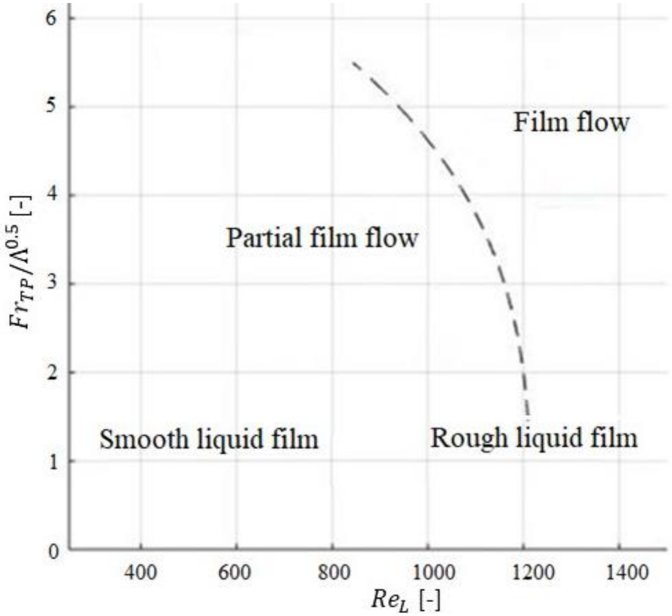
FPMs:
- Prediction tools
- Describe which flow pattern is expected

General FPM by Tao et al. (2018):
- vertical downward PHEs
- Mainly air-water
- Expected applicable **for ammonia**

Proposed new FPM
- Downward condensing ammonia
- PHEs, current geometry

Can be used to **optimize accuracy** of FPM by Tao et al. (2018)





Conclusions & recommendations

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Conclusions & recommendations

Main research question
'Which flow patterns are dominant inside the PHE condenser and how do they relate to its performance?'

Improved design

Conclusions

Flow patterns
- Partial film flow
- Film flow

Partial film flow
- $G \leq 64\ [\mathrm{kgm^{-2}s^{-1}}]$
- ϵ_A increases with x

Film flow
- $G \geq 81\ [\mathrm{kgm^{-2}s^{-1}}]$

Flow pattern maps (FPMs)
- Results contradict FPMs
- New FPM is proposed

Performance calculations
- Flow patterns show different Heat transfer characteristics
- Use results to improve performance calculations

Recommendations

Perform more flow visualization experiments with ammonia

In order to:

- Improve performance calculations
- Prevent faulty heat exchanger design
- Reduce unnecessary costs

In **Natural Refrigeration** applications.

Questions?

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Techno-economic assessment of CO_2 refrigeration systems with geothermal integration

Fabio Giunta - KTH – Royal Institute of Technology, Sweden

Webinar, October 9, 2020

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Agenda

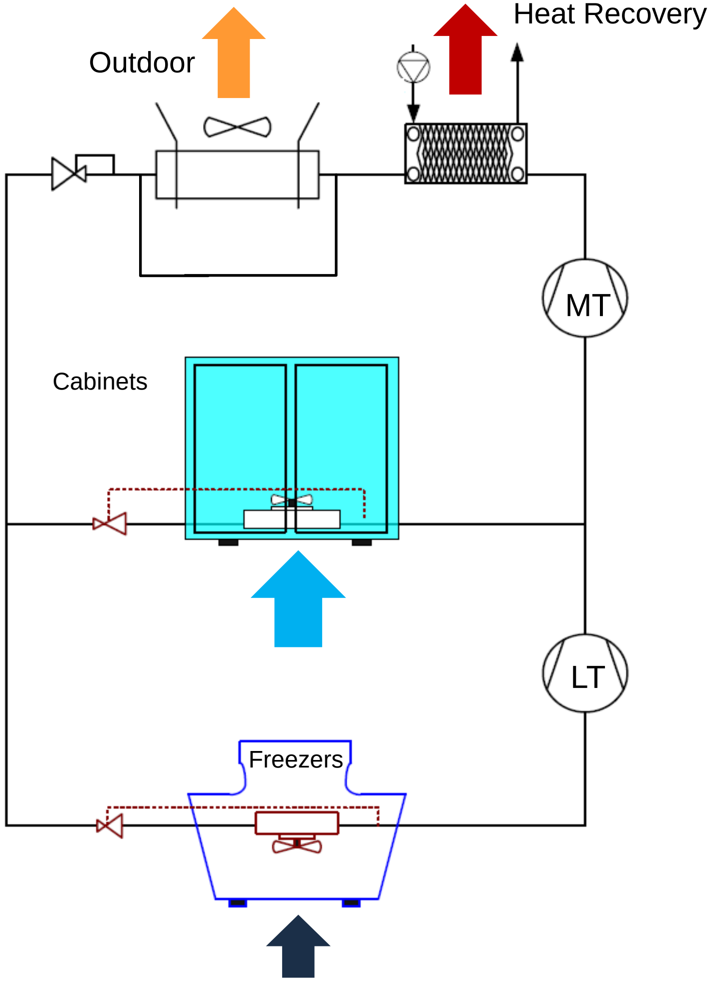
- Objectives
- Introduction
- Field measurements analysis
- Techno-economic analysis of the geothermal integration
- Conclusion & future work

Objectives

In relation to supermarkets’ CO_2 refrigeration systems integrated with geothermal storage

- Assess the **heat recovery control strategy**
- Evaluate the **efficiency of the heat recovery** system
- Assess the **economic savings** related to the geothermal storage
- Identify the most important **parameters affecting the cost-effectiveness**
- Suggest relevant future work

Introduction - Supermarkets’ CO_2 Transcritical Booster System



The most common CO_2 refrigeration system installed in supermarkets is a transcritical booster system. In these systems the heat recovered can cover both tap water and space heating demand. The heat is recovered in the so-called “heat pump mode”. This consists of increasing the discharge pressure of the MT compressors to recover heat at higher temperatures. When the system performs a transcritical cycle the COP heat recovery is particularly high, thanks to the properties of the refrigerant.

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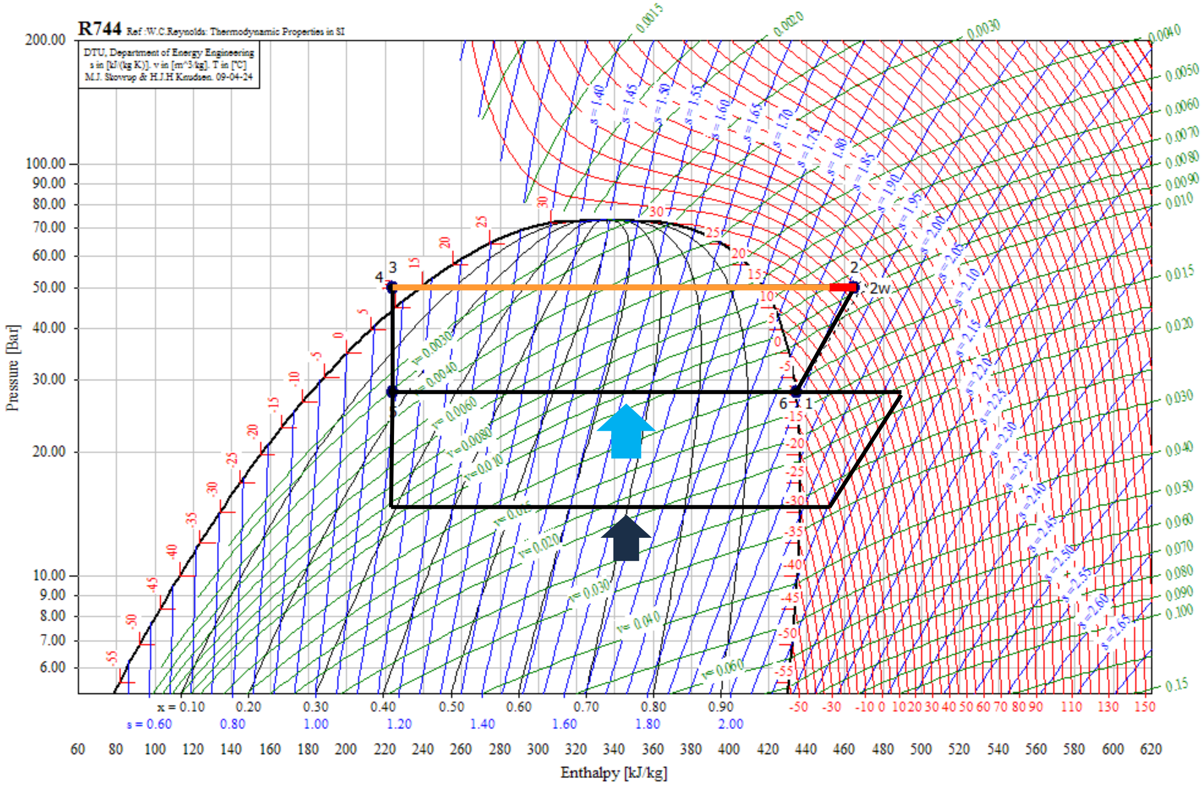

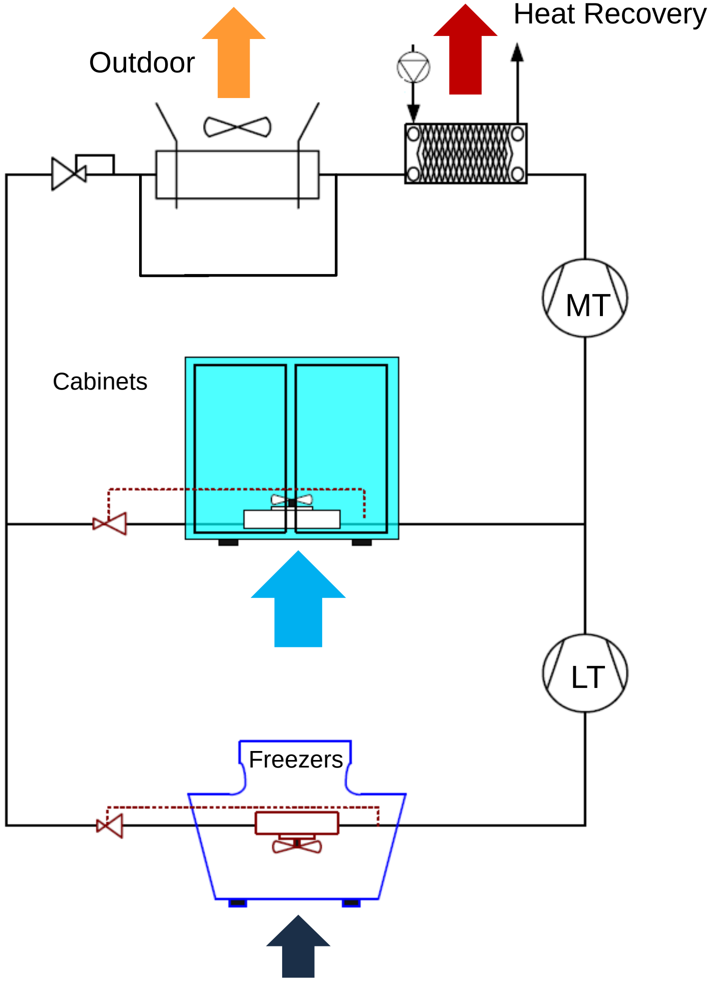

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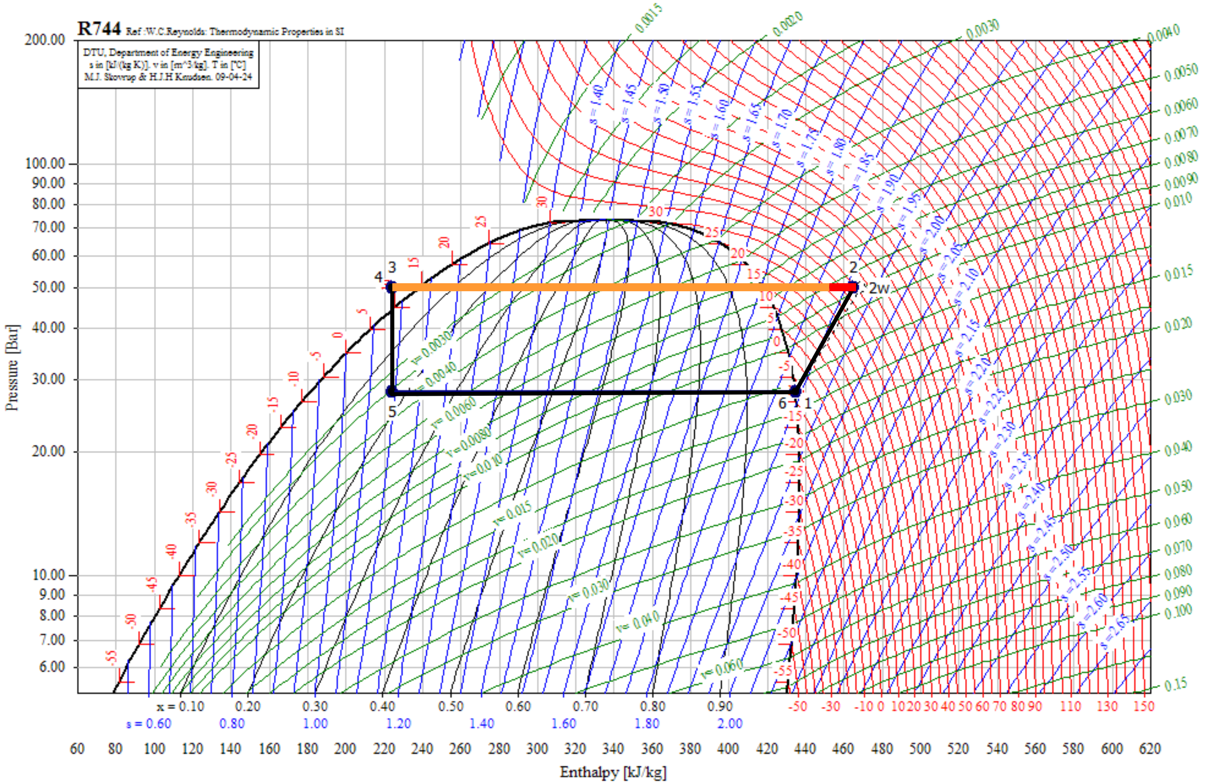
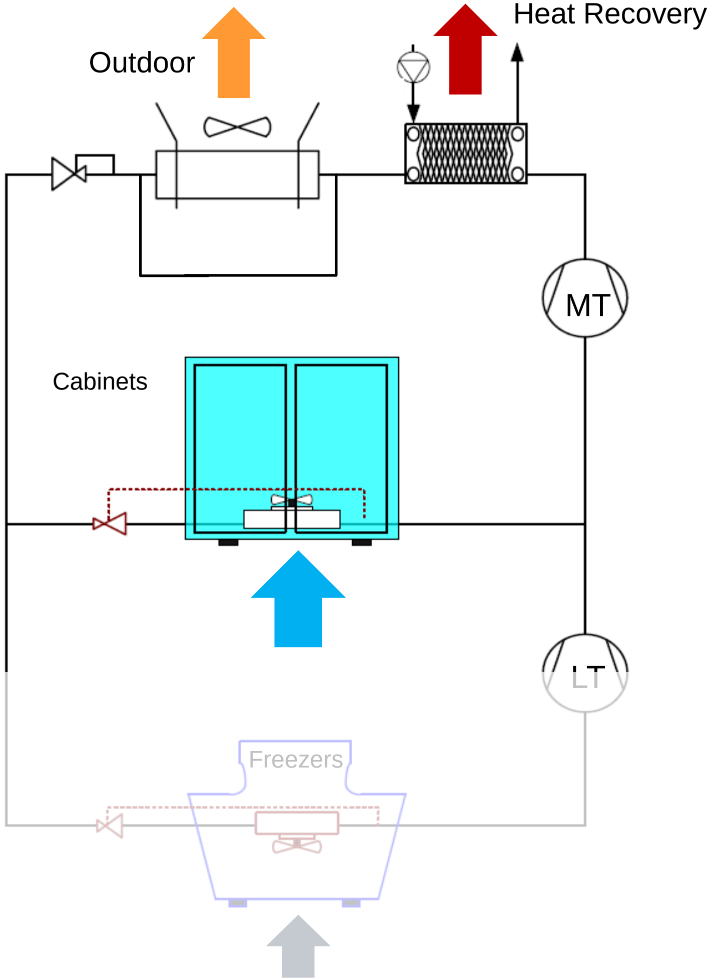


50 bar



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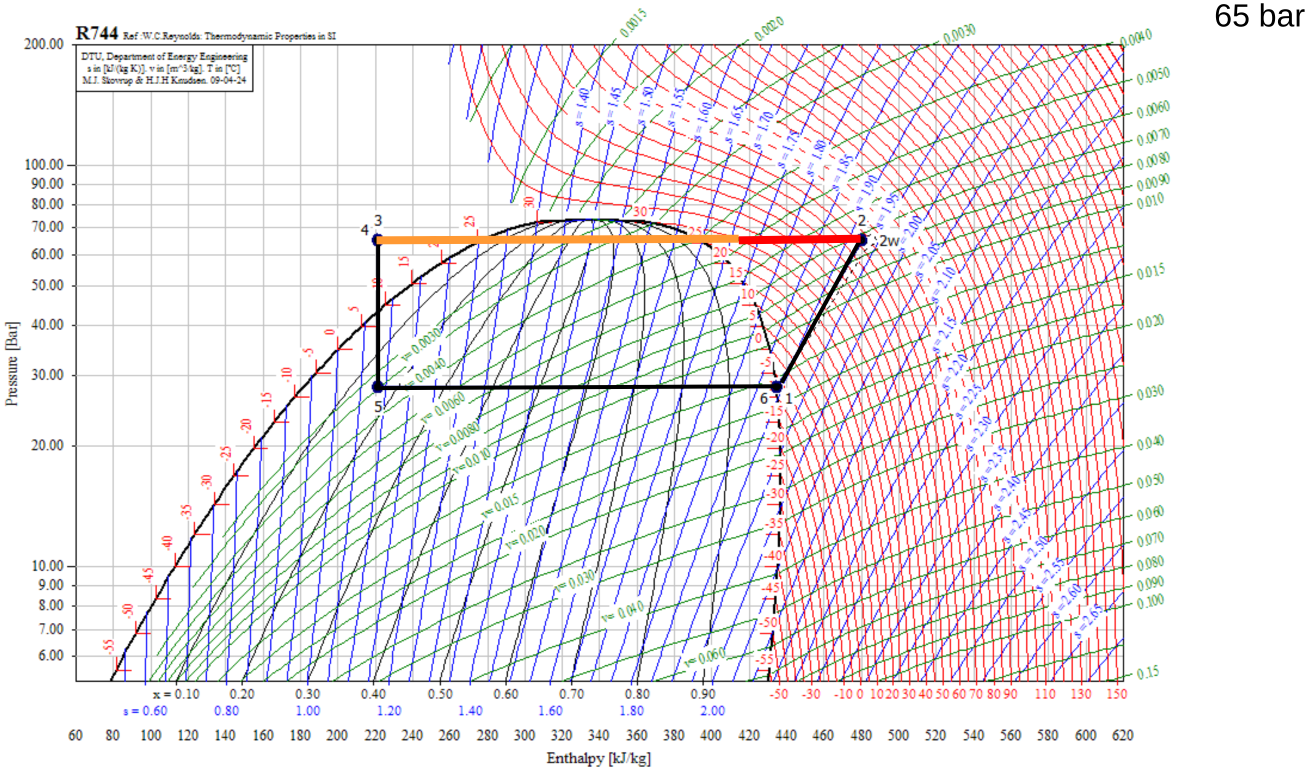

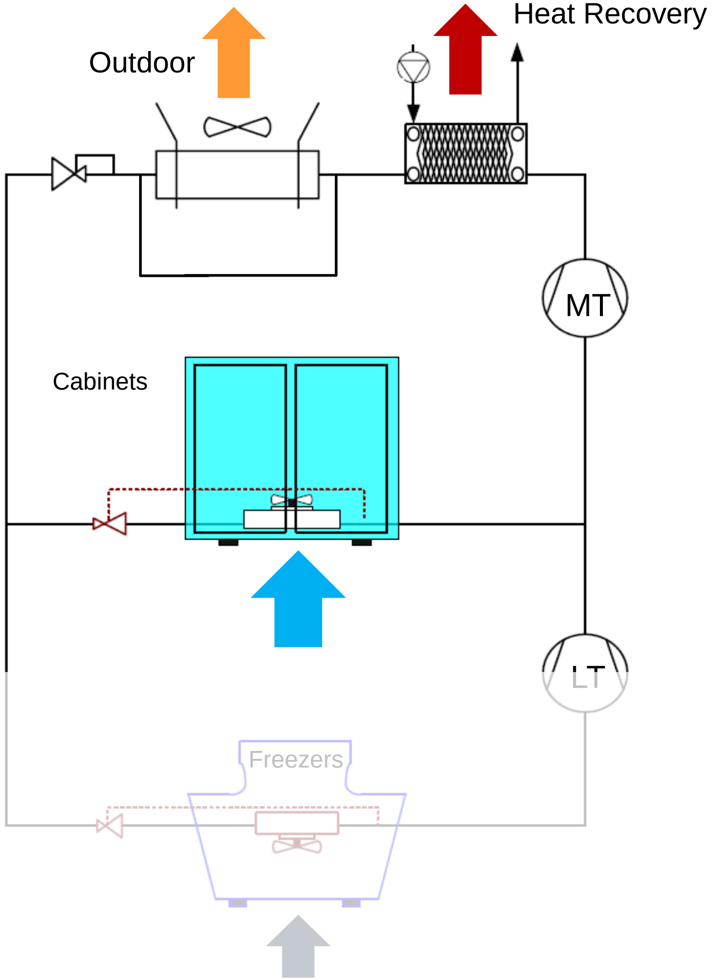

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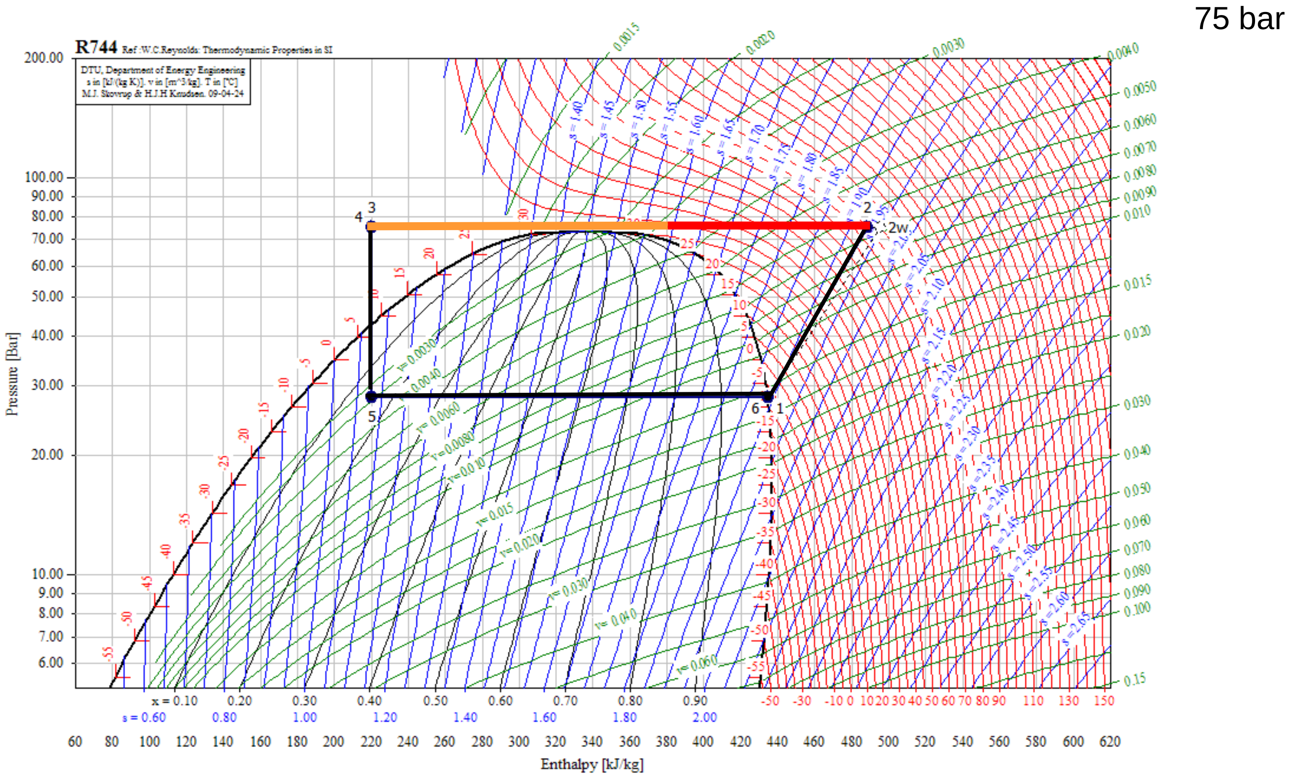

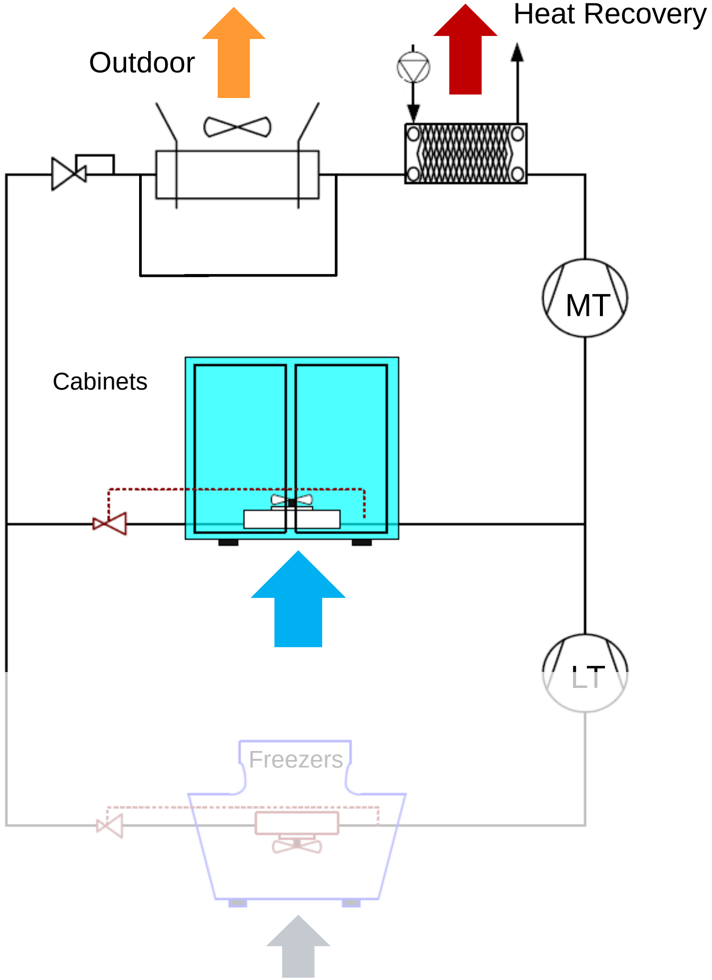

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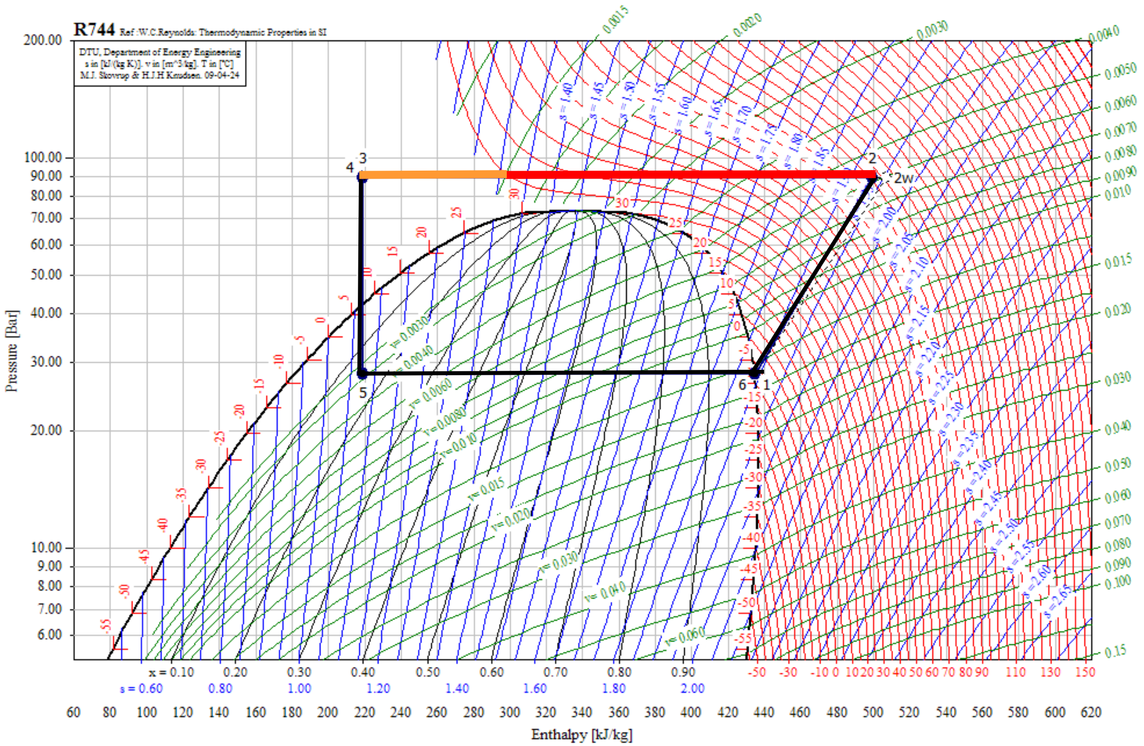
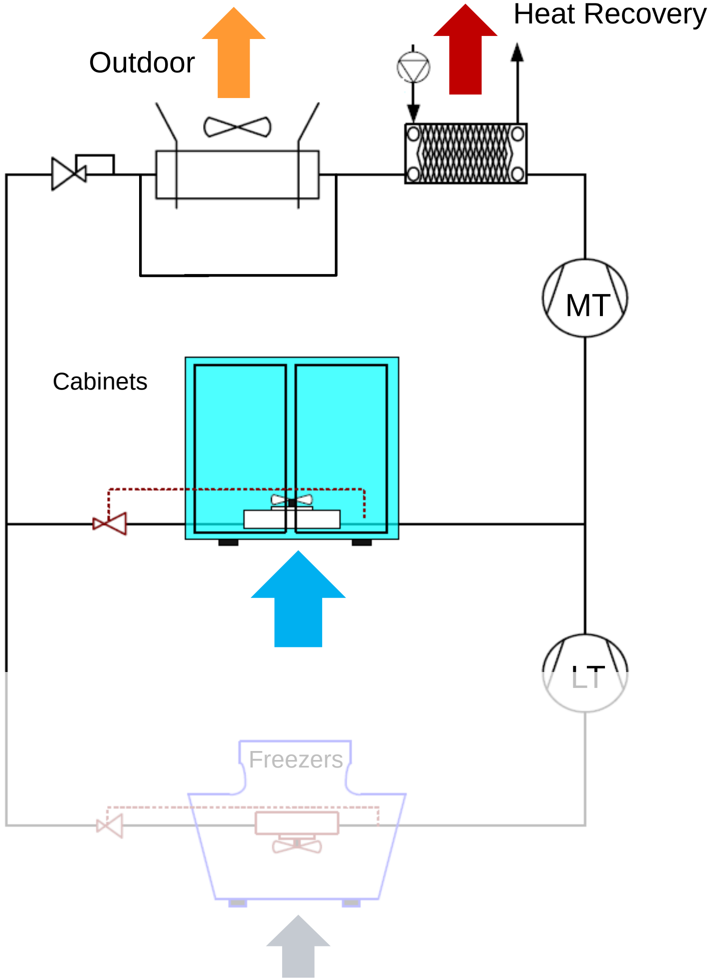


90 bar



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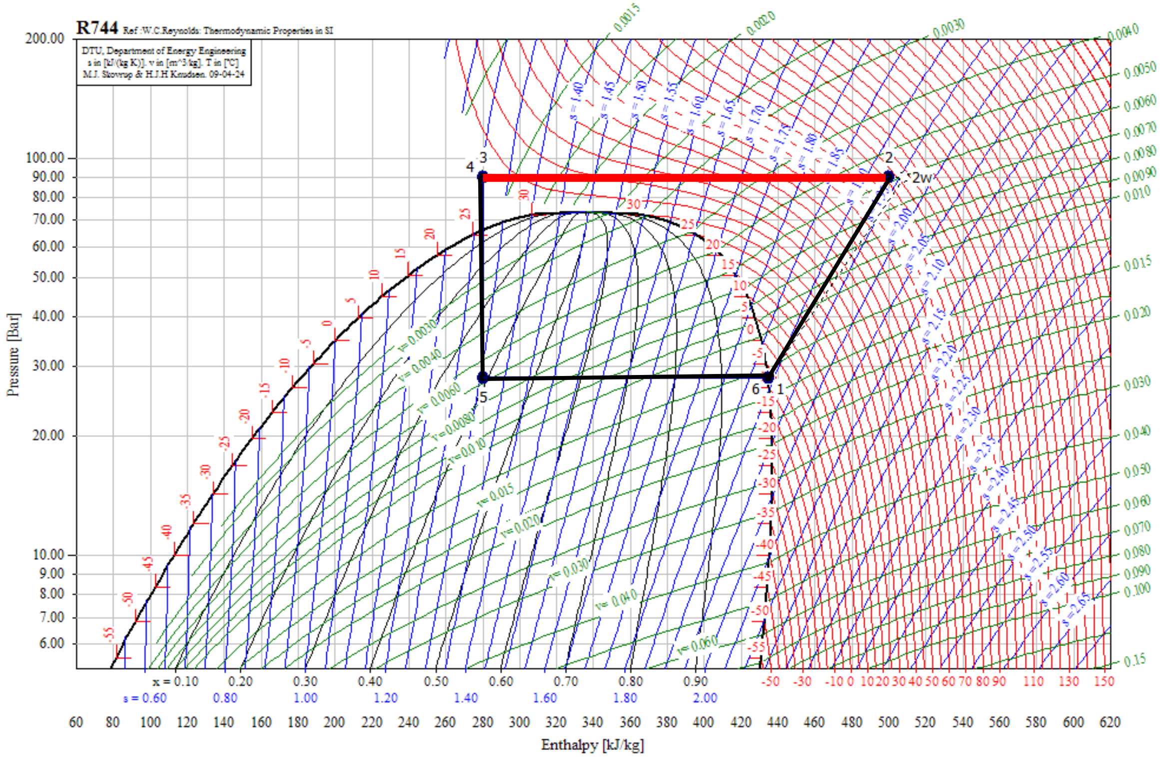
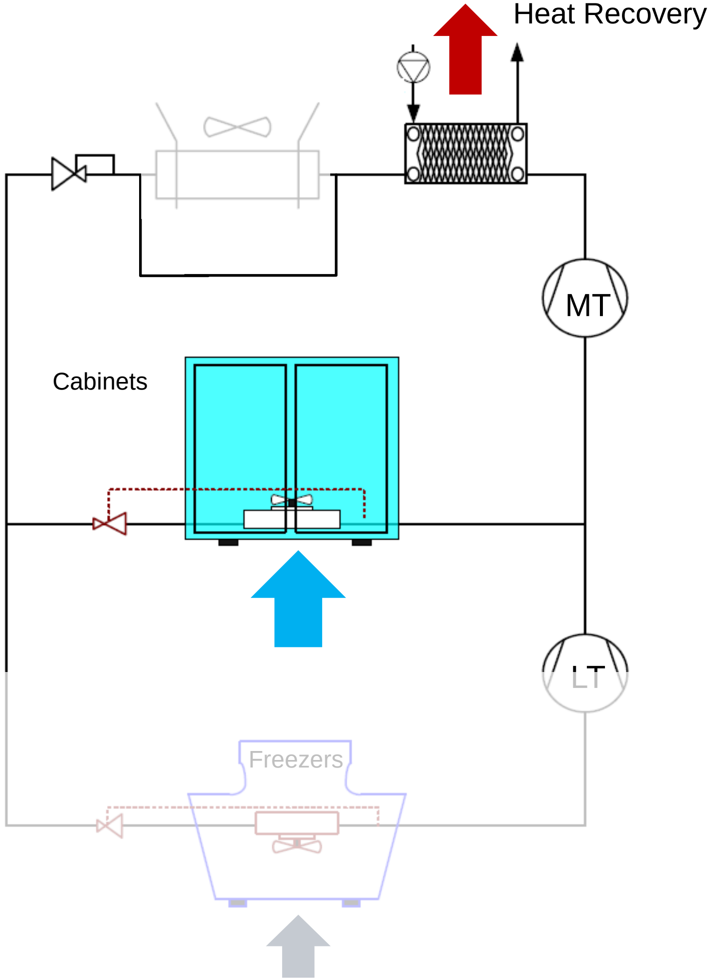


Gas Cooler by-pass



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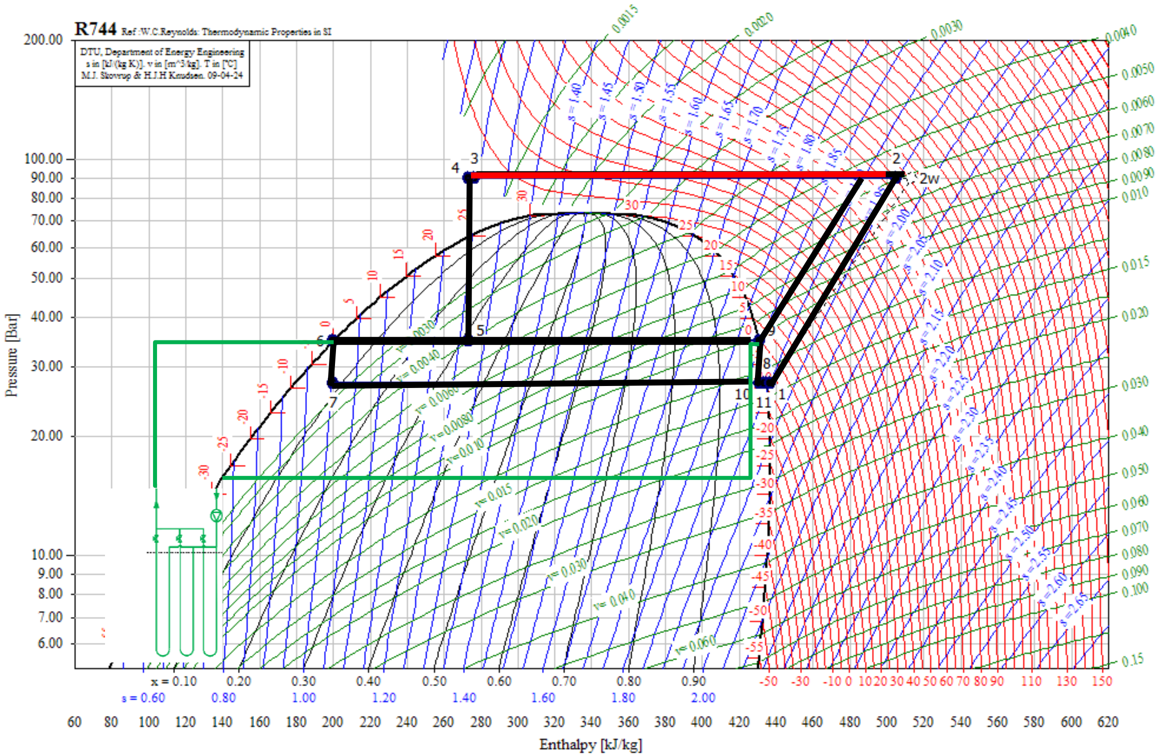
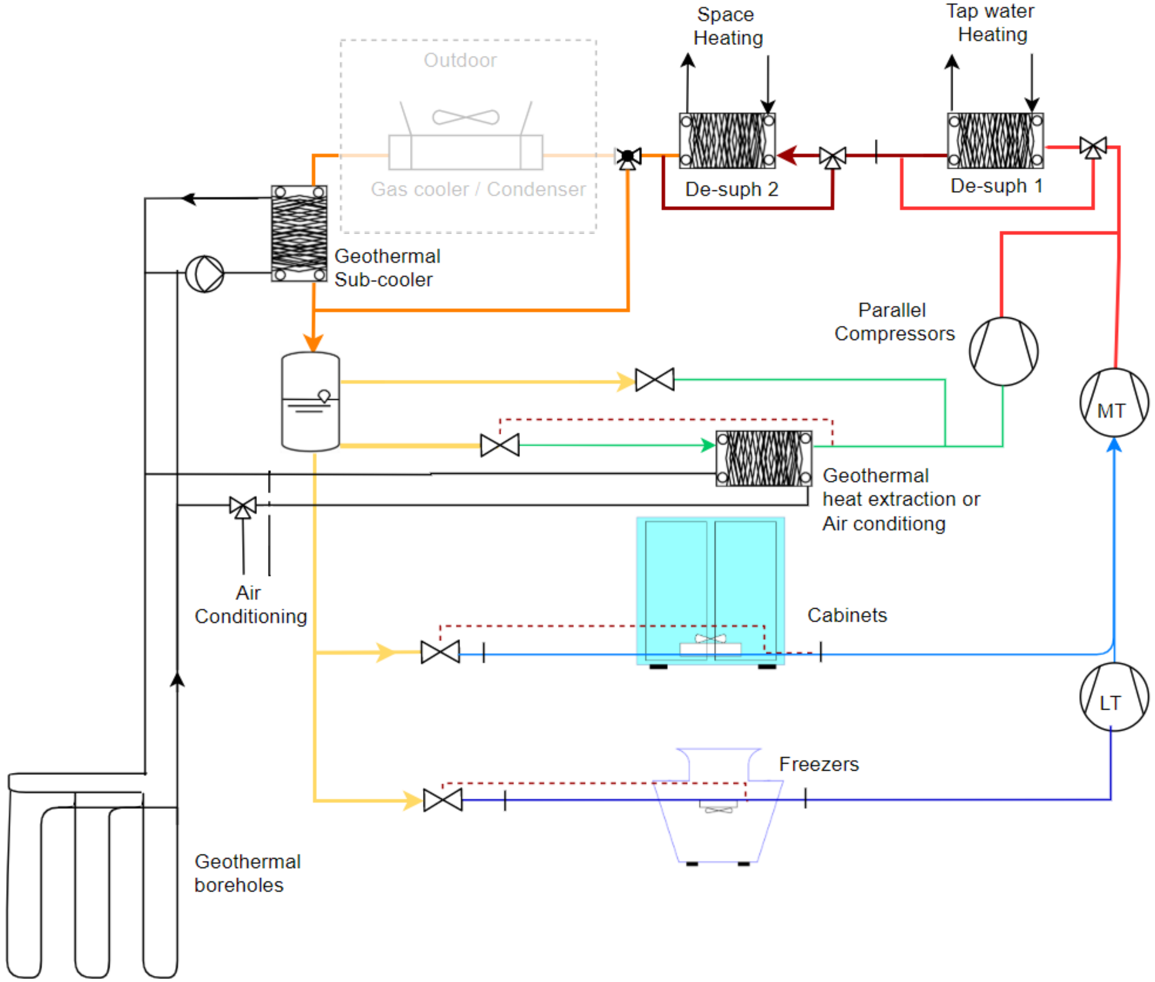
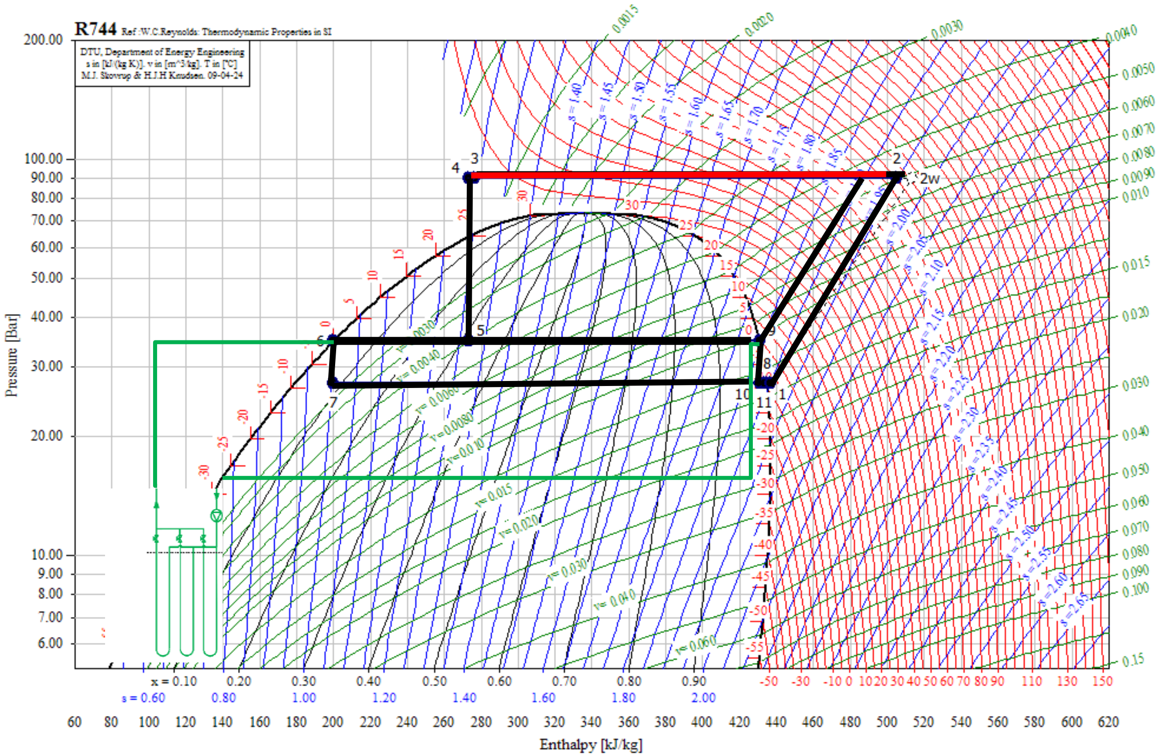
Introduction - CO_2 Transcritical Booster System with geothermal integration

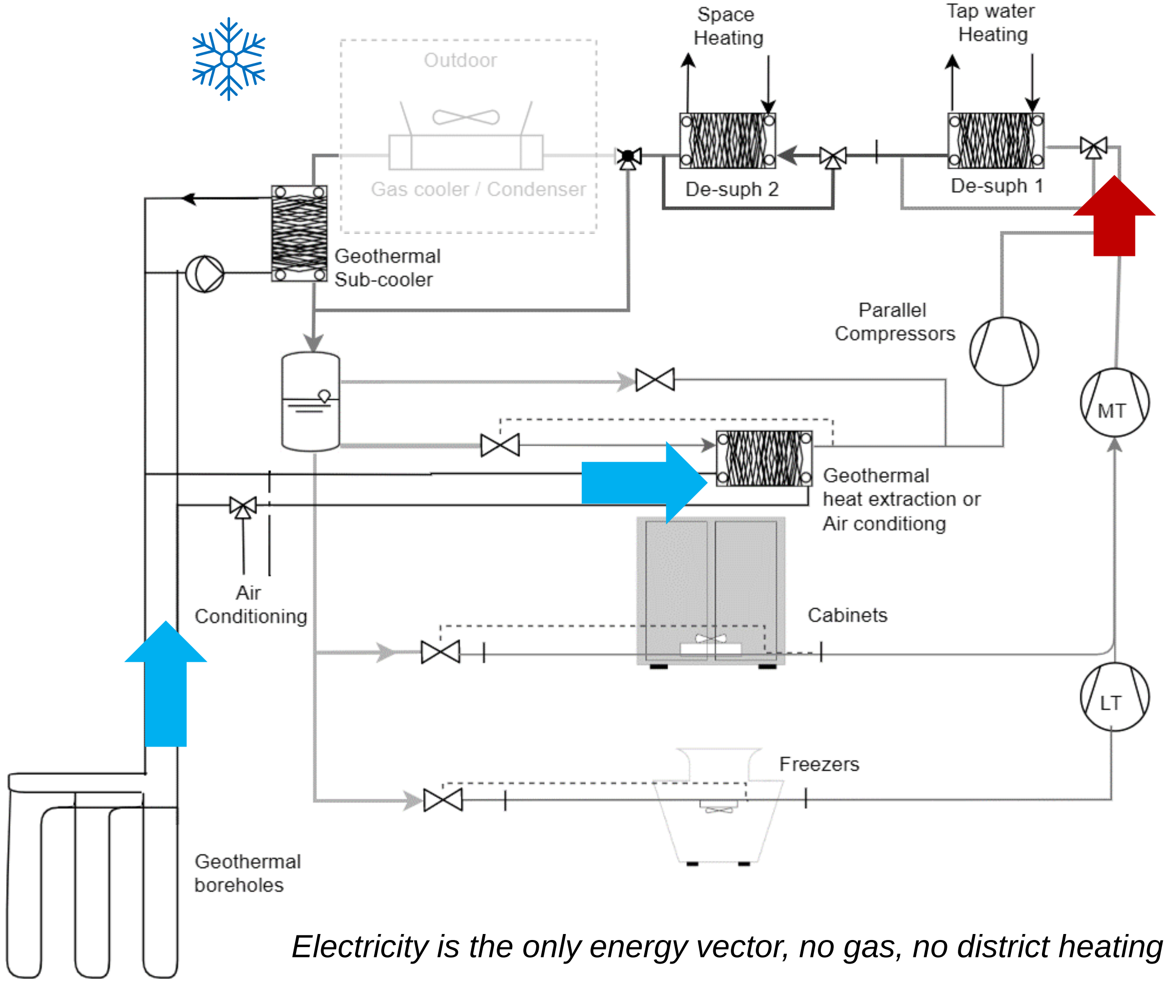


In the coldest period of the year, when the heat recovered from cabinets and freezers cannot cover the heating demand, heat is extracted from the geothermal storage. Since in summer, the ground is colder than the outdoor air, the geothermal storage is "re-charged" sub-cooling the refrigerant. Parallel compressors are used to extract heat from the ground.



Introduction - CO$_2$ Transcritical Booster System with geothermal integration





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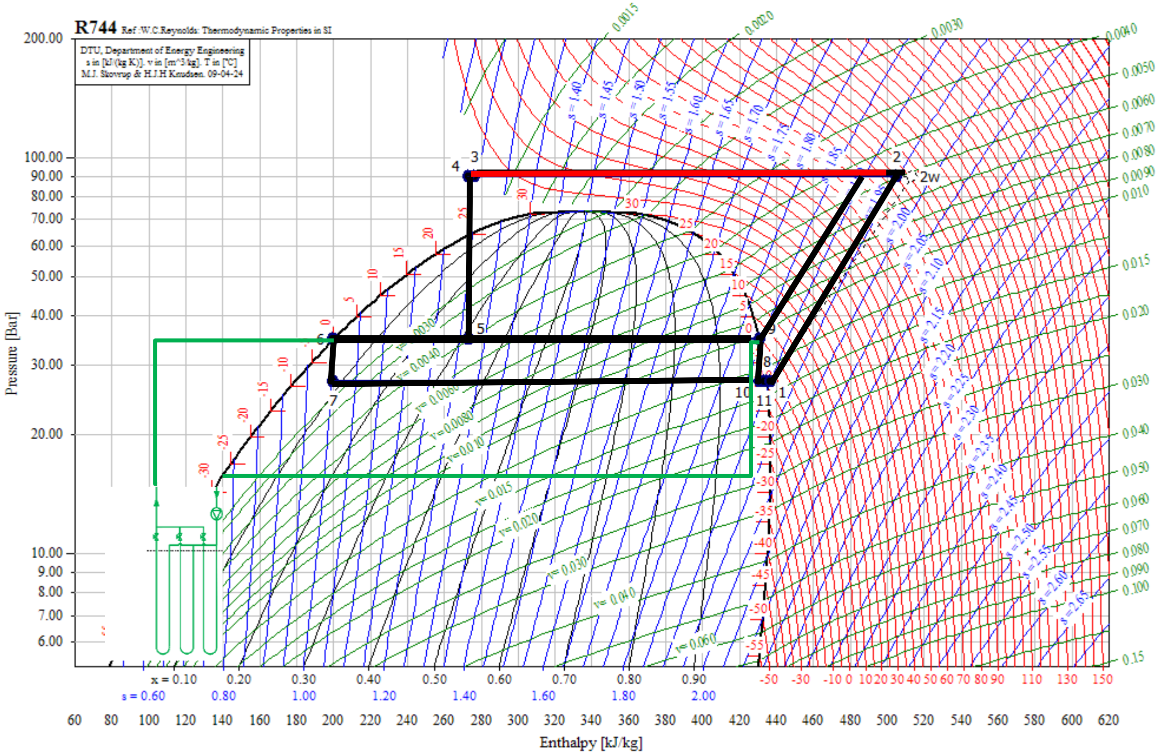
Electricity is the only energy vector, no gas, no district heating

Introduction - CO_2 Transcritical Booster System with geothermal integration



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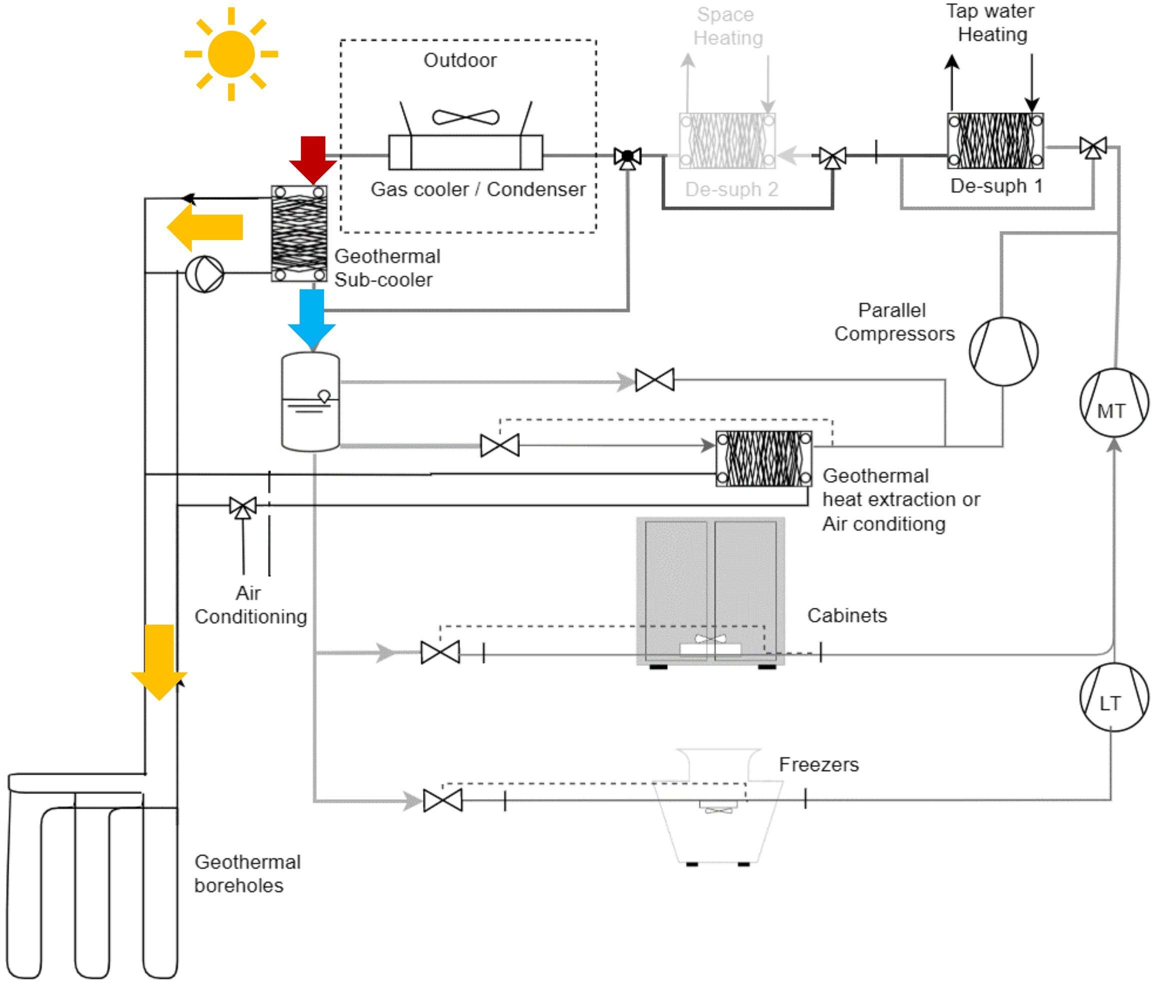


Methodology

Field Measurements Analysis

↓

Inputs as a function of the outdoor temperature

↓

Modelling with BIN Hours Method

↓

Model validation with Power Meters Readings

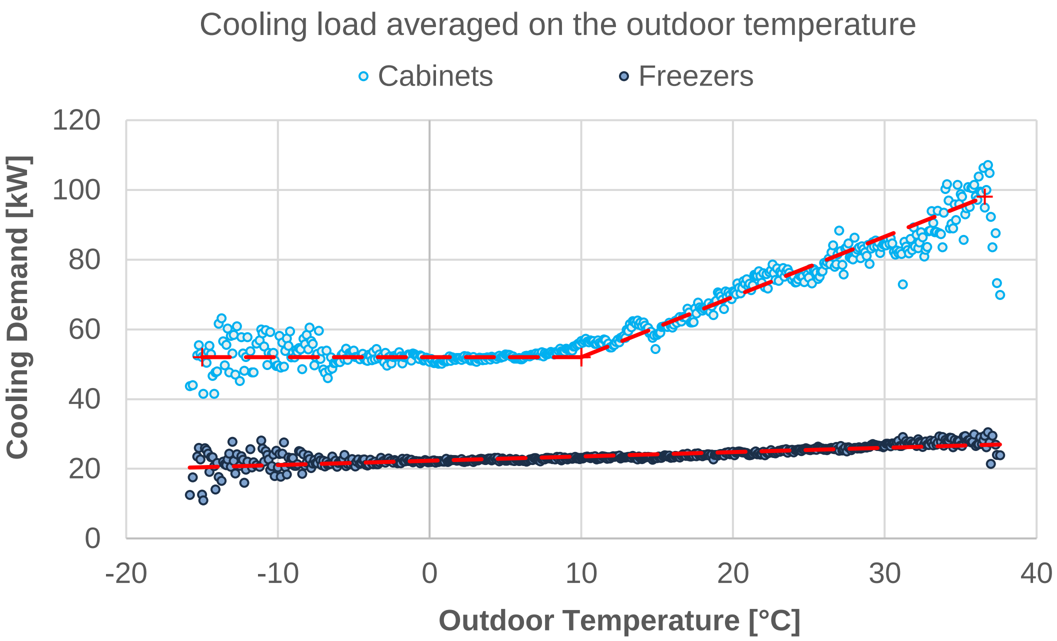
↓

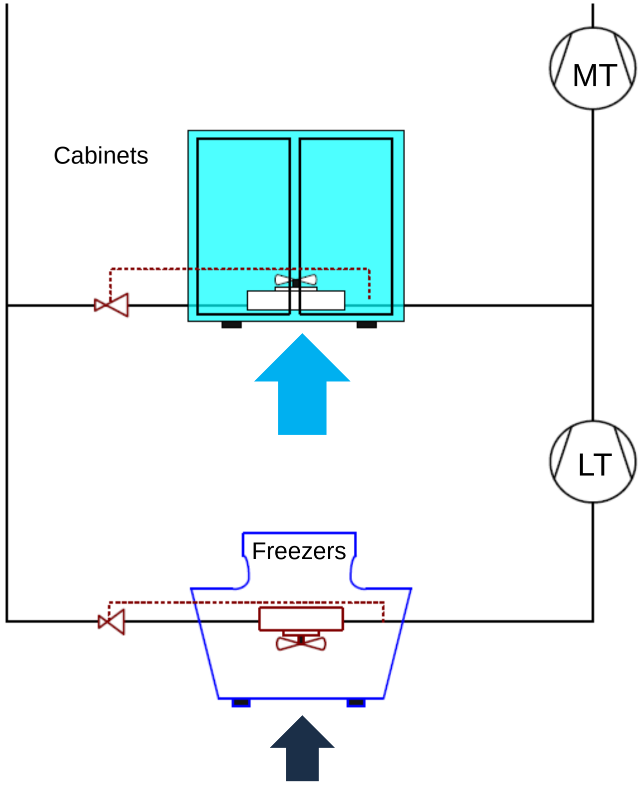
Geothermal Field Optimization and Techno-economic analysis

↓

Sensitivity Analysis

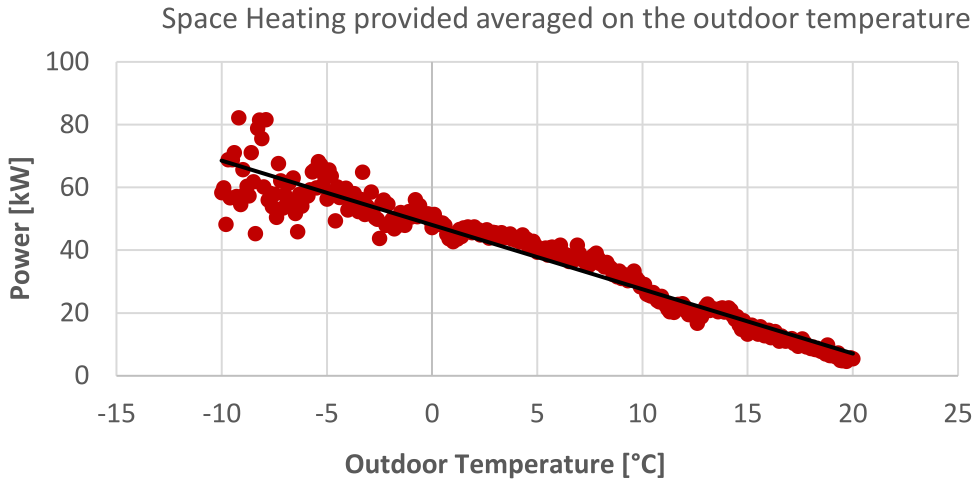
Field Measurements – Cooling Demands

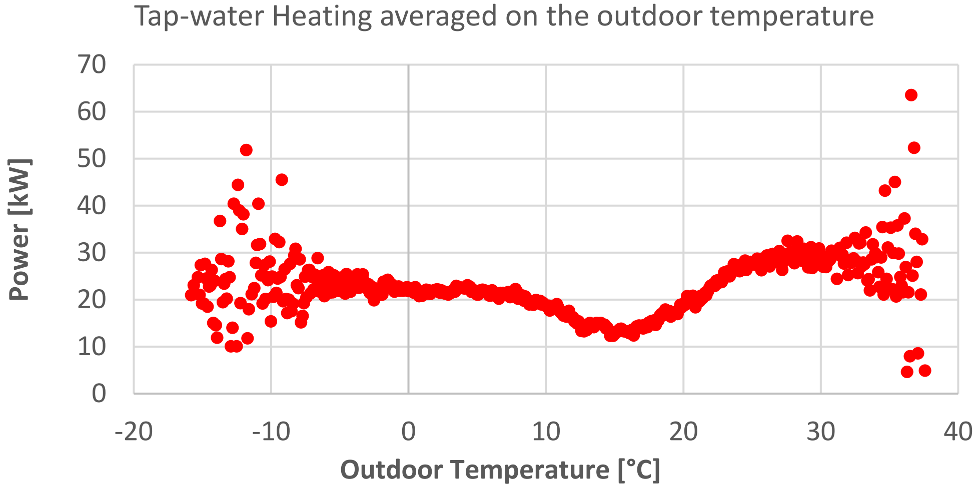


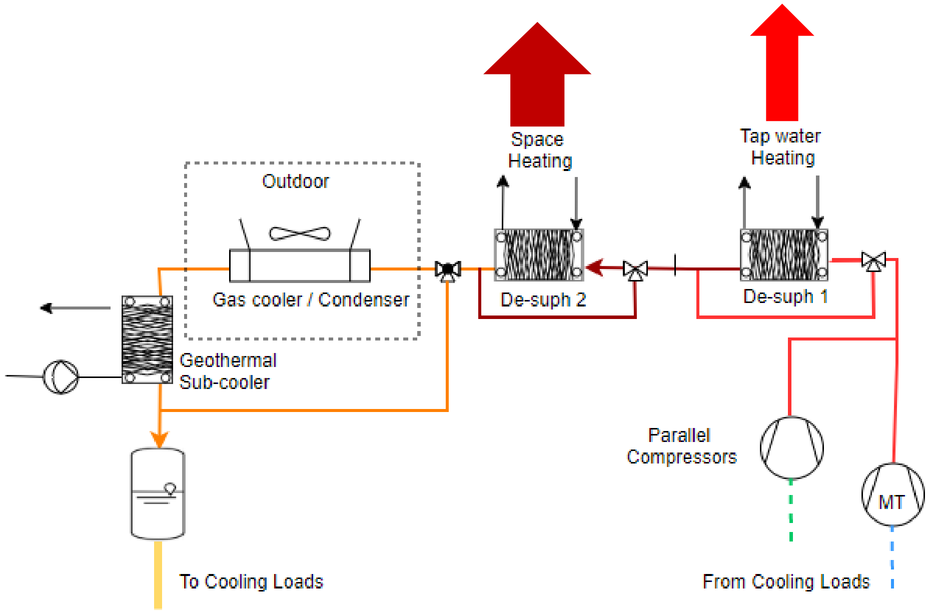


The typical cooling demand of the cabinets in a supermarket increases when the heating period ends. This is due to a rise in indoor absolute humidity which is translated into a more frequent defrosting in the cabinets. The cooling demand of the freezers is more stable since there is less air exchange with the supermarket's indoor environment

Field Measurements – Heat Recovery

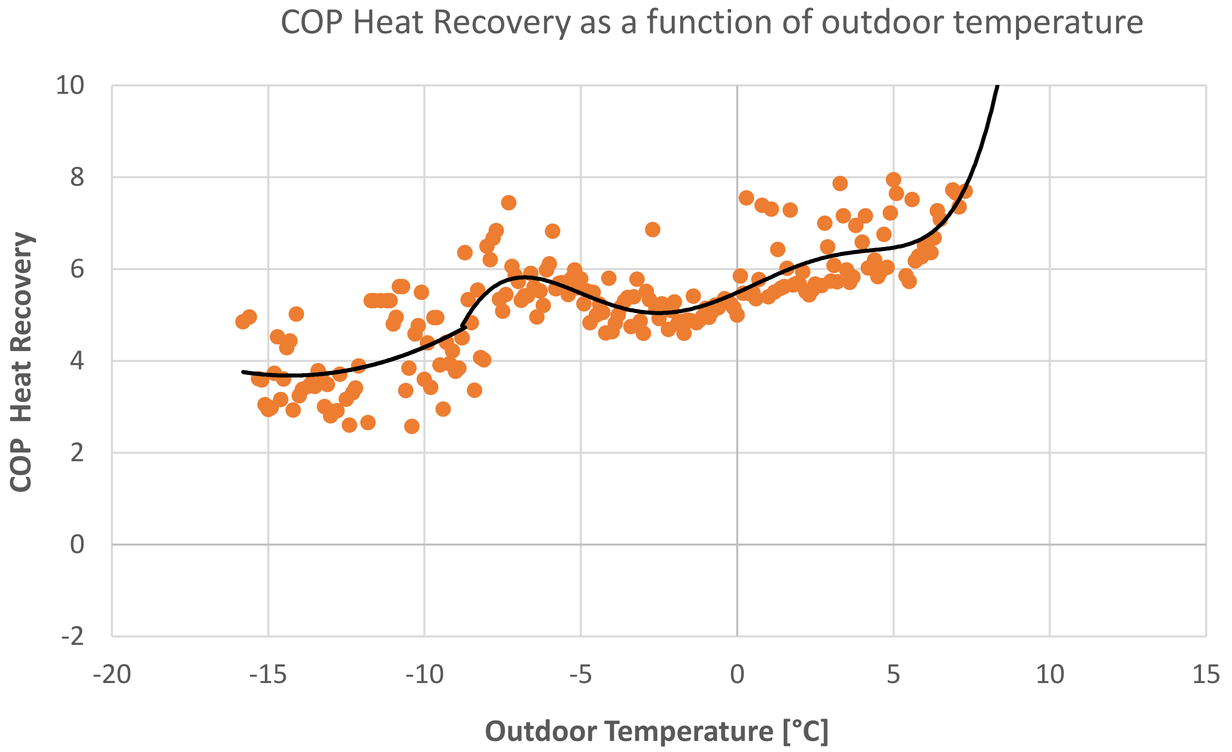






The heat recovery system is driven by the space heating demand. The tap-water demand is considered a secondary product. Therefore, the pressure is increased only when the space heating demand requires it. This is the reason for a decrease in high-temperature heat (tap-water) supply between 10 and 20°C. Electric resistances are used to provide the (small) extra heating capacity for tap-water demand.

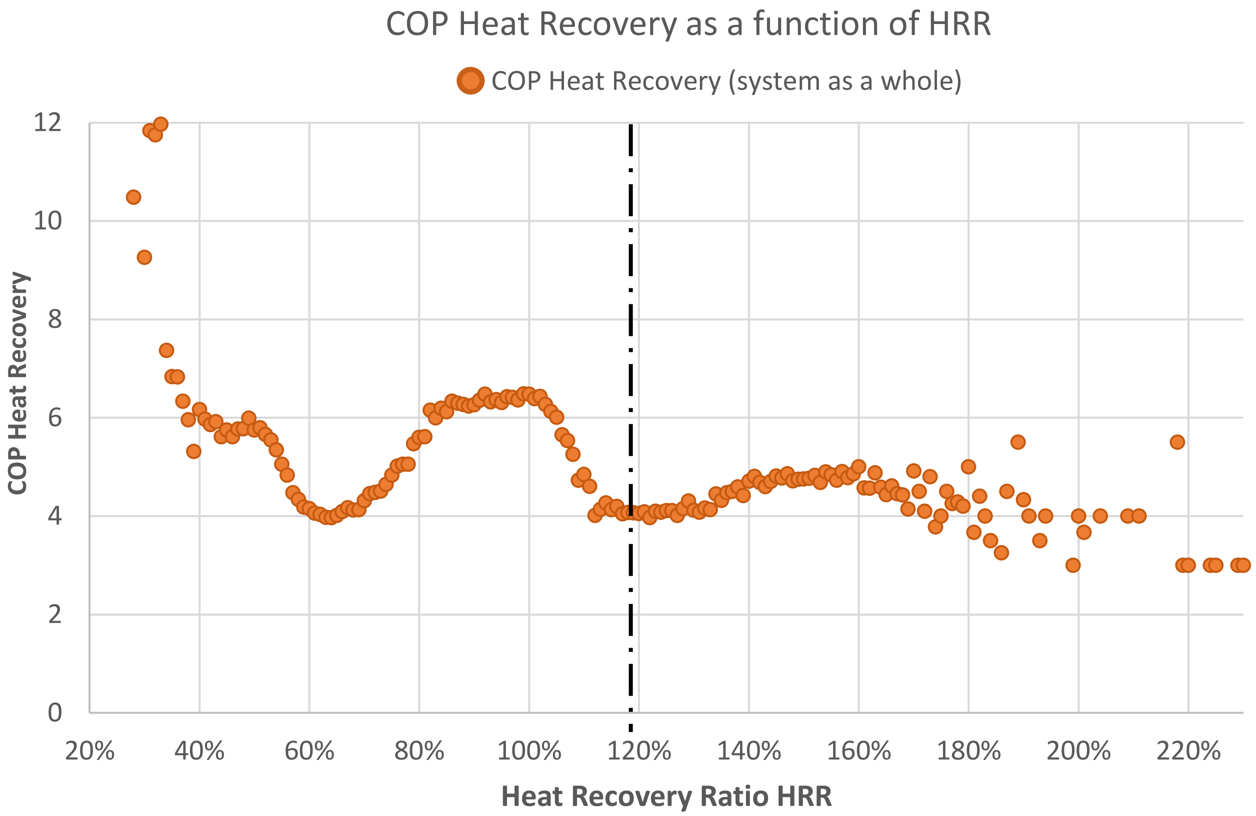
Field Measurements – COP Heat Recovery



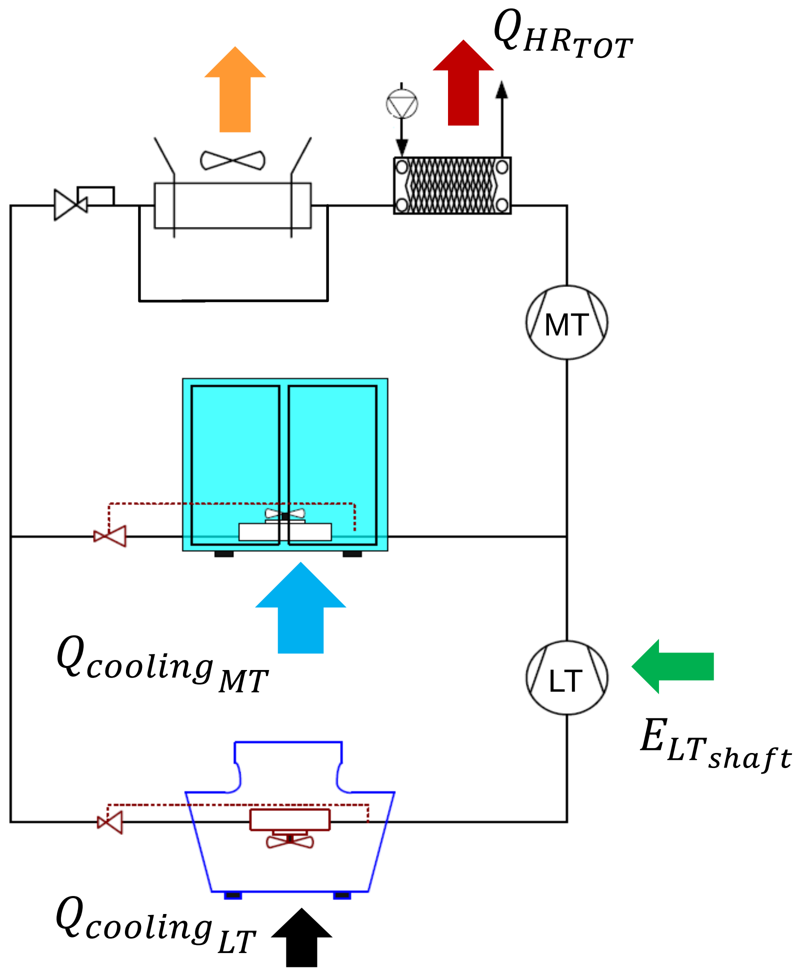
$$COP_{HR} = \frac{Q_{HR_{TOT}}}{E_{TOT} - E_{cool\ only}}$$

The electricity spent only for recovering the heat $(E_{TOT} - E_{cool\ only})$ *is calculated as the total electricity spent* (E_{TOT}) *and the* ***electricity that would have been spent if the system had satisfied only the cooling load*** $(\boldsymbol{E_{cool\ only}})$**.**

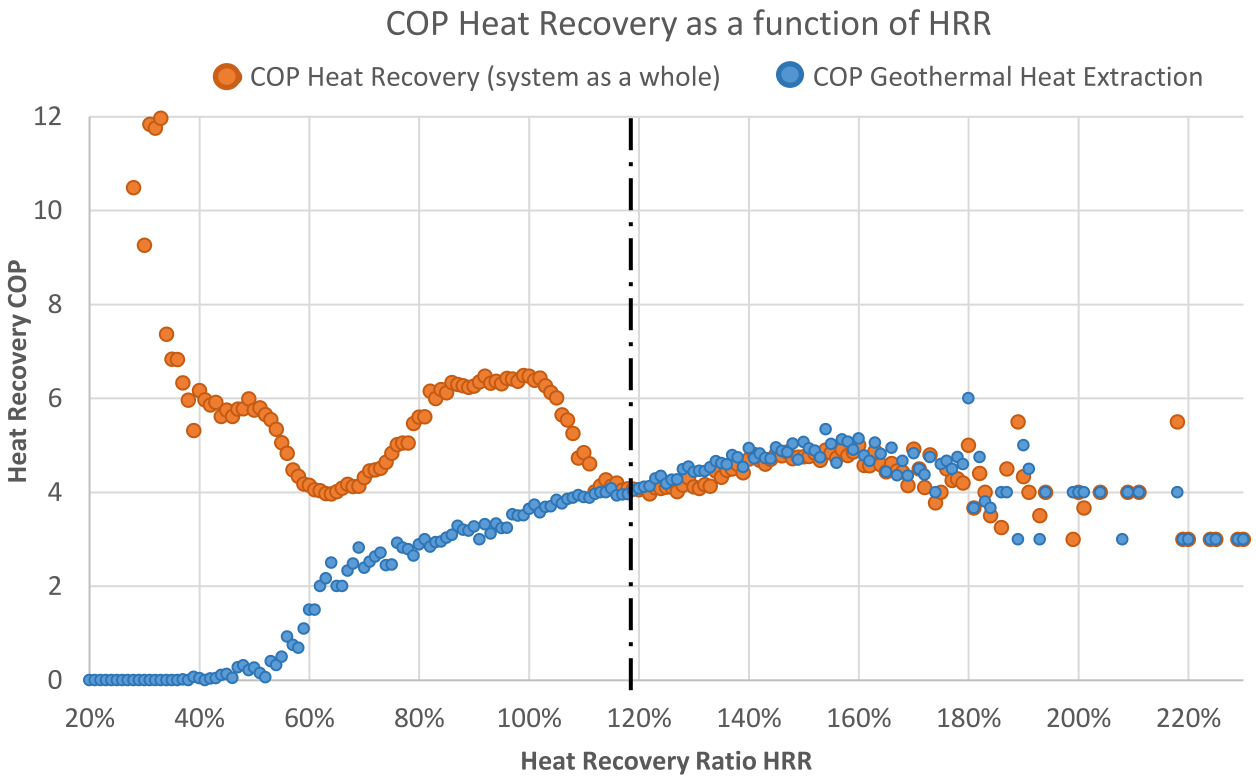
Field Measurements – COP Heat Recovery



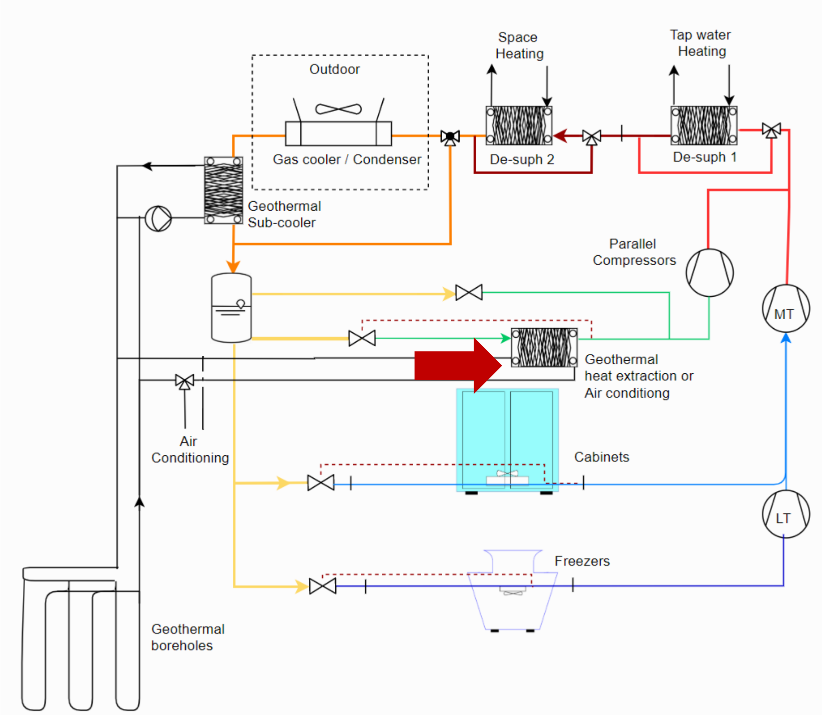
$$HRR = \frac{Q_{HR_{TOT}}}{Q_{cooling_{MT}} + Q_{cooling_{LT}} + E_{LT_{Shaft}}}$$



Field Measurements – COP Heat Recovery

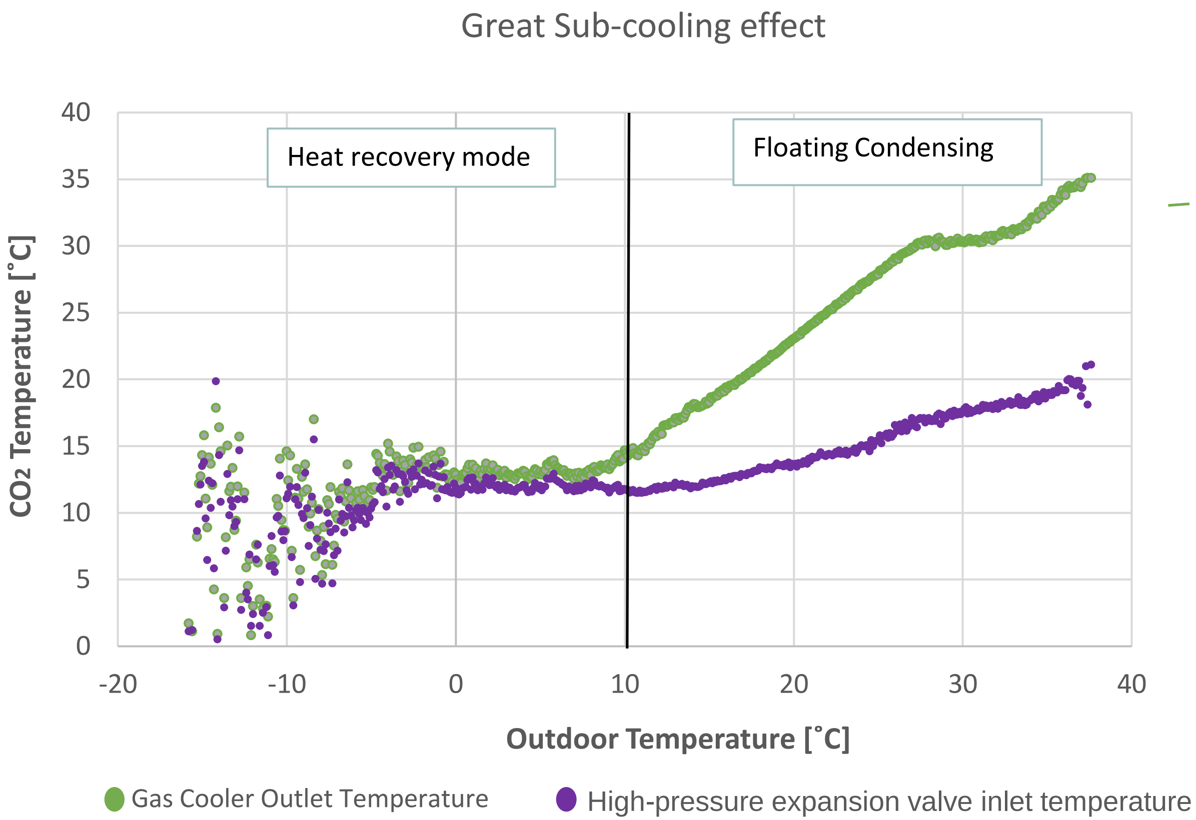


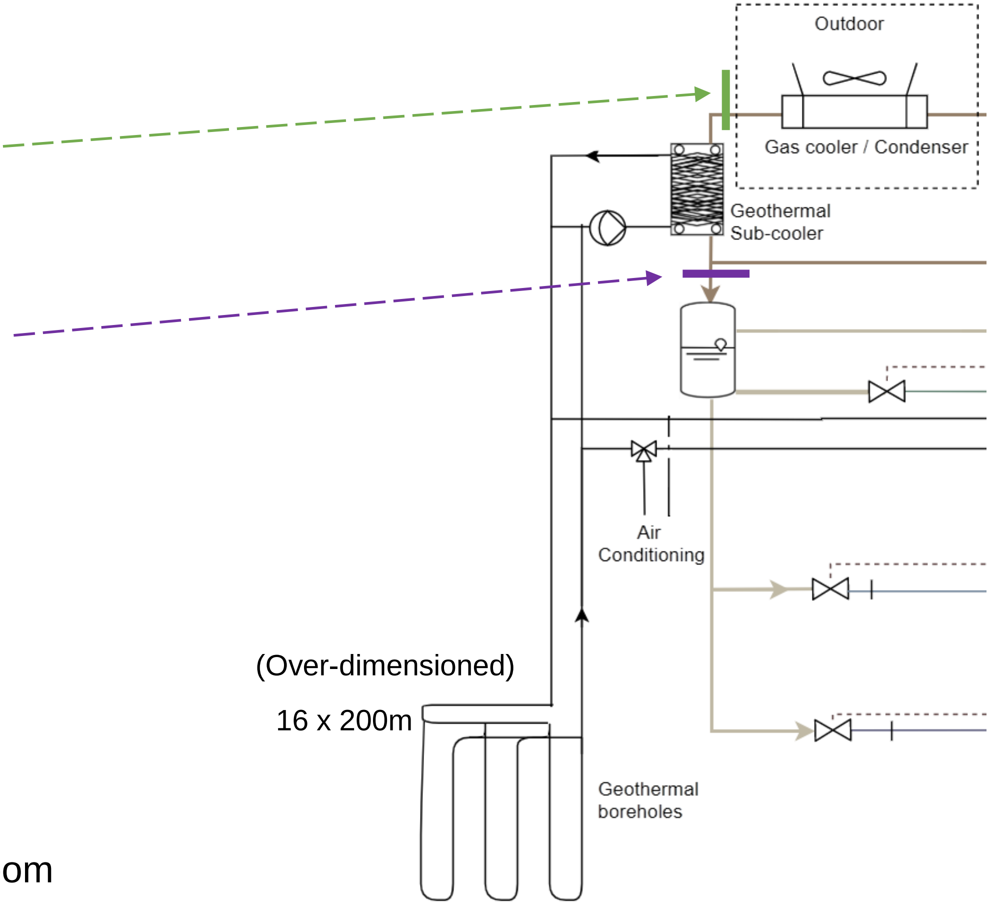
$$COP_{geo\ extraction} = \frac{Q_{geo_{supplied}}}{E_{parallel\ compressors} + E_{secondary\ pumps}}$$



*When the COP geothermal extraction and total COP heat recovery overlaps it means that **geothermal heat pump function is working in steady conditions**. This happens **only during the peaks of heating demand**. In other words, the parallel compressors are forced to work in start-and-stop for low values of HRR.*

Field Measurements – Sub-cooling



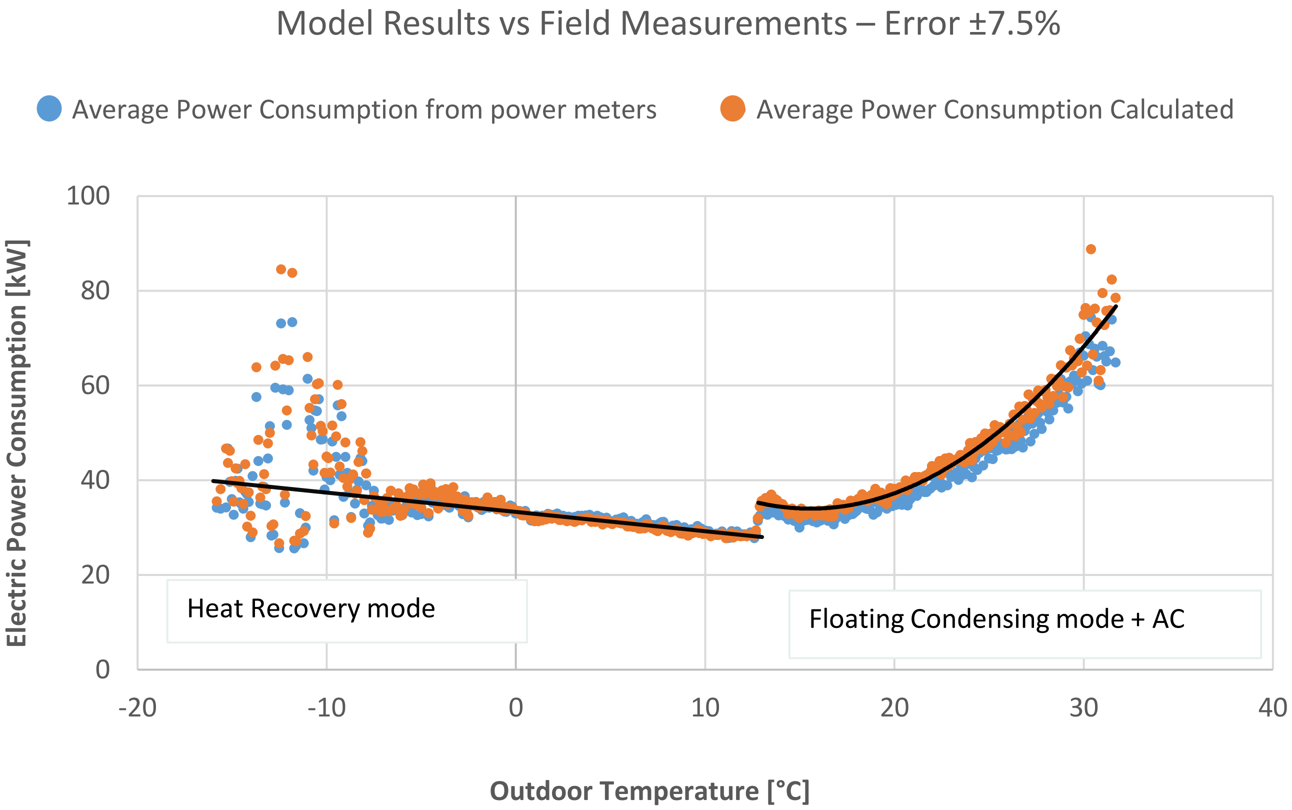


(Over-dimensioned)

16 x 200m

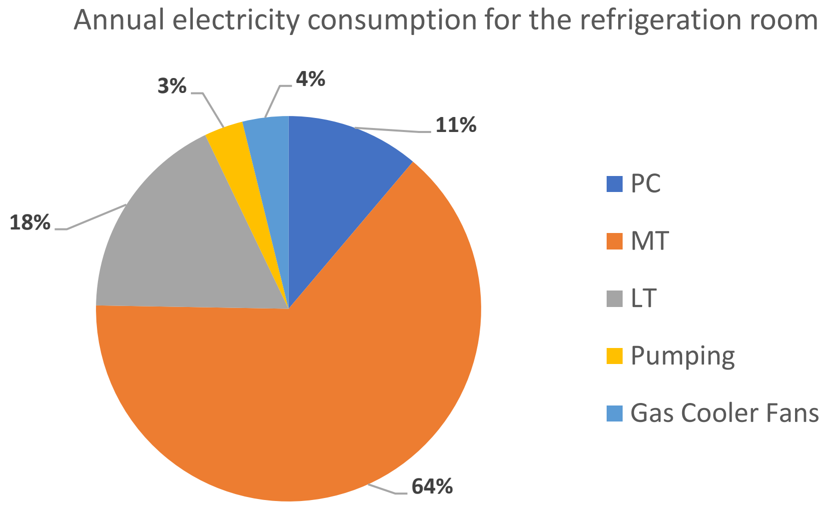
8% yearly electricity savings on the power consumed by the machine room

Model validation - through power meters readings

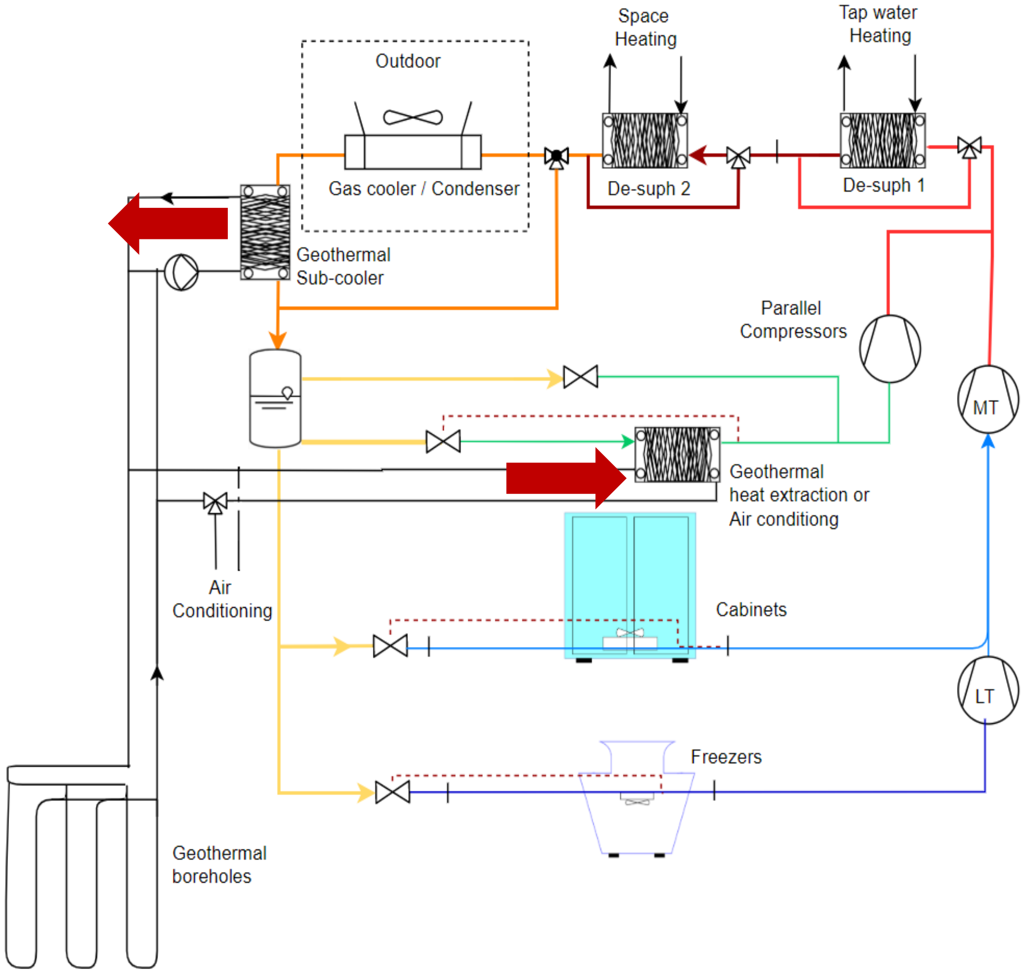


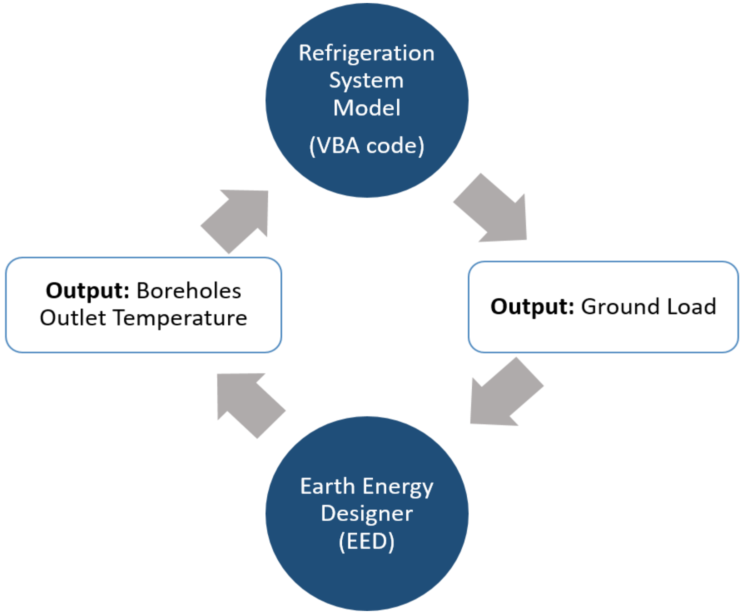
A model representing the system was built to simulate the effect of potential improvements and different sizes of the geothermal storage.

The model was validated comparing the expected power consumption and the readings from the power meter installed in the machine room.



How to size a geothermal storage for this application?





Refrigeration System Model (VBA code)

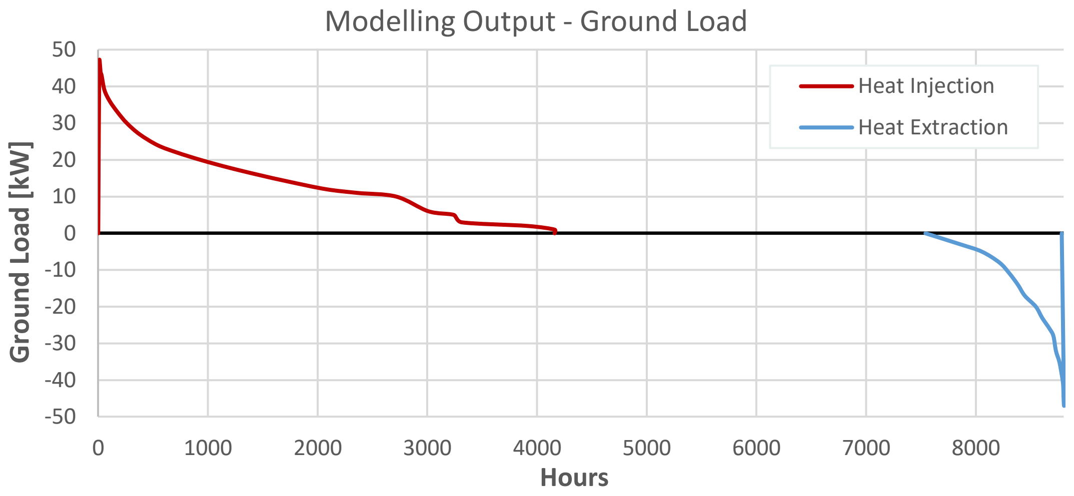
Output: Ground Load

Earth Energy Designer (EED)

Output: Boreholes Outlet Temperature

The amount of heat exchanged with the ground influences the temperature of the secondary refrigerant which in turns influences the amount of heat extracted (efficiency of the heat pump function) or injected (capability to sub-cool the CO_2). This means that the techno-economic assessment needs to be solved through an iterative process!

Techno-economic assessment



The ground load represents the amount of heat extracted from or injected into the ground in one year.

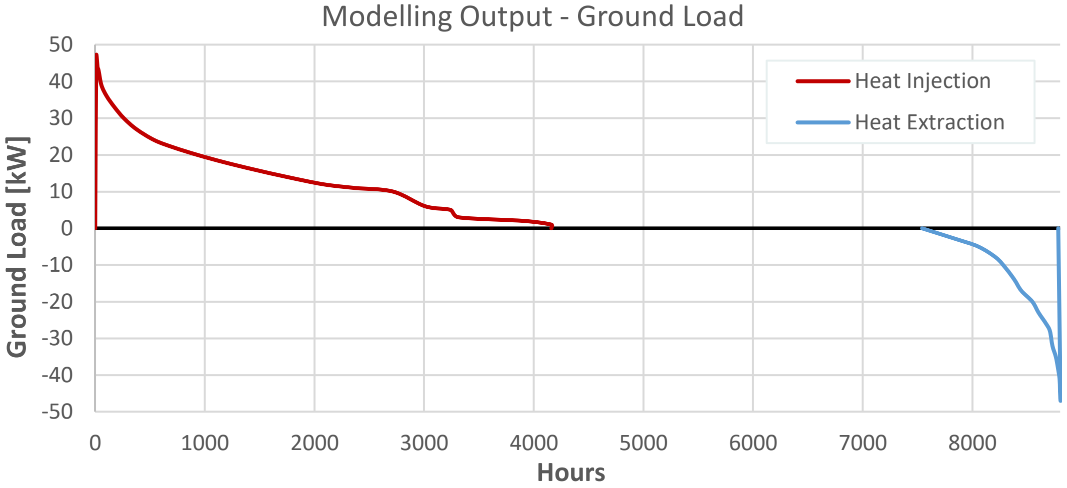
The ground is extremely unbalanced. This means the amount of heat injected in summer is much more than the heat injected in winter. This increases the necessary size of the storage reducing its cost-effectiveness.

Techno-economic assessment

$$-\Delta NPV = \Delta CAPEX + \Delta OPEX$$

$$\left(\text{Investment Cost for the Alternatives} - \text{Investment Cost for geothermal function}\right) + \left(\text{Discounted Energy Cost Without Geothermal Storage} - \text{Discounted Energy Cost With Geothermal Storage}\right)$$

Present Value of the Addtional Investment Cost + Present Value of the Operational Savings



The ground load represents the amount of heat extracted from or injected into the ground in one year.

The ground is extremely unbalanced. This means the amount of heat injected in summer is much more than the heat injected in winter. This increases the necessary size of the storage reducing its cost-effectiveness.

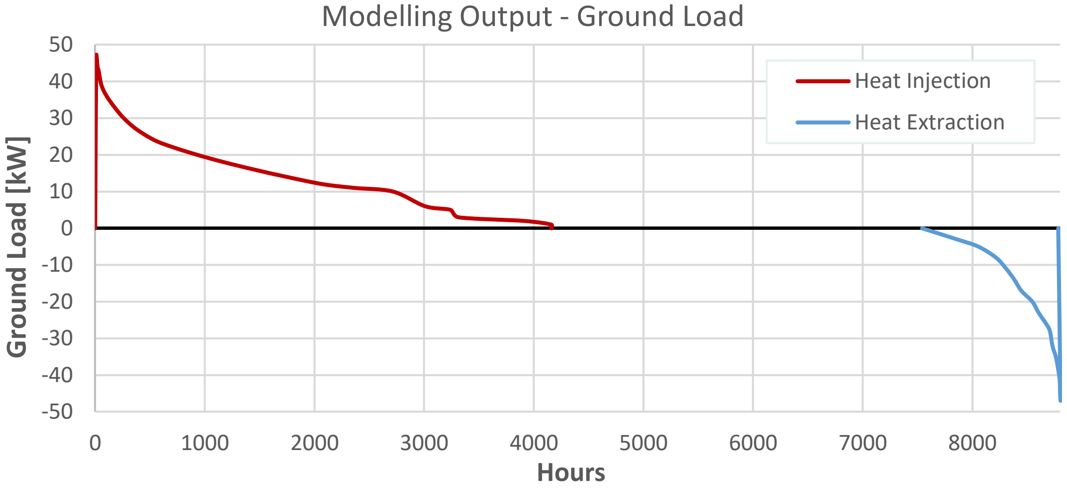
Techno-economic assessment

$$-\Delta NPV = \Delta CAPEX + \Delta OPEX$$

Investment Cost for the Alternatives − Investment Cost for geothermal function + Discounted Energy Cost Without Geothermal Storage − Discounted Energy Cost With Geothermal Storage

Present Value of the Addtional Investment Cost + **Present Value of the Operational Savings**

The present value of the operational savings represents the amount that the supermarket should be willing to pay per meter of storage, taking into account only the operational savings. ***This does not take into account a potential difference in the CAPEX.***



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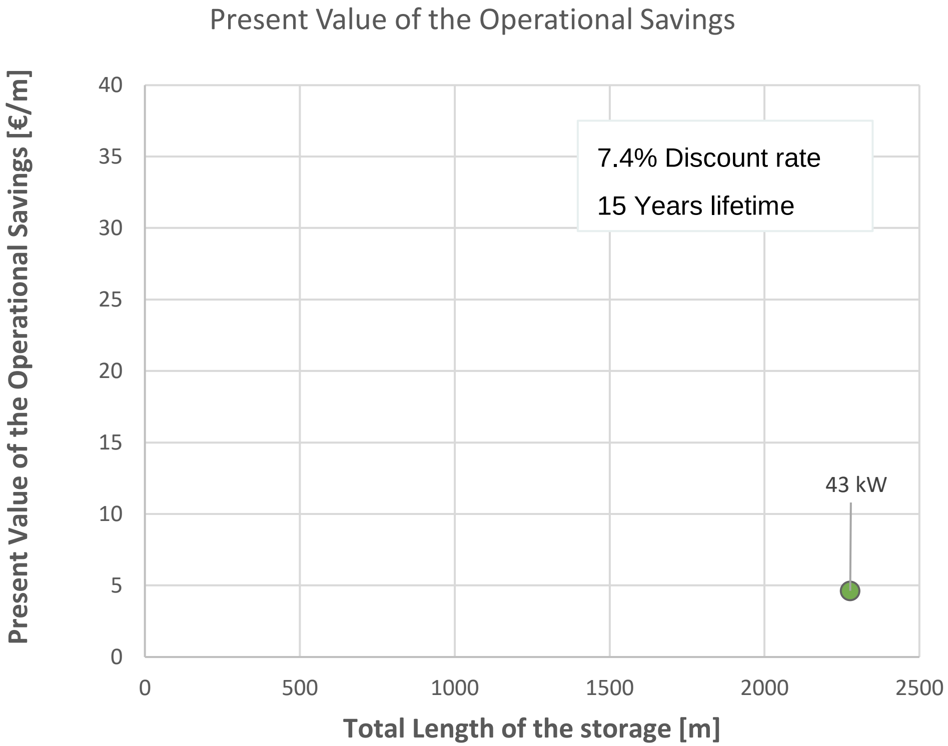
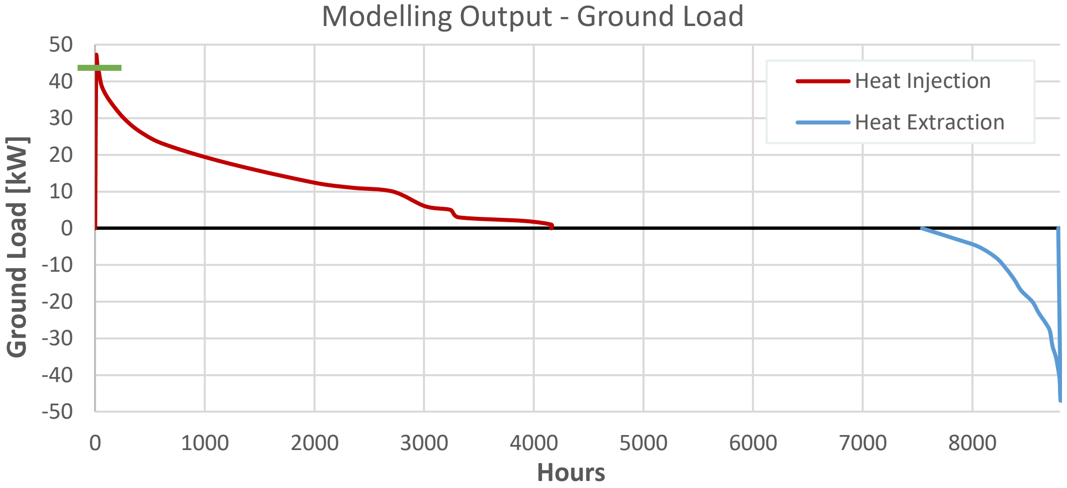
Techno-economic assessment





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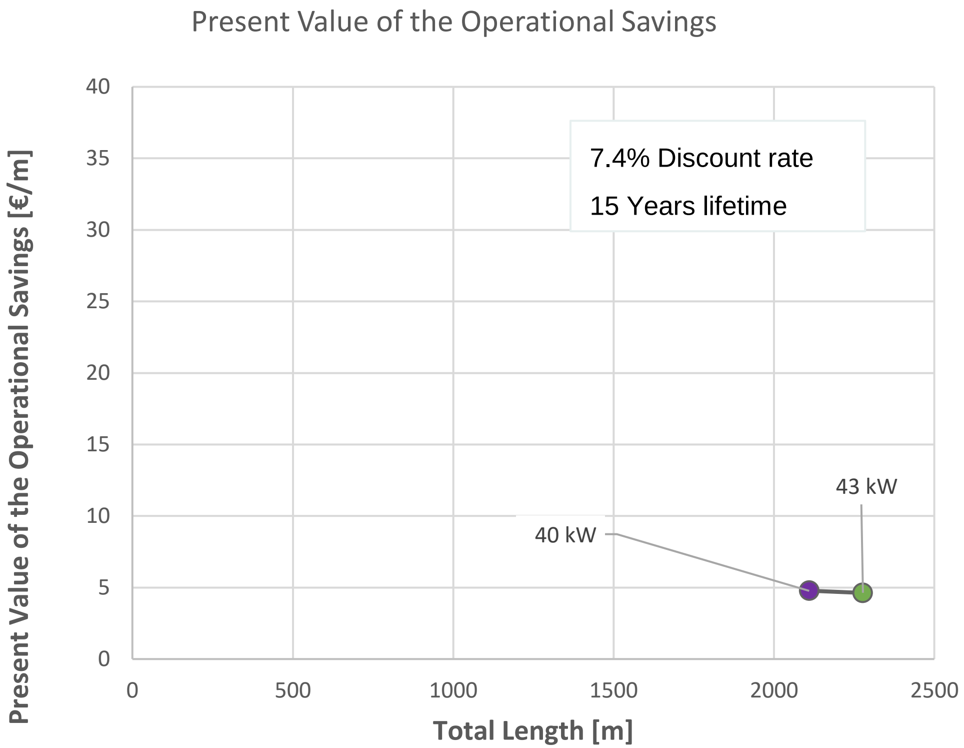
Moreover, also the power peaks of heat injected (in this application) are one of the parameters driving the size of the storage.

Techno-economic assessment



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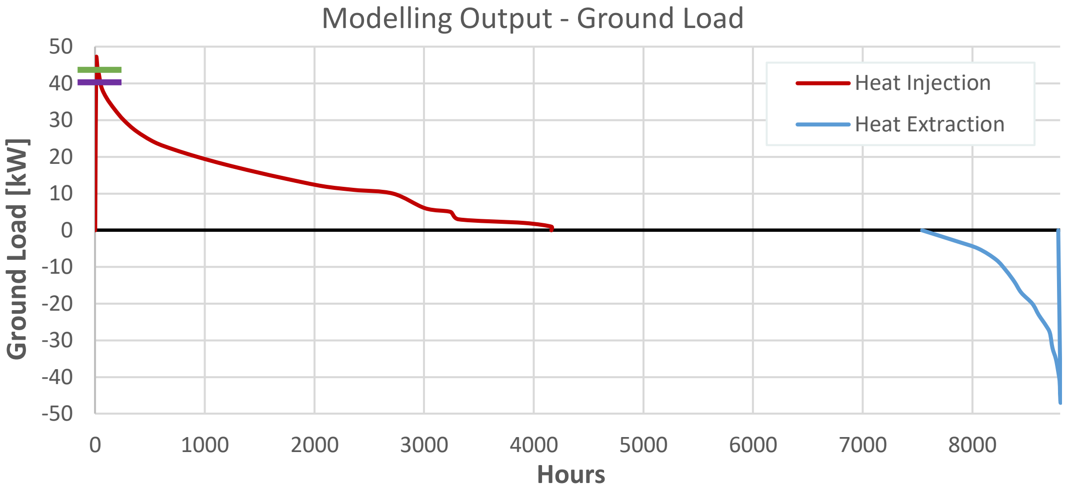

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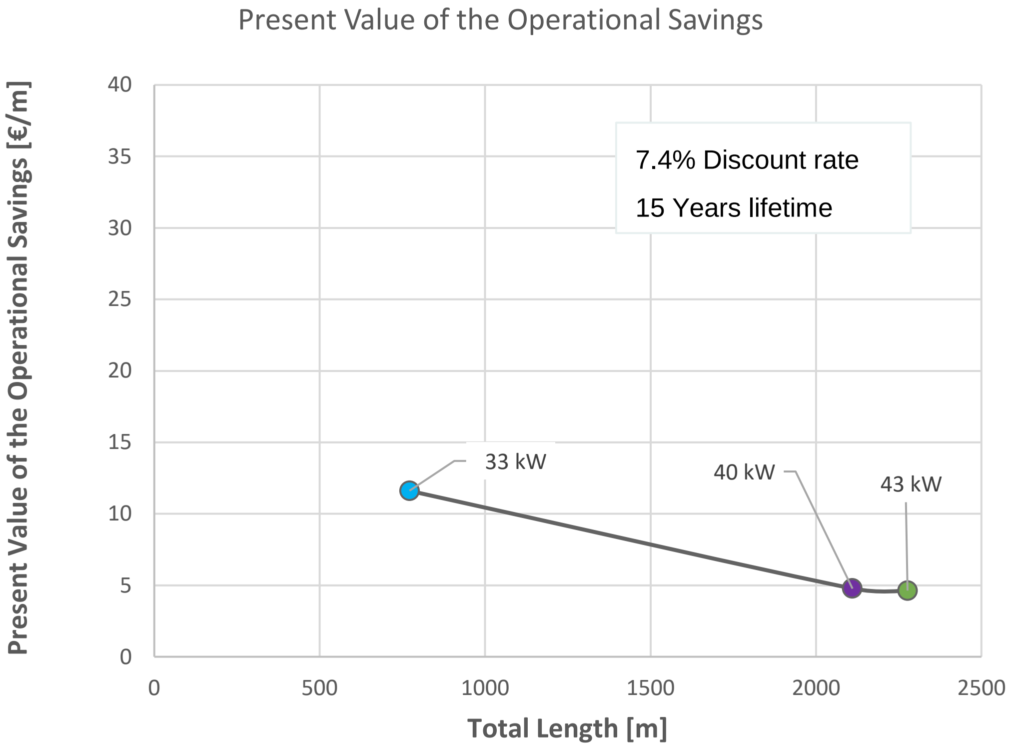

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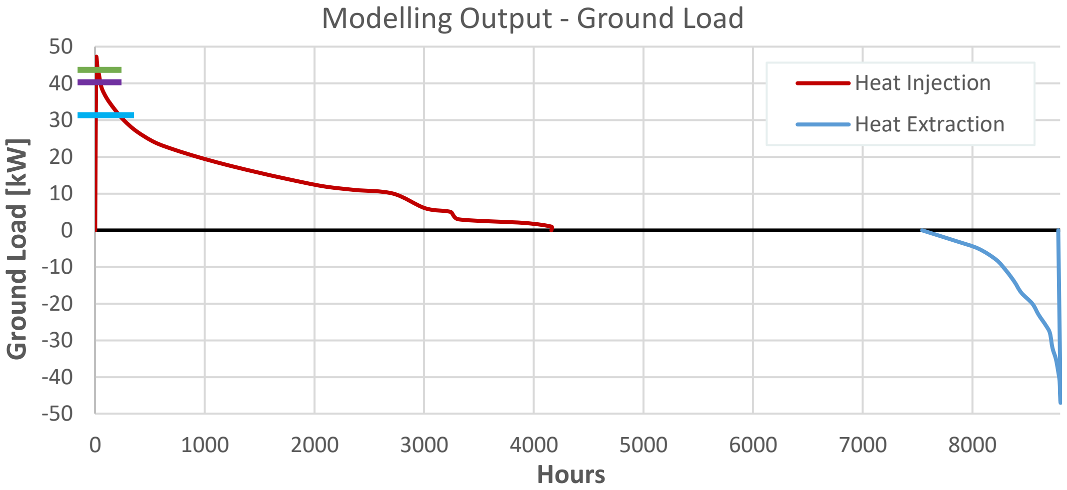

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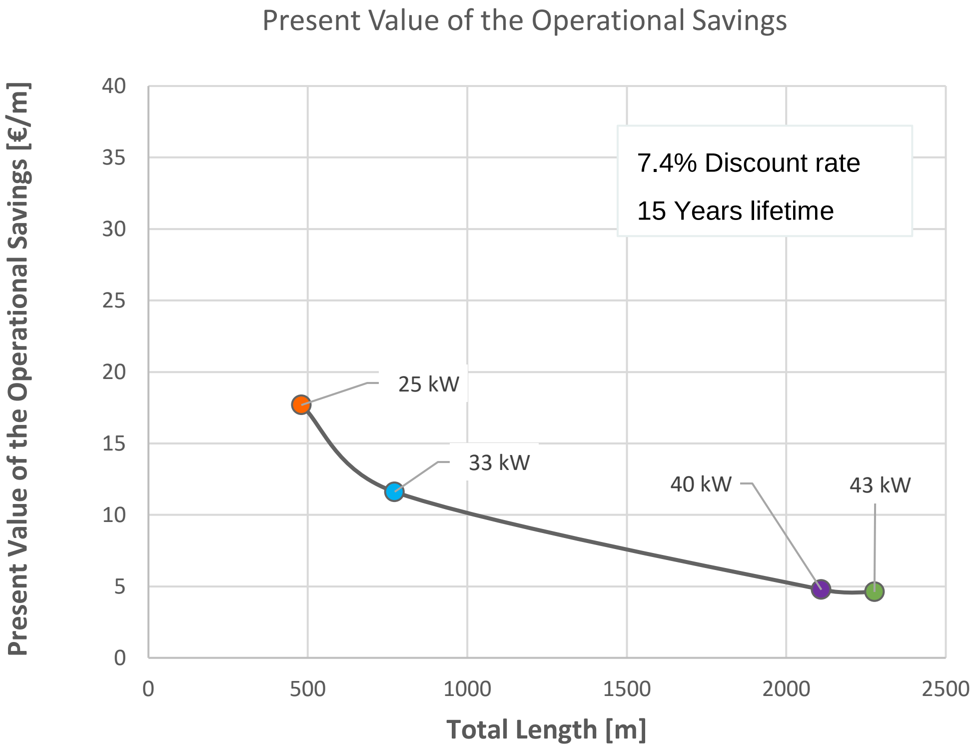

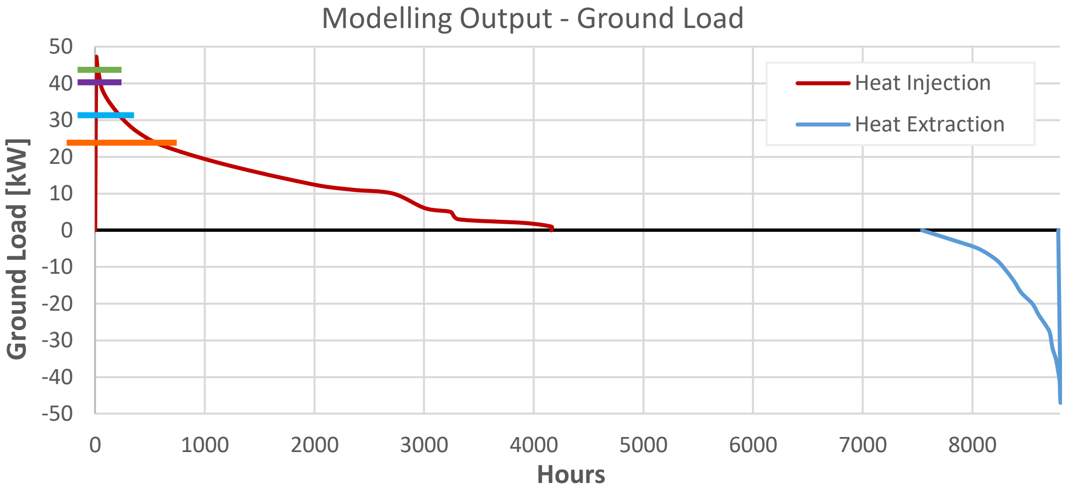

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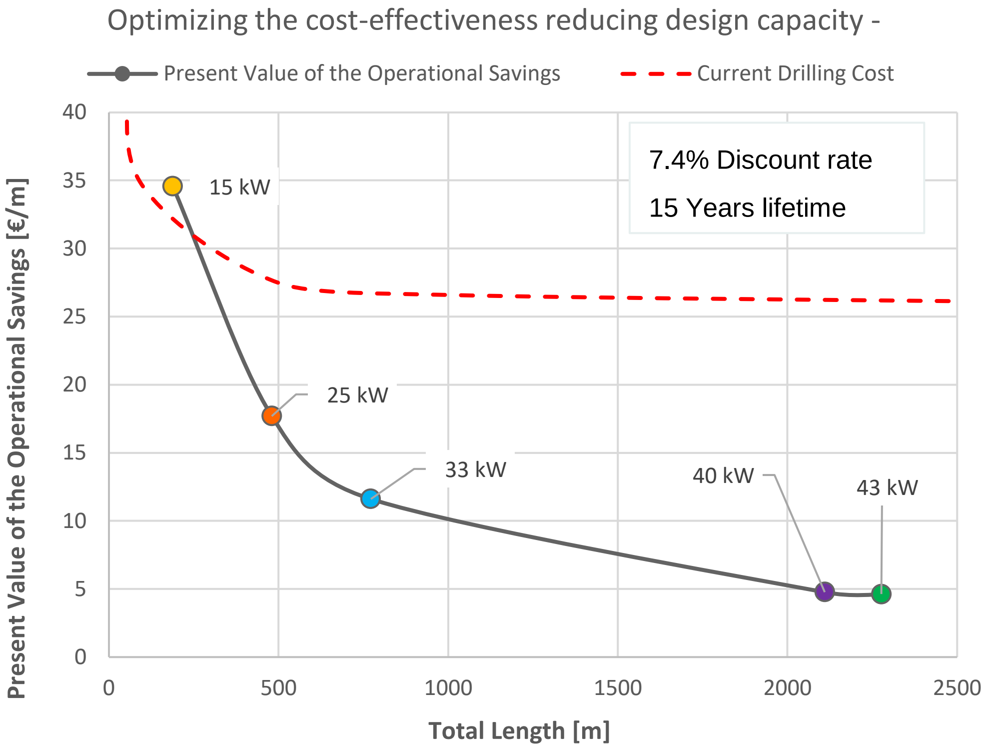

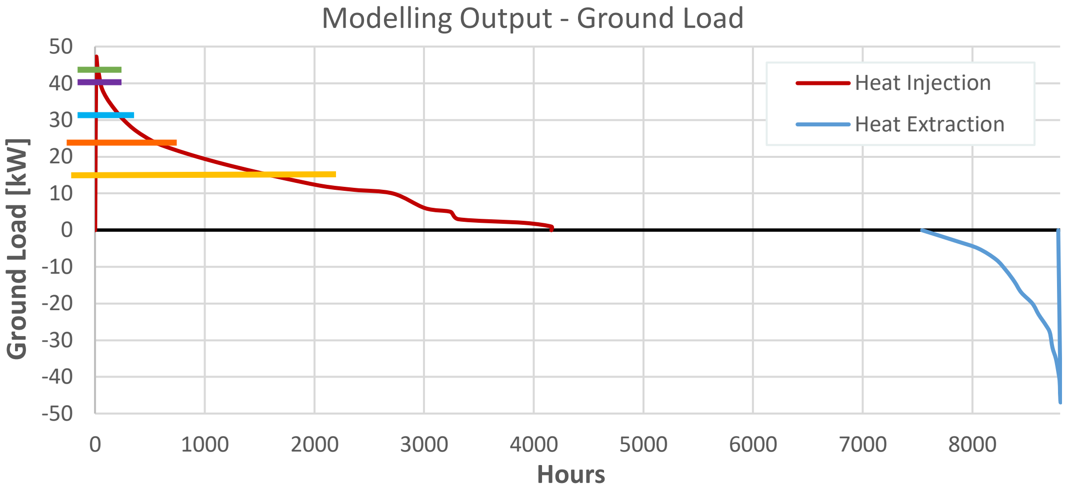

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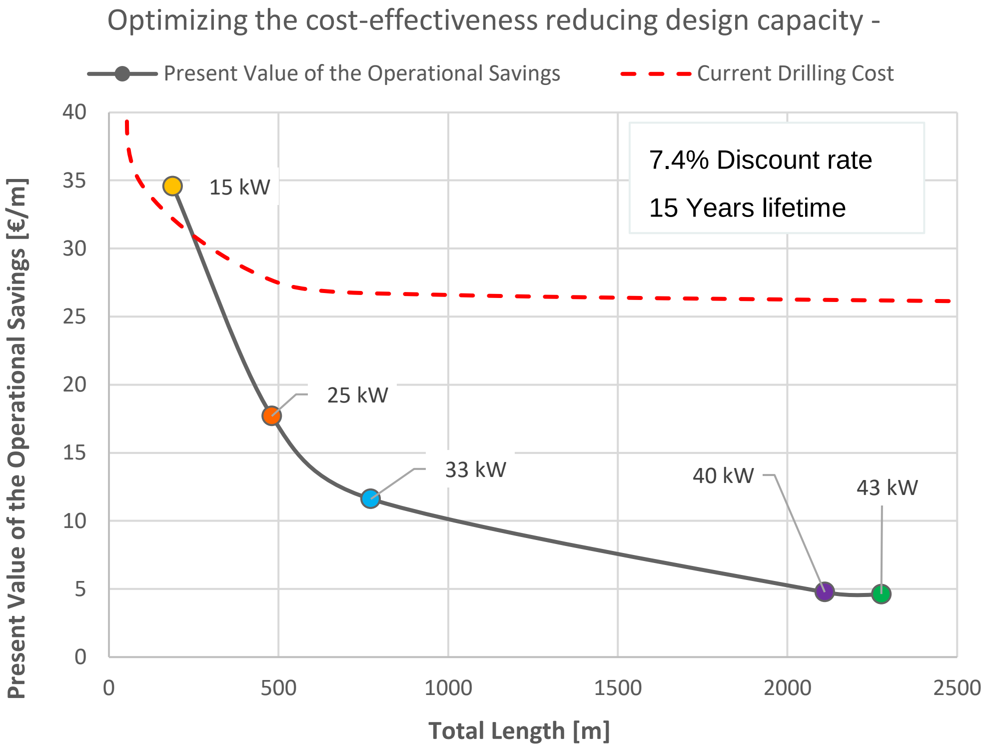

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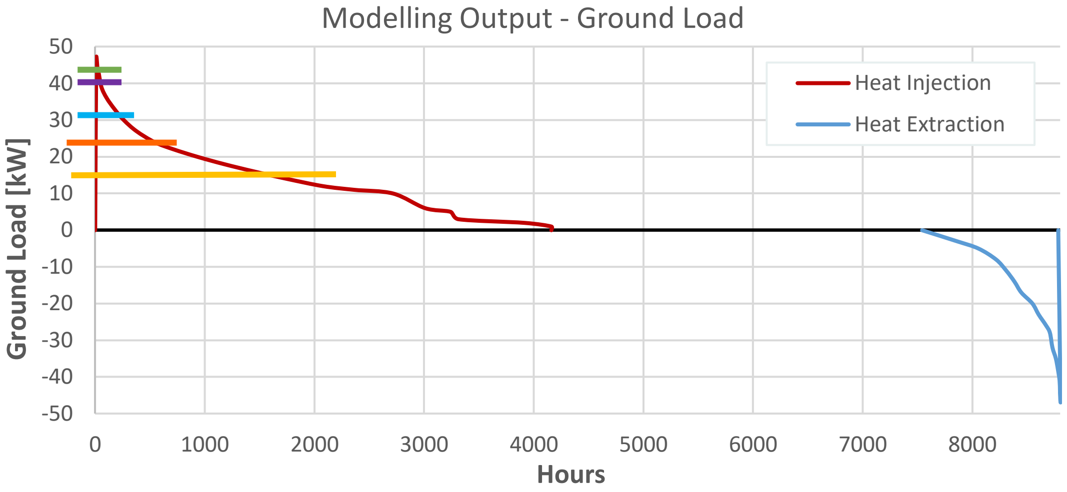
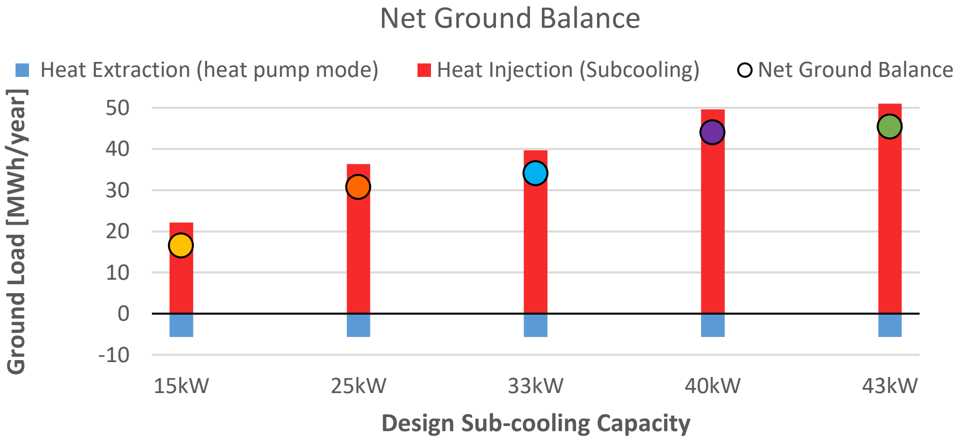
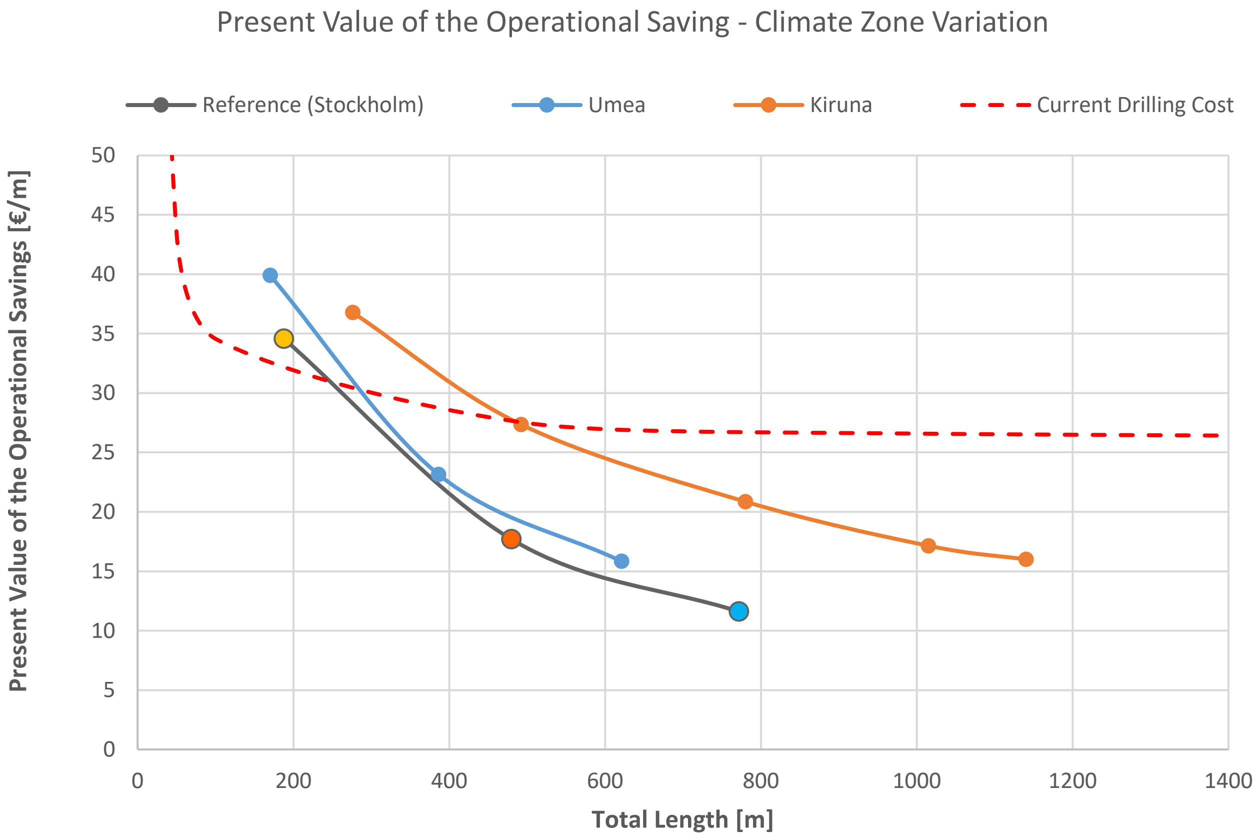


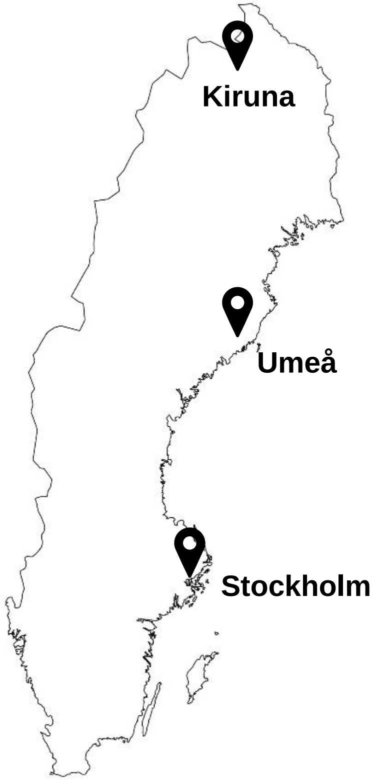


Sensitivity Analysis – Supermarket size

Different cooling demand profiles were tested, varying the other parameters proportionally (e.g. heating demand).

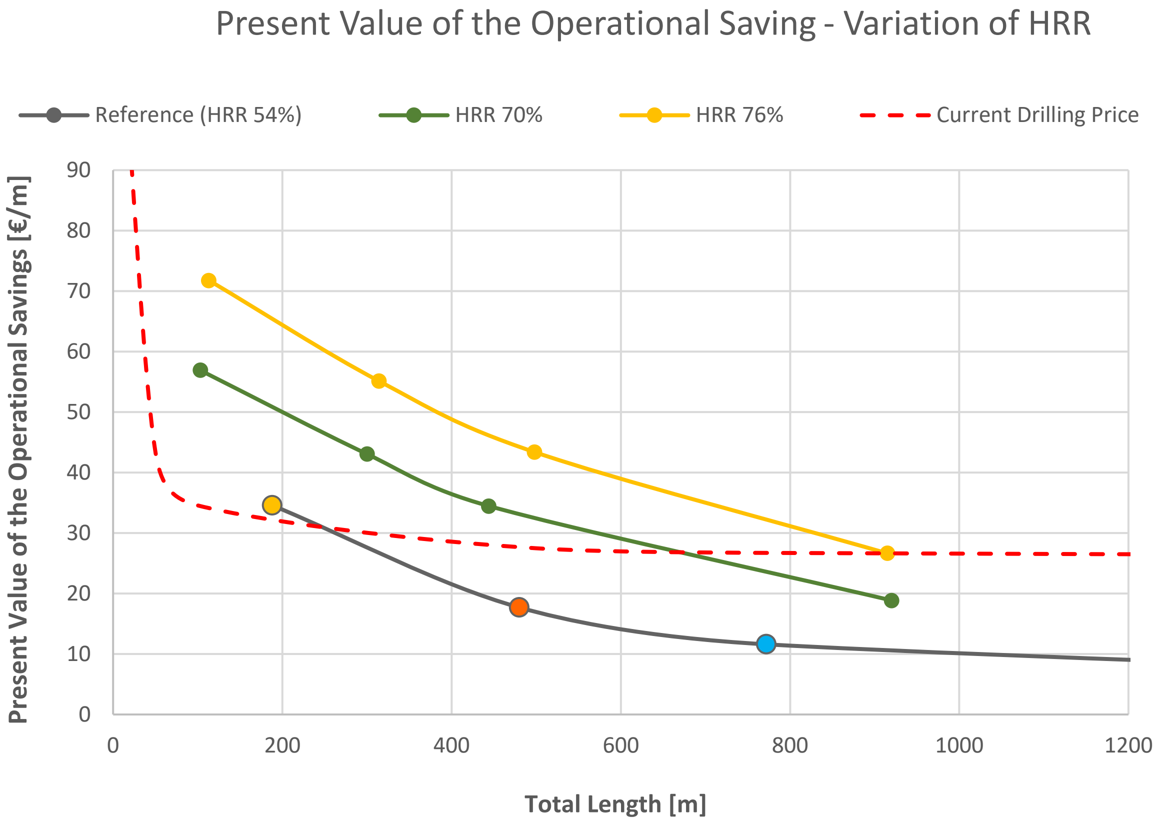
Sensitivity Analysis – Climate zone



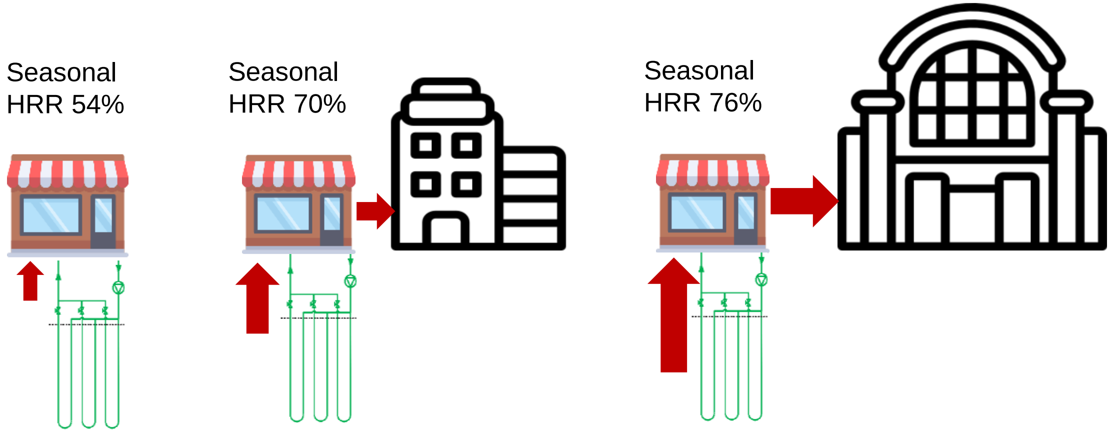


Different climate zones were tested. This was performed using BIN hours from other climate zones.

Sensitivity Analysis - Heat Recovery Ratio



$$HRR = \frac{Heat\ Recovered}{Total\ Cooling\ Load}$$



*Different values of heat recovery ratio were tested. A higher heat recovery ratio means operating a system with a higher heating demand for the same cooling load. Typical examples of systems operating with a high heat recovery ratio are **supermarkets embedded in shopping malls or ice rinks exporting heat to the neighbouring facilities.***

Conclusion

- The COP heat recovery can compete with the most modern heat pumps
- The **operational savings only do not pay back the installation cost.** There must be **savings on the CAPEX** when **comparing alternatives** for satisfying the peaks of heating demand.
- The average **HRR is the parameter** affecting the cost-effectiveness the most

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Future Work:

- Is it possible and profitable to use these systems for **exporting heat to district heating networks** in **power-to-heat** applications?
- Is it cost-effective to use **air-to-CO_2 load evaporators** instead of a geothermal integration?

Thank You!

Questions?

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