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Køle- ogvarmepumpeforum 2023 - Update on Technical Application Advancements & 8thInternational Symposium on Advances in Refrigeration and Heat Pump Technology

Collection of presentations

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Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

DTU Construct
Department of Civil and Mechanical Engineering

Køle- og Varmepumpeforum 2023

2023 Update on Technical Application Advancements & 8th International Symposium on Advances in Refrigeration and Heat Pump Technology

Collection of presentations

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2023 Update on Technical Application Advancements &
8th International Symposium on Advances in Refrigeration and Heat Pump Technology

Collection of presentations
March 2023

By
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Published by: DTU Construct, Koppels Allé 404, DK-2800 Kgs. Lyngby Denmark
www.construct.dtu.dk

Preface

Køle- og Varmepumpeforum was held for the third time on March 23, 2023. As organizers, we once again were happy to observe that the event seems to be attractive for the community working in the field and that more than 200 participants joined the meeting.

The event is a joint meeting consisting of two tracks. Update on Technical Application Advancements is organized by DKVF and Dansk Køl & Varme. It is focused on presenting the state of the art in the field of refrigeration and heat pumps, while the Symposium on Advances in Refrigeration and Heat Pump Technology is arranged by DTU and the Danish Technological Institute with a focus on disseminating new results from research and development projects partly funded by public sources like EUDP, Elforsk and the Danish Independent Research Council.

In addition to the two tracks, the day covers plenary keynotes. This year Bente Tranholm Schwarz from the European Commision, DG Clima, gave the main keynote talk on the status of European Policy in the field of refrigerants, in particular the F-Gas regulations.

Wiebke Meesenburg from DTU and Wiebke Brix Markussen from Danish Technological Institute held a mini keynote with focus on recruitment of women to the sector. This inititative was continued by a networking dinner after the main event.

For the Symposium track, Veronika Wilk from Austrian Institute of Technology gave the keynote talk on Digitalization and Internet of Things for Heat Pumps which is also the topic of an ongoing annex under the International Energy Agency Program for Heat Pumping Technologies.

It was a pleasure to be able to include the event DKVF Best student project award into the program again. Four candidates had been nominated by their university supervisors. The DKVF-appointed committee decided to give the award to Rikke Cilius Pedersen from DTU.

This collection includes all presentations from the day as well as the four student award posters.

The organizers thank all speakers and participants for their contribution to making the day a success, which it was a great pleasure for us to be allowed to organize.

Dansk Køl & Varme
Søren Bülow

DKVF Dansk Køle- og Varmepumpeforening
Jonas Sønder Nielsen
Kristian Fredslund

Danish Technological Institute
Claus Schøn Poulsen
Wiebke Brix Markussen

DTU Construct
Jonas Kjær Jensen
Brian Elmegaard

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1 Keynotes Køle- og varmepumpeforum 2023

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EUROPEAN GREEN DEAL

Future F-gas rules & their impact on refrigeration and heat pumps

Bente Tranholm Schwarz, European Commission
Refrigeration and heat pump forum,
Copenhagen 23 March 2023

Paris Agreement – global goals

- Mitigation (reducing emissions)
  - Limit temperature rise to well below 2C and pursue efforts to limit it to 1.5C compared to pre-industrial times
- Adaptation
  - Enhance adaptive capacity, strengthen resilience and reduce vulnerability to climate change

PARIS2015
UN CLIMATE CHANGE CONFERENCE
COP21·CMP11

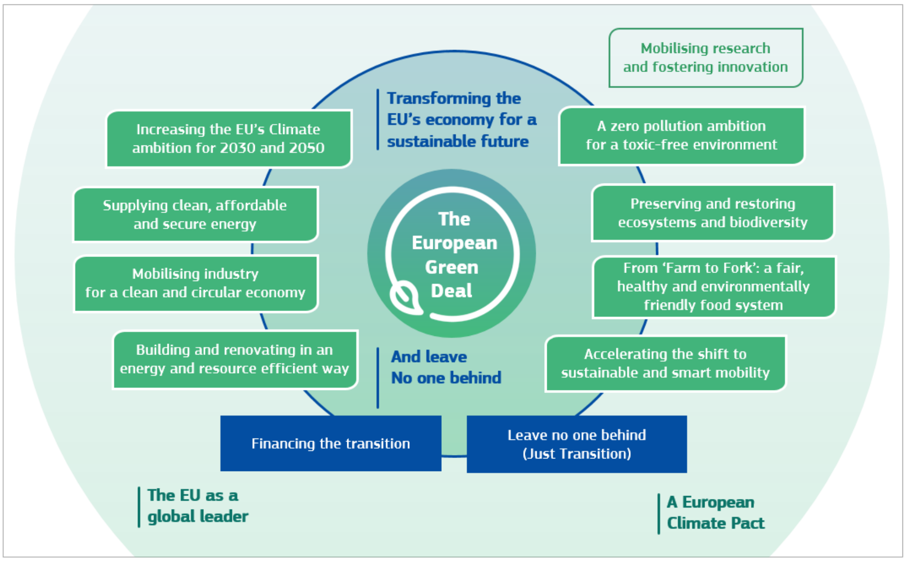
European Commission

Global phase-down of hydrofluorocarbons (HFCs)

- The **Montreal Protocol**, on protecting the ozone layer, was extended to include HFCs (**Kigali Amendment 2016**)
- It means all countries in the world must **gradually limit their production and use of highly-warming hydrofluorocarbons (HFCs) => Business oportunity**
- The Kigali Amendment can **potentially reduce global warming by up to 0.5ºC by 2100,** compared to business-as-usual
- This will **contribute to achieving the Paris Agreement Goals**

European Commission

The **European Green Deal**



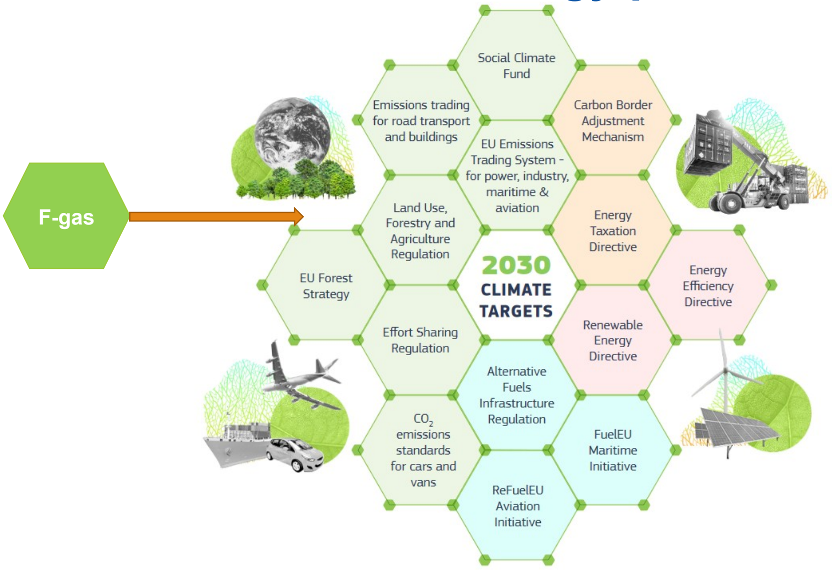
European Commission

The European Climate Law

- The European Climate Law Regulation of 30 June 2021
- Union-wide climate-neutrality objective 2050
- New **2030** target of at **least 55% net** greenhouse gas emissions reduction
- Recognition of the need to enhance the EU's **carbon sink**

European Commission

EU climate and energy polices & …



European Commission

& REPowerEU to reduce EU dependency

- Russia's unjustified military aggression against Ukraine, triggering price volatility and energy insecurity.
- REPowerEU = Roadmap to reduce dependency on Russian fossil fuels based on 3 pillars:
  - Higher energy savings
  - Diversification
  - Massive acceleration in investments in renewables,

European Commission

Repower EU & heat pumps

- Increase renewable energy to 45% of the energy mix by 2030
- Increase energy efficiency 11.7% by 2030 compared to 2020
- Need around 30 million new heatpumps by 2030

  → Huge business opportunity for the sector

- **New production capacity must be future-proof!**
- **Upcoming Commission Action Plan for heat pumps**.

European Commission

The F-gas policy & European Green Deal / REPowerEU

- New F-gas rules are part of the "honeycomb of measures" to achieve the 2030 and 2050 climate objectives!
- F-gas emissions count under the Member States' emission reduction targets for sectors not covered by the EU emission trading system!
- High deployment of energy efficient AC/heat pumps is essential to achieve GHG emission savings from buildings and reduce dependency.
- Energy efficiency first

European Commission

Building on a successful F-gas rules

Regulation (EU) No 517/2014

Some highlights: within 5 years only (2015-2019)

- EU F-gas demand dropped 13%, HFC demand dropped 47% (CO_2e)
- F-gases in imported equipment dropped by 33% (CO_2e)
- Emission in the refrigeration sector dropped 62% (CO_2e)
- More reclaimed gases and smaller leakage rates
- The F-gas Regulation has been an innovation driver:

Quotes from industry stakeholders:

"EU F-gas Regulation is the Gold Standard" or

"EU F-gas Regulation is in fact a World F-gas Regulation"

European Commission

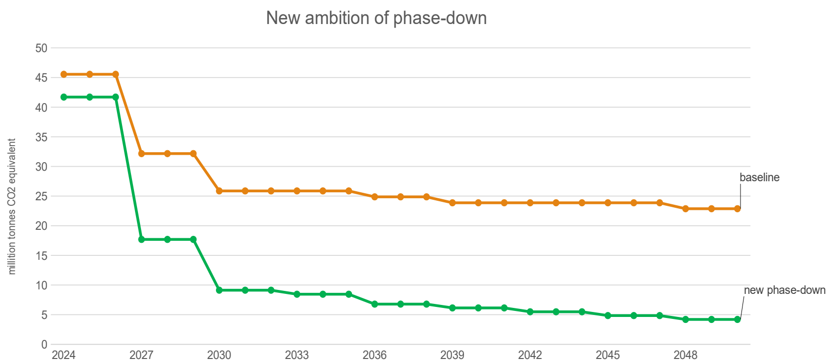
Main proposed changes to the F-gas rules

- Additional Placing on the market and use prohibitions
- Less annual quota in the HFC phase-down and quota is needed for supply to more sectors
- New HFC Quota allocation price of 3 €/tCO2
- Extending containment measures (certification and training attestation, leak checks …) to more activities and gases
- Clearer provisions for customs + “harmonised “ penalties

European Commission

The proposed HFC phase-down (quota system)

Potential climate impact of new HFCs coming onto the EU market to be reduced by almost 95% in 2030 and 98% from 2015 to 2050



Approximation taking into account the inclusion of HFC equipment in 2017 and MDI HFC use from 2024.

European Commission

Some important new prohibitions in the Commission's proposal

***In addition to strict HFC phase-down** (bans steering demand)*

- Switchgear between 2026 to 2030 (GWP ≥ 10 or ≥ 2000 or …]
- Self-contained AC & heat pumps from 2025 (GWP 150*)
- AC & heat pumps split systems < 12 kW from 2027 (GWP 150*)
- AC & heat pumps split systems >12 kW from 2027 (GWP ≥ 750*)
- Use of gases GWP ≥ 2500 in smaller refrigeration equipment (charge size also below 40 tCO_2e

* Possible to go above GWP limit if safety requires.

European Commission

Consistency with REPowerEU

Commission proposal took the HFC need related to high heat pump growth into account in its F-gas proposal by:

- Setting prohibition dates that allow sufficient time for increasing/ adapting manufacturing capacity to solutions that already exist.
- Having an economy wide phase-down, with likely quota buffers (i.e. HFC demand from other sectors will be lower than estimated).
- Costs to consumers will not increase overall.
- Using less HFCs means reducing our dependency on third countries.

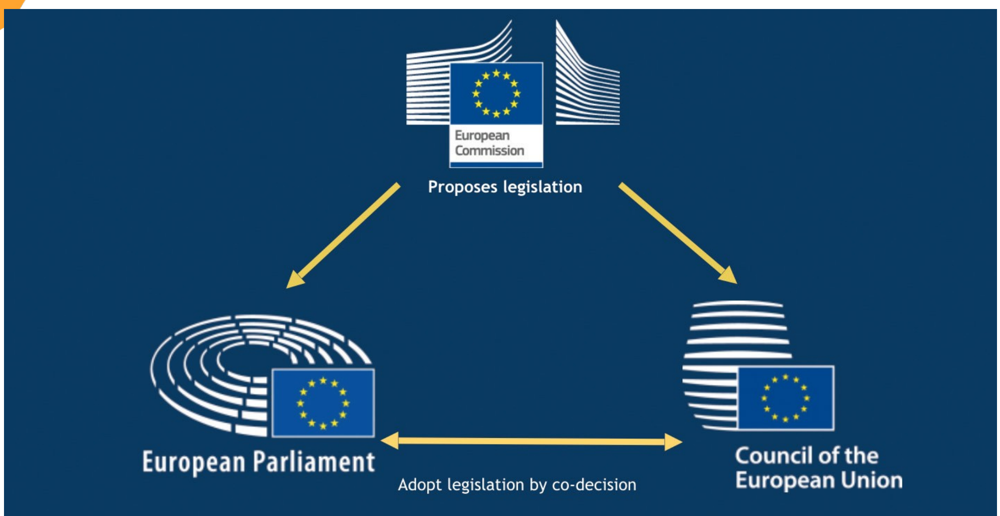
European Commission

Impacts of the proposal

- **Emission reductions:** Avoid cumulatively 310 MtCO2e on top of the 420 MtCO2e achieved through current Regulation by 2050 (i.e. in total same as GHG emissions in 2019 in BENELUX + FRANCE)
- **Climate neutrality**: Emissions in 2050 estimated to be 14 MtCO2e (92 MtCO2 in 2019).
- **Overall costs** to consumers will be moderate and even negative due to energy savings in refrigeration and AC
- **Reducing HFC use = lowering EU dependency** on imports
- **Better control** and less illegal trade
- Green **innovation and growth.** Enabling companies to make the shift to climate-friendly alternatives now = first mover advantage.

European Commission

Commission's F-gas Proposal - just the start



European Commission

The negotiations

- **Council (Member States)** : Soon agreeing on a mandate for their negotiations with the European Parliament
- **European Parliament:**
  - Voted amendments to the Commission's proposal in the Environment, Public Health and Safety (ENVI) Committee 1 March
  - Vote in Plenary 29 March => their mandate to negotiate with the Council.
- **Negotiations** between the Council, Parliament and Commission starting soon – outcome ???
- Adoption date and entry into force ?????

European Commission

Where is the European Parliament heading?????

ENVI Amendments to the Commission's proposal (voted yes to 76 amendments)
European Parliament vote on 29 March ???

(17) Plug-in room, ***monoblock*** and other self-contained air-conditioning and heat pump equipment that contain fluorinated greenhouse gases.	1 January ***2026***
(18) Stationary split air-conditioning and split heat pump equipment: (a) Single split systems ***including fixed double duct systems*** containing less than 3 kg of fluorinated greenhouse gases listed in Annex I, that contain, or whose functioning relies upon, fluorinated greenhouse gases;	1 January ***2027***
(b) Split systems of a rated capacity of up to and including 12 kW containing, or whose functioning relies upon, fluorinated greenhouse gases; (c) Split systems of a rated capacity of more than 12 kW ***and up to 200 kW*** containing, or whose functioning relies upon, fluorinated greenhouse gases with GWP of 750 or more, except when required to meet safety standards. ***(ca) Split systems of a rated capacity of more than 200 kW containing, or whose functioning relies upon, fluorinated greenhouse gases.***	1 January ***2028***

What will Council agree on in their mandate????

European Commission

Where is the European Parliament heading?????

ENVI Amendment proposal to the Commission's proposal
European Parliament vote on 29 March ????

(14a)	*Stationary refrigeration equipment, that contains, or whose functioning relies upon, fluorinated greenhouse gases.*		*1 January 2027*
(15a)	*Transport refrigeration*	*in vans and ships that contain, or whose functioning relies upon, fluorinated greenhouse gases.*	*1 January 2027*
		in trucks, trailers and reefer containers that contains, or whose functioning relies upon, fluorinated gases	*1 January 2029*
(23a)	*Mobile air conditioning in passenger and cargo ships, buses, trams, and trains that contain, or whose functioning relies upon, fluorinated greenhouse gases.*		*1 January 2029*
(23b)	*Mini, displacement and centrifugal chillers that contain, or whose functioning relies upon, fluorinated greenhouse gases.*		*1 January 2027*

What will Council agree on in their mandate????

European Commission

Where are you heading?

- Using a refrigerant with the lowest possible global warming potential that is as energy efficient as the traditional HFC refrigerant.
- Become or continue to be a first mover!

European Commission

The European Green Deal
Is the
EU’s growth and innovation strategy

European Commission

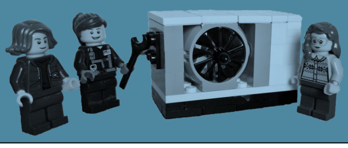
Thank you

European Commission

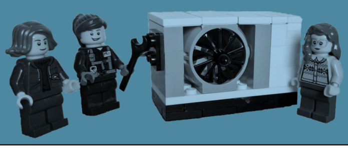
Women in refrigeration and heat pump technology

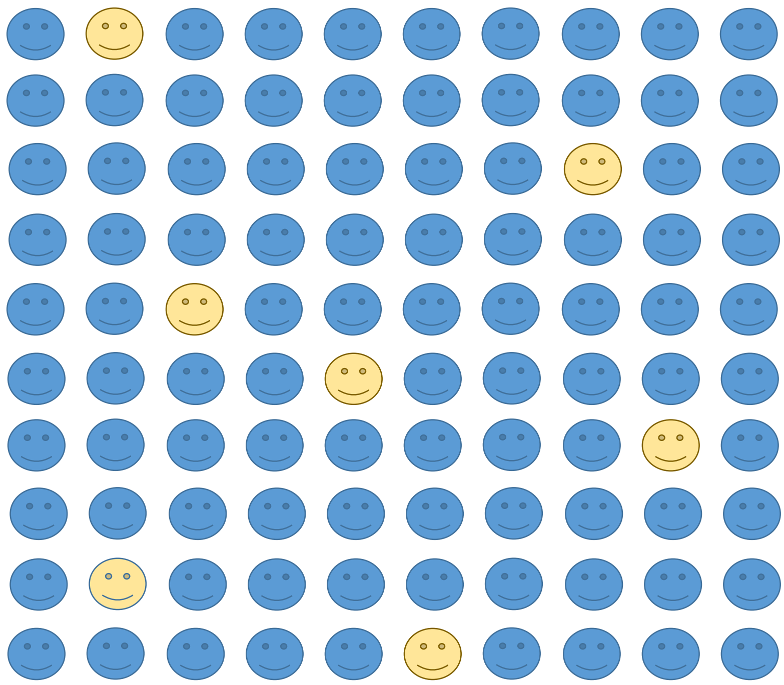
Wiebke Meesenburg and Wiebke Brix Markussen

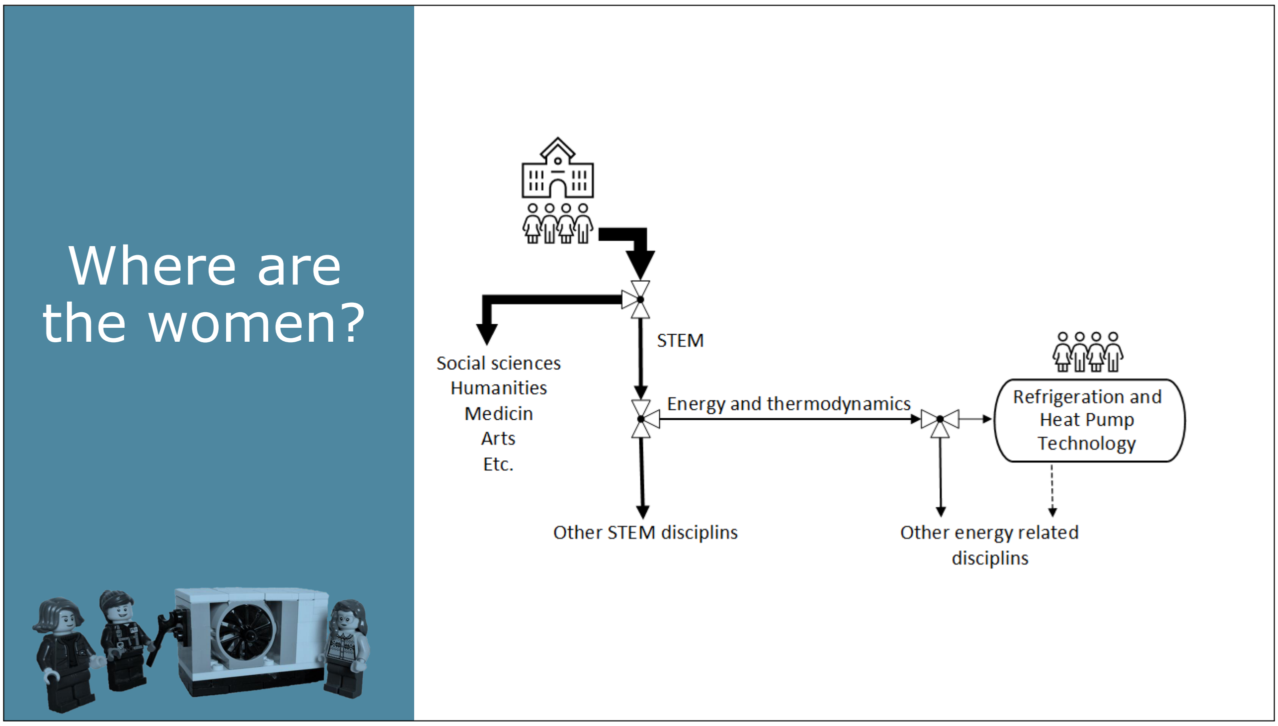
Køle- og Varmepumpeforum 2023

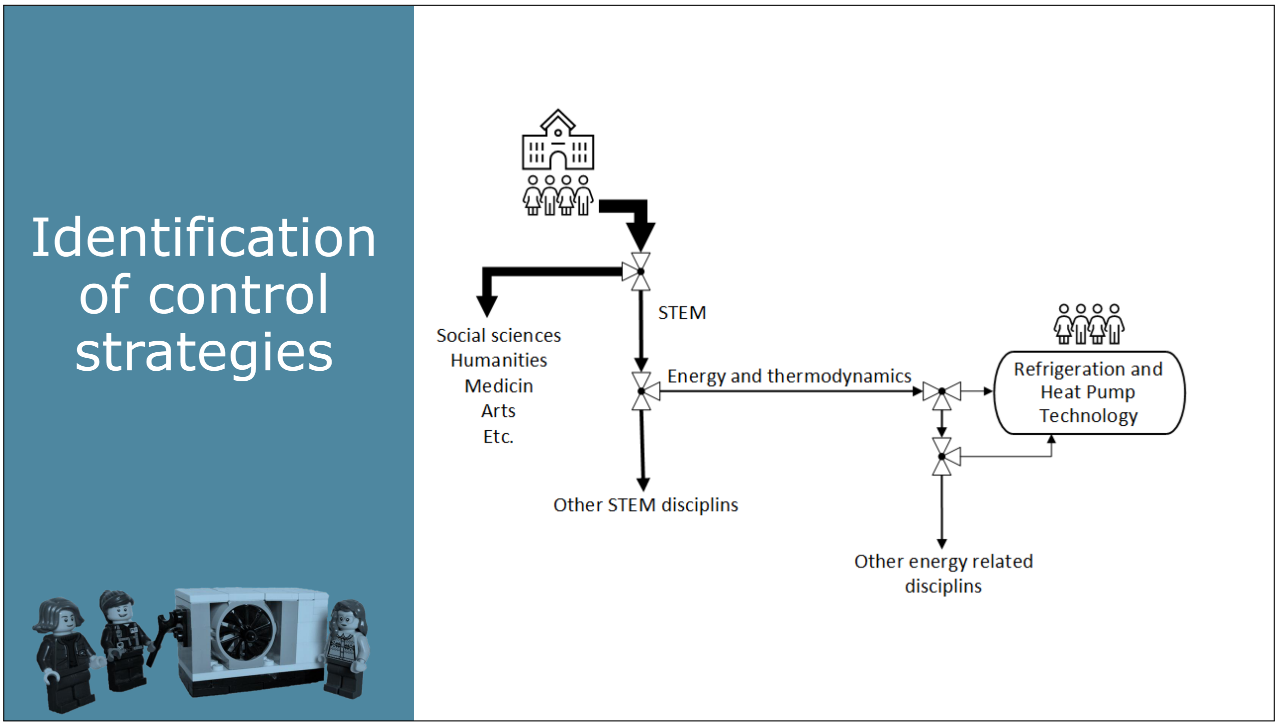


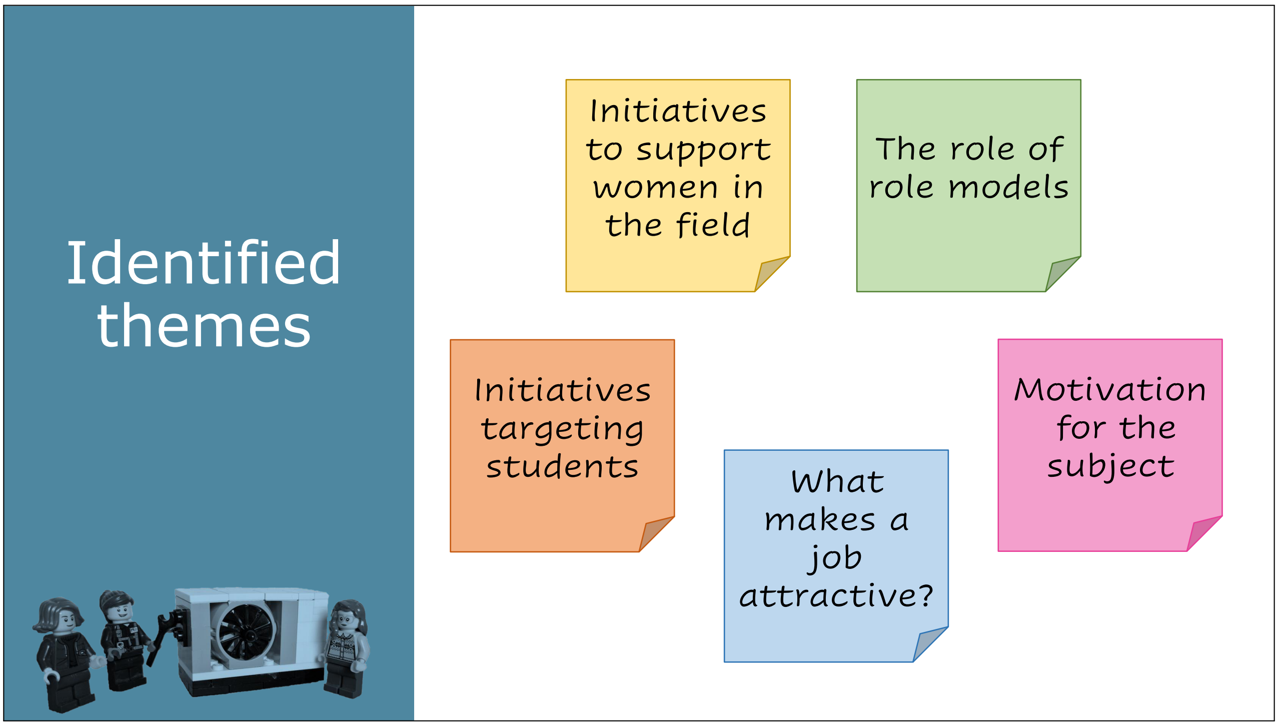
Where are the women?

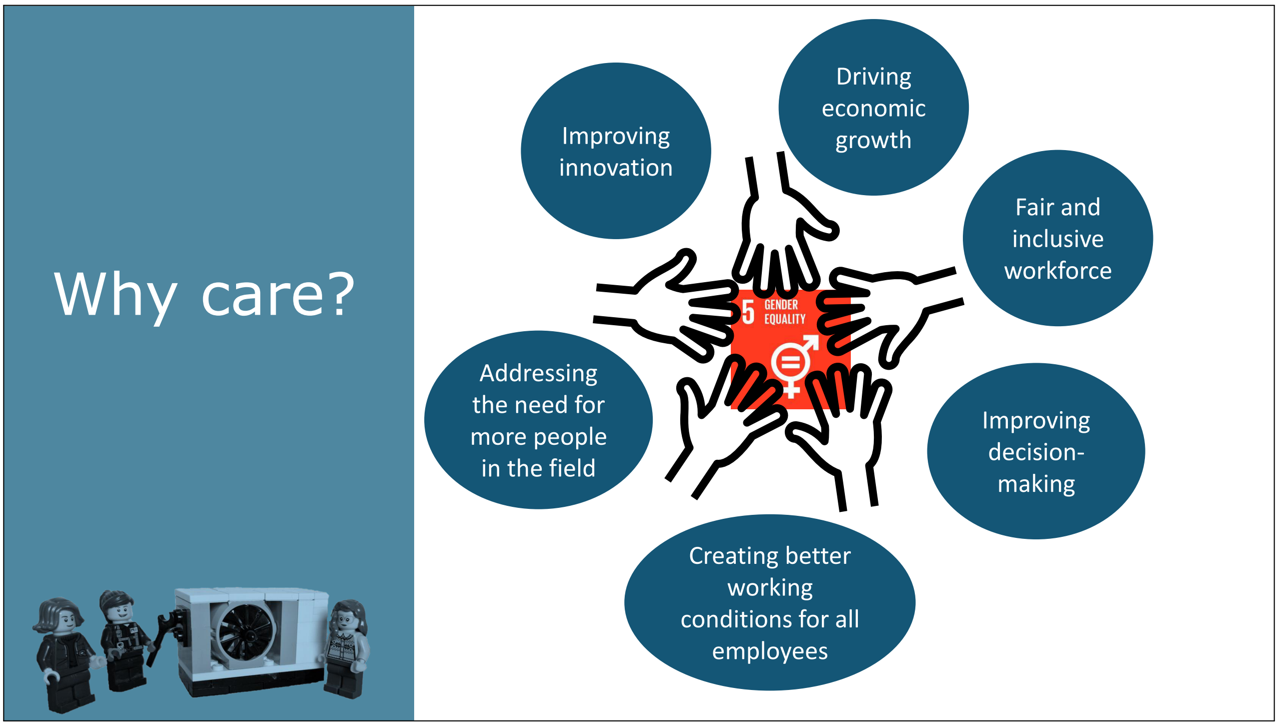





Where are the women?
STEM
Social sciences
Humanities
Medicin
Arts
Etc.
Energy and thermodynamics
Refrigeration and Heat Pump Technology
Other STEM disciplins
Other energy related disciplins


Identification of control strategies
STEM
Social sciences
Humanities
Medicin
Arts
Etc.
Energy and thermodynamics
Refrigeration and Heat Pump Technology
Other STEM disciplins
Other energy related disciplins


Identified themes
Initiatives to support women in the field
The role of role models
Initiatives targeting students
What makes a job attractive?
Motivation for the subject


Why care?
Improving innovation
Driving economic growth
Fair and inclusive workforce
Addressing the need for more people in the field
Improving decision-making
Creating better working conditions for all employees
5 GENDER EQUALITY

And what does ChatGPT say about this?

There once was a field quite chilly

Where women were scarce, oh so silly

But as they increased in number

Innovation did no longer slumber

And the industry thrived, oh so willy-nilly!

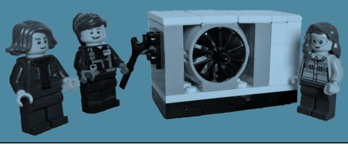
Thank you for your attention!

Role of role models

Role models are people that inspire us and from whom we may learn how to deal with different situations or problems. Here, we want to discuss the role of role models and how we can support women to find role models within the field that they can mirror themselves in.

Questions

- Did you have a role-model when you entered the field of refrigeration and heat pump technology?
- How could you make female role models visible in your company?
- How could a network for women in refrigeration and heat pump technology help to highlight career opportunities for women in the field?
- How could a mentoring program targeting young women look like?

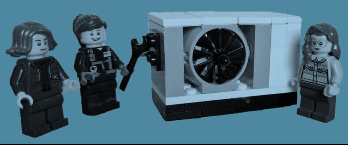


Role of role models

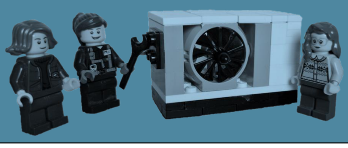
Inspirational quotes

"Half of the women had no role model. The ones who had a role model had been influenced by either someone working in the RACHP sector, a teacher or a family member. Actually, the top three factors that had influenced their decision to pursue a RACHP career were (1) someone already working in the RACHP sector, (2) individual initiative through reading and research and (3) school." (Women in Cooling – a Worlwide survey)

"In addition to gender-specific stereotypes, the interest of young women in STEM-education is reduced by anticipated and experienced male-dominated corporate cultures and a lack of role models (Solga & Pfahl, 2009). According to a recent study, the schoolgirls interviewed know hardly any female role models who practice a STEM profession, while male friends or relatives in STEM professions were known almost twice as often (IU Internationale Hochschule, 2022)." (Translated from German, Impuls-Studie)



Motivation of the topic

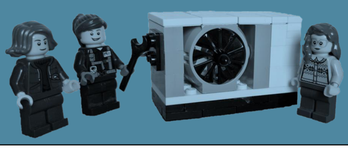


To attract more (female) engineers and technicians, it is important to highlight what is interesting and relevant about working with refrigeration and heat pump technology. Here, we want to gather what motivates us to work with these topics and which aspects are important to highlight in communication.

Questions

- What motivated you when you first chose to pursue a career within refrigeration and heat pump technology?
- What motivates you today to stay in the field of refrigeration and heat pump technology?
- Would you expect a difference between what motivates different genders?
- Which aspects would be relevant to communicate on company web pages and in job advertisements to attract more (female) applicants?

Motivation of the topic



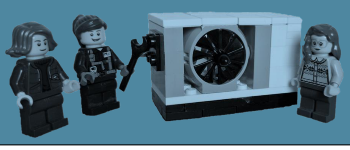
Inspirational quotes

"Diegmann et al. (2017) report that young women have insufficient knowledge about the specific areas of activity in engineering professions. Their surveys show that girls hardly notice any social and creative references to STEM professions. According to current findings, direct insights into the job description through internships and summer jobs as well as discussions with people from the immediate environment seem to be particularly decisive for the choice of a technical education (IU Internationale Hochschule, 2022)." (Translated from German, Impuls-Studie)

"Women were mostly motivated by the environmental impact of a career in RACHP, the feeling of carrying out work that is useful to society, the fact that is an interesting subject area, the diversity of roles available and the job security associated with the sector. Interestingly, earning the respect of their colleagues represented the proudest career achievement for many women. Previous studies have shown that support from co-workers, namely male colleagues, is crucial to maintain women in engineering positions and further their careers." (Women in Cooling – a Worlwide survey)

What makes a job attractive

What makes a job attractive for you? Here we want to gather, how the everyday life at work should look like to be attractive for (female) employees. We gather concrete ideas, how workplaces within the field can become even more attractive and how this can be communicated.



Questions

- Which aspects make your job attractive on a daily basis?
- How would an ideal work day/ work place look like for you?
- Which aspects make your job attractive on a superior level?
- Would you expect a difference between what employees of different gender value in a job?
- What initiatives could increase the attractiveness of a job for all genders?

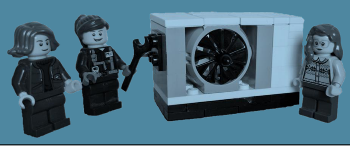
What makes a job attractive

Inspirational quotes

"The further development of technical expertise through training, education and further education was particularly important for many female engineers who took part in our study and decisive for whether they felt valued in the company." (Translated from German, Impuls-Studie)

"The interviews show that many female engineers would like companies to rethink an equal distribution of parental leave between fathers and mothers. In their opinion, both female and male employees should be able to take parental leave without prejudice. In order to actively encourage fathers to take parental leave over a longer period of time, the interviewed engineers believe it is important to create incentives within the company and to dispel prejudices." (Translated from German, Impuls-Studie)

Initiatives to support women in the field



Here, we want to discuss ideas for specific initiatives that companies can take to become (even) more attractive for female employees at all stages of their career.

Questions

- Which initiatives could help to attract more female applicants for job openings?
- Which initiatives could help to retain female employees?
- Which initiatives could help attracting women working in related industries to the field of refrigeration and heat pump technology (change of industry)?
- How could a network for women in refrigeration and heat pump technology help to retain female employees in the field?

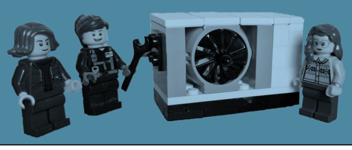
Initiatives to support women in the field

Inspirational quotes and examples

- “The (red: German) mentoring program Femtec.Alumnae Mentoring (FAMe), for example, is aimed at young professionals who are assigned an experienced mentor. Mentor and mentee belong to different generations and professional groups. The support usually focuses on topics such as strategic career planning, professional and personal development, work-life balance, family and career.” (Translated from German, Impuls-Studie)

- “The further development of technical expertise through training, education and further education was particularly important for many female engineers who took part in our study and decisive for whether they felt valued in the company." (Translated from German, Impuls-Studie)

Initiatives targeting students



Here, we want to discuss ideas for specific initiatives that companies, organizations and universities can take to arouse the students' interest for the field of refrigeration and heat pump technology.

Questions

- Which initiatives could help to clear the picture of the "type of work" carried out in the refrigeration and heat pump technology field?
- Which initiatives could widen the students' knowledge about companies in the field?
- Which initiatives could be made on a company level?
- Which initiatives could be made on a school/university level?

Initiatives targeting students

Inspirational quotes and examples

- “Diegmann et al. (2017) report that young women have insufficient knowledge about the specific areas of activity in engineering professions. Their surveys show that girls hardly notice any social and creative references to STEM professions. According to current findings, direct insights into the job description through internships and summer jobs as well as discussions with people from the immediate environment seem to be particularly decisive for the choice of a technical education (IU Internationale Hochschule, 2022).” (Translated from German, Impuls-Studie)
- High-Five-Girls Mentoring: https://high5girls.dk/en/mentors/
- Competitions like: “Ambassador for a day” https://www.ambassadorforaday.dk/
- Science Day (former Girls’ Day in Science)

References

- (Impuls-Studie) Lea Daling, Johanna M. Werz, Paulina Blessing, Esther Borowski, Ingrid Isenhardt INGENIEURINNEN IM MASCHINEN- UND ANLAGENBAU FRAUEN FÜR TECHNISCHE BERUFE GEWINNEN UND HALTEN Qualitative Studie im Auftrag der IMPULS-Stiftung, Frankfurt/Main WZL | Lehrstuhl für Fertigungsmesstechnik und Qualitätsmanagement & IMA | Informationsmanagement im Maschinenbau RWTH Aachen University, 2023, https://impuls-stiftung.de/wp-content/uploads/2023/03/Ingenieurinnen-im-Maschinenbau_IMPULS-Studie-Februar-2023.pdf

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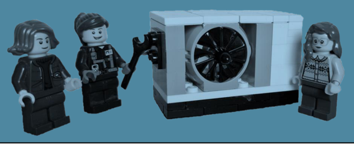


2 2023 Update on Technical Application Advancements

Contents

ADVANSOR

LT ONLY SYSTEMS AND EJECTORS

Kenneth Bank Madsen, 23.03.2023

ADVANSOR

Welcome

Kenneth Bank Madsen
Technical Director

kbm@advansor.com

Agenda

- LT only systems - Control of intermediate pressure – COP hunter
- Ejectors in LT only systems

ADVANSOR

Low Temperature Systems

Challenges

- Energy consumption on low temperature systems
- Discharge temperatures (moving to new markets with warmer climate)
- Condensation in Desuperheater in cold climate
- Unstable superheat on MT suction due to the use of liquid injection

Solution

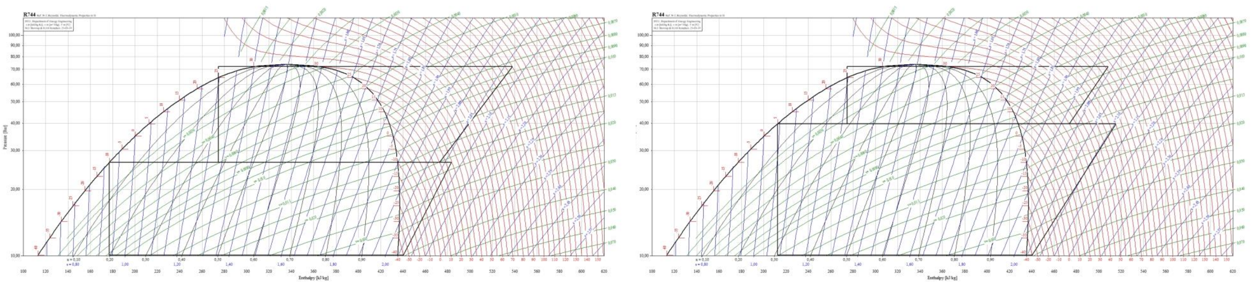
- Change of Control Strategy – COP Hunter
- New option for LT only systems – Liquid Power Cooler

ADVANSOR

INTERMEDIAT PRESSURE CONTROL
COP HUNTER

ADVANSOR

Intermediate pressure control



There is a COP optimal intermediate pressure that we are following but there are also other bennefits and drawbacks:

- Lower discharge temperature on HP stage at high intermediate pressure => Possible to opperate in warmer climate
- Less gas for recompression from expansion at high intermediate pressure => smaller HP compressors
- Less enthalpy difference in LT evaporator at high intermediate pressure => larger LP compressors
- Eliminate risk of condensation in desuperheater

ADVANSOR

New Control Strategy: COP Hunter

COP Hunter

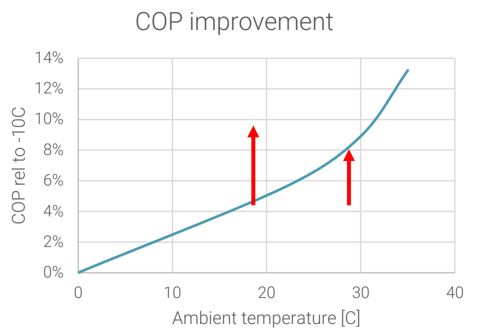
New control strategy of LT only systems, developed by Advansor - an algorithm that ensures maximum COP in all operation points.

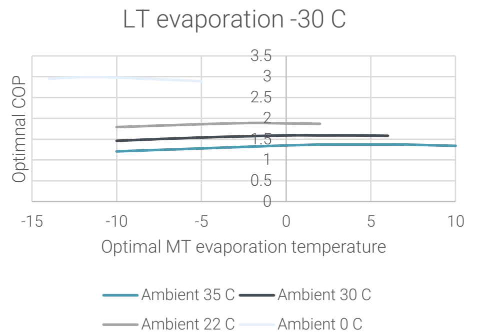
Benefits

- Minimum energy consumption
- Reduction of discharge temperature
- Reduced use of liquid injection
- Eliminate risk of condensation in the desuperheater
- Reduction of total m³/h on transcritical compressors

Downsides

- Higher mass flow in LT suction





NEW EJECTOR TECHNOLOGY “LIQUID POWER COOLER”

ADVANSOR

Energy optimization problems on LT systems

- In the last 10 years massive amounts on new technology has been added into transcritical CO_2 systems, like parallel compression and ejectors.
- This has helped transcritical CO_2 become competitive also on energy in warmer climates.
- None of the technologies apply on low temperature systems till now.

ADVANSOR

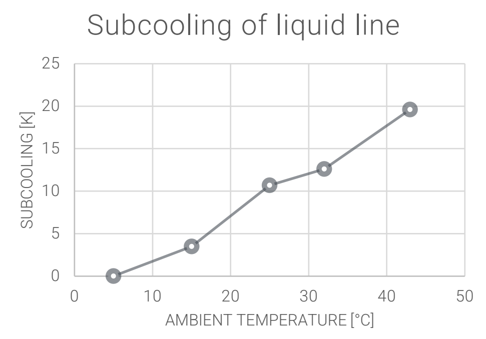
New Option: Liquid Power Cooler

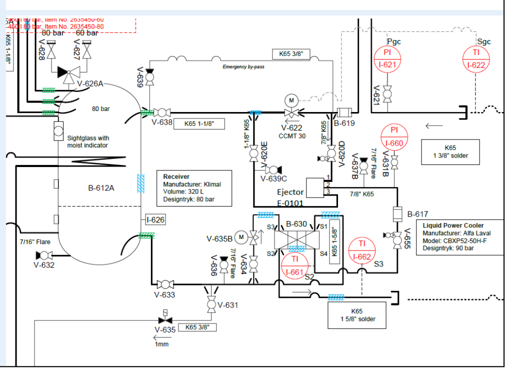
Liquid Power Cooler

System developed by Advansor making it possible to sub cool liquid line without compromising optimal receiver pressure.

Benefits

- Higher COP
- Increased capacity
- Mass flow reduction in liquid line
- The option fit on the rack
- Requires no start-up assistance
- No special installation requirement



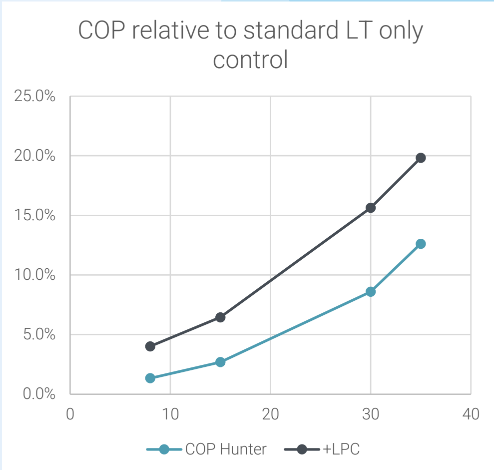


Combination of the two

The combination of COP Hunter and Liquid Power Cooler will result in the most energy efficient LT only system available in the market.

Benefits

- Highest possible COP
- Subcooling of liquid line
- Mass flow reduction in liquid line
- Pressure drop reduction in liquid line, LT suction
- Reduction of discharge temperature
- Eliminate risk of condensation in the desuperheater
- Reduced use of liquid injection
- Reduction of total m3/h on transcritical compressors



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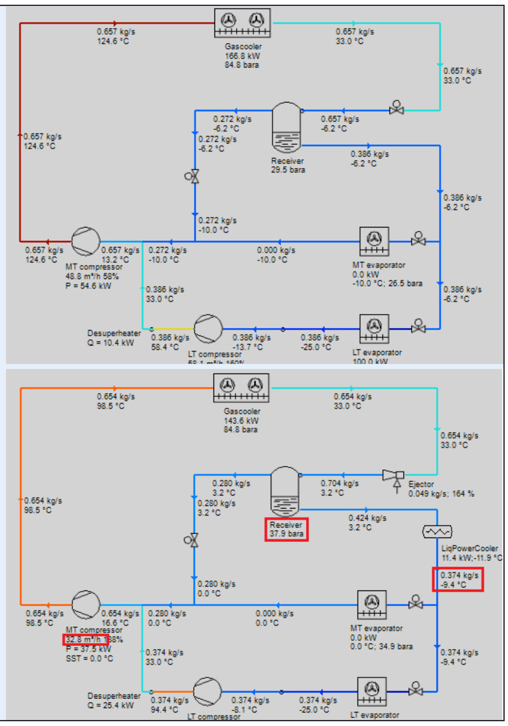
Case 1 – LT only

- 100 kW LT only @ -35 °C
- Platform: CuBig
- Located in Norway

Design Point comparison (30 °C ambient)

- COP increase of 16%
- Transcritical compressors total m3/h reduced by 33%
- Subcooling of 12,6 K

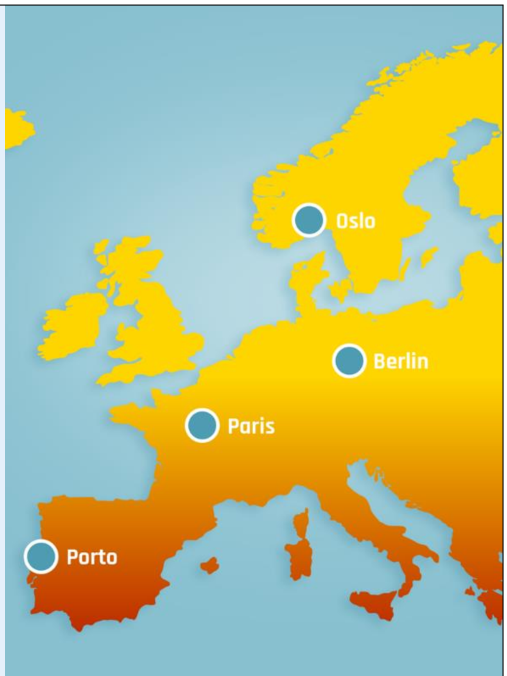
Advansor deliver LT systems from 20 kW to 750 kW
Liquid Power Cooler can be delivered for the whole range



Yearly Savings LT only Systems

*Reference system: standard LT only 200 kW @ -35 °C
0,3 €/kWh

	SCOP	Pay back time
Norway - Oslo	2,3%	1,6 years
Germany - Berlin	2,9%	1,3 years
France - Paris	3,5%	1,0 years
Portugal - Porto	4,2%	0,9 years



ADVANSOR

Wrap up

With the latest technology steps transcritical CO_2 systems it is now possible to build:

- Smaller racks with less compressors
- More efficient racks
- More robust systems

ADVANSOR


THANK YOU FOR LISTENING!
ADVANSOR

Low Charge NH_3 and Energy Efficiency

Stefan S. Jensen
ssjensen@scantec.com.au
Scantec Refrigeration Technologies Pty. Ltd.

Maintaining Innovation

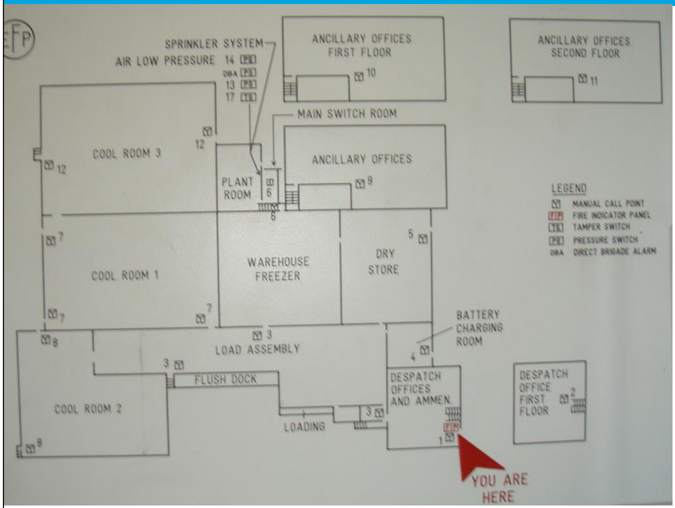
TECHNOLOGIES | DESIGN | CONSTRUCTION | SERVICING

Introduction

1) First Low Charge NH_3 plant ~30 years ago – now >30 plants in commercial operation
2) Success is highly dependent upon evaporator design and evaporator injection control
3) It is clear that saturation of the suction line network of expansive overfeed plants with high-density, liquefied refrigerant significantly jeopardizes system energy efficiency
4) Tank (also called Gravity) Distributors expand evaporator operating envelope
5) Low Charge NH_3 offers NH_3 operating inventory reductions of 30-50 times in the air coolers and 4-5 times charge reduction in systems compared with liquid overfeed
6) Low Charge NH_3 is highly suitable for conversion from HFC to NH_3 using pre-packaged, plug and play engine rooms – simple pay-back ~5 years based on $300/MWh
7) Replacement of conventional, screw compressor based, NH_3 overfeed cold storage plant with centralized, low charge NH_3 plant can deliver a simple pay-back of five years based on unit energy costs of $150-200/MWh

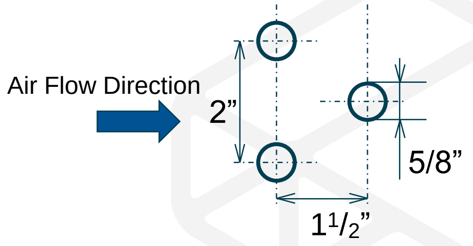
Maintaining Innovation

First DX NH_3 System



~anno 1990

- Ceiling suspended Fe/Zn IDC's with this geometry:



- Hot gas defrost; supply through distributor, condensate return to intercooler

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First DX NH_3 System

- Circuited for 2.5-3K NH_3 Δp in the freezer air coolers at full load
- Circuited for counter flow between air and refrigerant, vertical headers
- NH_3 expansion valves of the pulse timing, electronic type
- Control algorithm of the P & I D type where "on" time is a function of the deviation from the set point and the period is constant (6 seconds)
- Expansion devices highly sensitive to impurities
- Compressor suction temperature 2-3K lower than design
- The entire plant is currently being replaced with a new, containerised, centralized, DX NH_3 plant as part of a major refurbishment by the Owner

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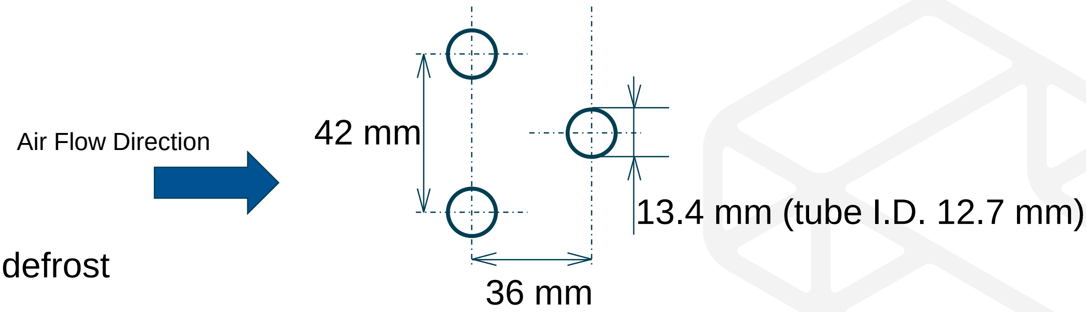
Second DX NH_3 System

- Ceiling mounted induced draught SS/Al evaporator of the following geometry:



- Electric defrost
- Pulse-timing TXV
- Counterflow

Result: **DISASTER**

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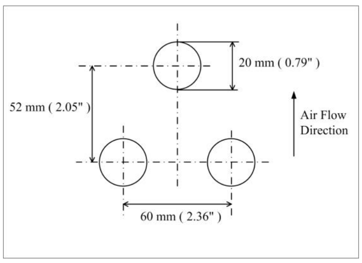
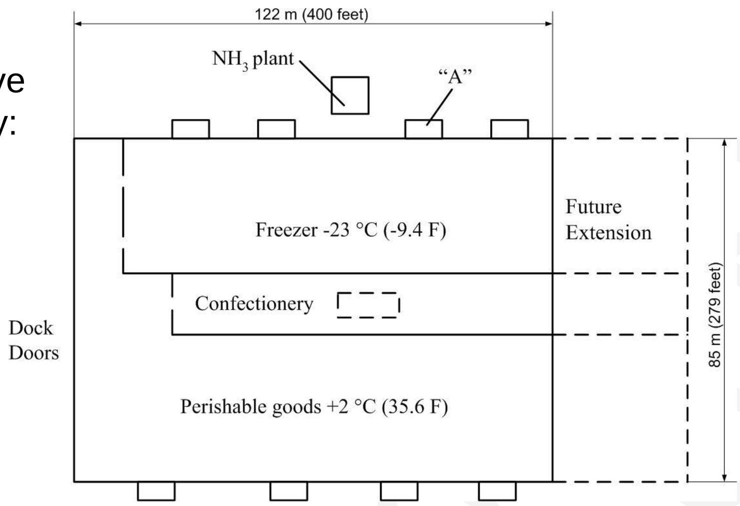
Third DX NH_3 System

Plan layout:

- Fe/Zn evaporators of the alcove type with the following geometry:



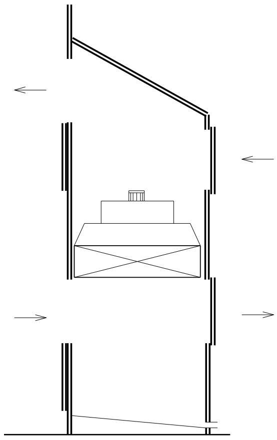


TECHNOLOGIES | DESIGN | CONSTRUCTION | SERVICING

Third DX NH_3 System

EXTERIOR OF ALCOVE UNIT

DURING NORMAL OPERATION



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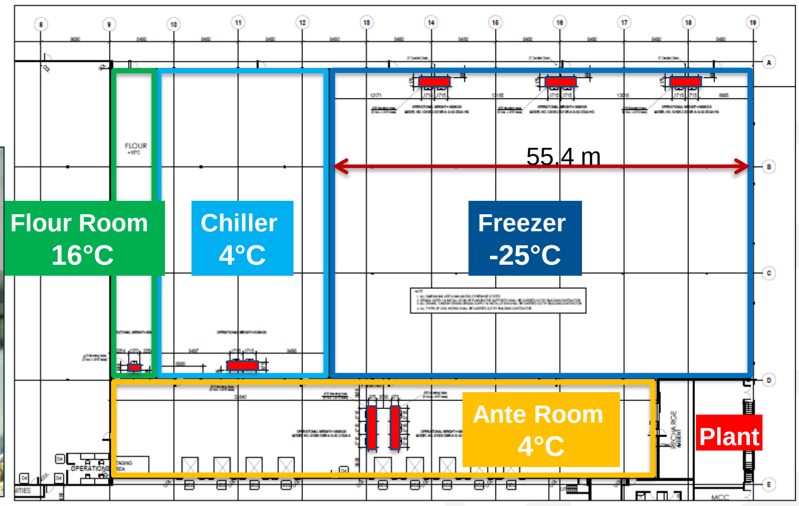
2013.....

Volume 43,000 m³

Not without problems:



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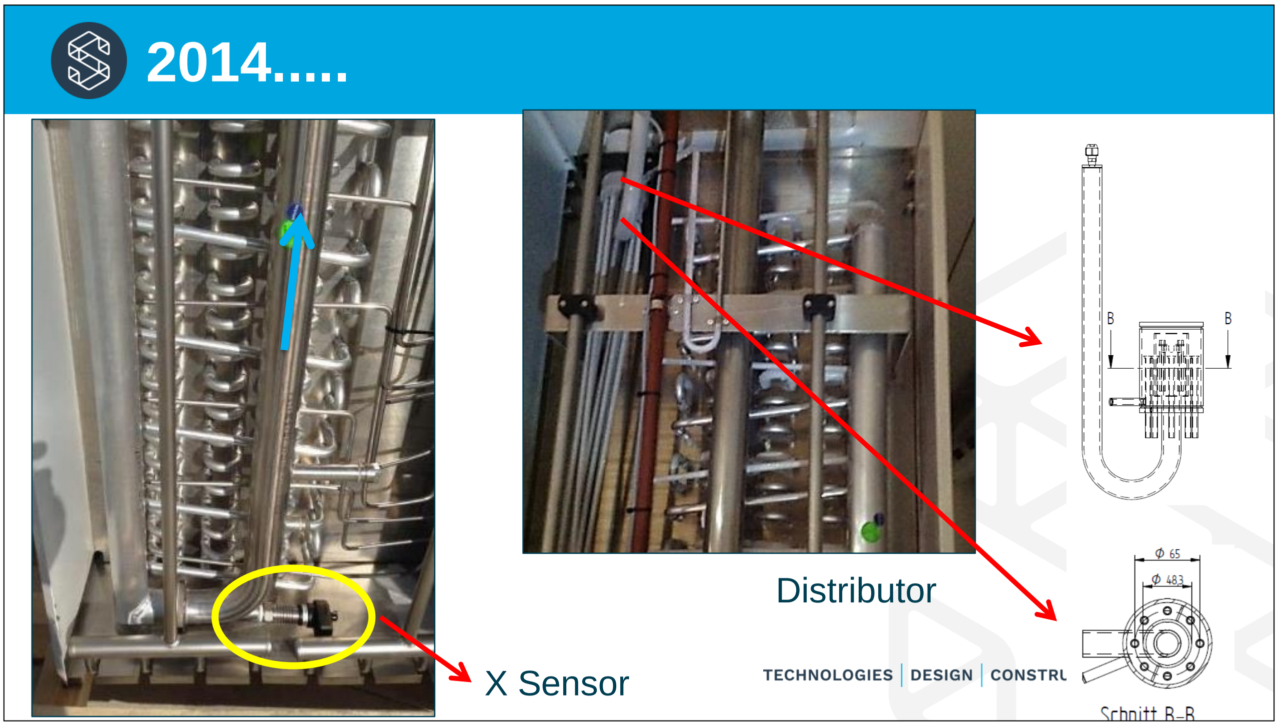
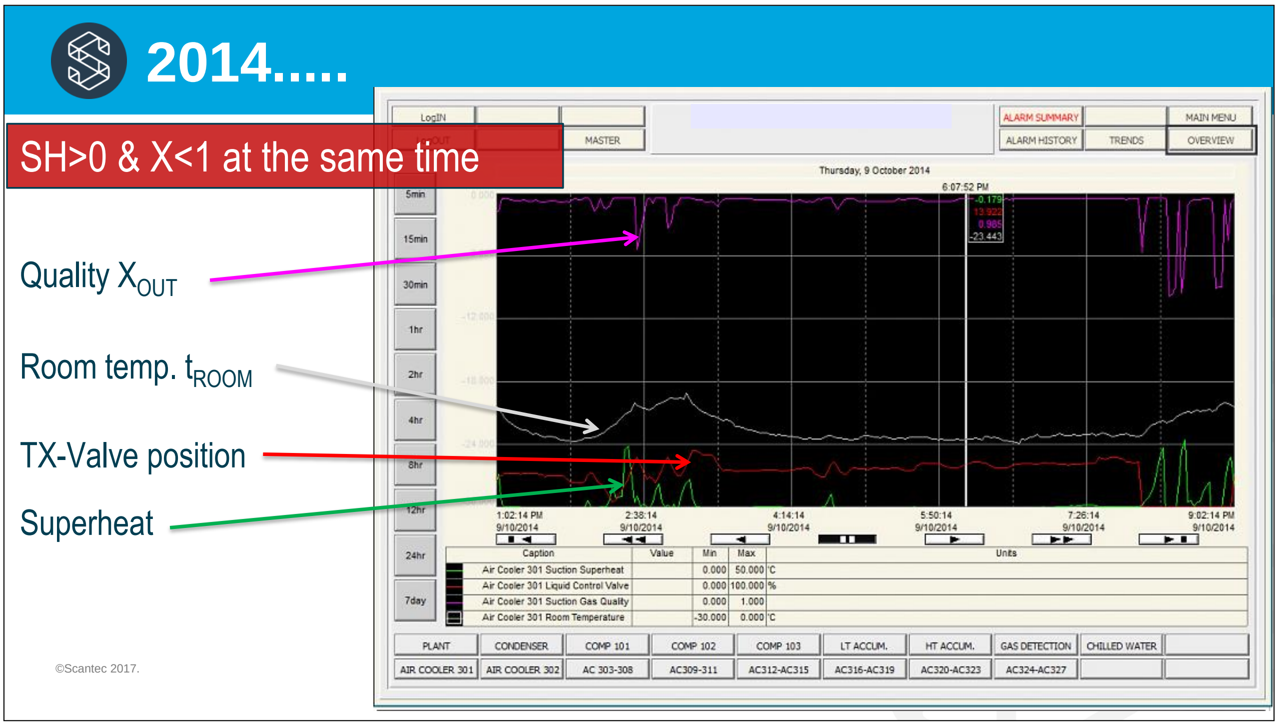
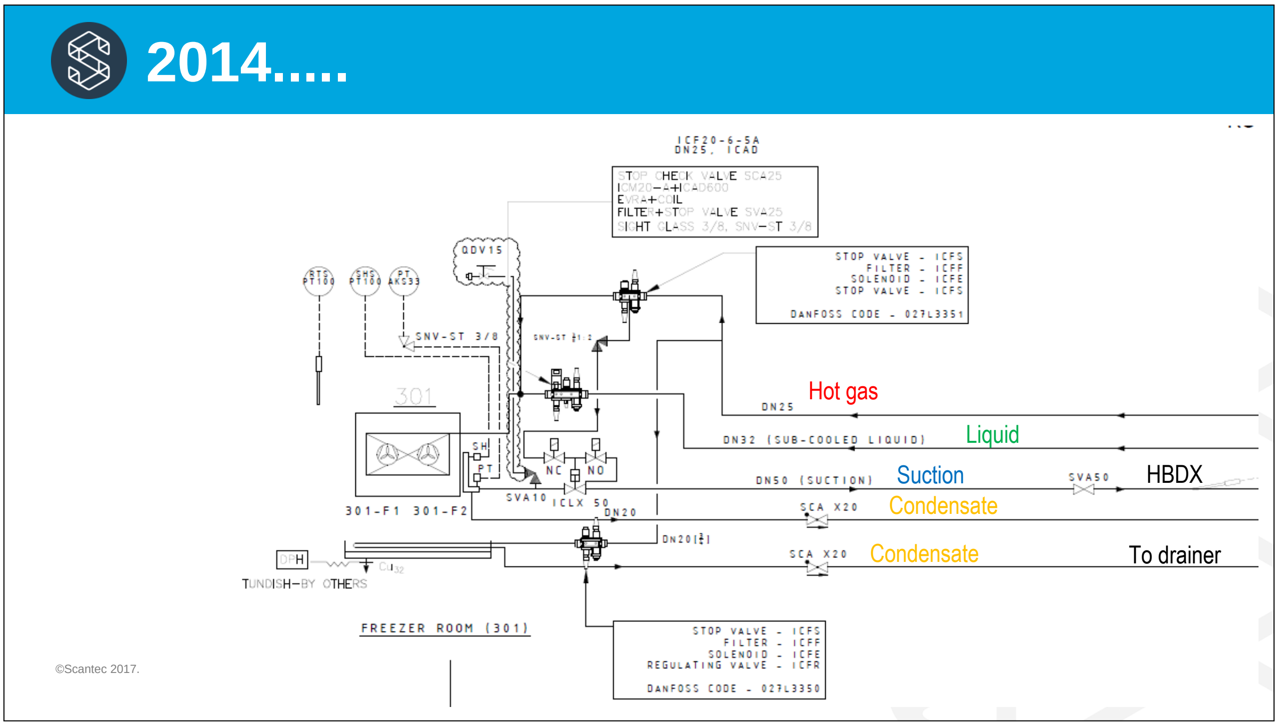
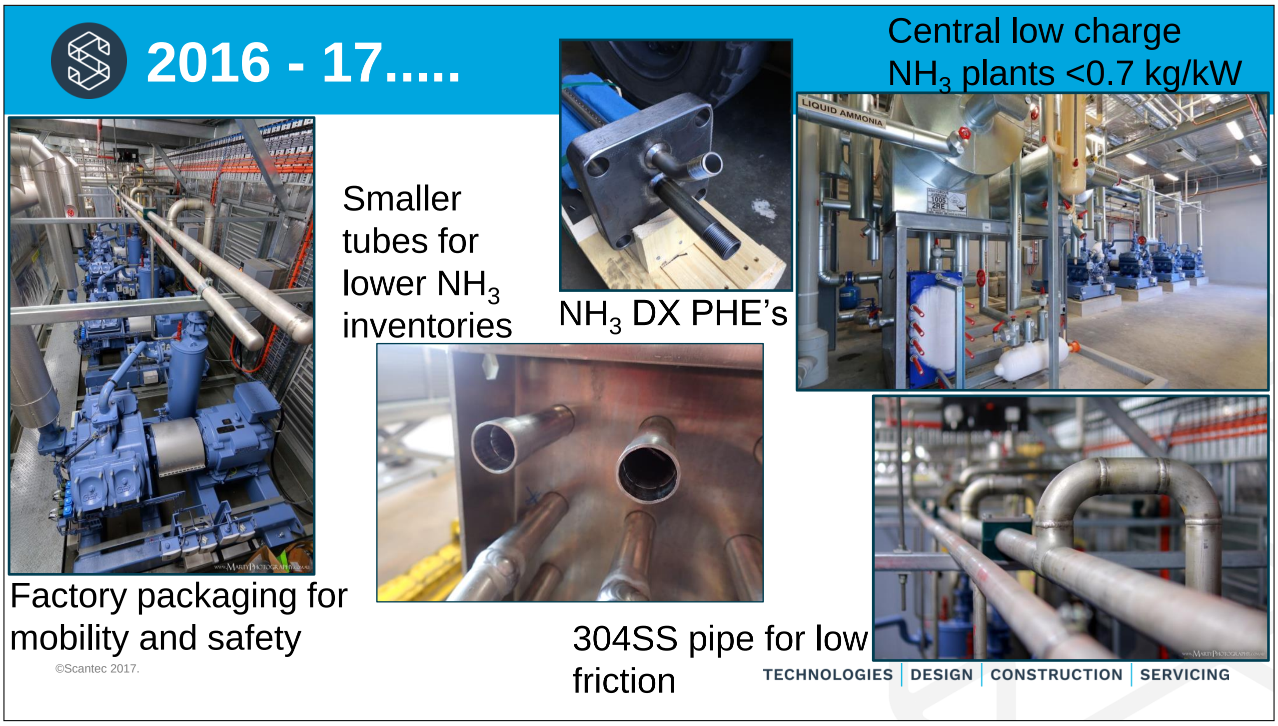


2014.....
X Sensor
Distributor
TECHNOLOGIES | DESIGN | CONSTRU
B
B
Ø 65
Ø 483
Schnitt B-B



2014.....
SH>0 & X<1 at the same time
Quality X_OUT
Room temp. t_ROOM
TX-Valve position
Superheat
©Scantec 2017.
LogIN
MASTER
ALARM SUMMARY
MAIN MENU
ALARM HISTORY
TRENDS
OVERVIEW
Thursday, 9 October 2014
5min
15min
30min
1hr
2hr
4hr
8hr
12hr
24hr
7day
Caption
Value
Min
Max
Units
Air Cooler 301 Suction Superheat 0.000 50.000 'C
Air Cooler 301 Liquid Control Valve 0.000 100.000 %
Air Cooler 301 Suction Gas Quality 0.000 1.000
Air Cooler 301 Room Temperature -30.000 0.000 'C
PLANT
CONDENSER
COMP 101
COMP 102
COMP 103
LT ACCUM.
HT ACCUM.
GAS DETECTION
CHILLED WATER
AIR COOLER 301
AIR COOLER 302
AC 303-308
AC309-311
AC312-AC315
AC316-AC319
AC320-AC323
AC324-AC327


2014.....
ICF20-6-5A
DN25, ICAD
STOP VALVE - ICFS
FILTER - ICFF
SOLENOID - ICFE
STOP VALVE - ICFS
DANFOSS CODE - 027L3351
Hot gas
DN25
DN32 (SUB-COOLED LIQUID)
Liquid
DN50 (SUCTION)
Suction
SVA50
HBDX
SCA X20
Condensate
SCA X20
Condensate
To drainer
301-F1 301-F2
FREEZER ROOM (301)
STOP VALVE - ICFS
FILTER - ICFF
SOLENOID - ICFE
REGULATING VALVE - ICFR
DANFOSS CODE - 027L3350
©Scantec 2017.


2016 - 17.....
Central low charge
NH3 plants <0.7 kg/kW
Smaller tubes for lower NH3 inventories
NH3 DX PHE's
Factory packaging for mobility and safety
304SS pipe for low friction
©Scantec 2017.
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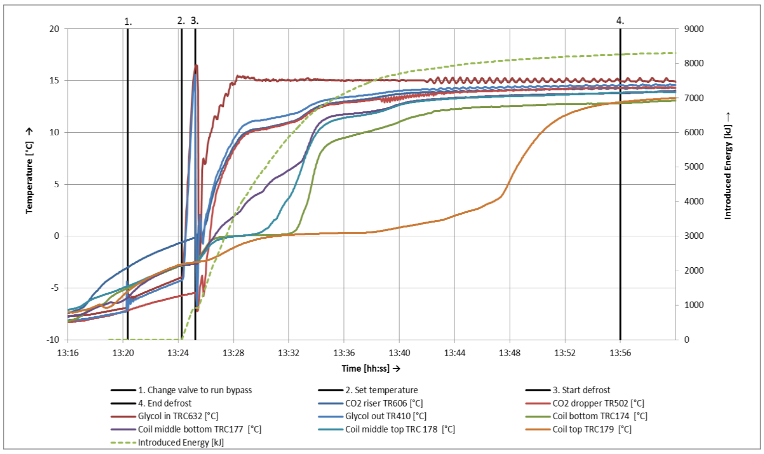
2017.....

"LOGAS" hot gas defrost minimizing intercooler NH_3 inventory



Cold store evaporator, 7 meters long, 160 kW cooling capacity

©Scantec 2017.

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2018 – things are getting larger....

No technical limits to size

50/50% freezer/chiller

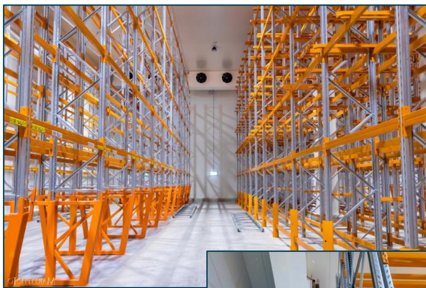
13,000 m^2 refrigerated area

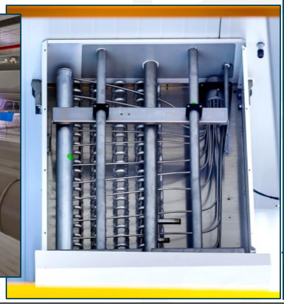
500/600 kW LT/HT

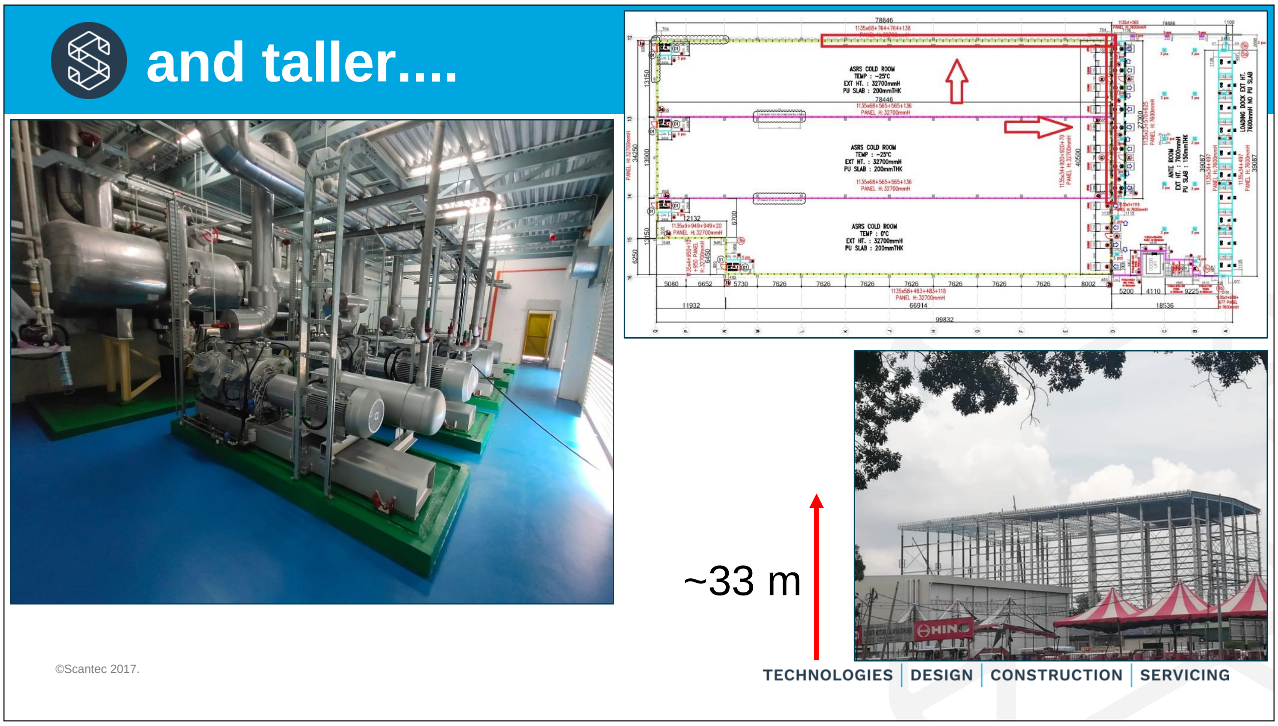
750 kg NH_3 (0.7 kg/kW)

10 kWh/m^3*a (storage)

17 kWh/m^3*a (50 t/day)






and taller....
~33 m
©Scantec 2017.
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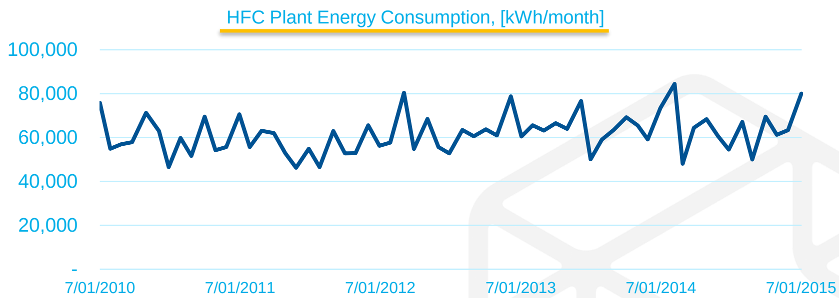
and also smaller....
New NH_3 DX System
PROPYLENE GLYCOL
NH_3 Inventory ~250 kg
TECHNOL

..smaller and very energy efficient....

Energy Savings



Specific Energy Consumption (SEC) Comparison

HFC, kWh/m^3*a	206
NH_3, kWh/m^3*a	88
Saving, %	57

©Scantec 2017.

NH_3 Readings:

Start date 3.10.2018; reading 5,107 kWh
End date 18.1.2019; reading 141,303 kWh

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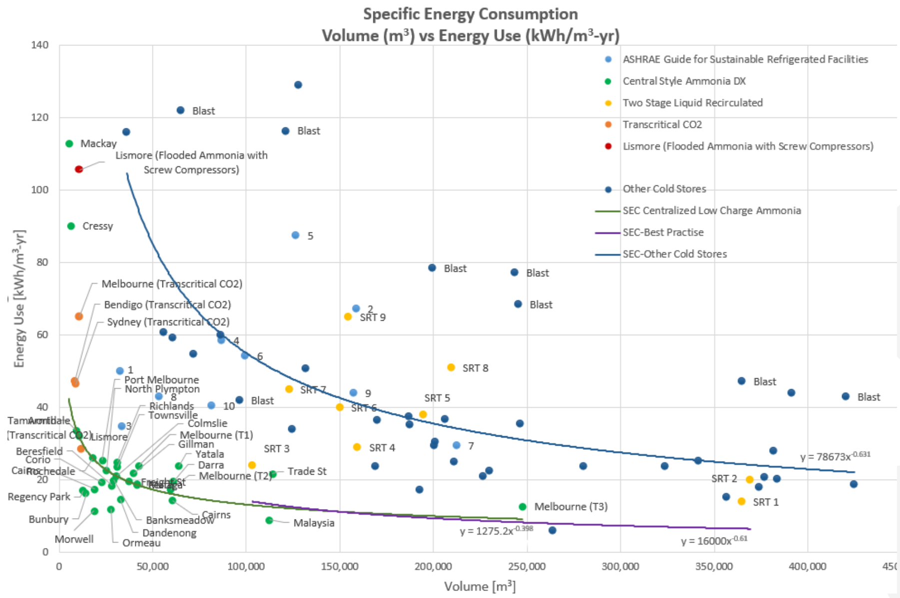
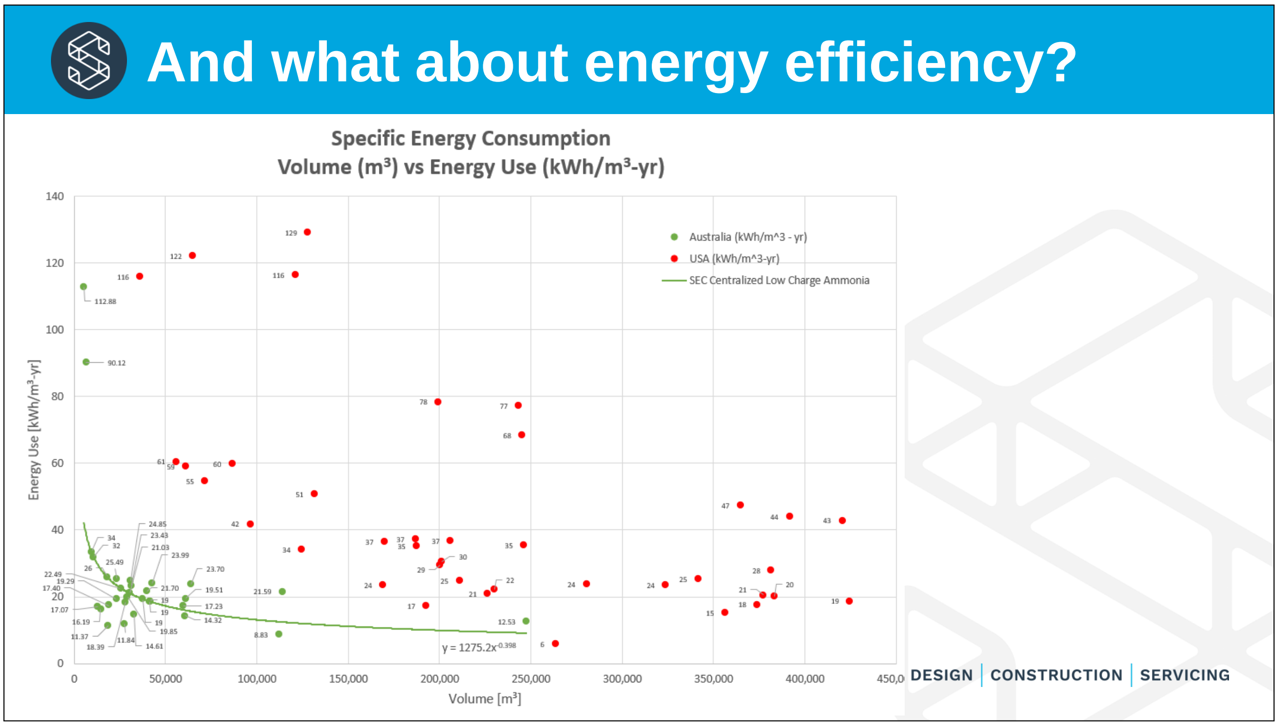
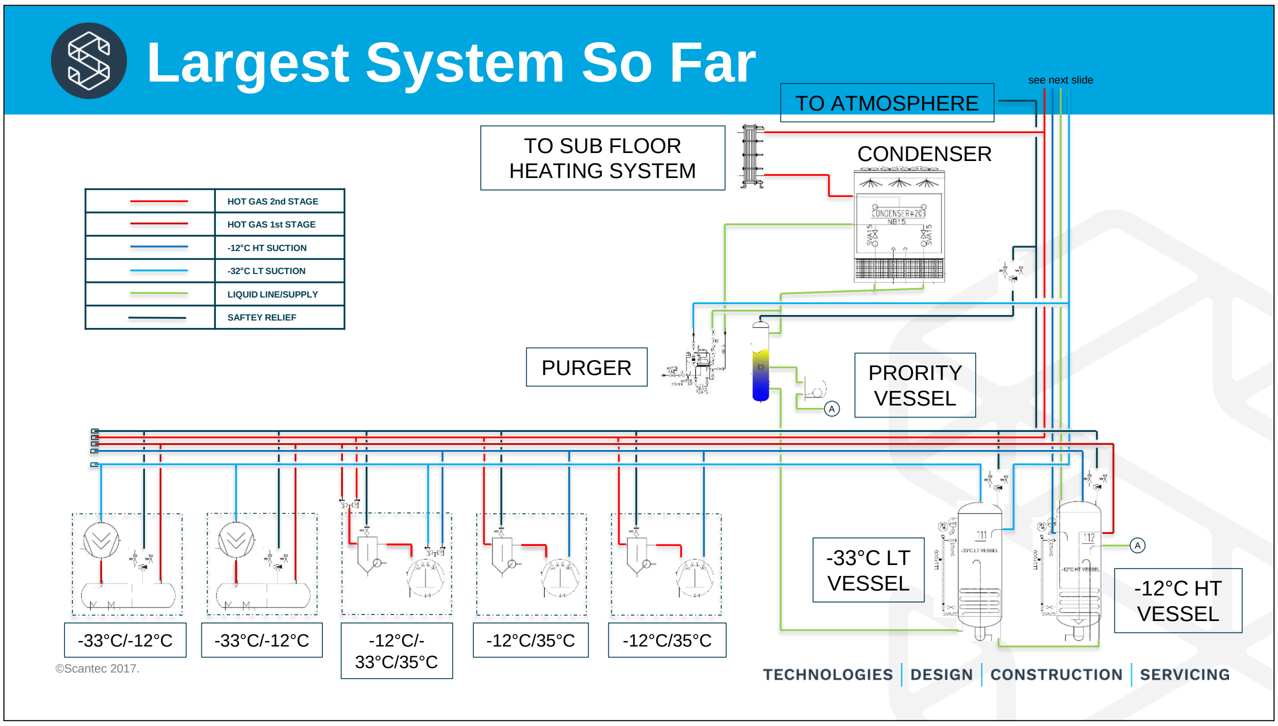
And what about energy efficiency?



DESIGN | CONSTRUCTION | SERVICING


And what about energy efficiency?
Specific Energy Consumption
Volume (m³) vs Energy Use (kWh/m³-yr)
Energy Use [kWh/m³-yr]
Volume [m³]
Australia (kWh/m^3 - yr)
USA (kWh/m^3-yr)
SEC Centralized Low Charge Ammonia
y = 1275.2x^-0.398
DESIGN | CONSTRUCTION | SERVICING


Largest System So Far
see next slide
TO ATMOSPHERE
TO SUB FLOOR HEATING SYSTEM
CONDENSER
HOT GAS 2nd STAGE
HOT GAS 1st STAGE
-12°C HT SUCTION
-32°C LT SUCTION
LIQUID LINE/SUPPLY
SAFTEY RELIEF
PURGER
PRORITY VESSEL
-33°C LT VESSEL
-12°C HT VESSEL
-33°C/-12°C
-33°C/-12°C
-12°C/-33°C/35°C
-12°C/35°C
-12°C/35°C
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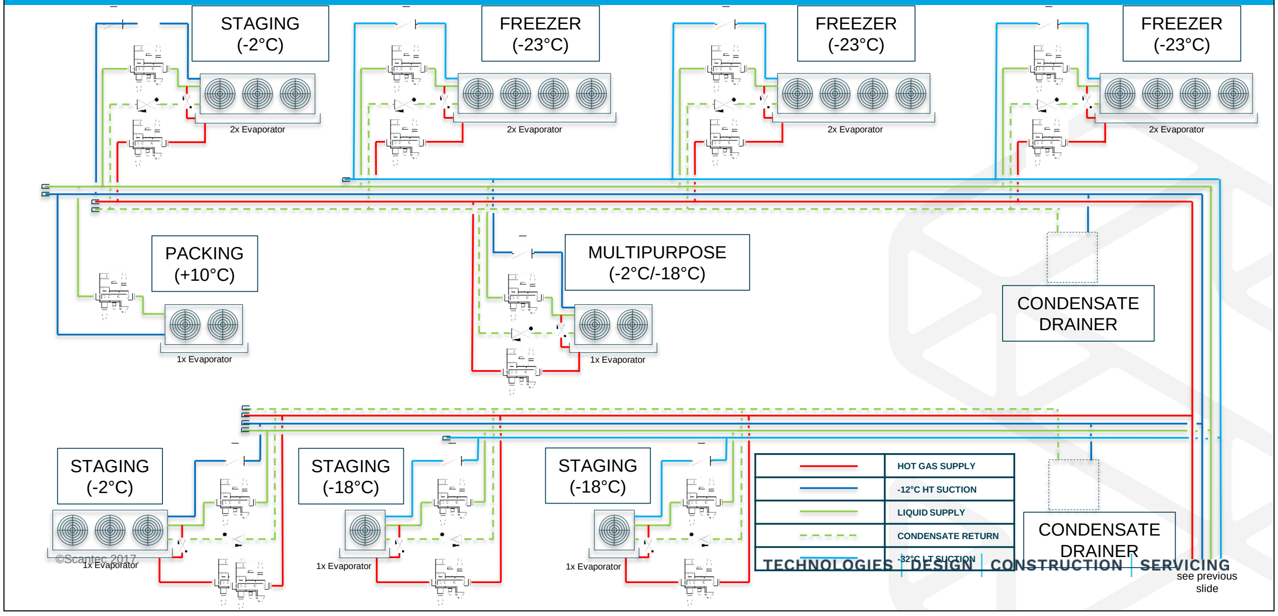
TECHNOLOGIES | DESIGN | CONSTRUCTION | SERVICING

Largest System So Far



TECHNOLOGIES | DESIGN | CONSTRUCTION | SERVICING

Largest System So Far

- Mixed 247,716 m³ refrigerated warehouse with blast freezing
- Low/medium temperature refrigeration capacities 885/358 kW
- Blast freezing refrigeration capacity 181 tons/48 hours (~379 kW)
- Low/Medium temperature refrigerated volume split 53/47%
- Peak power consumption 734 kW
- Approximately 32 km of subfloor heating pipes
- Overall ammonia inventory approximately 1000 kg
- Total operating ammonia inventory in the evaporators ~40 kg

TECHNOLOGIES | DESIGN | CONSTRUCTION | SERVICING

Largest System So Far

Recorded Energy Performances

- Annual projected SEC=8.5 kWh·m^{-3}·year^{-1} (storage only)
- Recorded SEC=9.2 kWh·m^{-3}·year^{-1} first four days after pull-down

Month	Consumption, kWh	SEC, kWh·m^{-3}·year^{-1}
September 2022	243,091	11.8
October 2022	261,555	12.7
November 2022	243,997	11.8
December 2022	278,220	13.5
January 2023	271,429	13.1

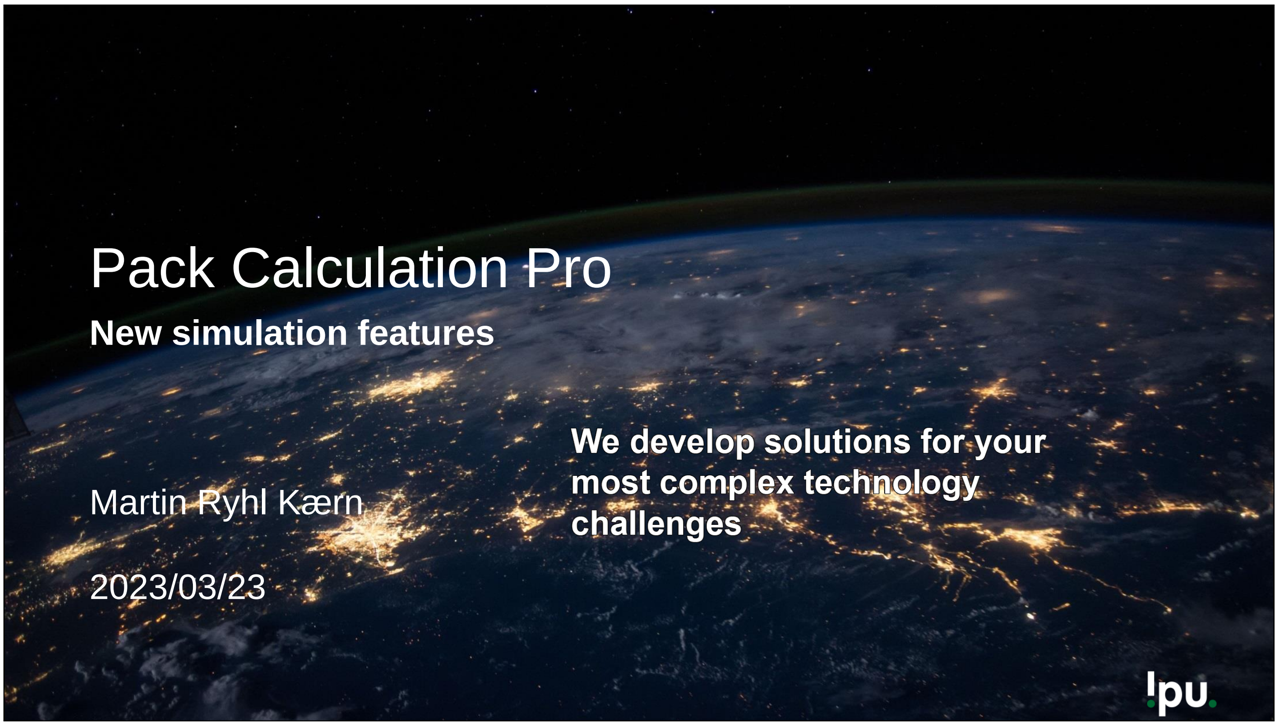
Blast Freezer throughputs unfortunately not provided by the client

TECHNOLOGIES | DESIGN | CONSTRUCTION | SERVICING

Thank You – Questions?

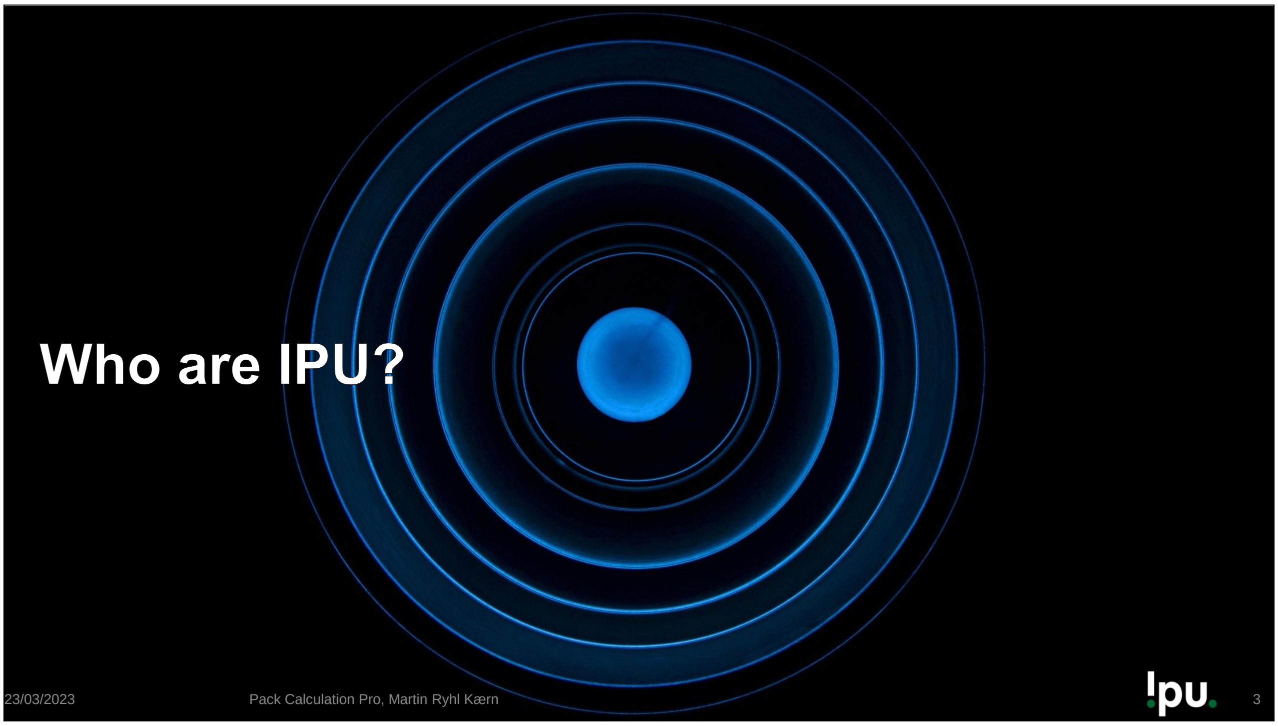
ssjensen@scantec.com.au

Maintaining Innovation



Agenda

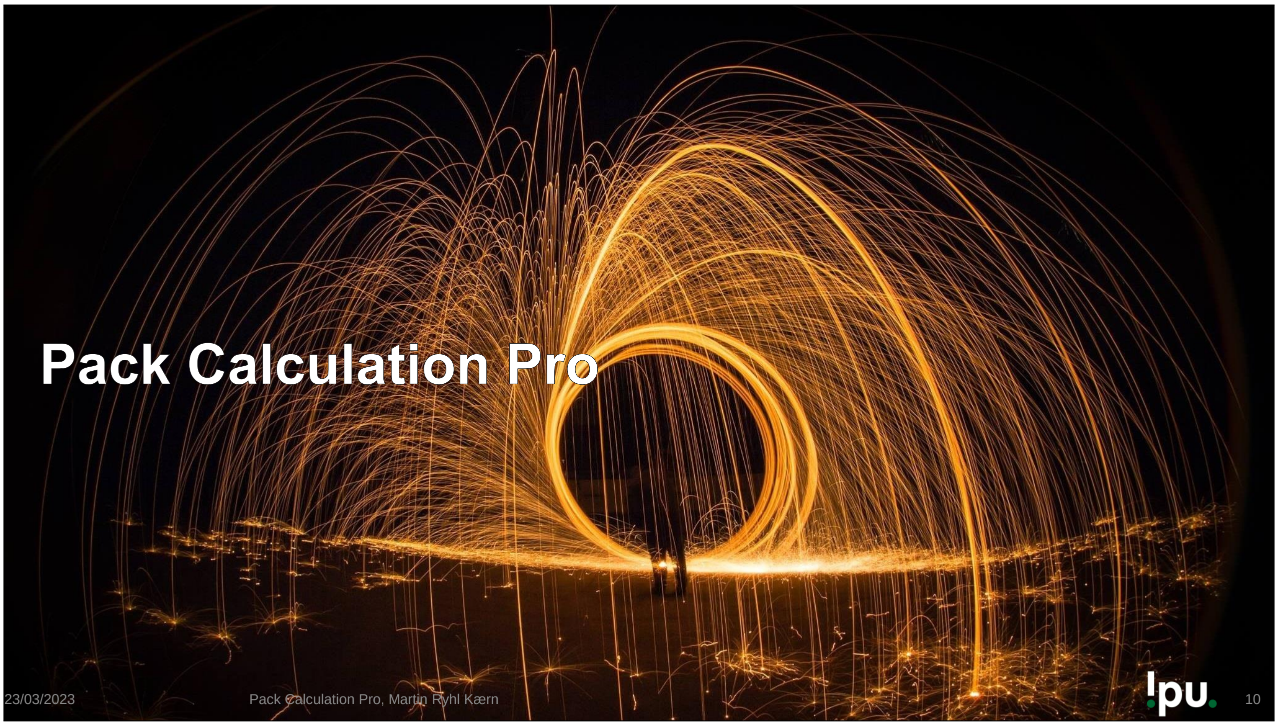
- Who are IPU?
- What is Pack Calculation Pro?
- History
- Main developments since “^5.0”
- Current and future developments “^5.3”
- Future perspectives



Who are IPU?

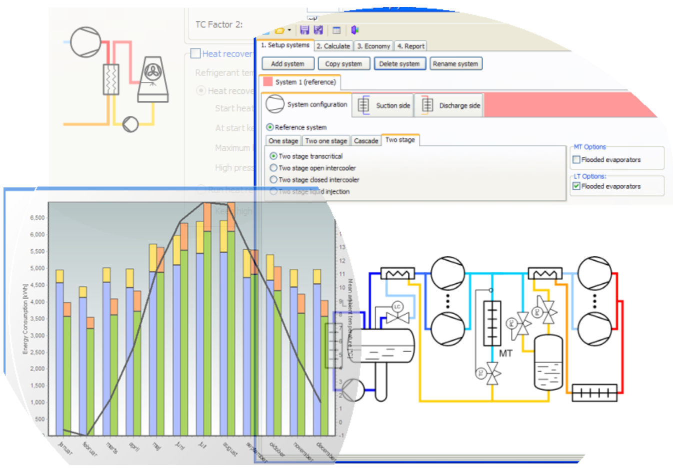
- A small company that bridges research and industry since 1956.
- >35 international specialists
- IPU work with 5 key areas:
  - Advanced Materials & Surfaces Technology
  - Thermodynamics and Energy Technology
  - Autonomous Systems and Robotics
  - Modelling of Physical Systems
  - Product- and Process Technology Development
- IPU have a long history in developing software solutions for refrigeration engineers.
  - Custom/selection software: Danfoss, Maersk, Emerson, Nilan, Heaten, Likido Ltd …
  - General/user software: **Pack Calculation Pro**, CoolTools, CoolPack, SecCool, Simple CO2 …

23/03/2023 Pack Calculation Pro, Martin Ryhl Kærn 7



What is Pack Calculation Pro?

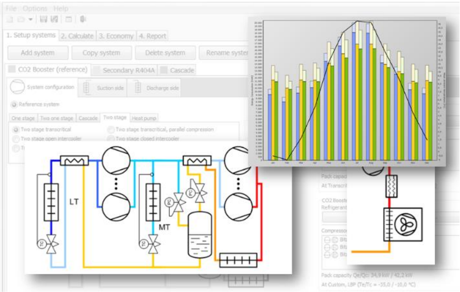
- Calculates
  - yearly energy consumption
  - life cycle costs (LCC)
  - CO2 emissions (TEWI)
- .. for many refrigeration and a few heat pump systems.
- Can be used to:
  - compare refrigerants.
  - compare system layouts.
  - compare components
  - compare control strategies
  - …



23/03/2023 Pack Calculation Pro, Martin Ryhl Kærn 11

What is Pack Calculation Pro?

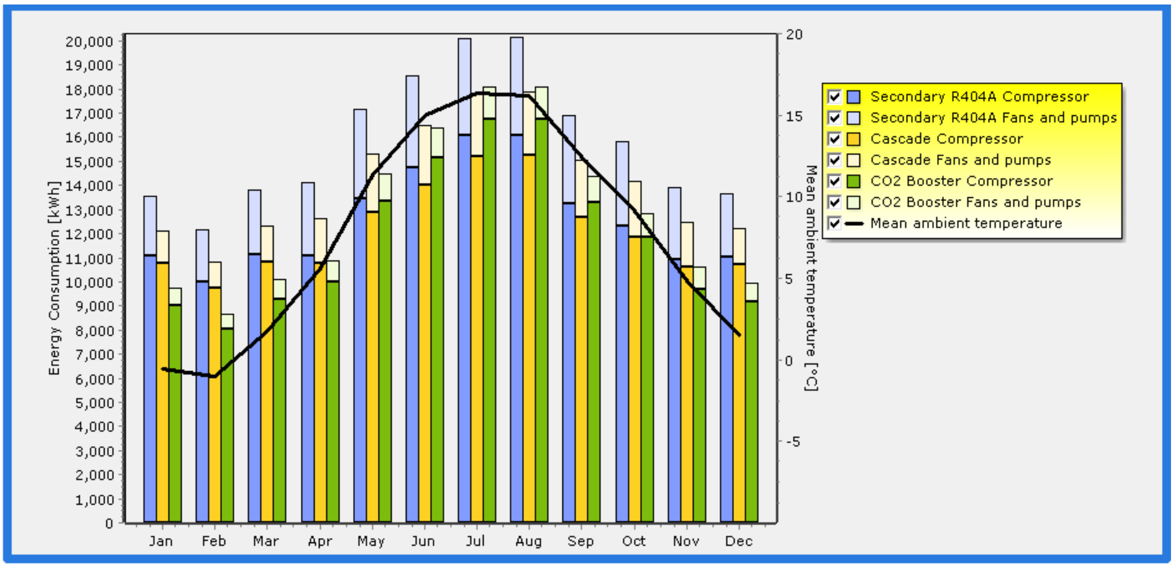
- Calculates every hour throughout the year
- Weather data for 3700 cities around the world
- 10000 compressor models (EN12900)
- 19 different cycles (6 one-stage, 13 two-stage)
  - 9 transcritical cycles (including ejector and parallel compression)
  - 2 heat pump cycles
- Evaporator configurations
  - Dry expansion, flooded evaporators, secondary circuit (brine)
- Condenser configurations
  - Air cooled, dry cooler, evaporative, cooling tower, water cooled, hybrid (adiabatic) cooler
- Additional features:
  - Load profiles, free cooling, groundwater cooling, heat recovery



EU-project "SuperSmart Supermarket" said:
… it [Pack Calculation Pro] is one of the most useful tools for planning the refrigeration system, since it includes many desired features (component database, user-friendly interface, automatic report generation) and also recent refrigeration system layouts.

23/03/2023 Pack Calculation Pro, Martin Ryhl Kærn 12

Results: yearly energy consumption



23/03/2023 Pack Calculation Pro, Martin Ryhl Kærn 13

Results: life cycle costs

Energy Prices | Life Cycle Costs | CO2 Equivalent Emissions

Update

Expected average interest rate: 3 %

Expected average inflation rate: 2 %

Expected lifetime: 10 years

Initial cost:

	Secondary R404A	Cascade	CO2 Booster
Cost of equipment [€]	50,000	35,000	50,000
Cost of installation [€]	40,000	70,000	60,000

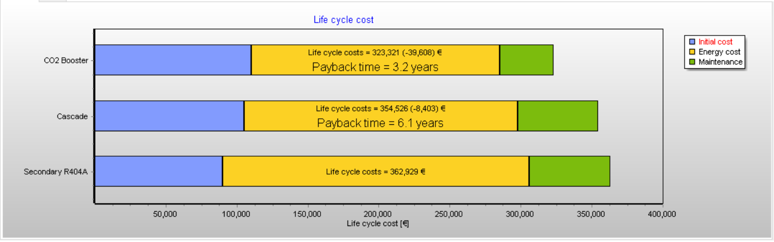
Annual operating cost:

	Secondary R404A	Cascade	CO2 Booster
Energy consumption [kWh]	189884.33	169315.02 (-20,569)	154160.28 (-35,724)
Backup heater consumption [kWh]	0.00	0.00 (0)	0.00 (0)
Cost of maintenance [€]	6,000	6,000	4,000

Result:

	Secondary R404A	Cascade	CO2 Booster
Effective interest rate [%]	0.98	0.98	0.98
Internal rate of return [%]	-	10.26	28.96
Total annual cost [€]	28,786	26,318 (-2,468)	22,499 (-6,287)
Payback time [years]	-	6.1	3.2
Total initial cost [€]	90,000 (25%)	105,000 (30%)	110,000 (34%)
Present value of maintenance cost [€]	56,888 (16%)	56,888 (16%)	37,925 (12%)
Present value of energy cost [€]	216,041 (59%)	192,639 (54%)	175,396 (54%)
Life cycle cost [€]	362,929	354,526 (-8,403)	323,321 (-39,608)

Diagram | Plot



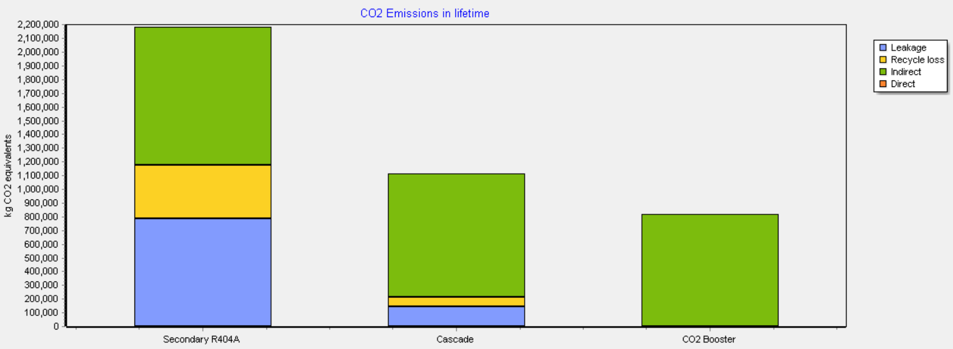
Results: CO2 emissions (TEWI)

Energy Prices | Life Cycle Costs | CO2 Equivalent Emissions

Update

	Secondary R404A (R404A)	Cascade_LT (R744)	Cascade_MT (R134a)	CO2 Booster (R744)
Refrigerant charge [kg]	200	100	100	200
Recycle rate [%]	50	0.0	50	0.0
Leakage rate[%/year]	10	10	10	10

	Leakage [kg CO2]	Recycle loss [kg CO2]	Indirect [kg CO2]	Direct [kg CO2]	Total [kg CO2]
Secondary R404A	784,400 (35.9%)	392,200 (18.0%)	1,006,387 (46.1%)	0 (0.0%)	2,182,987
Cascade	143,100 (12.9%)	71,600 (6.4%)	897,370 (80.7%)	0 (0.0%)	1,112,070
CO2 Booster	200 (0.0%)	200 (0.0%)	817,049 (100.0%)	0 (0.0%)	817,449



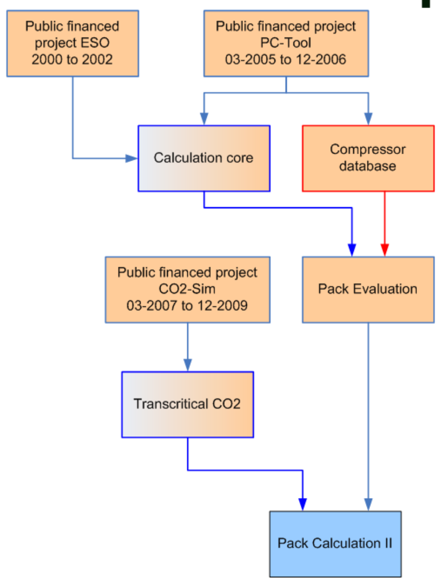
History

- Originally developed for supermarket refrigeration systems

- Through different public financed projects

- Pack Evaluation (2006)
- Pack Calculation II (2010)
- Pack Calculation III (2012)
- Pack Calculation Pro IV (2014)
- Pack Calculation Pro V (2021)

- Price 399 € per year



23/03/2023 Pack Calculation Pro, Martin Ryhl Kærn 16

History

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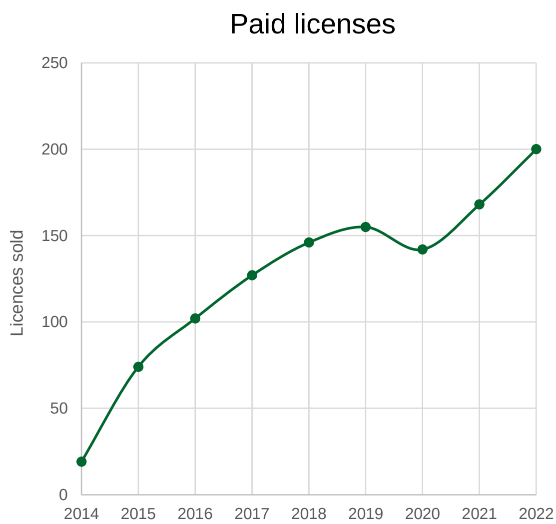
- Through different public financed projects

- Pack Evaluation (2006)
- Pack Calculation II (2010)
- Pack Calculation III (2012)
- Pack Calculation Pro IV (2014)
- Pack Calculation Pro V (2021)

- Price 399 € per year



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Main developments since “^5.0”

- New compressors (511 Frascold, 1700 Bitzer, 1800 Dorin …)
- New refrigerants
- Cycles:
  - One/two-stage transcritical with low pressure lift ejector
  - One/two-stage transcritical with high pressure lift ejector and parallel compression
  - Two-stage cascade heat pump
- Rating points UI
  - Simulates user-defined operation points

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Current & future developments “^5.3”

- Cycles:
  - Two-stage transcritical with open intercooler
  - One-stage transcritical heat pump
  - Boiler system (reference)
- Rating points UI
  - State points
  - Log(p)-h diagrams
  - T-Q diagrams
- Advanced condenser/gas-cooler
- Advanced hybrid (adiabatic) cooler
- Commercial ejector library
- New profile editor for cooling and heating demand

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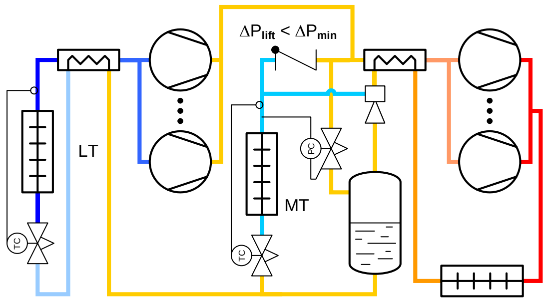
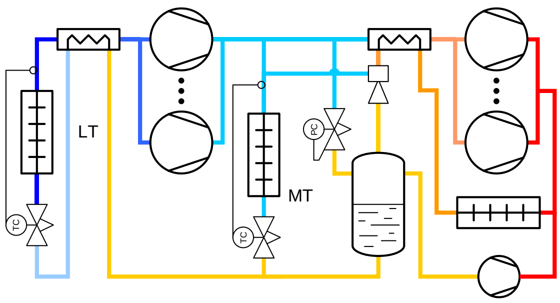
Cycles with ejector

Two-stage transcritical
with low-pressure lift ejector



Two-stage transcritical
with parallel compression
with high-pressure lift ejector



Cycles with ejector

- Ejector cycles are experimental
- Ejector map based on (Haider and Elbel, 2021)

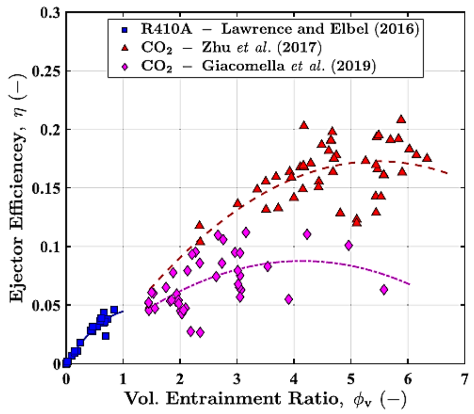
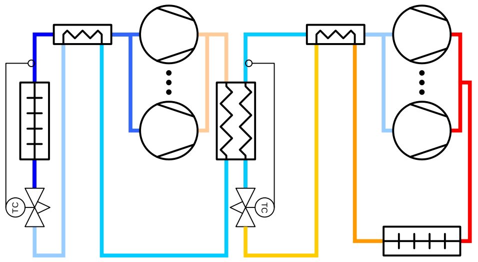


Table B.1
Coefficients of $\hat{\eta}_{ejec,map}$, APD and range of ϕ_v for the ejectors.

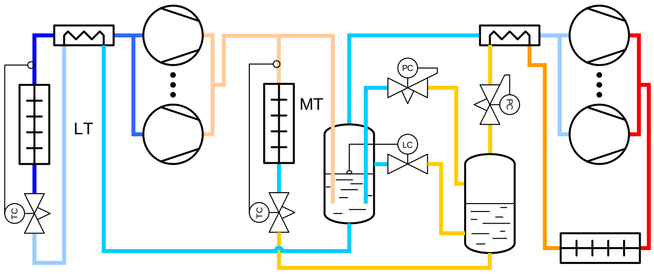
Ejector	Refrigerant	Study/Description	APD	Coefficient of $\hat{\eta}_{ejec,map}$		ϕ_v range
1	CO_2	This study	8.9%	C_1	−0.021	1.5 <
				C_2	0.052	ϕ_v <
				C_3	−0.004	5
2	R134a	Lawrence and Elbel (2014), D5xL40	4.7%	C_1	−0.0021	7 <
				C_2	0.0023	ϕ_v <
				C_3	−3e-05	35
3	R134a	Lawrence and Elbel (2014), D5xL60	5.8%	C_1	−0.0032	3.5 <
				C_2	0.0041	ϕ_v <
				C_3	−5.59e-05	55
4	R134a	Lawrence and Elbel (2014), D5xL70	7.5%	C_1	−0.0055	4.5 <
				C_2	0.0033	ϕ_v <
				C_3	−6.65e-05	40
5	R410A	Lawrence and Elbel (2016)	7.2%	C_1	−3.3e-06	0 <
				C_2	0.0767	ϕ_v <
				C_3	−0.0321	0.85
6	CO_2	Zhu et al. (2017)	10.7%	C_1	−0.0313	1.5 <
				C_2	0.0747	ϕ_v <
				C_3	−0.0068	6.4
7	CO_2	Giacomelli et al. (2019)	26%	C_1	−0.0084	1.5 <
				C_2	0.0464	ϕ_v <
				C_3	−0.0056	5.5

Other cycles

Two-stage cascade heat pump



Two-stage transcritical with open intercooler



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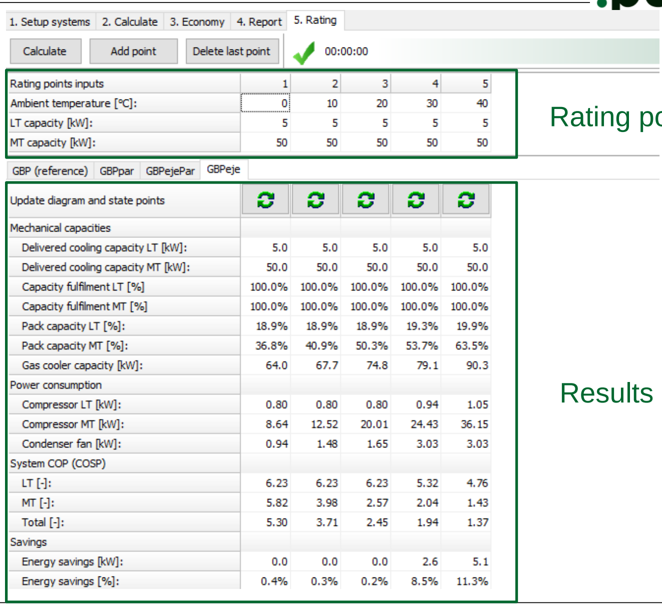
Rating points UI

- Calculates single operating points
- Useful for initial design phase
- And for calculating seasonal performance (SCOP) according to standards



Rating points inputs	1	2	3	4	5
Ambient temperature [°C]:	0	10	20	30	40
LT capacity [kW]:	5	5	5	5	5
MT capacity [kW]:	50	50	50	50	50

Update diagram and state points					
Mechanical capacities					
Delivered cooling capacity LT [kW]:	5.0	5.0	5.0	5.0	5.0
Delivered cooling capacity MT [kW]:	50.0	50.0	50.0	50.0	50.0
Capacity fulfilment LT [%]	100.0%	100.0%	100.0%	100.0%	100.0%
Capacity fulfilment MT [%]	100.0%	100.0%	100.0%	100.0%	100.0%
Pack capacity LT [%]:	18.9%	18.9%	18.9%	19.3%	19.9%
Pack capacity MT [%]:	36.8%	40.9%	50.3%	53.7%	63.5%
Gas cooler capacity [kW]:	64.0	67.7	74.8	79.1	90.3
Power consumption					
Compressor LT [kW]:	0.80	0.80	0.80	0.94	1.05
Compressor MT [kW]:	8.64	12.52	20.01	24.43	36.15
Condenser fan [kW]:	0.94	1.48	1.65	3.03	3.03
System COP (COSP)					
LT [-]:	6.23	6.23	6.23	5.32	4.76
MT [-]:	5.82	3.98	2.57	2.04	1.43
Total [-]:	5.30	3.71	2.45	1.94	1.37
Savings					
Energy savings [kW]:	0.0	0.0	0.0	2.6	5.1
Energy savings [%]:	0.4%	0.3%	0.2%	8.5%	11.3%

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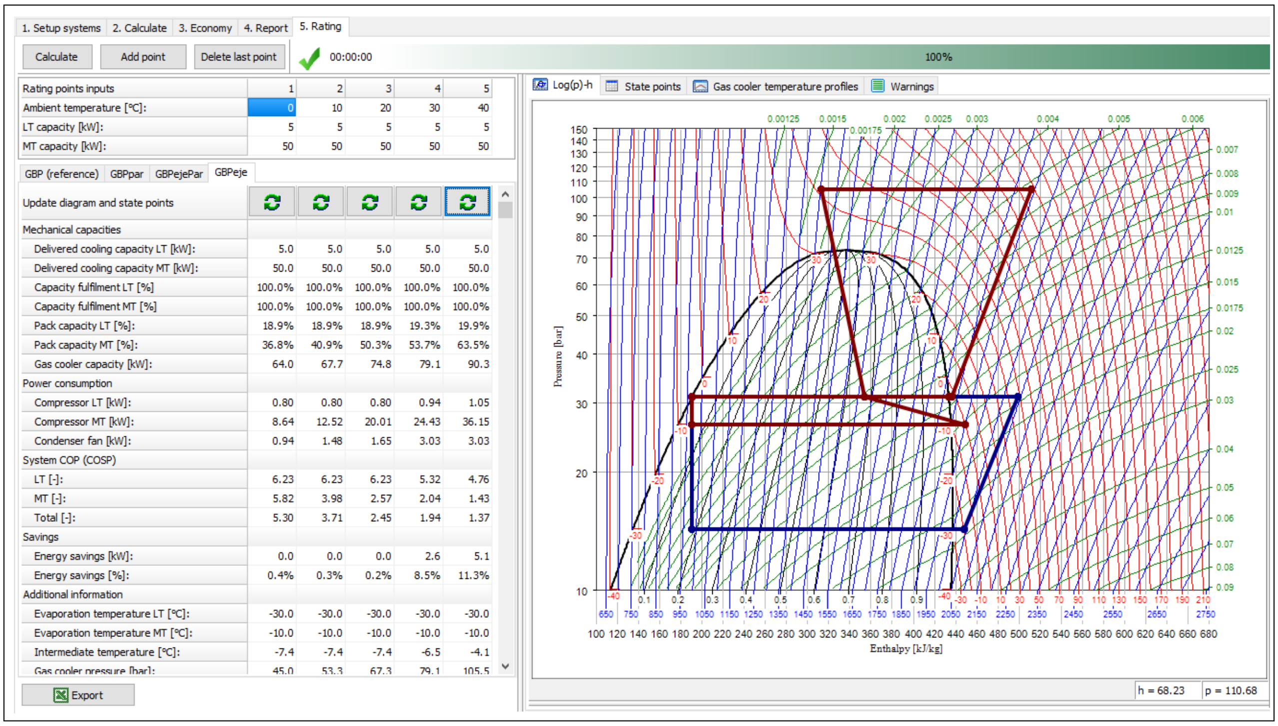
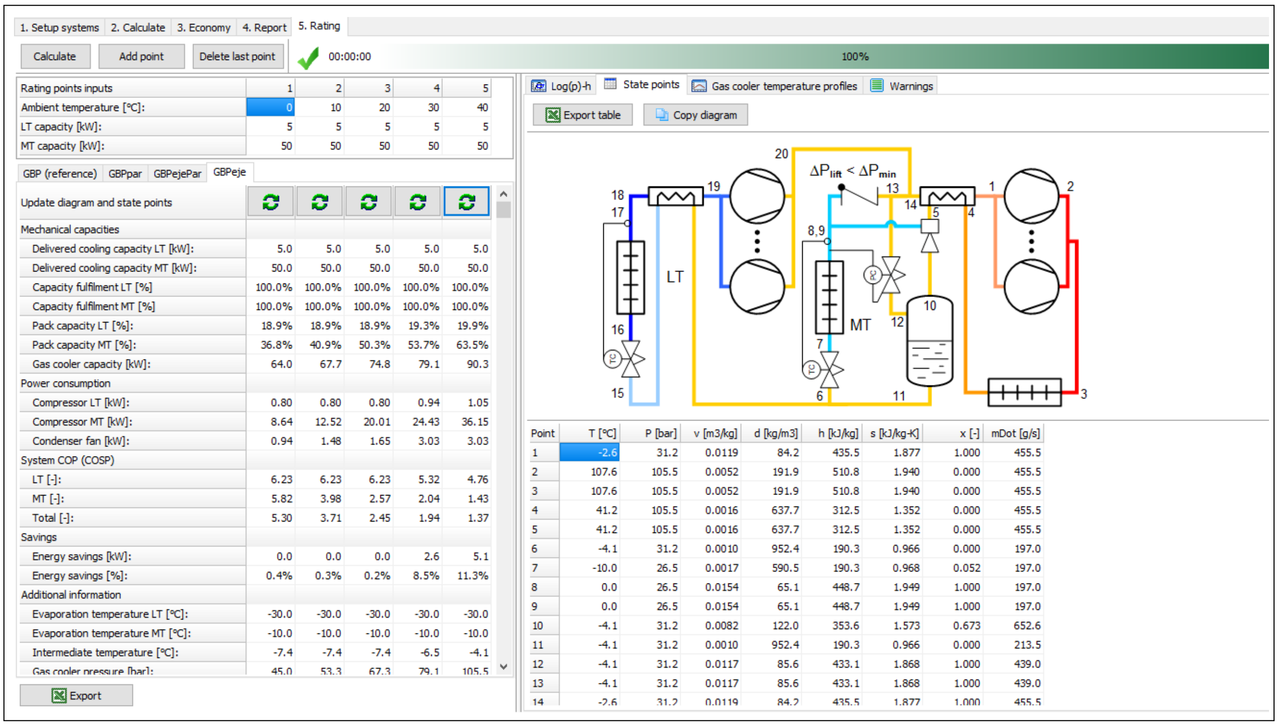
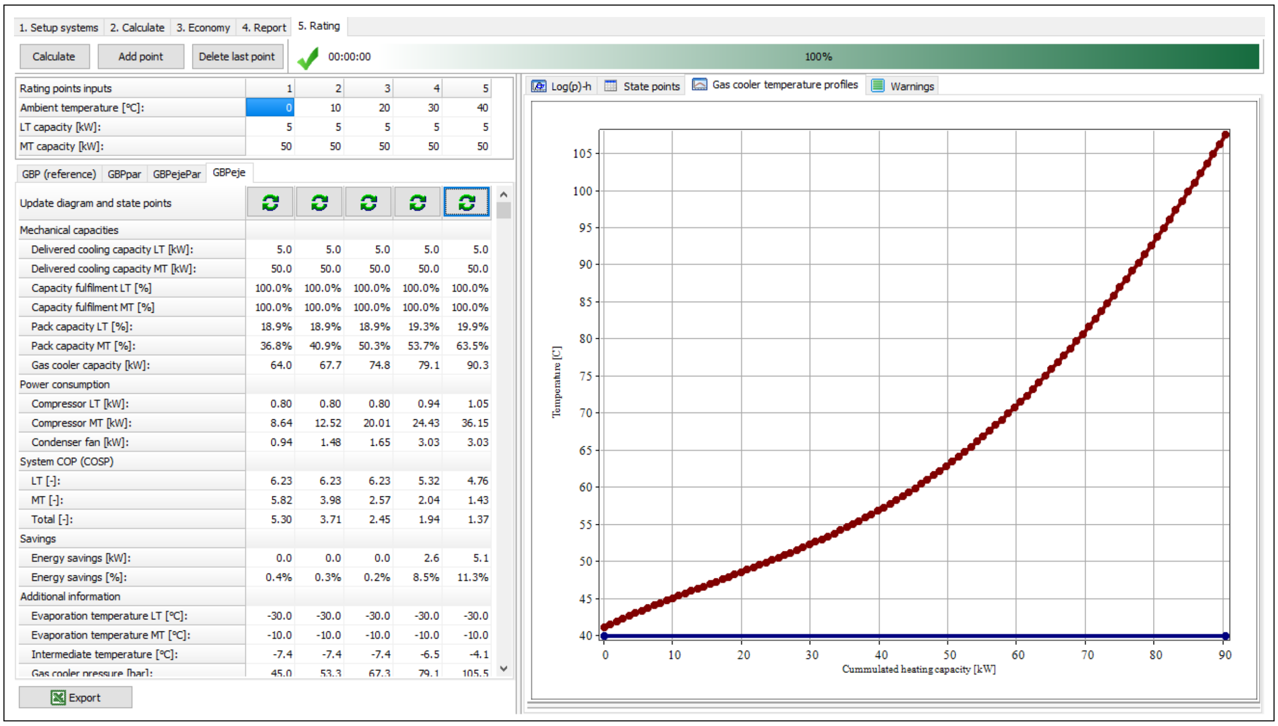

1. Setup systems
2. Calculate
3. Economy
4. Report
5. Rating
Calculate
Add point
Delete last point
00:00:00
100%
Rating points inputs 1 2 3 4 5
Ambient temperature [°C]: 0 10 20 30 40
LT capacity [kW]: 5 5 5 5 5
MT capacity [kW]: 50 50 50 50 50
GBP (reference)
GBPpar
GBPejePar
GBPeje
Update diagram and state points
Mechanical capacities
Delivered cooling capacity LT [kW]: 5.0 5.0 5.0 5.0 5.0
Delivered cooling capacity MT [kW]: 50.0 50.0 50.0 50.0 50.0
Capacity fulfilment LT [%] 100.0% 100.0% 100.0% 100.0% 100.0%
Capacity fulfilment MT [%] 100.0% 100.0% 100.0% 100.0% 100.0%
Pack capacity LT [%]: 18.9% 18.9% 18.9% 19.3% 19.9%
Pack capacity MT [%]: 36.8% 40.9% 50.3% 53.7% 63.5%
Gas cooler capacity [kW]: 64.0 67.7 74.8 79.1 90.3
Power consumption
Compressor LT [kW]: 0.80 0.80 0.80 0.94 1.05
Compressor MT [kW]: 8.64 12.52 20.01 24.43 36.15
Condenser fan [kW]: 0.94 1.48 1.65 3.03 3.03
System COP (COSP)
LT [-]: 6.23 6.23 6.23 5.32 4.76
MT [-]: 5.82 3.98 2.57 2.04 1.43
Total [-]: 5.30 3.71 2.45 1.94 1.37
Savings
Energy savings [kW]: 0.0 0.0 0.0 2.6 5.1
Energy savings [%]: 0.4% 0.3% 0.2% 8.5% 11.3%
Additional information
Evaporation temperature LT [°C]: -30.0 -30.0 -30.0 -30.0 -30.0
Evaporation temperature MT [°C]: -10.0 -10.0 -10.0 -10.0 -10.0
Intermediate temperature [°C]: -7.4 -7.4 -7.4 -6.5 -4.1
Gas cooler pressure [bar]: 45.0 53.3 67.3 79.1 105.5
Export
Log(p)-h
State points
Gas cooler temperature profiles
Warnings
Pressure [bar]
Enthalpy [kJ/kg]
h = 68.23
p = 110.68


1. Setup systems
2. Calculate
3. Economy
4. Report
5. Rating
Calculate
Add point
Delete last point
00:00:00
100%
Log(p)-h
State points
Gas cooler temperature profiles
Warnings
Export table
Copy diagram
LT
MT
ΔP_lift < ΔP_min
Point T [°C] P [bar] v [m3/kg] d [kg/m3] h [kJ/kg] s [kJ/kg-K] x [-] mDot [g/s]
1 -2.6 31.2 0.0119 84.2 435.5 1.877 1.000 455.5
2 107.6 105.5 0.0052 191.9 510.8 1.940 0.000 455.5
3 107.6 105.5 0.0052 191.9 510.8 1.940 0.000 455.5
4 41.2 105.5 0.0016 637.7 312.5 1.352 0.000 455.5
5 41.2 105.5 0.0016 637.7 312.5 1.352 0.000 455.5
6 -4.1 31.2 0.0010 952.4 190.3 0.966 0.000 197.0
7 -10.0 26.5 0.0017 590.5 190.3 0.968 0.052 197.0
8 0.0 26.5 0.0154 65.1 448.7 1.949 1.000 197.0
9 0.0 26.5 0.0154 65.1 448.7 1.949 1.000 197.0
10 -4.1 31.2 0.0082 122.0 353.6 1.573 0.673 652.6
11 -4.1 31.2 0.0010 952.4 190.3 0.966 0.000 213.5
12 -4.1 31.2 0.0117 85.6 433.1 1.868 1.000 439.0
13 -4.1 31.2 0.0117 85.6 433.1 1.868 1.000 439.0
14 -2.6 31.2 0.0119 84.2 435.5 1.877 1.000 455.5
Export



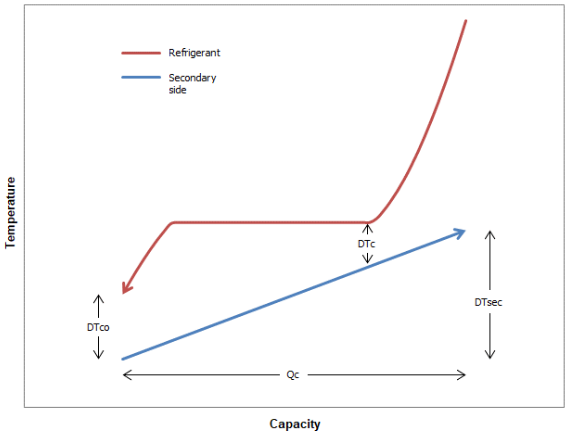
Rating points inputs	1	2	3	4	5
Ambient temperature [°C]:	0	10	20	30	40
LT capacity [kW]:	5	5	5	5	5
MT capacity [kW]:	50	50	50	50	50

Update diagram and state points					
Mechanical capacities					
Delivered cooling capacity LT [kW]:	5.0	5.0	5.0	5.0	5.0
Delivered cooling capacity MT [kW]:	50.0	50.0	50.0	50.0	50.0
Capacity fulfilment LT [%]	100.0%	100.0%	100.0%	100.0%	100.0%
Capacity fulfilment MT [%]	100.0%	100.0%	100.0%	100.0%	100.0%
Pack capacity LT [%]:	18.9%	18.9%	18.9%	19.3%	19.9%
Pack capacity MT [%]:	36.8%	40.9%	50.3%	53.7%	63.5%
Gas cooler capacity [kW]:	64.0	67.7	74.8	79.1	90.3
Power consumption					
Compressor LT [kW]:	0.80	0.80	0.80	0.94	1.05
Compressor MT [kW]:	8.64	12.52	20.01	24.43	36.15
Condenser fan [kW]:	0.94	1.48	1.65	3.03	3.03
System COP (COSP)					
LT [-]:	6.23	6.23	6.23	5.32	4.76
MT [-]:	5.82	3.98	2.57	2.04	1.43
Total [-]:	5.30	3.71	2.45	1.94	1.37
Savings					
Energy savings [kW]:	0.0	0.0	0.0	2.6	5.1
Energy savings [%]:	0.4%	0.3%	0.2%	8.5%	11.3%
Additional information					
Evaporation temperature LT [°C]:	-30.0	-30.0	-30.0	-30.0	-30.0
Evaporation temperature MT [°C]:	-10.0	-10.0	-10.0	-10.0	-10.0
Intermediate temperature [°C]:	-7.4	-7.4	-7.4	-6.5	-4.1
Gas cooler pressure [bar]:	45.0	53.3	67.3	79.1	105.5

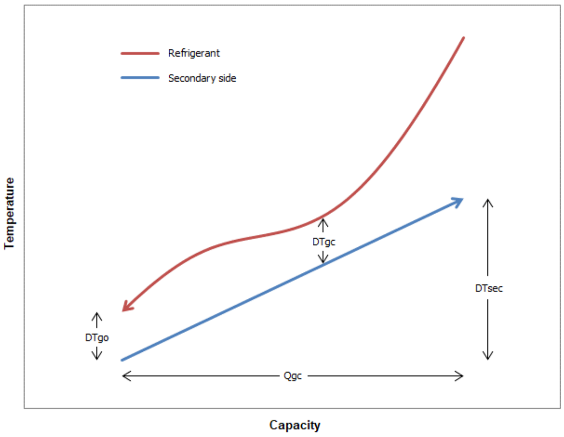
Advanced condenser/gas-cooler

- Calculates/satisfies internal pinch

Condenser



Gas cooler



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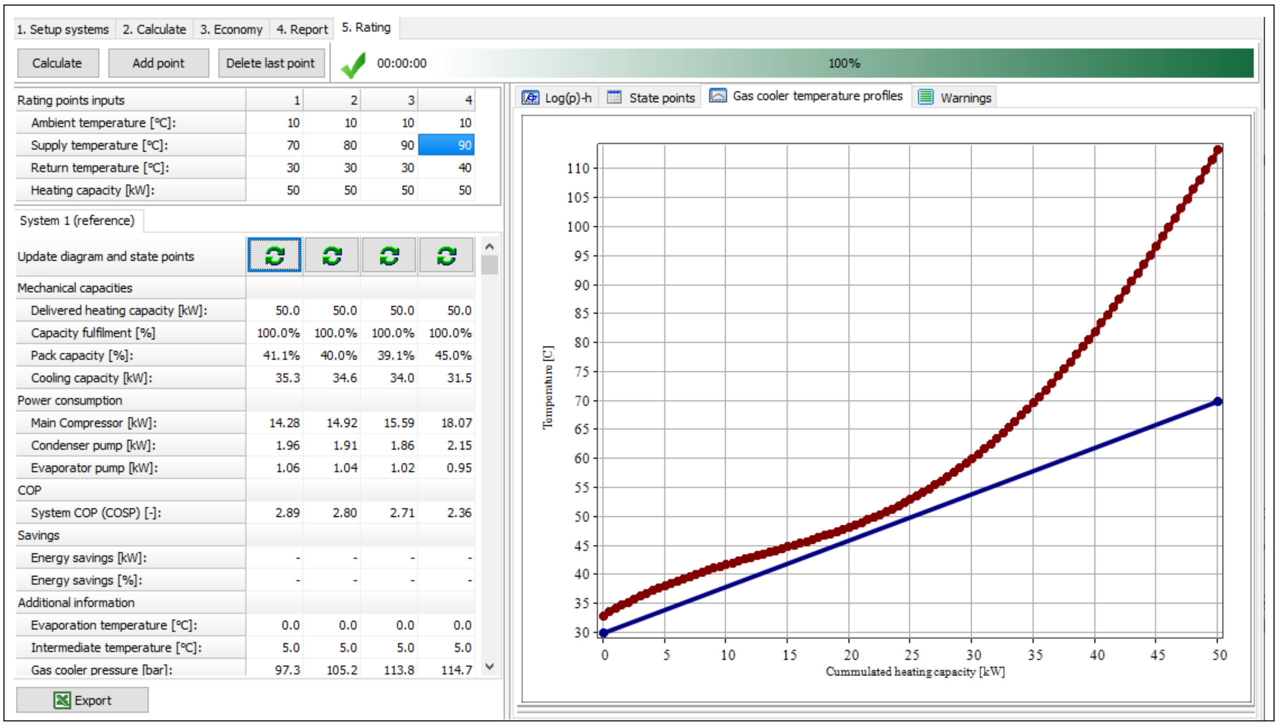
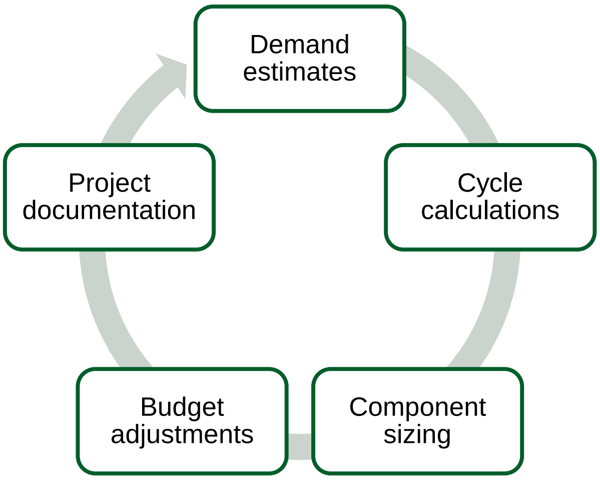

1. Setup systems
2. Calculate
3. Economy
4. Report
5. Rating
Calculate
Add point
Delete last point
00:00:00
100%
Rating points inputs 1 2 3 4
Ambient temperature [°C]: 10 10 10 10
Supply temperature [°C]: 70 80 90 90
Return temperature [°C]: 30 30 30 40
Heating capacity [kW]: 50 50 50 50
System 1 (reference)
Update diagram and state points
Mechanical capacities
Delivered heating capacity [kW]: 50.0 50.0 50.0 50.0
Capacity fulfilment [%] 100.0% 100.0% 100.0% 100.0%
Pack capacity [%]: 41.1% 40.0% 39.1% 45.0%
Cooling capacity [kW]: 35.3 34.6 34.0 31.5
Power consumption
Main Compressor [kW]: 14.28 14.92 15.59 18.07
Condenser pump [kW]: 1.96 1.91 1.86 2.15
Evaporator pump [kW]: 1.06 1.04 1.02 0.95
COP
System COP (COSP) [-]: 2.89 2.80 2.71 2.36
Savings
Energy savings [kW]: - - - -
Energy savings [%]: - - - -
Additional information
Evaporation temperature [°C]: 0.0 0.0 0.0 0.0
Intermediate temperature [°C]: 5.0 5.0 5.0 5.0
Gas cooler pressure [bar]: 97.3 105.2 113.8 114.7
Export
Log(p)-h
State points
Gas cooler temperature profiles
Warnings
Temperature [C]
Cummulated heating capacity [kW]


Future perspectives
23/03/2023
Pack Calculation Pro, Martin Ryhl Kærn
ipu

Project lifecycle support goal

- IPU plan to support the whole project lifecycle with Pack Calculation Pro:
  - Early estimates of demand profiles for heating and cooling load based on templates.
  - Calculation of thermodynamic cycles with automatically sized compressors and HX.
  - Rough estimates of plant costs based on simple economic models.
  - Iterative refinement of calculation results by gradually including more information.
- UX research process
- Initiated work on the new user interface!



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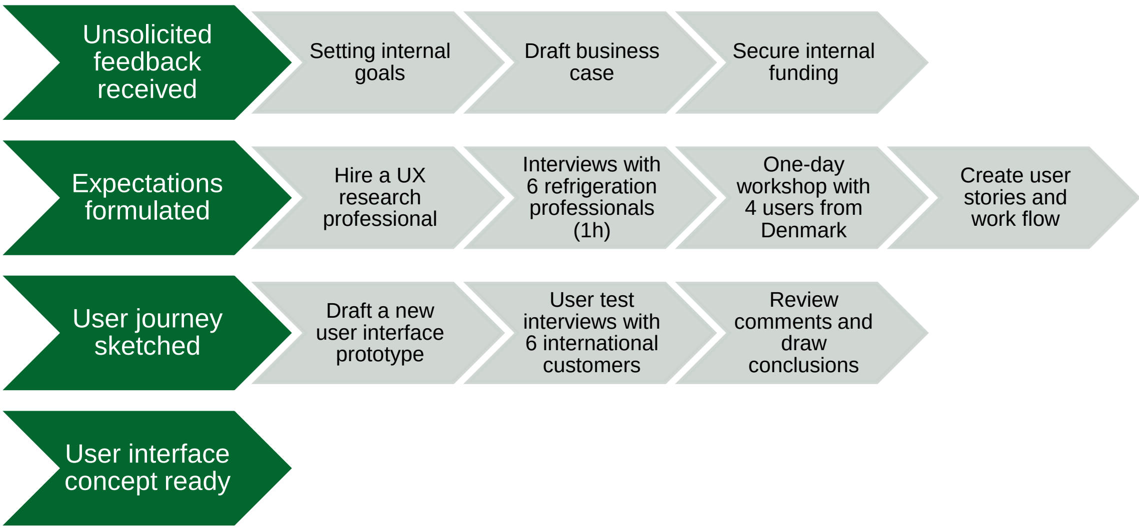
UX Research Process



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ipu.

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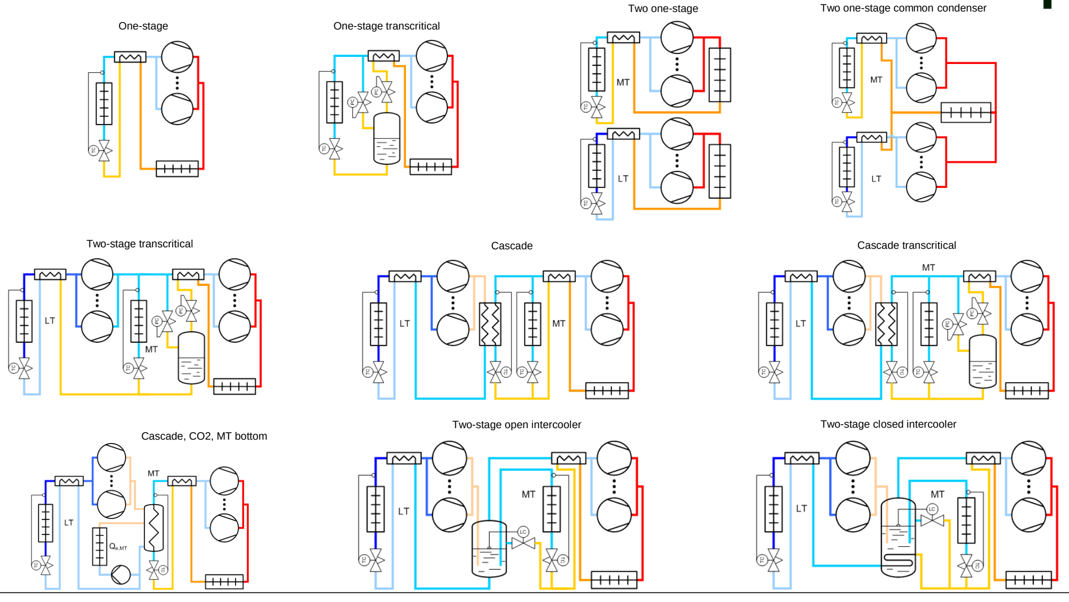
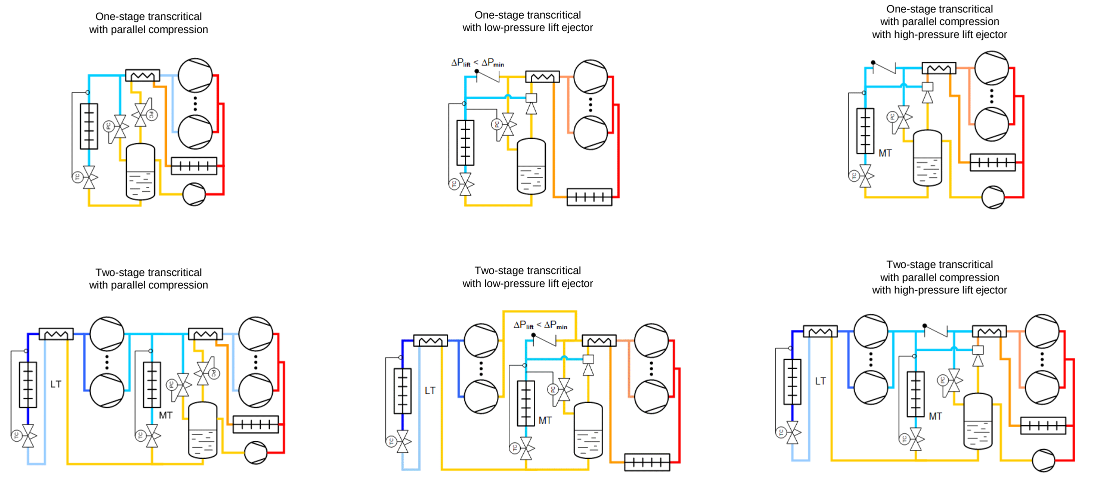
Backup slides

Basic cycle configurations

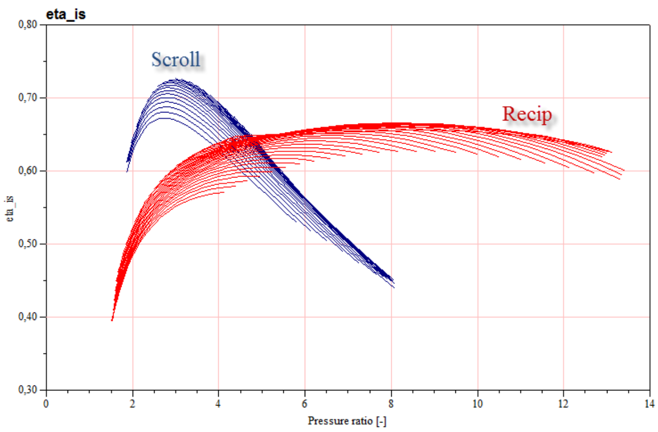


Parallel compression and ejectors



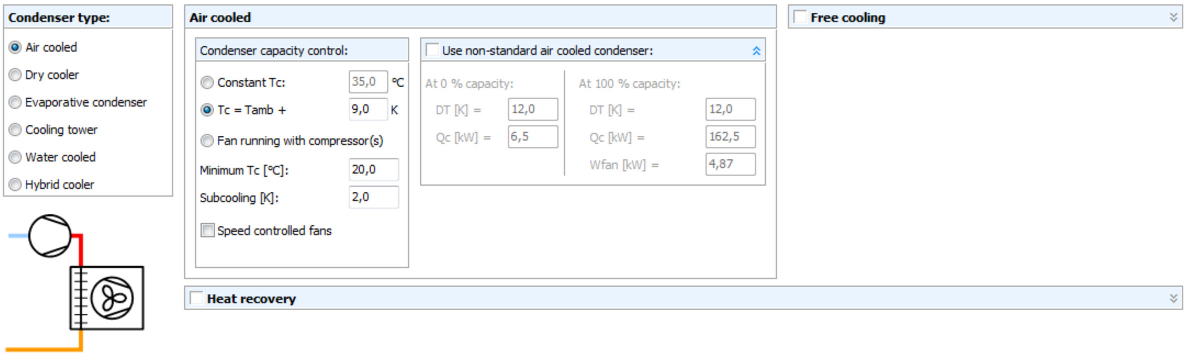
Compressors

- Polynomials based on manufacturers data (EN 12900):
  - If part load polynomials are not available (cylinder unloading, speed, slide,…), general models are used based on available data.
  - Rating condition from polynomials changed to isentropic and volumetric efficiency which are kept constant (independent of superheat)



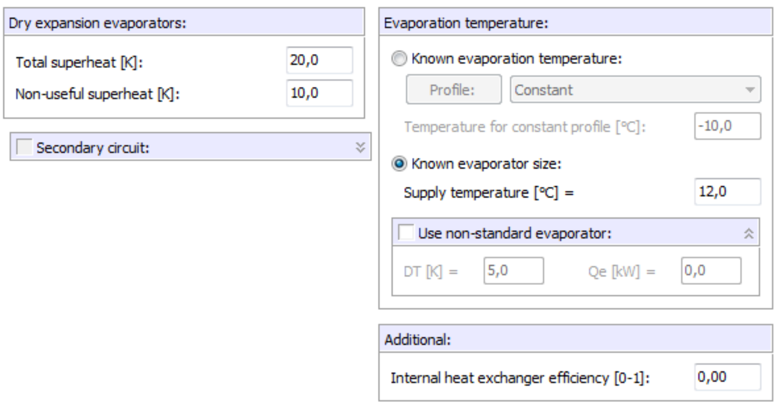
Condensers

- Different models for different condenser types:
  - From simple UA model to Merkel-equations for cooling towers
  - Condensing temperature generally controlled
  - At high ambient temperature, condensing temperature automatically raised, if condenser too small



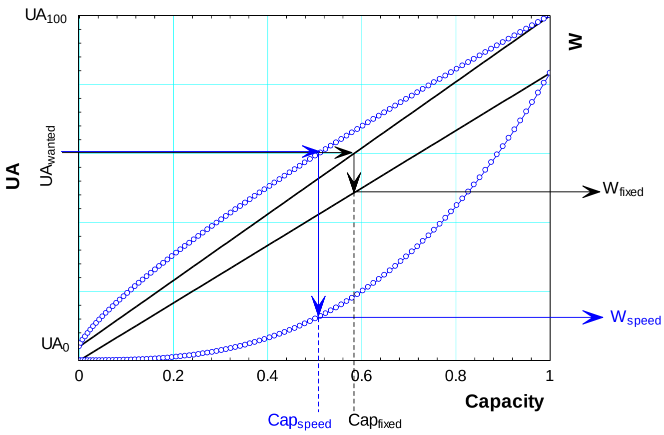
Evaporators

- Evaporation temperature is typically known for refrigeration systems
  - Users can decide to let evaporation temperature float and instead give a supply temperature
- Evaporation temperature floats for heat pumps (similar to condensers for refrigeration)



Fans and pumps

- Speed controlled: calculated based on typical exponential relations
- Fixed speed: linear relation (on/off)



$$Capacity_{fixed} = \frac{UA - UA_0}{UA_{100} - UA_0}$$

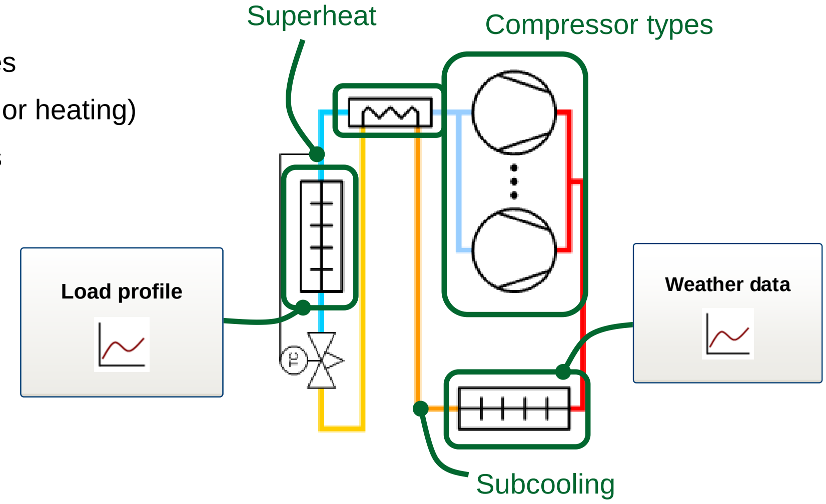
$$Capacity_{speed} = \left(\frac{UA - UA_0}{UA_{100} - UA_0}\right)^{\frac{1}{0.8}}$$

$$W_{fixed} = W_{100} \cdot Capacity_{fixed}$$

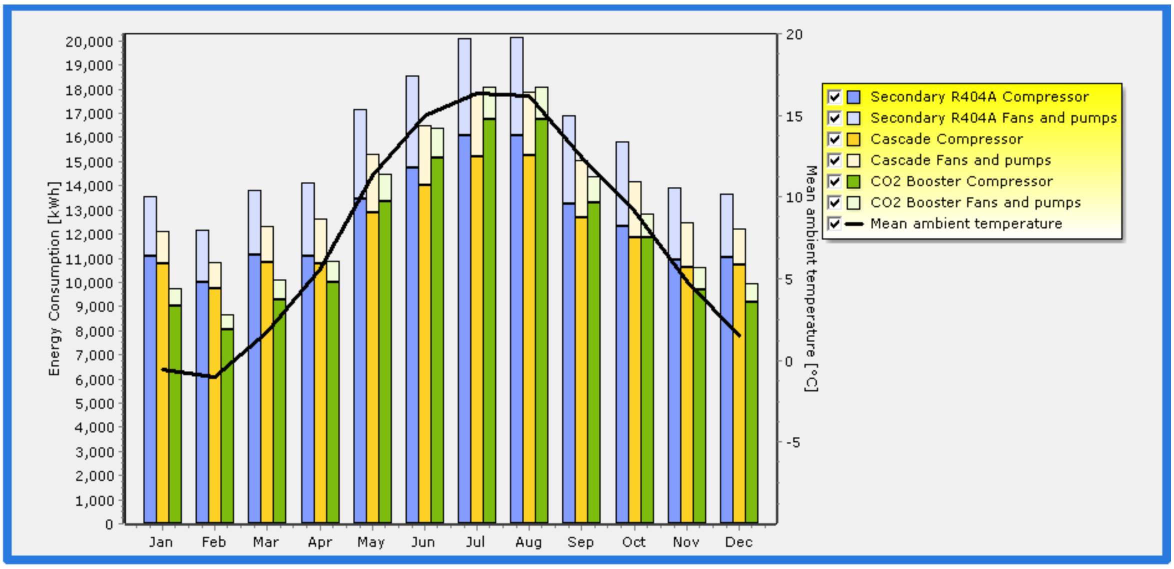
$$W_{speed} = W_{100} \cdot Capacity_{speed}^{2.8}$$

Calculation process

1. Define system
2. Set up compressor pack
3. Define heat exchanger sizes
4. Define load profile (cooling or heating)
5. Define operating conditions
6. Select location
7. Calculate



Results (yearly energy consumption) - CO2, R404A, R134a/CO2 cascade



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Results (life cycle costs) - CO2, R404A, R134a/CO2 cascade

Energy Prices | Life Cycle Costs | CO2 Equivalent Emissions

Update

Expected average interest rate: 3 %

Expected average inflation rate: 2 %

Expected lifetime: 10 years

Initial cost:

	Secondary R404A	Cascade	CO2 Booster
Cost of equipment [€]	50,000	35,000	50,000
Cost of installation [€]	40,000	70,000	60,000

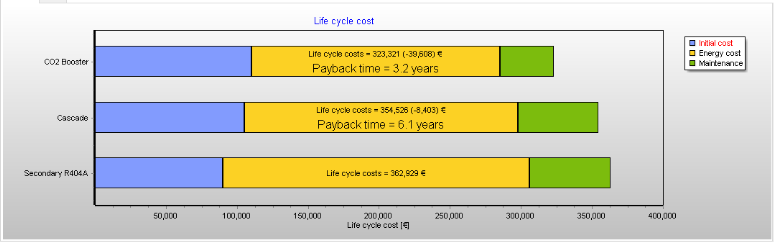
Annual operating cost:

	Secondary R404A	Cascade	CO2 Booster
Energy consumption [kWh]	189884.33	169315.02 (-20,569)	154160.28 (-35,724)
Backup heater consumption [kWh]	0.00	0.00 (0)	0.00 (0)
Cost of maintenance [€]	6,000	6,000	4,000

Result:

	Secondary R404A	Cascade	CO2 Booster
Effective interest rate [%]	0.98	0.98	0.98
Internal rate of return [%]	-	10.26	28.96
Total annual cost [€]	28,786	26,318 (-2,468)	22,499 (-6,287)
Payback time [years]	-	6.1	3.2
Total initial cost [€]	90,000 (25%)	105,000 (30%)	110,000 (34%)
Present value of maintenance cost [€]	56,888 (16%)	56,888 (16%)	37,925 (12%)
Present value of energy cost [€]	216,041 (59%)	192,639 (54%)	175,396 (54%)
Life cycle cost [€]	362,929	354,526 (-8,403)	323,321 (-39,608)

Diagram | Plot



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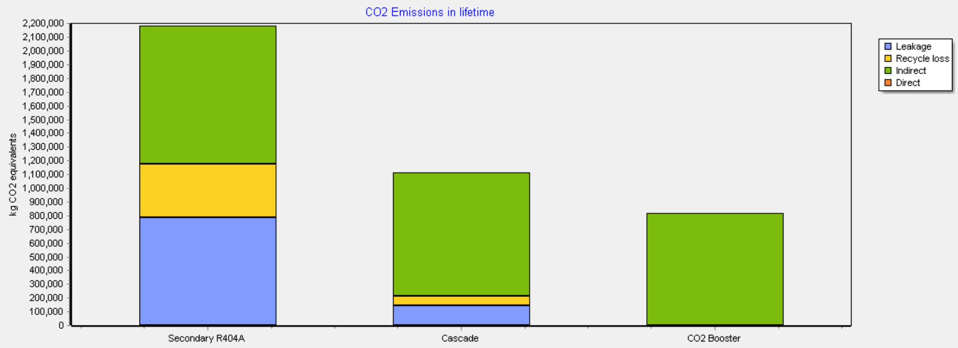
CO2 emissions (TEWI) - CO2, R404A, R134a/CO2 cascade

Energy Prices | Life Cycle Costs | CO2 Equivalent Emissions

Update

	Secondary R404A (R404A)	Cascade_LT (R744)	Cascade_MT (R134a)	CO2 Booster (R744)
Refrigerant charge [kg]	200	100	100	200
Recycle rate [%]	50	0.0	50	0.0
Leakage rate[%/year]	10	10	10	10

	Leakage [kg CO2]	Recycle loss [kg CO2]	Indirect [kg CO2]	Direct [kg CO2]	Total [kg CO2]
Secondary R404A	784,400 (35.9%)	392,200 (18.0%)	1,006,387 (46.1%)	0 (0.0%)	2,182,987
Cascade	143,100 (12.9%)	71,600 (6.4%)	897,370 (80.7%)	0 (0.0%)	1,112,070
CO2 Booster	200 (0.0%)	200 (0.0%)	817,049 (100.0%)	0 (0.0%)	817,449



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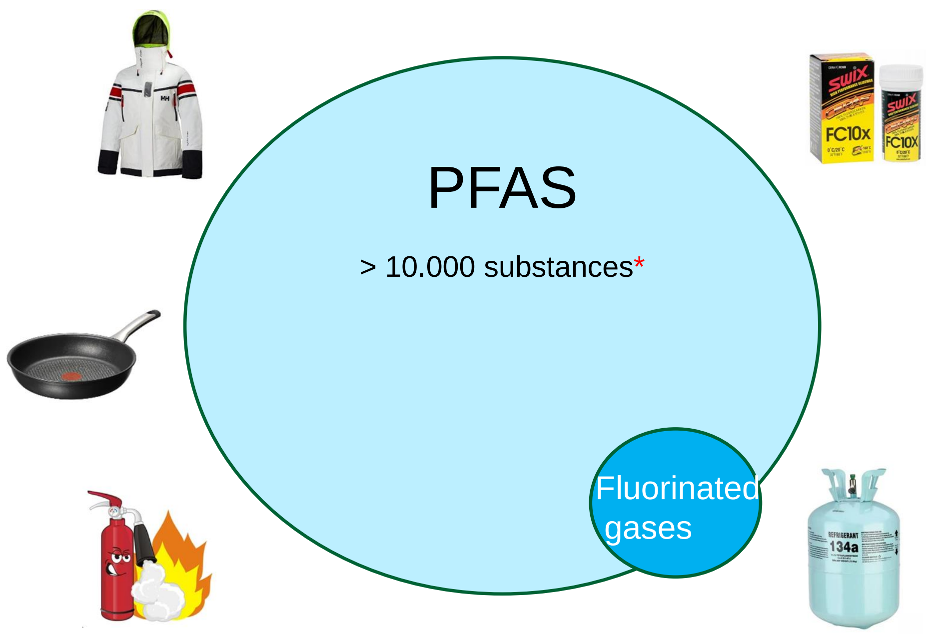
Ministry of Environment of Denmark
Environmental Protection Agency

PFAS restriction proposal and fluorinated gases

Køle- og varmepumpeforum 2023

23 March 2023
Toke Winther

PFASs = Per- and PolyFluoroAlkyl Substances



- Refrigeration
- Heat pumps
- Aircondition
- Etc.

* OECD (2021) PFAS definition: Substances that contain at least one –CF2– or one –CF3 group, without any H/Cl/Br/I attached to it (with some exceptions)

Restriction proposal - content

- **REACH = Registration, Evaluation, Authorisation and restriction of Chemicals**

- **Restriction proposal:**
  - ✓ Chemical identity
  - ✓ Hazards, risks, effects
  - ✓ Applications
  - ✓ Availability of alternatives
  - ✓ Socioeconomic analysis – impact assessment

- **PFAS restriction proposal**

Preparation

May – July 2020
Call for evidence

July 2021 – Oct 2021
2nd stakeholder consultation

Oct 2021 – Jan 2023
Drafting of proposal

Stakeholder interviews, literature search, meetings

Jan 2020
First meeting

13 January 2023
Submission of proposal

7 February 2023
Publication of proposal

Restriction process – next steps

Next steps – key messages (consultation)

- **Dossier submitter cannot amend dossier on own initiative**
- **Information needs to be submitted to Public Consultation**
- **Information submitted on sector level is preferred (instead of individual submissions)**
- **Well-substantiated scientific evidence is key:**
  - ✓ Alternatives, impacts (costs and benefits), missed uses, tonnages and emissions, R&D efforts, etc.
  - ✓ If available, quantitative information is preferred
- **Guiding questions from ECHA committees**
- **Position papers and unsubstantiated claims are not useful**
- **Link to Public Consultation:** **https://comments.echa.europa.eu/comments_cms/AnnexXVRestrictionDossier.aspx?RObjectId=0b0236e1885e69de**

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PFAS - basis for restriction

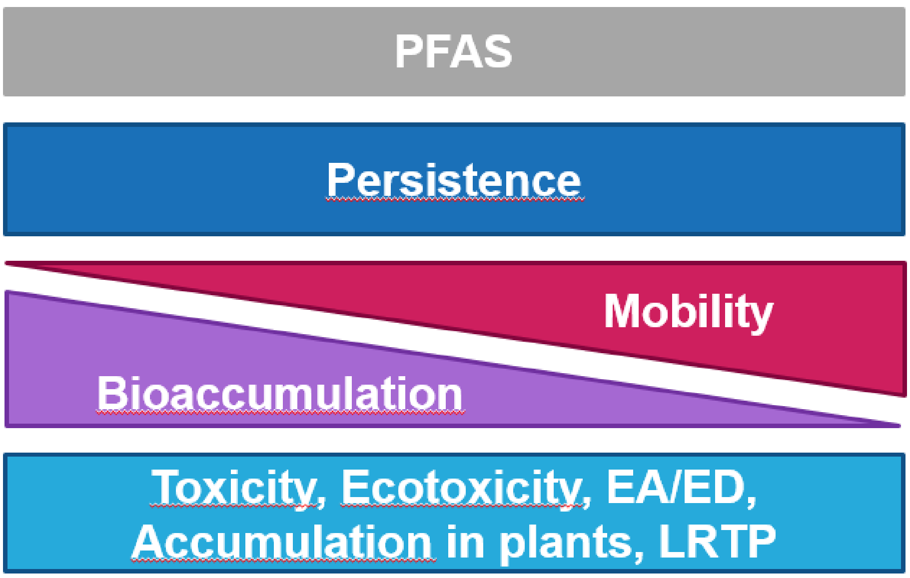
Global focus

- **Exposure to PFAS in general has gained increasing attention**
  - ✓ EU chemicals strategy for sustainability
- **PFAS linked to pollution of the environment, including drinking water, food and feed**
- **Some PFASs already restricted in the EU (PFOS, PFOA, C9-C14 PFCAs)**
  - ✓ This proposal does not affect these existing restrictions
  - ✓ Decision making for restrictions on PFHxS and PFHxA is ongoing
- **Several restrictions in non-EU countries**
  - ✓ Certain US States (California, Washington, NY, etc.), Australia

«Forever chemicals»

- All PFASs in scope of this restriction proposal are either persistent themselves or degrade to other persistent PFASs
- Persistence due to strength of the carbon-fluorine bond
- PFASs remain in environment for decades to centuries

Hazard Assessment



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Function of PFASs

Combination of useful properties from technical viewpoint

- Water, oil and dirt repellency
- Durability under extreme conditions:
  - ✓ temperature, pressure, radiation, chemicals
- Electrical and thermal insulation
- Surfactants, refrigerants...

→ Used in high tonnages in many different sectors

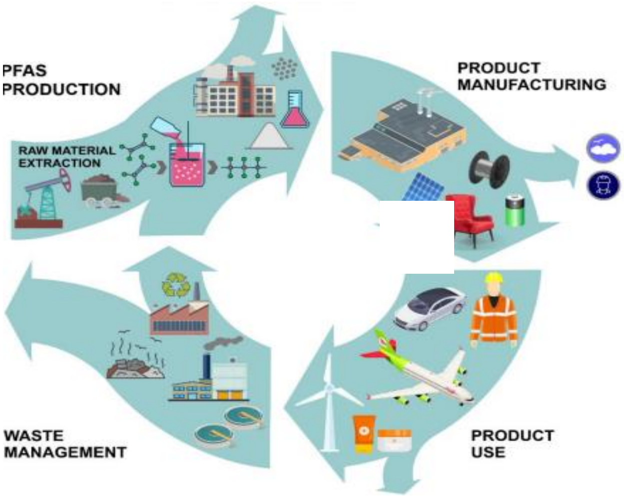
Sectors/uses of PFASs

- Industrial processes
- Firefighting foams
- TULAC Food contact materials (incl. packaging)
- Metal plating/metal products
- Consumer mixtures
- Ski wax
- Transport
- Applications of fluorinated gases
- Electronics and semiconductors
- Energy sector
- Construction products
- Lubricants
- Petroleum and mining
- Medical devices
- Cosmetics
- Other uses

Emissions

75 000 tonnes of emissions in 2020

4.4 million tonnes of emissions over 30 years including an estimated increase of PFAS use



Source: https://ec.europa.eu/environment/pdf/chemicals/2020/10/SWD_PFAS.pdf

Analysis of alternatives

- **Alternatives already adopted in many sectors/uses**
- **For some sectors alternatives already identified but time needed to implement or alternatives not available in sufficient quantities (e.g. industrial food and feed production)**
- **In other sectors research and development still needed (e.g. medical devices)**

Risk characterisation

- Risks are not adequately controlled, and releases should be minimised…
- … because of accumulation over time which leads to levels likely to cause effects for humans and environment

- Risks of PFASs are considered as non-threshold
- Releases are used as a proxy for risk

- Effectiveness of the proposed restriction is based on the effectiveness of emission reduction

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Proposed restriction: Ban

Ban on manufacture, use and placing on the market

- As substances on their own

- As a constituent
- A mixture
- An article

} ≥ 25 ppb for any PFASs
≥ 250 ppb for sum of PFASs
≥ 50 ppm * for PFASs

* If total fluorine exceeds 50 mg F/kg the manufacturer, importer or downstream user shall upon request provide to the enforcement authorities a proof for the fluorine measured as content of either PFASs or non-PFASs.

Annex XV report (page 4-8) para. 2
https://echa.europa.eu/documents/10162/1c480180-ece9-1bdd-1eb8-0f3f8e7c0c49

Restriction Options (RO‘s) assessed

RO1

Full ban of all uses

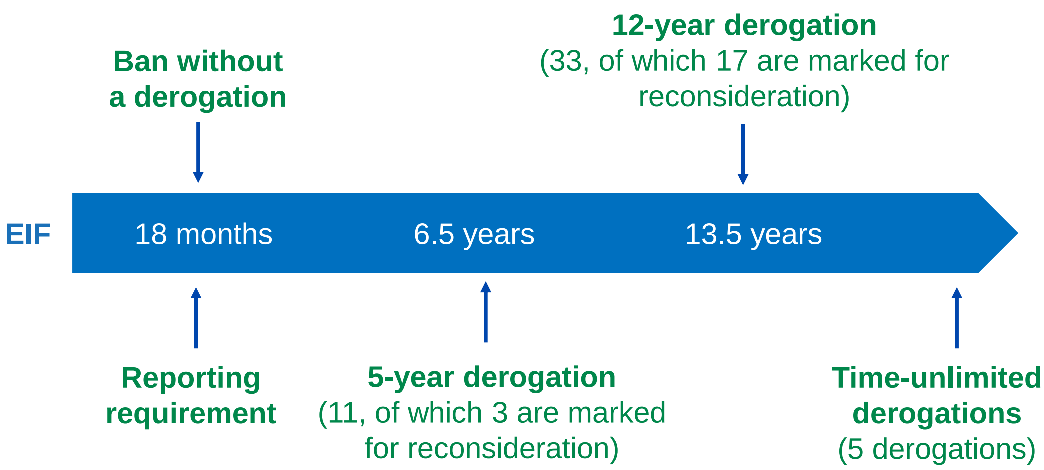
- Transition period: 18 months

RO2

Ban with use-specific derogations

- Transition period: 18 months
- Duration of derogation:
  - 5-years (based on set criteria relating to alternatives)
  - 12-years (based on set criteria relating to alternatives)
  - Time-unlimited derogations (specifically justified)

Phase-out timelines



Proposed restriction: Reporting

Mandatory reporting in relation to majority of derogations

Who
- Active substances: Manufacturers, importers
- Uses of fluorinated gases & uses with 12 - year derogation period:
  - Substance & articles: Manufacturers, importers
  - Mixtures: Formulators

What
- Information on the use (which derogation)
- Identity and quantity of substance placed on market

Annex XV report (page 4-8) para. 7
https://echa.europa.eu/documents/10162/1c480180-ece9-1bdd-1eb8-0f3f8e7c0c49

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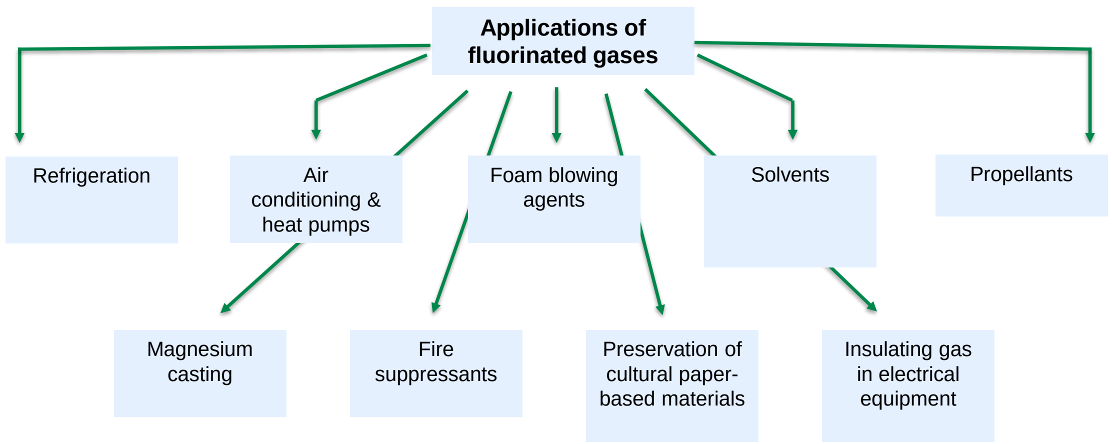
Implications for fluorinated gases

23 March 2023
Toke Winther

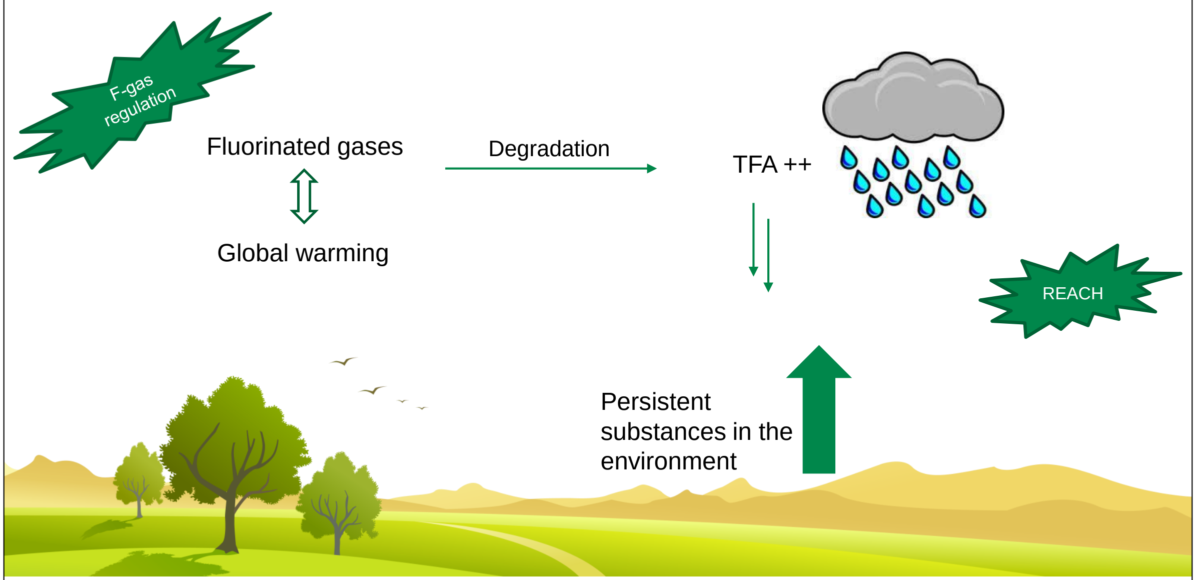
Applications – fluorinated gases



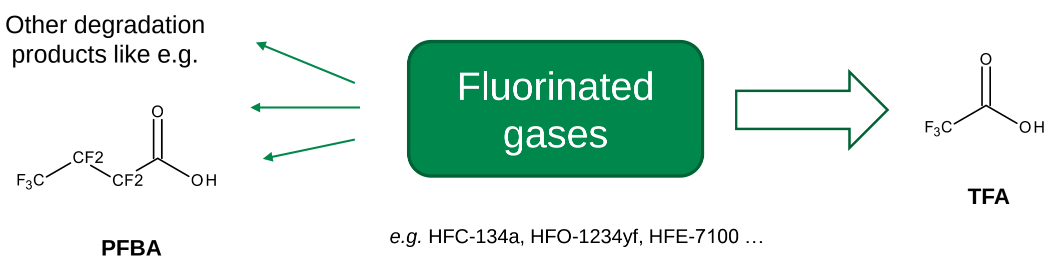
Tonnages and emissions

Application	Tonnage range	Emission range % emitted in manufacturing and use phase	Emission contribution Contribution to total emission [%]
Applications of fluorinated gases	> 10 000	5 – 25	> 50
Textiles, upholstery, leather, apparel & carpets	> 10 000	5 – 25	10 – 50
Medical devices	> 10 000	5 – 25	5 – 10
Manufacture	> 10 000	0 – 5	1 – 5
Food contact materials and packaging	> 10 000	0 – 5	0 – 1
Transport	> 10 000	0 – 5	0 – 1
Construction products	1 000 – 10 000	25 – 75	1 – 5
Electronics and semiconductors	1 000 – 10 000	5 – 25	0 – 1
Lubricants	1 000 – 10 000	5 – 25	0 – 1
Petroleum and mining	1 000 – 10 000	0 – 5	0 – 1
Energy sector	1 000 – 10 000	0 – 5	0 – 1
Metal plating and manufacture of metal products	100 – 1 000	0 – 5	0 – 1
Cosmetics	10 – 100	> 95	0 – 1
Consumer mixtures	10 – 100	75 – 95	0 – 1
Ski wax	0 – 10	25 – 75	0 – 1

Concerns – fluorinated gases



Atmospheric degradation of fluorinated gases



TFA in beer and tea

Food Chemistry 351 (2021) 129304

Contents lists available at ScienceDirect

Food Chemistry

journal homepage: www.elsevier.com/locate/foodchem

ELSEVIER

Short communication

Ultrashort-chain perfluoroalkyl substance trifluoroacetate (TFA) in beer and tea – An unintended aqueous extraction

Marco Scheurer, Karsten Nödler *

TZW: DVGW-Technologiezentrum Wasser, Karlsruher Str. 84, 76139 Karlsruhe, Germany

ARTICLE INFO

Keywords:
Alcoholic and non-alcoholic beverages
Perfluoroalkyl substances
Polyfluoroalkyl substances
Aqueous extraction
Brewing process
Trifluoroacetate

ABSTRACT

Trifluoroacetate (TFA) is an ultrashort-chain perfluoroalkyl substance, which is ubiquitously present in the aqueous environment. Due to its high mobility, it accumulates in plant material. The study presented here shows for the first time that TFA is a widely spread contaminant in beer and tea / herbal infusions. In 104 beer samples from 23 countries, TFA was detected up to 51 μg/L with a median concentration of 6.1 μg/L. An indicative brewing test and a correlation approach with potassium (K) indicate that the main source of TFA in beer is most likely the applied malt. It could be proven that the impact of the applied water is negligible in terms of TFA, which was supported by the analysis of numerous tap water samples from different countries. The unintended extraction of TFA was also demonstrated for tea / herbal infusions with a median concentration of 2.4 μg/L.

https://www.sciencedirect.com/science/article/pii/S0308814621003095

TFA in groundwater

- TFA identified in 219 of 247 (89%) groundwater samples in DK. Max concentration 2.4 μg/L
- DK limit value for TFA in drinking water 9 μg/L

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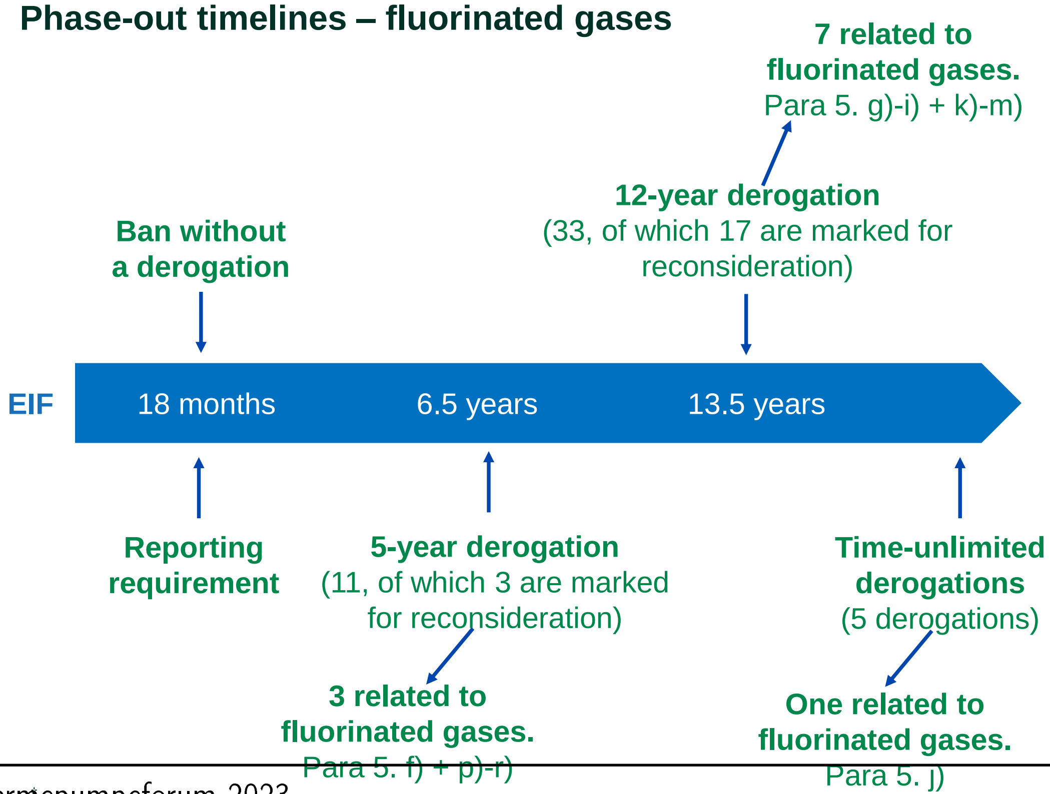
Chemical scope of the PFAS restriction (Fluorinated gases)

- **Wide scope – group regulation**
- **-CF_2- or -CF_3 (without any H/Cl/Br/I attached to it)**
- **Included: e.g** HFC-125, HFC-134a, HFC-227ea, HFO-1234yf, HFO-1234ze, HFO-1336mzz,…
- **Not included:** HFC-23, HFC-32, HFC-152a, HCFC-141b, HFO-1132a

Foto: Torgrim Asphjell, Miljødirektoratet

Phase-out timelines – fluorinated gases



(timelimited) derogations related to fluorinated gases

- **5 j. refrigerants in HVACR-equipment in buildings where national safety standards and building codes prohibit the use of alternatives;**
- **5 i. maintenance and refilling of existing HVACR equipment put on the market before [18 months after EiF] and for which no drop-in alternative exist until 13.5 years after EiF;**
- **5 f. refrigerants in low temperature refrigeration below -50 °C until 6.5 years after EiF;**

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ECHA
EUROPEAN CHEMICALS AGENCY

Per- and polyfluoroalkyl substances (PFAS)

EC / List no: - CAS no: -

CLP Annex VI Index number	
Further substance information	Per- and polyfluoroalkyl substances (PFASs) defined as: Any substance that contains at least one fully fluorinated methyl (CF3-) or methylene (-CF2-) carbon atom (without any H/Cl/Br/I attached to it). A substance that only contains the following structural elements is excluded from the scope of the proposed restriction: CF3-X or X-CF2-X', where X = -OR or -NRR' and X' = methyl (-CH3), methylene (-CH2-), an aromatic group, a carbonyl group (-C(O)-), -OR'', -SR'' or –NR''R''', and where R/R'/R''/R''' is a hydrogen (-H), methyl (-CH3), methylene (-CH2-), an aromatic group or a carbonyl group (-C(O)-).
Submitter(s)	Germany Denmark Netherlands Norway Sweden
Details on the scope of restriction	Restriction on the manufacture, placing on the market and use of PFASs.
Reason for restriction	PFASs are, or ultimately transform into, persistent substances, leading to irreversible environmental exposure and accumulation. Due to their water solubility and mobility, contamination of surface, ground- and drinking water and soil has occurred in the EU as well as globally and will continue. It has been proven very difficult and extremely costly to remove PFASs when released to the environment. In addition, some PFASs have been documented as toxic and/or bioaccumulative substances, both with respect to human health as well as the environment. Without taking action, their concentrations will continue to increase, and their toxic and polluting effects will be difficult to reverse.
Remarks	
Status	Submitted
Date of intention	15-Jul-2021
Expected date of submission	13-Jan-2023
Withdrawal date	
Reason for withdrawal	
Start of Call for Evidence consultation	19-Jul-2021
Deadline for comments on the Call for Evidence	17-Oct-2021
Start of second Call for Evidence consultation	
Deadline for comments on the second Call for Evidence	
Start of third Call for Evidence consultation	
Deadline for comments on the third Call for Evidence	
Restriction report (and annexes)	Annex A Annex B Annex C Annex D Annex E Annex F Annex G Appendix E4 Appendix G1 Appendix G2 Annex XV report
Information note on restriction report	

https://echa.europa.eu/registry-of-restriction-intentions/-/dislist/details/0b0236e18663449b

- **Annex XV report** = «summary» (200 s)
  - Restriction entry = page 4-8
- **Annex A** (A.3.9) = use
- **Annex B.9** (B.9.9) = exposure
- **Annex E** (E.2.8) = alternatives and socio-economic analysis

Webinar 5. april, ECHA

https://echa.europa.eu/-/restriction-of-per-and-polyfluoroalkyl-substances-pfass-under-reach

Next steps – key messages

- Public Consultation 22 March – 25 September 2023
- Well-substantiated scientific evidence as input is key

KØLE- OG VARMEPUMPEFORUM 2023

CONFERENCE MARCH 23RD

Technical experiences from operating large CO2 heat pumps

1) Køber løsninger – ikke produkter
2) TCO – mulighed for at sælge den gode løsning
3) Levere det du lover – temperatur, kapacitet, COP

FENAGY FUTURE ENERGY SOLUTIONS

FENAGY

Manufacturer of heat pumps and refrigeration systems in Aarhus

- Office of engineers and production in Lystrup (just outside Aarhus) Denmark
- 50 dedicated employees
- Refrigeration systems and heat pumps
- Focus on CO_2 as refrigerant, but also HC's (isobutane and propane)
- Heat pumps and refrigeration systems (200 kW – 2 MW per unit)
- 20 projects delivered of more than 50 MW heat -> 5% better performance

Heat pumps
District heating and industry

Refrigeration systems
Chillere, DX racks, Freezing

Vision
Leading OEM of industrial heat pumps and refrigeration systems for sustanable production of heat and cold

Mission
We poduce heat pumps and refrigeration units for the industry and utility sector

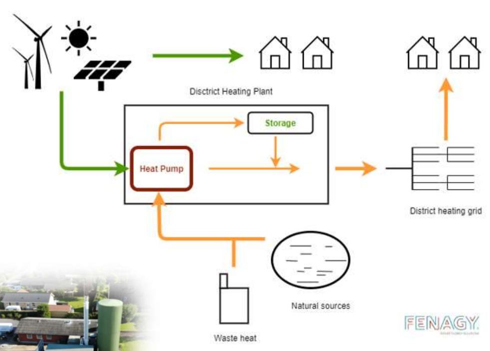
Aim
To contribute to the green transition thrue electrification and combied heat and cooling (CHC)

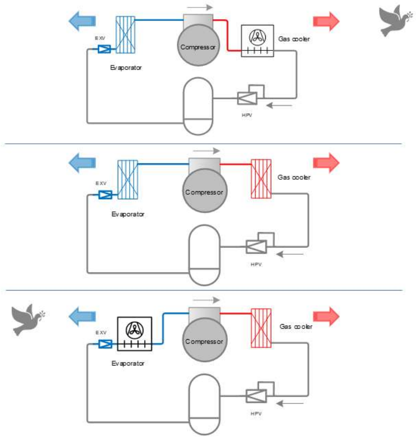
Values

Honesty
Reliability
Constant care
Humbleness
Passion

FENAGY

Heat pumps and CHC - district heating and industry





FENAGY

De kommercielle erfaringer med varmepumpe-projekter i fjernvarmen

- ❖ Udbud
- ❖ Nutidsværdi og TCO
- ❖ Elpriser
- ❖ Levetid
- ❖ Driftssikkerh
- ❖ Temperatur-sa
- ❖ Service-kontrakter
- ❖ Garanti-forlængelse
- ❖ Driftssikring
- ❖ Bankgarantier
- ❖ Cash-flow

- ❖ Projektledelse (store projekter)
- ❖ Performance-test
- ❖ Måletolerancer
- og vibrationer
- ❖ ABT18
- ❖ Boder
- ❖ Bodsmaksimering

Du skal ville det!

FENAGY

New 2023 models -> H1800 -> H2600

Kombineret køl/ varme, fabriksbyggede og mobile enheder CO_2 som kølemiddel

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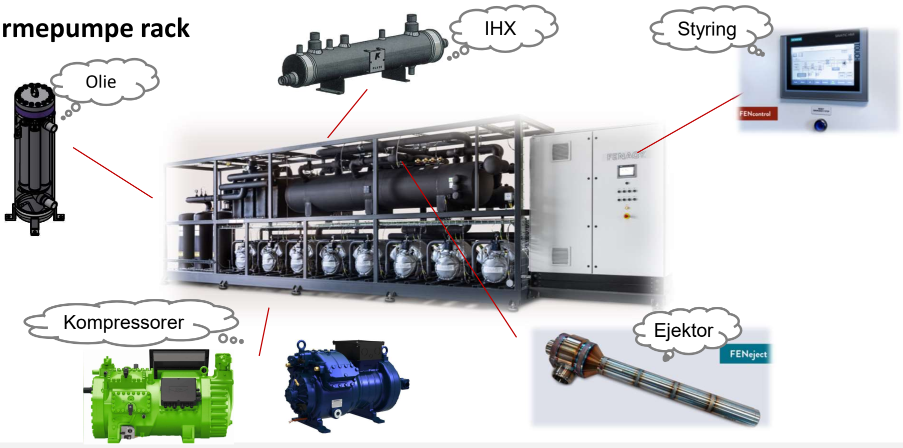
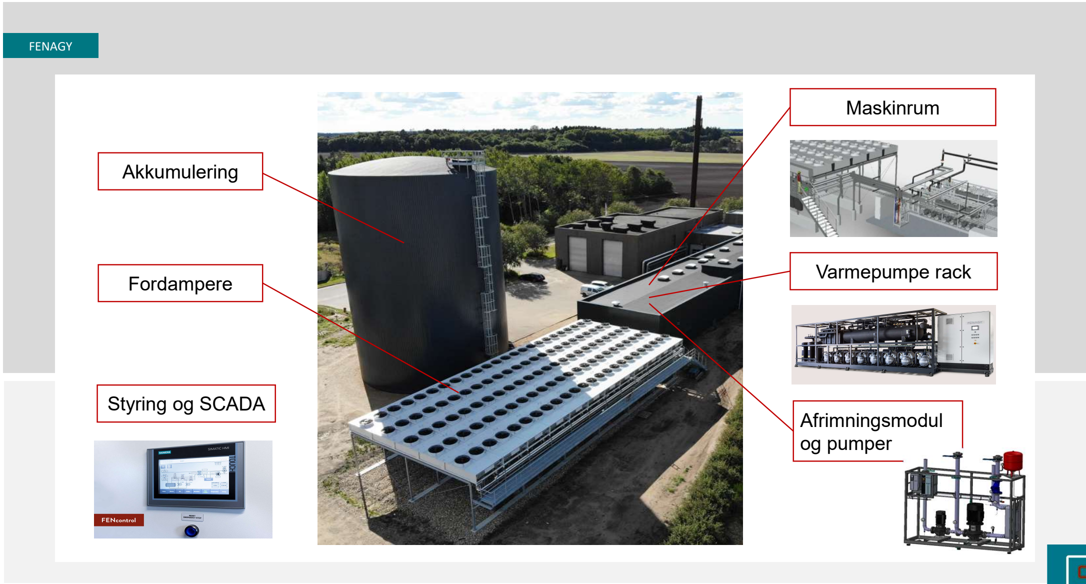
Varmepumpe rack





District heating company expands their existing biomass based production with a heat pump

YEAR: **2022**
MODEL: **2 x H1800-AW**
APPLICATION: **Air-to-Water heat pump**
CAPACITY (HEAT): **3.5 MW (0° C Ambient, 35/70° C hot water)**
COP: **2,96**
DEFROST METHOD: **Glykol**


Air-to-water heat pump combined with
a wood chip boiler and storage tank
YEAR: 2021
MODEL: H1200 AW 3+3D
APPLICATION: Air-to-Water Heat Pump
CAPACITY (HEAT): 1.2 MW (5 °C Ambient, 36/70 °C Hot Water)
HEAT SOURCE: Air
COP: 2.8
DEFROST METHOD: Glycol


Aalborg utility have installed
a district cooling plant at IKEA Aalborg
IKEA
YEAR: 2022
MODEL: H1200-AW / WW - 4+4B
APPLICATION: Air-to-Water og Water-to-Water heat pump
CAPACITY (HEAT): 1200 kW (5 °C Evaporation, 72/40 °C Hot water)
CAPACITY (cool): 8/13 °C Hot water
HEAT SOURCE: Air
COP: 3
AFRIMNINGSMETODE: Glycol

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Development projects

Coming soon

EJECTOR/ EXPANDER	Controller	NEW CO_2 RANGE WITH BIGGER COMPONENTS	REVERSIBEL UNIT	NEW HC RANGE FOR WW-HP	SMARTCO2HP 30-200 kW
Both HP and LP ejector Postdoc + 3xEUDP projects Prototype expander	FENcontrol New functions incl. defrost, cloud, digi-twin, base-line, smart-monitoring	Bitzer 8 cyl Gas cooler Oil sep	Combined heat and cooling	High temp application Isobutane as working fluid	New controls Further development

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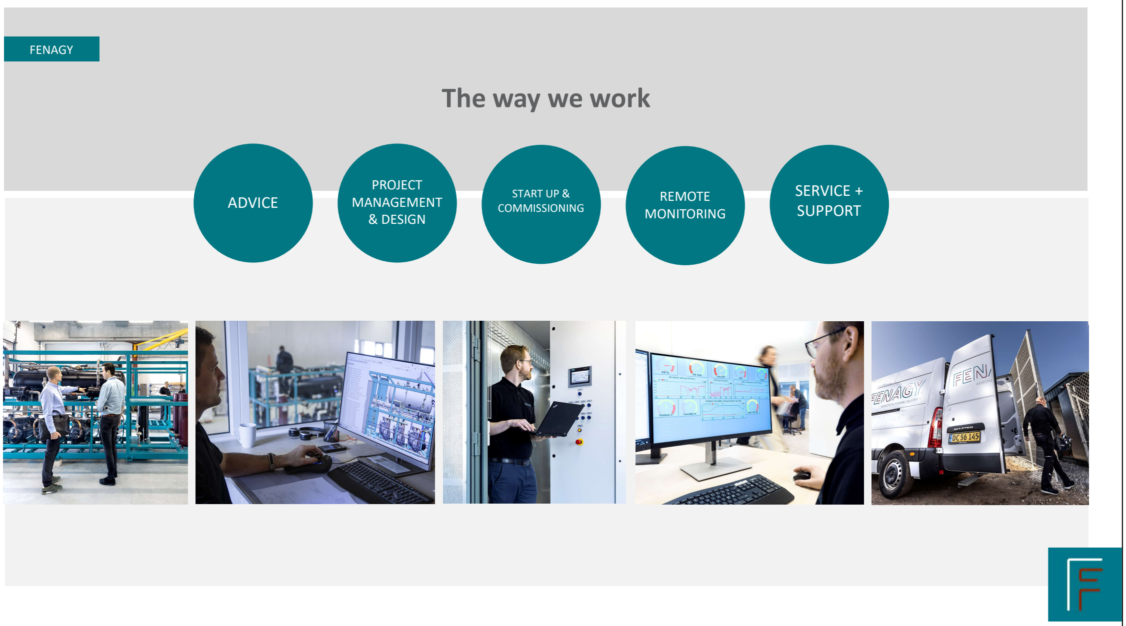
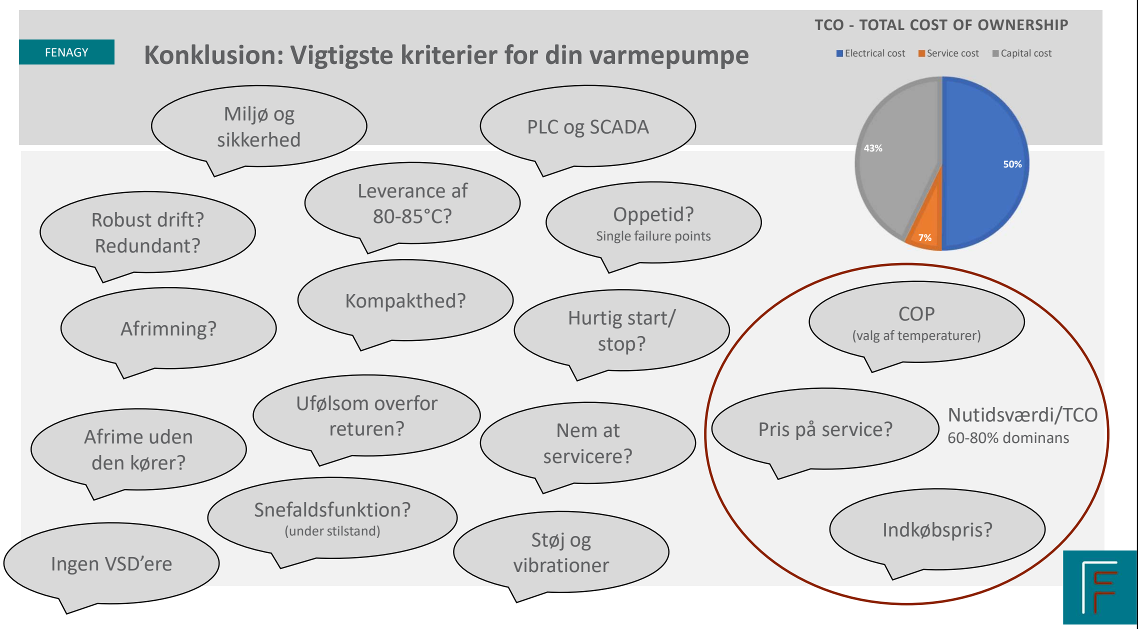
Value chain

- PRODUCT/ PROJECT DESIGN ++
- PRODUCTION +++
- INSTALLATION -
- COMMISSIONING ++
- SERVICE/ MONITORING ++


FENAGY
The way we work
ADVICE
PROJECT MANAGEMENT & DESIGN
START UP & COMMISSIONING
REMOTE MONITORING
SERVICE + SUPPORT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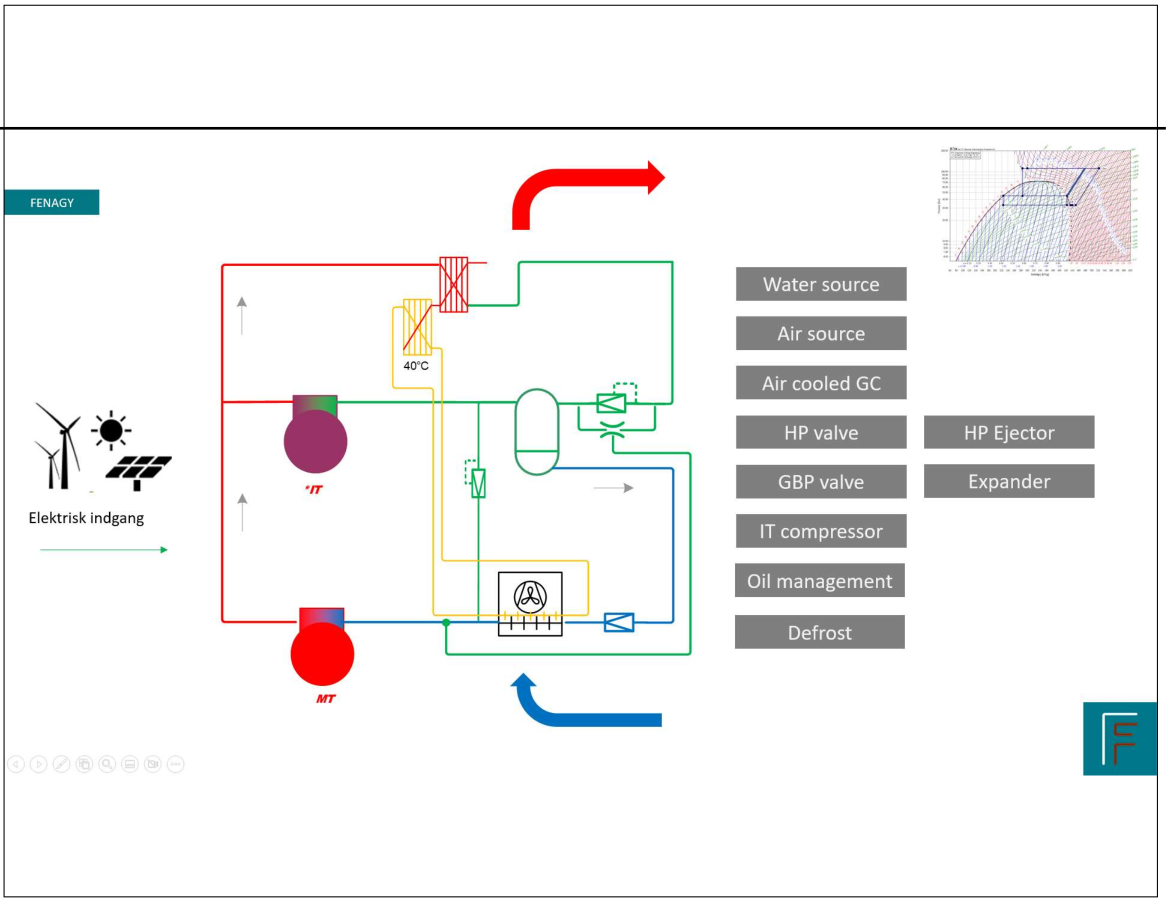
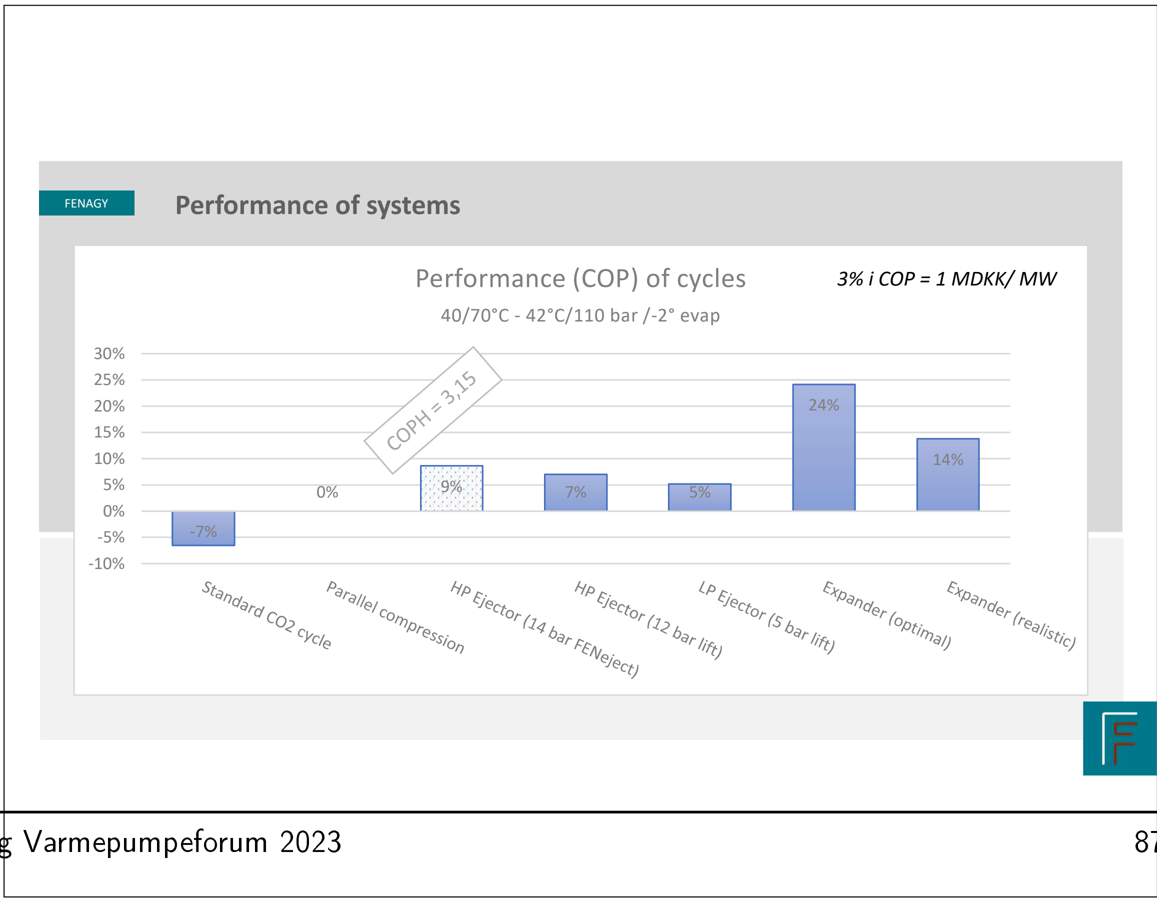
Konklusion: Vigtigste kriterier for din varmepumpe
TCO - TOTAL COST OF OWNERSHIP
Electrical cost
Service cost
Capital cost
43%
50%
7%
Miljø og sikkerhed
PLC og SCADA
Robust drift? Redundant?
Leverance af 80-85°C?
Oppetid?
Single failure points
Afrimning?
Kompakthed?
Hurtig start/ stop?
COP
(valg af temperaturer)
Afrime uden den kører?
Ufølsom overfor returen?
Nem at servicere?
Pris på service?
Nutidsværdi/TCO
60-80% dominans
Snefaldsfunktion?
(under stilstand)
Ingen VSD’ere
Støj og vibrationer
Indkøbspris?


FENAGY
40°C
IT
MT
Elektrisk indgang
Water source
Air source
Air cooled GC
HP valve
GBP valve
IT compressor
Oil management
Defrost
HP Ejector
Expander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Performance of systems
Performance (COP) of cycles
40/70°C - 42°C/110 bar /-2° evap
3% i COP = 1 MDKK/ MW
COPH = 3,15
30%
25%
20%
15%
10%
5%
0%
-5%
-10%
-7%
0%
9%
7%
5%
24%
14%
Standard CO2 cycle
Parallel compression
HP Ejector (14 bar FENeject)
HP Ejector (12 bar lift)
LP Ejector (5 bar lift)
Expander (optimal)
Expander (realistic)

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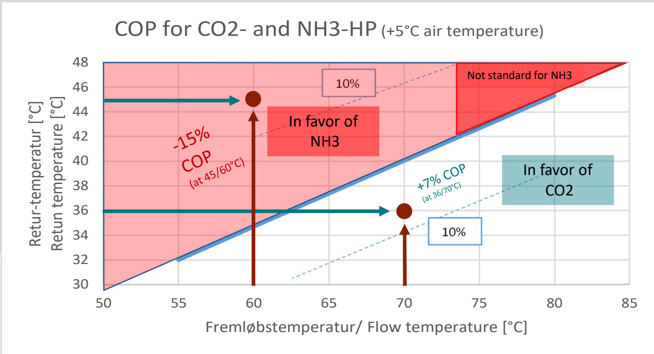
Comparison between CO_2 and NH_3 heat pumps



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Main technical considerations for AW-HP's

- ❑ Performance
  - ❑ Ejector technology
- ❑ Evaporator design
- ❑ Cold air-recirculation
- ❑ Noise
- ❑ Defrost and winter "functions"
- ❑ Fast start/ stop for electrical grid balancing

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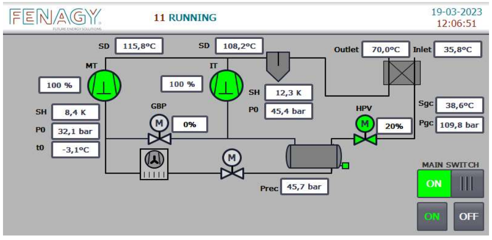
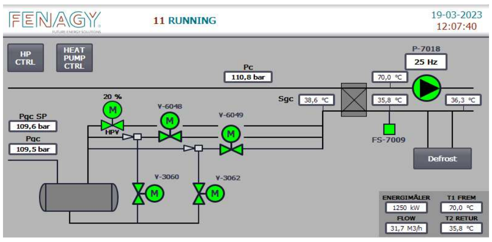
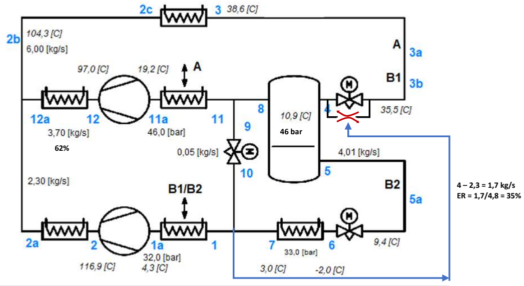
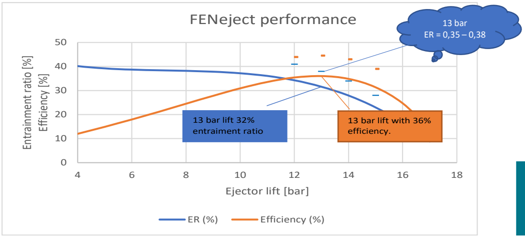
Ejector performance









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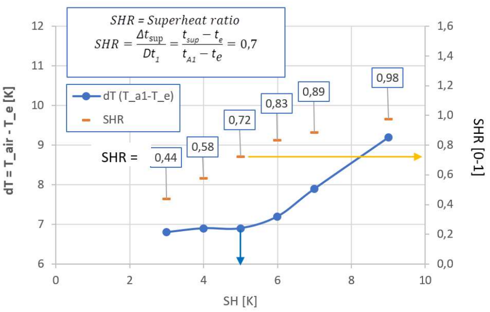
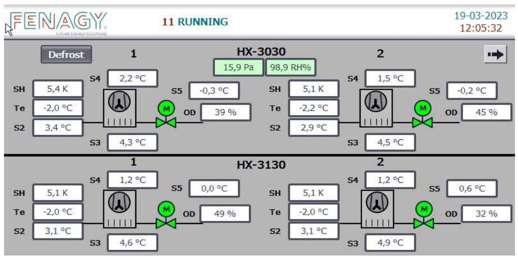
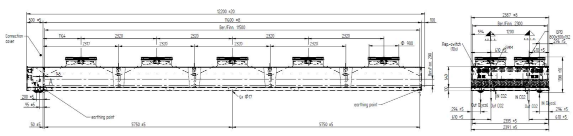
Main technical considerations for AW-HP's – evaporator design

Flatbed + up-flow /draw through

- DX-configuration – pros/ cons
- Design of the coil – circuiting + capillaries
- Control of liquid injection
- Balancing the air-flow







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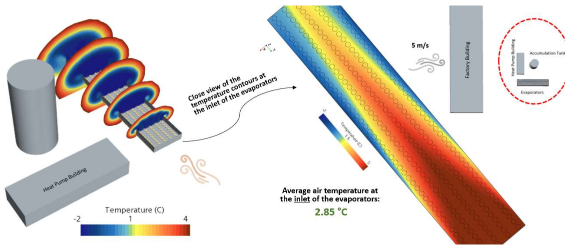
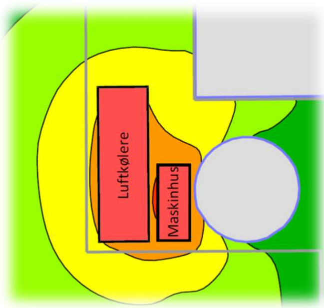
Cold air re-circulation + Noise and vibration

- Simulation always done for larger projects
- Minimum 0,6K penalty on inlet air
- Could be 3-4K if condition is not optimal
- Performance test below 3 m/s should be avoided

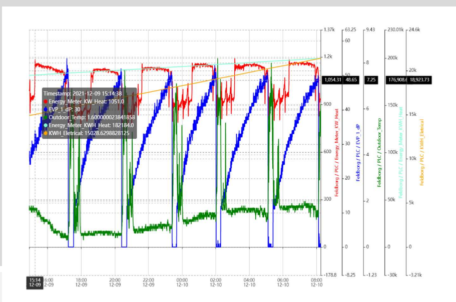


- Noise simulations always performed
- Measurement after commissioning
- Acoustic panels / fan control
- Vibration dampers / springs



FENAGY

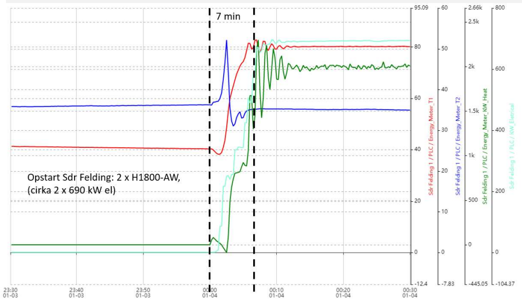
Performance during defrost and winter functions

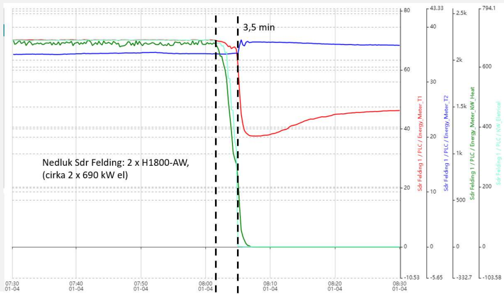


FENAGY

Spille med på el-markedet (system-ydelser)

- FENcontrol leverer allerede indenfor mFRR – men hvad mere
- Fuld start/ stop
- Individuelle kompressorer





FENAGY

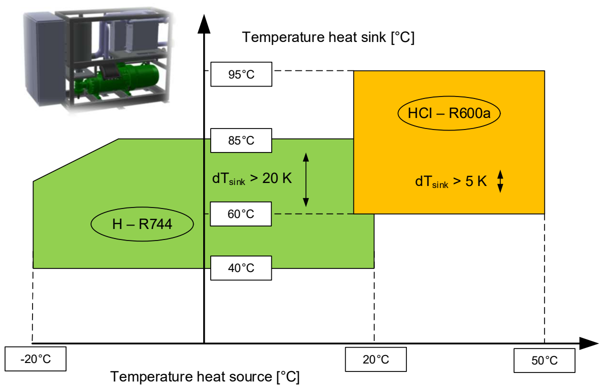
HCI – units with isobutane (reach for new applications)

Where is HCI beneficial:

- High temperature level of the heat source
- High temperature demand on heat sink
  - but little dT of sink ☺

What applications:

- Industrial application with food industry
- Applications with the energy sector
  - Biogas
  - PtX
  - Geothermal
- As "sub-cooler" for our CO2-HP's



Køle- og varmepumpeforum 2023

TECHNICAL BUSINESS CASE BEHIND LARGE DISTRICT HEAT HEAT PUMPS

1 Køle- og varmepumpeforum 2023 Technical business case behind large district heat pumps PlanEnergi

WHO IS PLANENERGI?

- Consulting engineering firm
- Over 39 years of renewable energy
- 50 employees
- Offices in:
  - Skørping
  - Aarhus
  - Copenhagen

- District heating
  - Master plans and basis for decision making
  - District heating expansions and conversions
  - Large-scale heat pumps
  - Excess heat
  - Solar District Heating
  - Thermal Energy Storages
  - Hydraulic and thermal analyses and optimization of networks
- Strategic Energy Planning
  - Mapping
  - Strategies
  - Action plans
  - Heat planning
- Biogas
- Spatial planning for PV-parks and wind turbines
- International research and development projects (IEA, Horizon etc.)

2 Køle- og varmepumpeforum 2023 Technical business case behind large district heat pumps PlanEnergi

Large scale heat pumps

Electrical driven heat pump: Efficient tool for electrifying heat supply in industry process heat.

As 20% of the European energy consumption in for space heating and domestic hot water.

In Denmark 60% of the households have district heating turning District Heating into an industry, having heat as the product.

Resent years heat pumps have been a mayor player in transforming the Danish district heating to non fossil which have matured the technologies (up to at least 85°C).

Conclusions and experience is also valid for other industries.

Why heat pumps

Postulate

Heat Pumps are "nice to have" not "need to have"

Heat pumps "just" deliver heat in a more appropriate way than the alternative.

It is all about

- COP
- COP
- COP

Why heat pumps

Postulate

Heat Pumps are "nice to have" not "need to have"

Heat pumps "just" deliver heat in a more appropriate way than the alternative.

It is all about

- ~~COP~~ Total cost of energy
- ~~COP~~ Total cost of energy
- ~~COP~~ Non fossil energy

…. which is not just COP!

Technical business case behind large heat pumps

Looking into "Total cost of energy" as the diver for

… ."just" deliver heat in a more appropriate way than the alternative"…

Due to legislations in Denmark the district heating companies must prove that a solution has the best socio-economic among a set of different scenarios before making the change.

The presentation focus on economic.

Project path

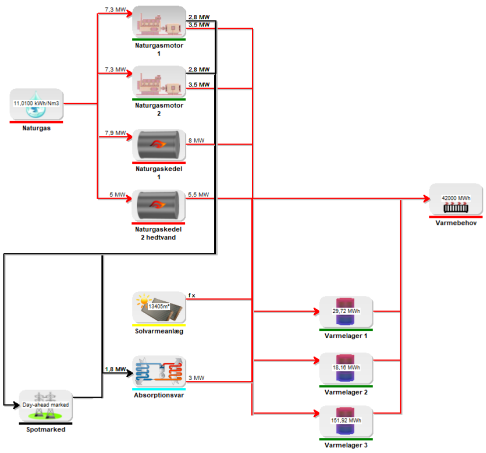
1. Feasibility study
2. Tender
3. Offer
4. > Contract > Installation > Commissioning

Feasibility study

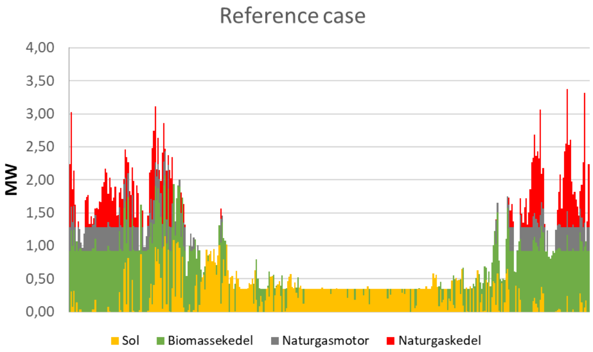
As heat pumps also have a cost of operation the economic is

the saving compared to the alternative heat production

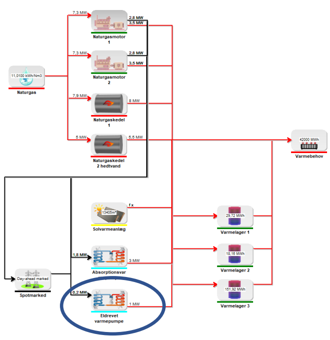
Hourly based system model

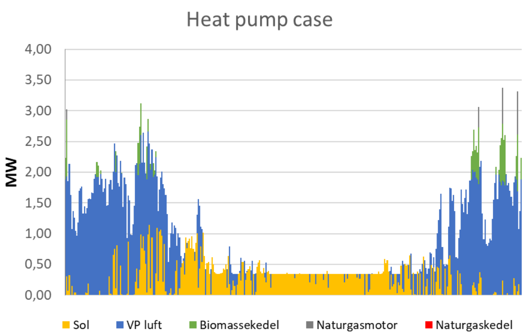


Duration curve



Feasibility study





Socio and privat economy

Grundberegning 2019 elspotår - Gns. Elpris ca. 297 kr./MWh_{el} Naturgas pris 1,95 kr./Nm^3 2021 Energiafgifter, elvarmeafgift 4 kr./MWh_{el}		0 Kraftvarme Reference	1 Kraftvarme 6 MW Luft/vand varmepumpe	2 Kraftvarme Udvidelse af solvarmeanlæg 6.000 m^2	3 Kraftvarme 5 MW Elkedel	4 Kraftvarme 6 MW VP + 5 MW Elkedel
Investering, Luft-vand varmepumpe*	kr.	0	45.000.000	0	0	45.000.000
Investering, Solvarmeanlæg**	kr.	0	0	7.800.000	0	
Investering, Elkedel**	kr.	0	0	0	5.000.000	5.000.000
Øvrige udgifter*	kr.	6.600.000	6.395.000	2.430.000	1.087.500	7.445.000
Samlet investering	**kr.**	**6.600.000**	**51.395.000**	**10.230.000**	**6.087.500**	**57.445.000**
Samlede kapitalomkostninger	**kr./år**	**296.977**	**2.312.599**	**388.126**	**227.642**	**2.538.553**
Samlede driftsomkosninger	**kr./år**	**13.610.900**	**7.525.100**	**12.556.518**	**13.221.963**	**7.285.398**
Driftsbesparelse	Kr./år	0	6.085.800	1.054.382	388.937	6.325.502
Nettobesparelse (driftsbesparelse - kapitalomkostninger)	kr./år		4.070.179	963.233	458.272	4.083.926
Simpel tilbagebetalingstid	år	-	8,4	9,7	15,7	9,1
Varmeproduktionspris	kr./MWh	331	234	308	320	234
Reduktion i varmeproduktionspris	kr./MWh	-	97	23	11	97
Besparelse pr. standardhus (18,1 MWh/år, 20 % nettab) inkl. moms	kr./år		2.741	649	309	2.750

** Kapitalomkostningerne er beregnet som et annuitetslån med real rente på 0,135%, løbetid på 20 år og løbende garantiprovision på 0,45%*

*** Kapitalomkostningerne er beregnet som et annuitetslån med real rente på 0,315%, løbetid på 25 år og løbende garantiprovision på 0,45%*

The “business case” in the Tender

The hourly base model turned into “project optimization tool” as a part of the Tender material.

Optimization parameters
- COP
- Size
- Cost of installation

Entreprisesum*		35.000.000	kr.	Entreprisesum for A. Hovedtilbud eksklusiv stipulerede ydelser						
Driftspunkt nr.		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Dellast		100%	50%	100%	100%	100%	100%	100%	100%	100%
Kold side										
Fremløbstemperatur til VP	°C	20,0	20,0	20,0	21,0	18,0	16,5	15,5	15,5	27,0
Returtemperatur, min. 10°C	°C	15,0	15,0	15,0	16,0	13,0	11,5	10,5	10,5	22,0
Vandmængde**	m3/h	1.067	581	1.160	1.161	1.159	1.153	1.138	1.160	1.159
Køleeffekt	kW	7.127	3.565	7.120	7.127	7.108	7.081	6.979	7.111	7.115
Tryktab	kPa	62	15	62	62	62	60	57	59	60
Elforbrug til pumper*	kW	18,4	2,5	20,0	19,8	19,9	19,3	18,0	19,0	19,3
Fordampningstemp.	°C	13	13	13	14	11	9	8	8	15
Varm side										
Tilgangstemperatur	°C	34,0	34,0	36,0	34,0	34,0	34,0	34,0	30,0	34,0
Afgangstemperatur	°C	71,0	71,0	71,0	71,0	71,0	71,0	71,0	65,0	71,0
Opvarmning	K	37,0	37,0	35,0	37,0	37,0	37,0	37,0	35,0	37,0
Varme-effekt*	kW	8.862	4.446	8.874	8.818	8.917	8.947	8.870	8.856	8.781
Flow	m3/h	210	105	222	209	211	212	210	222	208
Tryktab	kPa	286	73	315	289	293	293	285	311	285
Elforbrug til pumper*	kW	16,7	2,1	19,5	16,8	17,2	17,3	16,6	19,2	16,5
El										
Kompressorer*	kW	1.813,0	923,0	1.835,0	1.773,0	1.898,0	1.962,0	1.983,0	1.825,0	1.745,0
Samlet elforbrug	kW	1.848,1	927,6	1.874,4	1.809,6	1.935,1	1.998,5	2.017,6	1.863,1	1.780,7
Effektivitet										
COP-varm	-	4,79	4,79	4,73	4,87	4,61	4,48	4,40	4,75	4,93
Lorentz-virkningsgrad***	-	51,08%	51,06%	51,78%	50,42%	51,92%	52,51%	52,92%	50,73%	41,92%
Nutidsværdi, gennemsnit		80.646.108	kr.	<--- Denne nutidsværdi bruges ifm. vurdering af tilbuddets totaløkonomi (jo højere desto bedre).						

<u>NPV (Net Present Value) as result</u> (in this case over 15 years)

The “business case” in the Tender

Case: Waste heat revocery

Green fields are inputs…

Entreprisesum*		35.000.000	kr.	Entreprisesum for A. Hovedtilbud eksklusiv stipulerede ydelser						
Driftspunkt nr.		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Dellast		100%	50%	100%	100%	100%	100%	100%	100%	100%
Kold side										
Fremløbstemperatur til VP	°C	20,0	20,0	20,0	21,0	18,0	16,5	15,5	15,5	27,0
Returtemperatur, min. 10°C	°C	15,0	15,0	15,0	16,0	13,0	11,5	10,5	10,5	22,0
Vandmængde**	m3/h	1.067	581	1.160	1.161	1.159	1.153	1.138	1.160	1.159
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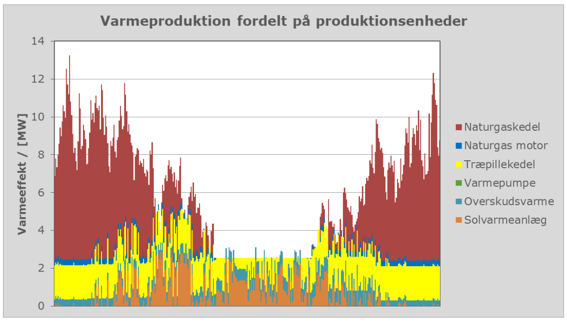
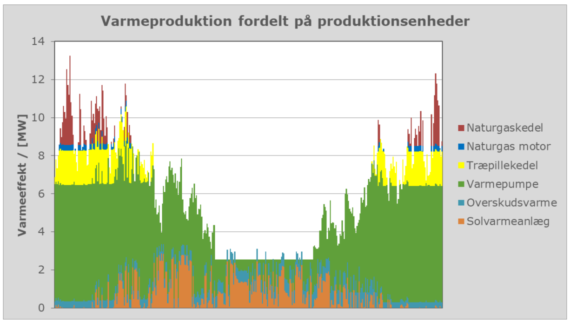
Tryktab	kPa	62	15	62	62	62	60	57	59	60
Elforbrug til pumper*	kW	18,4	2,5	20,0	19,8	19,9	19,3	18,0	19,0	19,3
Fordampningstemp.	°C	13	13	13	14	11	9	8	8	15
Varm side										
Tilgangstemperatur	°C	34,0	34,0	36,0	34,0	34,0	34,0	34,0	30,0	34,0
Afgangstemperatur	°C	71,0	71,0	71,0	71,0	71,0	71,0	71,0	65,0	71,0
Opvarmning	K	37,0	37,0	35,0	37,0	37,0	37,0	37,0	35,0	37,0
Varme-effekt*	kW	8.862	4.446	8.874	8.818	8.917	8.947	8.870	8.856	8.781
Flow	m3/h	210	105	222	209	211	212	210	222	208
Tryktab	kPa	286	73	315	289	293	293	285	311	285
Elforbrug til pumper*	kW	16,7	2,1	19,5	16,8	17,2	17,3	16,6	19,2	16,5
El										
Kompressorer*	kW	1.813,0	923,0	1.835,0	1.773,0	1.898,0	1.962,0	1.983,0	1.825,0	1.745,0
Samlet elforbrug	kW	1.848,1	927,6	1.874,4	1.809,6	1.935,1	1.998,5	2.017,6	1.863,1	1.780,7
Effektivitet										
COP-varm	-	4,79	4,79	4,73	4,87	4,61	4,48	4,40	4,75	4,93
Lorentz-virkningsgrad***	-	51,08%	51,06%	51,78%	50,42%	51,92%	52,51%	52,92%	50,73%	41,92%
Nutidsværdi, gennemsnit		80.646.108	kr.	<--- Denne nutidsværdi bruges ifm. vurdering af tilbuddets totaløkonomi (jo højere desto bedre).						

The "business case" in the offer

Reference case:

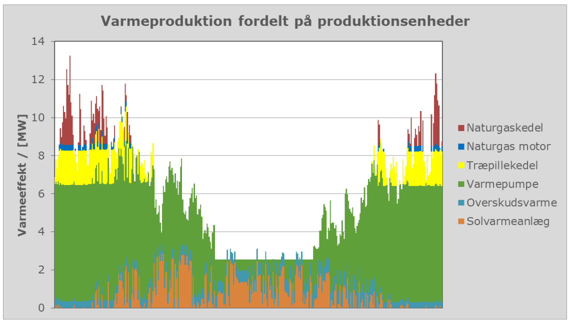


Heat pump case:

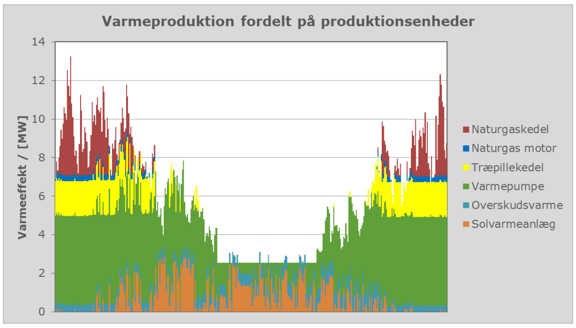


The "business case" in the offer

Reference HP case:



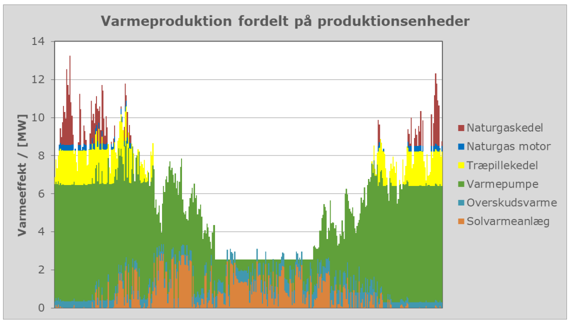
Heat pump -20% size:

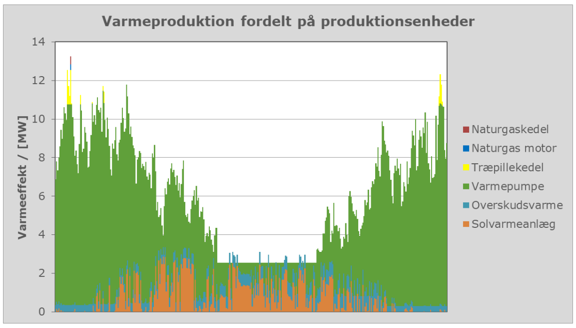


The "business case" in the offer

Reference HP case:

Heat pump +70% size:





The "business case" in the offer

Optimization of the offered solution

Overall approach:

- If a change result in higher NPV the extra investment is "payed back" over period of calculation (in the case 15 years)

As an expensive heat source (natural gas) is replaced a larger heat pump seems ideal, but…

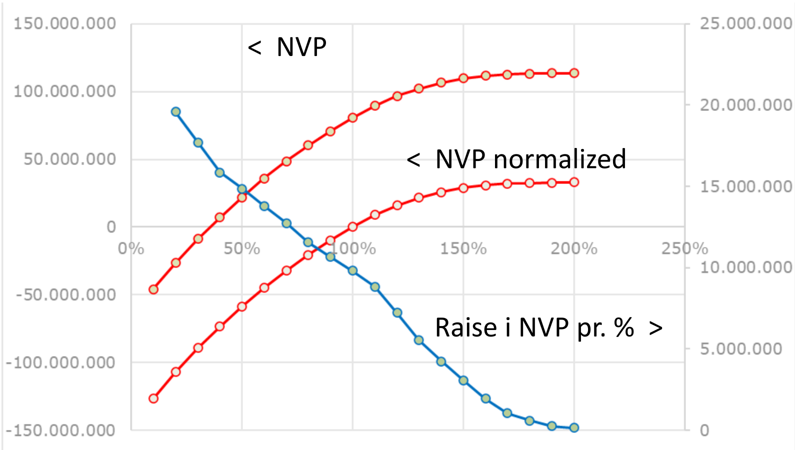
NVP is reduced 1:1 of a higher investment in the heat pump.

The “business case” in the offer

Impact of heat pump size on NPV:

Having the same investment:

Less operating hours result in less income pr. %



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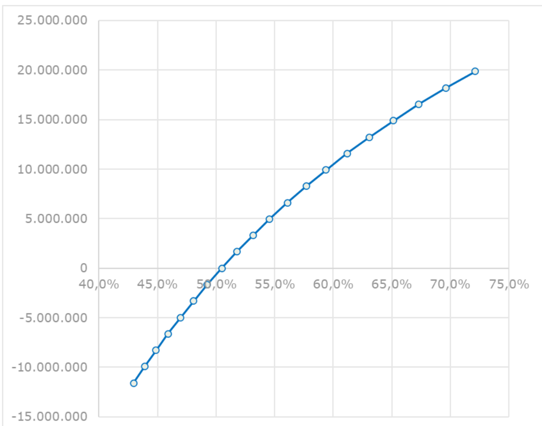
The “business case” in the offer

Impact of heat pump COP (as Lorenz efficiency) on NPV:

Having the same investment:

Higher COP > Higher NPV

+ 5 %-points gives +5.000.000 kr over 15 years to more investment



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Summing up

- The market for large scale heat pumps is huge.
  - (Process) Industry
  - District heating
- The volume of the district heating industry (in Denmark) has matured the largescale heat pump business up to around 85°C (...95°C)

  (...The next is the 120°C district heating business...)
- The models and tools used with success for feasibility study in district heating can be used for other industries also.
- The business case for large scale heat pumps is close related to
  - the alternative heating source
  - The operating hours and thereby the duration curve

  ....resulting in an optimization process based on
  - Prize
  - COP
  - Size

Thank you

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Phone: +45 2060 3975
Email: lr@planenergi.dk

High temperature industrial heat pumps – now and in the future

Alexander Cohr Pachai, Cordin Arpagaus, Armin Hafner

Alexander Cohr Pachai
Global Consultancy ApS

Conference Køle- og Varmepumpeforum 2023, March 23rd

The warning

Pace and scale of climate action are insufficient to tackle climate change.

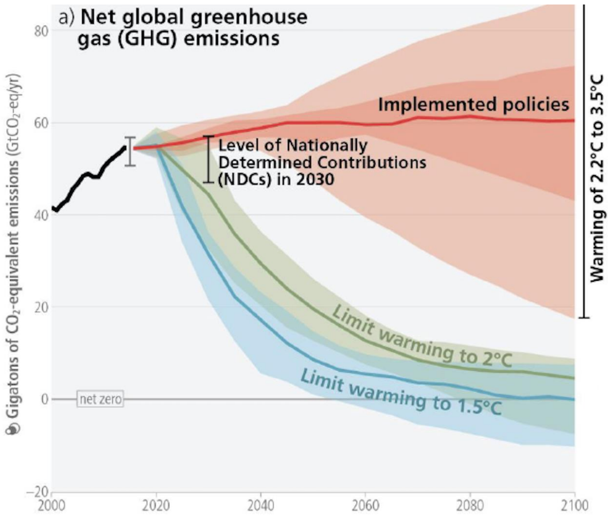
Accelerated action required.

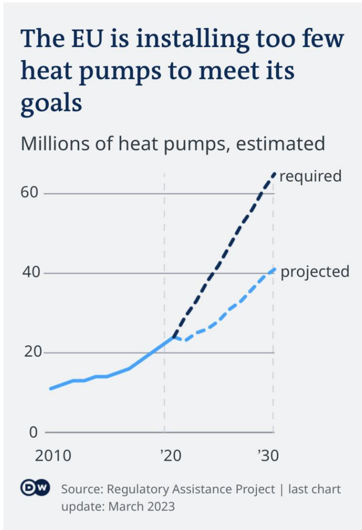
Sixth Assessment Report | Synthesis Report

ipcc

Conference Køle- og Varmepumpeforum 2023, March 23rd

Deutsche Welle with the same message





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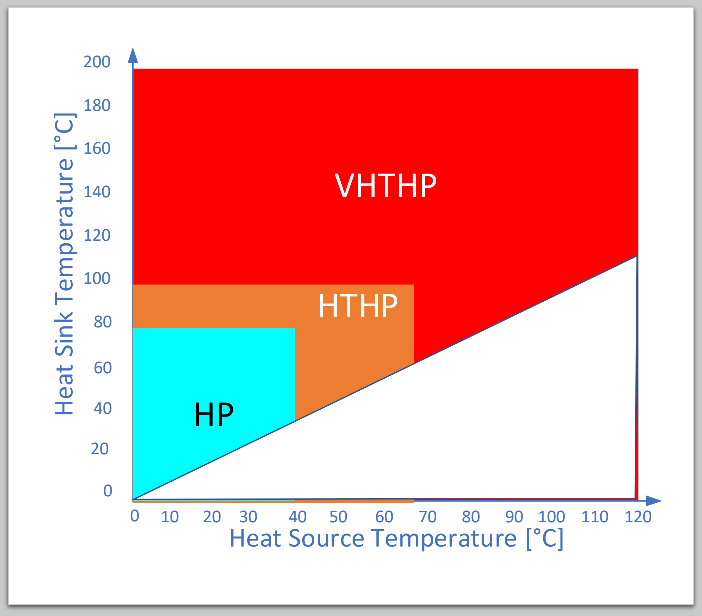
High temperature heat pumps

- How high is high?
  - High enough for what?
  - Where is the market?
  - Which temperature?
  - EN 14825
- Which working fluids?
- Which standards?
- Which certificates?
- Is the man-power there?



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Decarbonisation – what impact will it have and why?

- Global warming and climate change
- Paris agreement say's not over 1.5°C to 2°C over pre-industrial time
- Air pollution from burning all fuels incl. painted building materials, waste containing PFAS at too low temperatures
- Premature death due to air pollution is estimated to be between 8 and 10mill/year
- Cost of climate change globally is catastrophic and astronomical, the longer we wait the more expensive
- COP27, COP28… and what's next …?? We need action NOW"

The solutions or some of them

Energy solutions:
Solar Power
Wind turbines
Hydropower
Hydrogen
and others

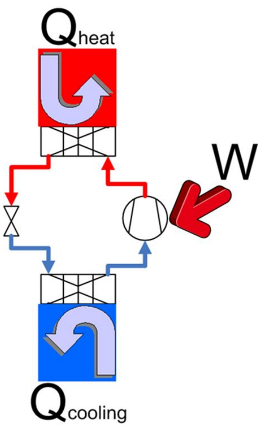
A refrigeration system and a heat pump are basically identical; BUT in a heat pump the warm side has a value

$$COPc = \frac{Qc}{W}$$
$$COPh = \frac{Qh}{W}$$
$$COPs = \frac{Qc + Qh}{W}$$

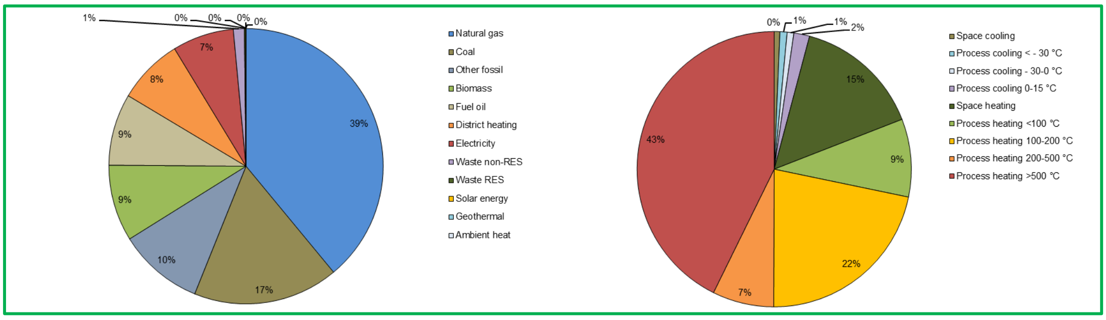
EN 14825:2018 define high temperature as everything over 65°C

District heating systems often work at temperatures 70°C and 130°C
Low temperature district heating can be as low as 30 to 40°C

If heat is recovered from a system connected to a cooling tower the savings on water and chemicals can be relatively high



Current energy source and temperatures



- Fossil fuels have to be replaced where possible by renewables and heat pumps
- Energy consumption in EU 27, 2021 was 16.982,6 TWh (Source: Intrastat)
- Temperature levels currently exploited and future levels
- Demonstration projects up to about 165°C

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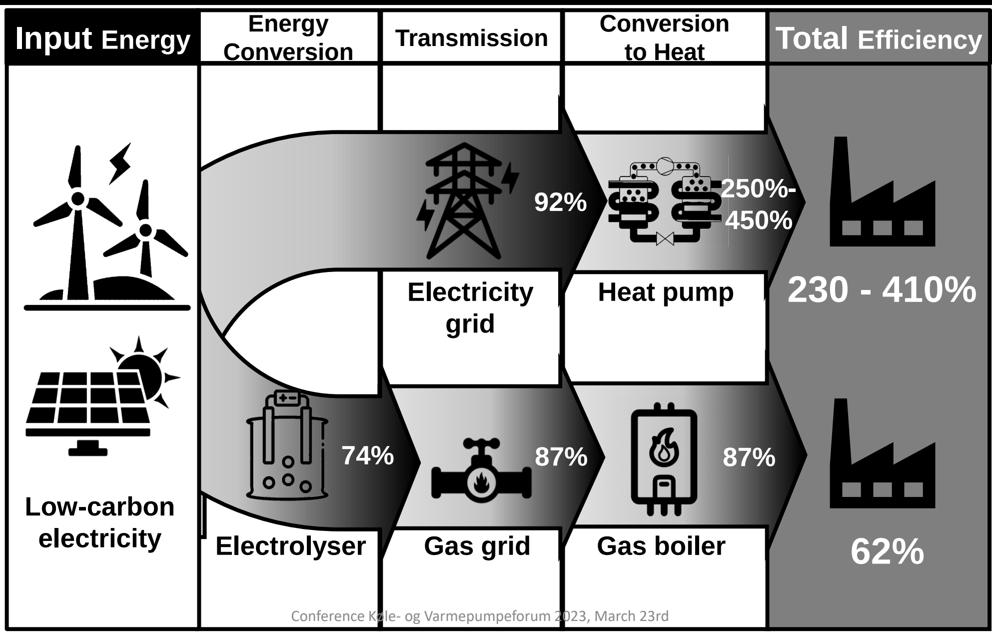
Is hydrogen the solution?



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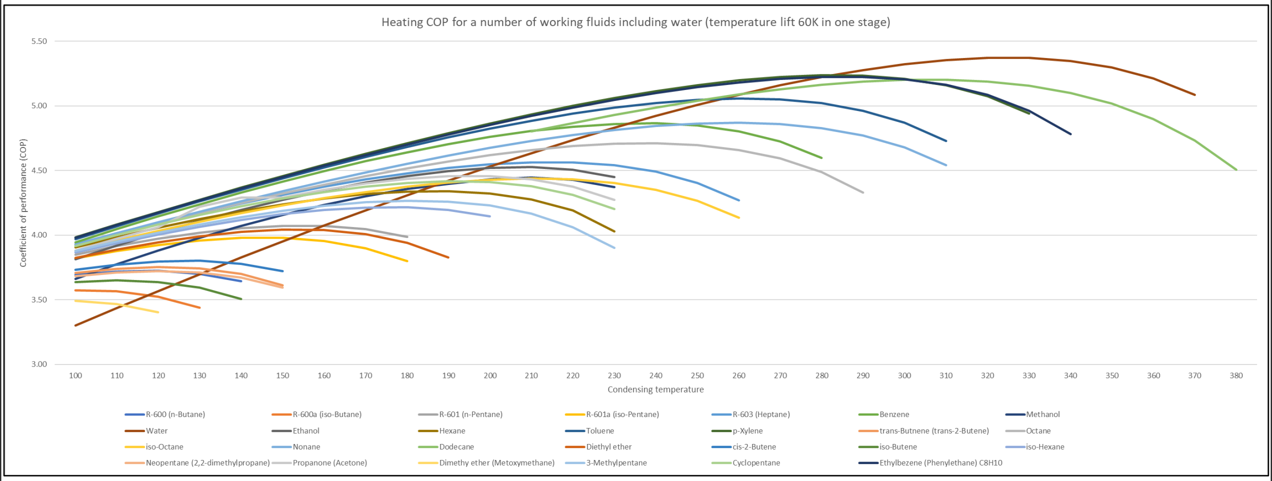
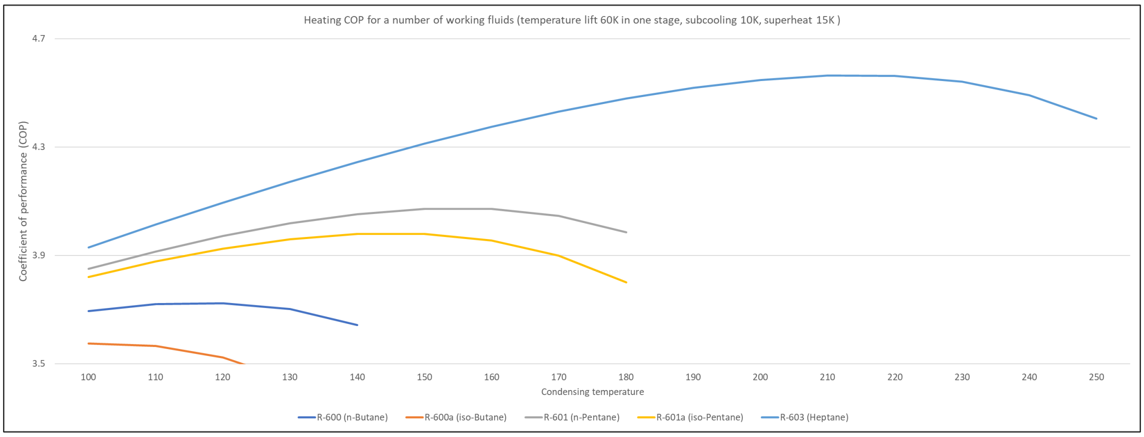
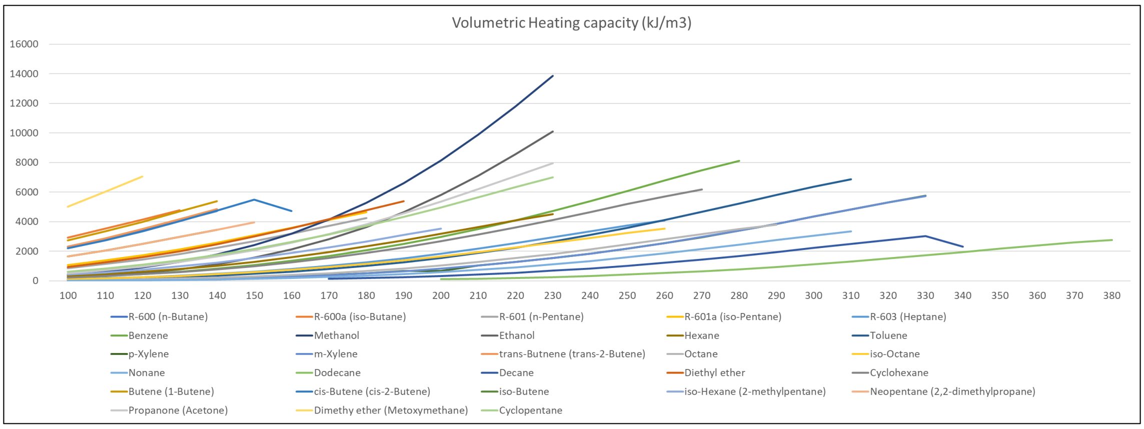
Screening a larger number of working fluids



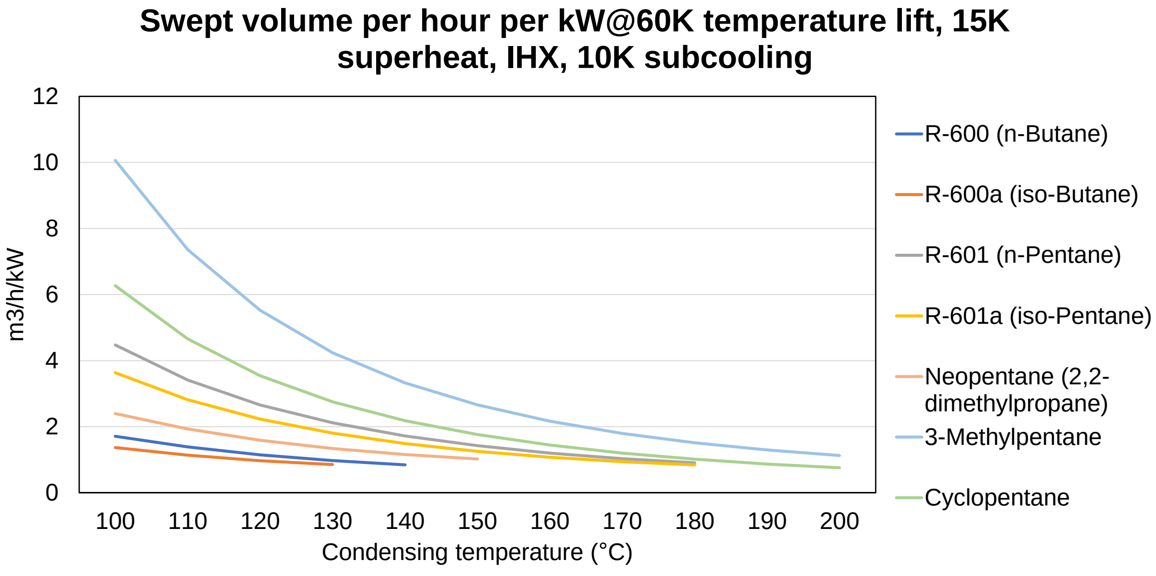
The COP is a popular value



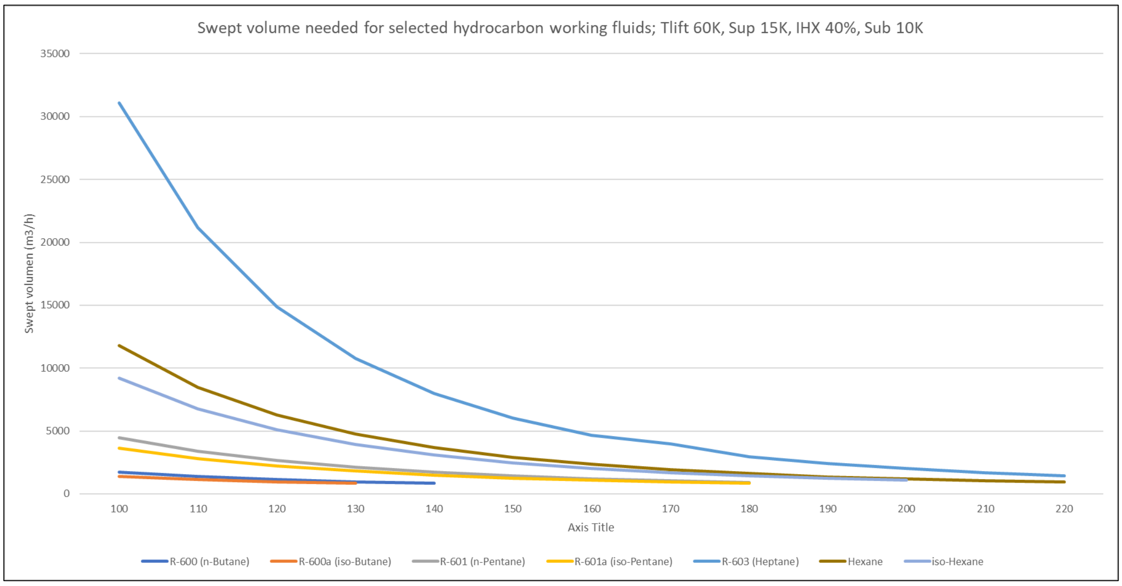
The Volumetric Heating Capacity



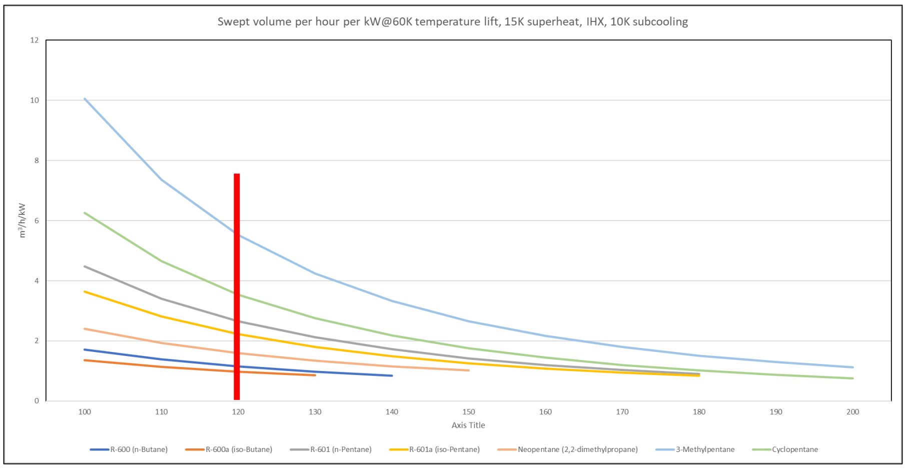
Swept volume in m³/h/kW



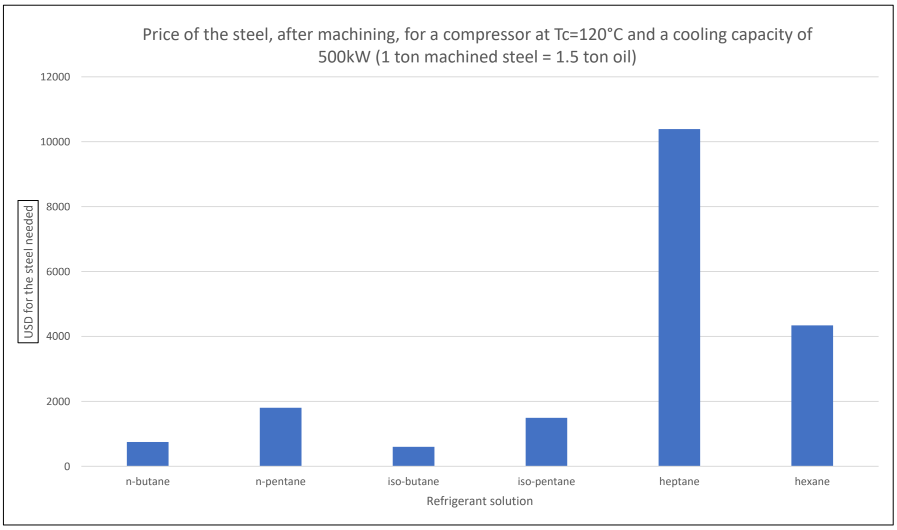
Swept volume in $m^3/h@1000kW_{cooling}$



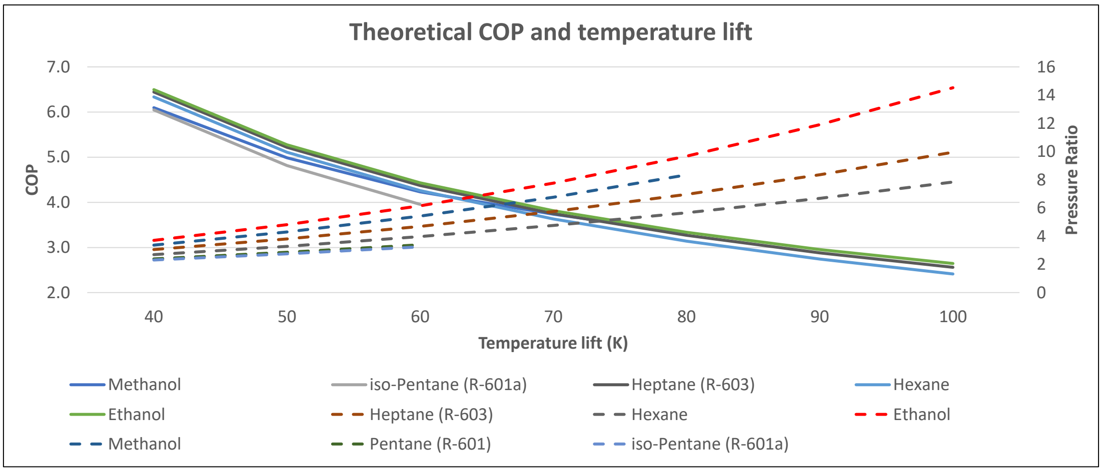
Swept volume has an impact on the CAPEX



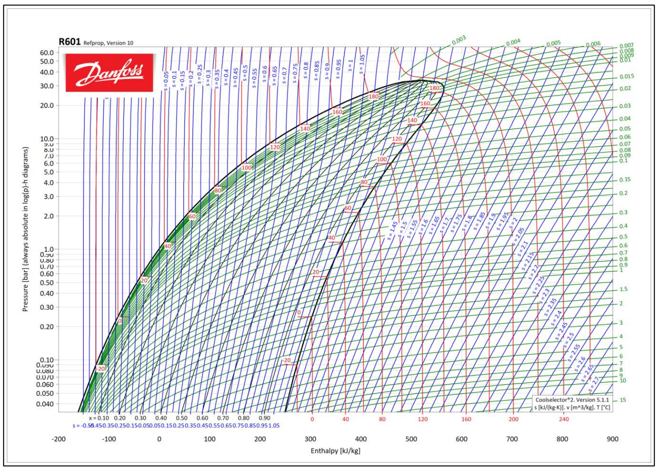
Relationship of swept volume and price of steel

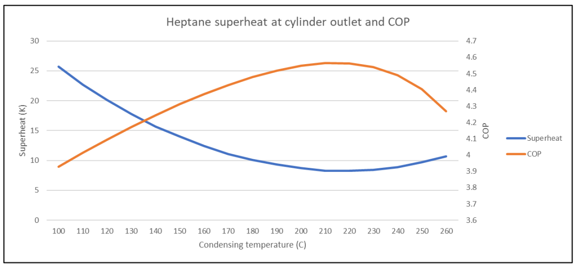


COP and high temperature lift



An interesting observation working with overhung fluids





Some of the analysed working fluids

Some fluids need careful thinking before used in a system

	Molar mass	Triple pt. Temp	Normal boiling pt.	Critical Point Temperature	Critical Point Pressure	Critical Point Density
Fluid name	kg/kmol	K	K	K	Mpa	kg/m^3
R-600 (n-Butane) CH3-2(CH2)-CH3	58.122	134.9	272.66	425.13	4	228
R-600a (iso-Butane) CH(CH3)3	58.122	113.73	261.4	407.81	3.629	225.5
R-601 (n-Pentane) CH3-3(CH2)-CH3	72.149	143.47	309.21	469.7	3.37	232
R-601a (iso-Pentane) (CH3)2CHch2CH3	72.149	112.65	300.98	460.35	3.378	236
R-603 (Heptane) CH3-5(CH2)-CH3	100.2	182.55	371.53	540.13	2.736	232
Benzene C6H6	78.112	278.67	353.22	562.02	4.9073	304.71
Methanol CH3OH	32.042	175.61	337.63	512.6	8.1035	275.56
Water H2O	18.015	273.16	373.12	647.1	22.064	322
Ethanol (ethyl alcohol) C2H6O	46.068	159	351.57	514.71	6.268	273.19
Hexane CH3-4(CH2)-CH3	86.175	177.83	341.86	507.82	3.034	233.18
Toluene (methylbenzene) CH3-C6H5	92.138	178	383.75	591.75	4.1263	291.99
p-Xylene (1,4-dimethylbenzene) C8H10	106.17	286.4	411.47	616.17	3.5315	286
m-Xylene (1,3-dimethylbenzene) C8H10	106.17	225.3	412.21	616.89	3.5346	282.93
trans-Butnene (trans-2-Butene) CH3-CH=CH-CH3	56.106	167.6	274.03	428.61	4.0273	236.38
Octane CH3-6(CH2)-CH3	114.23	216.37	398.77	569.32	2.497	234.9
iso-Octane (2,2,4-trimethylpentane) (CH3)2CHCH2C(CH3)3	114.23	165.77	372.36	544	2.572	242.16
Nonane CH3-7(CH2)-CH3	128.26	219.7	423.91	594.55	2.281	232.14
Dodecane CH3-10(CH2)-CH3	170.33	263.6	489.3	658.1	1.817	226.55
Decane CH3-8(CH2)-CH3	142.28	243.5	447.27	617.7	2.103	233.34
Diethyl ether C4H10O	74.122	156.92	307.6	466.7	3.644	264
Cyclohexane cyclo-C6H12	84.159	279.47	353.87	553.6	4.0805	271.33
1-Butene CH3-CH2-CH-CH2	56.106	87.8	266.84	419.29	4.0051	237.89
cis-2-Butene CH3-CH=CH-CH3	56.106	134.3	276.87	435.75	4.2255	238.12
iso-Butene (2-methyl-1-propene) CH2=C(CH3)2	56.106	132.4	266.15	418.09	4.0098	233.96
iso-Hexane (2-methylpentane) (CH3)2CH(CH2)2CH3	86.175	119.6	333.36	497.7	3.04	233.97
Neopentane (2,2-dimethylpropane) C(CH3)4	72.149	256.6	282.65	433.74	3.196	235.93
Propannone (Acetone) (CH3)2CO	58.079	178.5	329.22	508.1	4.7	272.97
Dimethy ether (Metoxymethane) (CH3)2O	46.068	131.66	248.37	400.38	5.3368	273.65
3-Methylpentane (CH3CH2)2CHCH3	86.18		336.38	506	3.1845	239.57
Cyclopentane cyclo-C5H10	70.133	179.7	322.41	511.72	4.5712	267.91
Ethylbezene (Phenylethane) C8H10	106.17	178.2	409.31	617.31	3.6224	291

Is there a market?

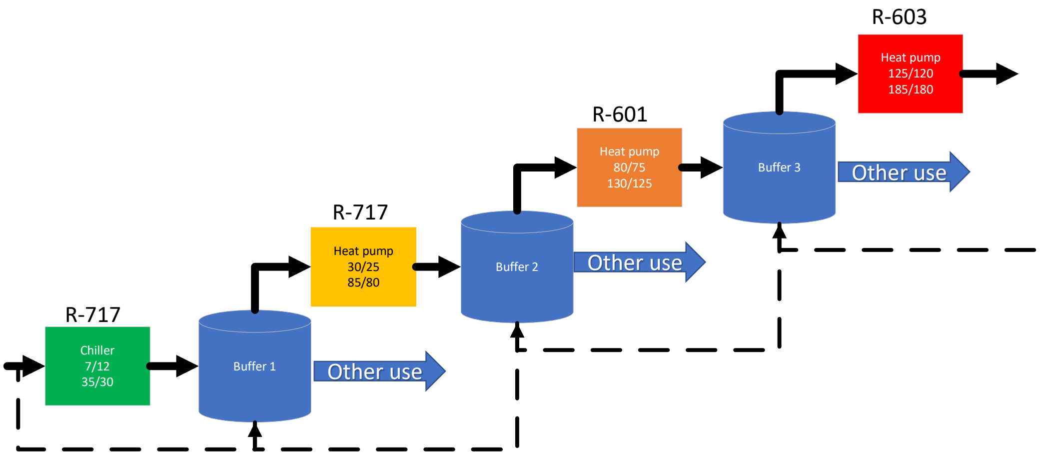
Summary of the EU28 industrial heat pump market potential.

Sector	Cumulative Heating Capacity, $\dot{Q}_{P,HPmarket}$ (GW)	EU28 Heat Pump Units, $N_{HPmarket}$ (#)	Heat Pump Process Heat Coverage, $Q_{P,HPmarket}$ (PJ/a)	Electricity Requirement, $E_{e,HPmarket}$ (PJ/a)	Heat Pump Relative Process Heat Coverage, $Q_{P,HPmarket}/Q_P$ (%)
Heat pump market to 150°C					
Paper	6.6	938	203	78	89%
Chemical	8.1	1164	252	59	85%
Food	5.0	1107	83	25	64%
Refinery	0.3	20	9	4	10%
Total (Σ)	20.0	3229	547	166	73%
Heat pump market to 200°C					
Paper	7.9	1351	245	94	69%
Chemical	9.1	1291	283	65	80%
Food	5.5	1463	98	31	51%
Refinery	0.5	69	14	6	6%
Total (Σ)	23.0	4174	641	195	57%

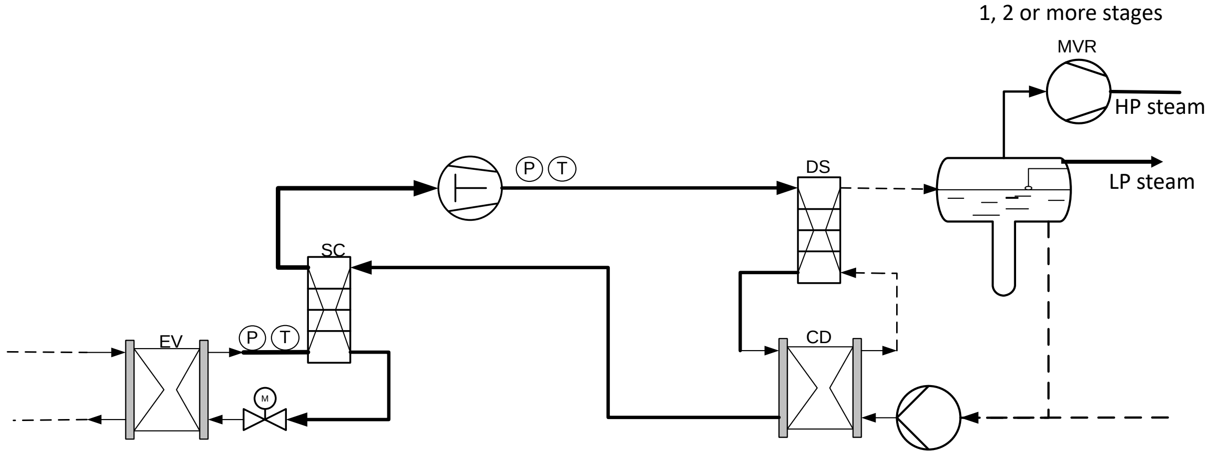
Source: Marina, A. et al, 2021

Conference Køle- og Varmepumpeforum 2023, March 23rd

The steps are to be integrated in to the production temperature levels



MECHANICAL VAPOUR RECOMPRESSION (MVR) for industrial processes

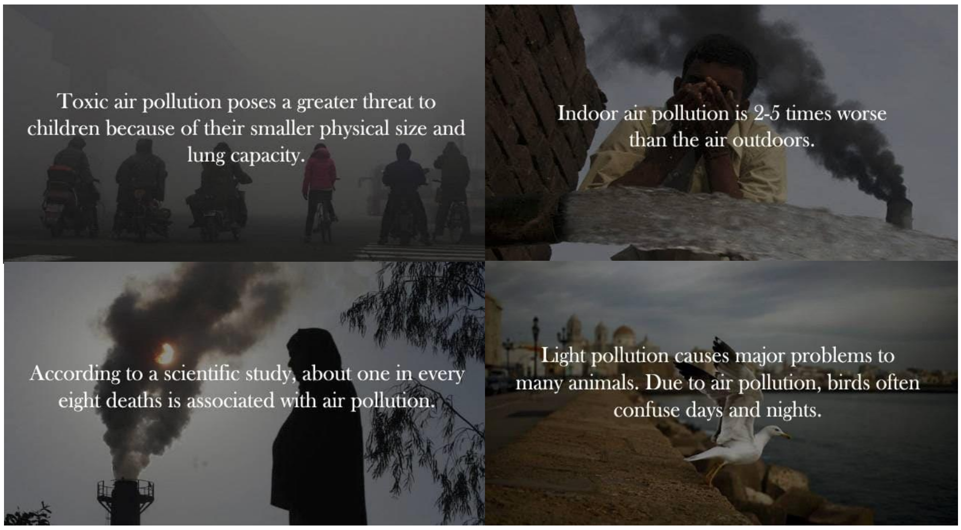


Where is technology on the Technology Readiness Level (TRL)?

Fraunhofer IEG · NRW.ENERGY 4CLIMATE · LEE NRW · Bundesverband Geothermie

- TRL 1 – basic principles observed
- TRL 2 – technology concept formulated
- TRL 3 – experimental proof of concept
- TRL 4 – technology validated in lab
- TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 7 – system prototype demonstration in operational environment
- TRL 8 – system complete and qualified
- TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

We do not have plan B for our planet – GWP is not the only challenge



Conclusions and future outlook

Electrification is possible and heat pumps will be an integrated part of the future
The industry can meet the challenge - if they give up delaying tactics
Users have to understand that the technology is being developed as we speak
We know the challenges and we can raise the funds if the users start pushing – and help to make it happen
The work here shown is a contribution to the work needed – but it cannot stand alone

Conclusions and future outlook

Electrification is possible and heat pumps will be an integrated part of the future
The industry can meet the challenge - if they give up delaying tactics
Users have to understand that the technology is being developed as we speak
We know the challenges and we can raise the funds if the users start pushing – and help to make it happen
The work here shown is a contribution to the work needed – but it cannot stand alone

– a lot of hard work is waiting for us … so lets get started

Thank you for your kind attention

Alexander Cohr Pachai
Global Consultancy ApS

Conference Køle- og Varmepumpeforum 2023, March 23rd

Boosting Industrial Efficiency with Very-high-temperature Heat Pumps (VHTHP)

23-MAR-23 – DKV Symposium, Copenhagen

Harald Nes Rislå, CTO & Co-founder, Heaten AS, Norway

HEATEN

Company Vision 2050 - Reduce CO_2 Emissions by 1 Gigaton

HeatBooster can save 1 Gigaton of CO_2 annually, by the year 2050

> Equal to all aviation emissions combined

Note: Numbers are based on renewable electricity sources.

-Annual CO_2 emissions from all air traffic is 1.0 Gigaton of CO_2
-Annual CO_2 emissions of Germany is 0.8 Gigatons
-Pulp and paper industry = 0.2 Gigatons

COMPANY

Heaten

- Heaten AS est. 2020 in Norway
- Company now based in Norway, Germany and Holland
- Development, production and delivery of industrial-scale, very-high-temperature heat pumps (VHTHPs) to large industrial customers
- History back to 2010
- Started with organic Rankine cycles (ORCs)
- Heat pump development since 2015
- In-house piston machine development (expander and compressor)
- Heaten personnel + external specialists (AVL, DTU, IPU)
- All core knowledge in-house

Public

SHAREHOLDERS & PARTNERS

Strong owners and partners

nysnø Climate Investments

Norwegian State Climate Investment Fund

Azolla Ventures Created by Prime Coalition

Created by Prime Coalition

Shell Ventures

The corporate venture capital arm of Shell

Valinor

Norwegian private investment company

AVL SCHRICK

The world's largest independent engine design company

Manufacturers

External Expert Consultants

Public

SOLUTION

The HeatBooster

Very-High-Temperature Heat Pump Technology

-Novel VHTHP technology based on VC cycle

-Tech developed over more than 10 years

-Process water or steam up to 200 °C

-Using waste heat sources

-Increases energy efficiency

-Replaces fossil fuels in “new” temperature ranges

-Large industry applications within food, plastics, pulp and paper, breweries, and drying processes.

-Cuts CO_2 emissions

-Serves **medium to high heat demands**

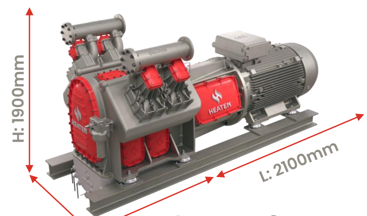
Public

HeatBooster product family

Unique multi-cylinder piston compressor technology

VHTHP based on an efficient, durable and highly flexible piston compressor technology

- Designed for very high output temperatures (up to 200°C)
- Direct low-pressure (LP) steam, up to 12 bar
- 1-8 MWth per HeatBooster (V4 – V16 compressors)
- Cascading or parallel installation enables up to 100 MWth
- 2 stages enable temperature lifts up to 140 K
- Designed for high-volume production
- HFO and HC working fluids with very low Global Warming Potential (GWP) of << 10
- Low-, medium-, high- and very-high-temperature heat pump with same hardware
- Low maintenance, long service life
- Enables high coefficient of performance (COP) over wide load ranges (20-100%)



V4 – up to 2 MW_{th}

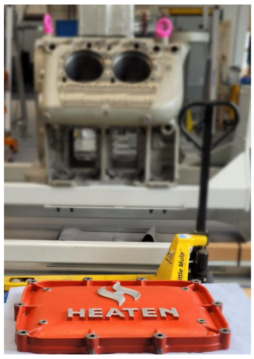
V16 – up to 8 MW_{th}

Public

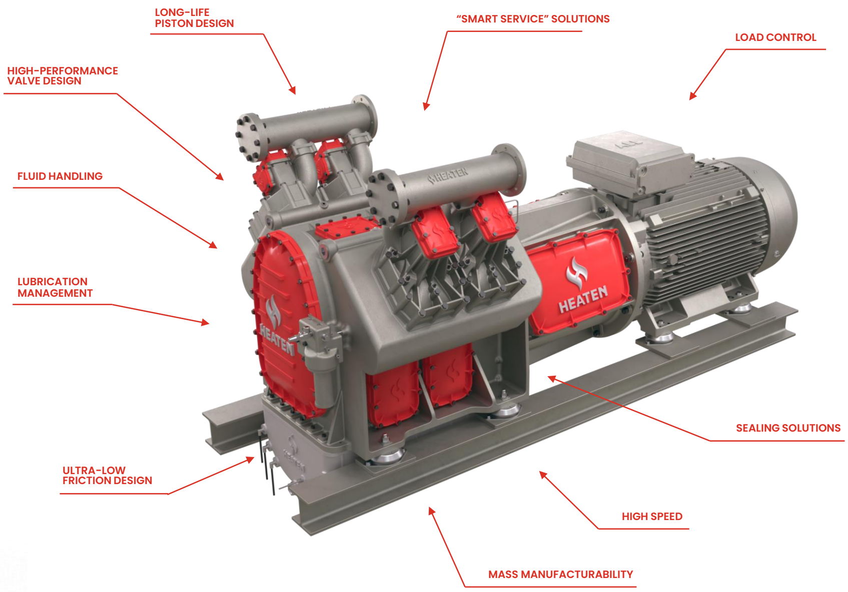
HeatBooster

Heaten's Approach

- Heaten is in full control of its own compressor design
- Compressor technology "tailor"-developed over many years to solve specific challenges – e.g. high temperatures and "future-ready"
- Ultra-low friction design
- Largest reciprocating (vapor) compressor to serve large heat demands
    - Handling the large energy/heat streams (e.g. 1 – 50 MW)
- Utilize existing heavy-duty combustion engine production lines



INNOVATION EXAMPLES



20 FOOT CONTAINER DEPICTED FOR SCALING PURPOSES

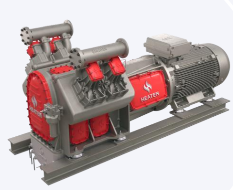
Advantages of Heaten's Piston Compressor

CAPACITY

- Biggest displacement per cylinder in the market.
- High speed up to 1,500 rpm using novel valve solution

EFFICIENCY

- Efficiency curve is "flat" over 20 – 100% load range.
- Typ. COP range of 50 to 55% of Carnot.



FLEXIBILITY

- Can use nearly all HFOs and HCs.
- Variable compression ratio: One hardware for all temperature outputs (80-200 °C).
- Multi-cylinder family enables adaption to each application.

"FROM GREY TO GREEN"

Heaten leverages existing heavy-duty combustion engine infrastructure for production.

PRODUCTION & COST

- Technology with the largest future production capacity potential.
- Global manufacturing base
- Technology based on well-established mass-production and scaling philosophy, utilizes all positive drivers in heavy-duty engine design where 4-16 cyl. engine families are common.

Public

SPECIFICATIONS, HB-L4

Nominal power / COP @ 40°C temperature lift		
Power output	kW_{th}	1500
Cooling power	kW_{th}	1200
El. power	kW_{el}	300
Heating COP		5

Dimensions and weight		
Length	mm	5,600
Width	mm	2,340
Height	mm	2,350
Weight	kg	11,900

Operating range		
Speed	RPM	300-1500
Temperature	°C	20-200

ABOVE INFORMATION IS SUBJECT TO CHANGE WITHOUT FURTHER NOTICE OR OBLIGATION. INFORMATION HEREIN SHOULD BE CONFIRMED BEFORE PLACING ORDERS. POWER OUTPUT/COP WILL VARY OVER THE OPERATING RANGE DUE TO WORKING FLUID PROPERTIES. PLEASE CONTACT HEATEN FOR EVALUATION OF YOUR APPLICATION.

COP = COEFFICIENT OF PERFORMANCE

Public


Typical installation
HeatBooster by
HEATEN


Application Overview
© 2023 Heaten AS
Public

APPLICATIONS

Typical Industry Examples

Media/Processes

- Hot Water
- Pressurized water
- Low pressure steam
- High pressure steam
- Process heat
- Process cooling
- Preheating
- Distillation
- Drying

Public

APPLICATIONS

Some Application Calculations

Lift from 80 to 120 °C Water/Water

Heating power	1.67 MW
Cooling power	1.35 MW
Electrical power	0.35 MW
Coefficient of Performance	4.80

Lift from 90 to 120 °C Water/Steam*

Heating power	1.91 MW
Cooling power	1.59 MW
Electrical power	0.35 MW
Coefficient of Performance	5.40

(*) Saturated steam
(**) 2-stage configuration assumed

Lift from 120 to 150 °C Steam*/Steam*

Heating power	1.30 MW
Cooling power	1.09 MW
Electrical power	0.27 MW
Coefficient of Performance	4.80

Lift from 30 to 180 °C Water/Steam***

Heating power	0.90 MW
Cooling power	0.40 MW
Electrical power	0.55 MW
Coefficient of Performance	1.60

-Pairing with MVR systems also possible (Mechanical vapor recompression)

Public

Some Use Cases

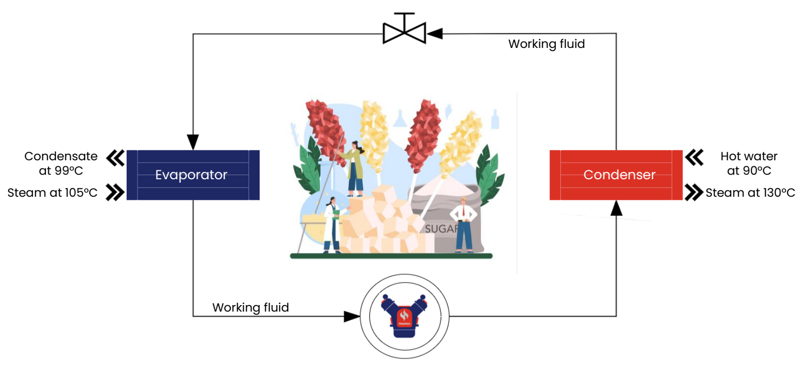
Public

CASE EXAMPLE

Crystallization and drying processes

Case Highlights	Values
Number of units	1 x HeatBooster HBL4 – Steam/Steam
COP	5.82
Power output	1.47 MW
Steam output	2.3 tons/h
Operating hours	8,000 h/year
Investment cost	€ 1.19 million*
Payback time	1.2 years**
CO_2 savings	2,795 tons/year

*Total installation cost including heat pump integration
**8.0 EUR cent/kWh - natural gas **15.0 EUR cent/kWh - electricity



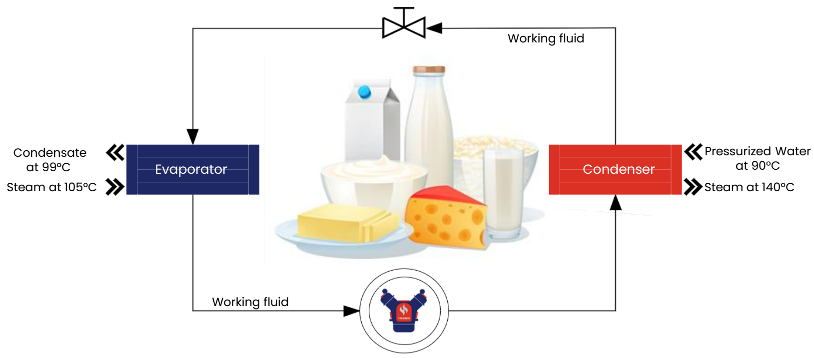
Public

CASE EXAMPLE

Pasteurization and other dairy processes

Case Highlights	Values
Number of units	1 x HeatBooster HBL4 – Steam/Steam
COP	4.78
Power output	1.20 MW
Steam output	2.2 tons/h
Operating hours	8,000 h/year
Investment cost	€ 1.19 million*
Payback time	1.5 years**
CO_2 savings	2,281 tons/year

*Total installation cost including heat pump integration
**8.0 EUR cent/kWh - natural gas **15.0 EUR cent/kWh - electricity



Public

Thank you!

post@heaten.com

GEA Engineering for a better world.

High temperature ammonia heat pumps

The Refrigeration and Heat Pump Forum 2023

Kenneth Hoffmann, 2023

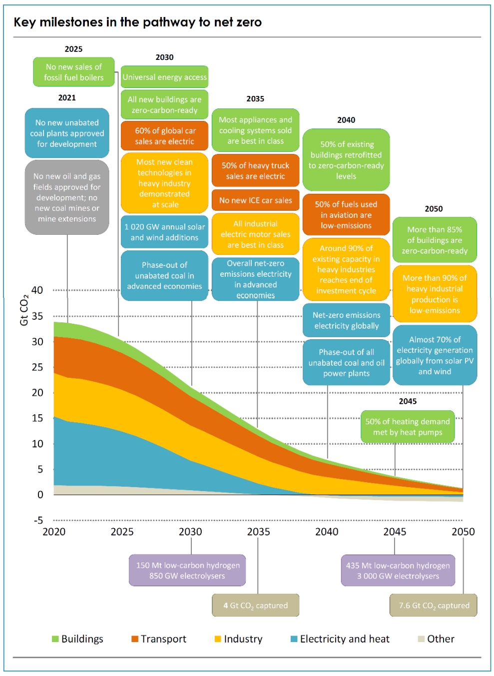
Global CO_2 emission

Pathway to net zero

A Roadmap for the Global Energy Sector (IEA)

2035: Most installation needs to be best in class cooling and heating efficiency

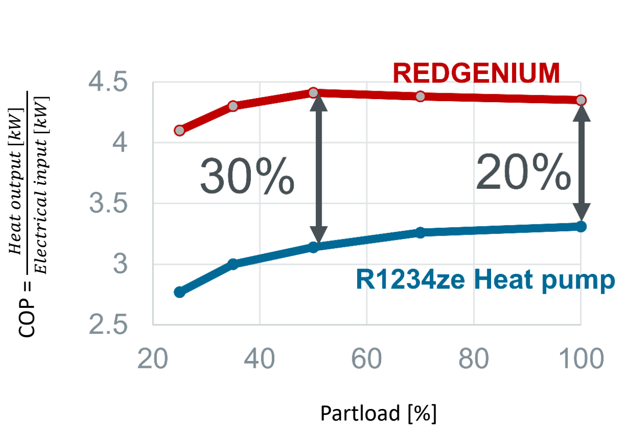
2045: 50% of heating demand met by heat pumps = 4.5EJ



GEA

Focus on ammonia

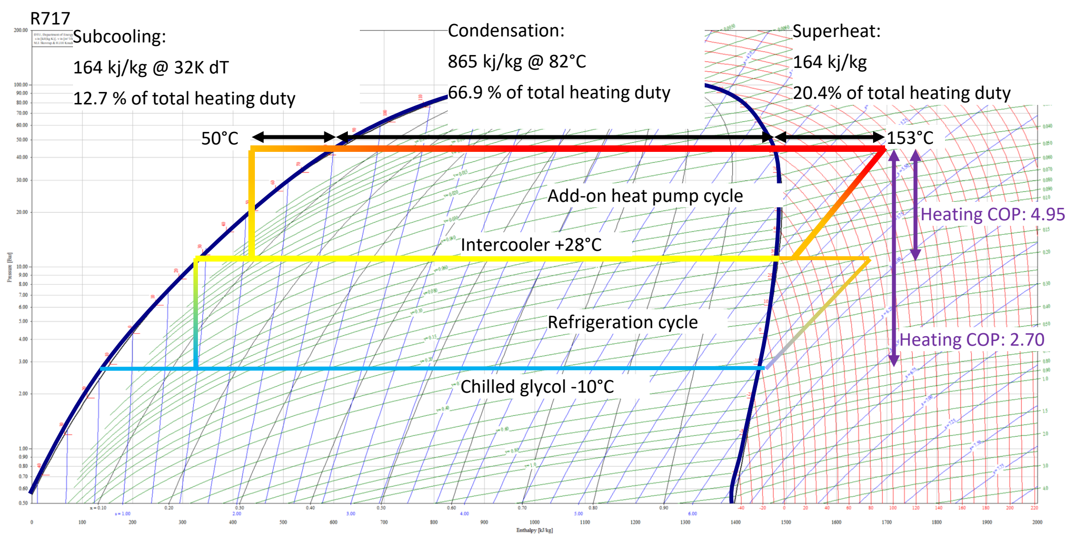
	REDGENIUM 1100 HP	R1234ze HEAT PUMP
Chilled water inlet	15˚C	15˚C
Chilled water outlet	10˚C	10˚C
Cooling duty	553 kW	494 kW
Heating water in	45˚C	45˚C
Heating water out	65˚C	65˚C
Heating duty	700 kW	701 kW
Heating COP	**4.06**	**3.31**
Refrigerant charge	41 kg	140 kg

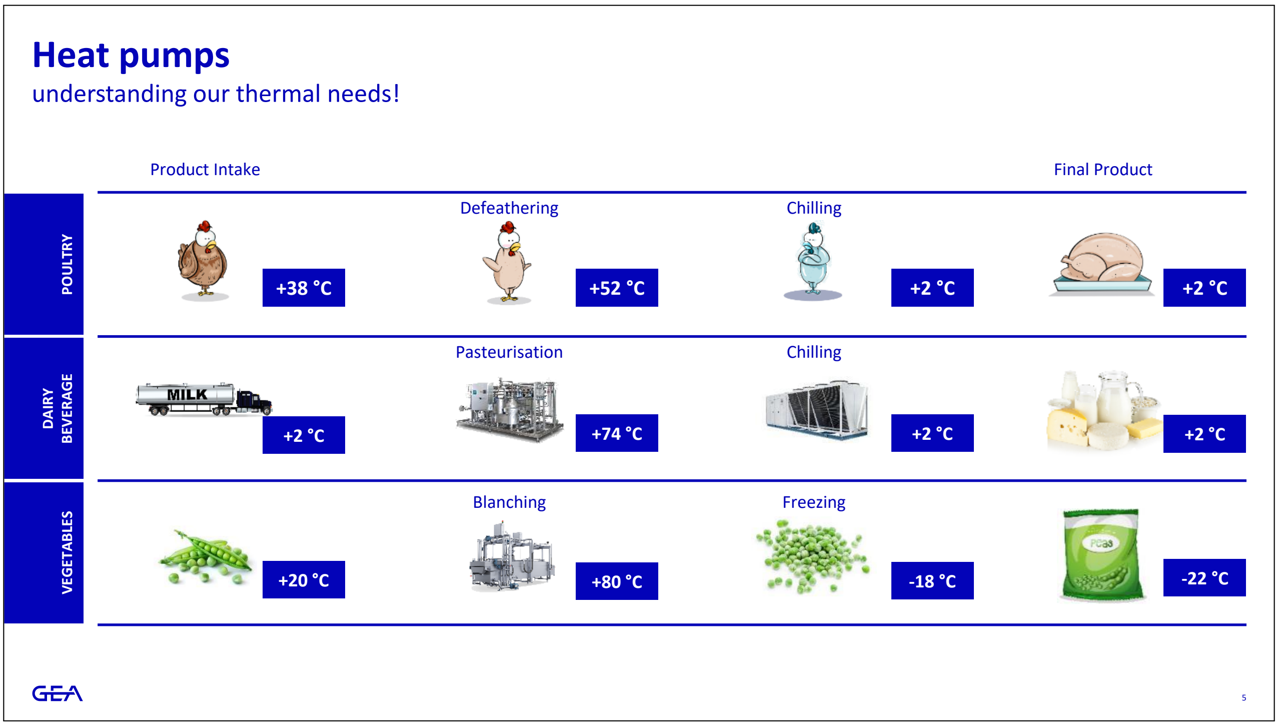


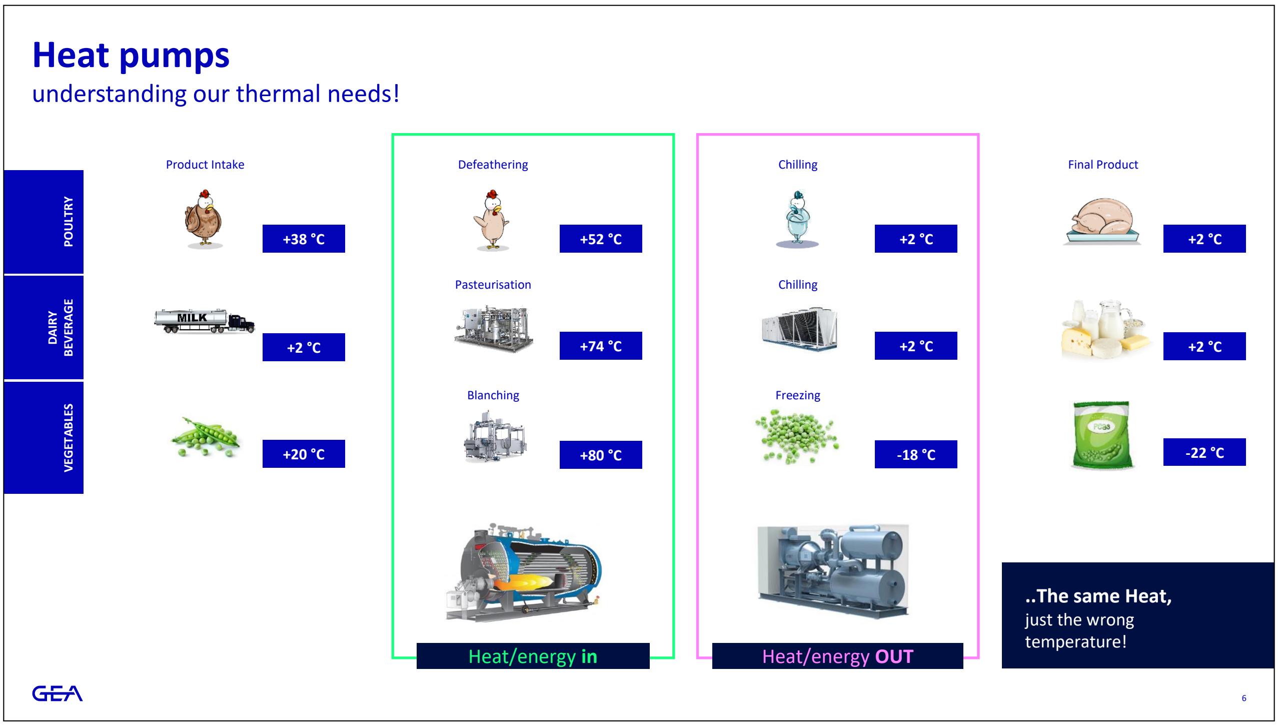
April 7, 2023 3

Refrigeration System with Add-on Heat Pump

Heating water from 45°C to 90°C




Heat pumps
understanding our thermal needs!
Product Intake
Final Product
POULTRY
Defeathering
Chilling
+38 °C
+52 °C
+2 °C
+2 °C
DAIRY BEVERAGE
MILK
Pasteurisation
Chilling
+2 °C
+74 °C
+2 °C
+2 °C
VEGETABLES
Blanching
Freezing
+20 °C
+80 °C
-18 °C
-22 °C
GEA
5


Heat pumps
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Product Intake
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POULTRY
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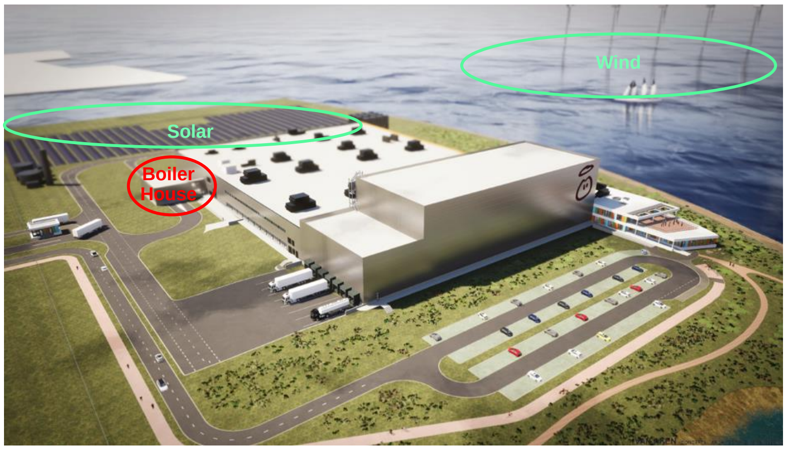
+2 °C
DAIRY BEVERAGE
MILK
+2 °C
Pasteurisation
+74 °C
Chilling
+2 °C
+2 °C
VEGETABLES
+20 °C
Blanching
+80 °C
Freezing
-18 °C
-22 °C
Heat/energy in
Heat/energy OUT
..The same Heat,
just the wrong
temperature!
GEA
6

Concept – Innocent Smoothies



10 MW, 6 Bar steam (160°C steam)
- Sterilization
- Pasteurization
- HVAC
- CIP
- Hot water
- Process heating

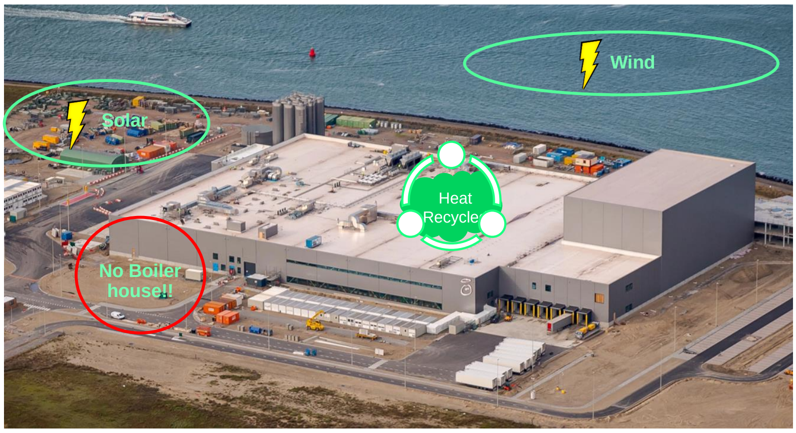
2 MW, cooling at +7°C
- HVAC

5 MW, cooling at -6°C
- Cold storage
- Process cooling

GEA

Reality – Innocent Smoothies

– Zero Carbon Production



1 MW, 3 Bar steam (130°C steam)
- Sterilization

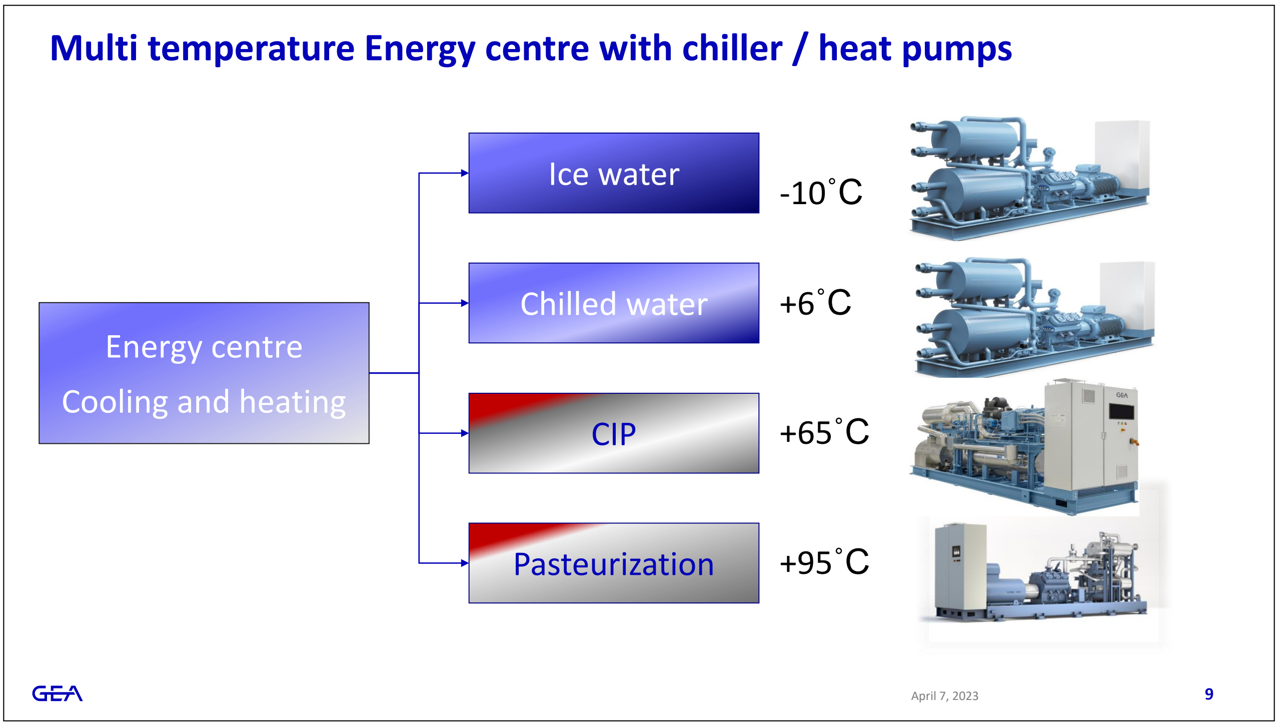
5 MW, 90°C hot water
- Pasteurization

2 MW, 65°C hot water
- HVAC
- CIP
- Hot water
- Process heating

2 MW, cooling at +7°C
- HVAC

5 MW, cooling at -6°C
- Cold storage
- Process cooling

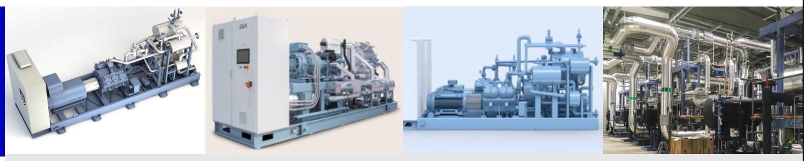
GEA

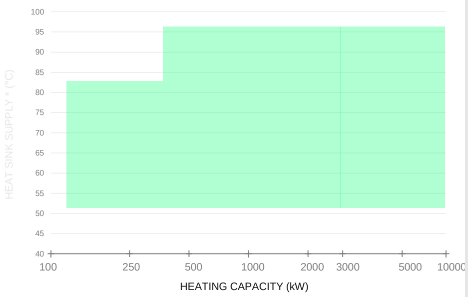

Multi temperature Energy centre with chiller / heat pumps
Energy centre
Cooling and heating
Ice water
-10˚C
Chilled water
+6˚C
CIP
+65˚C
Pasteurization
+95˚C
GEA
April 7, 2023
9


Standard heat pumps
GEA
April 7, 2023
10

GEA Ammonia Heat Pump Portfolio

Temperature – Capacity Application Diagram





The highlighted area shows the range of supply temperatures for the heating demand and the heating capacity at ambient heat source level.

RedGenium

Standard reciprocating compressor heat pump

- 11 types
- up to +95 °C
- 150 – 2,500 kW

Highlights:

- highest supply temperatures
- best-in-class efficiency
- lowest energy consumption
- lowest total costs

RedAstrum

Standard screw compressor heat pump

- 7 types
- up to +85 °C
- 500 – 3,000 kW

Highlights:

- low footprint
- high differential pressures
- large heat source to heat sink temperature lifts

Blu-Red Fusion

Standard chiller plus heat pump combination

- multiple types
- up to +95 °C
- 500 – 2,500 kW

Highlights:

- combined cooling and heating
- highest efficiency
- unique flexibility: full cooling and heating, reduced heating and chiller-only modes possible

Custom unit

Customized recip. and screw heat pumps

- all compressors
- up to +95 °C
- 250 – 10,000 kW

Highlights:

- widest application range
- up to highest capacities
- many flexible design and configuration options

11

GEA RedGenium Standard at a Glance

Driveline with compressor

- RECIPS:
  5 HP series (4x sizes)
  V HP series (3x sizes)
  VXHP series (4x sizes)

GEA Omni high-end controller

With complete power panel including inverter ready to "plug-and-play"

High-efficient heat exchanger set

- COLD SIDE: GEA-patented evaporator/separator-combination
- HOT SIDE: Desuperheater (option), Condenser, Subcooler (option)

Intelligent arrangement, individual configuration lowers the condensing temperature and hence the compressor workload

Significant efficiency raise!

GEA

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RedGenium range

Model	Energy uptake (kW) @ Water +37/+32 °C or Ref plant Condenser = 33°C	Condensing capacity (kW) Water +50/+70°C	Absorbed power (kW)	Efficiency COPH	NH3 Charge (kg)
RedGenium 35 - 65*	221 - 446	261 - 521	42 - 83	6.22	24 - 39
RedGenium 300**	636	742	115	6.45	40
RedGenium 450**	974	1134	177	6.42	51
RedGenium 600**	1290	1500	229	6.54	69
RedGenium 350***	826	970	153	6.34	55
RedGenium 550***	1255	1460	228	6.41	68
RedGenium 750***	1675	1950	292	6.64	88
RedGenium 950***	2067	2400	363	6.61	114

* Max water outlet: 80°C, **Max water outlet: 70°C, ***Max water outlet: 95°C

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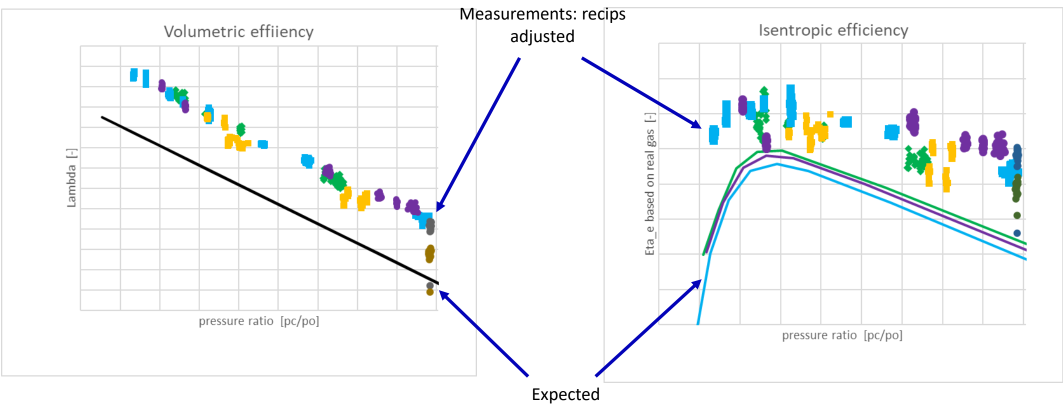
Test of V XHP Reciprocating compressor

Efficiency results



GEA

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GEA RedAstrum Standard at a Glance

Driveline with compressor

- SCREWS:
  M series (6x sizes)
  LT series (1x size)

High-efficient heat exchanger set

- COLD SIDE:
  GEA-patented evaporator/separator-combination
- HOT SIDE:
  Oil cooler,
  Condenser,
  Subcooler (option)

Intelligent arrangement, individual configuration lowers the condensing temperature and hence the compressor workload

Significant efficiency raise!

GEA Omni high-end controller

With complete power panel including inverter ready to "plug-and-play"

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RedAstrum range

Model	Energy uptake (kW) @ Water +40/+35 °C or Ref plant Cond. P = 37°C	Condensing capacity (kW) Water +40/+70°C	Absorbed power (kW)	Efficiency COP_H	NH3 Charge (kg)
RedAstrum EC*	620	745	139	5.37	61
RedAstrum ED*	730	880	161	5.46	61
RedAstrum HE*	900	1100	199	5.51	84
RedAstrum HG*	1100	1300	224	5.79	93
RedAstrum MH*	1400	1700	296	5.72	98
RedAstrum ML*	1600	1950	326	5.95	130
RedAstrum RM**	2000	2350	402	5.89	141
RedAstrum RN**	2450	2900	498	5.83	165

* Max water outlet: 80°C, **Max water outlet: 85°C

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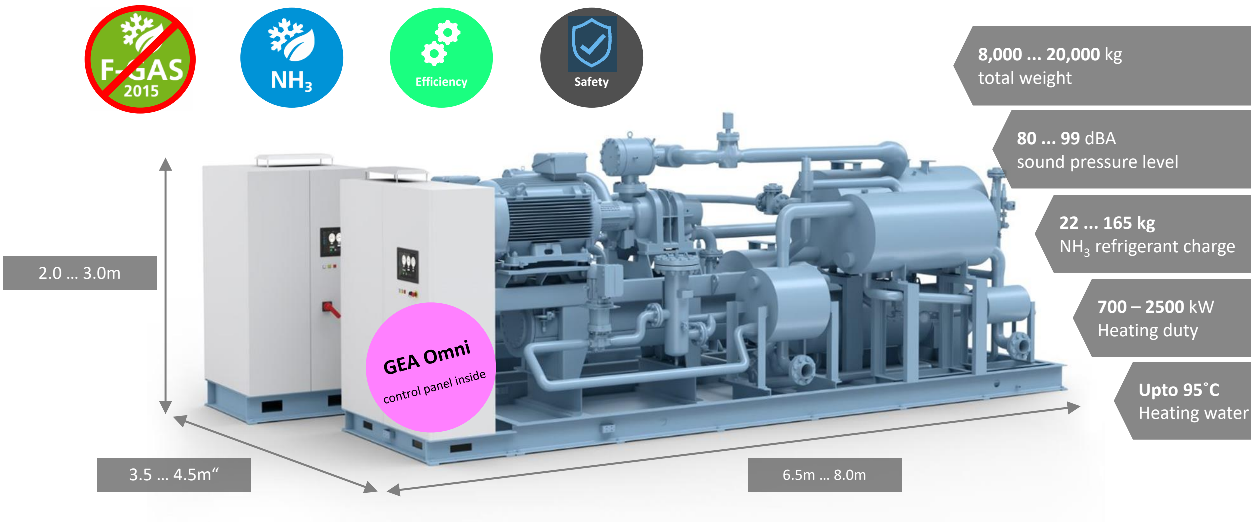
Blu – Red Fusion



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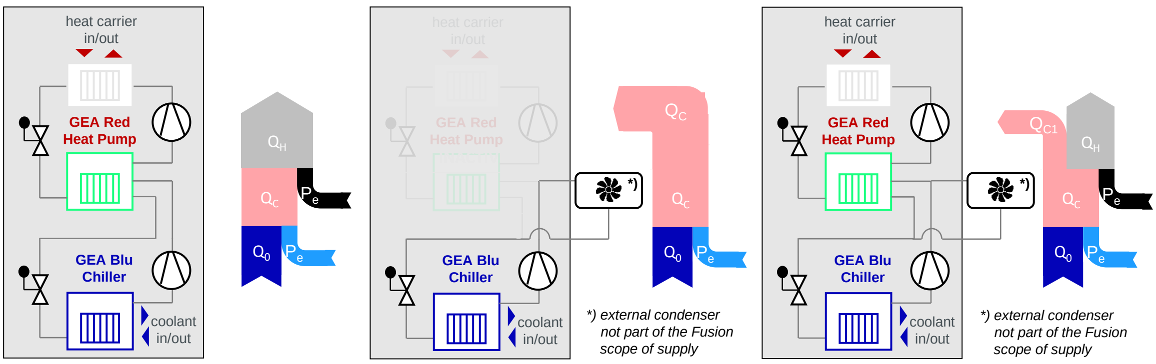
GEA Blu-Red Fusion Operating Modes

Flexible modes allow typical and varying operating requirements!



► Mode 1

Heating and cooling capacity matching

► Mode 2

No heating required, "Chiller-only"

► Mode 3

Less heating required than possible

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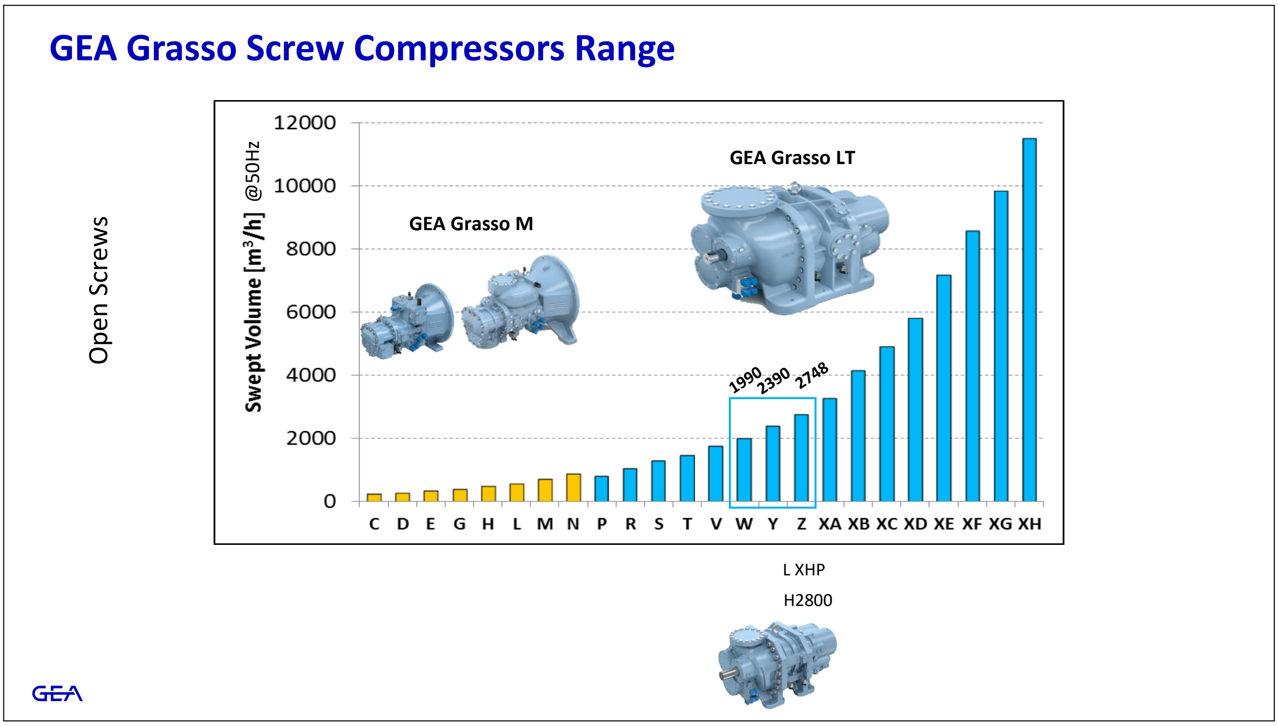
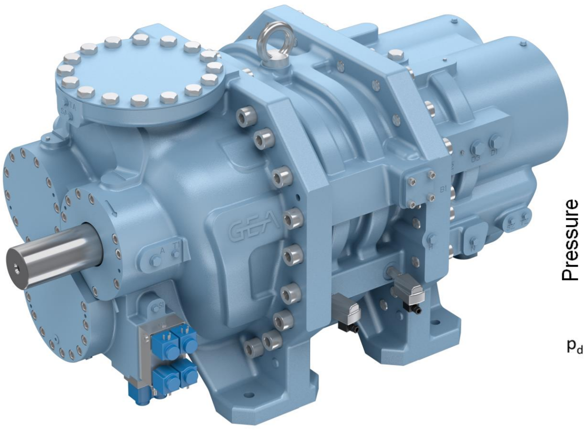
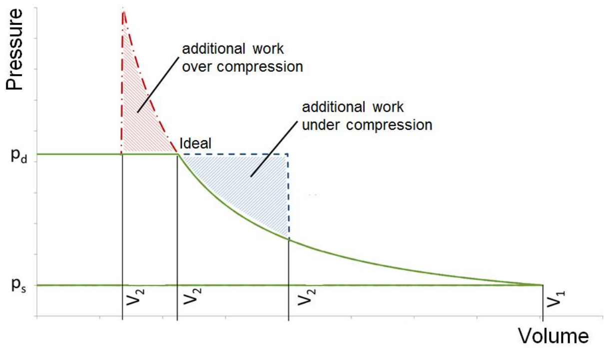
Customized heat pumps
GEA
April 7, 2023
19


GEA Grasso Screw Compressors Range
Open Screws
Swept Volume [m³/h] @50Hz
12000
10000
8000
6000
4000
2000
0
GEA Grasso M
GEA Grasso LT
1990
2390
2748
C D E G H L M N P R S T V W Y Z XA XB XC XD XE XF XG XH
L XHP
H2800
GEA

GEA Grasso L XHP



1. New rotor design
2. Triax bearings
3. Variable Vi
- Optimised compression ratio
- Minimised vibration
3. Economised
- Improved efficiency



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Reference operation points H2800

NH3 heat pumps

Operation point	t_0 [°C]	t_C [°C]	Heating capacity [kW]*
#1	30	95	6760
#2	45	95	9430
#4	0	80	3160
#5	0	90 + Economizer	4240

*at 2940 rpm (50Hz power system)

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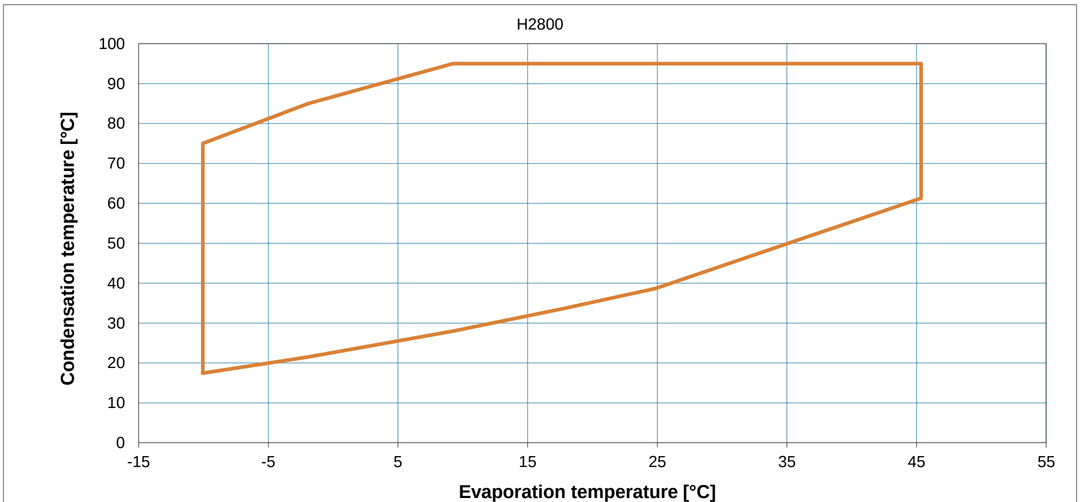
Operation range for NH3



NH3, 3K superheat, t_oil=75 °C, 3600 1/min, bareshaft, optimum vi

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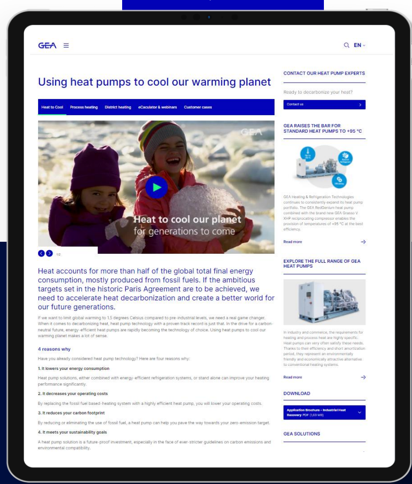
Contact Information

GEA.com/heat-to-cool



Kenneth Hoffmann

Kenneth.Hoffmann@gea.com

Heat pump application manager

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Engineering for a better world.
GEA.com

å

3 8th International Symposium on Advances in Refrigeration and Heat Pump Technology

Contents

DIGITALISATION AND IOT FOR HEAT PUMPS

V. Wilk
Austrian Institute of Technology GmbH

Køle- og varmepumpeforum 2023, Copenhagen, 23.3.2023

DIGITALISIERUNG AND IOT HEAT PUMPS – IEA HPT ANNEX 56

IoT = Internet of Things

Linking everyday objects and devices into networks

IoT heat pumps:

- equipped with software, sensors, network connection
- collect data and interact with other "things

Picture: Canva

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ENERGY TRANSITION IN THE EU

Expectations for digital technologies in the energy transition:

- unleash the full potential of flexible energy generation and consumption
- provide system optimisation
- substantial operational savings and savings in network infrastructure
- support energy system integration by dynamic and interlinked flows of energy carriers
- allow for more diverse markets to be connected with another
- provide the necessary data to match supply and demand both at local or at system-wide level and close to real time
- help optimising the use of the existing grid capacity and identifying bottlenecks quicker

→ EU Action Plan for digitalisation in the energy system

28.04.2023 3

ENERGY TRANSITION IN THE EU

EU Action Plan (10/2022)

- helping consumers control their energy consumption and bills through new digital tools and services

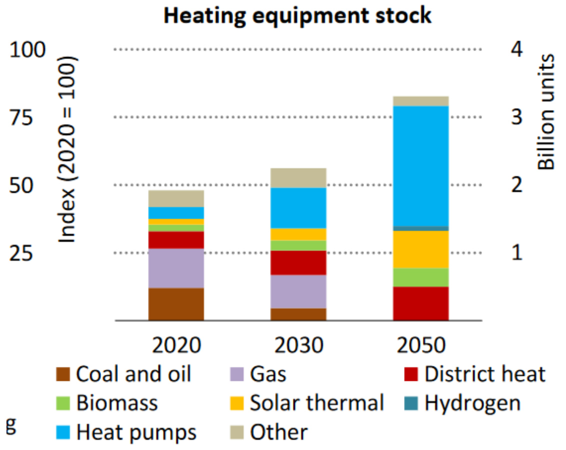
- controlling energy consumption in the ICT sector, including through an environmental labeling system for data centers, an energy label for computers, and measures to increase the transparency of energy consumption by telecommunications services

- strengthening the cybersecurity of energy networks through new legislation, including a Network Code for cybersecurity aspects of cross-border electricity flows

EU Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Digitalising the energy system - EU action plan. COM(2022) 552 final, October 2022, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022DC0552&from=EN

28.04.2023 4

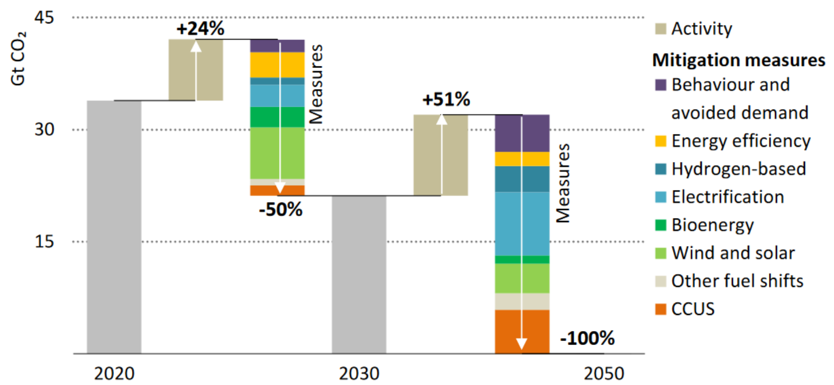
HEAT PUMPS IN BUILDINGS



IEA: Net Zero by 2050 - A Roadmap for the Global Energy Sector, 2021

IMPACT OF MITIGATION MEASURES

Figure 2.12 ▷ Emissions reductions by mitigation measure in the NZE, 2020-2050



Digitalisation is included in Avoided demand = energy service demand changes from technology developments

Digitalisation and smart controls enable efficiency gains that reduce emissions from the buildings sector by 350 Mt CO_2 by 2050.

IEA: Net Zero by 2050 - A Roadmap for the Global Energy Sector, 2021

DIGITALISATION AND IOT FOR HEAT PUMPS - IEA HPT ANNEX 56

Project duration: 01/2020 – 12/2022

Participants:

- Austria: AIT Austrian Institute of Technology (OA), TU Wien, University of Applied Sciences Burgenland
- Denmark: Danish Technological Institute, Technical University of Denmark, Energy Machines ApS
- France: EDF
- Germany: Fraunhofer Institute for Solar Energy Systems ISE, RWTH Aachen
- Norway: SINTEF
- Switzerland: Hochschule Luzern
- Sweden: RISE, KTH

Further information: https://heatpumpingtechnologies.org/annex56

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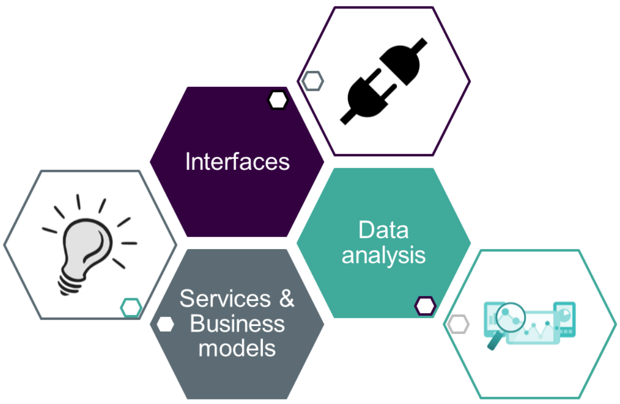
DIGITALISATION AND IOT FOR HEAT PUMPS - IEA HPT ANNEX 56

- interviews and surveys on the state of digitalisation in the participating countries
- ca. 30 use cases
- household and industrial heat pumps
- analysis of similarities and differences



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USE CASES FOR IOT HEAT PUMPS

- *Heat pump operation optimization*
  - monitoring and remote control
  - adaption to user habits
  - adjustment of the heating curve
  - scheduling of production and downtimes
  - continuous set-point tuning
  - interaction with other components (e.g. PV, solar thermal, storage, etc.)
  - use flexible tariffs
- *Predictive maintenance*
  - learnings from performance benchmarks
  - advanced data analytics

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USE CASES FOR IOT HEAT PUMPS

- *Heat pump operation commissioning*
  - set point tuning
  - comparison to performance benchmarks
  - learnings about the system layout and possible improvements for future installations
- *Flexibility provision*
  - pooling of household heat pumps
  - providing flexibility as balancing reserve
  - providing flexibility to DSO/TSO for congestion management or voltage control
- *Heat as a service*
  - different model of ownership (leasing, renting, buying heat instead of heating equipment)

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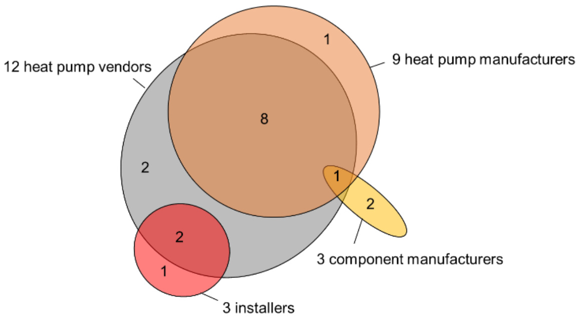
MARKET SURVEY IN AUSTRIA

- all participants offer IoT products and services
  - products: heat pumps that have connectivity or smart components, such as compressors or sensors, etc.
  - services: marketing of flexibility, remote maintenance, monitoring, etc.
- 66% have products in the portfolio or in use in larger numbers
- 33% are evaluating or developing products or have first products in use

16 participants = 53% of manufacturers



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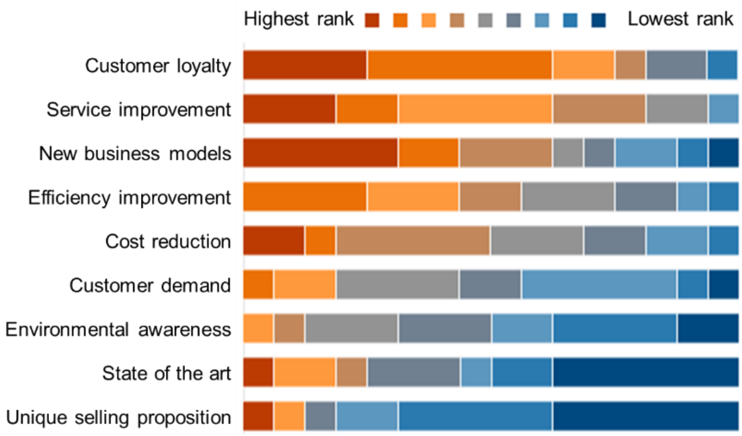
MARKET SURVEY IN AUSTRIA

Motivation to introduce IoT products and services?



further results will be presented at the IEA HPT conference in Chicago in 05/2023

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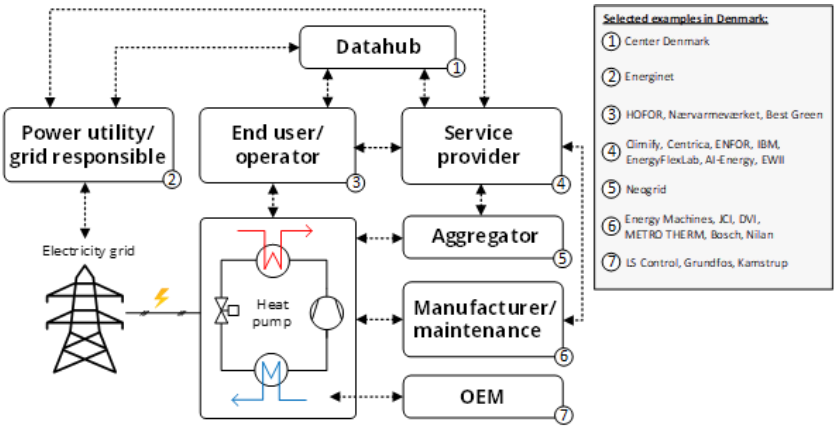
IOT HEAT PUMPS IN DENMARK



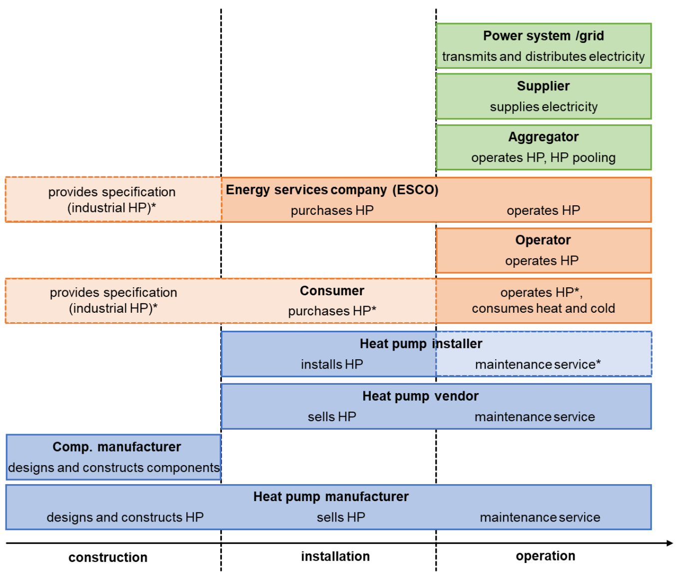
28.04.2023

J. L. Poulsen, J. J. Aguilera, and W. B. Markussen, "IoT Annex 56 - Digitalization and IoT for Heat Pumps - Country Summary for Denmark", 2023.

13

BUSINESS MODELS

- multiple stakeholders
- new business models for
  - HP operation optimization
  - predicative maintenance
  - heat as a service
  - flexibility provision



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BUSINESS MODELS

- value proposition for the consumers:
  - lower costs, higher efficiency, higher reliability
- heat pump value chain (component and heat pump manufacturers, vendors, installers):
  - new products and services
  - more responsibility for efficiency than in traditional business models
- energy system (aggregators, suppliers, grid, etc.):
  - strong need for flexibility to compensate for fluctuating generation
  - sector coupling with heat pumps (power/heat),
- ESCO:
  - help to spread heat pumps as their service requires less involvement of the consumers

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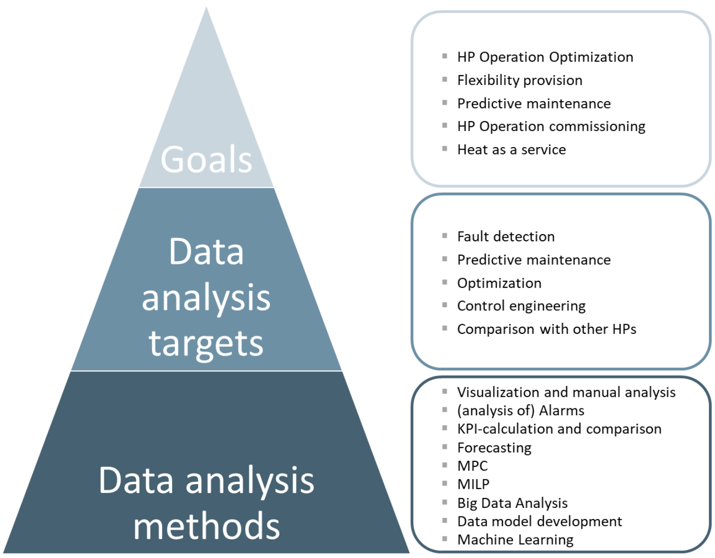
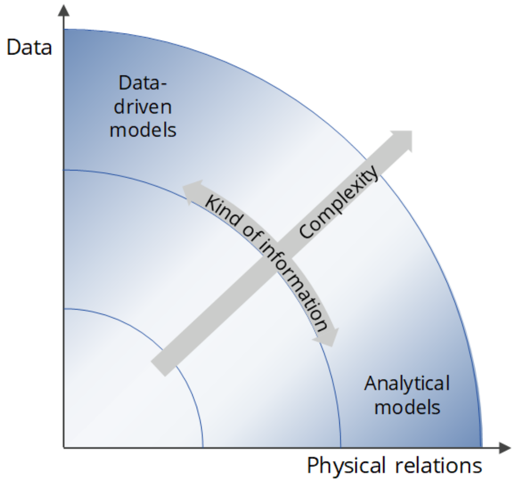
DATA ANALYSIS



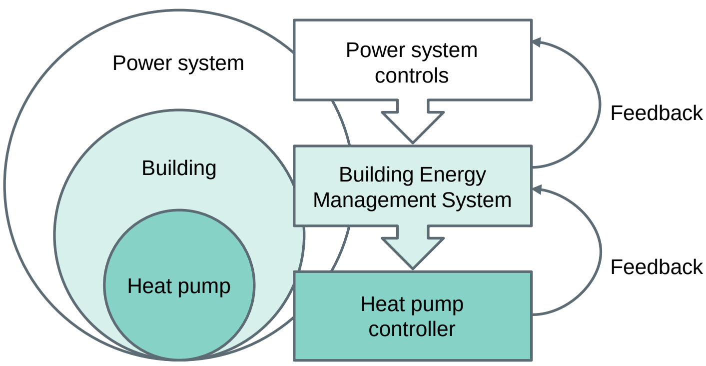
28.04.2023 Internet of things for Heat Pumps – Task 3: Data Analysis – Final Report (draft), IEA HPT TCP Annex 56, 2023 16

MODELLING OF HEAT PUMPS



28.04.2023 Hybrid models based on data and physical relations (source: Danish Technological Institute) 17

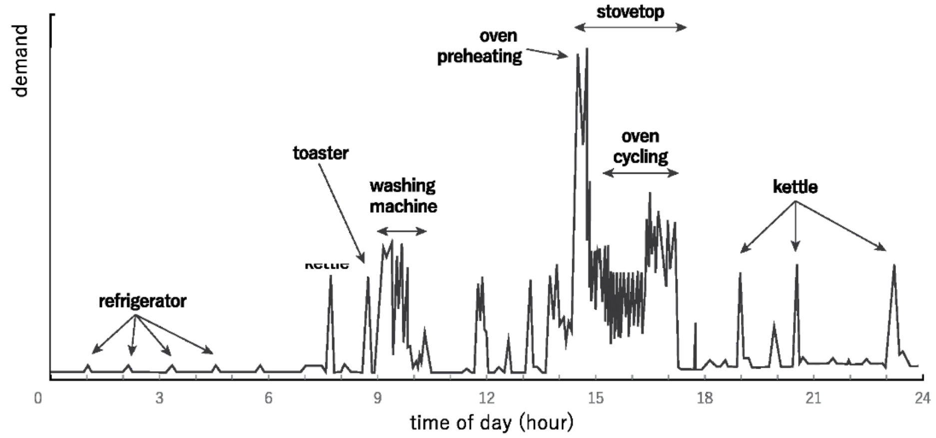
ORCHESTRATION



28.04.2023 Illustration after Fischer, D., Madani, H. On heat pumps in smart grids: A review, Renewable and Sustainable Energy Reviews 70 (2017) 342–357. 18

PRIVACY

Managing privacy concerns



Source: Newborough and Augood (1999), "Demand-side management opportunities for the UK domestic sector" (reproduced courtesy of the Institution of Engineering and Technology).

13 © OECD/IEA 2018

28.04.2023 C. Pottinger, Digitalization & Energy, Highlights der Energieforschung 2018, https://nachhaltigwirtschaften.at/resources/iea_pdf/events/20180320_highlights/01_pottinger_Digitalization-Energy.pdf?m=1521537623& 19

CONCLUSION AND OUTLOOK

Opportunities

for the user:

- optimize heat pump operation to reduce energy consumption
- performance monitoring
- better interaction and alignment with other assets
- integration in high level control systems

for the grid:

- offering flexibility in a pool of heat pumps
- providing frequency reserve with large scale heat pumps

for the heat pump manufacturer:

- predictive maintenance
- fault detection and diagnosis
- performance benchmarks
- new services such as pooling

Challenges

- cyber security
- data protection
- privacy concerns
- standards

https://heatpumpingtechnologies.org/annex56


AUSTRIAN INSTITUTE OF TECHNOLOGY
THANK YOU!
IoT for heat pumps
V. Wilk
Austrian Institute of Technology GmbH
The collaboration in the IEA Annex 56 is gratefully acknowledged. Thanks to TU Wien, University of Applied Sciences Burgenland, Institute of Technology Assessment of the Austrian Academy of Sciences, Danish Technological Institute, Technical University of Denmark, Energy Machines ApS, EDF, Fraunhofer Institute for Solar Energy Systems ISE, RWTH Aachen, SINTEF, Hochschule Luzern, RISE, KTH for their contributions.
The Austrian IoT Annex project is carried out within the framework of the IEA Research Cooperation on behalf of the Austrian Federal Ministry for Climate Protection, Environment, Energy, Mobility, Innovation and Technology.
IEA Research Cooperation
Part of open4innovation
FFG
Promoting Innovation.
Federal Ministry
Republic of Austria
Climate Action, Environment, Energy, Mobility, Innovation and Technology

DEVELOPMENT OF FAST REGULATING HEAT PUMPS USING DYNAMIC MODELS

Wiebke Meesenburg, DTU Construct
Kenneth Rugholm Kramer, Danish Technological Institute

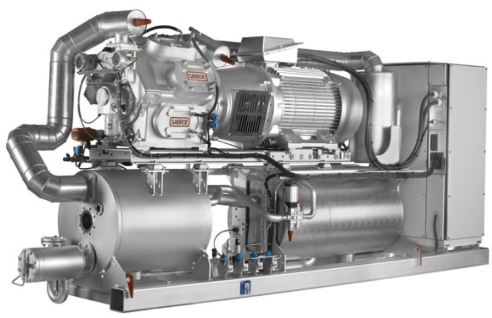
March 23RD

8th INTERNATIONAL SYMPOSIUM on Advances in Refrigeration and Heat Pump Technology

Johnson Controls DTU TEKNOLOGISK INSTITUT

AGENDA

- Purpose and project team
- Modelling of Heat pump system
  - Dynamic component models
  - Software tool
  - Validation based on measurement data
- Analysis of fluctuating boundary conditions
- Perspective for virtual test bench.



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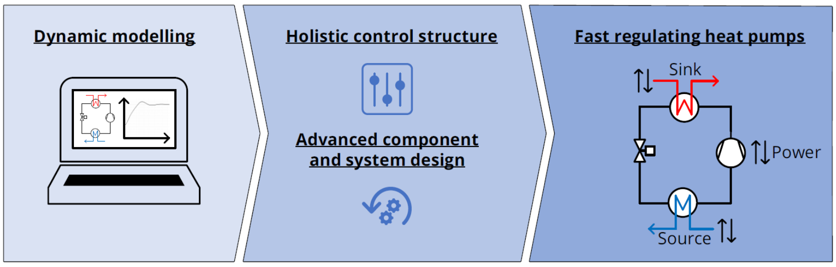
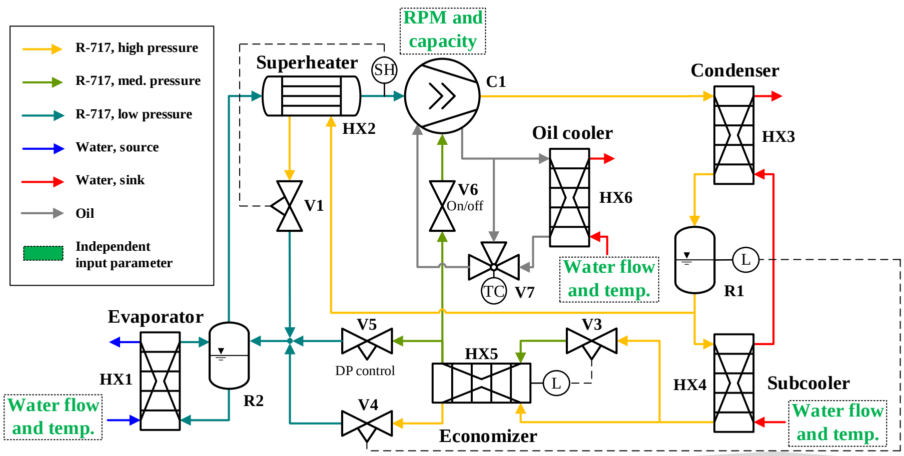
PURPOSE AND PROJECT GROUP



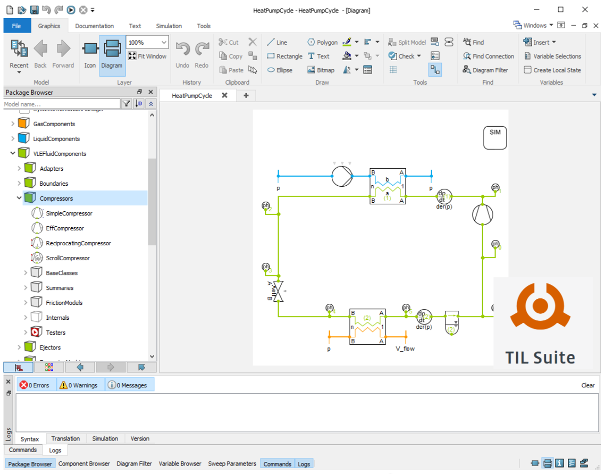
- WP 1 - Develop advanced dynamic component models
- WP 2 - Analysis of selected system configurations under dynamic operating conditions (Model and reality)
- WP 3 - Optimizing system design considering dynamic operation
- WP 4 - Based on the mathematical model, a holistic management must be developed

HEAT PUMP SYSTEM WITH SCREW COMPRESSOR



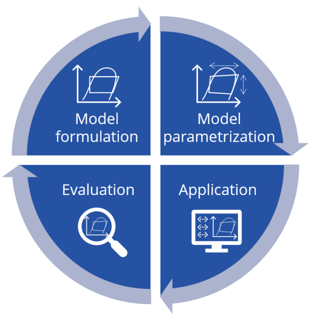
DYNAMIC MODELLING WITH DYMOLA/TIL SUITE

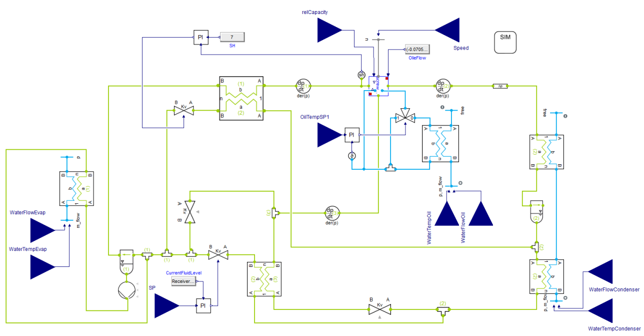
- Modelling and dynamic simulation of thermal systems using Dymola with TIL suite library.
- A wide range of standard components available incl. refrigerant properties.
- Graphical user interface.



DYNAMIC MODELLING

Modelling procedure:

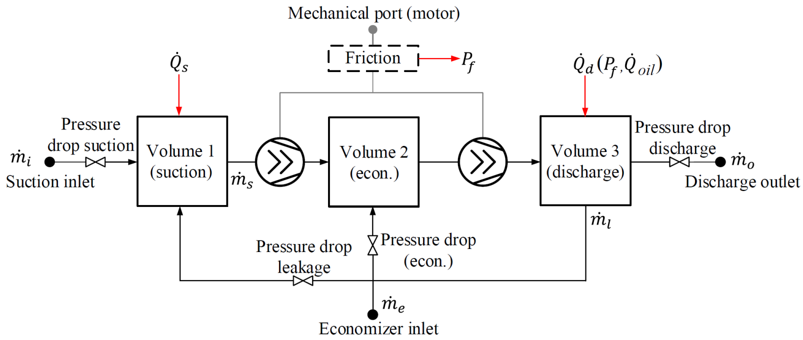




- Challenge
  - Screw compressor
  - PI-controller
  - Thermosyphon

DEVELOPMENT OF ADVANCED DYNAMIC COMPONENT MODELS
EXAMPLE: SCREW COMPRESSOR MODEL

- Screw compressor with economizer port and oil cooling
- The model is based on a finite volume method.
  - Conservation of mass
  - Conservation of energy
- The mass flow is defined based on pressure drop (Saint-Venant and Wantzel)
- Empirical correlations describing frictional losses and port cross-sectional areas



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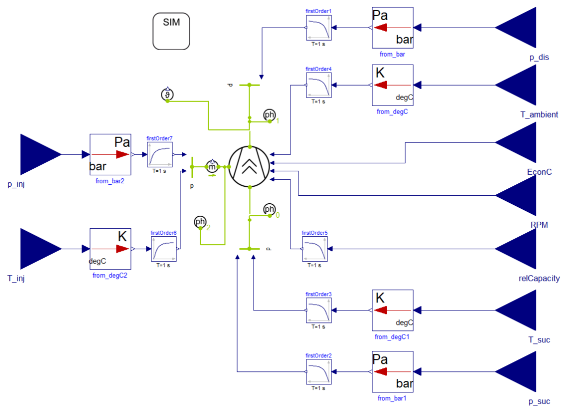
DEVELOPMENT OF ADVANCED DYNAMIC COMPONENT MODELS
EXAMPLE: SCREW COMPRESSOR MODEL

- The model contains a series of parameters that can be fitted so that the compressor matches validation data, for example:
  - Friction parameters
  - Valve areas for Saint-Venant and Wantzel pressure drop (flow)
  - Displacement
- ModelFitter toolchain: Model in Dymola → FMI → Optimization tool in Excel → new model parameter.



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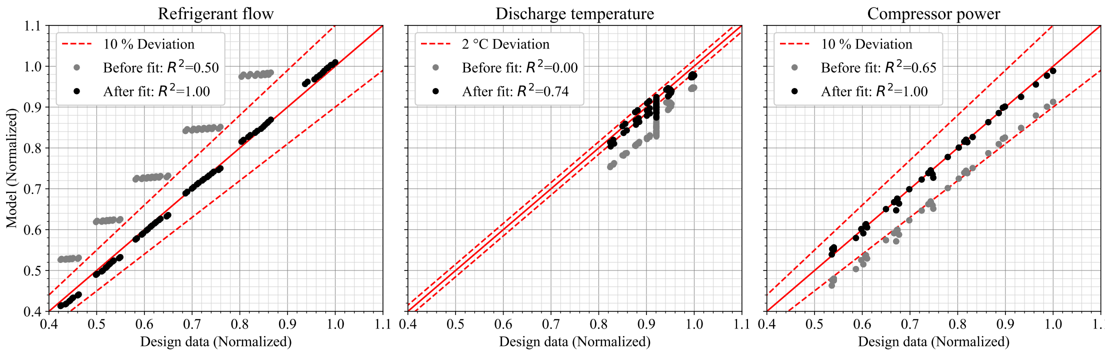
DEVELOPMENT OF ADVANCED DYNAMIC COMPONENT MODELS
EXAMPLE: SCREW COMPRESSOR MODEL

- Validation:



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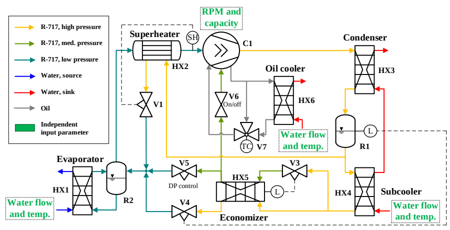
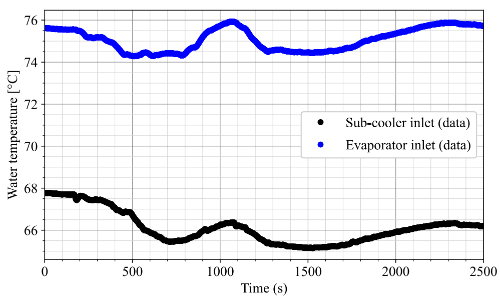
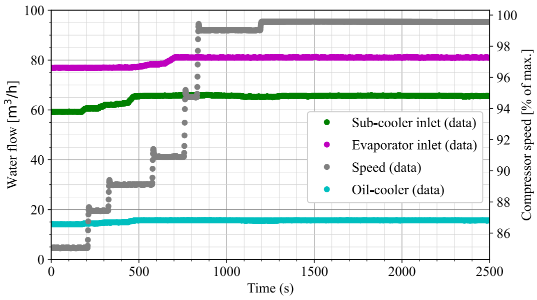
VALIDATION BETWEEN DATA AND THE DYNAMIC MODEL



- Case with these dynamic input parameters:





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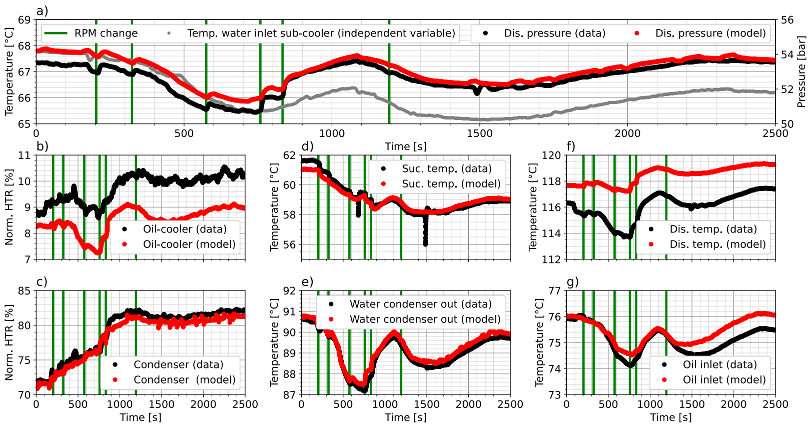
VALIDATION BETWEEN DATA AND THE DYNAMIC MODEL

Results:



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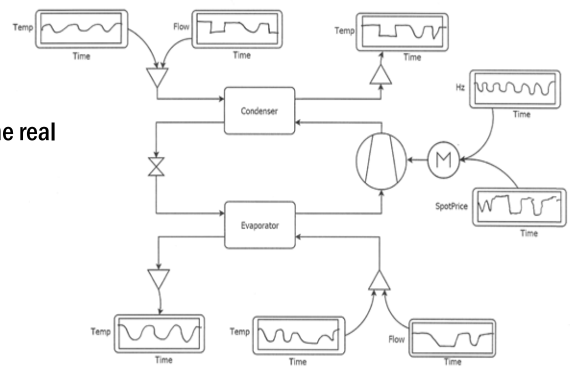
VIRTUAL TEST BENCH

- Addition to the real test set-up
- Enables tests that cannot be practically conducted on the real test set-up
- Enables to test the system under extreme conditions
- Quick results



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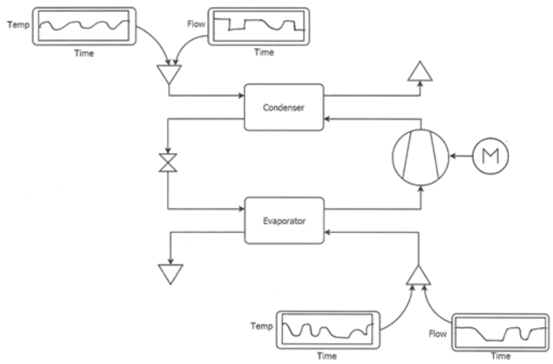
ANALYSIS OF FLUCTUATING BOUNDARY CONDITIONS

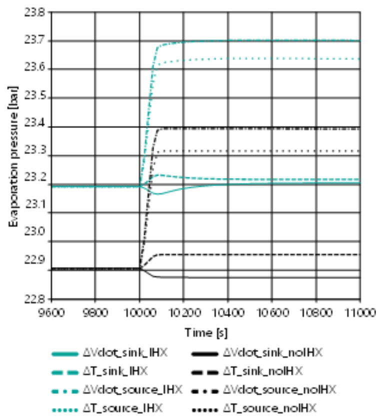
- Test of influence of changes in boundary conditions on the heat pump cycle
  - Sink/Source temperature : -2 K/min to 2 K/min, step size: 0.25 K/min
  - Sink/Source flow rate : -20 %/min to 20 %/min, step size: 2.5 %/min
- Real heat pump set-up &Heat pump set-up without suction line HX

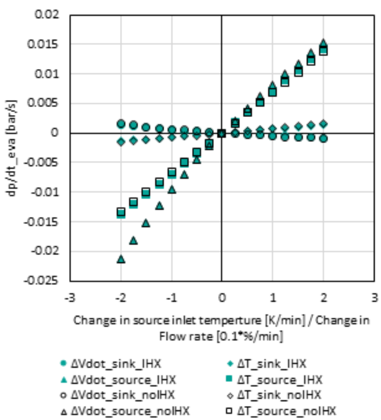


Johnson Controls DTU TEKNOLOGISK INSTITUT

ANALYSIS OF FLUCTUATING BOUNDARY CONDITIONS

Response of evaporation pressure





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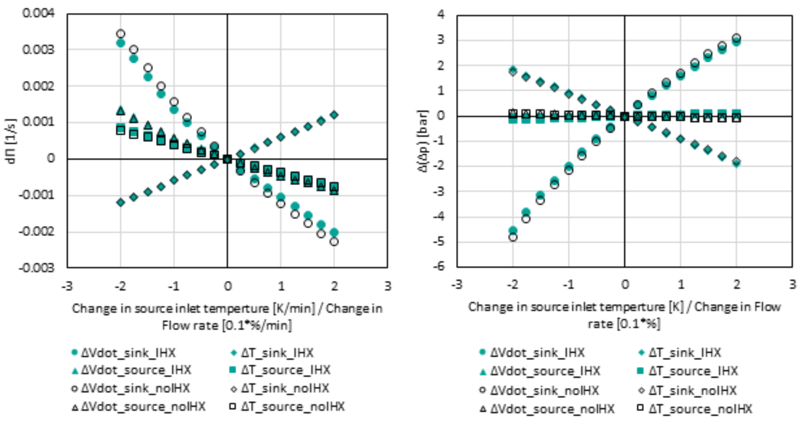
ANALYSIS OF FLUCTUATING BOUNDARY CONDITIONS

Response of pressure ratio and pressure difference



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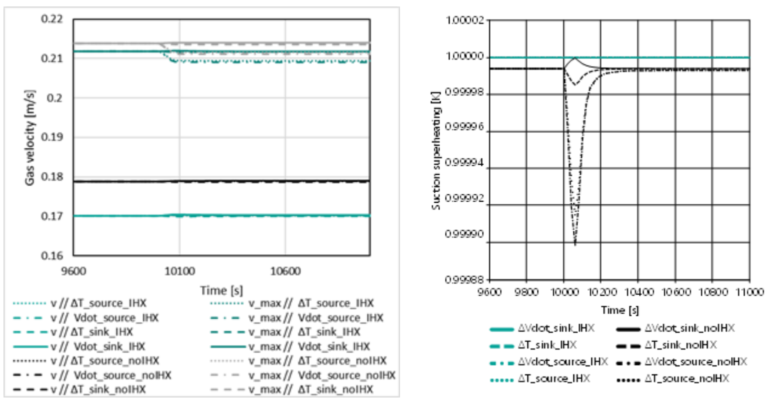
ANALYSIS OF FLUCTUATING BOUNDARY CONDITIONS

Test for risk of liquid floodback and sudden condensation in suction line



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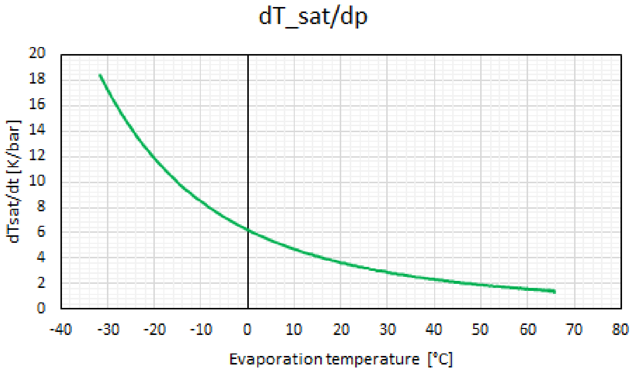
INFLUENCE OF EVAPORATION TEMPERATURE

How does the effect of sudden changes depend on the operating conditions?

Can the limitations of allowable pressure gradients be optimized?



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PERSPECTIVE

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EUDP
The Energy Technology
Development and
Demonstration Programme
The project "Development of fast-regulating heat pumps using dynamic models" is funded by EUDP – Energy Technology Development and Demonstration Program.
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DTU
TEKNOLOGISK
INSTITUT

SuPrHeat

DEVELOPING A HIGH-TEMPERATURE HEAT PUMP TECHNOLOGY CONCEPT

23.03.2023 - Copenhagen

Benjamin Zühlsdorf, Centre Project manager, PhD
Martin Pihl Andersen, PhD Student

SuPrHeat DTU DANISH TECHNOLOGICAL INSTITUTE

INDUSTRIAL PROCESS HEAT DEMAND – EU28

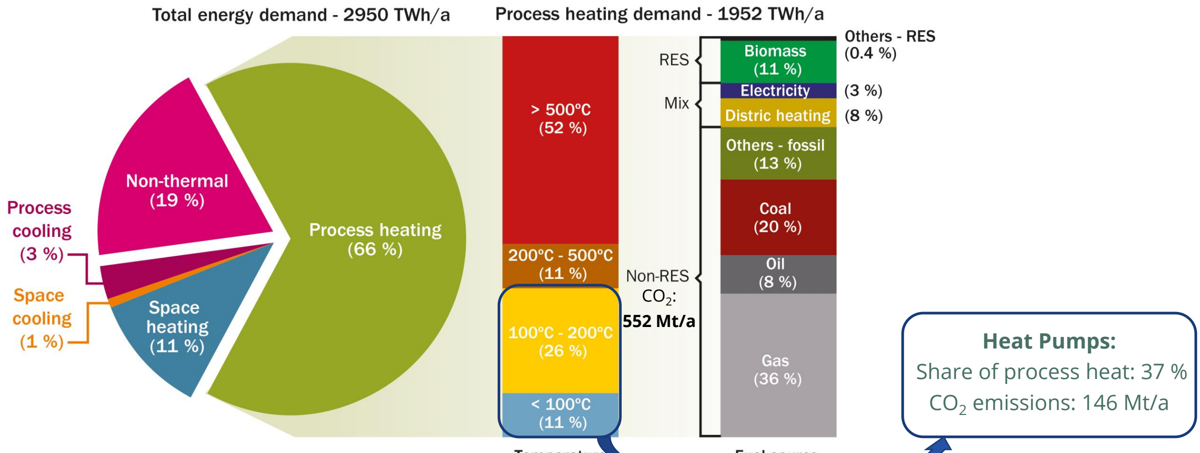

Figure based on Heat Roadmap Europe

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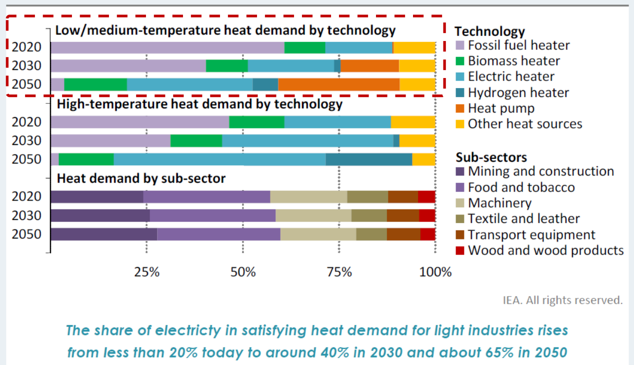
ELECTRIFICATION AND ENERGY EFFICIENCY ARE KEY FOR REACHING SUSTAINABILITY TARGETS

Figure 3.20 ▷ Share of heating technology by temperature level in light industries in the NZE



The share of electricty in satisfying heat demand for light industries rises from less than 20% today to around 40% in 2030 and about 65% in 2050

Source: "*Net Zero by 2050 – A Roadmap for the Global Energy Sector*, International Energy Agency, 05/2021, https://www.iea.org/reports/net-zero-by-2050

- IEA estimates that natural gas will be steadily phased out by heat pumps and electric heaters, especially for temperatures up to 200 °C to 250 °C
- Developed countries must go first and be front runners
- The Danish industry should reduce emissions by 1.9 mio. tons of CO2 per year. **25 %** are to be obtained by "**Electrification and heat pumps**", mainly implemented between 2025 to 2030 (Klimarådet)
- EU discusses an end of fossil fuel use for processes <200 °C by 2027 in the RED III, art. 21

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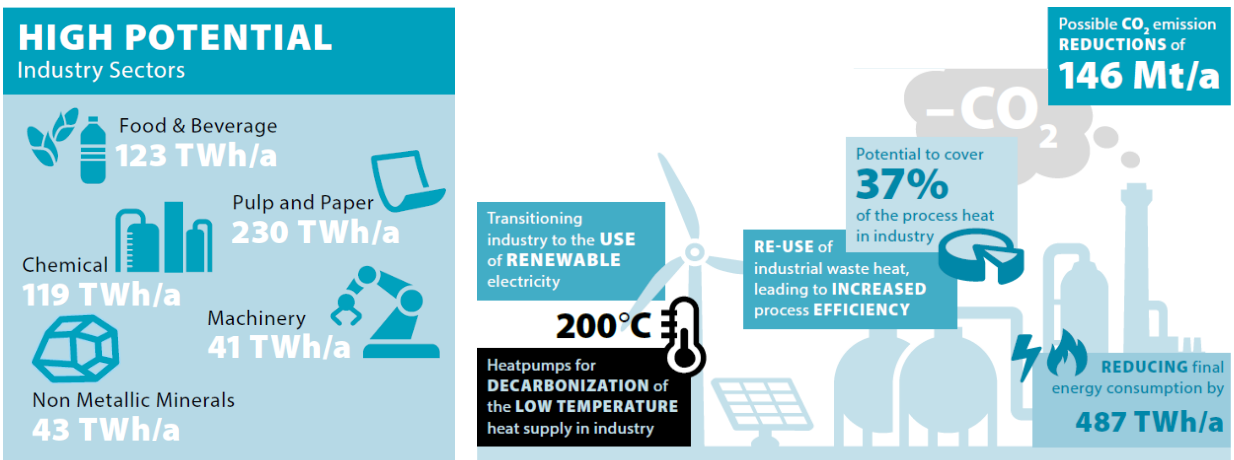
HTHP APPLICATION POTENTIAL

SuPrHeat



White Paper: *Strengthening Industrial Heat Pump Innovation – Decarbonizing Industrial Heat*

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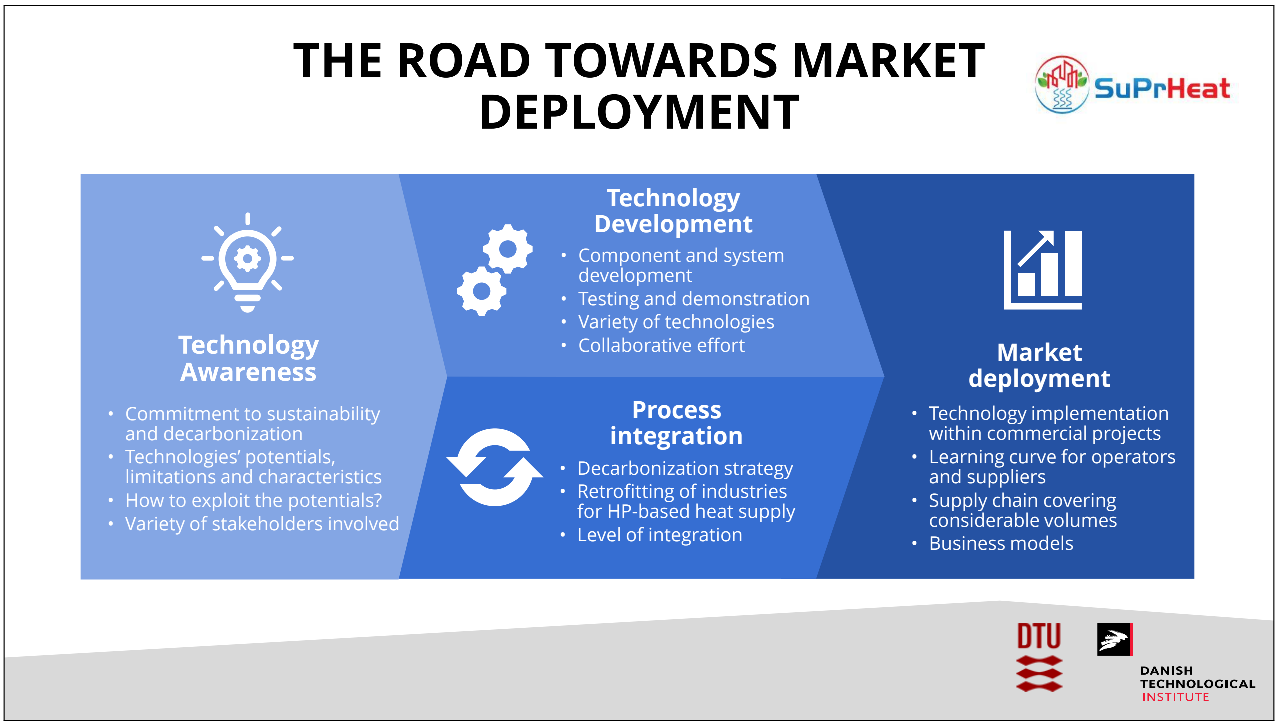
THE ROAD TOWARDS MARKET DEPLOYMENT
SuPrHeat
Technology Awareness
Commitment to sustainability and decarbonization
Technologies' potentials, limitations and characteristics
How to exploit the potentials?
Variety of stakeholders involved
Technology Development
Component and system development
Testing and demonstration
Variety of technologies
Collaborative effort
Process integration
Decarbonization strategy
Retrofitting of industries for HP-based heat supply
Level of integration
Market deployment
Technology implementation within commercial projects
Learning curve for operators and suppliers
Supply chain covering considerable volumes
Business models
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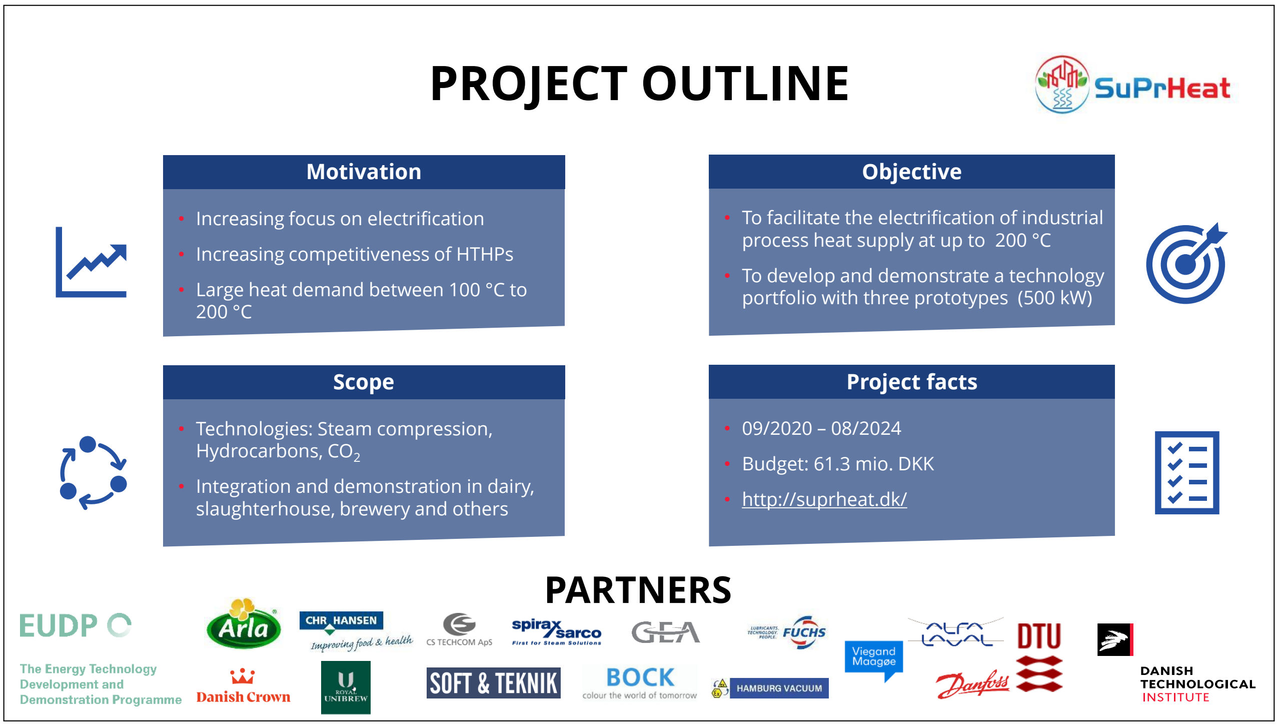
PROJECT OUTLINE
SuPrHeat
Motivation
Increasing focus on electrification
Increasing competitiveness of HTHPs
Large heat demand between 100 °C to 200 °C
Objective
To facilitate the electrification of industrial process heat supply at up to 200 °C
To develop and demonstrate a technology portfolio with three prototypes (500 kW)
Scope
Technologies: Steam compression, Hydrocarbons, CO_2
Integration and demonstration in dairy, slaughterhouse, brewery and others
Project facts
09/2020 – 08/2024
Budget: 61.3 mio. DKK
http://suprheat.dk/
PARTNERS
EUDP
The Energy Technology Development and Demonstration Programme
Arla
CHR HANSEN
Danish Crown
SOFT & TEKNIK
BOCK
GEA
FUCHS
HAMBURG VACUUM
Viegand Maagøe
Danfoss
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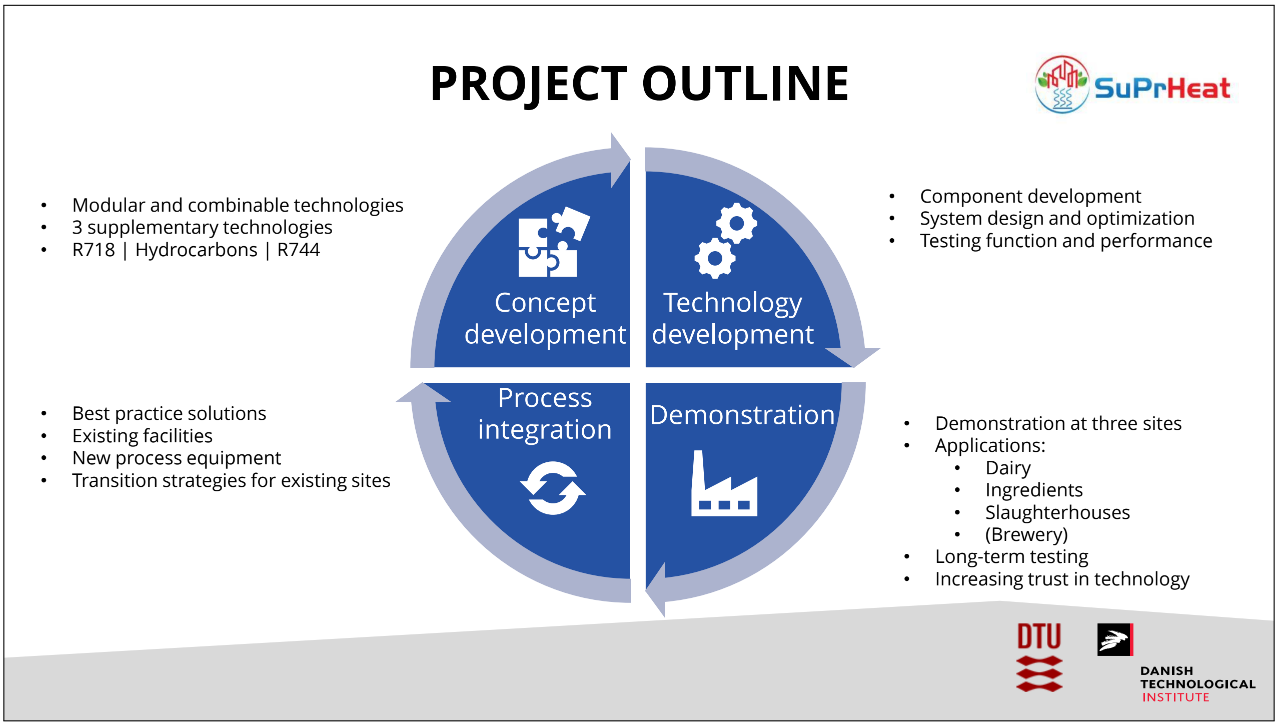
PROJECT OUTLINE
SuPrHeat
Modular and combinable technologies
3 supplementary technologies
R718 | Hydrocarbons | R744
Concept development
Technology development
Component development
System design and optimization
Testing function and performance
Best practice solutions
Existing facilities
New process equipment
Transition strategies for existing sites
Process integration
Demonstration
Demonstration at three sites
Applications:
Dairy
Ingredients
Slaughterhouses
(Brewery)
Long-term testing
Increasing trust in technology
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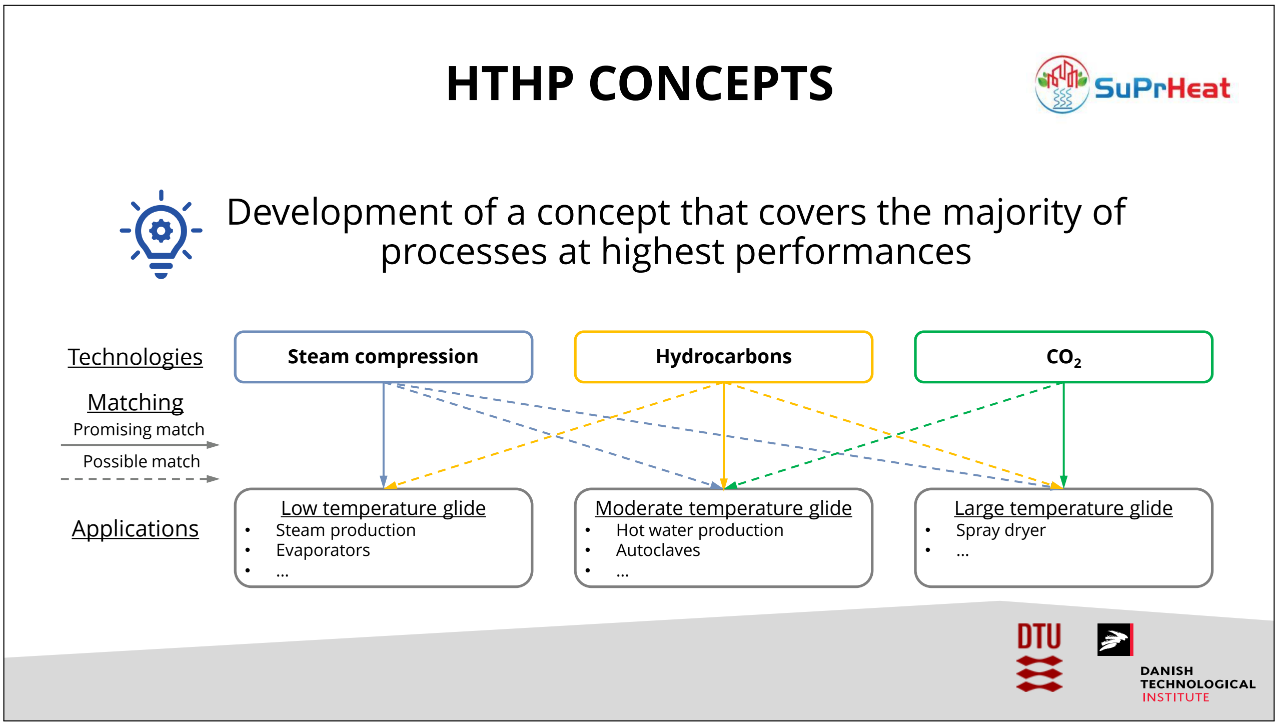
HTHP CONCEPTS
SuPrHeat
Development of a concept that covers the majority of processes at highest performances
Technologies
Steam compression
Hydrocarbons
CO_2
Matching
Promising match
Possible match
Applications
Low temperature glide
Steam production
Evaporators
...
Moderate temperature glide
Hot water production
Autoclaves
...
Large temperature glide
Spray dryer
...
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NATURAL REFRIGERANTS AS BASELINE

Natural refrigerants

- Availability at low cost
- Existing extensive knowledge
- Future-proof

Water/ammonia (R-717, R-718)

- High heat capacity
- Low throttling loss
- High discharge temperatures

Hydrocarbons (R-60...)

- Average compression work and heat capacity
- Low discharge temperatures
- Large throttling loss (can be mitigated)
- Require superheat

Carbon dioxide, CO_2 (R-744)

- Large temperature glides
- High pressures, compact components
- Low heat capacity
- Large throttling loss (can be mitigated)

Refrigerant	Ref. No.	Normal boiling point [°C]	Critical temperature [°C]	Safety class
Butane	R-600	-0.5	152.0	A3
Isopentane	R-601a	27.8	187.3	A3
CO_2	R-744	-	31.0	A1
Ammonia	R-717	-33.3	132.4	B2L
Water	R-718	100.0	373.9	A1

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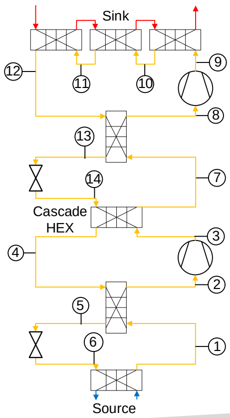
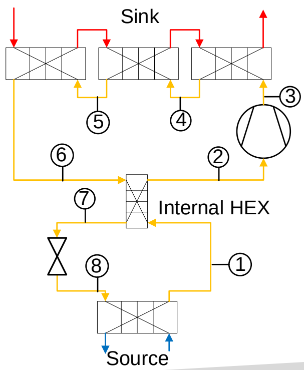
BUILDING A HEAT PUMP PORTFOLIO

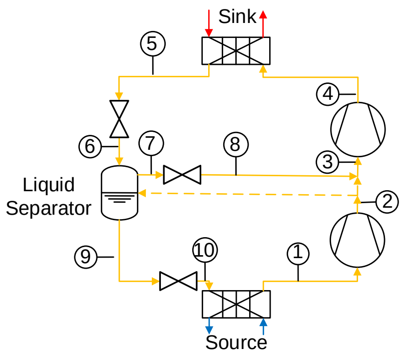
+ Combine refrigerants
+ Large lifts



+ Provide superheat
+ Lower throttling loss



+ Reduce discharge temperature
+ Lower compression losses



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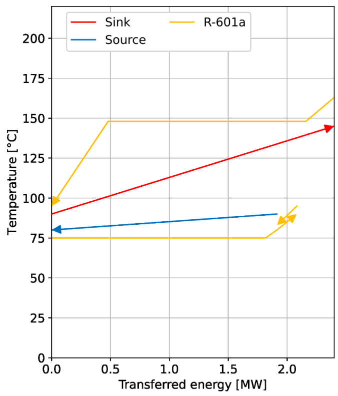
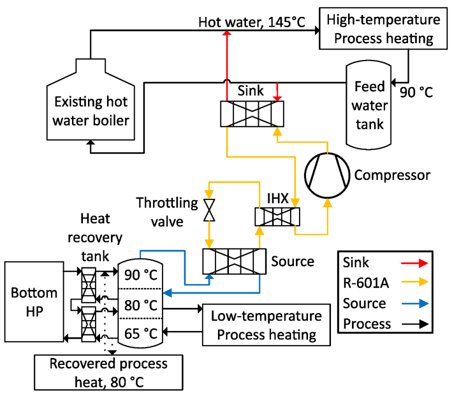
A BREWERY, PRODUCTION OF HOT WATER





Wort boiling with hot water system using R-601a from heat recovery tank

- A brewery uses 2.4 MW of hot water at 145 °C for wort boiling distributed several temporally offset batches in parallel. The remaining processes are covered by the heat recovery tank.
- Water returns from the high-temperature processes at 90 °C which is heated back up to 145 °C by the heat pump keeping the conventional gas boiler as a back-up.
- 90 °C hot water from the heat recovery tank supplies the heat pump and returns at 80 °C. The tank is supplied by a ammonia heat pump and recovered process heat.

Heating COP		4.93
Heating capacity		2.4 MW
Sink	Source	90 °C → 145 °C | 90 °C → 80 °C
Refrigerant		Isopentane, R-601a
Important remarks		COP of 2.49 w. bottom HP ATEX required

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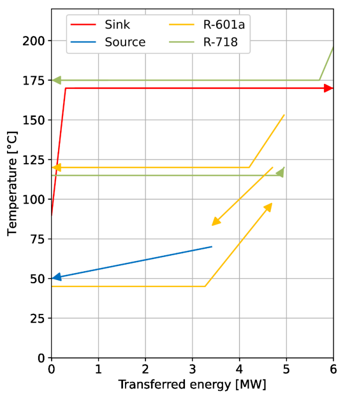
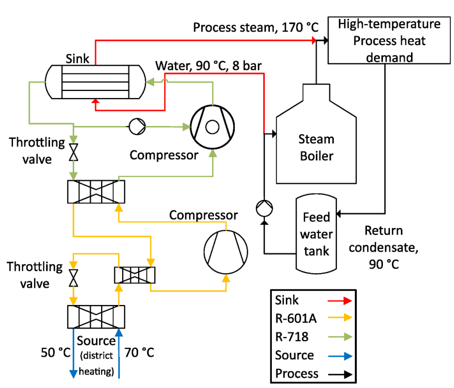
8 BAR STEAM FROM DISTRICT HEATING





Steam production at 8 bar at culture production facility

- The dairy culture production facility consumes 10.5 t/hr of 8 bar steam at maximum capacity covering all processes.
- The steam condensate returns from the process at 90 °C to the feed water tank. The water is pressurized before being evaporated in the heat pump sink exiting as saturated steam at 170 °C.
- The local 70 °C district heating network, which already supplies the facility with space heating, is used as the heat source of the heat pump returning at 50 °C.

Heating COP		2.31
Heating capacity		6 MW
Sink	Source	90 °C → 170 °C | 70 °C → 50 °C
Refrigerant		Isopentane and water
Important remarks		ATEX required, Cascade heat pump

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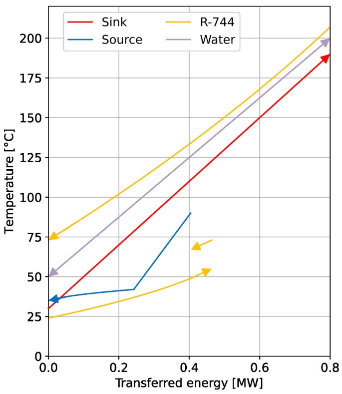
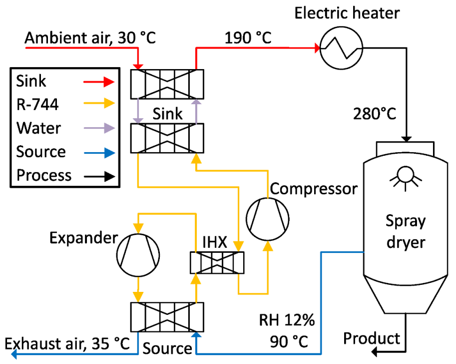
SPRAY DRYER ELECTRIFICATION





Drying of fish food at 280 °C in spray dryers using R-744 brayton heat pump

- A protein rich substance is dried in several parallel spray dryers using 15,000 kg/hr of dry air heated to 280 °C.
- Ambient air is heated from 30 °C to 190 °C in a heat exchanger connected to the heat pump by a secondary water loop before an electric heater raises the temperature to 280 °C w. a total COP of 1.77.
- The exhaust air comes out at 90 °C at 12 % relative humidity which is used as the source of the heat pump.

Heating COP	2.02	
Heating capacity	0.8 MW	
Sink / Source	30 °C → 190 °C	90 °C → 35 °C
Refrigerant	Carbon dioxide, R-744	
Important remarks	High pressures 150 bar Compact cycle	

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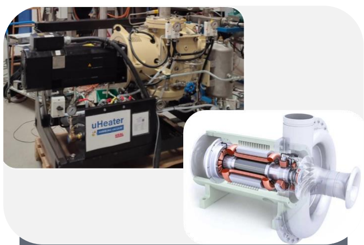
HTHP TECHNOLOGIES

SuPrHeat



Steam compression system

- Spindle compressor: High pressure ratio and T_{Lift}
- 2-stage turbo compressor: high flows and T_{lift} up to 50 K
- Full-scale test: 2023
- On-site demo: 2024

Hydrocarbon system

- Butane (R600) → 120 °C
- Isopentane (R601a) → 160 °C
- Bock piston compressors
- Full-scale test: 04/2023
- On-site demo: 2024

CO_2 system

- CO_2 (R744) → 180 °C
- Bock piston compressors
- Single-stage with ejectors
- Full-scale test: 2023
- On-site demo: 2024

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NEXT STEP: TESTING THE HYDROCARBON SYSTEM

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CONCLUSION

- Large potential in various industrial processes, existing plants and novel process equipment.
- The boundary conditions vary considerably → different heat pump technologies required
- R-744, R-718, and hydrocarbons, are able to deliver steam, hot water, or air between 100 °C and 200 °C at competitive performances
- Natural refrigerants exhibit different properties making them suitable for a concise, future-proof technology portfolio.
- Demonstration of three 500 kW pilot plants in next two years

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Development of a hybrid heat pump integrating renewable energy

Thor Mikkelsen & Christian Bahl

DANISH TECHNOLOGICAL INSTITUTE

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Agenda

- **Introduction to RES4BUILD**
- **Danish pilot system**
- **Magnetocaloric heat pump**
- **Evaluation process of the pilot system**
- **Greek pilot system**

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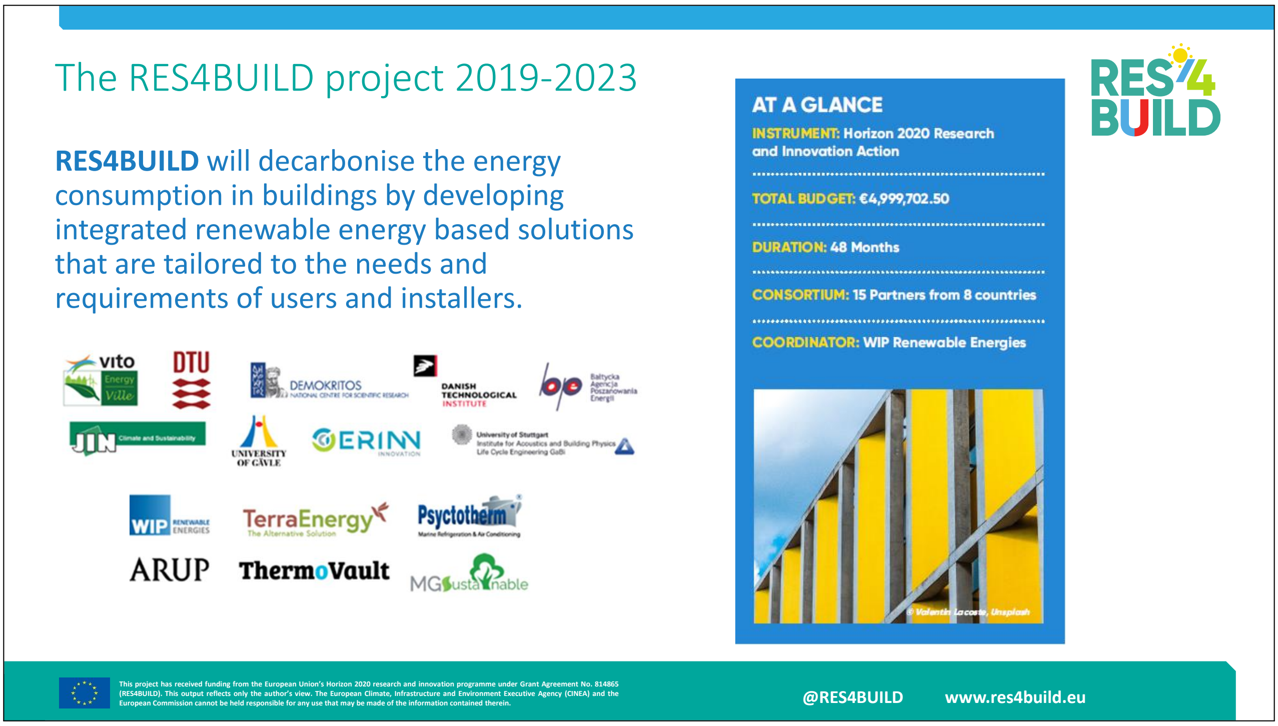

The RES4BUILD project 2019-2023
RES4BUILD will decarbonise the energy consumption in buildings by developing integrated renewable energy based solutions that are tailored to the needs and requirements of users and installers.
AT A GLANCE
INSTRUMENT: Horizon 2020 Research and Innovation Action
TOTAL BUDGET: €4,999,702.50
DURATION: 48 Months
CONSORTIUM: 15 Partners from 8 countries
COORDINATOR: WIP Renewable Energies
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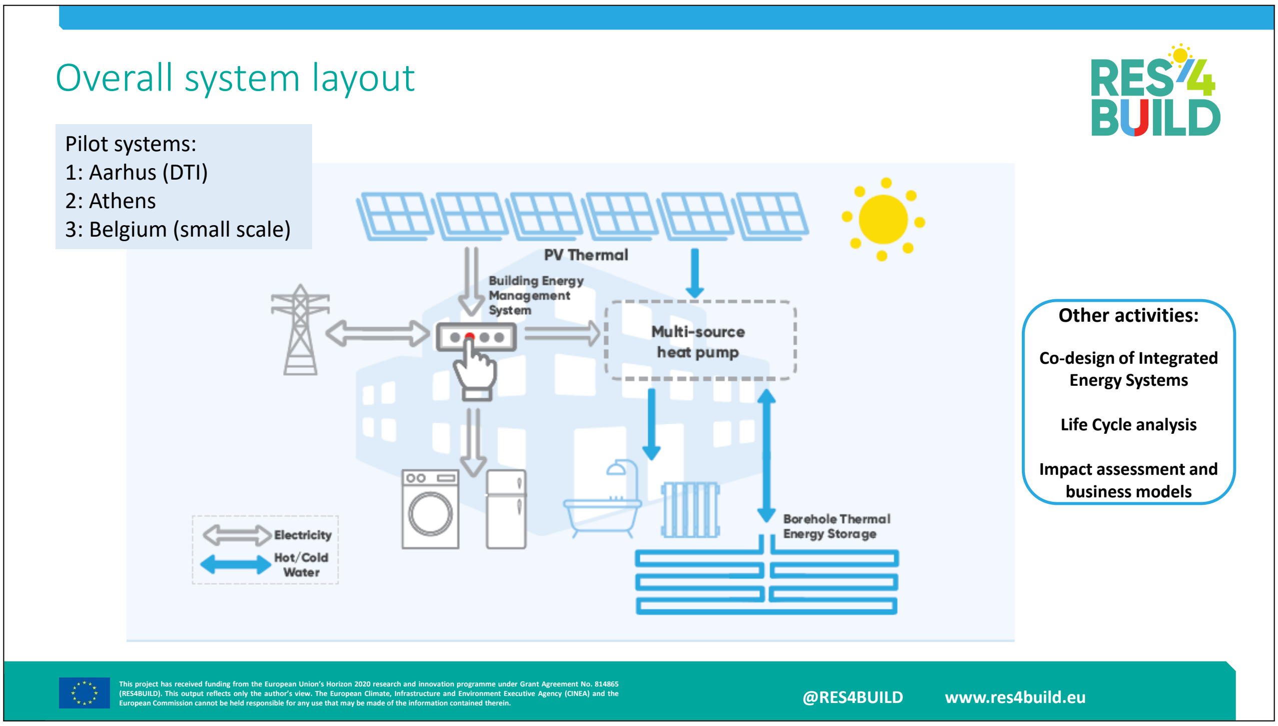

Overall system layout
Pilot systems:
1: Aarhus (DTI)
2: Athens
3: Belgium (small scale)
PV Thermal
Building Energy Management System
Multi-source heat pump
Borehole Thermal Energy Storage
Electricity
Hot/Cold Water
Other activities:
Co-design of Integrated Energy Systems
Life Cycle analysis
Impact assessment and business models
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Danish Partners

Danish Technological Institute

- Testing vapor compression heat pump
- Assembling and testing a full pilot system

Technical University of Denmark

- Developing novel magnetocaloric technology and components
- Testing magnetocaloric heat pump

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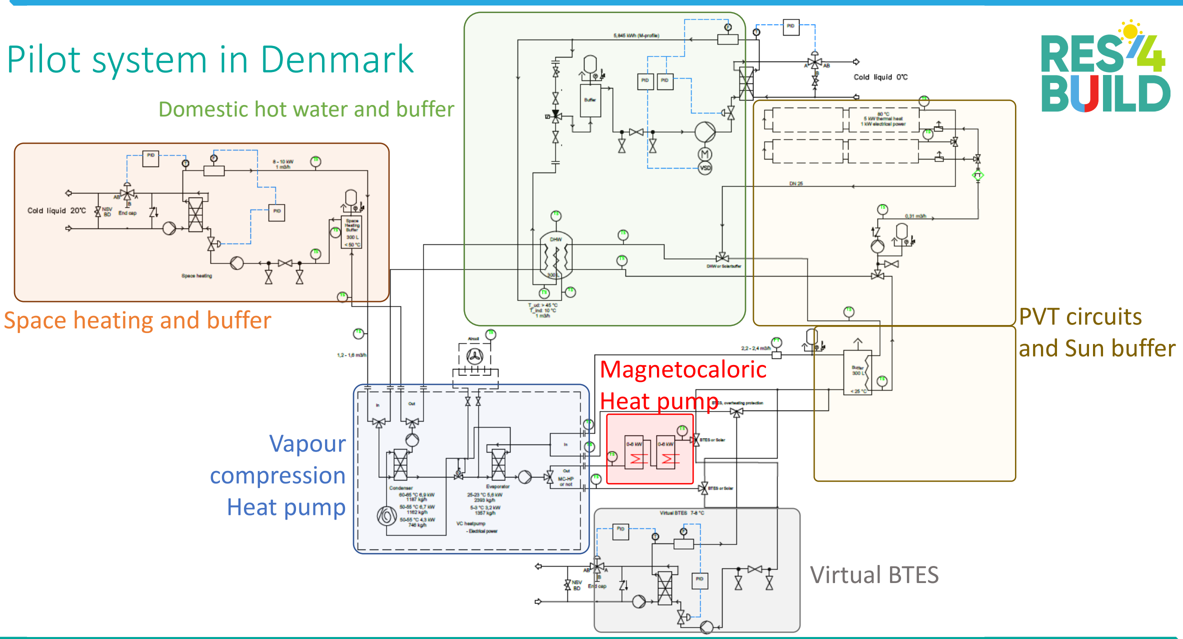
Pilot system in Denmark



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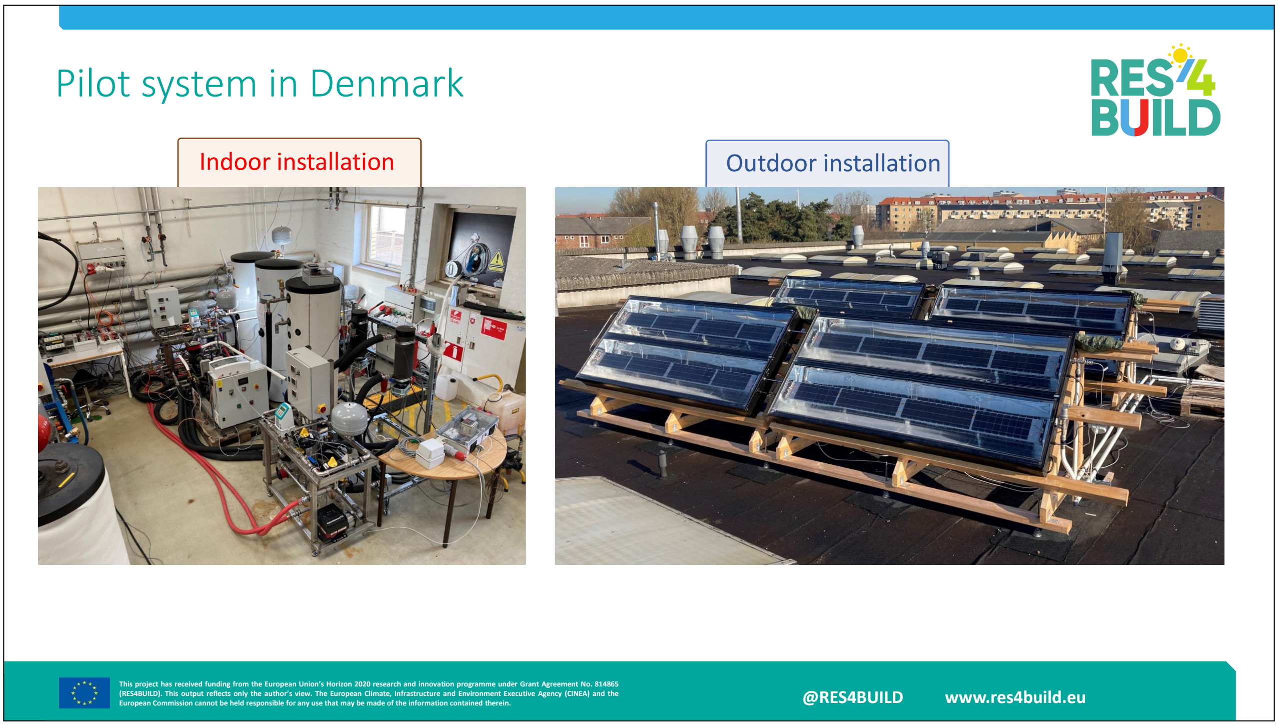
Pilot system in Denmark
RES4BUILD
Indoor installation
Outdoor installation
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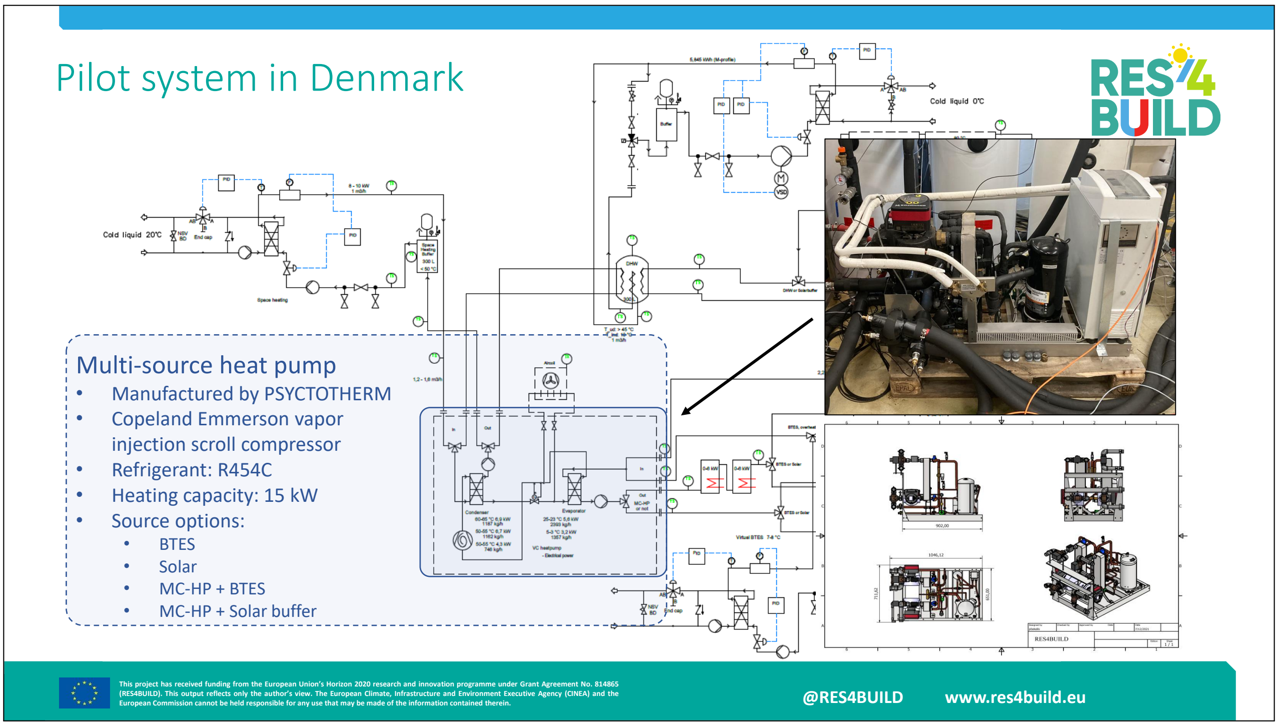
Pilot system in Denmark
RES4BUILD
Cold liquid 20°C
Cold liquid 0°C
Multi-source heat pump
• Manufactured by PSYCTOTHERM
• Copeland Emmerson vapor injection scroll compressor
• Refrigerant: R454C
• Heating capacity: 15 kW
• Source options:
• BTES
• Solar
• MC-HP + BTES
• MC-HP + Solar buffer
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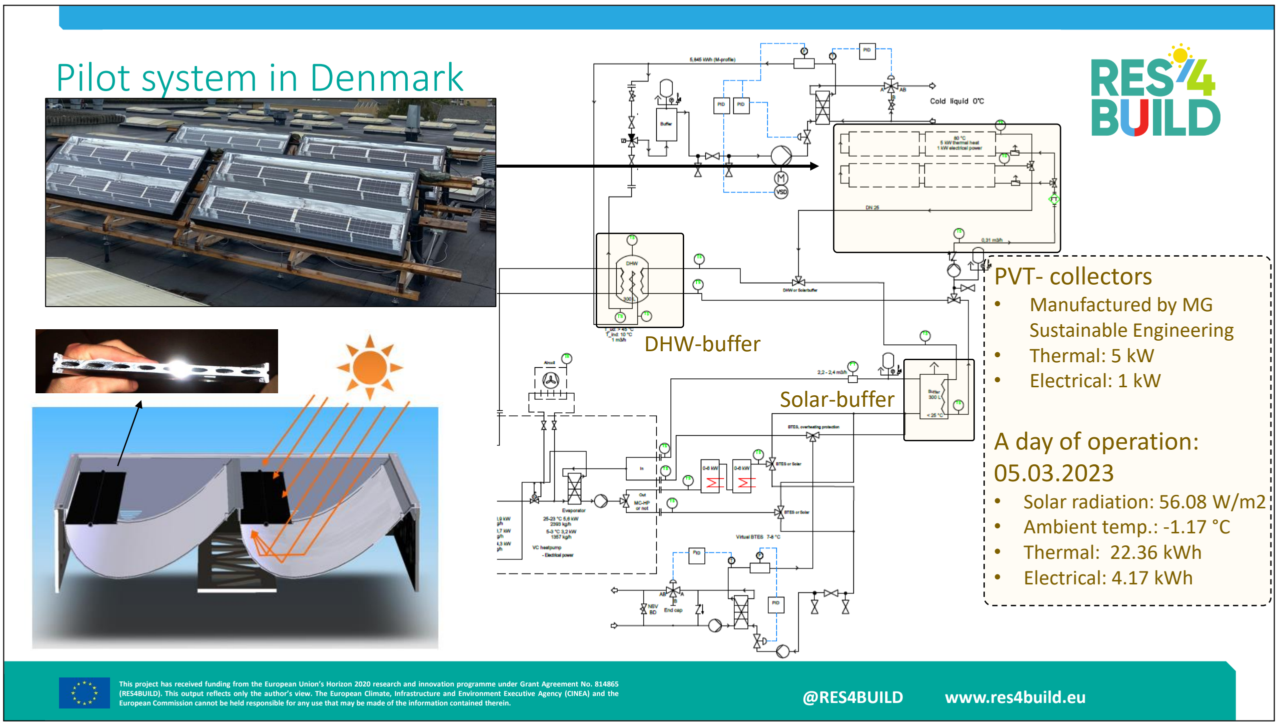
Pilot system in Denmark
RES4BUILD
DHW-buffer
Solar-buffer
Cold liquid 0°C
PVT- collectors
• Manufactured by MG Sustainable Engineering
• Thermal: 5 kW
• Electrical: 1 kW
A day of operation: 05.03.2023
• Solar radiation: 56.08 W/m2
• Ambient temp.: -1.17 °C
• Thermal: 22.36 kWh
• Electrical: 4.17 kWh
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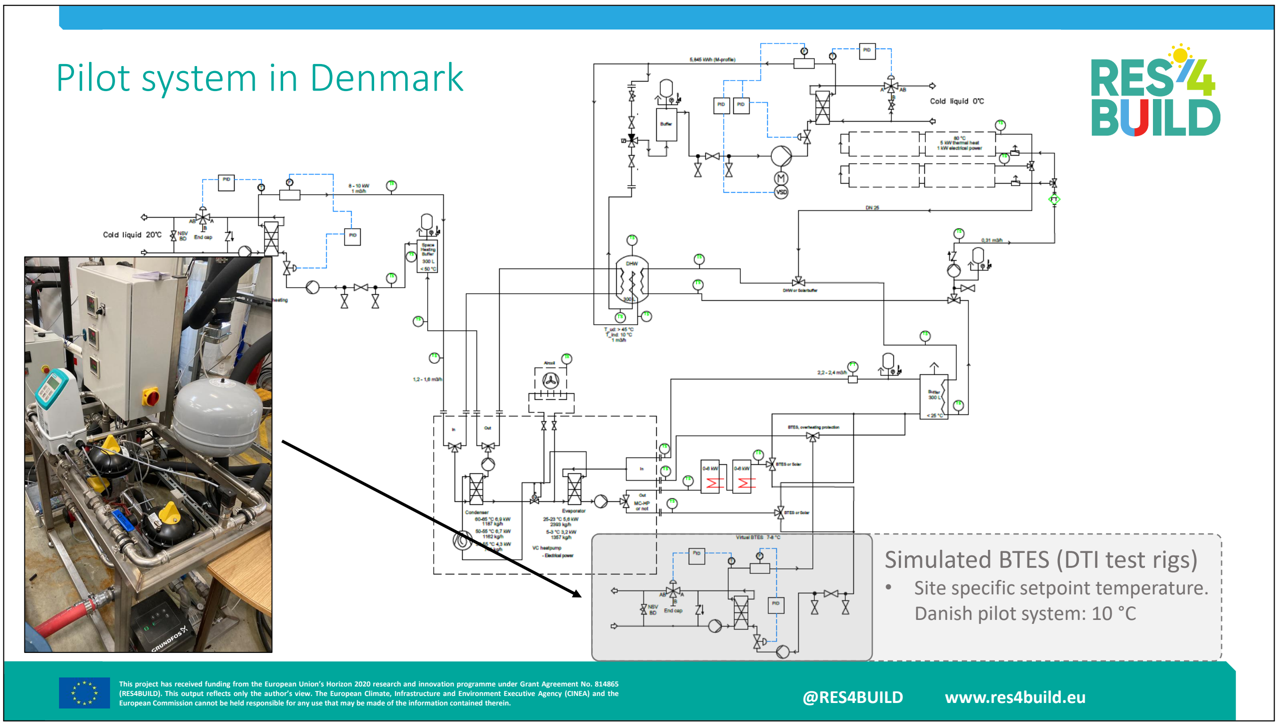
Pilot system in Denmark
RES4BUILD
Cold liquid 0°C
Cold liquid 20°C
Simulated BTES (DTI test rigs)
• Site specific setpoint temperature. Danish pilot system: 10 °C
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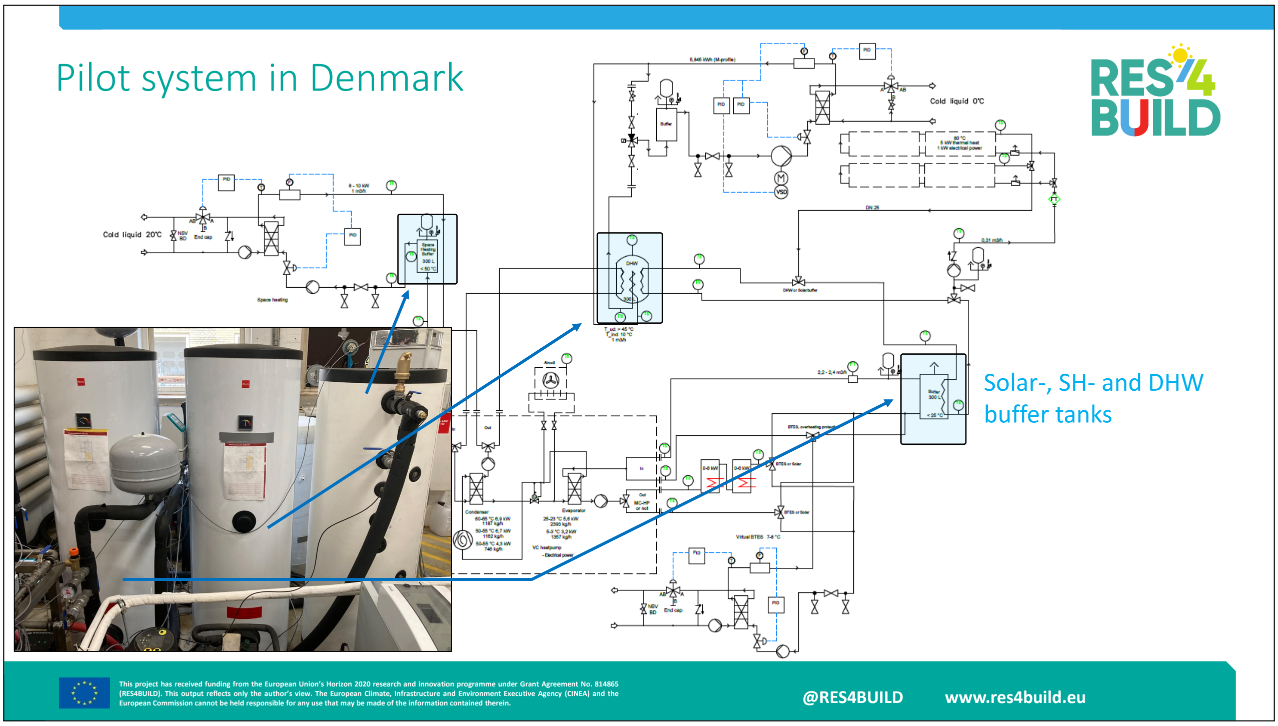
Pilot system in Denmark
RES4BUILD
Cold liquid 20°C
Cold liquid 0°C
Solar-, SH- and DHW buffer tanks
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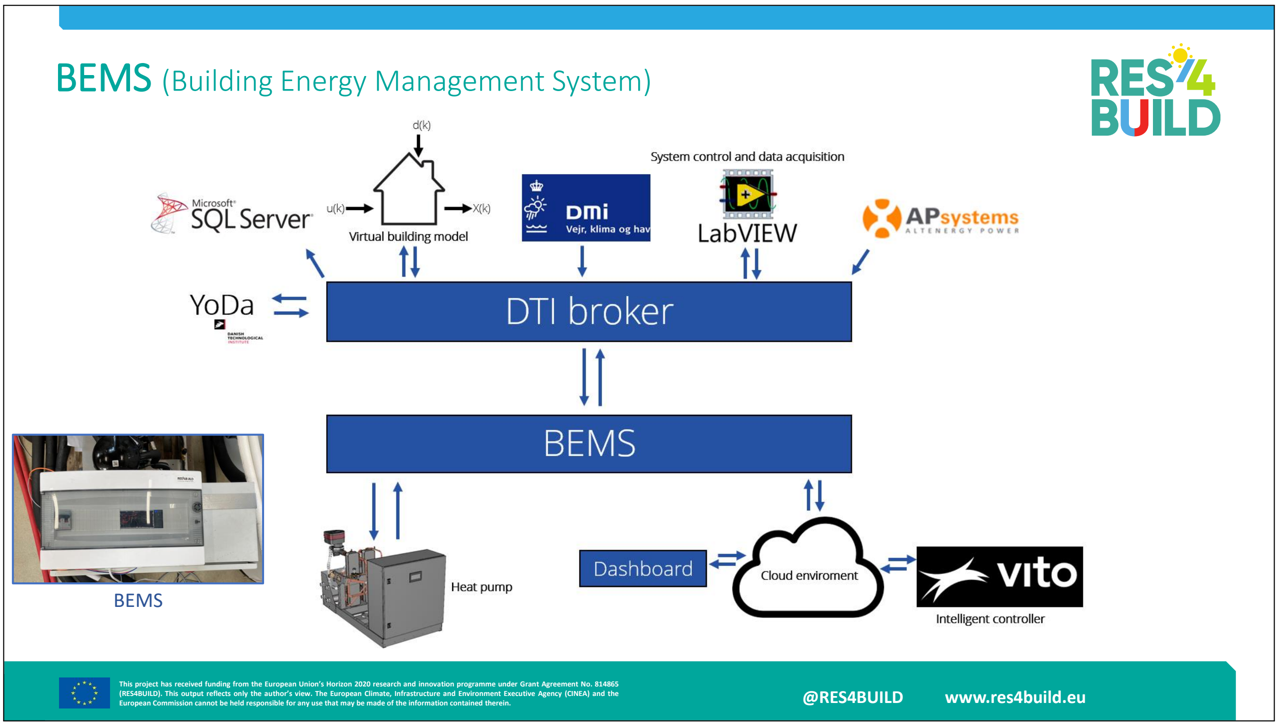
BEMS (Building Energy Management System)
RES4BUILD
d(k)
u(k)
X(k)
Microsoft SQL Server
Virtual building model
DMI Vejr, klima og hav
System control and data acquisition
LabVIEW
APsystems
YoDa
DTI broker
BEMS
BEMS
Heat pump
Dashboard
Cloud enviroment
vito
Intelligent controller
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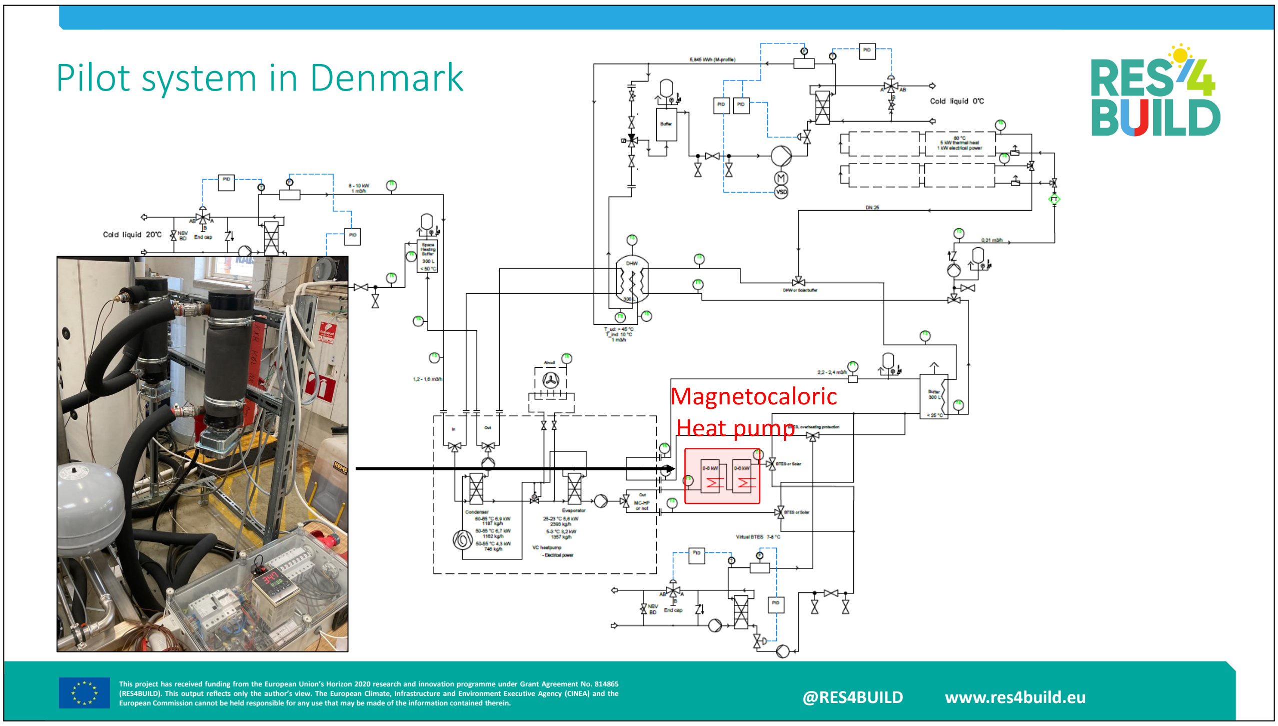
Pilot system in Denmark
RES4BUILD
Cold liquid 20°C
Cold liquid 0°C
Magnetocaloric
Heat pump
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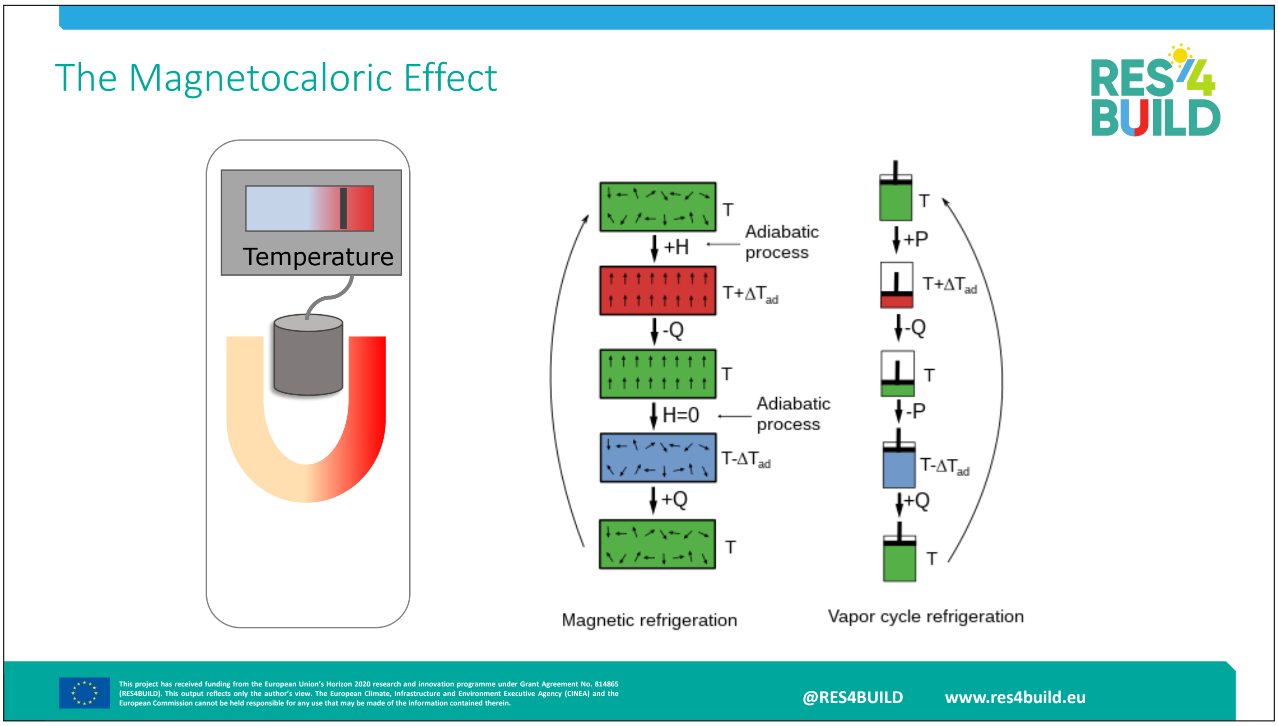
The Magnetocaloric Effect
RES4BUILD
Temperature
T
+H
Adiabatic process
T+ΔTad
-Q
T
H=0
Adiabatic process
T-ΔTad
+Q
T
T
+P
T+ΔTad
-Q
T
-P
T-ΔTad
+Q
T
Magnetic refrigeration
Vapor cycle refrigeration
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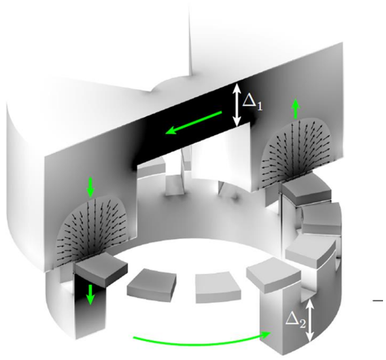
The magnet

RES4BUILD

- Material: NdFeB (N50 and N50M)
- Max. magnetic field: 1.6 T
- Total NdFeB mass: 80 kg



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Magnetocaloric materials

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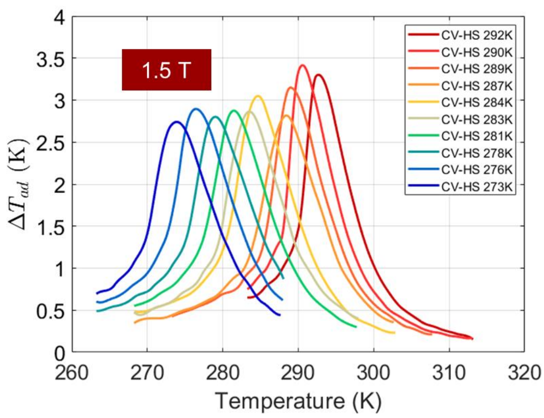
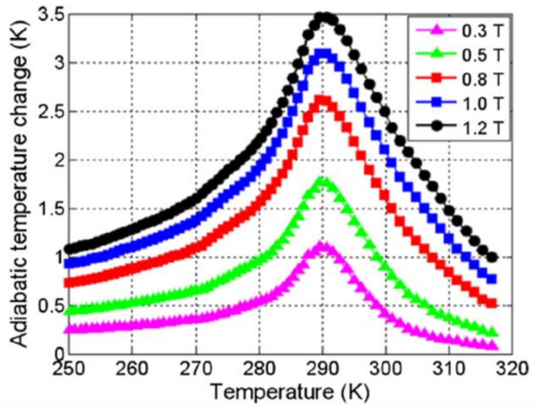


LaFeSiMnH



Gadolinium

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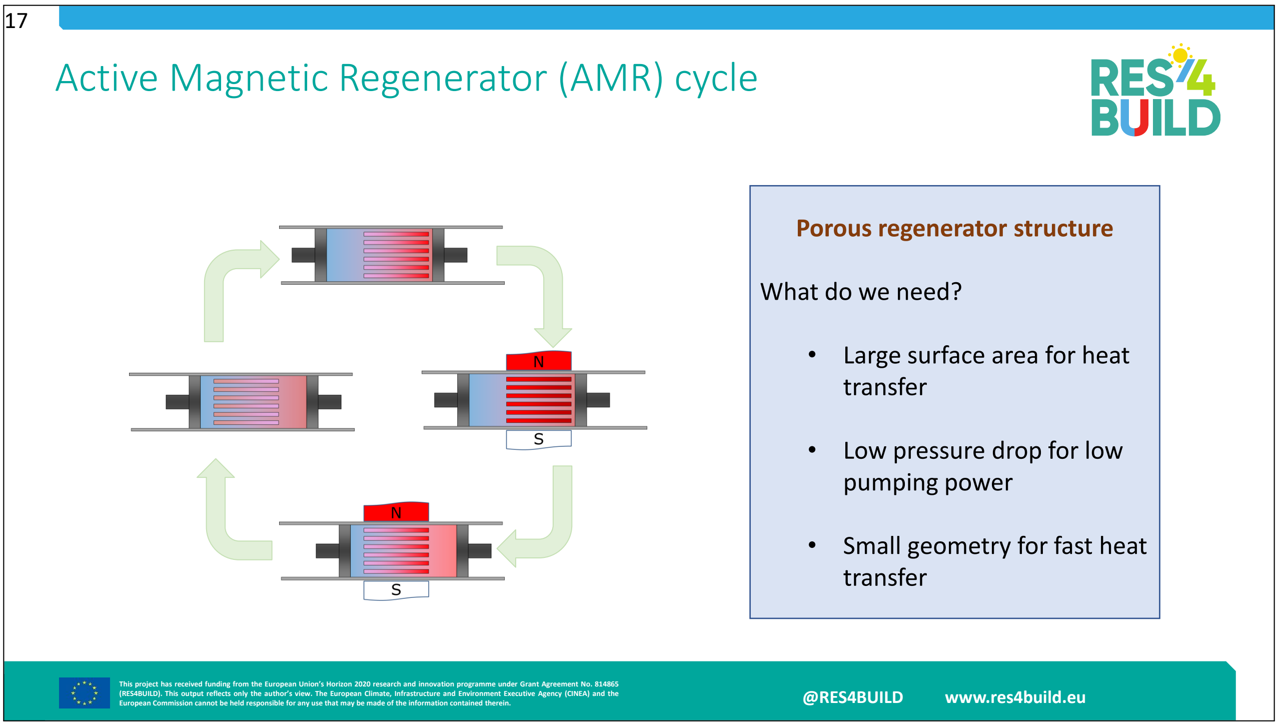
17
Active Magnetic Regenerator (AMR) cycle
RES4BUILD
N
S
N
S
Porous regenerator structure
What do we need?
• Large surface area for heat transfer
• Low pressure drop for low pumping power
• Small geometry for fast heat transfer
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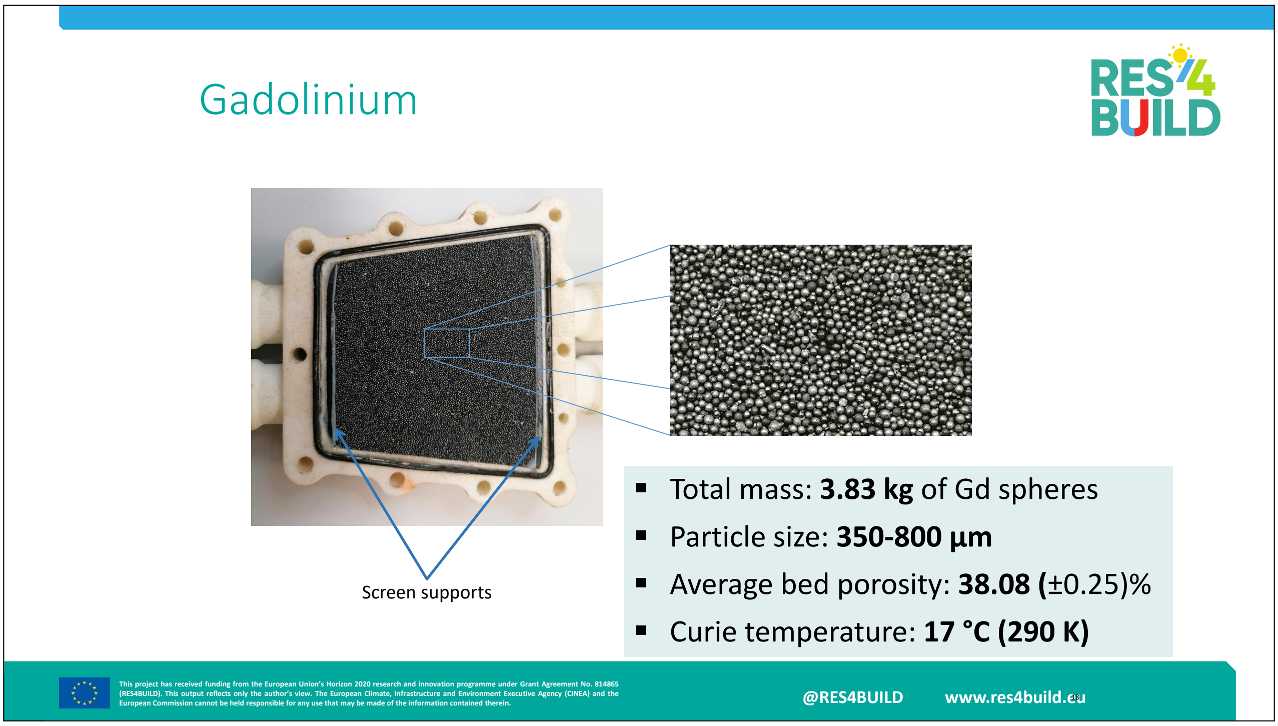
Gadolinium
RES4BUILD
Screen supports
▪ Total mass: 3.83 kg of Gd spheres
▪ Particle size: 350-800 µm
▪ Average bed porosity: 38.08 (±0.25)%
▪ Curie temperature: 17 °C (290 K)
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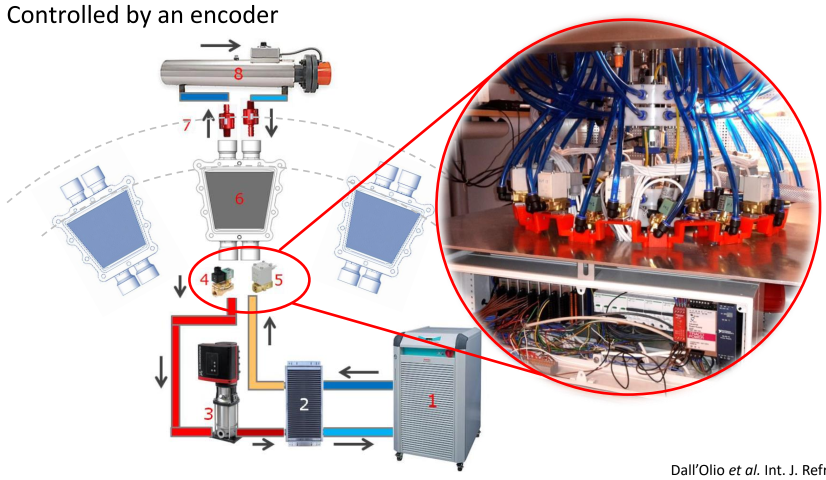
Flow system

- 26 electrically operated solenoid valves controlling the flow
- Controlled by an encoder



Dall'Olio *et al.* Int. J. Refrigeration 132 (2021) 243

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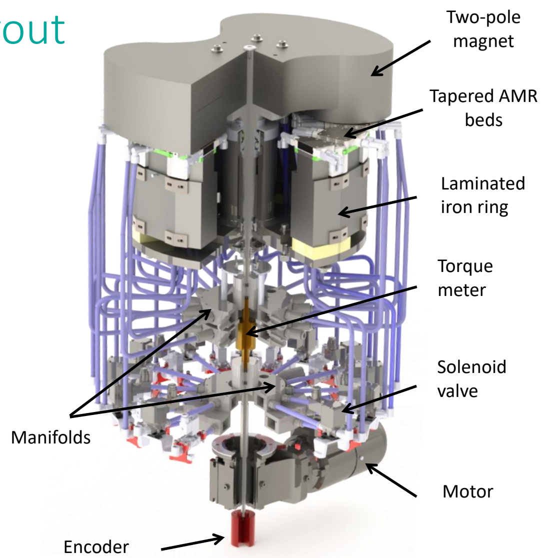
System layout



Dall'Olio *et al.* Int. J. Refrigeration 132 (2021) 243

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The Magnetocaloric heat pump in action

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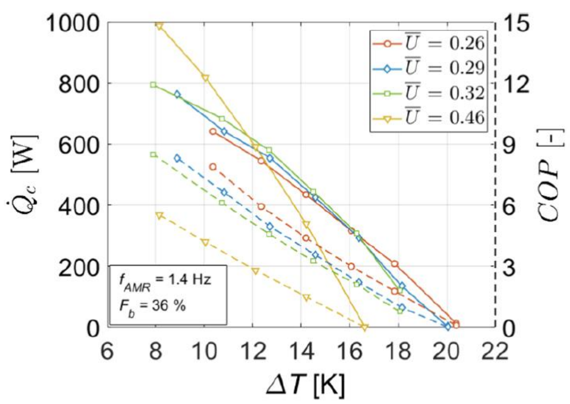
Heating Performance at different utilizations

Operating conditions

- T_{hot} = 301 K
- f_{AMR} = 1.4 Hz

$$COP_c = \frac{\dot{Q}_c}{\dot{W}_{mag} + \dot{W}_{pump}}$$



- Higher cooling powers can be obtained at higher utilization and lower spans
- 10.1 K span with 818 W cooling power and cooling COP of 4.2 (14.5% of ideal)

Masche *et al.* Appl. Therm. Engineer. 204 (2022) 1177947

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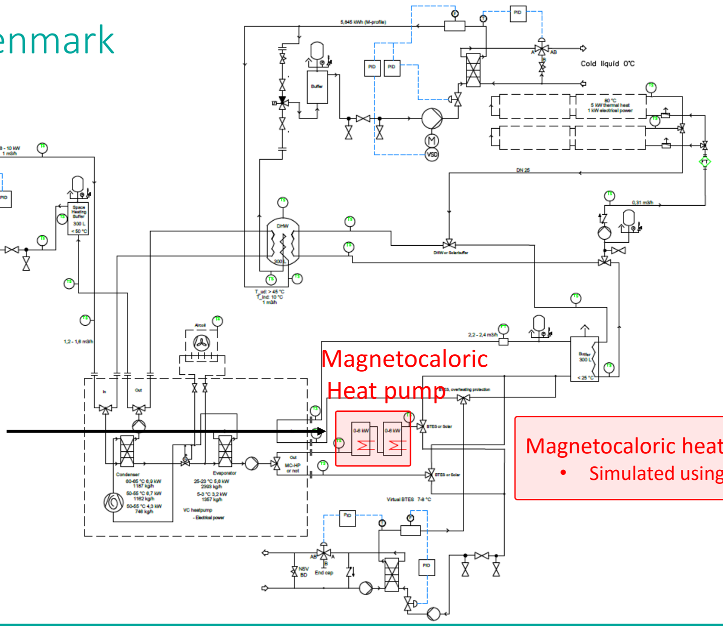
Pilot system in Denmark



Magnetocaloric heat pump
- Simulated using 2 x 6 kW heaters

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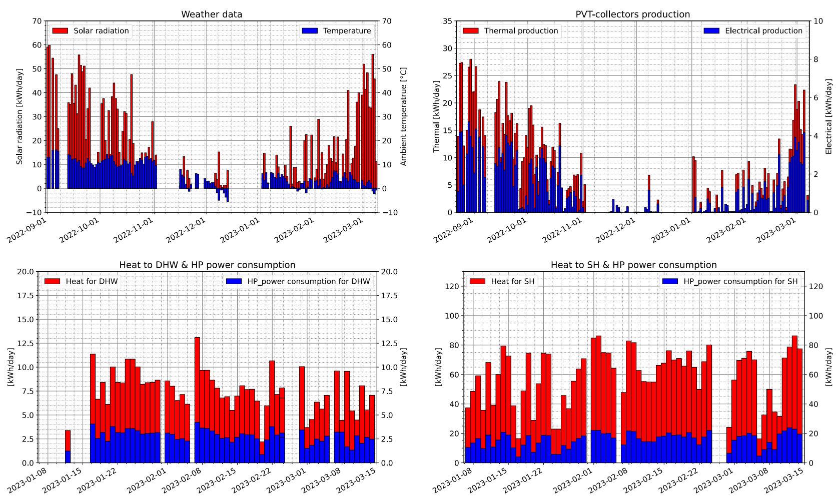
Evaluation of overall system



- Concept validation of the RES4BUILD system based on results for a whole year covering all seasons.
- 110 measurements collected across the different platforms.
- Process available test results and use them in regression analysis.
- Calculate the annual net electricity and the renewable energy share.
- Collecting data since start of August 2022 up and until now.

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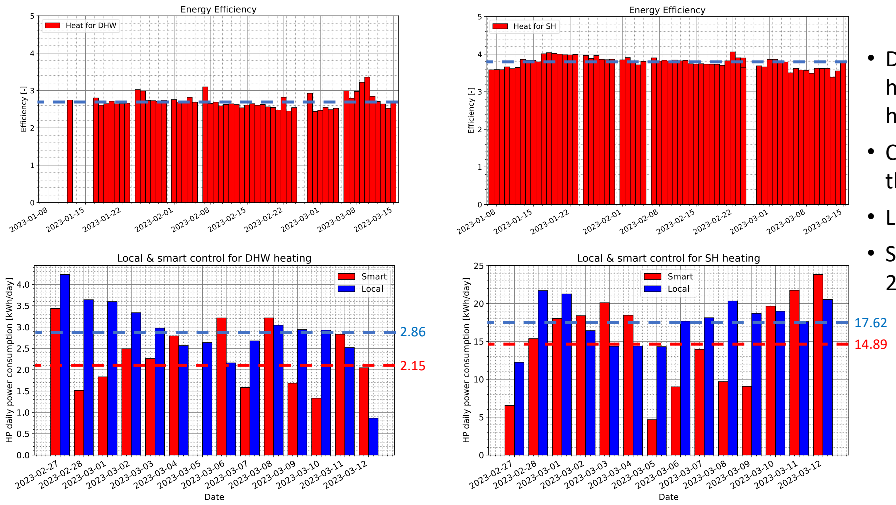
Evaluation of overall system

RES4BUILD



- Daily energy efficiency for domestic hot water: 2.70 and for space heating: 3.77
- Comparing the local control with the intelligent smart controller
- Local: 06 to 19 February 2023
- Smart: 27 February to 12 March 2023

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Pilot system in Greece

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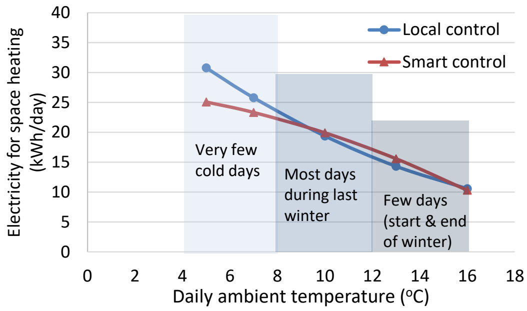
Results – winter period (local and smart control)



- During cold days, the smart control manages better the energy flows and reduces the electricity consumption.
- Daily ambient temperature was around 10 °C during most days of 2022/2023 winter, with the two control modes showing similar results.
- During warmer winter days, the smart control shows slightly higher consumption mostly due to the larger number of start-stops.

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Questions/comments?
Visit the website for more information: www.res4build.eu
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DIGITAL TWINS FOR LARGE-SCALE HEAT PUMPS AND REFRIGERATION SYSTEMS

8TH INTERNATIONAL SYMPOSIUM ON ADVANCES IN REFRIGERATION AND HEAT PUMP TECHNOLOGY

2023-03-23

JONAS LUNDSTED POULSEN, DANISH TECHNOLOGICAL INSTITUTE
JOSÉ JOAQUÍN AGUILERA PRADO, DTU CONSTRUCT

DTU

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AGENDA

- Overview of project
- Demonstration case - digital twin for heat pump system for district heating operating with seawater and ammonia
  - Modelling of system
  - Graphical-user interface for digital twin
  - Example of digital twin based service: Optimization
- Adaptive model-based monitoring for a large-scale heat pump

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DIGITAL TWINS FOR LARGE-SCALE HEAT PUMP AND REFRIGERATION SYSTEMS

Motivation
Enhanced services through digital twins
Monitoring | Fault detection/diagnosis | Optimized operation

Objectives
Reducing the effort for creating digital twins
Improved services and better exploitation of potentials

Approach
Developing reusable, modular and self-learning models
Developing advanced methods for system analysis

Project facts
02/2020 – 01/2024 | EUDP Project
Budget: 18.6 mio. DKK | 8 Partners

DANISH TECHNOLOGICAL INSTITUTE
DTU
Technische Universität Braunschweig
Danfoss
Kredsløb
TLK-Thermo GmbH
AKCENTRALEN
Super køl

www.digitaltwins4hprs.dk

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DIGITAL TWIN CONCEPT

Advanced system monitoring

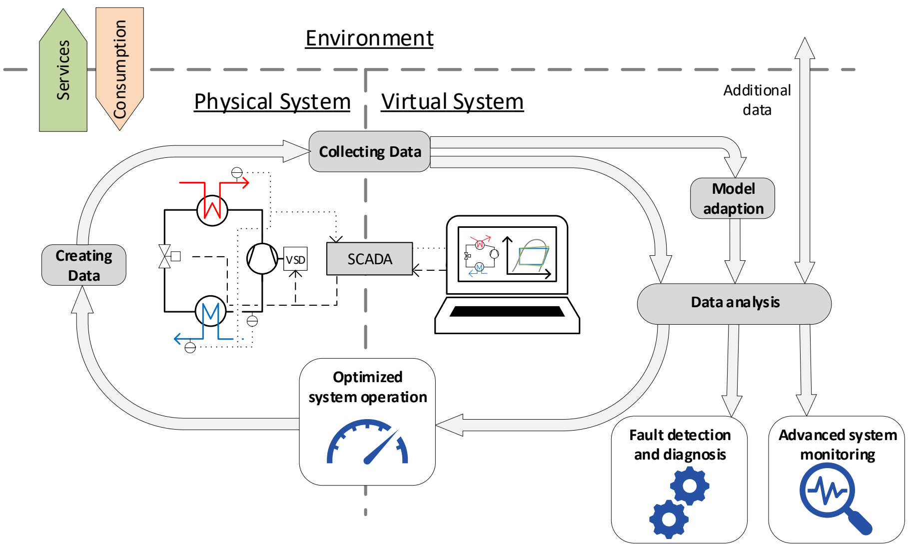
- Performance benchmarking
- Analysis of functionality and performance
- Validity check
- Soft sensors

Fault detection and diagnosis

- Fault mechanism monitoring incl. early-stage warning and predictive maintenance
- Model-based interpretation of system alerts

Optimized system operation

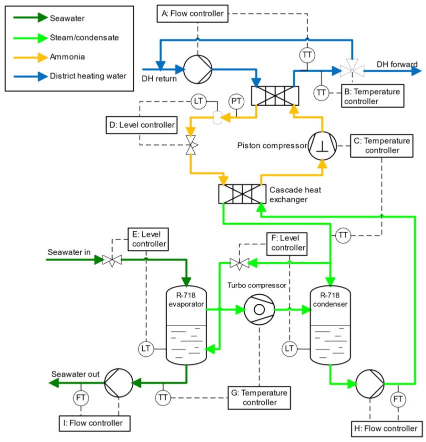
- Continuous set-point tuning
- Scheduling of production and downtime



DEMO. CASE - HEAT PUMP FOR DISTRICT HEATING OPERATING WITH SEAWATER AND AMMONIA

- Capacity ~1 MW
- Heat source: Seawater
- Bottom cycle: R-718 with turbocompressor
- Top cycle: R-717 with piston compressor
- Installation: 2020 by Johnson Controls
- Operator: Kredsløb
- Data sharing: 120 operating parameters continuously sent to secure SQL database

Top cycle: HeatPac 108S-V.



Heat pump system located in Maskinrummet, Århus Ø, Denmark [Kollision, 2020].

Bottom cycle: Steam compression with axial multi-stage compressor.

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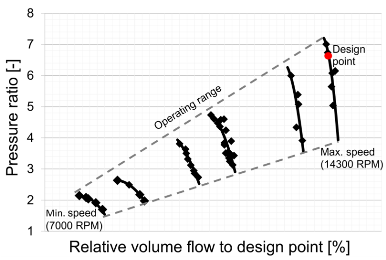
MODELLING

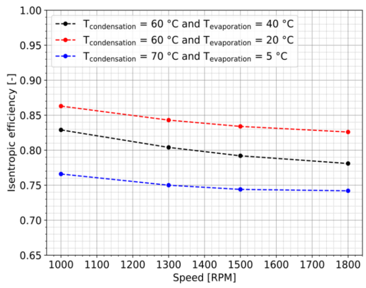
Turbocompressor:
- Data maps of key variables made based on previous experimental results.
- Map generation made with TLK software "DataMap Creator".

Piston compressor:
- Linear regression models used to create polynomia fit for η_{is} and η_{vol}, based on varying conditions in design software.

Heat exchangers:
- Modelled as discritized corrugated plate heat exchangers
- Parametrization of correction factors for the overall UA values to match operating data.



Dependency of PR and flow for turbo comp.

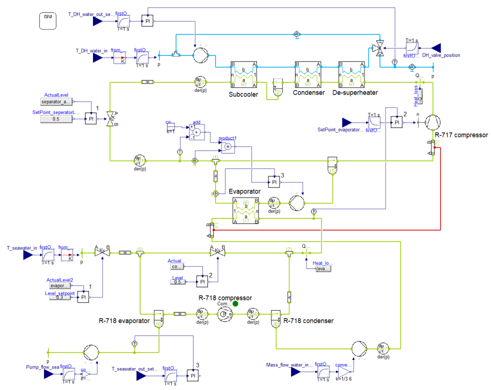


Isentropic efficiency for piston comp.

Dymola

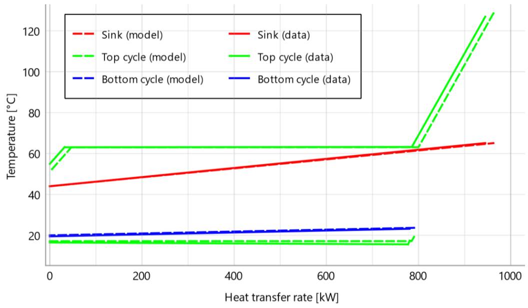
Modelica

TIL Suite

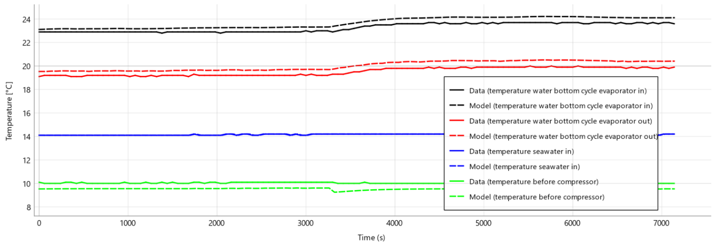


Graphical interface for dynamic system model.

VALIDATION OF MODEL

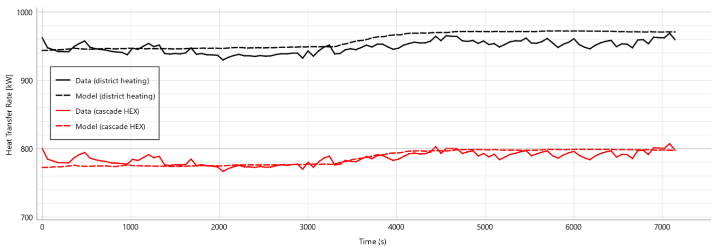


TQ diagram (at t = 3600 s).



Temperatures over time in bottom cycle.

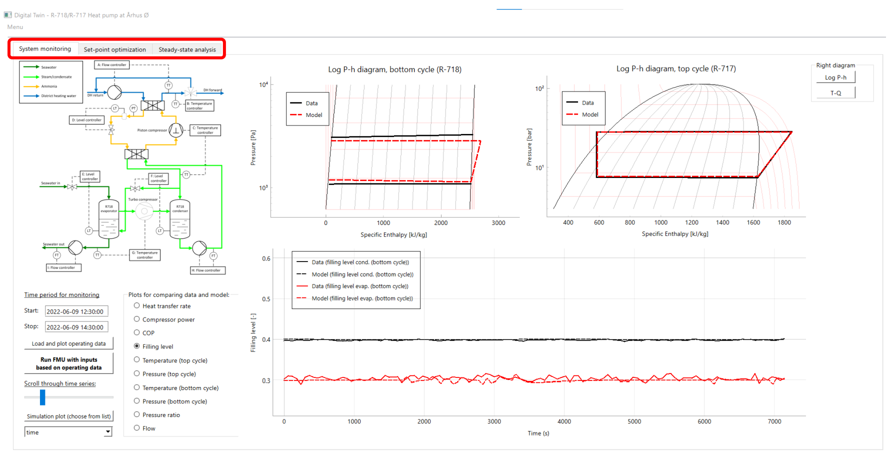
- 150 RPM increase of turbo-compressor speed at t = 3200 s.
- Acceptable small offsets, and dynamic effects represented by model.



Heat transfer rates over time for top cycle.

GUI FOR DIGITAL TWIN TO OPERATOR

- Program interface made with Qt designer
- Python scripts for operating data pre/post-processing, linking user interface with operating data, and simulating model (FMU).
- Comparison of operating data and simulation data, including predefined plots, log(P)-h diagrams, and T-Q diagrams.
- Fans with services:
  - Monitoring
  - Optimization
  - Steady state analysis



Graphical user interface (GUI) for Digital Twin.

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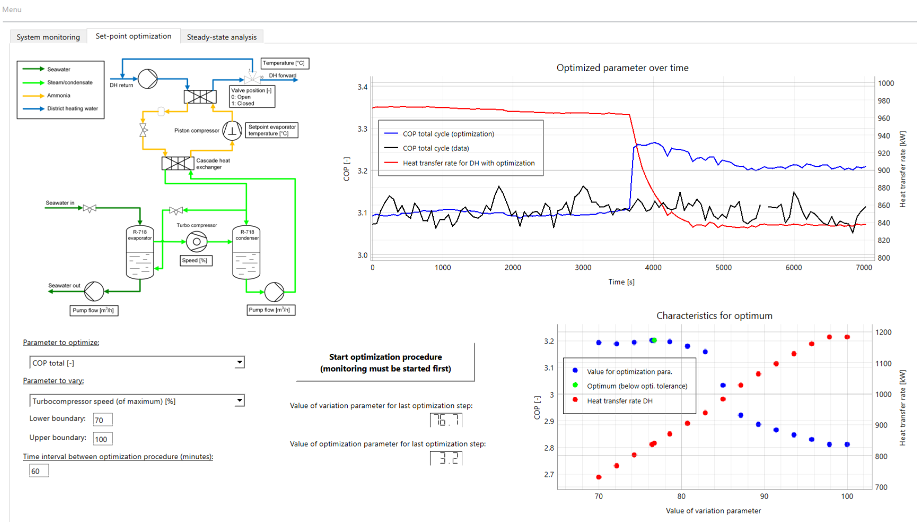
EXAMPLE OF DIGITAL TWIN BASED SERVICE: OPTIMIZATION

- Optimization framework for continuous set-point optimization of e.g. the compressor speeds for optimizing COP.
- Parameter to optimize and vary in drop-down lists.
- Time interval for new set-point can be chosen.
- Algorithm uses an optimization function from the SciPy package in Python to find an optimum in the given bounded interval.



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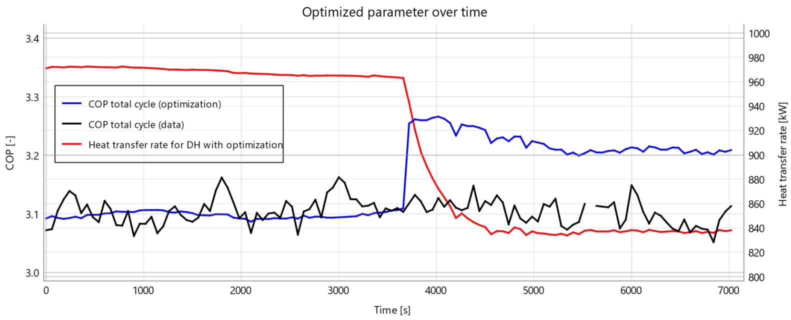
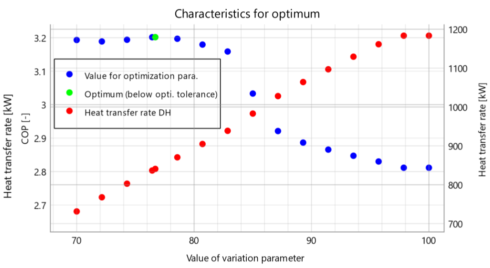
EXAMPLE OF DIGITAL TWIN BASED SERVICE: OPTIMIZATION

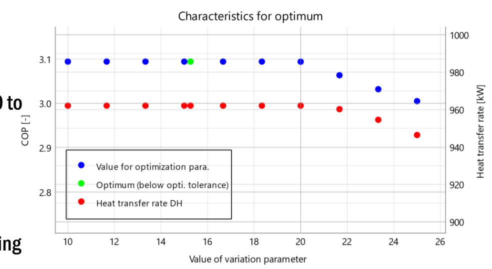


Optimization of turbo. speed over time.



Characteristics of optimization (turbo. speed).

- Setpoint for turbo comp. speed initial 84 %.
- Optimization after 1 hour suggests 76 % for comp. speed increasing the model COP from 3.10 to 3.25.
- Heat transfer rate change predicted to drop from 960 kW to 840 kW.
- Example 2: Optimizing the top cycle piston comp. suggets max. RPM.
- Framework can be used to find best compromize between COP and heat transfer rate depending on the prices for power and district heating.



Characteristics of optimization of process out temperature for top cycle (compressor RPM).

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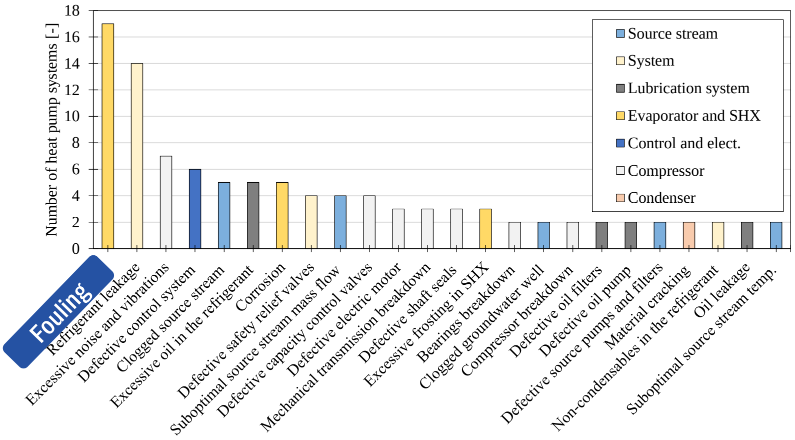
ADAPTIVE MODEL-BASED MONITORING FOR A LARGE-SCALE HEAT PUMP PRONE TO FOULING

BACKGROUND: FAULTS IN LARGE-SCALE HEAT PUMPS

- Common faults found in the literature



Source: Aguilera et al. (2022), "A review of common faults in large-scale heat pumps". Renewable and Sustainable Energy Reviews

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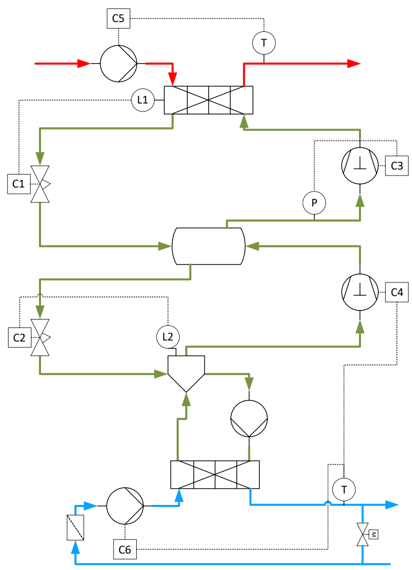
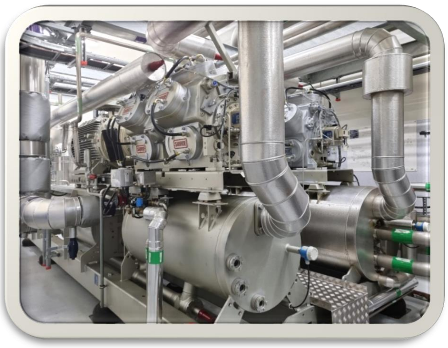
CASE STUDY

- District heating heat pump prone to fouling



Characteristics:

- **Nominal heating capacity:** 2 MW
- **Refrigerant:** R-717
- **Compressor type:** Reciprocating
- **Evaporator and condenser type:** Plate-and-shell
- **Heat source:** Industrial waste heat
- **Heat sink:** District heating



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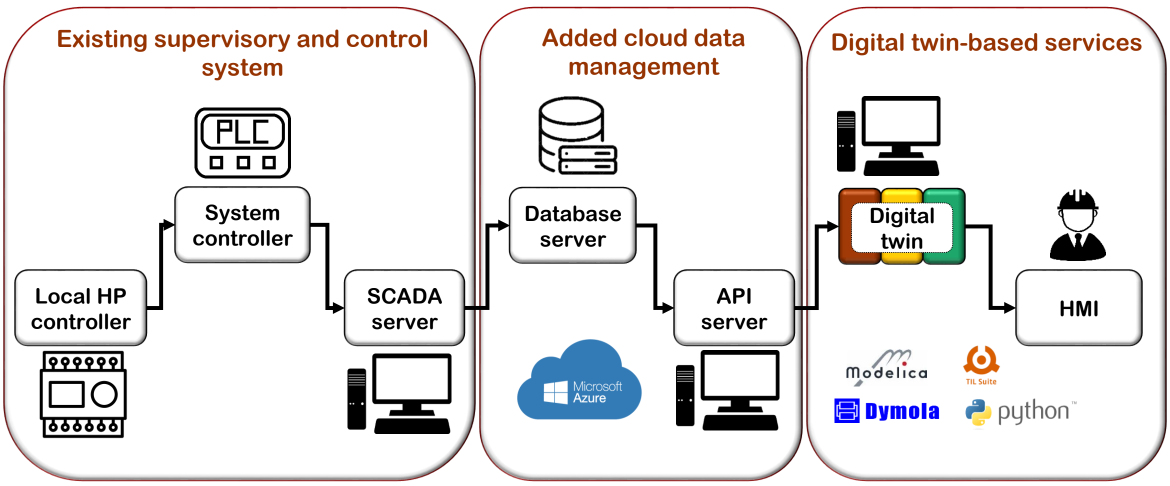
DIGITAL TWIN FRAMEWORKS

- Overview of modular structure



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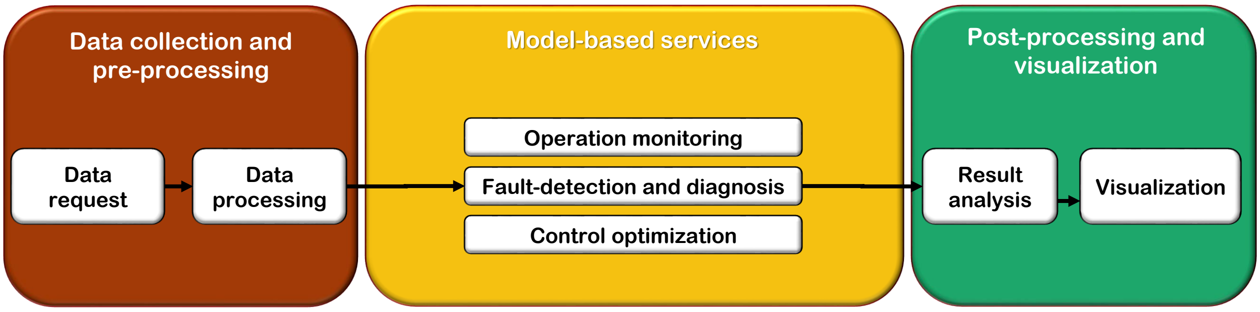
DIGITAL TWIN FRAMEWORKS

- Overview of modular structure



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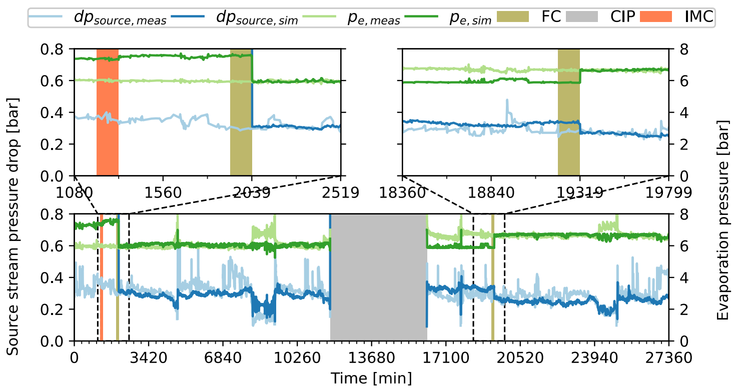
ADAPTIVE MODEL-BASED MONITORING

- Real-time simulation of fouling effects



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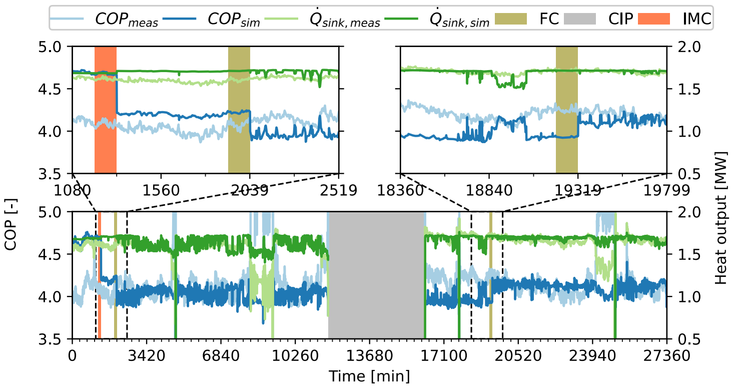
ADAPTIVE MODEL-BASED MONITORING

❑ Real-time simulation of HP performance



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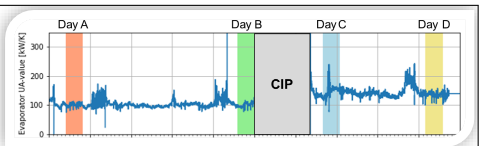
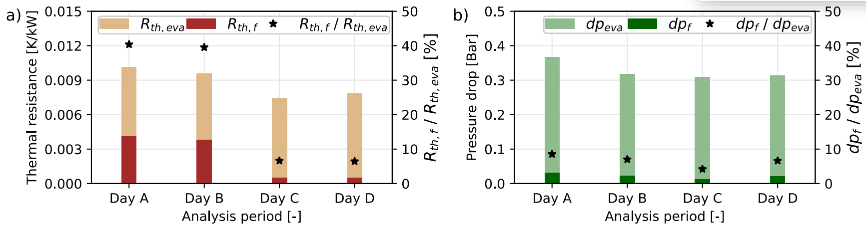
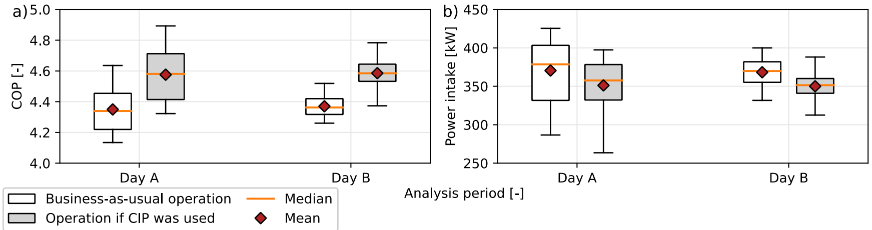


❑ Estimated effects of fouling



❑ Simulation of CIP implementation



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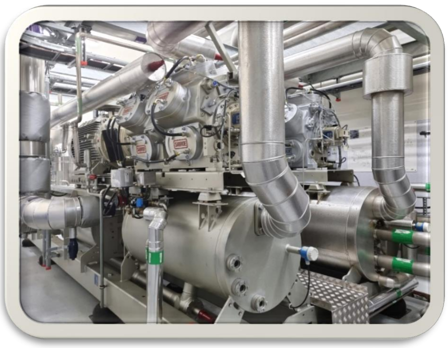
DIGITAL TWIN-BASED SERVICES FOR LARGE-SCALE HEAT PUMPS

- What are the next steps?



- Implementation of online set point optimization
- Development of a graphical user interface of the frameworks developed
- Inclusion of forecasting methods for fouling and secondary streams
- Further investigate Digital Twin based services together with demo. partners. Both for refrigeration systems and heat pump systems, e.g. refrigerant leakage and insufficient defrosting.

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EUDP

The Energy Technology Development and Demonstration Programme

The project "Digital Twins for large-scale heat pump and refrigeration systems" is funded by EUDP – The Energy Technology Development and Demonstration Programme

For more information, please visit: https://www.digitaltwins4hprs.dk/

Thank you for your attention!

USE OF MECHANICAL SUBCOOLING TO INCREASE CO2 HEAT PUMP PERFORMANCE

Pierre-Jean Delêtre

23-03-2023

Køle- og varmepumpeforum 2023

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CONTEXT

- High return temperatures in applications like district heating (CO2MIX4Heat project)
- Impact on performance of all types of refrigerant but more important on CO2
- Idea: use an extra vapor compression cycle to use the heat either from return water or CO2 exiting gas cooler

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SYSTEM CONFIGURATIONS

Three different configurations explored:

- Base heat pump
- Direct Dedicated Mechanical Subcooling (DDMS)
- Indirect Dedicated Mechanical Subcooling (IDMS)

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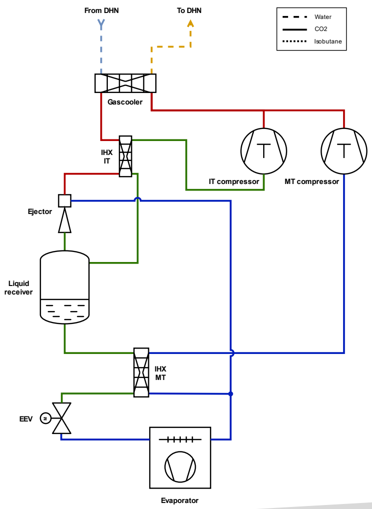
BASE HEAT PUMP



- Air as heat source
- High pressure ejector
- Parallel compression
- Internal heat exchangers

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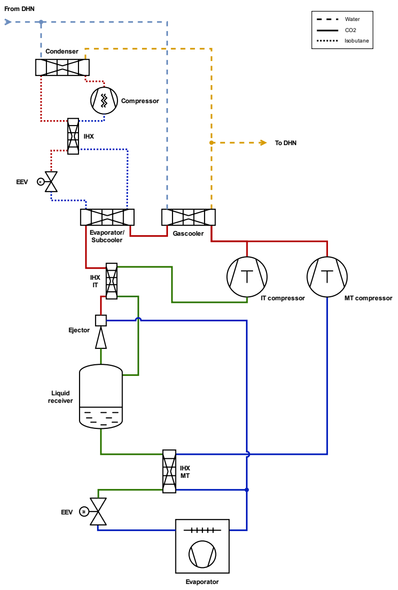
DIRECT DEDICATED MECHANICAL SUBCOOLING (DDMS)



- Additional vapor compression cycle using isobutane
- Aftercool the CO2 exiting the gascooler (down to 37°C)
- Heat the district heating water from return to supply temperature

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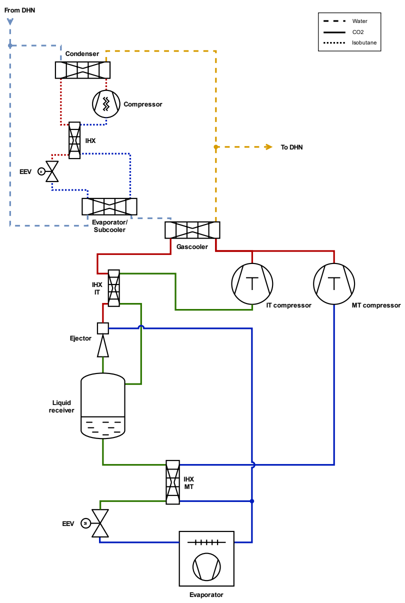
INDIRECT DEDICATED MECHANICAL SUBCOOLING (IDMS)



- Additional vapor compression cycle using isobutane
- Cool down the water before it enters the gascooler (down to 35°C)
- Heat the district heating water from return to supply temperature

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MODEL

- Base CO2 heat pump: Fenagy H1800
  - 1800 kW at 35/70 °C with 5 °C air temperature and 85% air humidity
  - 3 MT compressors and 3 IT compressors (Bitzer)
- Fenagy's calculation program (build with Engineering Equation Solver (EES))

  → Modified to integrate mechanical subcooling configurations
- R600a heat pump:
  - Bitzer compressor for performance data
  - Pinch model for heat exchangers

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WORKING CONDITIONS

Parameter	Value	Unit
Air temperature	-12 → 18	°C
Return temperature	40 → 55	°C
Supply temperature	60 → 80	°C
Relative air humidity	85	%
Evaporator superheat (CO2)	5	K
Evaporator superheat (R600a)	5	K
Condenser subcooling (R600a)	2	K
Auxiliary power without/with defrost	6/8	kW
Fan power	8.9	kW
Pump power	1.1	kW
dP discharge	1	bar
dP suction	1	bar
Defrost efficiency	50	%
Defrost threshold temperature	5	°C
Receiver pressure	Suction pressure + 12	bar
Gas cooler pressure	Optimal	bar

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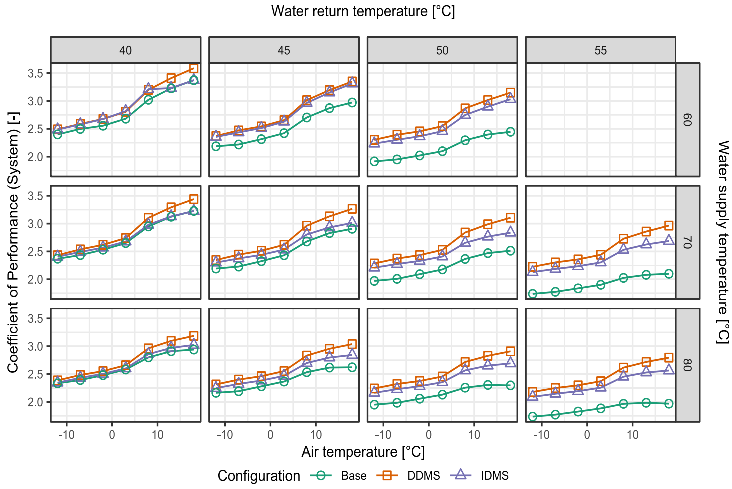
COEFFICIENT OF PERFORMANCE



COP of the overall system:

- No significant effect under 45°C return temperature
- Significant improvements for higher return temperatures
- Relative gain higher for smaller temperature differences
- Performance is highest for DDMS

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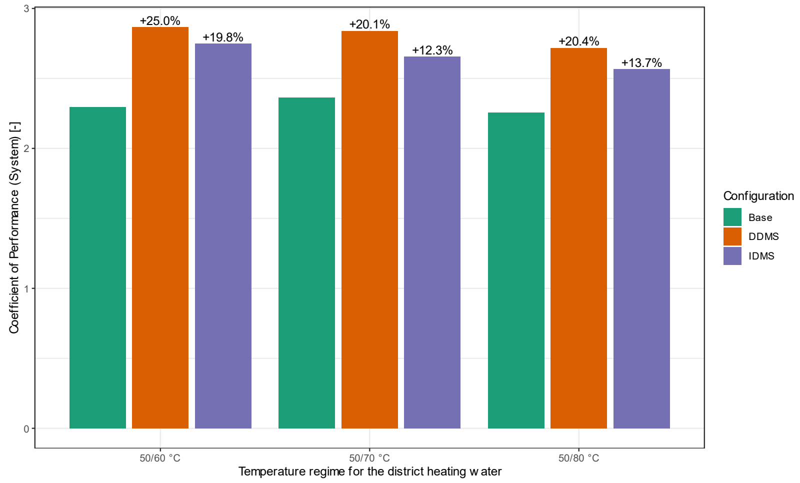
COEFFICIENT OF PERFORMANCE



Specific conditions: air temperature 8°C

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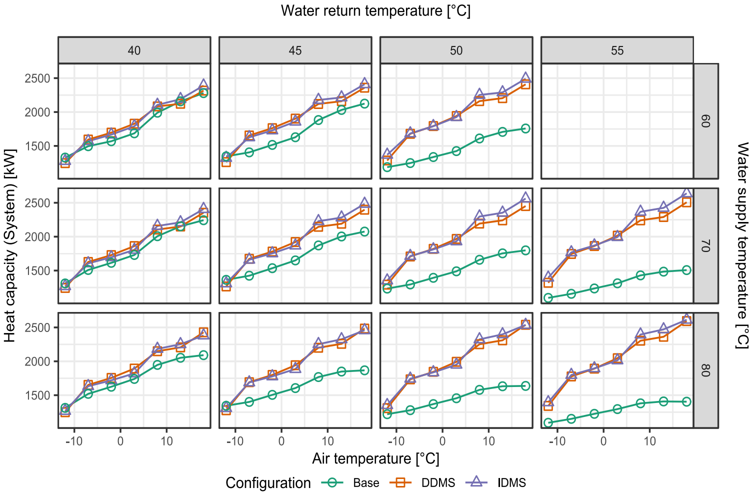
HEAT CAPACITY



Heat Capacity of the overall system:

- Similar capacity under 45°C return temperature
- Higher capacity above 45°C, with a high increase for high return temperature
- Capacity higher for IDMS

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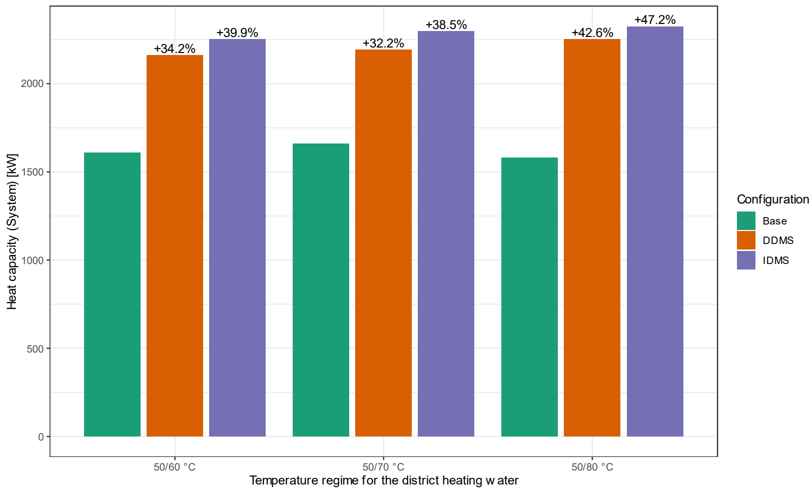
HEAT CAPACITY



Specific conditions: air temperature 8°C

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AVERAGE VALUES

Variable	Base	DDMS	Gain (Base)	IDMS	Gain (Base)
Heat capacity [kW]	1578	1934	22.5%	1967	24.6%
Power consumption [kW]	669	714	6.7%	759	13.5%
COP [-]	2.35	2.71	14.9%	2.59	9.8%

Average on all conditions (air temperature, water return and supply temperatures)

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SUMMARY

- System interesting when return temperatures >45°C
- Up to 36.5% COP gain for 55/65 °C compared to base case
- Average COP improvement for DDMS and IDMS is 14.9% and 9.8%, respectively
- Increased thermal capacity by on average 22.5% for DDMS and 24.6% for IDMS
- COP of direct mechanical subcooling higher than indirect: extra pinch so suction pressure lower for IDMS

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DIRECT OR INDIRECT?

- Better COP for DDMS
- Smaller components for DDMS compared to IDMS
- DDMS: evaporator pressure 130 bar (gascooler pressure)
- IDMS provides extra stability to the system
- IDMS easier to “encapsulate” → ATEX directive
- Better integration with existing systems for IDMS

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IMPROVEMENTS/FUTURE WORK

- Use real historical data instead of fixed inputs
- Technico-economical analysis: is the extra (heavy) investment worth it
- Different temperature levels for isobutane condenser and CO2 gascooler → optimal COP
- Test unit for isobutane heat pump at DTI (IDMS configuration)

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QUESTIONS

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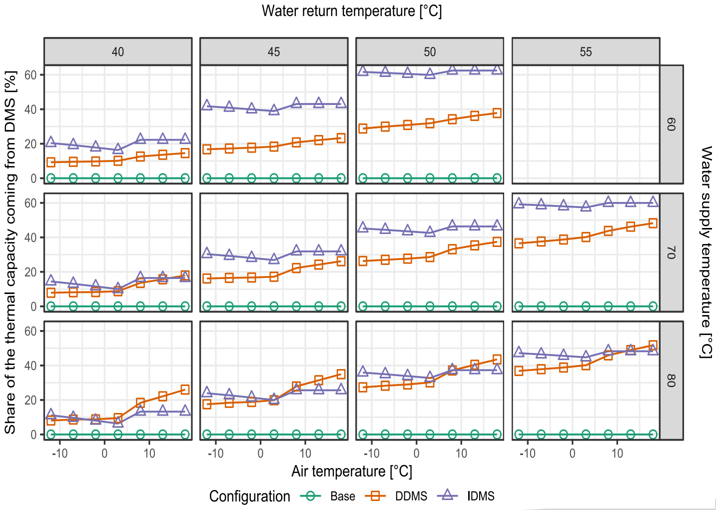
SHARE OF THE DMS IN THE TOTAL CAPACITY



- Up to 60% of the heat provided by the DMS

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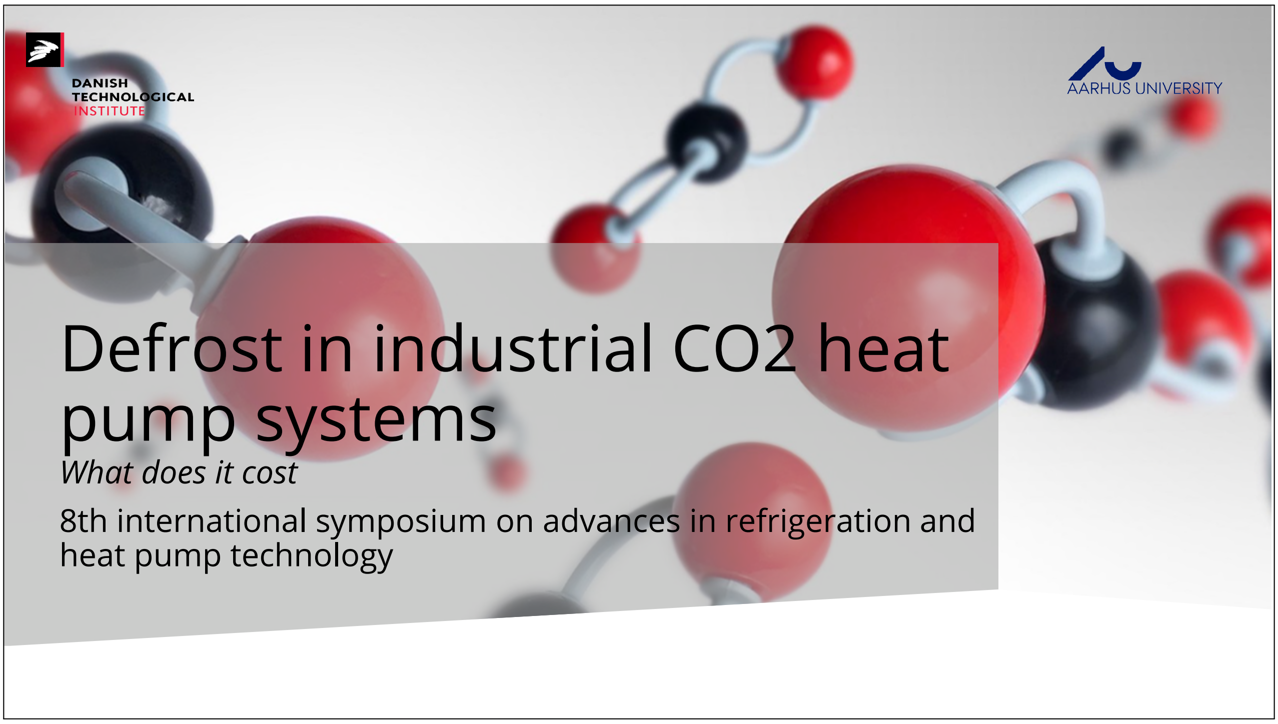
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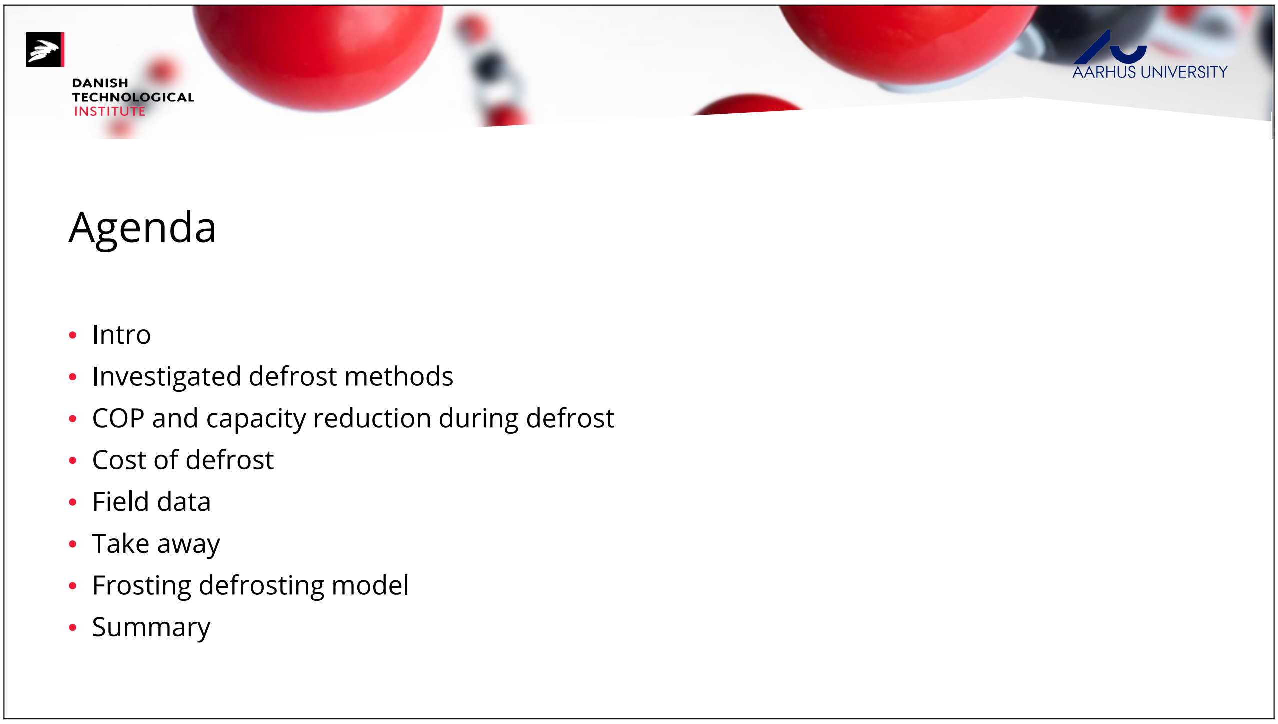
AARHUS UNIVERSITY
Defrost in industrial CO2 heat pump systems
What does it cost
8th international symposium on advances in refrigeration and heat pump technology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Agenda
Intro
Investigated defrost methods
COP and capacity reduction during defrost
Cost of defrost
Field data
Take away
Frosting defrosting model
Summary

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The CO2MIX4Heat project

- A/W heat pump for district heating
- A/W Test heat pump 100 kW
- Field test 600 kW
- Financed by support from EUDP

EUDP

FENAGY FUTURE ENERGY SOLUTIONS

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GÜNTNER WÄRMEAUSTAUSCHER HEAT EXCHANGERS

Danfoss

VAHTERUS

DANSK FJERNVARME

AARHUS UNIVERSITET

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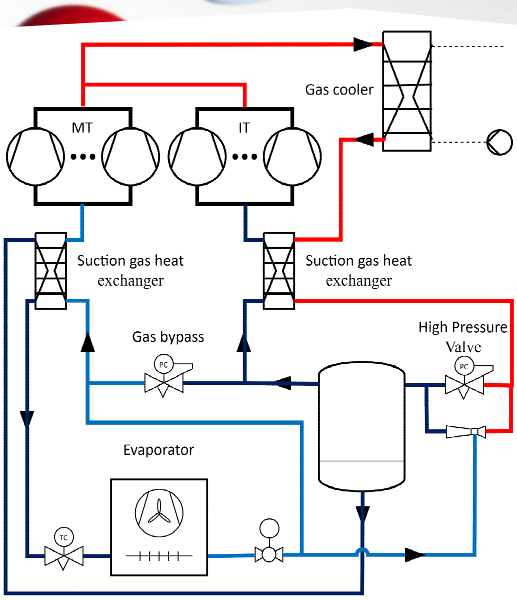
Basic cycle

- Evaporation temperature -1,3°C
- Evaporator SH 5K
- Air in 5°C / 85% RH out 1,2°C / 100% RH
- Heating capacity 589kW
- No control of compressor speed
- COP not defrosting 3,27
- Defrost capacity 52 kW



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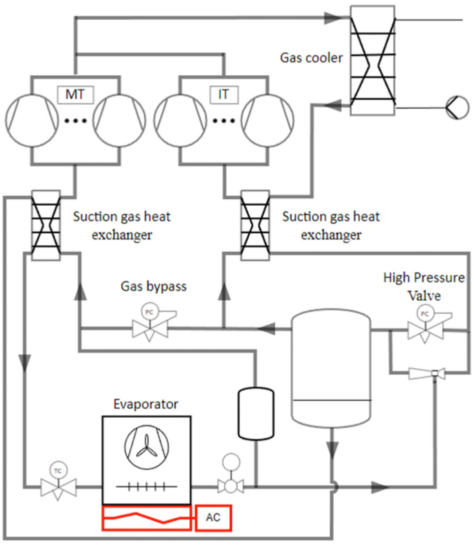
Electrical defrost

- The defrost capacity 52 kW



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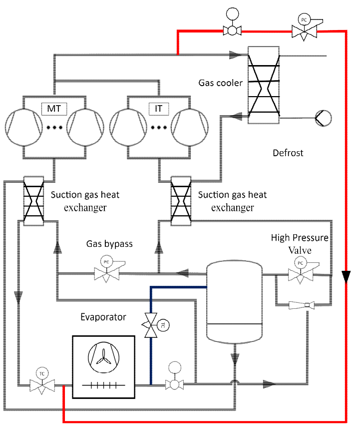
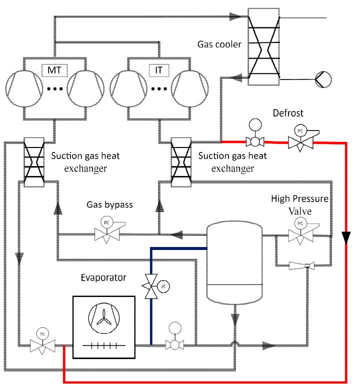
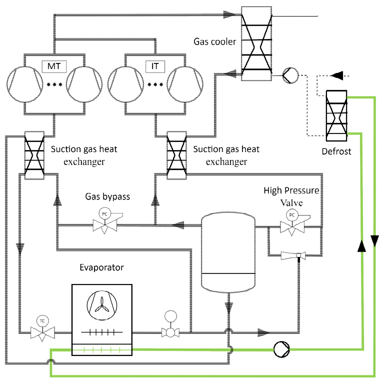
Investigated defrost methods



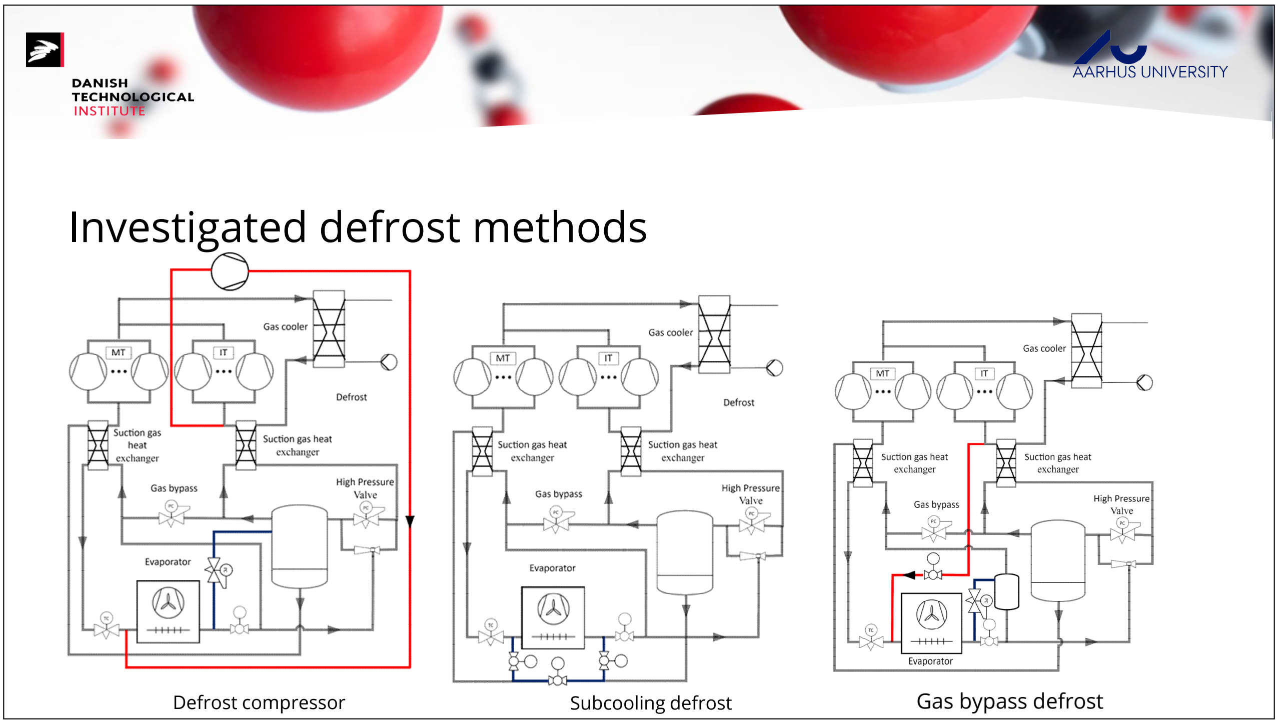
High temperature high pressure



Low temperature and high pressure



Glycol defrost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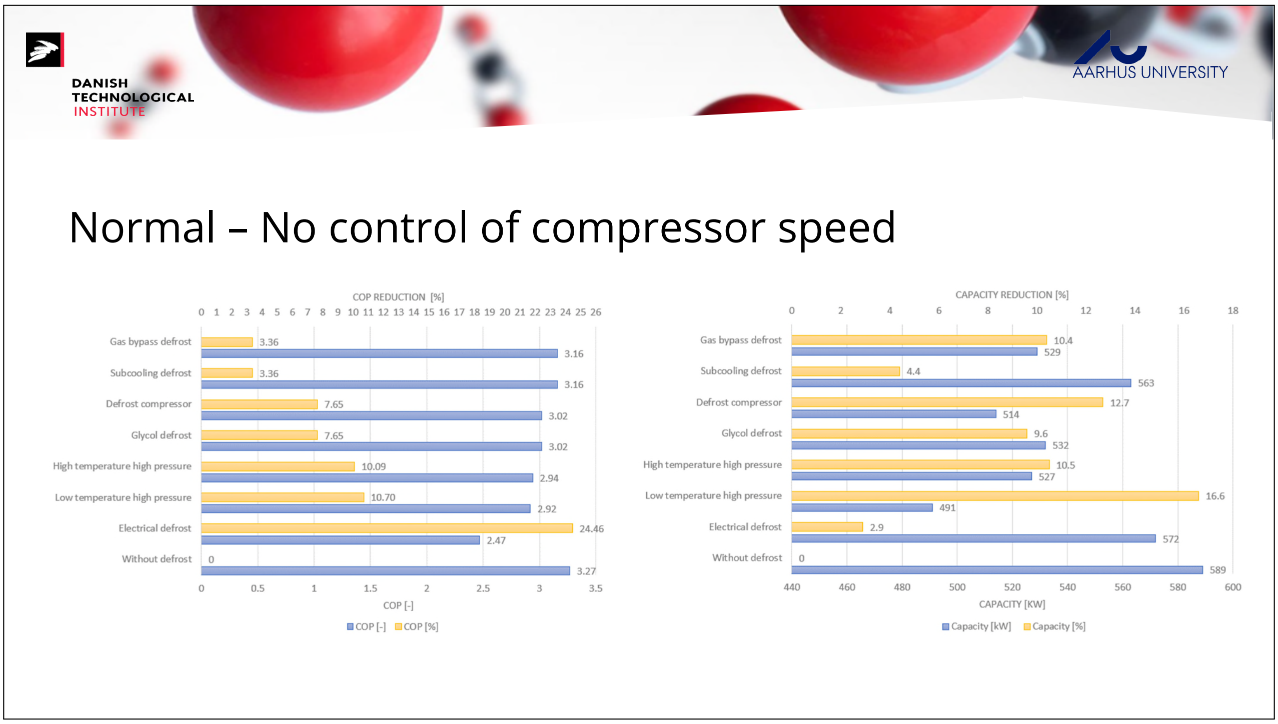
Investigated defrost methods
Gas cooler
MT
IT
Defrost
Suction gas heat exchanger
Gas bypass
High Pressure Valve
Evaporator
Defrost compressor
Subcooling defrost
Gas bypass defrost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Normal – No control of compressor speed
COP REDUCTION [%]
Gas bypass defrost 3.36 3.16
Subcooling defrost 3.36 3.16
Defrost compressor 7.65 3.02
Glycol defrost 7.65 3.02
High temperature high pressure 10.09 2.94
Low temperature high pressure 10.70 2.92
Electrical defrost 24.46 2.47
Without defrost 0 3.27
COP [-]
COP [-] COP [%]
CAPACITY REDUCTION [%]
Gas bypass defrost 10.4 529
Subcooling defrost 4.4 563
Defrost compressor 12.7 514
Glycol defrost 9.6 532
High temperature high pressure 10.5 527
Low temperature high pressure 16.6 491
Electrical defrost 2.9 572
Without defrost 0 589
CAPACITY [KW]
Capacity [kW] Capacity [%]

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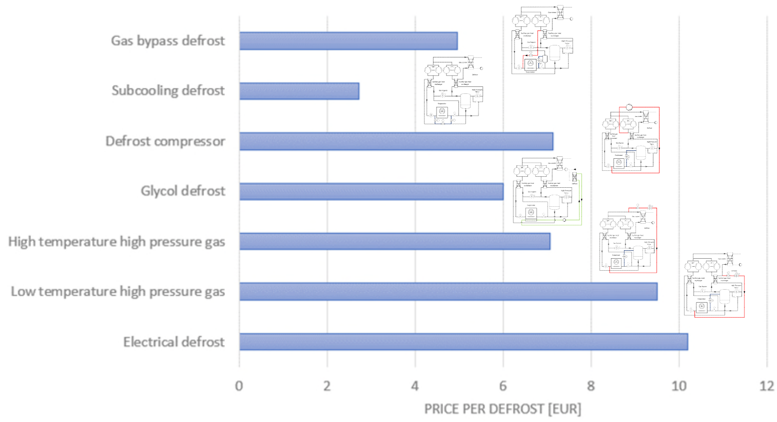
Cost of defrost

- Price of heat
  - 101 EUR/MWh
  - 760 DKK/MWh
- Price of electricity
  - 240 EUR/MWh
  - 1800 DKK/MWh
- Total defrost time 40 min
- Melting ice for 20 min



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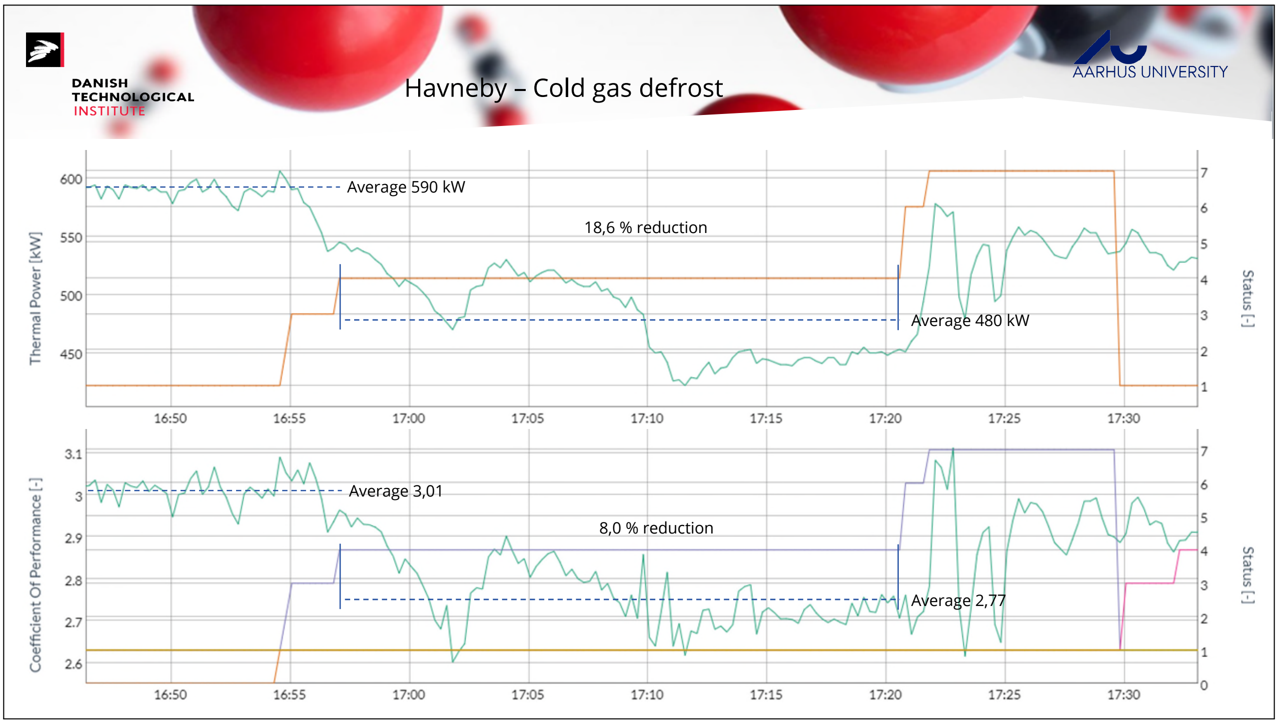
Field data

Havneby

Aalborg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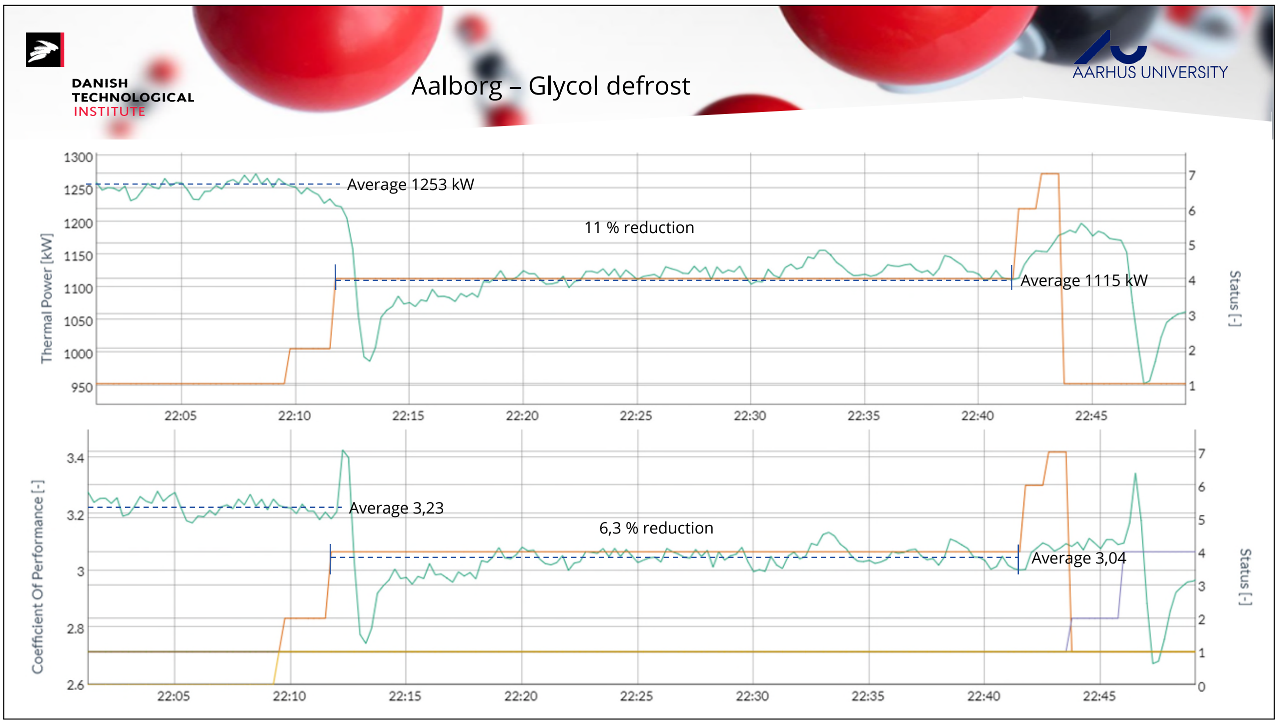
Havneby – Cold gas defrost
Thermal Power [kW]
Average 590 kW
18,6 % reduction
Average 480 kW
Status [-]
Coefficient Of Performance [-]
Average 3,01
8,0 % reduction
Average 2,77


DANISH TECHNOLOGICAL INSTITUTE
AARHUS UNIVERSITY
Aalborg – Glycol defrost
Thermal Power [kW]
Average 1253 kW
11 % reduction
Average 1115 kW
Status [-]
Coefficient Of Performance [-]
Average 3,23
6,3 % reduction
Average 3,04

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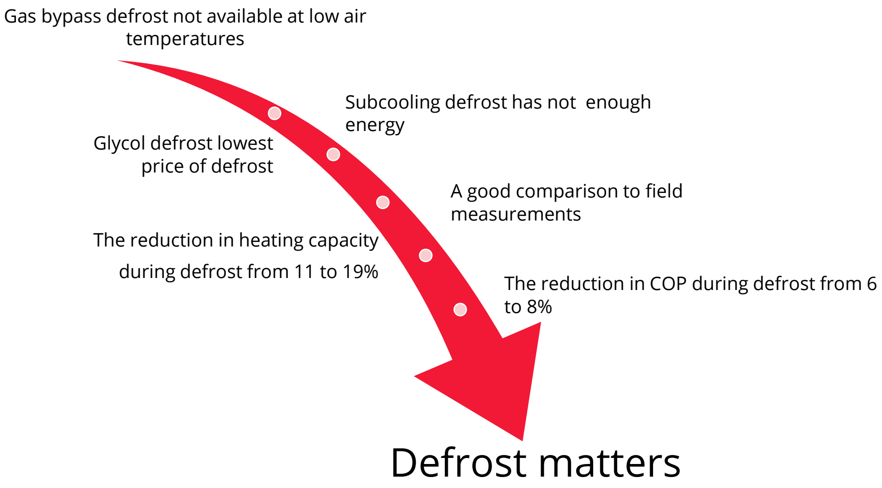
Take away



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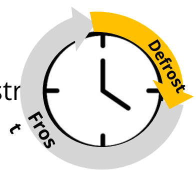
Further steps

- Optimize defrost duration, frequency, and control str



- The current model is purely thermodynamic
  → assumptions have to be made to estimate defrost duration & frequency
- The 'evaporator model' will be incorporated into the cycle model

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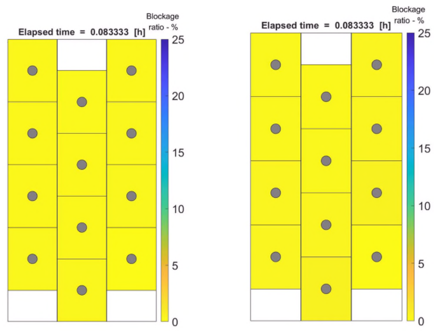
The evaporator model – frost phase

- Conservation equations (1D) solved separately for air and refrigerant sides
- Condensation/frosting rate based on mass transfer between humid air and tube/ice surface
- Quasi-steady

Frost formation on one evaporator (stop at average ice thickness of 0,5 mm)



Evap. temp. reduced by 2 K

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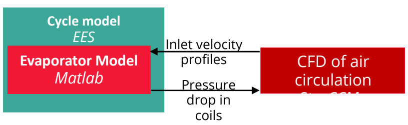
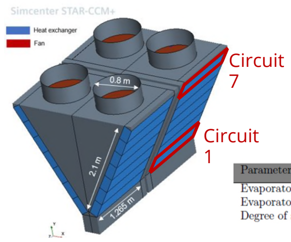
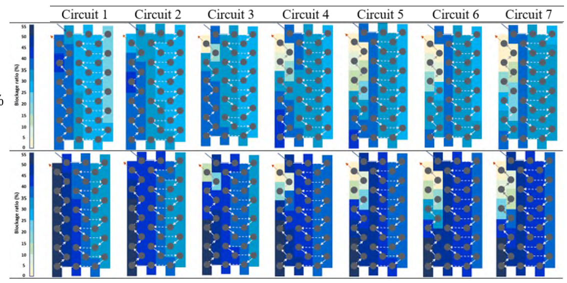
The evaporator model – frost p

- Possible coupling with CFD for non-uniform inlet air
- Computational cost!





Parameter	Value	Unit
Evaporator pressure	26.4	bar
Evaporator saturation temperature	-10.1	°C
Degree of superheat	7	K



T_{air} = 2°C RH = 70%

T_{air} = 2°C RH = 85%

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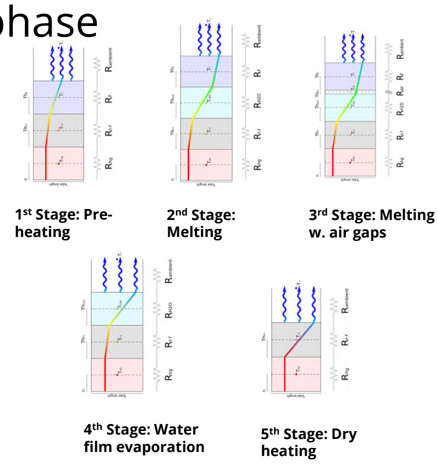
The evaporator model – defrost phase (in progress)

- The defrost process subdivided into 5 stages
- Conservation equations solved for gas, tube wall, frost, water, and air control volumes
- Transient model



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Summary

Cycle model →

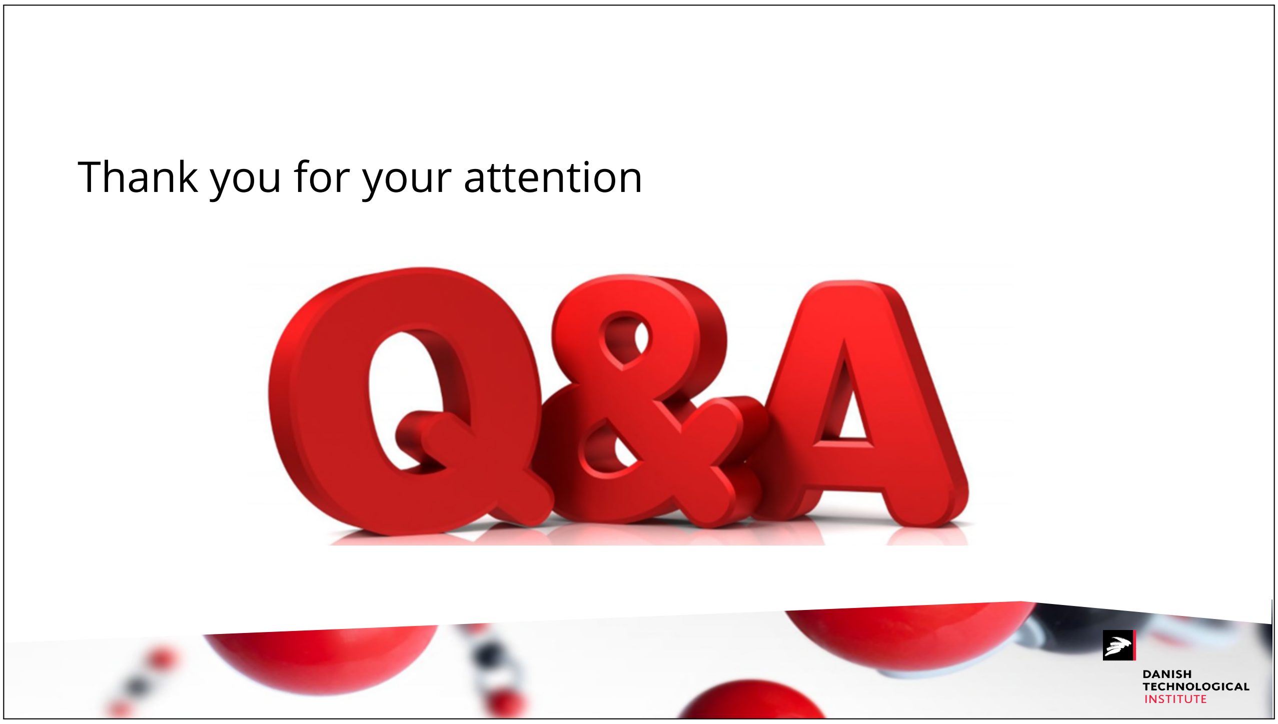
- Identification of candidate defrost methods

Cycle + evaporator model →

- Optimal defrost time + frequency
- Correlation of defrost time with control parameters (pressure drop / fin temperature)

Field test →

- Functional analysis of suggested control strategy


Thank you for your attention
Q&A
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NATURAL REFRIGERANT MIXTURES FOR LOW-CHARGE HEAT PUMPS

Matteo Caramaschi
Industrial PhD Student
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/nnovationsfonden DTU KTH NIBE METRO THERM

AGENDA

- Background – Residential heat pump market
- Modelling natural refrigerants and their mixtures
- Case study
- Experimental setup
- A future for natural mixtures ?

SINCE 2019, MORE THAN **20 NEW REFRIGERANTS** WERE APPROVED :

THE GREAT MAJORITY ARE **MIXTURES**

ALL ARE **SYNTHETIC**

F-GAS Regulation

GWP
Global Warming Potential

HFCs

R-134a R-454B R-32 R-407C R-410a

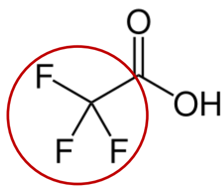
REACH Directive

PFAS
Perfluoroalkyl chemicals

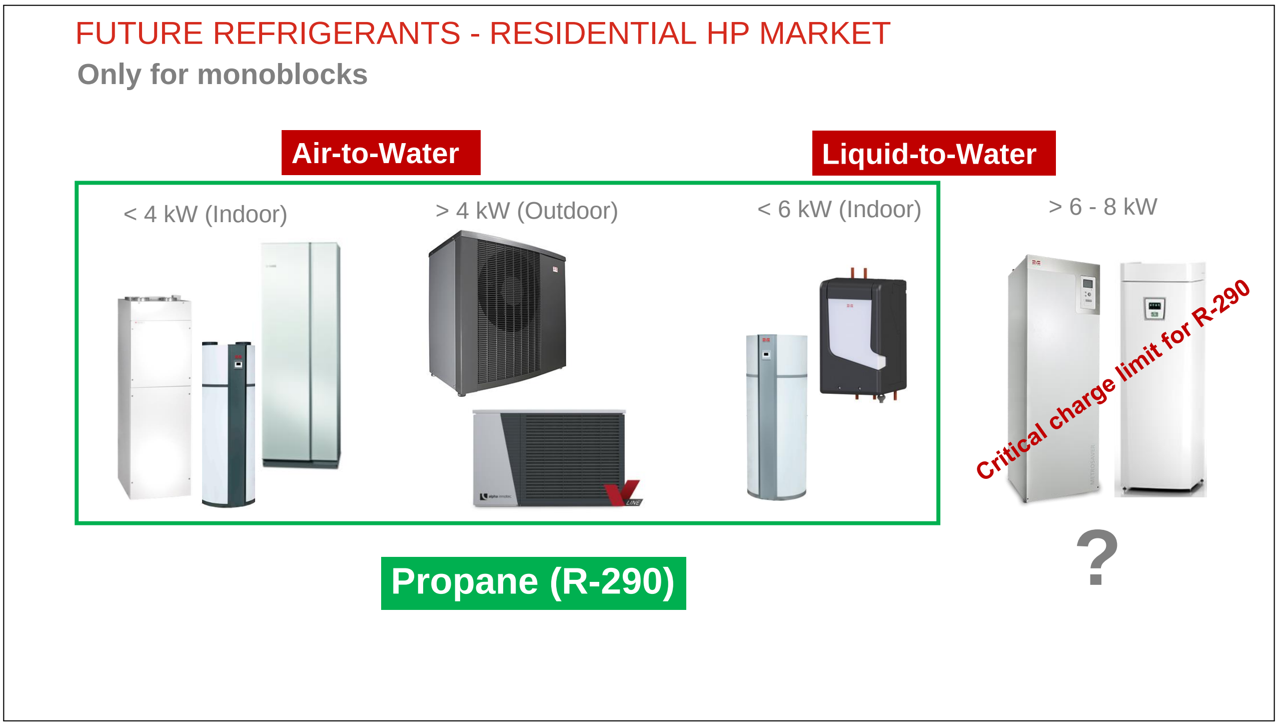
HFOs

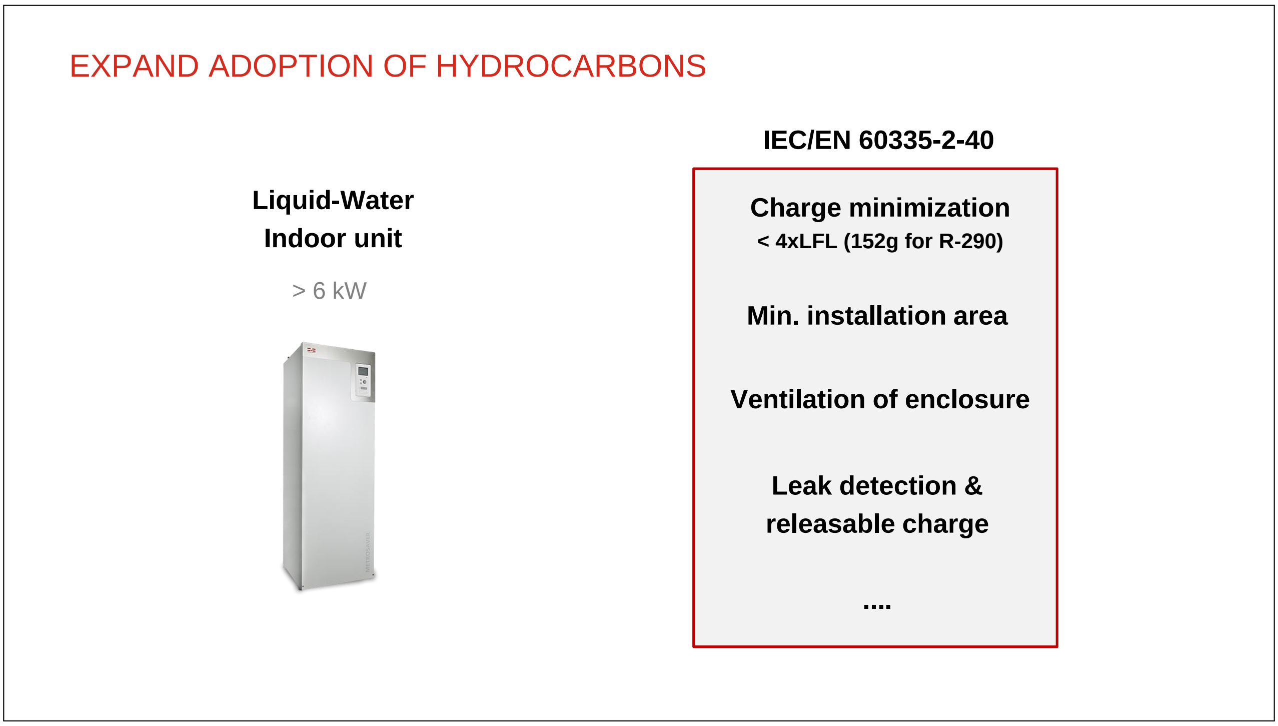
R-1234yf R-1234ze R-1234xx

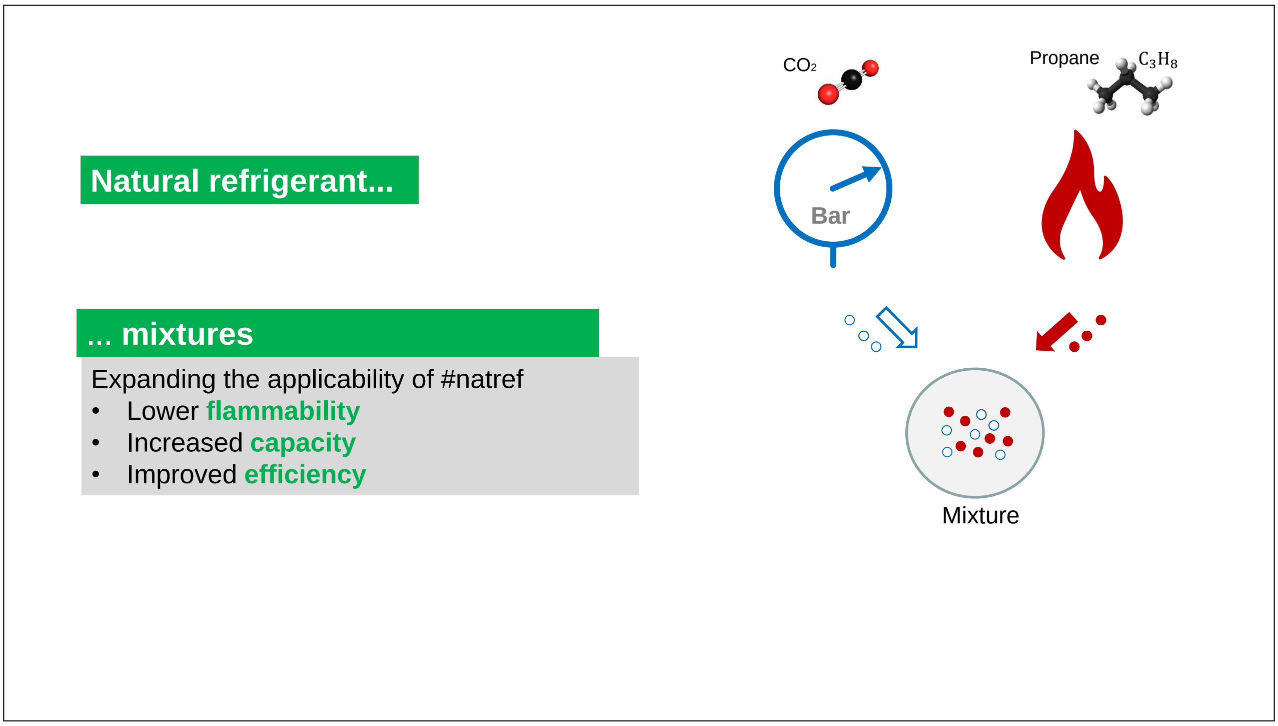
TFA
Trifluoroacetic acid

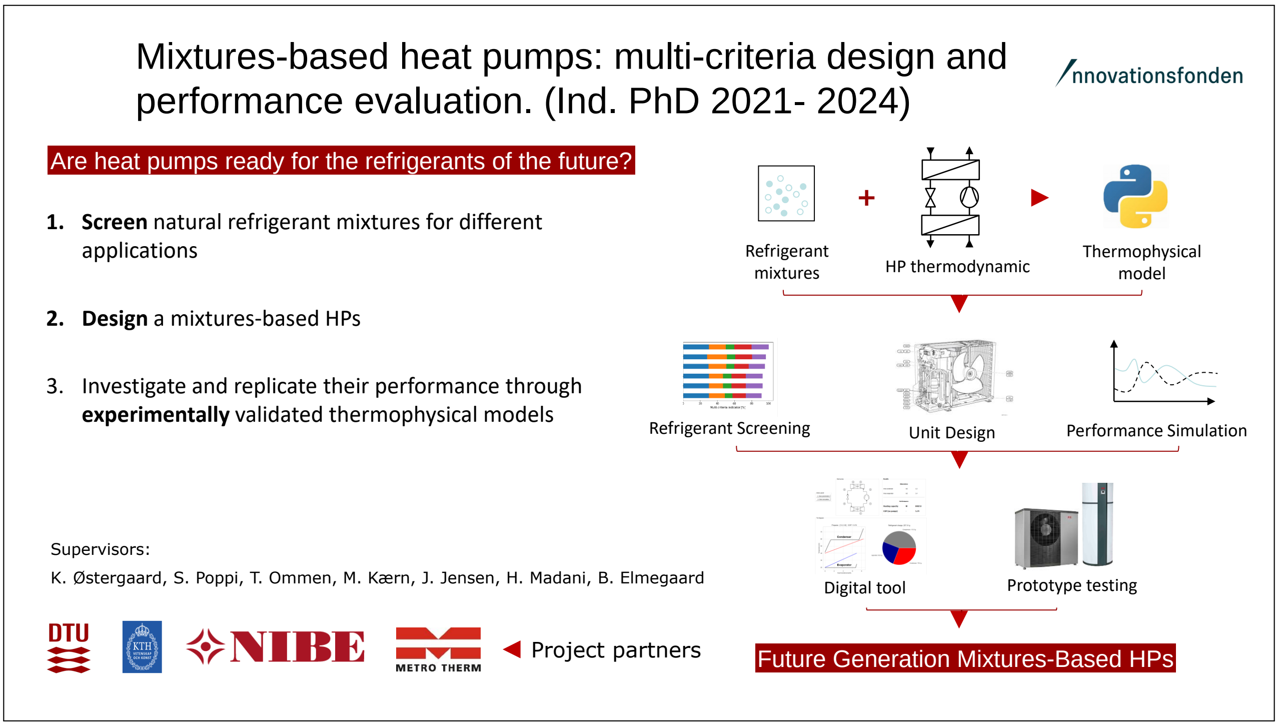


TOWARDS F-FREE REFRIGERANTS..


FUTURE REFRIGERANTS - RESIDENTIAL HP MARKET
Only for monoblocks
Air-to-Water
Liquid-to-Water
< 4 kW (Indoor)
> 4 kW (Outdoor)
< 6 kW (Indoor)
> 6 - 8 kW
Critical charge limit for R-290
Propane (R-290)
?


EXPAND ADOPTION OF HYDROCARBONS
Liquid-Water
Indoor unit
> 6 kW
IEC/EN 60335-2-40
Charge minimization
< 4xLFL (152g for R-290)
Min. installation area
Ventilation of enclosure
Leak detection &
releasable charge
....


Natural refrigerant...
CO2
Propane
C3H8
Bar
... mixtures
Expanding the applicability of #natref
• Lower flammability
• Increased capacity
• Improved efficiency
Mixture

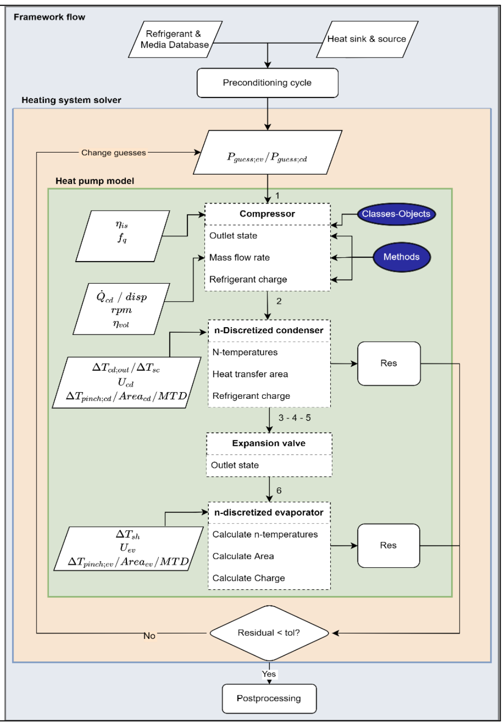

Mixtures-based heat pumps: multi-criteria design and performance evaluation. (Ind. PhD 2021- 2024)
Innovationsfonden
Are heat pumps ready for the refrigerants of the future?
1. Screen natural refrigerant mixtures for different applications
2. Design a mixtures-based HPs
3. Investigate and replicate their performance through experimentally validated thermophysical models
Refrigerant mixtures
HP thermodynamic
Thermophysical model
Refrigerant Screening
Unit Design
Performance Simulation
Digital tool
Prototype testing
Future Generation Mixtures-Based HPs
Supervisors:
K. Østergaard, S. Poppi, T. Ommen, M. Kærn, J. Jensen, H. Madani, B. Elmegaard
DTU
NIBE
METRO THERM
Project partners

HEAT PUMP MODEL

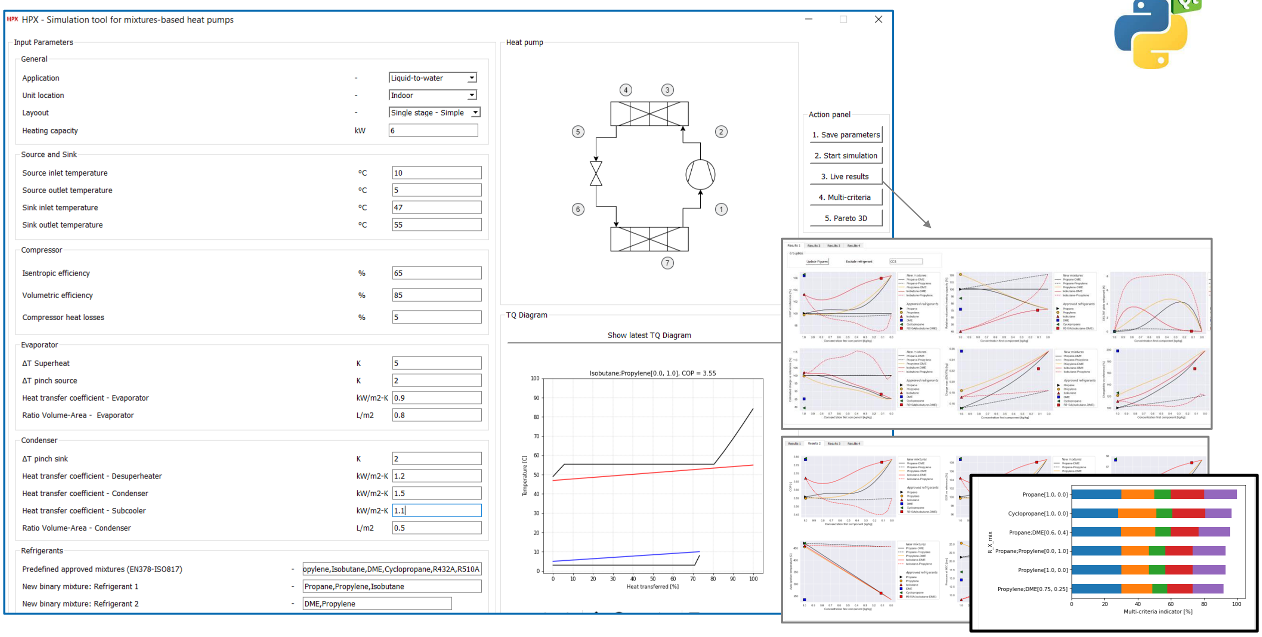
- Hybrid Newton Rapson solver: **Scipy.optimize**
  - Iteratively adjusting P_{ev} & P_{cd}
  - 2 x Residuals: ΔT_{pinch} (or Areas or MTD)
- OOP approach
  - Extendable & exchangeable components

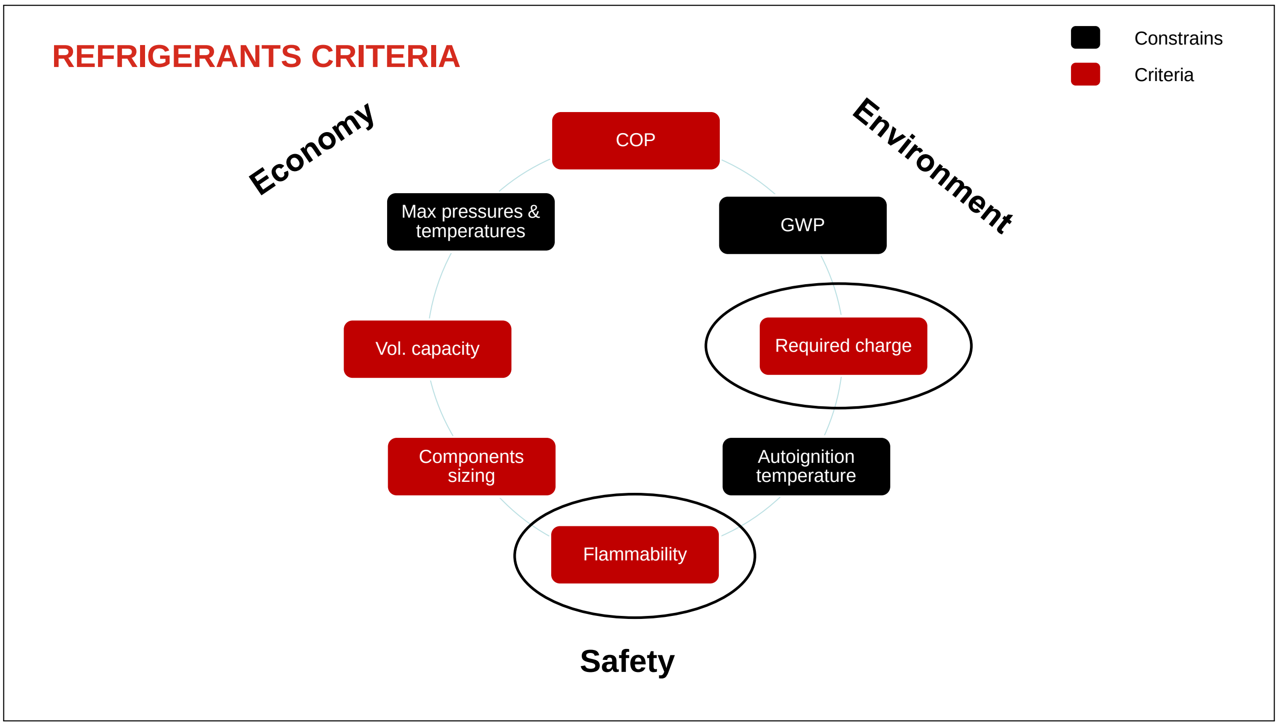
New

- REFPROP or **CoolProp also with mixtures**
- **Charge estimation** as screening variable

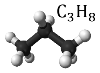


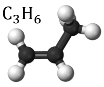
SCREENING TOOL

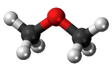




NATURAL REFRIGERANTS

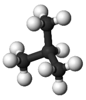
Propane  C_3H_8

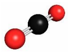
Propylene C_3H_6 

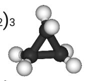
DME C_2H_6O 

Refrigerant	GWP	LFL kg/m3	AUTO INGNITION T	DISCHARGE T	PRESSURE	VOL. CAPACITY	COP Low T	COP High T	Main issues
R-290 (Propane)	<3	0.038	470	Low	Medium	Medium	High	Medium	Flammability
R-744 (CO2)	1	-	-	High	High	Highest	Low	High	Pressure
R-600a (Isobutane)	<3	0.043	460	Low	Low	Low	Medium	Highest	Vol capacity / flammability
R-1270 (Propylene)	<2	0.046	455	Medium	Medium	High	High	Medium	Flammability
R-C270 (Cyclopropane)	<3	-	495	High	Medium	Medium	Highest	High	Cost, flammability
R-E170 (DME)	<1	0.064	235	Medium	Low	Low	Highest	Highest	Compatibility / flammability

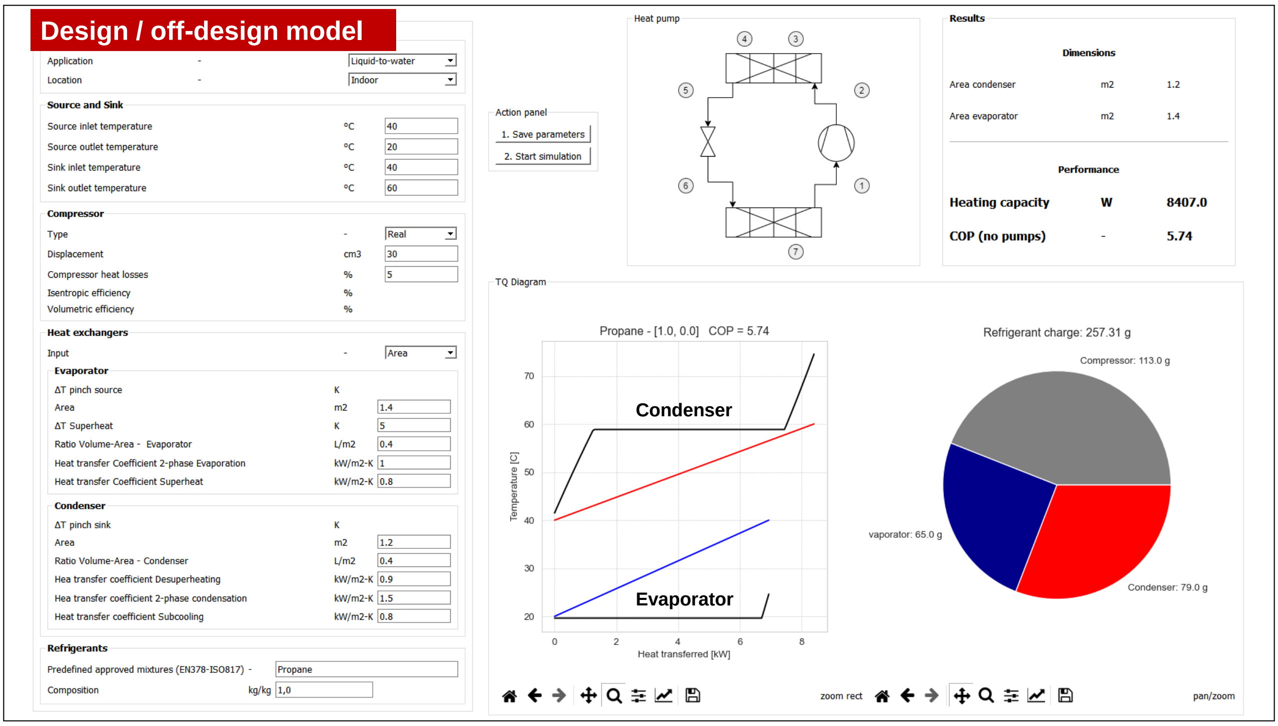
$HC(CH_3)_3$

Isobutane 

CO_2 

$(CH_2)_3$ 

Cyclopropane



RESULTS - NATURAL MIXTURE VS R290

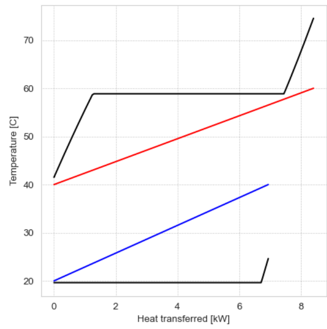
✓ **Slightly higher discharge temperature:**
- +7K

✓ **Glide:**
- 8K at 60°C

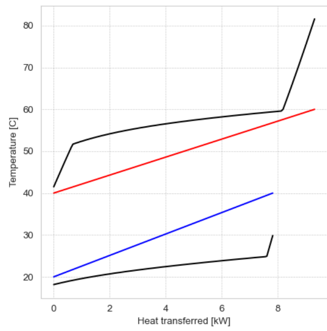
✓ **Improved performance:**
- + 8.5% in COP while
- + 10.8% in Heating capacity

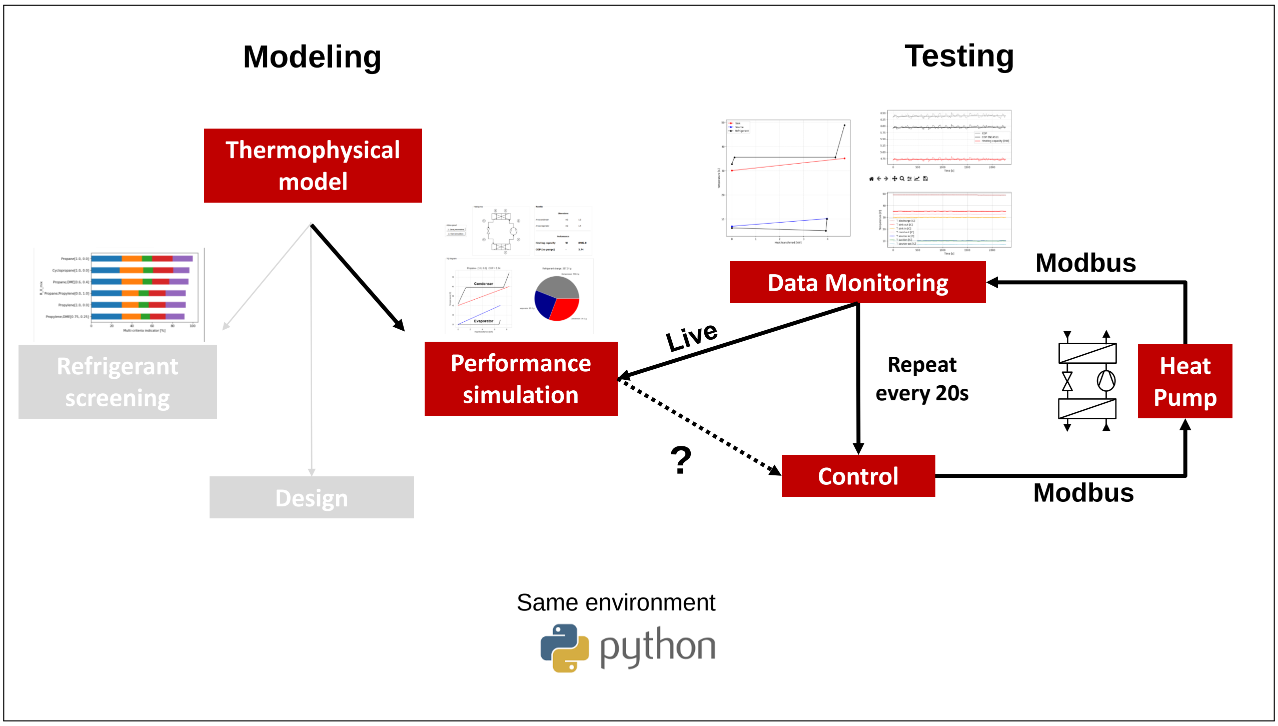
✓ **Reduced flammability**
- > +40% allowed refrigerant amount

R290



Natural Mixture

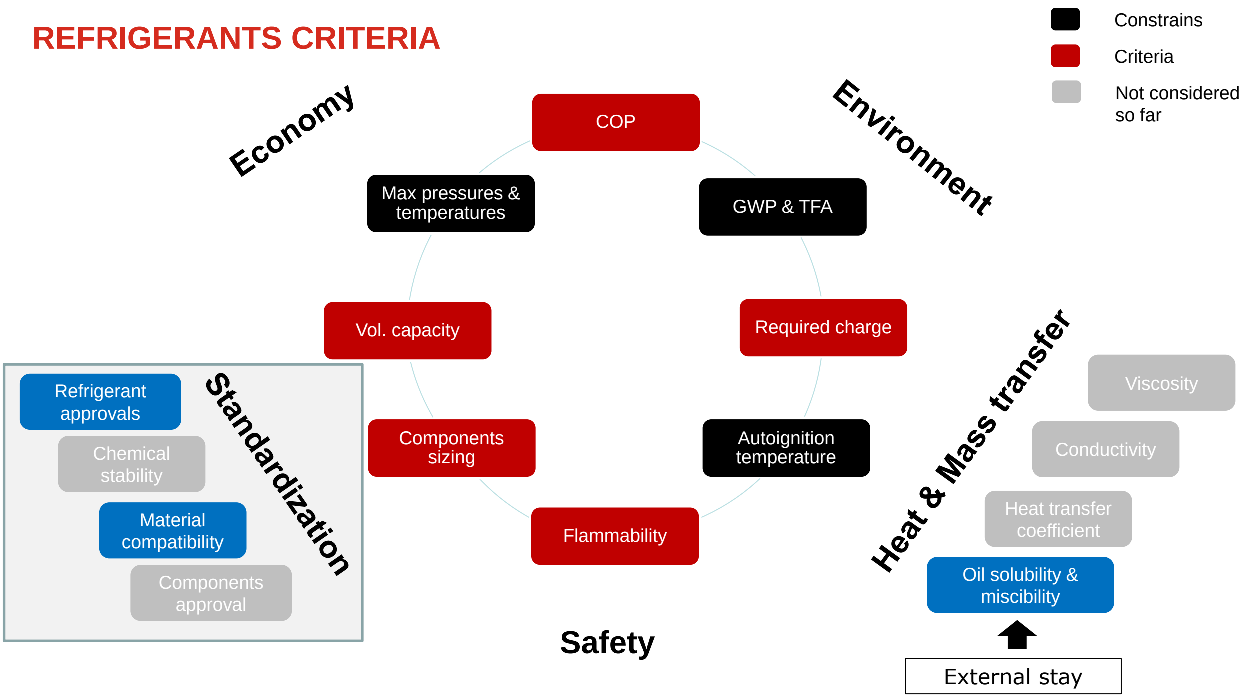




FROM R-290
TO R-490 ?

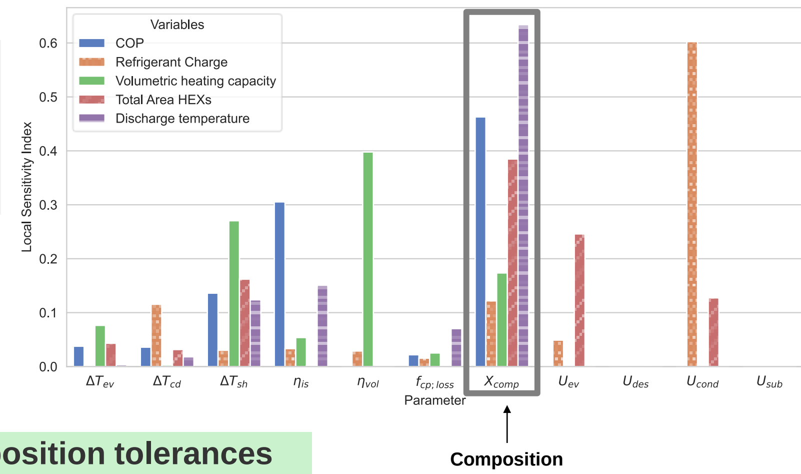
BARRIERS TO OVERCOME

REFRIGERANTS CRITERIA



COMPOSITION SENSITIVITY - PROPANE 95 % / CO2 5 %

Uncertainty on the composition of a blend containing CO_2 can have a significant effect on performance.



--> Minimize allowed composition tolerances

COMPONENTS APPROVAL WITH NEW FLAMMABLE REFRIGERANT

Technical steps

- ✓ Feasibility analysis / simulation
- ✓ Chemical stability
- ✓ Material compatibility
- ✓ Prolonged testing
- ✓ Safety testing Low Voltage Directive
  - Ignition temperature and sources

Economical requirement:
Strong market demand

Pre-requirement: **available approved refrigerant**

APPROVING A NEW REFRIGERANT

Technical requirements

- ✓ Thermodynamic data
- ✓ Toxicity data
- ✓ Leak simulation and test (WCFF)
- ✓ Low Flammability Limit testing
- ✓ Safety class determination

Application to ASHRAE 34 / ISO 817

Possible economical challenges:

- ✓ Refrigerants available in nature
  - IP hard to protect
  - Low selling price compared to HFCs/HFOs

→ Challenging business model for refrigerant manufacturers

CONCLUSIONS

- ✓ Model-based results suggest that, for some applications, mixtures may extend the range of applicability of natural refrigerants:
  - Improve COP & Capacity
  - Reducing flammability and increasing allowed refrigerant charge
- ✓ Testing on a heat pump prototype monitored, controlled and simulated in same environment are ongoing
- ✓ The development and approval of new natural mixtures may require:
  - Minimal blend composition tolerance
  - Strong market demand for driving the approval of components with new blends
  - Involvement of refrigerant and components manufacturers

EN 378 / ASHRAE 34 – APPROVED NATURAL REFRIGERANT MIXTURES

Approved Mixture	Components [Mass Concentration]
R-432A	Propylene [80%], DME [20%]
R-433B	Propylene [5%], Propane [95%]
R-433C	Propylene [75%], Propane [25%]
R-510A	DME [88%], Isobutane [12%]
	Many others

Several existing approved synthetic mixtures:
HFCs & HFOs **+ CO_2**

Missing approved natural options:
Hydrocarbons **+ CO_2**

More than 4 new mixtures are approved every year

… will the next one be natural ?

Latest refrigerants approved: Addenda to Standard 34-2019 (ashrae.org)

THANK YOU
FOR YOUR ATTENTION

Project Partners

DTU KTH NIBE METRO THERM

Innovationsfonden

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4 DKVF Best Student Project Award 2023 Posters

Contents

Exergoeconomic analysis and optimization of liquefaction and purification system for post-combustion CO_2 capture

Rikke Cilius Pedersen
PhD student
DTU Construct

INTRODUCTON

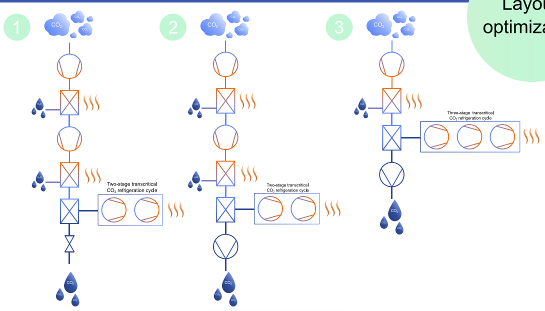
In the combat against climate change, carbon capture technologies are expected to play an important role in the reduction of anthropogenic CO_2 emissions from heavy-emitting industries. However, many of the process steps in the carbon capture value chain are still on development stage and not ready for large-scale deployment.

The focus of this thesis was the liquefaction and purification process, which is the connecting process between the separation of CO_2 at the point source and the following transport. Previous studies indicate that this process step can account for a significant share of the total transport costs. Therefore, it is important to understand how the cost of the process can be minimized and how it is affected by different design requirements.

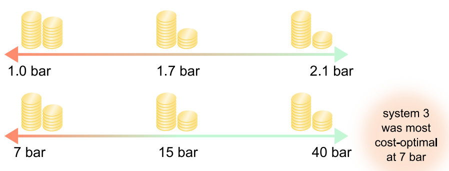
METHODS

Exergy analysis → Exergo-economic analysis → Parameter optimization → Layout optimization

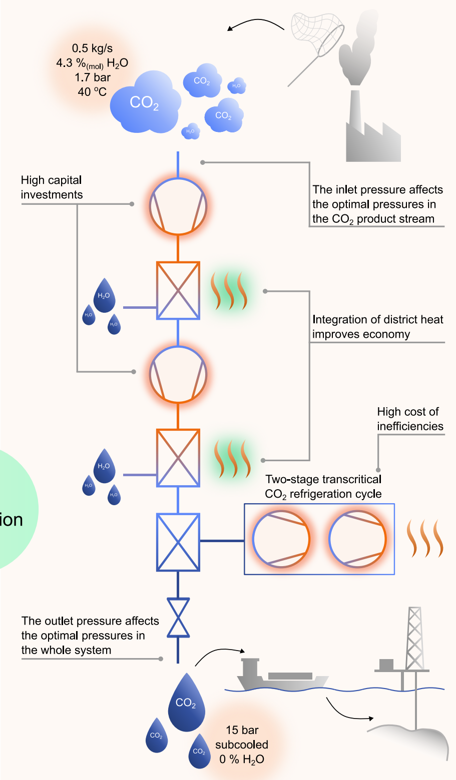
RESULTS



	1	2	3
Liquefaction pressure	15.5 bar	14.4 bar	7.5 bar
Liquefaction temperature	-28 °C	-30 °C	-48 °C
Levelized costs	138 DKK/t CO_2	137 DKK/t CO_2	148 DKK/t CO_2
COP_{system}	0.96	0.98	0.94
$COP_{refrigeration}$	1.74	1.74	1.34



SYSTEM OVERVIEW



CONCLUSIONS

The greatest share of losses occured during purification, while the refrigeration cycle accounted for the majority of thermodynamic inefficiencies.

The compressors were the greatest source of costs. Pressures throughout the system should be optimized to ensure optimal operation of the compressors.

The costs increased when the inlet pressure of captured CO_2 decreased, while a greater inlet pressure reduced costs.

The costs increased when the required outlet pressure decreased, while a greater outlet pressure did not affect costs.

Optimization of the pressures throughout the captured CO_2 stream was important when the inlet pressure changed, while the pressures in the refrigeration cycle should also be optimized for a change in the outlet pressure.

Thesis access

Performance Optimization of a Transcritical CO_2 Supermarket Refrigeration System Equipped with an Ice Tank

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(c) Aalborg University (AAU), Department of Electronic Systems, Aalborg, 9220, Denmark

ABSTRACT

Due to the low critical temperature of CO_2, the CO_2 supermarket refrigeration systems are often forced to operate in a transcritical regime, which results in poor energy efficiency. In order to overcome this performance penalization, the integration of an ice tank to cool down the CO_2 leaving the condenser/gas cooler is considered in this work. A novel optimization method was proposed to minimize the overall energy consumption by optimally scheduling trade-off between the discharge mode and the charge mode. The solution of the optimization problem was achieved based on Particle Swarm Optimization (PSO). The proposed strategy was applied to five sample locations (Copenhagen, Birmingham, San Francisco, Sydney and New Delhi) representing different climates. The results obtained showed an energy saving ranging from 6 % to 8 % for the hottest day and from 0.4 % to 2.9 % for the entire year compared to the CO_2 system without the ice tank.

Keywords: Carbon Dioxide, Cold Thermal Energy Storage, Commercial Refrigeration, Energy Saving, R744

INTRODUCTION

The refrigeration sector plays a crucial role in today's society with enormous contributions in food, health, energy and environmental domains.
The European Union (EU) is pushing the whole refrigeration sector towards the adoption of low-to-zero GHG working fluids, with particular emphasis on natural refrigerants. Being virtually ideal from an environmental and safety perspective (i.e. negligible Global Warming Potential, zero Ozone Depletion Potential, non-toxic, non-flammable), carbon dioxide is widely accepted as a future-proof refrigerant for commercial refrigeration applications (Gullo et al., 2018).

Latent cold thermal energy storages, such as ice tanks, can lead to substantial energy savings thanks to the shift of part of the refrigeration load from more adverse (i.e. daytime) to more favourable (i.e. night-time) operating conditions, i.e. peak load shaving (Heerup and Green, 2014). The purpose of this work is to develop a control strategy to maximize the energy efficiency of the overall system for running modes including seasonal dependent ambient temperature variations.

SYSTEM DESCRIPTION

Investigated refrigeration system

The system investigated in this work is shown in Figure 1 in which a single-stage transcritical CO_2 vapour-compression supermarket refrigeration system equipped with an ice tank is depicted.

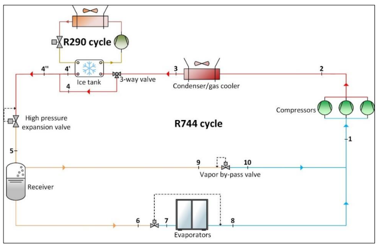

Figure 1. Schematic of the investigated transcritical CO_2 supermarket refrigeration system

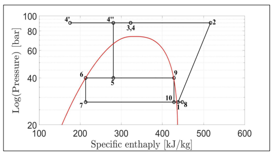

Figure 2. *Log(p)-h* diagram of the transcritical CO_2 refrigeration system equipped with an ice tank at the ambient temperature of 35 °C

PROPOSED APPROACH FOR ENERGY OPTIMIZATION

Figure 3 illustrates the controller block diagram of the entire refrigeration system. The top two control loops regulate the pressure levels at the receiver tank and the suction manifold. The next two controllers handle the pressure and temperature at the outlet of the gas cooler and finally the ice tank controller regulates the refrigerant temperature before entering the receiver tank by manipulating the 3-way valve's opening degree. Here, the opening degree of the three-way valve controls the discharge rate ($\dot{Q}_s$) of the ice tank.

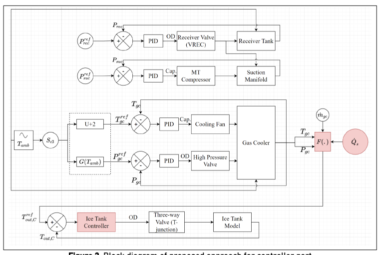

Figure 3. Block diagram of proposed approach for controller part

This parameter, which was suggested by Henze et al. (1997), directly represents the amount of transferred cooling power during operating modes of the ice tank. so:

$$\begin{cases} \dot{Q}_s > 0 & : \quad Ice-tank\ is\ in\ discharge\ mode \\ \dot{Q}_s < 0 & : \quad Ice-tank\ is\ in\ charge\ mode \\ \dot{Q}_s = 0 & : \quad Ice-tank\ is\ in\ idle\ mode \end{cases}$$

Constraints

Developing feasible optimization solution based on the developed model requires several constraints to make sure that operational boundaries of the system are not violated. In this application following constraints are proposed:

1. No change in liquid fraction after 24 hours.
2. Discharge and charge rate limits caused by maintaining enough pressure in the receiver.
3. Liquid fraction range
4. Smoothness of changes in charge/dishcarge rate during the day.

Cost function

The cost function is defined as the consumed electrical energy by the compressors:

$$J\big(u(1),u(2),\dots,u(N)\big) = \sum_{i=1}^{N} \dot{W}(i)$$

$$\dot{W}(i) = \begin{cases} \dot{W}_n(i) = f_1\big(T_{amb}(i)\big), & \dot{Q}_s\ (i) = 0, \quad Idle \\ \dot{W}_D(i) = f_2\left(T_{amb}(i), \dot{Q}_s(i)\right), & \dot{Q}_s(i) > 0, \quad Discharge \\ \dot{W}_C(i) = \dot{W}_C^{R290}(i) + \dot{W}_n(i) = f_3\left(T_{amb}(i), \dot{Q}_s(i)\right), & \dot{Q}_s(i) < 0, \quad Charge \end{cases}$$

RESULTS AND DISCUSSION

To investigate the performance of the proposed approach, the simulations are run for a full year considering the logged ambient temperature of 2021 in 5 cities. As a sample of selected cities, figure 4 shows the ambient temperature of New Delhi in 2021 on an hourly basis. The optimization problem has run for each day separately and the results are logged. From the daily results, two days are highlighted; the hottest day of the year (the 9th of June in which the highest temperature is reported) and the coldest day of the year (the 25th of December). Different quantities of the simulated supermarket in New Delhi for hottest of the year is represented in Figure 4.

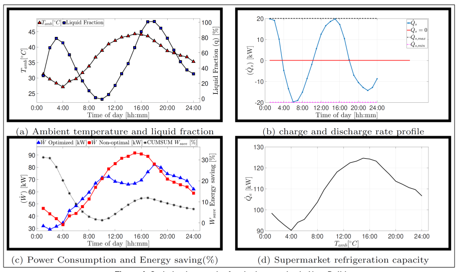

Figure 4. Optimization results for the hottest day in New Delhi

Table 1 represents a summary of the simulated results. In this table, the average ambient temperature of each city over the whole year is given in the first row. Other rows of the table provide the energy saving on the hottest day and for the entire year in terms of both MWh and percentage. One can conclude that the MWh energy saving is directly correlated with the ambient temperature while it is not necessarily the case for the percentage of energy saving. This could be due to the inadequate size of ice tank used for the supermarket in New Delhi (The size of ice tank has been kept the same for all cities for the purpose of comparison). This can also be observed in Figure 4b where the discharge rate has reached to its maximum value.

Table 1. Possible energy savings using ice tank in different cities on the hottest day and for the whole year 2021

	Copenhagen	Birmingham	San Francisco	Sydney	New Delhi
Average temperature in 2021 $[°C]$	8.32	9.68	13.09	17.85	24.70
$\dot{W}_{save}$ $[kWh]$ Hottest Day	32 (6.36 %)	51 (6.8 %)	54 (7.1 %)	78.6 (7.9 %)	103 (6.6 %)
$\dot{W}_{save}[MWh]$ in 2021	0.3 (0.41 %)	0.4 (0.54 %)	0.7(0.73%)	4.3(2.92 %)	7.1 (2.52 %)

CONCLUSIONS

This study dealt with performance optimization of a transcritical supermarket refrigeration system with CO_2 as its refrigerant by utilizing an ice tank unit. By discussing the effects of ice tank on the pressure enthalpy diagram of the refrigeration cycle:

- An energy optimization approach was proposed to determine the charge and discharge rates of the ice tank considering the operational constraints.
- By assuming a good forecast of the next day ambient temperature, the optimization problem is solved once a day to determine the charging profile of the ice tank tor the next day.
- The results of the optimization algorithm for five cities from different continents show an energy saving up to 7.9 % on the hottest day and up to 2.9 % over the year.
- A trend of increasing energy saving based on the location is related to the ambient temperature of each location.
- The higher the normal ambient temperature is in a location the more possibility of energy saving exist, and hence using ice tanks (cold storage) in this climate is economically justified.

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DTU Construct
DEPARTMENT OF Civil and Mechanical Engineering

ENGINEERING TOMORROW

Performance optimization for reclaiming heat efficiently in a CO2 refrigeration system

Authors: Christoffer Brun Bak Petersen & Lean Schrøder-Knudsen
Supervisor: Wiebke Brix Markussen
External collaboration: Danfoss, Salvatore Piscopiello

Problem statement:
Which cost-effective technologies can be integrated in an existing trans-critical CO2-refrigeration system to enhance the flexibility and the efficiency of heat recovery (HR)?
How do these technologies compare in terms of performance, heat recovery, flexibility and cost in a cold and moderate cold climate?

Introduction

CO2 can be used as a refrigerant with no additional environmental impact and is now being used increasingly in different applications. CO2 refrigeration systems is increasingly being installed in supermarkets [1], which are primarily located in colder climates. Because of the low critical temperature of CO2, compared to normal operating temperatures for a refrigeration system, it can operate trans-critically, depending on the ambient temperature. CO2 is very sensitive to changes in pressure in the transcritical area, where the isotherms are very close, which means temperature increases rapidly with minor pressure increases. This leads to a high temperature waste heat flow that typically is dissipated to the ambient. To increase the efficiency the heat can be utilized, which will increase the total performance of the system.

By request from and through conversations with Danfoss it is decided to investigate two technologies with specific configurations which can be implemented to improve the amount of heat produced, and specifically in cold and moderate cold climates (Helsinki and Stuttgart respectively). The first technology is the implementation of an air source false load evaporator connected to MT pressure level. The second is a heat pump set after the gas cooler. Also, it is decided that the heat recovery is only used for internal distribution inside the supermarket as space heat (SH).

Method

The load and temperature profiles are necessary to determine the heat and cooling demands at a specific ambient temperature. The loads for the supermarket are determined based on the method used by Giunta and Sawalha [2], which is an up-dated version of Karampour and Sawalha's research about the state of the art for integrated CO2 refrigeration systems for supermarkets [3], see figure 1.

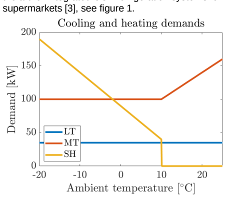

Figure 1: *The relation between the alternative heating/cooling demand and the ambient temperature*

The demand curve along with the temperature profile from the two selected areas, Helsinki and Stuttgart, was used as the specific load settings for the models.

System setups

The systems are designed as three different models; a benchmark (gas cooler only), one with an added false load evaporator (yellow marked area) and one with a heat pump bypassing the gas cooler (purple marked area), see figure 2.

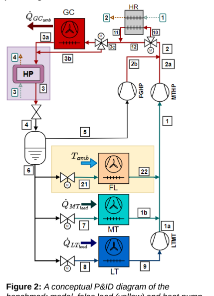

Figure 2: *A conceptual P&ID diagram of the benchmark model, false load (yellow) and heat pump (purple)*

Control strategies (From Danfoss)

The benchmark model is then objected to the control strategy as seen in figure 3, where the conditions for the exit of the gas cooler is changed according to the heat demand. The foundation of the strategies is designed by Danfoss.

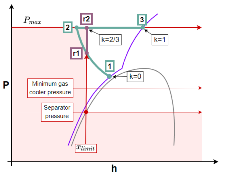

Figure 3: *Control strategy for the Benchmark model including limitations. K is the control parameter for pressure/temperature, varying SH production.*

The control strategy for the FL is almost identical to the benchmark but activates the FL when the state reaches step 2 (pressure limitation), see figure 4.

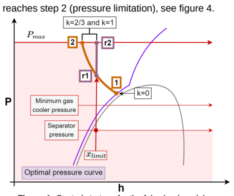

Figure 4: *Control strategy for the false load model including the limitations*

For the Heat pump model, the control strategy is not yet optimized and therefore the following strategy is assumed and implemented in the model, see figure 5.

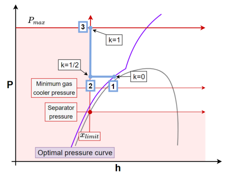

Figure 5: *Control strategy for the false load model including the limitations*

In order to compare the different models, the term ΔHC [−] is created as a change in heat cost for the extra heat recovery compared to the optimal refrigeration setpoint. Also, the term HR_{ratio} is used in order to define the production ratio of SH compared to cooling.

General model setpoints

In order to evaluate the amount of heat recovery each system can deliver, the setpoints in Table 1 are decided.

Table 1: *Setpoints for the heat recovery models*

Name	Description	Value	Unit
$\dot{Q}_{MT}$	Cooling load middle temperature	100	kW
$\dot{Q}_{LT}$	Cooling load low temperature	35	kW
$T_{eva,MT}$	Saturation Temperature in MT	−8	°C
$T_{eva,LT}$	Saturation Temperature in LT	−32	°C

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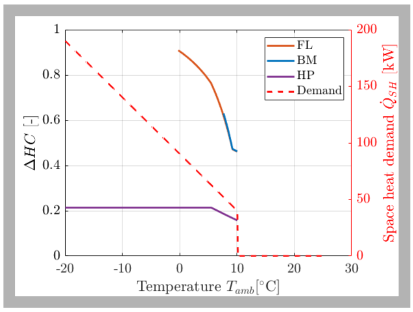


Figure 9: *The cost of extra heat, ΔHC, for each of the three models are shown in the temperature range with a certain space heat demand, shown by the red dotted line. Temperature range only shown where full demand can be delivered.*

Results

It is found that the maximum heat output for the benchmark and false load models are not able to deliver the full amount of heat demand throughout the year, where the heat pump model fulfills the demand, see figure 6.

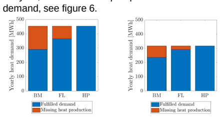


Figure 6: Yearly demand fulfilled, Helsinki (left) and Stuttgart (right)

For the benchmark and false load model the ΔHC is shown to be identical until the activation of the FL model, which has implemented an ideal on/off control strategy to cater for a demand in between the FL activation point, see figure 7.

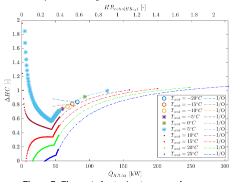


Figure 7: *The cost of extra heat recovery for a combination of the benchmark and the false load model. Dotted lines is ON/OFF storage control between BM end and FL activation point*

For the heat pump model it is shown that the heat pump was able to deliver the full heat demand at all ambient temperatures, and a ΔHC much lower than the other models. The heat pump model is simulated using an on/off control with the activation of the heat pump, see figure 8.

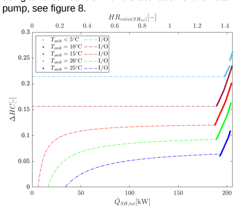


Figure 8: *The cost of extra heat recovery for a the HP model. Dotted lines show implementation of ON/OFF strategy.*

Figure 9 compares the flexibility and cost of extra SH produced for the BM, FL and HP models. It is clearly shown that the HP model is the best solution, as it is flexible enough to cover the SH demand at all ambient temperatures and with a significantly lower ΔHC than the FL and BM. When given a specific case the same is apparent.

The BM and FL models show better performance with higher temperature until summer, where heat demand is very low, see figure 10. The HP model is better at lower temperatures, which is counteracting the actual COP of the HP unit. This is related to the control strategy; with higher ambient temperature the heat pump will have a larger amount of OFF-time (BM model). where the overall COP is lower.

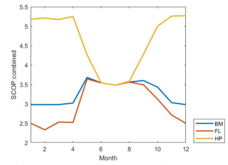


Figure 10: Seasonal SCOP variation during a year for Helsinki (best reference year: 2013)

Discussion & Conclusion

Assumptions regarding heat, pressure loss, and perfect controls are simplifying the models, but not affecting the objective of comparing cost and performance indicators of the different technologies.

In alternative load cases, where SH demand and/or SH minimum activation temperature is changed, HP was still seen to be best.

Helsinki, which is the colder climate, show a lower SCOP for BM and FL compared to Stuttgart, which is the moderate cold climate, while SH demand is highest in Helsinki, which makes for a worse evaluation. The opposite relation is seen for the HP model, where SCOP is slightly better in Helsinki, as the HP is ON more of the time. Generally it is possible to gain a large fraction of the heat demand in the two climates for all the models.

The FL model is a very simple and inexpensive way to change the configuration to produce more SH in cold climates, but the operation expenses could seem to be high.

Although the HP can deliver the full heat demand at a lower cost than the other technologies, the possible implementation requires a larger initial investment. The control strategy needs to be fully developed, and the cost of the heat pump in itself need to be evaluated and compared to the operating expenses.

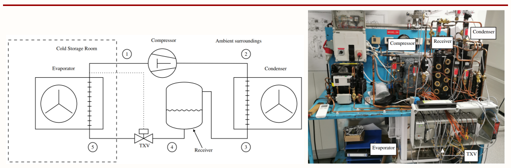
Digital Twins for Fault Detection in Heat Pumps and Refrigeration Systems

Christian Mikael Wolf

Introduction

The field of refrigeration spans wide across many applications but also has a great environmental impact due to the refrigerant used and the energy consumption of these systems [1]. This impact is even greater due to the faulty operation which is often undetected for numerous systems. The use of fault detection and diagnostics has been known for decades but with limited commercial use within the field of refrigeration systems [2]. Currently, data-driven fault detection and diagnostics methods are the most common but the use of physics-based digital twins does have several advantages. In this thesis, a physics-based digital twin for fault detection in heat pumps and refrigeration including a liquid line receiver which can simulate fouling and leakage has been developed.

Method



(a) (b)

Figure 1: (a) Schematic of the vapour compression cycle investigated and (b) the experimental setup

In this thesis, the digital twin was modelled following the ideology of the simulation process. This is an iterative method which strives towards the lowest level of detail needed, meaning that complexity is only added to the model if needed [3]. This led to the system being modelled by using compressor polynomials, moving boundary discretised heat exchangers accounting for void fraction along with air-side heat transfer coefficient, fan characteristics, a steady state thermal expansion valve model and a simple receiver model. Furthermore, two approaches for estimating the heat transfer coefficient over finned tubes. The fouling was modelled by introducing an additional air side pressure drop over a heat exchanger based on the thickness of material growth on the fins and leakage as loss of refrigerant charge. The model was validated against an experimental setup. Furthermore, the model has been used to generate synthetic fault-free and faulty operational data both regarding fouling and leakage. The data has been used to train a fault detection and diagnostics tool based on a decision tree machine learning algorithm. The accuracy of the fault detection and diagnostics tool has been investigated based on several parameter sets.

Results and discussion

The digital twin has been successfully validated against the fault-free and faulty operation of an experimental setup with regards to fouling, see fig. 2. The heat transfer model proposed by Granryd proved to result in the lowest deviation from experimental data. Leakage was not possible to experimentally validate due to the limitations of the experimental setup. The digital twin was used to investigate the influence of fouling and leakage. The fouling proved to have a great negative impact on the performance of the system due to changes in operational conditions but had small influences on the mass distribution within the components. Whereas leakage results in no impact on system performance due to the receiver in the system acting as a refrigerant buffer allowing other components to operate at optimal conditions if a liquid level in the receiver was present.

The digital twin was used for data generation of fault-free and faulty operational data used for training and testing of a fault detection and diagnostics tool. The fault detection and diagnostics tool was able to predict single simultaneous occurring faults with great accuracy when using the first parameter set and low accuracy for set 2, see table 1. Firstly, this highlighted that a level measurement in the receiver was a necessity for detecting leakage and secondly, the UA-value proved to be the best parameter for fouling detection, even a simple estimation of the UA-value which is used in the parameter set 1. The fault detection and diagnostics tool had lower accuracy in predicting multiple faults occurring simultaneously. The study also highlighted the sensitivity of a fault detection and diagnostics tool with regard to fault severity as lower accuracy was observed when the fault severity was low.

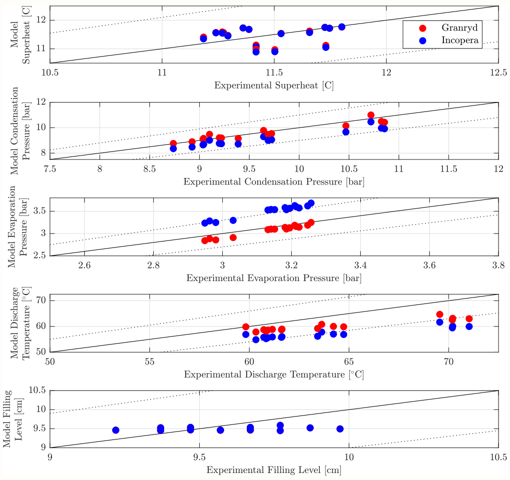


Figure 2: Comparison between model obtained and experimentally obtained results. The solid line indicates where model and experimental data are equal and the dotted lines are ± 10 % deviation indicators. Heat transfer model proposed by Granryd and Incropera [4, 5].

Table 1: Confusion matrices for 2 parameter sets with settings of fouling $[0, 20\%]$, refrigerant charge of $[100\%, 90\%]$. Categories are 1) Fault free, 2) Condenser Fouling, 3) Evaportor Fouling and 4) Leakage

(a) Parameter sets

1	$T_{air,cond,i}$, $T_{air,evap,i}$, $UA_{cond,est}$, $UA_{evap,est}$, L_{fill}, $\Delta T_{app,evap}$, $\Delta T_{app,cond}$
2	$T_{air,cond,i}$, $T_{air,evap,i}$, $\Delta T_{app,evap}$, $\Delta T_{app,cond}$, $\Delta T_{s,evap}$

(b) Parameter Set 1

Cat.	1	2	3	4
1	16	1	4	-
2	-	21	-	-
3	3	-	18	-
4	-	-	-	21

(c) Parameter Set 2

Cat.	1	2	3	4
1	1	-	-	20
2	5	1	1	14
3	-	1	1	19
4	20	-	1	-

Conclusion

The results of this study proved that a digital twin was able to be validated and used for the generation of synthetic data for training a fault detection and diagnostics tool. This study should be seen as a preliminary showcase of the great possibilities of using physics-based digital twins and the fault detection and diagnostics tool in unison.

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International Symposium on Advances in Refrigeration and Heat Pump Technology 2023

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