Electrification by high temperature heat pumps

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Technology for a better society

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KEY QUALIFICATIONS Heat Pumps, Drying technology, Refrigeration
Thermal process engineering, Heat and mass transfer, Food Technology, Food properties and quality,

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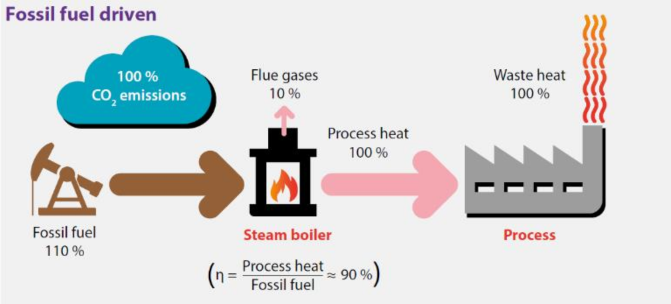
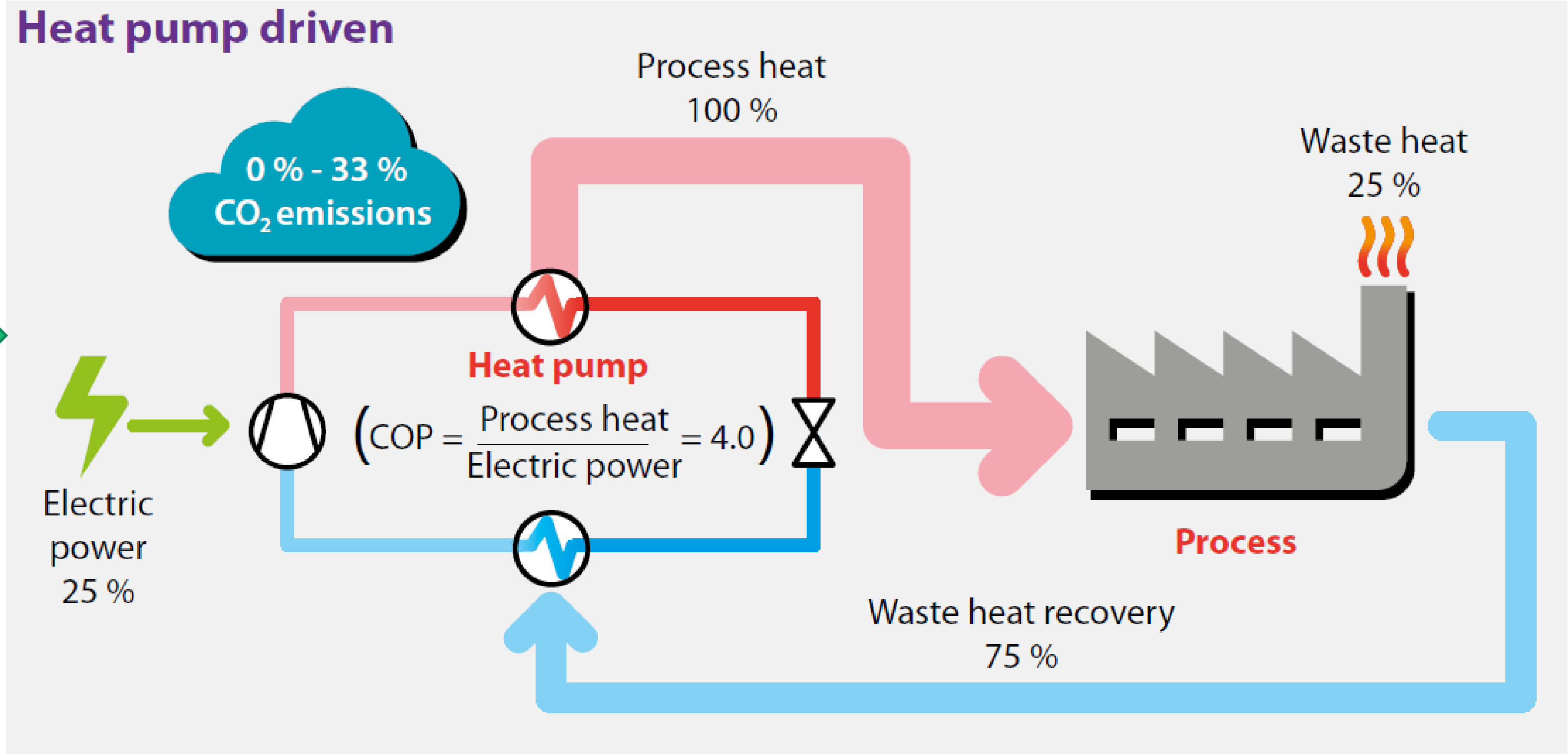
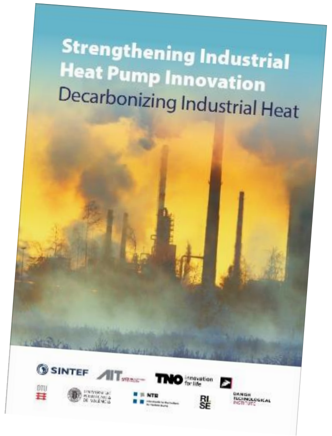
since 2012	SINTEF Energy Research, Department Thermal Energy
2011 – 2012	Post-Doc at NTNU, *Energy efficiency in drying processes*
2007 – 2011	PhD at NTNU, *Study of high intensity, airborne ultrasound in atmospheric freeze drying.*
2002 – 2007	University of applied science, Konstanz Germany, Process and Environmental engineering, Diploma thesis: *Dimensioning of drying and conditioning unit for soybeans.*

What can the heat pump do in an electrified future?







https://www.sintef.no/globalassets/sintef-energi/industrial-heat-pump-whitepaper/2020-07-10-whitepaper-ihp-a4.pdf

What is the Technological Readiness Level of HTHP ?

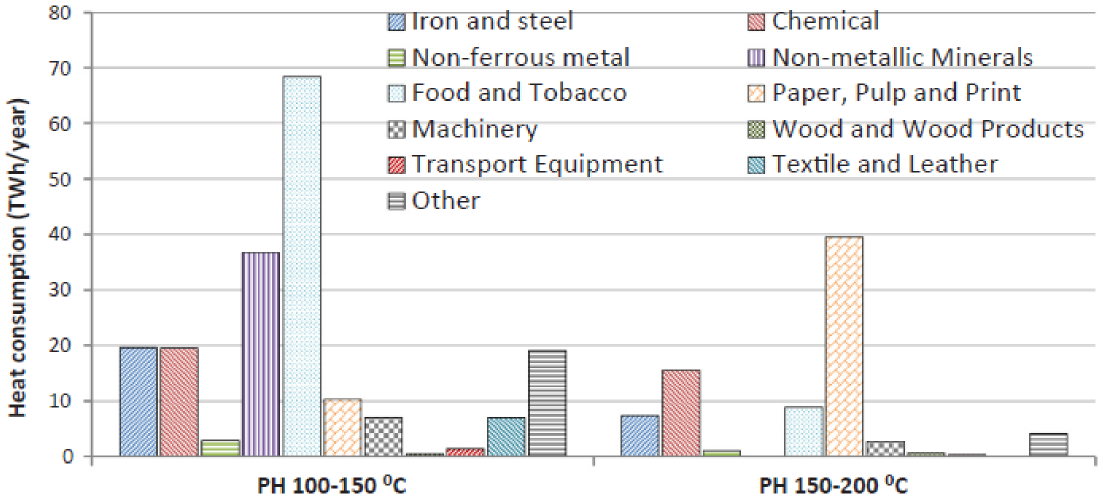
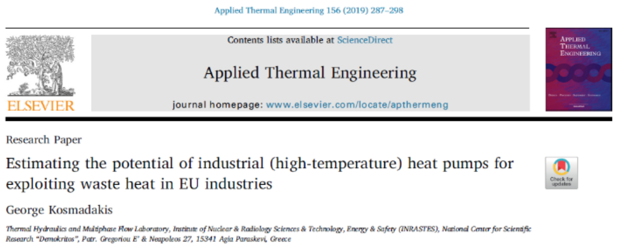


Fig. 3. Heat consumption within the two temperature bands of interest per industrial sector in EU.

https://www.sciencedirect.com/science/article/abs/pii/S1359431118376087?via%3Dihub



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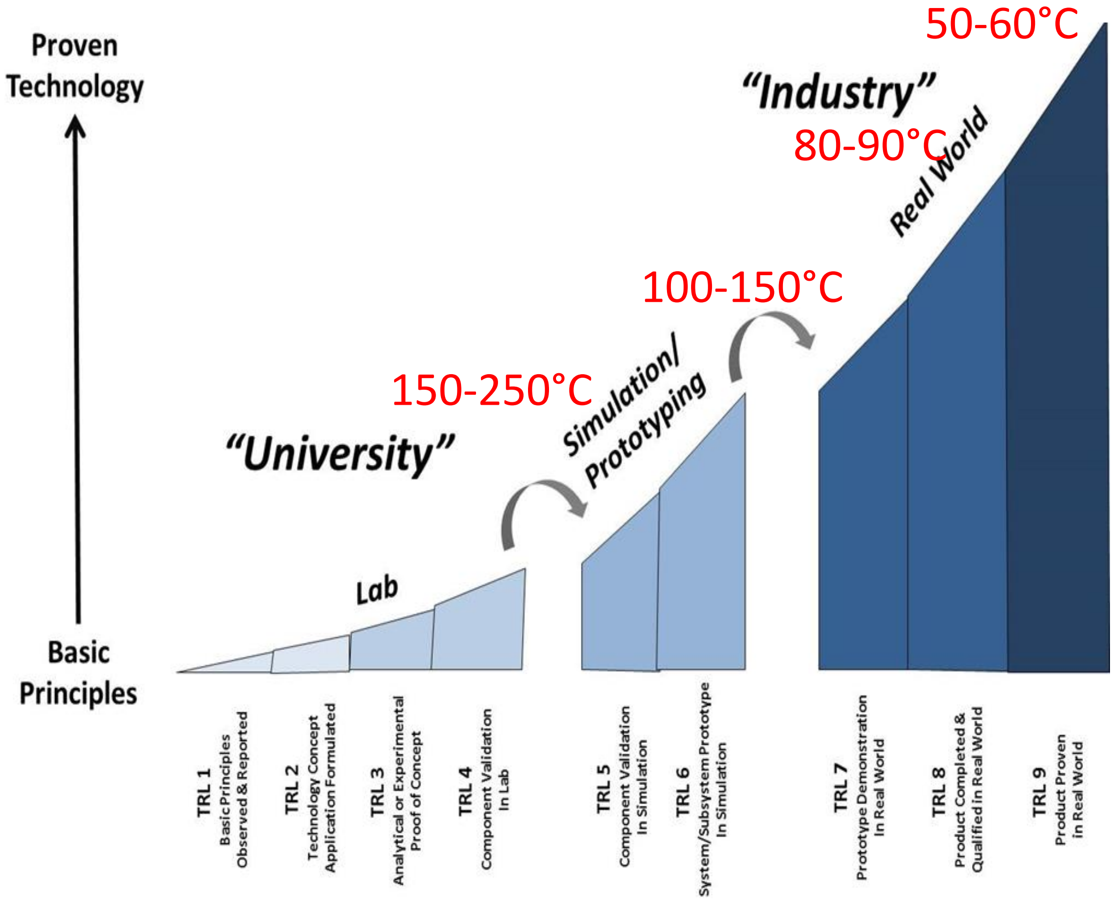
Research Paper

Estimating the potential of industrial (high-temperature) heat pumps for exploiting waste heat in EU industries

George Kosmadakis

Thermal Hydraulics and Multiphase Flow Laboratory, Institute of Nuclear & Radiology Sciences & Technology, Energy & Safety (INRASTES), National Center for Scientific Research "Demokritos", Patr. Gregoriou E' & Neapoleos 27, 15341 Agia Paraskevi, Greece



What is the heat source for high temperature (steam producing) heat pumps?

- → Industrial Waste heat
- → Ambient Air
- → Renewable energy Sources
- → Geothermal
- → Simultaneous cooling demand
- →...

- How can we integrated this heat source with the steam demand?
- What is the recovery temperature?

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IEA Annex-58 High Temperature Heat Pumps

State of the art, demonstration cases and development perspectives

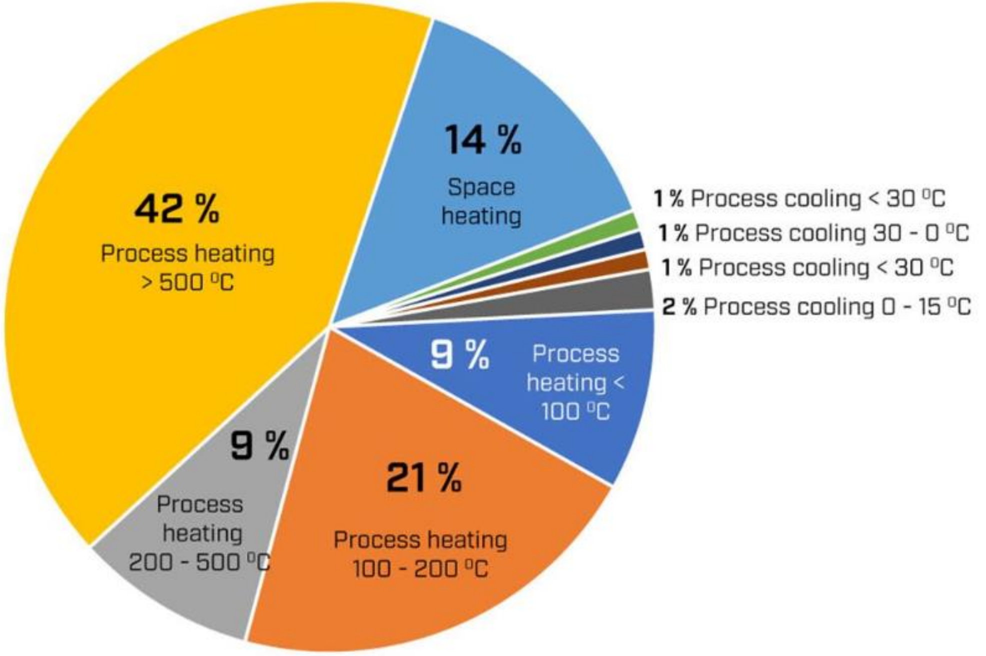
Ole Marius Moen

Technology for a better society

IEA HPT

Motivation

- European process heating and cooling accounts for 50 % of the final energy consumption of the industry
- High-temperature heat pumps are a key solution to replace fossil fuel-based heat supply for industrial processes
- 500 TWh potential - 21% of heat demand between 100-200°C
- Few demonstrated cases



Source: Heat Roadmap Europe (2017), *Profile of the heating and cooling demand in 2015*

Introduction and Objectives

- Working group under Technology Collaboration Program (TCP) umbrella of IEA
- Participating organisations operating as National Teams
- Lead by operating agent, Benhamin Zühlsdorf, DTI
- 3 year duration (M1 2021 – M12 2023)

Annex name:	Annex 58 about High-Temperature Heat Pumps
Operating Agent:	Benjamin Zühlsdorf, PhD, bez@dti.dk Danish Technological Institute, Energy and Climate
Participating countries:	• Austria • Belgium • Canada • Denmark • France • Germany • Japan • Netherlands • Norway • Switzerland
Homepage:	https://heatpumpingtechnologies.org/annex58/

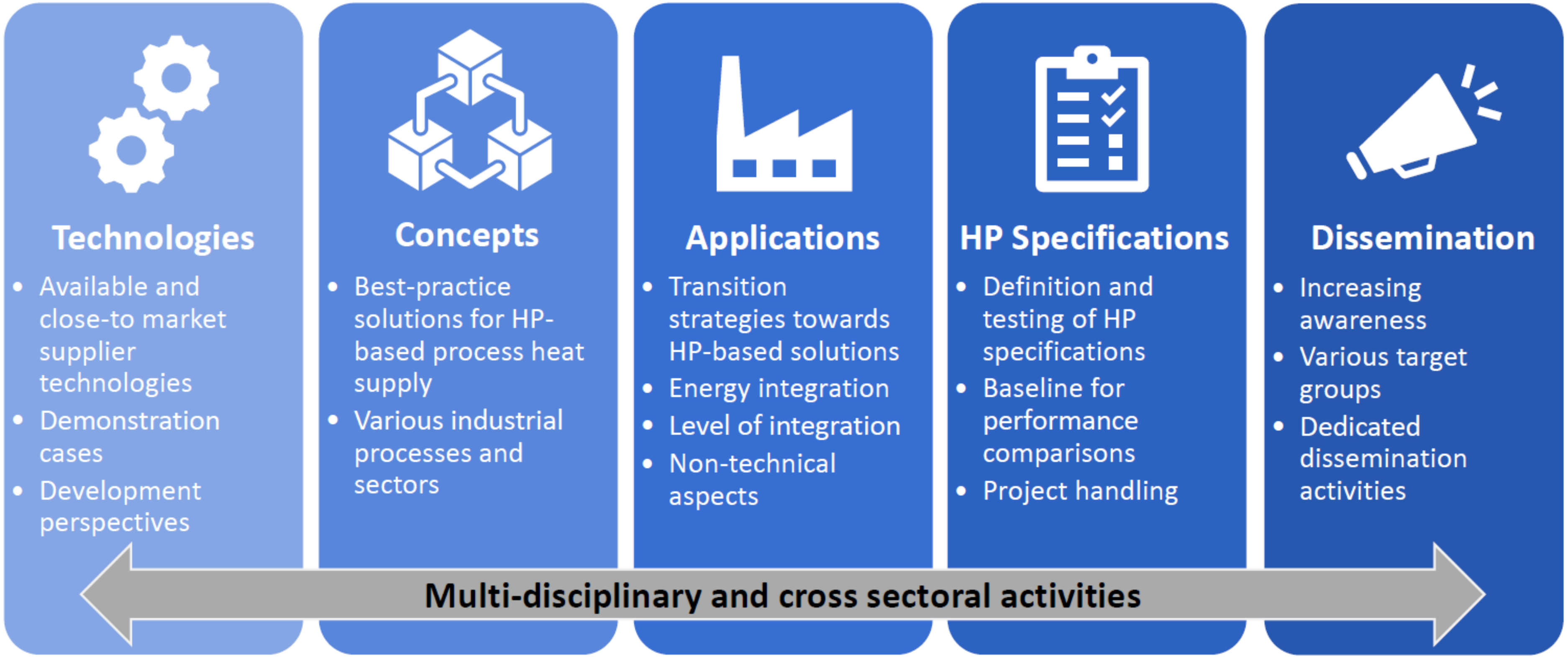
Objectives

- Provide overview of HTHP technology, possibillities and applications
- Identify bottlenecks and technological developments needs
- Develop best practice recommandations
- Improve understanding among stakeholders

Norwegian Team Contribution

- Norwegian Team: SINTEF
- 50% Supported by Enova: 950 kNOK for the whole period
- Participating on bi-monthly annex-meetings
- Contribute to the annex-deliverables,
  - Task1: Technology development from a Norwegian perspective
- Share knowledge and experience from relevant projects

Scope of activities



Source: Zühlsdorf, B., et al (2022), IEA HPT Annex 58 about High-Temperature Heat Pumps - State of the art review, demonstration cases and development perspectives, HTHP Symposium

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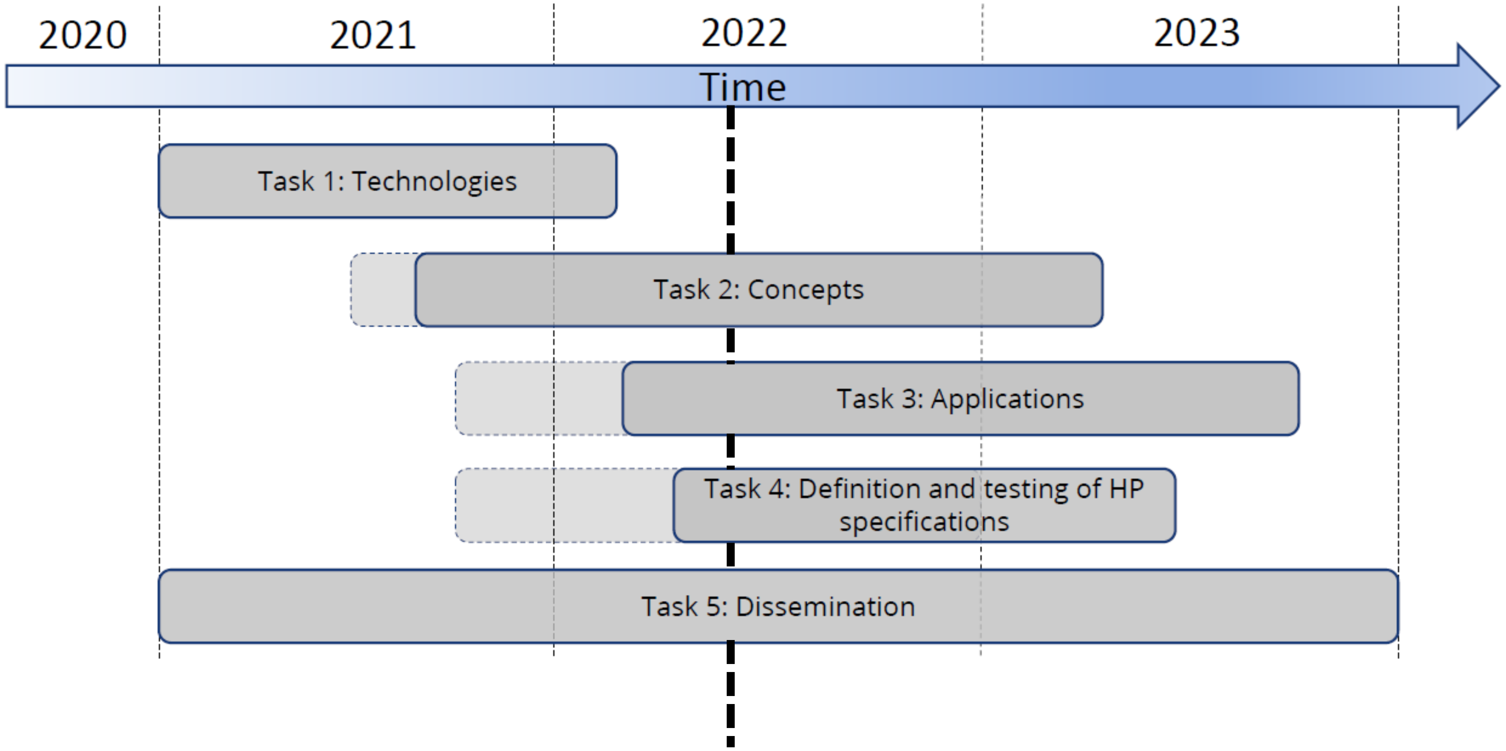
Timeline



Task Lead	Reporting
DTI	Joint Report
OST/DTI	Joint Report
AIT/DTI	Joint Report
DTI	Joint Report
DTI	-

Source: Zühlsdorf, B., et al (2022), IEA HPT Annex 58 about High-Temperature Heat Pumps - State of the art review, demonstration cases and development perspectives, HTHP Symposium

Task 1: Technologies

- Overview of supplier technology with heat supply > 100°C
  - Market available (TRL 8-9)
  - Prototype and demonstration systems (TRL 6-7)
  - Lab/small-scale prototypes (4-5)
- Overview of demonstration systems
- Development perspectives

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Comparison between supplier technologies

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 0.5 MW to 2 MW with reciprocating compressor, or 1 MW to 5 MW with screw compressor.

Temperature range: Sink out from 70 °C to 120 °C, with max. temperature lift of 90 °C.

Working fluid: Ammonia and water.

Compressor technology: Piston, screw compressors.

Specific investment cost for installed system without integration: From 200 €/kW up to 600 €/kW depending of the effect and the number of compressors.

TRL level: TRL9 (20+ heat pumps in operation)

Expected lifetime: 20+ years.

Size: Depending on power of the heat pump: max. footprint for 2 MW system is 3.6 m x 6.5 m.

Task 1 – Norwegian contribution

- Technology Mapping and description:
  - Norwegian HTHP Technology and system suppliers
  - Demo cases
- Norwegian heat demand, heat pump potential and future development perspectives
- Overview of current and previous research projects

Annex 58 High-Temperature Heat Pumps

www.heatpumpingtechnologies.org/annex58/

HEATEN

HeatBooster
Heaten AS

Figure 1: HeatBooster VHTHP

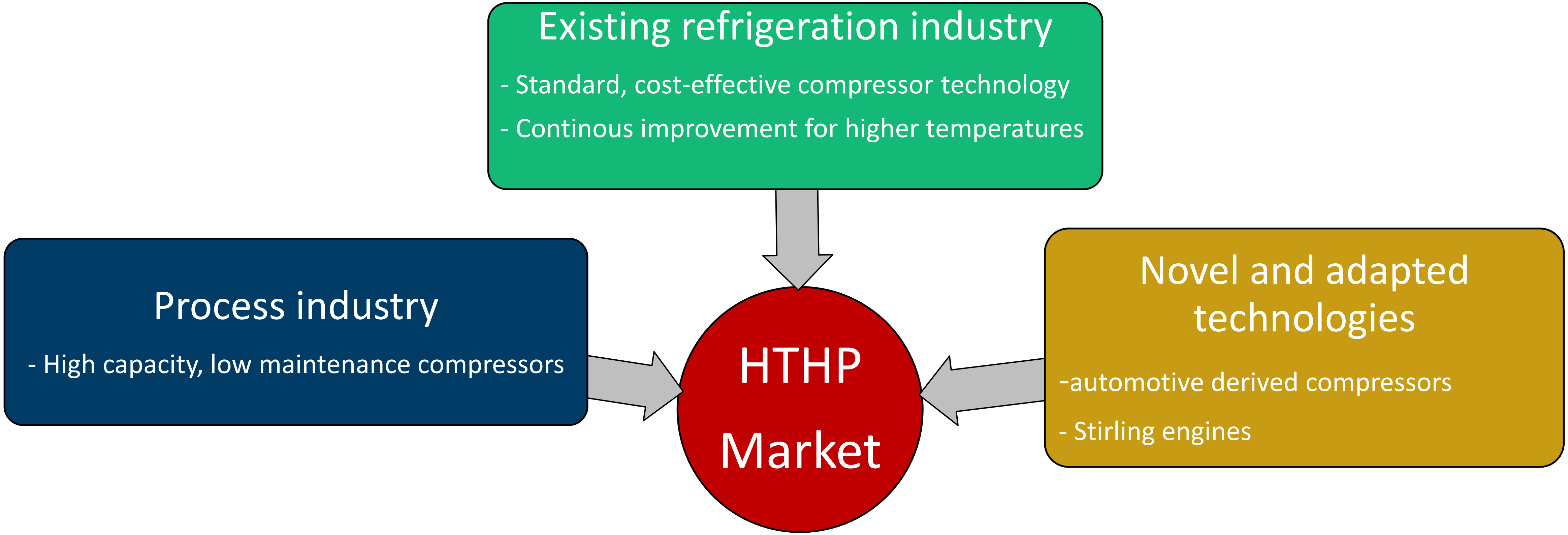
Summary of Technology

Heaten's patented very-high-temperature heat pump is based on an efficient, durable and highly flexible piston compressor. The HeatBooster turns waste heat into process heat with a value, and is the only technology that can provide an output temperature up to 165 °C.

- The HeatBooster system layout is a one-stage, closed-loop vapor compression heat pump ideal for single or cascade configurations. The heart of the heat pump is a reciprocating compressor.
- The driving energy of the HeatBooster is electricity.
- There are vast opportunities for implementation of Heaten's technology. Some of the relevant applications are district heating, sugar refining, pulp & paper, plastics manufacturing, drying systems and breweries.
- The table below shows typical expected performances under relevant operating conditions. The performance data are based on the actual performance of an industrial 200 kW thermal pilot system, including design and performance improvements.
- Heaten's piston compressor can utilize heavy-duty production tooling and facilities worldwide.
- The HeatBooster uses standard lubricant types that are compatible with the respective working fluids.
- Heaten is currently scaling up the current technology platform to a product family in the megawatt range
- The suitable heat transfer fluid on the source and sink sides is water or steam. The temperature range for the heat source is 2 – 150 °C, and the temperature range for the heat sink is 70 – 200 °C.
- The HeatBooster has a rapid start-up and shut-down time and has a turn-down ratio down to about 20 %. It can handle rapid load changes.
- Standard units span from 1 to 6 MW (can also be delivered as direct-steam version).

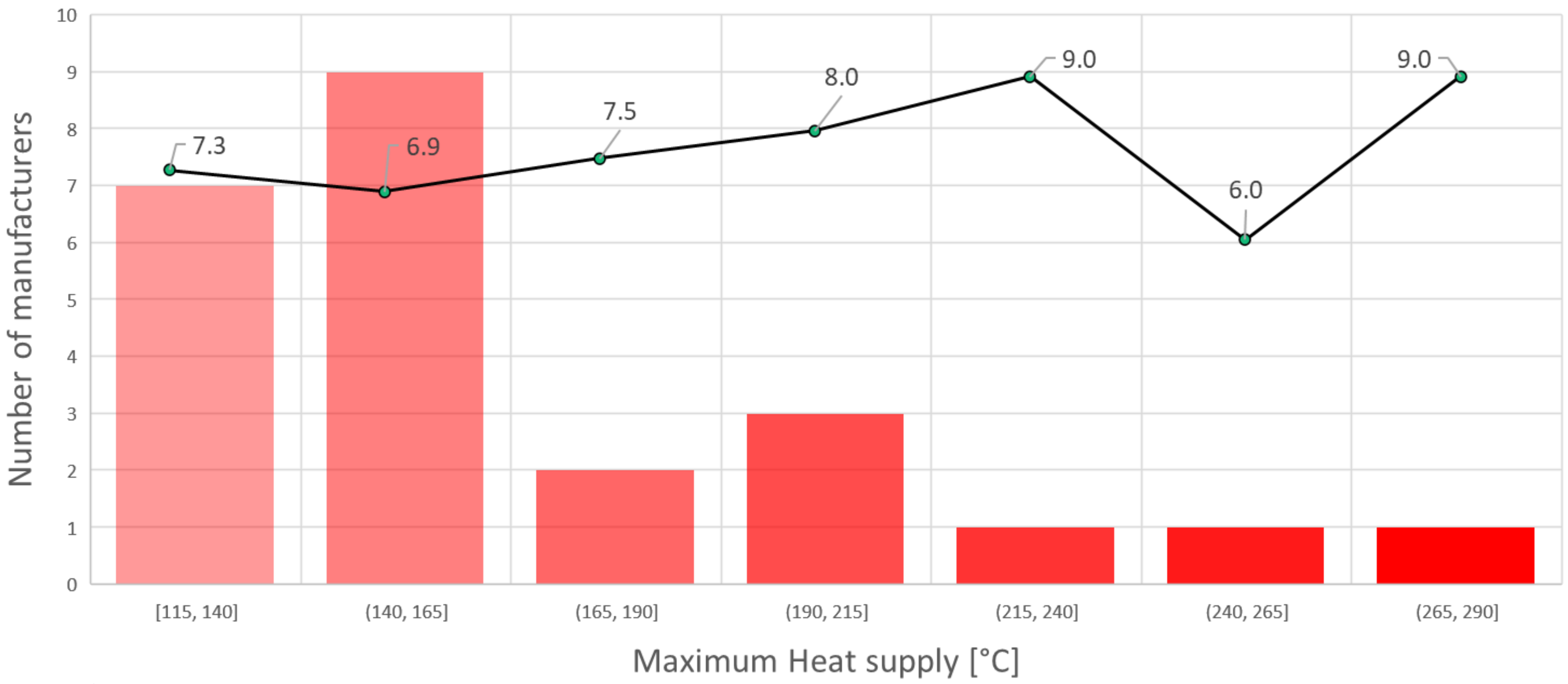
IEA Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)

Supplier technology overview



Supply temperatures

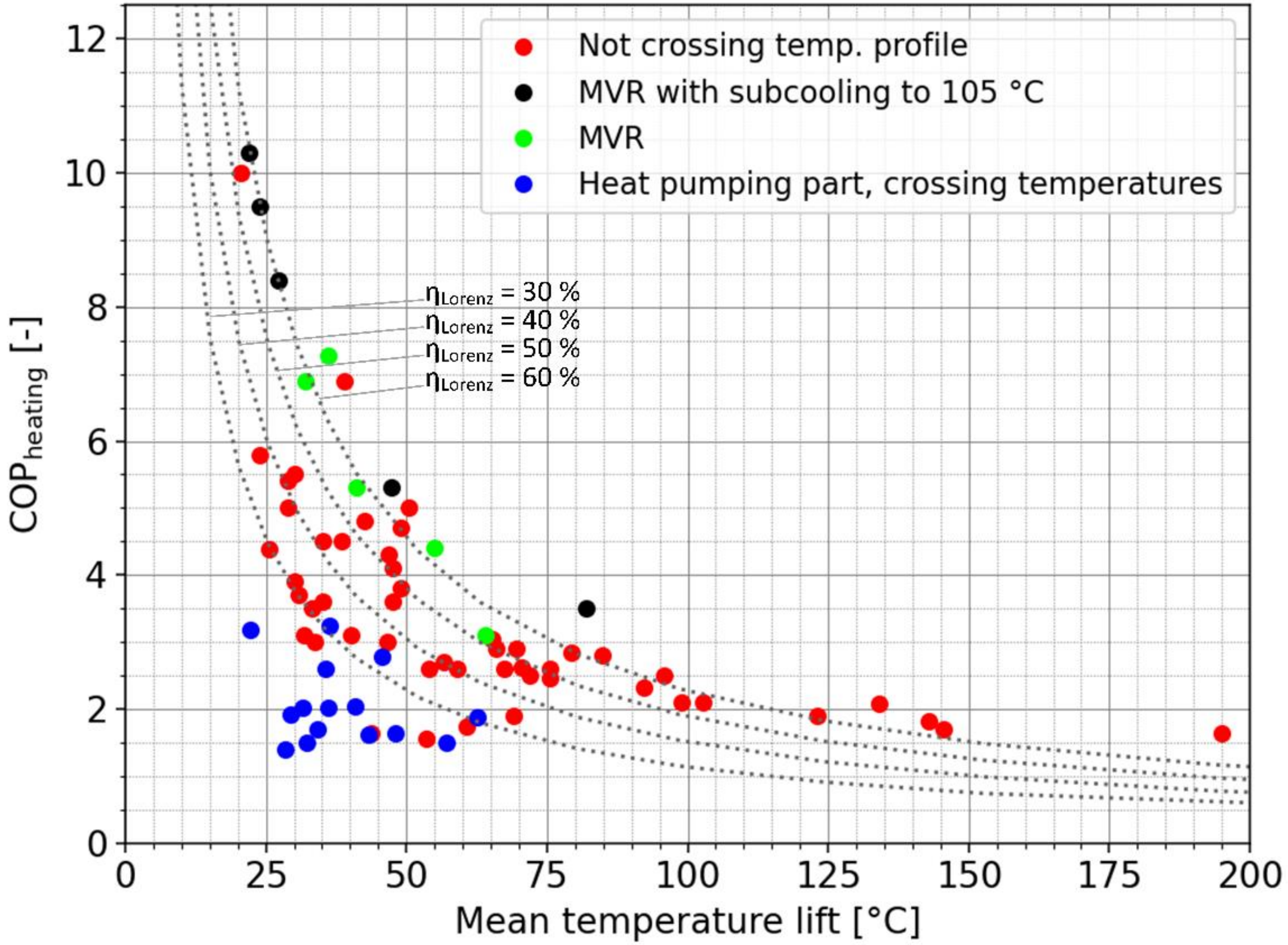
Maximum heat supply [°C] and number of manufacturers



Indicated TRL levels

COP and efficiencies

- Strong correlation between $COP_{heating}$ and the mean temperature lift
- Lorenz efficiencies typically 30-60%
- Efficiencies tend to increase for higher temperature lifts
- MVR based systems reported highest efficiencies

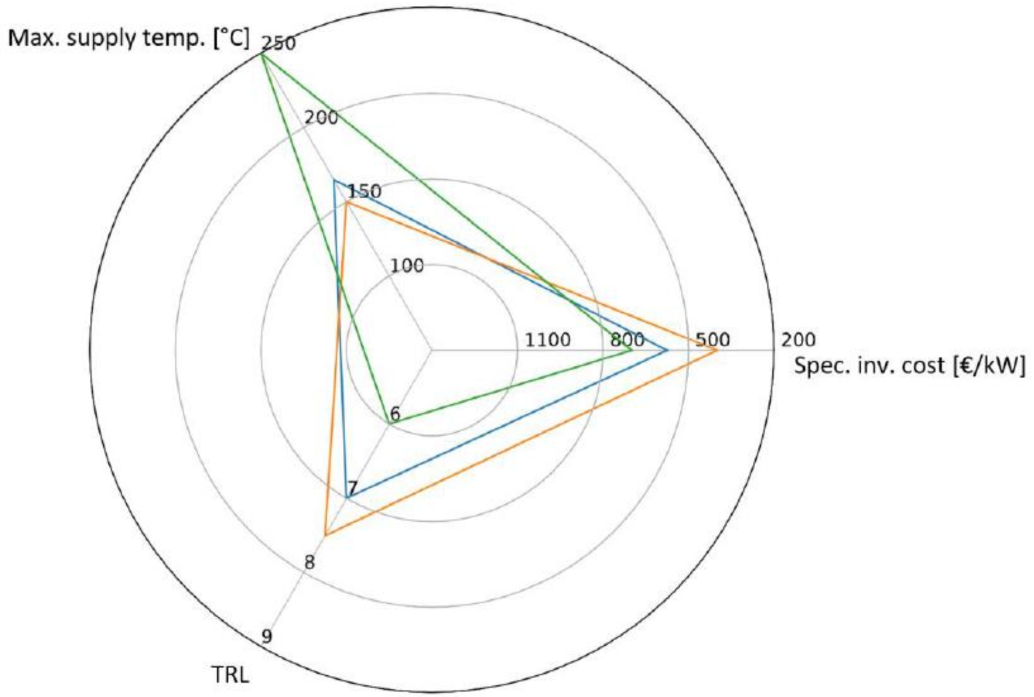


Source: IEA Heat Pumping Technologies Programme Annex 58 (2022), Task 1: Technologies State of the art and ongoing developments for systems and components (draft report)

Task 1 – Technology summary

Key summary:

- TRL: 4-9
- Max. heat supply temperatures: 115 – 280 °C
- Capacities: 0.03 MW – 70 MW
- Specific investment costs: 150 – 2000 €/kW
- Large variation in technology (working fluid, compressors)
- Trade-off between temperature, costs, and TRL

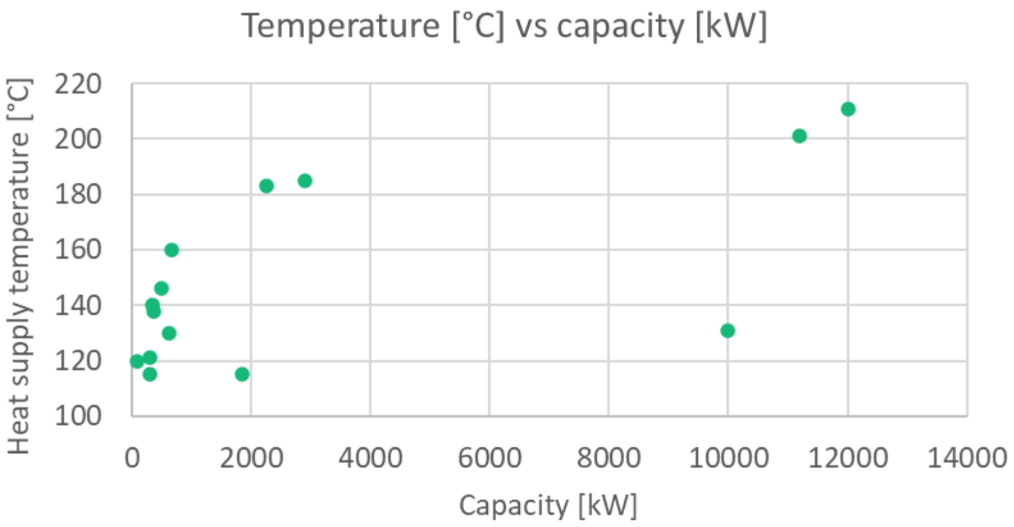


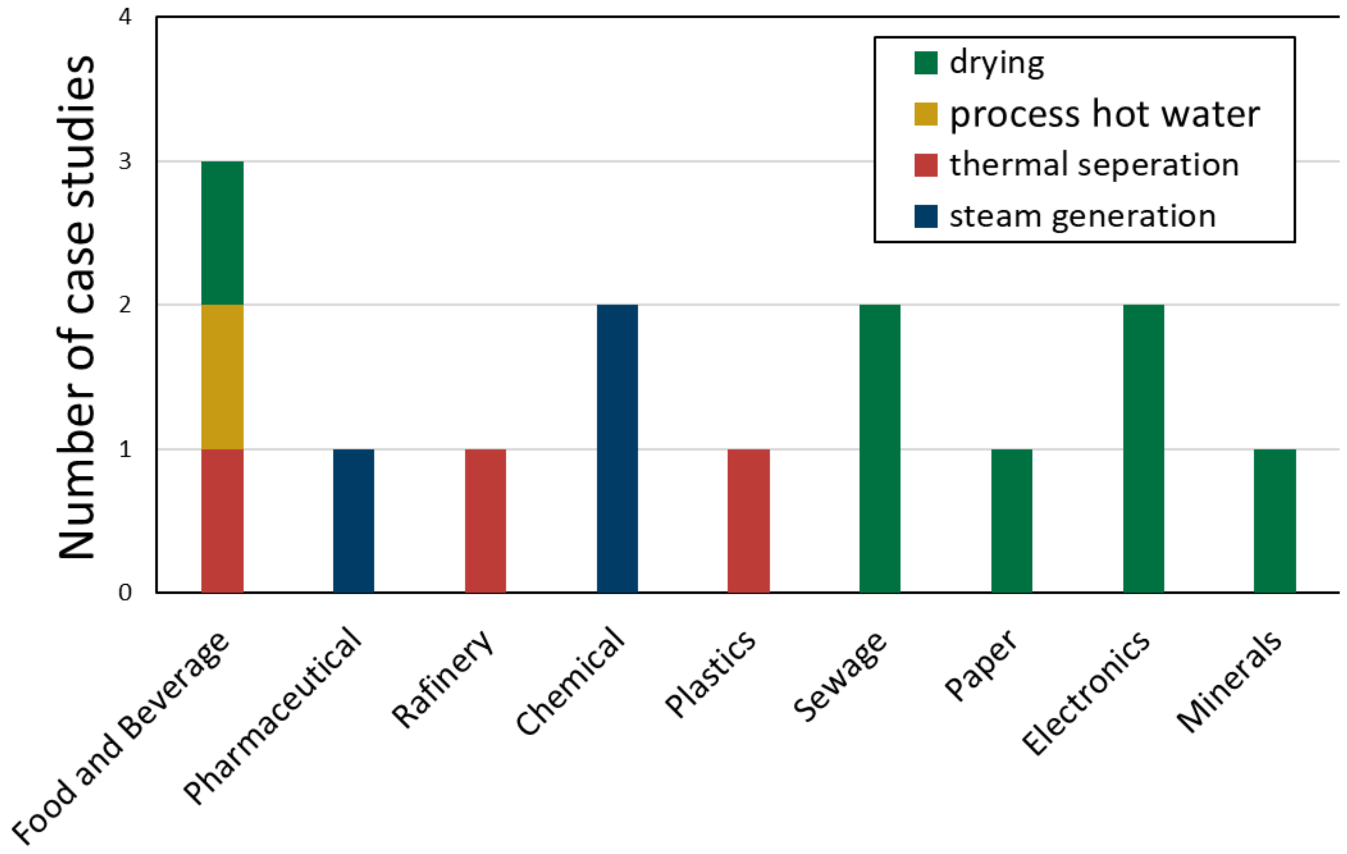
3 examples of dependencies for HTHP technologies

Source: Zühlsdorf, B., et al (2022), IEA HPT Annex 58 about High-Temperature Heat Pumps - State of the art review, demonstration cases and development perspectives, HTHP Symposium

Overview of demonstration cases

- 12 demonstration cases
- Varied accross different industries
- Applications
  - Steam generation for thermal separation
  - Steam and air based drying
  - Hot water generation





Source: IEA Heat Pumping Technologies Programme Annex 58 (2022),
Task 1: Technologies State of the art and ongoing developments for systems and components (draft report)

Development perspectives

Temperature →

120-140°C | 160-180°C

Applications:
- Pressurized hot water
- Low pressure steam generation, Steam and air based drying

Technology perspectives
- Commerical heat pumps available
- Large number of technologies near market ready
- Closed cycle heat pumps
- Synthetic and natural refrigerants (CO_2, HCs, HFOs, ammonia-water, LP steam)
- Cost reduction through standardisation

Applications:
- Medium pressure steam generation, drying and distilliation

Technology perspectives
- Large competition of suppliers and technologies
- Steam as working fluid becomming attractive, either stand-alone or as a top cycle
- Pentane, Helium (Stirling cycle)
- Open loop and closed loop heat pumps
- First commercial systems in place
- 2-4 years for wider market deployment

Applications:
- High pressure steam generation

Technologies

A few demonstration plants existing

- Large scale MVR technology (R-718)
- Reversed Brayton (CO_2)
- Stirling cycle
- Heat transformers

- Need more technology developement:
- More prototypes expected for demonstration: 2-4 years

INDUSTRIAL HIGH TEMPERATURE HEAT PUMP FOR SIMULTANEOUS PROCESS COOLING AND HEATING

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IEA HPT TCP National Workshop – Heat pumps in Norway, Oslo 10.05.2022

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Component development,
Lab and industrial pilot scale tests

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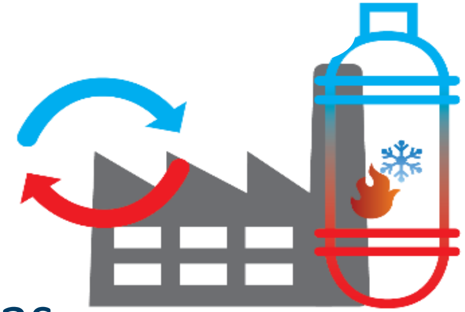
Outline

1. Motivation and Background
2. HTHP cases for dairy production
   i. Retrofit of Existing dairy
   ii. New build dairy
3. Comparison of HTHP perfromance
4. Summary

Challenges are opportunities – Low-emission concepts combined with energy-efficient solutions will strengthen the industry

- Industrial process sectors heavily relies on fossil fuel
- Climate targets are not reached due to lack of market ready technology
- Long return of investment for climate-friendly energy supply
- Low temperature excess heat is not utilized
- Awareness of HTHP-technologies is gaining momentum ☺
- Primary energy reduction will reduce dependency on Russian natural gas
- Demand for natural refrigerants as consequence of the regulation



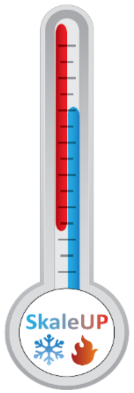
1st generation - Natural	2nd generation - HF	3rd generation - HFC	4th generation - HFO
(1830-1930)	(1930-1990)	(1990-2010)	(2010-?)
Work	Safety	Ozone protection	Global warming

Degradation to HF und TFA

Focus

Natural refrigerants

- CO_2
- NH_3
- H_2O
- HCs
- ++



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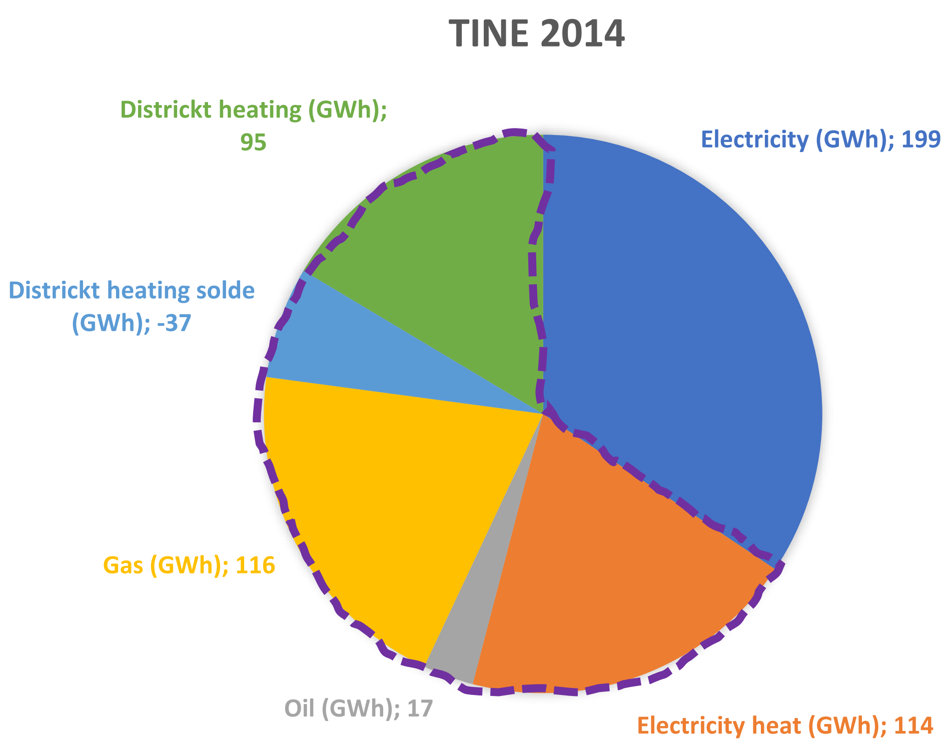
Motivation – HTHP enables industry to increase energy efficiency and reduce GHG-emissions



- **TINE aims to produce all diary products with renewable energy in 2025**

- **Situation for dairy production in 2014**
  - Total energy consumption 503 GWh
  - Heating 305 GWh
  - Large demand for heating in temperature range of 90°C to 180°C

→ HTHPs and HPs can help TINE to achieve this goal

Implementation cases

Case 1 – RETROFIT : Tine dairy Trondheim (Norway)

- Annual production: 75 mio. liter milk
- Cold supply:
  - 4 NH_3-condensing units (2700 kW_{th}, -1,5 °C / 33 °C)
- Process heat supply:
  - Hot water transcritical CO_2-Heat pump 160 kW_{th}, 0 °C / 10 °C bis 75 °C
  - Process electrical heat 3000 kW_{th} 95 °C/115 °C
  - District heating and oil burner as 100% Backup

Case 2 – NEW (2019): Tine dairy Bergen (Norway)

- Annual production: 43,4 mio. liter Liter milk products
- Photo voltaic : 6 000 m²
- Completely integrated process cold (-1,5°C) and hat supply (snow smelting 20°C to Pasteurisation 95°C)

Heat pump city of the year 2019 in the Decarb Industry category

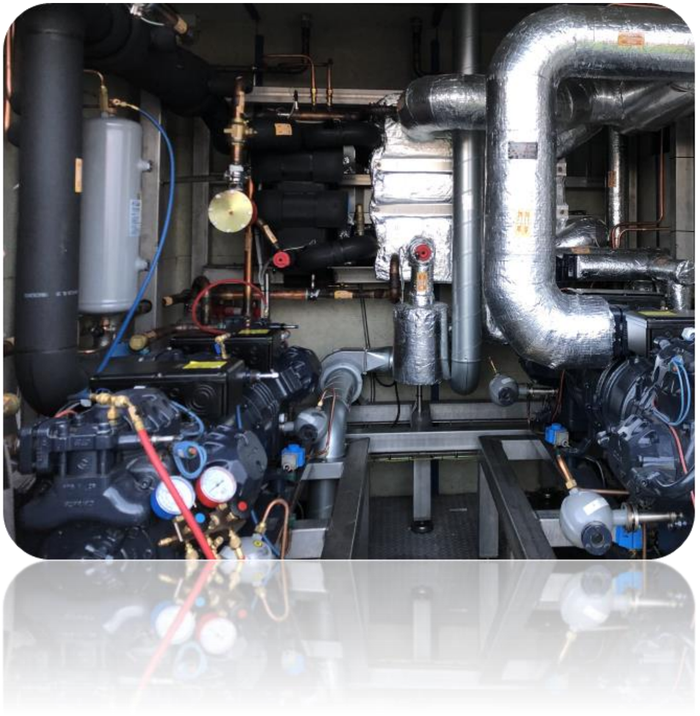
This project represents the first dairy in Norway entirely supplied by heat pumps, the first one without fossil or direct electric heating. This solution provides a reduction of the energy consumption of 40% compared with other regular dairies located in Bergen.

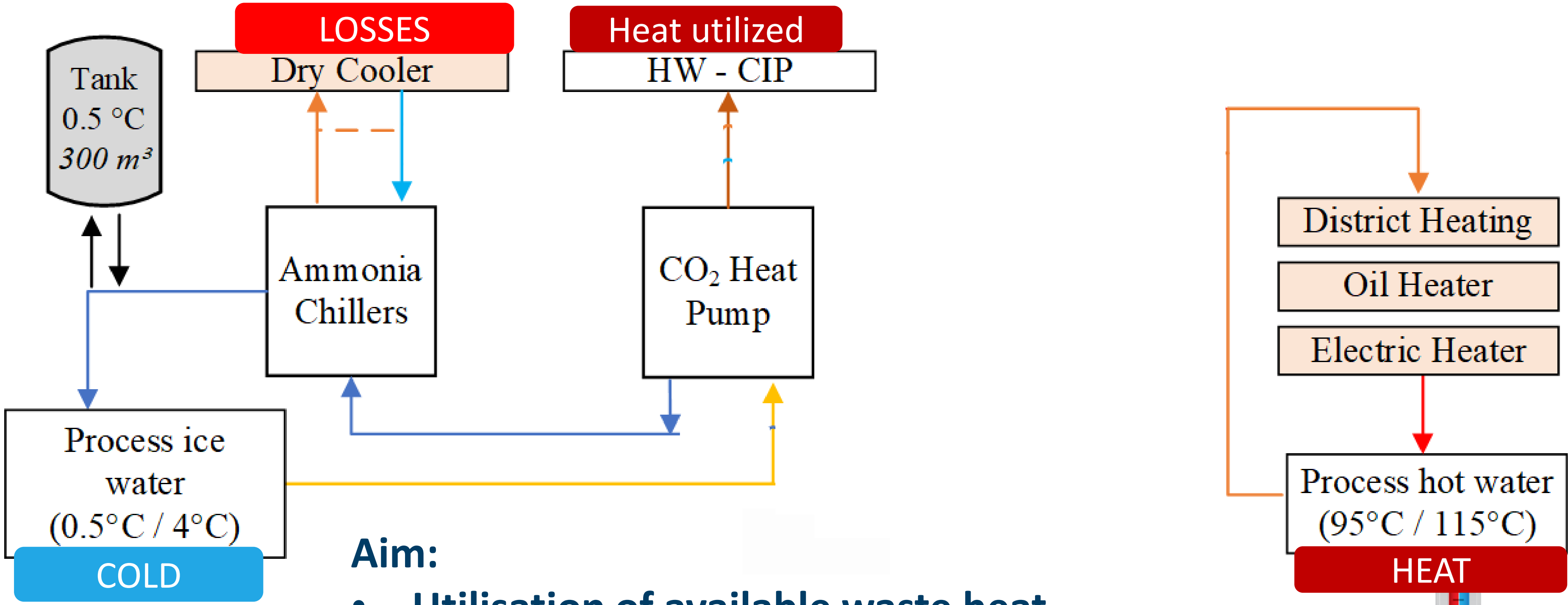
Sources: https://www.tine.no

RETROFIT – HTHP for combined cold and heat supply

Simplified process diagram – Process ice water and process hot water

HTHP-is connected in series with existing chillers and boilers → 100% Backup





Aim:

- **Utilisation of available waste heat**
- **Reduction of energy consumption**
- **Reduction of CO_2 Emissions**

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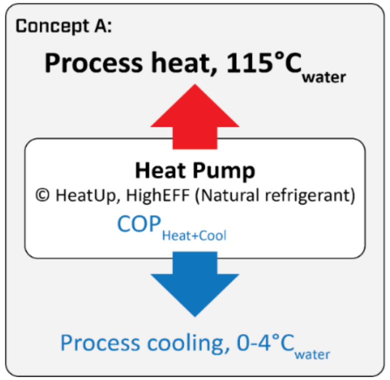
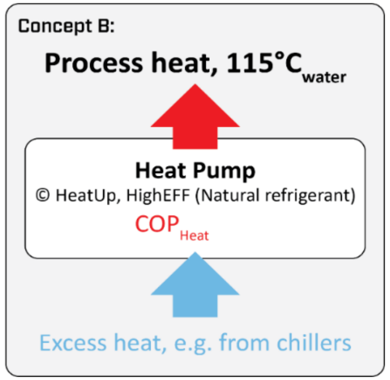
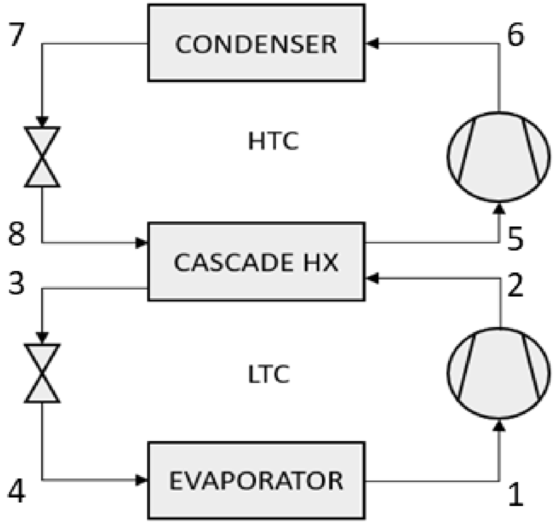
RETROFIT - Propane-Butane cascade HTHP

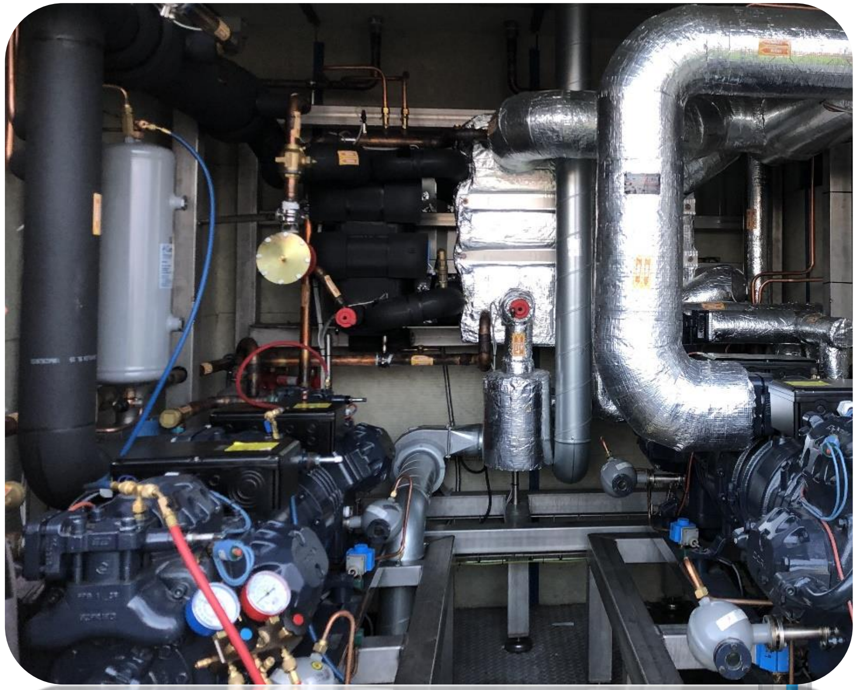
- HT circuit with R600 (Butane)
  LT circuit with R290 (Propane),
- Sink temperatures up to 115 °C achievable with moderate pressures about 20 bar
- Source temperatures (-15°C) 0 to 30°C
- High temperature lift (70…120 K)
- HTHP is mounted in 10 feet shipping container build after EN-NS-378

➢ **Pilot installed available and flexible system (high TRL-level)**









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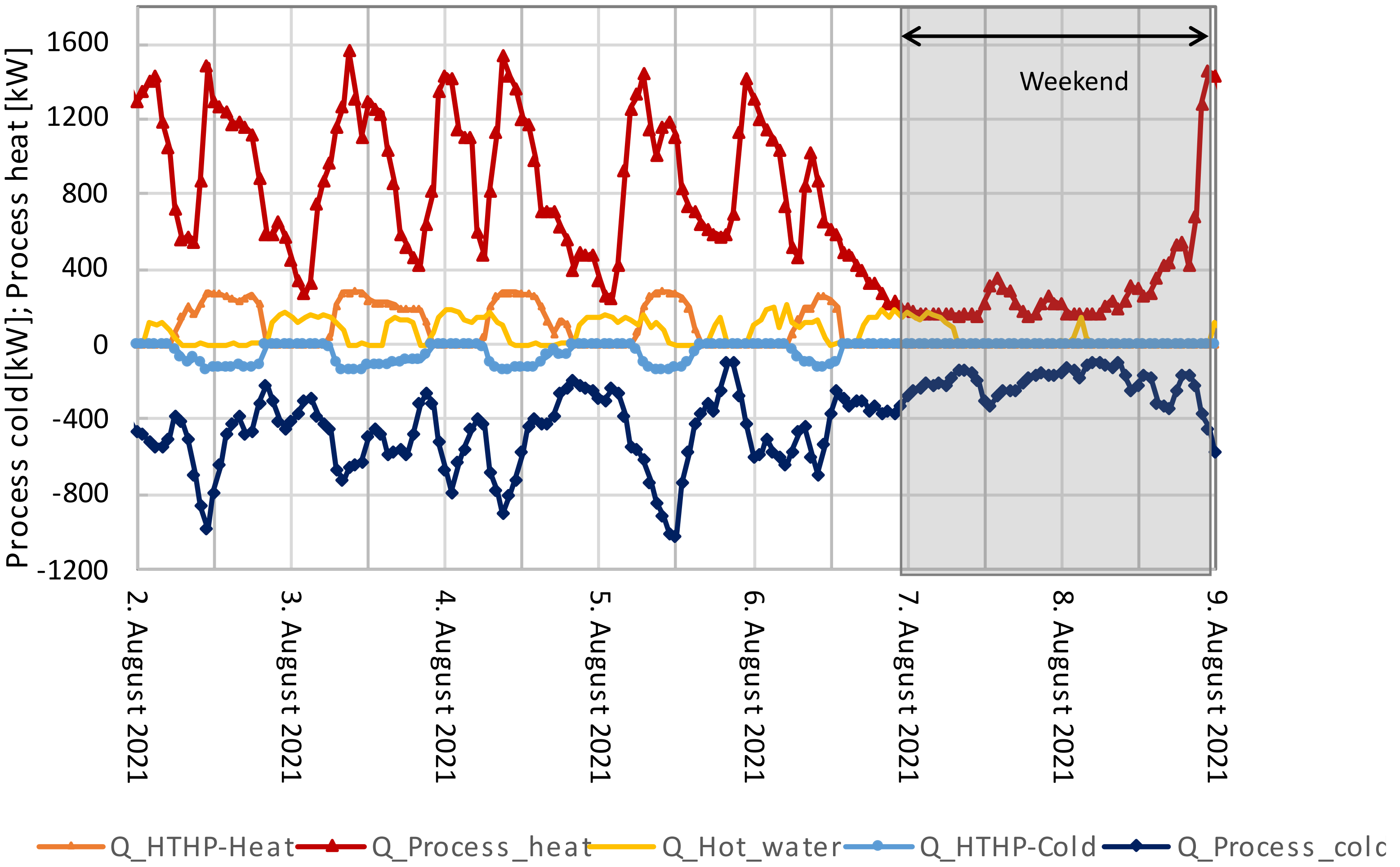
RETROFIT - Process cold and heat demand (excluding storage and building)

Characteristics

- Large variation in heat consumption
- Large variation in cold consumption
- Low consumption at the weekend
- Good match between cold and heat demand

Energy demand

- Process heat 117 MWh
- Hot water 10,7 MWh
- Process cold 77 MWh
- Primary energy (electricity) 126 MWh
- HTHP-Cascade 80 kW to 282 kW @ 90°C to 107°C



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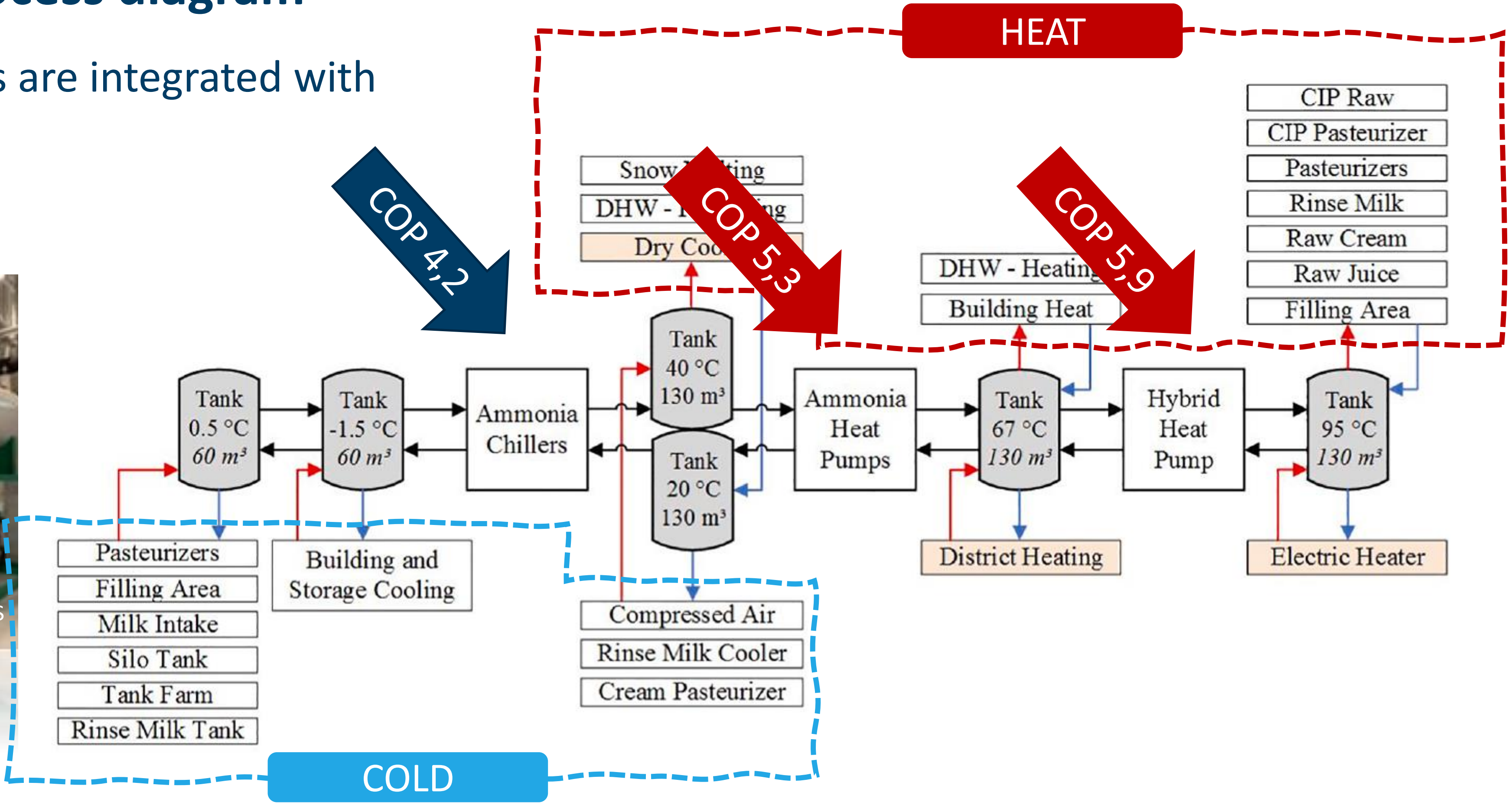
Schlemminger et al. - IEA HPT TCP National Workshop – Heat pumps in Norway, Oslo 10.05.2022

NEW dairy - Fully heat pumps based system

Simplified process diagram

All dairy process are integrated with each other

Source: Hybrid Energy AS



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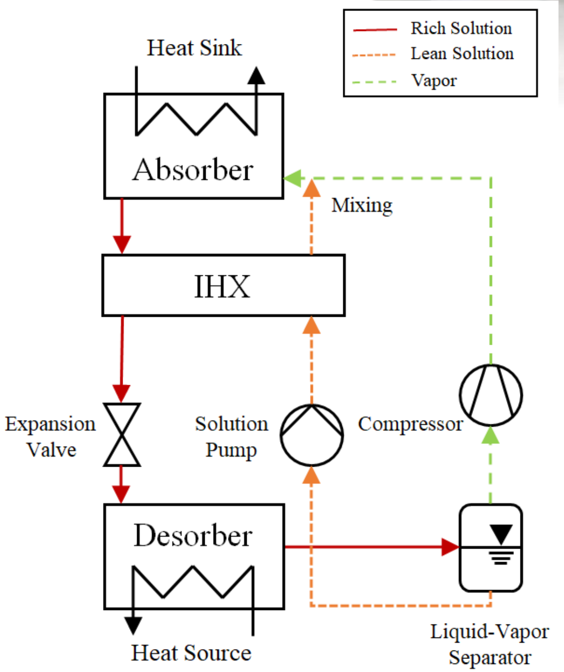
The system design has focus on maximal waste heat utilisation. 95% waste heat utilisation were documented.

NEW dairy -Hybrid adsorption-compression HTHP

- Vapor compression cycle with additional solution circuit
- NH_3-H_2O mixture as working fluid pair (zeotropic mixture)
- Heat sink temperature up to 120 °C (130 °C) with comparably low pressure ratio (3..6) and moderate high pressure 25 bar (32 bar)
- High temperature lift with large heat source and sink glides (>30 K)

➢ **High system flexibility and adaptability due to solution circuit**

➢ **Very high TRL Level (standard NH_3 components)**



Ahrens, M. et al. (2019) Development of ammonia-water hybrid absorption-compression heat pumps, in: 25th IIR International Congress of Refrigeration. IIF-IIR, Montréal , Canada, pp. 4942–4949

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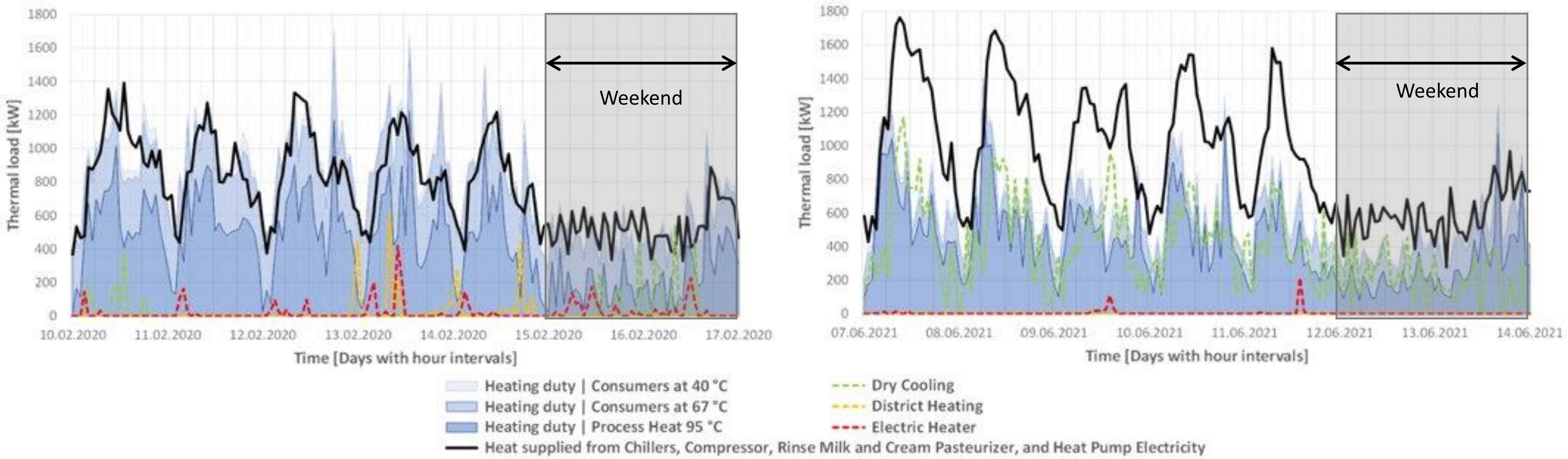
NEW – Cold and heat demand (entire dairy)

Winter

Summer



- ➢ Available heat and cold consumption are matching well
- ➢ Peak are covered by the storages
- ➢ Very very little use of backup system (3%)
- ➢ **Weekend operation can be optimised**

- ➢ Cooling demand is dominating
  → too much waste heat available
- ➢ Very very very little use of backup system (<1%)
- ➢ **Optimised weekend operation**

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Comparison of refrigeration HP and HTHP systems

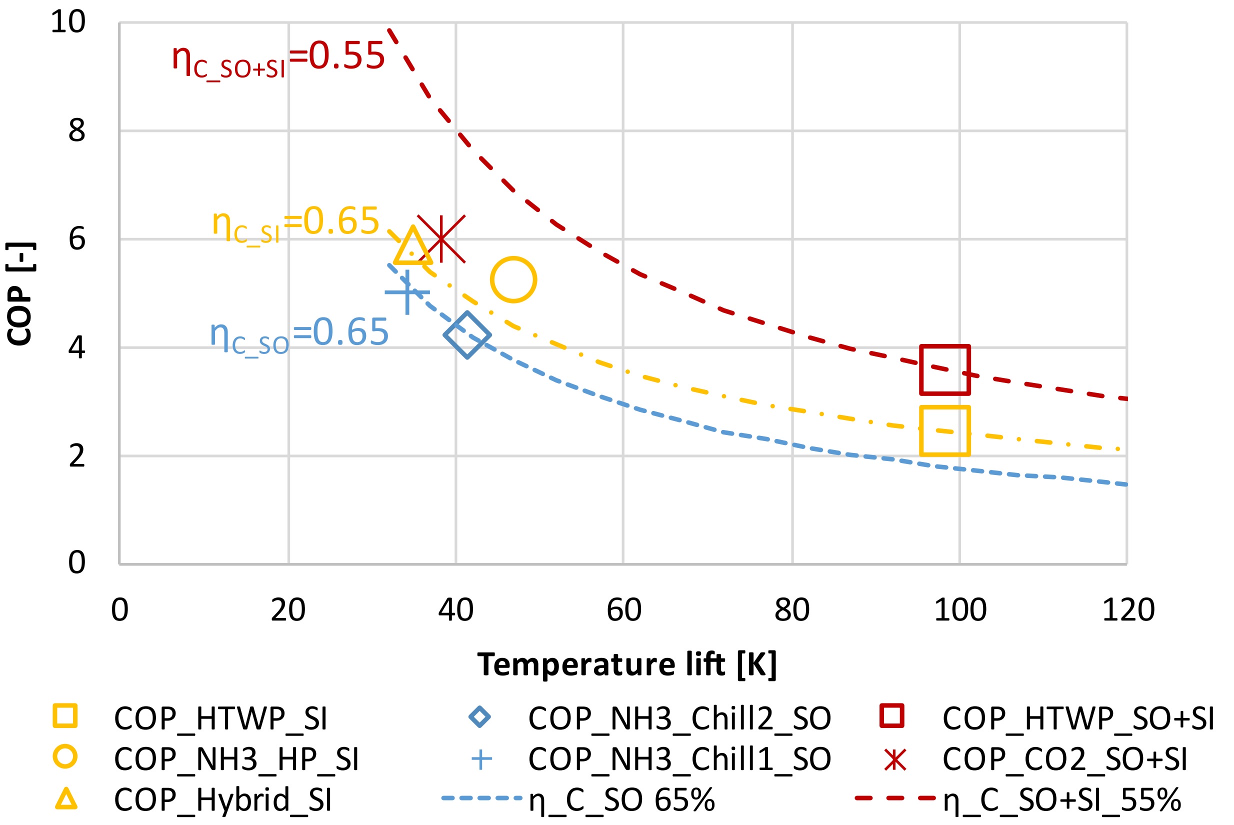
Analysis covers

- NH_3-Chillers
- NH_3-Heat pumps
- Transcritical CO_2-HP for ice water 0.5°C to 4°C and HW 10°C to 75°C production
- NH_3/H_2O Hybrid HTHP
- R290/R600-Cascade HTHP

➢ **Variation in Temperature lift and COP**

➢ **Comparable Carnot-efficiencies**

➢ **Simulations utilisation of evaporator and condenser/gas cooler side is important for high temperature lifts**



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Summary and conclusions

- Simultaneous utilisation of evaporator and condenser/gas cooler is key
- New dairy:
  - Reduced process temperature requirements from 120 °C to **95°C**
  - Optimal thermal storage temperature level and size
  - Energy savings up to 65%
  - CO_2-Reduction 95% (compared to gas + NH_3-chiller)
- Dairy retrofit:
  - High Temperature lift (>110K) Cascade required --> high flexibility
  - Industrial pilot R290/R600 300kW$_{th}$ @ 110°C to 115 °C integrated and in full operation
  - Energy saving potential 62%, CO_2-Reduction potential 94%
  - Energy saving potential at Trondheim site 54%

Source: www.hybridenergy.no

➢ **Chillers, HP und HTHP with natural working fluids are favourable for sustainable and efficient food production**

➢ **Using natural refrigerants can prevent the uncertainty of future restrictions and ensure future-proof operation**

Thank you for your attention ☺

Forskningsrådet

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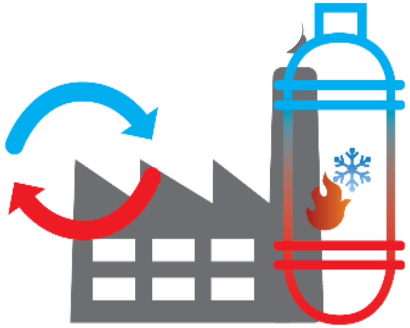


SkaleUP

Sustainable and efficient heat pump development for combined process heat and cool

DryFiciency
Michael Bantle

DryFiciency: Industrial Demonstration

High temperature heat pumps up to 160ºC

Closed loop heat pump | **Open loop heat pump**

Brick drying

Wienerberger AG
Uttendorf (AT)

Starch drying

AGRANA Stärke GmbH
Pischelsdorf (AT)

Bio sludge drying

Scanship A/S
Drammen (NO)

The project has received funding from the European Union’s Horizon 2020 programme for energy efficiency and innovation action under grant agreement No. 723576.

Open loop demo: Scanship

Refrigerant R718 (water)

- **Abundance and Safety:**
  - Most abundant elements on earth; low cost and nearly unlimited available
  - From environmental point of view: water is ideal refrigerant above 0°C
  - Non-toxicity, non flammable, 0 Ozone Depletion Potential, 0 Global Warming Potential
- **Regulatory Relief:**
  - Not subject to present or future environmental or safety regulations
- **Efficiency:**
  - High latent heat of evaporation (2270 kJ/kg); 4-5 times higher than hydrocarbons or CO2
  - Critical temperature: 380-386° C
  - General high COP
- **Disadvantages**
  - Requires high volume flow
  - High superheating during compression

Open Loop heat pump: expectations and results

Speed	Speed	$\dot{m}$ (at 1bar)	Pressure ratio	Tsat	Tlift	Heat delivery	COP	COP_{Carnot}	η_{system}
RPM	%	kg/h	-	°C	K	kW	-	-	%
72000/ 81000	90/90	756	4.23	146	45.6	494	**4.54**	9.2	49.4
68000/ 81000	85/90	648	4.05	144	44.0	423	**4.8**	9.5	50.4 %
64000/ 81000	80/90	720	3.59	140	39.7	461	**5.2**	10.4	50.5 %
64000/ 76500	80/85	684	3.44	138	38.2	440	**5.1**	10.8	47.1 %
60000/ 76500	75/85	648	3.21	136	35.9	413	**5.8**	11.4	50.5 %
56000/ 72000	70/80	576	2.83	132	31.5	367	**6.4**	12.8	50.0 %
52000/ 67500	65/75	504	2.49	127	27.3	325	**6.5**	14.7	44.2 %
48000/ 63000	60/70	360	2.32	125	24.9	226	**8.7**	16.0	54.7 %

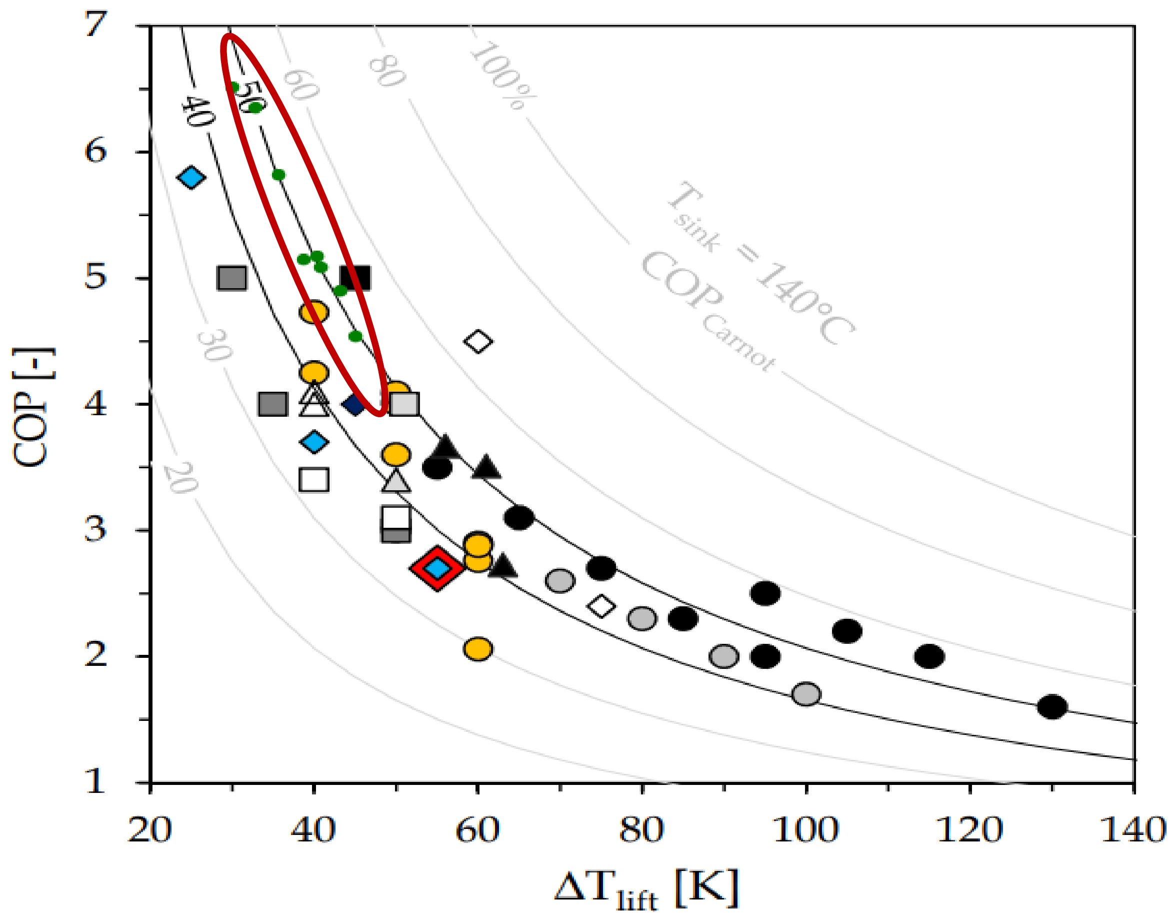
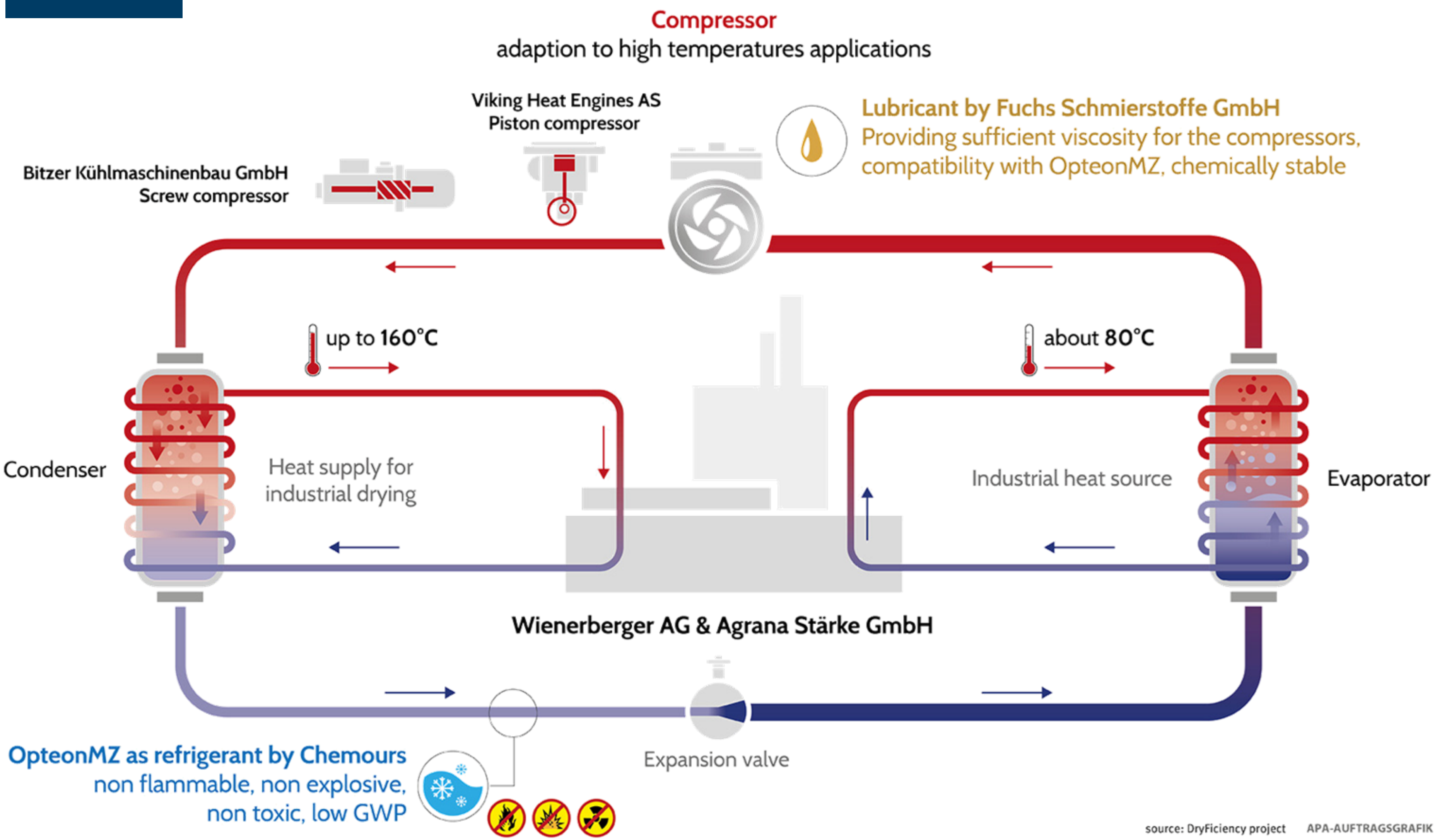
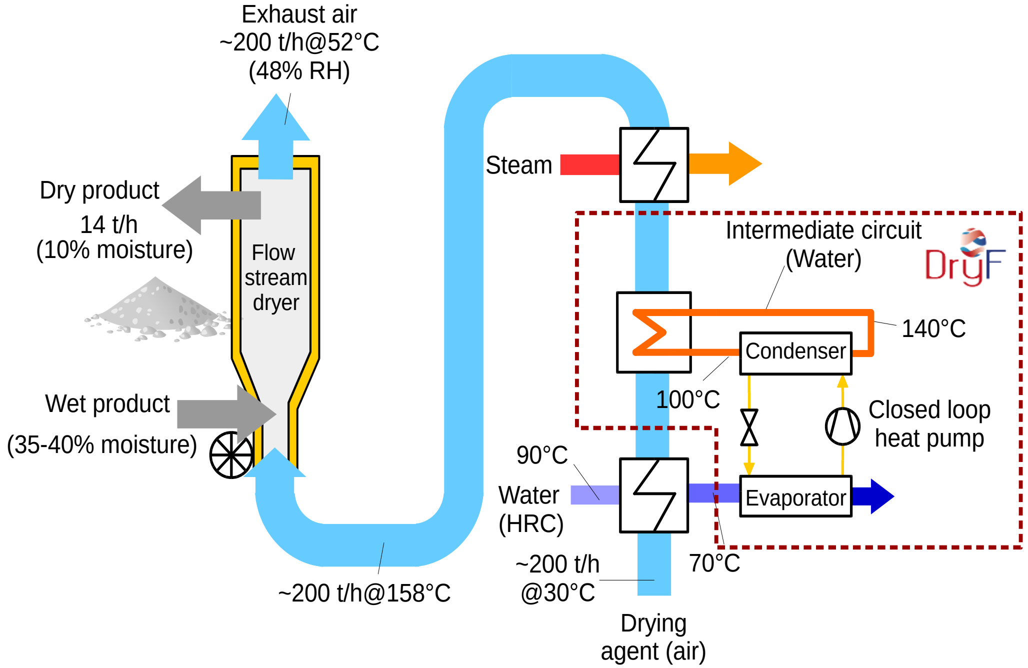


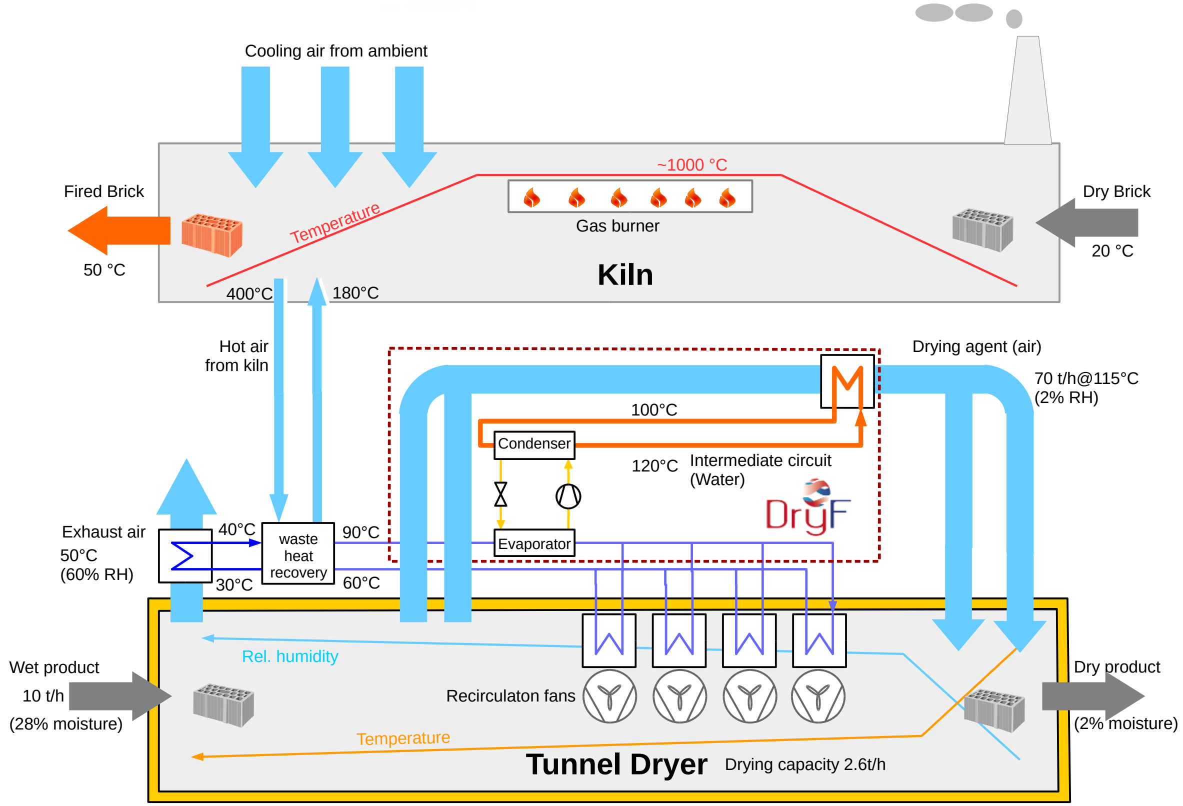
Figure modified from C. Apargaus, Book: "Hochtemperatur Wärmepumpen"

CLOSED LOOP HEAT PUMP



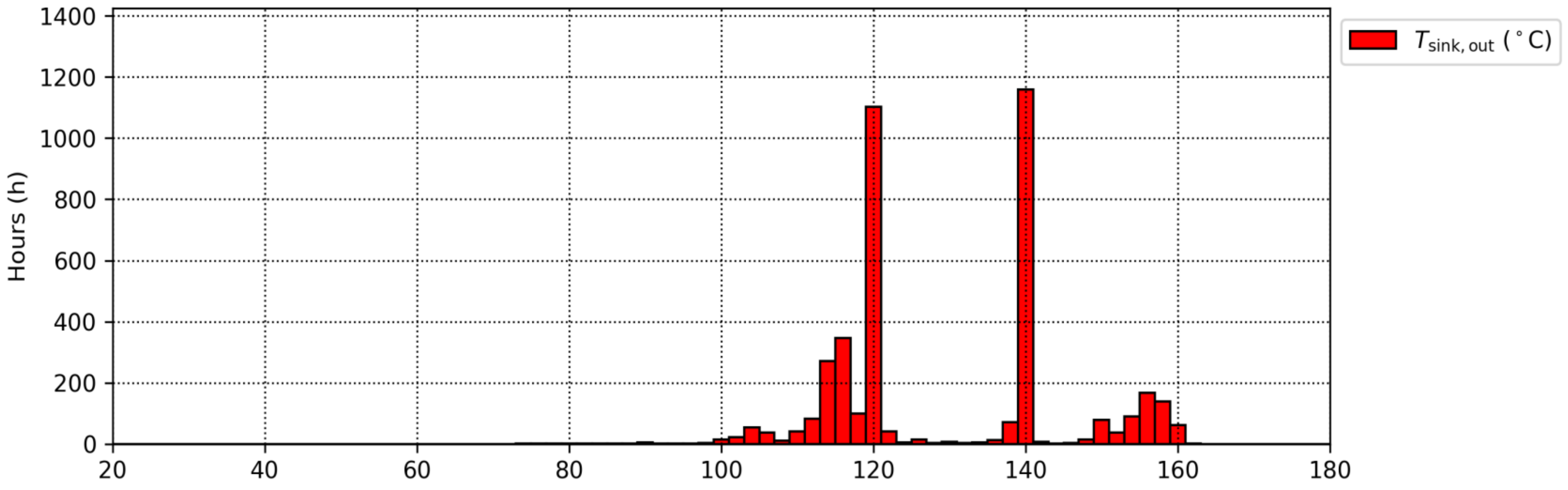
Integration Principle



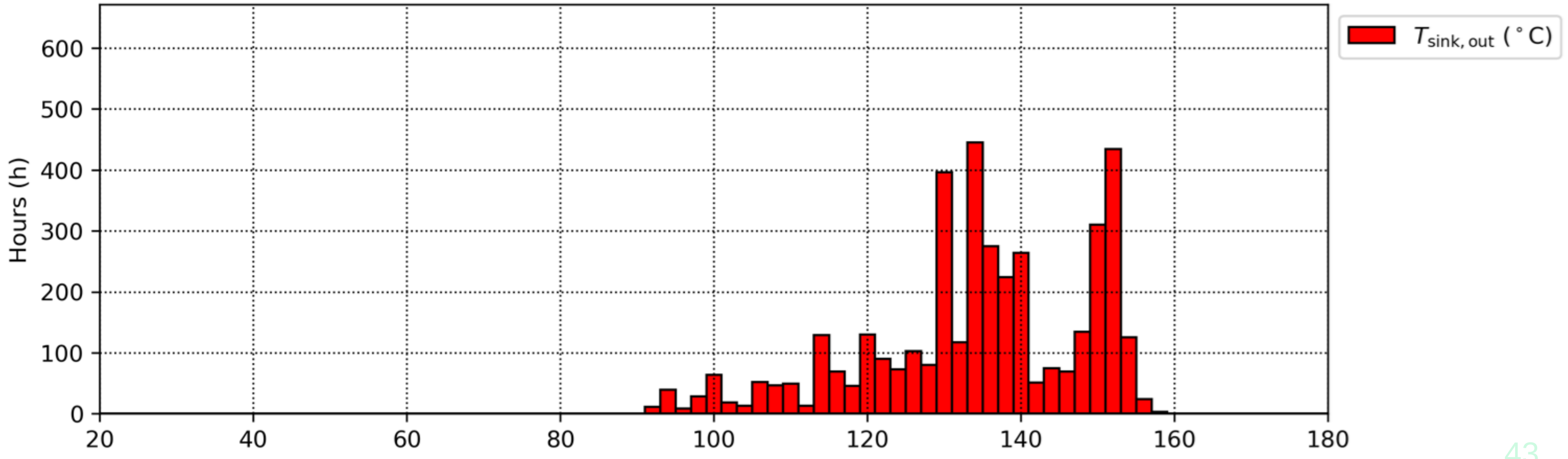


Performance: Operating Hours

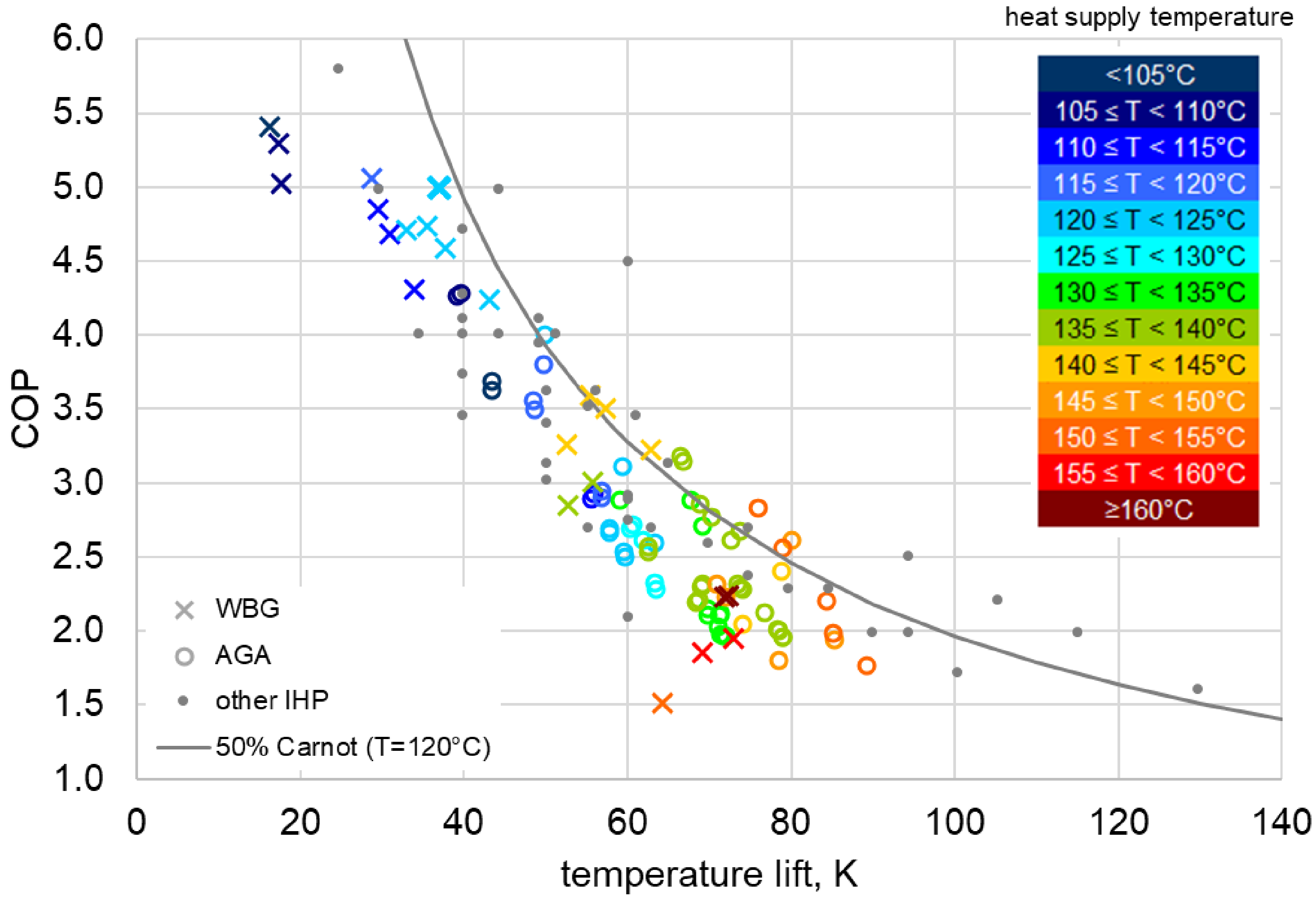
- WBG:
  4020 h until 31.8.2021



- AGA:
  4008 h until 31.8.2021



Overview on heat pump operation



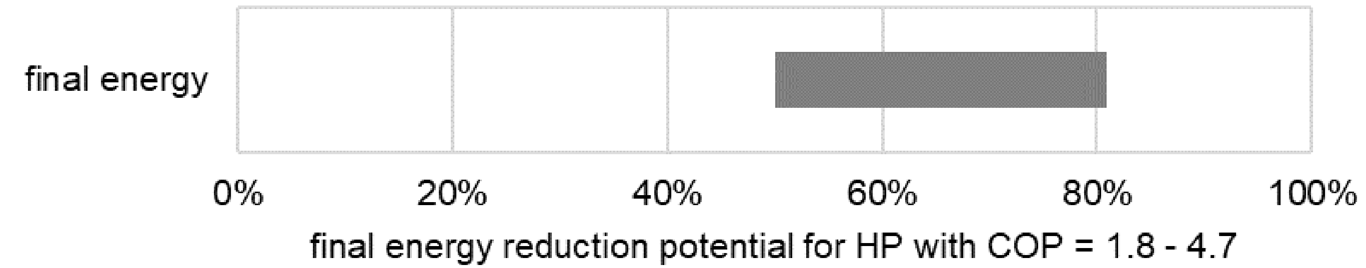
other IHP from Arpagaus et al. High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials, Energy (152), p.985-1010, 2018.

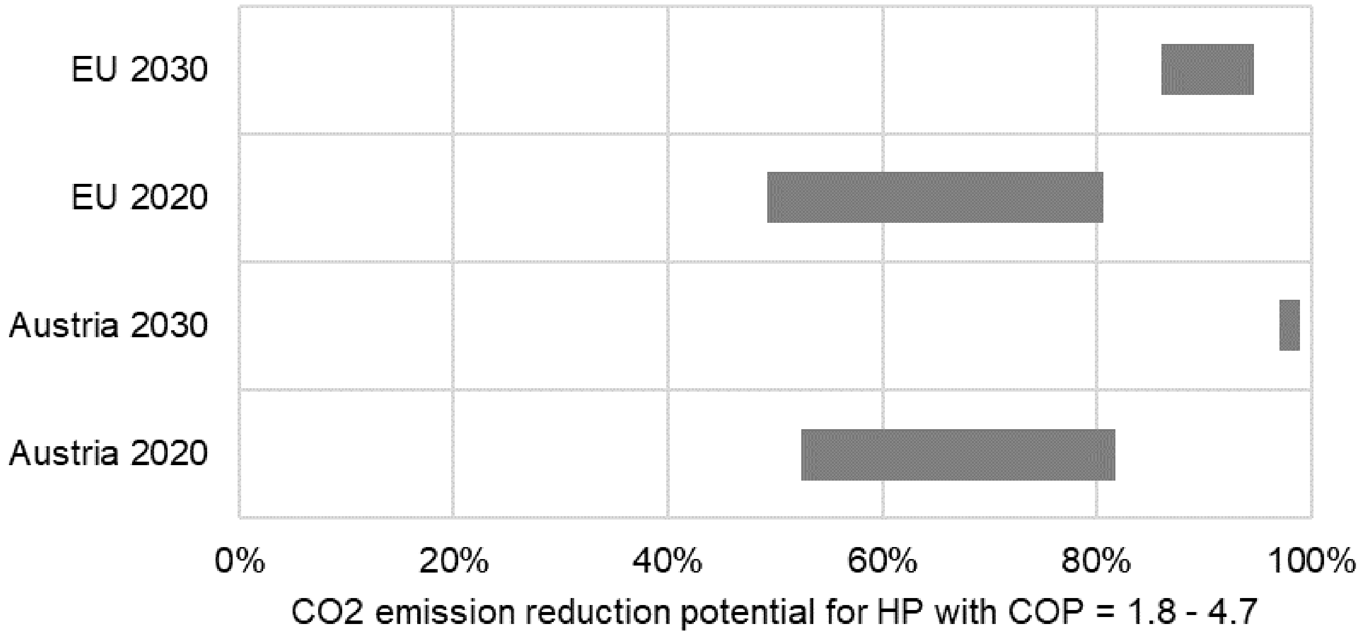
Impact of the demonstrators

	Agrana	Wienerberger
heat supply temperature	138ºC	120ºC
final energy reduction	2388 MWh/a = 72%	2163 MWh/a = 82%
primary energy reduction	1690 MWh/a = 46%	1904 MWh/a = 66%
CO_2 emissions reduction	659 t/a = 73%	592 t/a = 83%

reductions compared to a natural gas burner with the same heating capacity

End energy and CO_2 emissions





Summary, Discussion and Questions

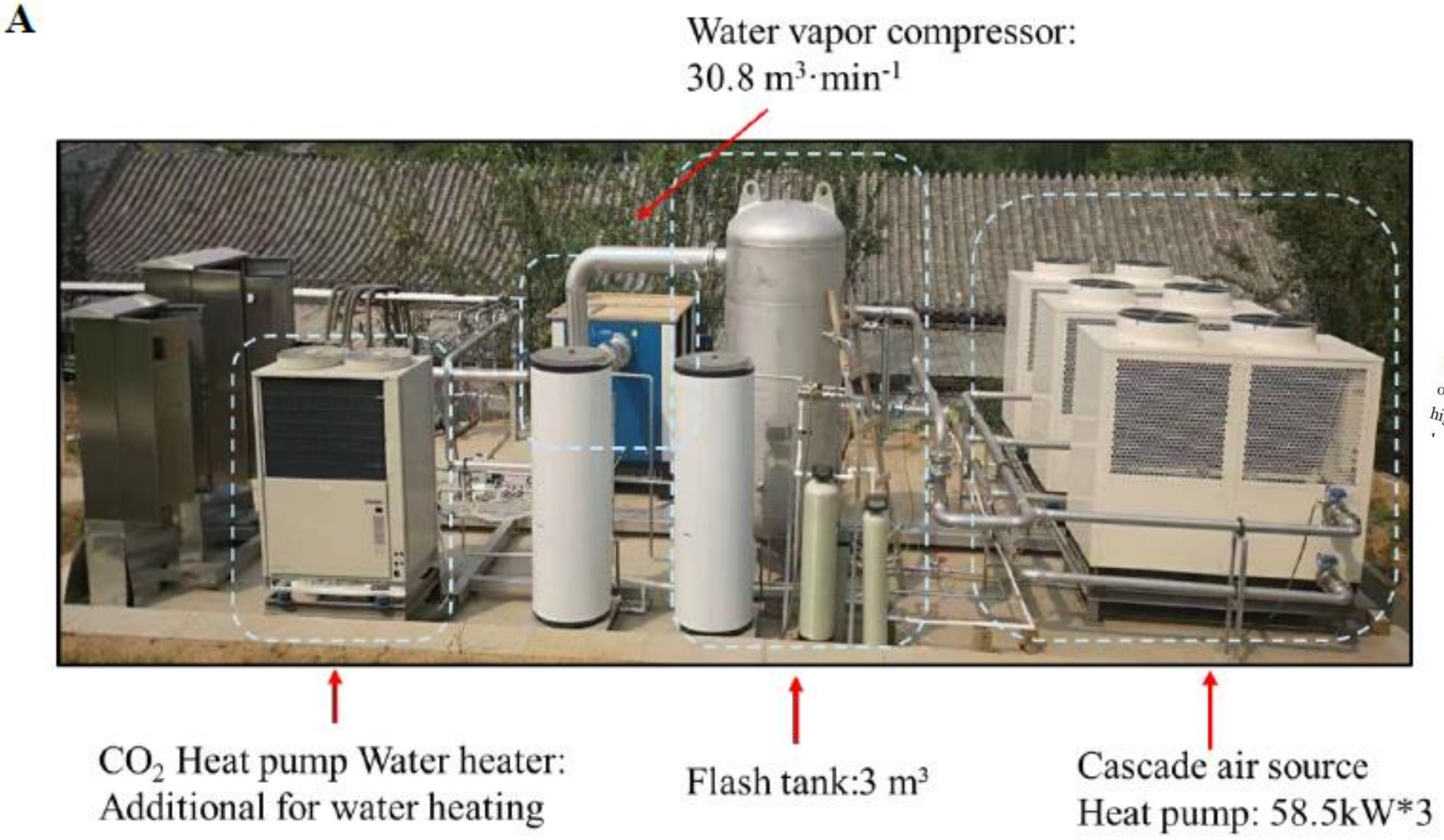
Summary and Discussion: Can we integrate HTHP in the industry?

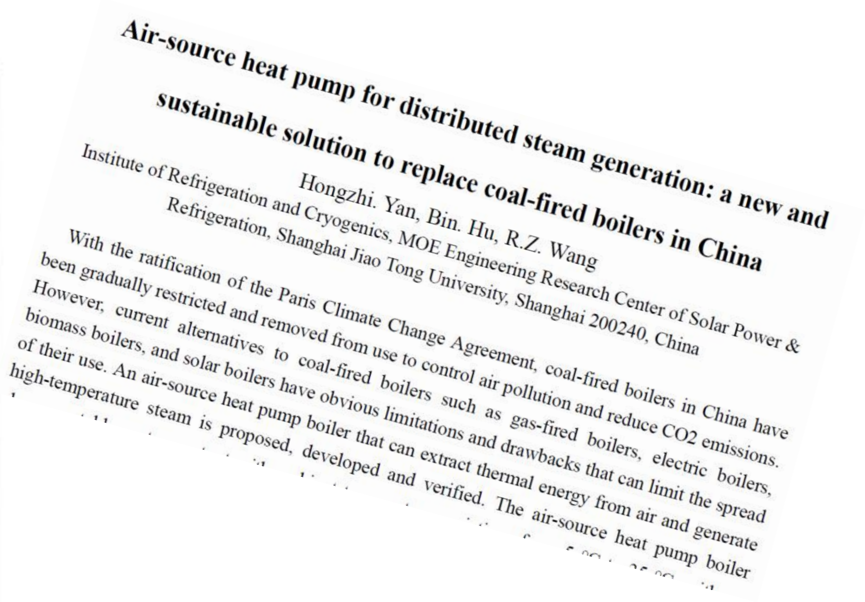
→Yes, …. but

- Realistic expectation about the achievable COP
  - COP between 2-3
  - SEC of the system must be evaluated
- Realistic expectation about the TRL → technical risk
- MVR-technology available for large capacities (>5 MW)
- Integration with the onsite excess heat source is challenging → high temperature lift
- Do we really need 150-180°C process heat?
  - What is a realistic product temperture?
  - Is it possible to develop "low-temperature" processes?
  - Is it possible to have high humidity exhaust air?

Technology for a better society

Steam producing air source heat pump (Research Centre HighEFF)




Air-source heat pump for distributed steam generation: a new and sustainable solution to replace coal-fired boilers in China

Hongzhi. Yan, Bin. Hu, R.Z. Wang

Institute of Refrigeration and Cryogenics, MOE Engineering Research Center of Solar Power & Refrigeration, Shanghai Jiao Tong University, Shanghai 200240, China

With the ratification of the Paris Climate Change Agreement, coal-fired boilers in China have been gradually restricted and removed from use to control air pollution and reduce CO2 emissions. However, current alternatives to coal-fired boilers such as gas-fired boilers, electric boilers, biomass boilers, and solar boilers have obvious limitations and drawbacks that can limit the spread of their use. An air-source heat pump boiler that can extract thermal energy from air and generate high-temperature steam is proposed, developed and verified. The air-source heat pump boiler

Cofficient of Performance of HTHP

"Ruled" by thermodynamic!

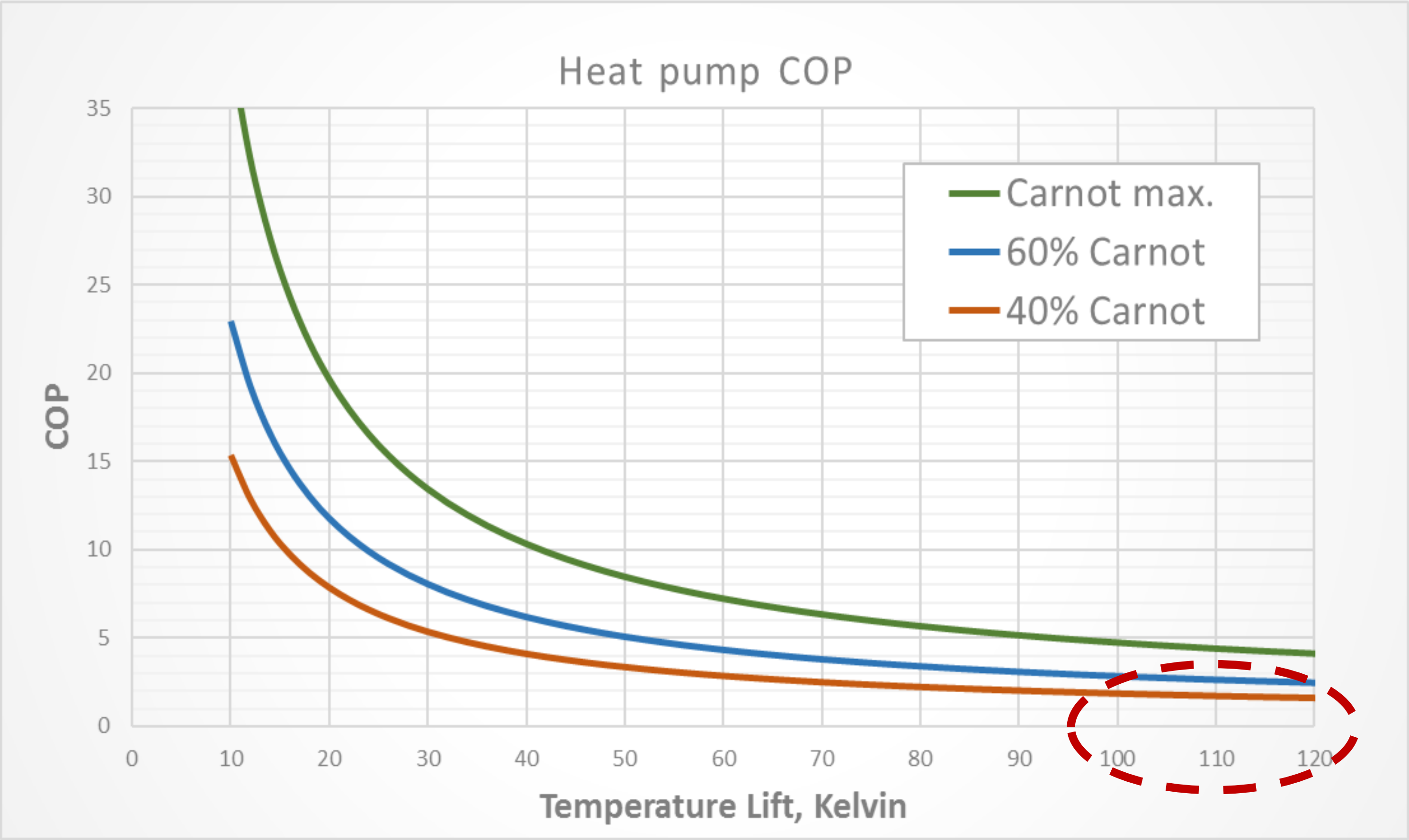
→High temperature lift

→Low COP

→High CAPEX

→High system complexity

Where is the techno-economic sweet-spot?



How could such a steam producing heat pump for pulp and paper industry look like?

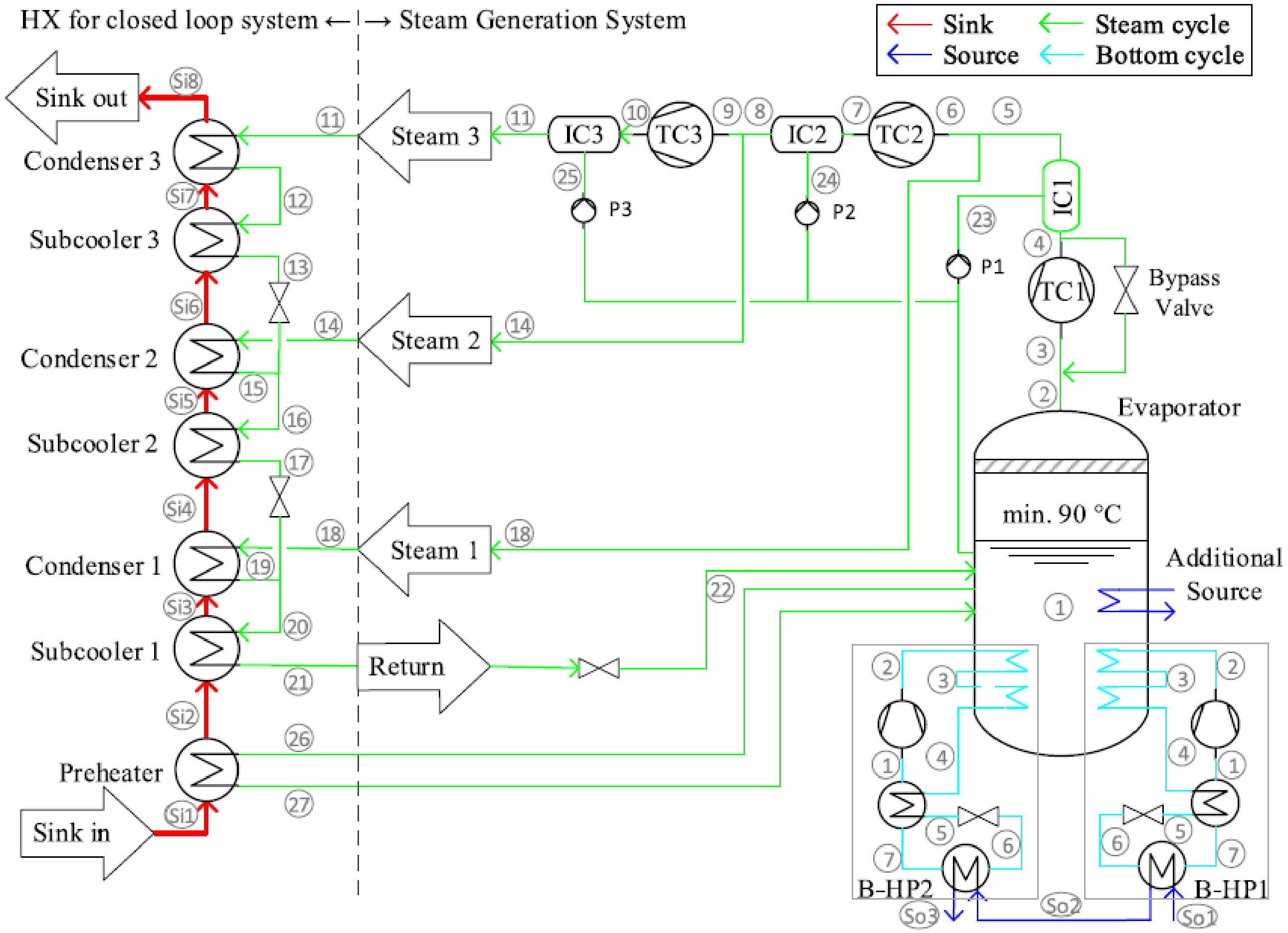


Fig. 1. Flow sheet of a cascade heat pump with a multi-stage R-718 cycle for steam generation or closed loop heat supply at different temperature levels (B-HP = Bottom heat pump, IC = Intercooler, P = Pump, TC = Turbocompressor).

- Combination of different heat pump cycles
- Bottom cycle lifts close to 100°C
- Top cycle operates with steam compression (R718)

Source: https://www.sciencedirect.com/science/article/pii/S2590174519300091?via%3Dihub

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Analysis of technologies and potentials for heat pump-based process heat supply above 150 °C

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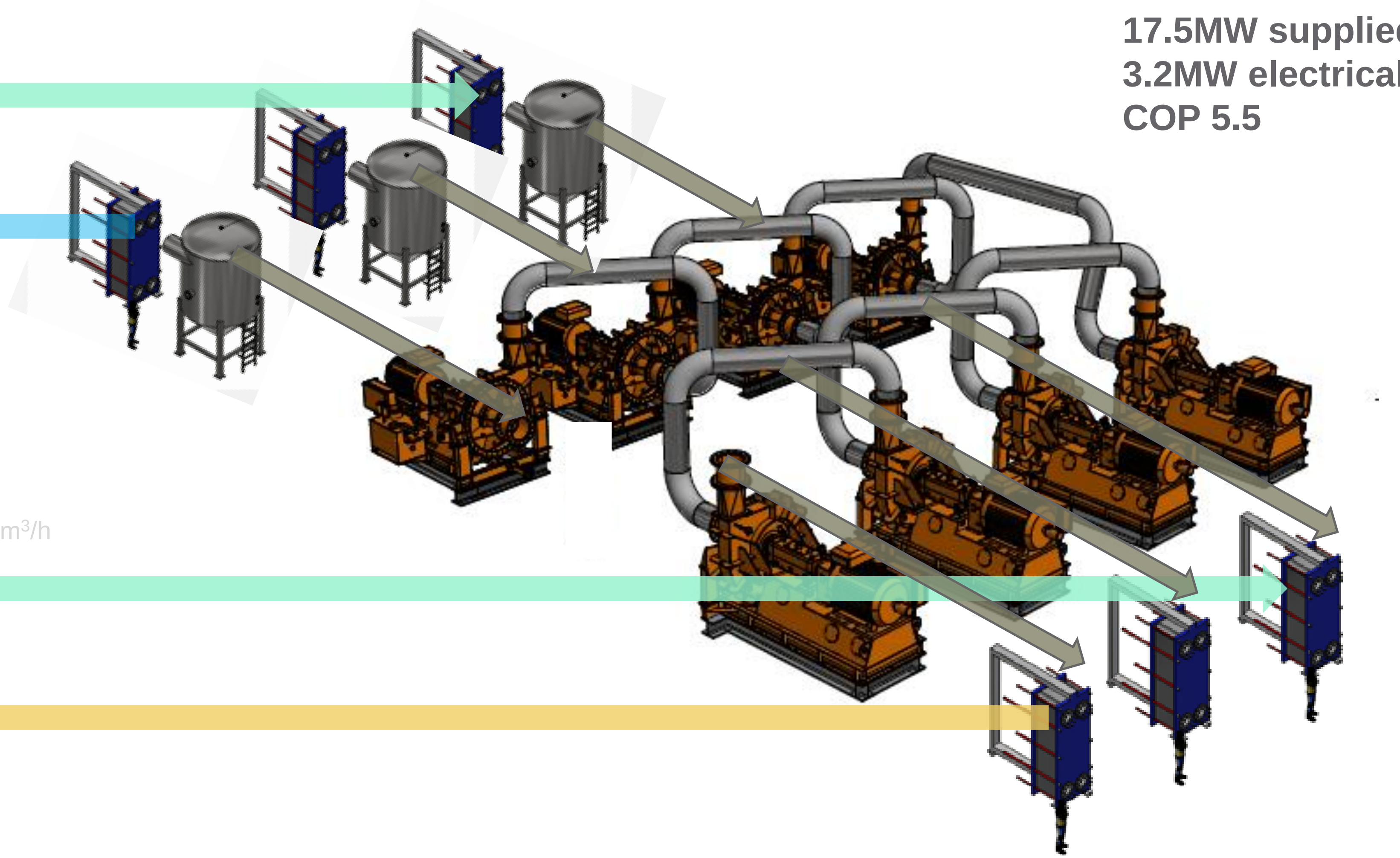
[c] SINTEF Energi AS, Department of Thermal Energy, 7465 Trondheim, Norway

CLOSED MVR-HP CIRCUIT

Energy source:

Water, 110’C, 425m³/h

Water, 80’C, 425m³/h



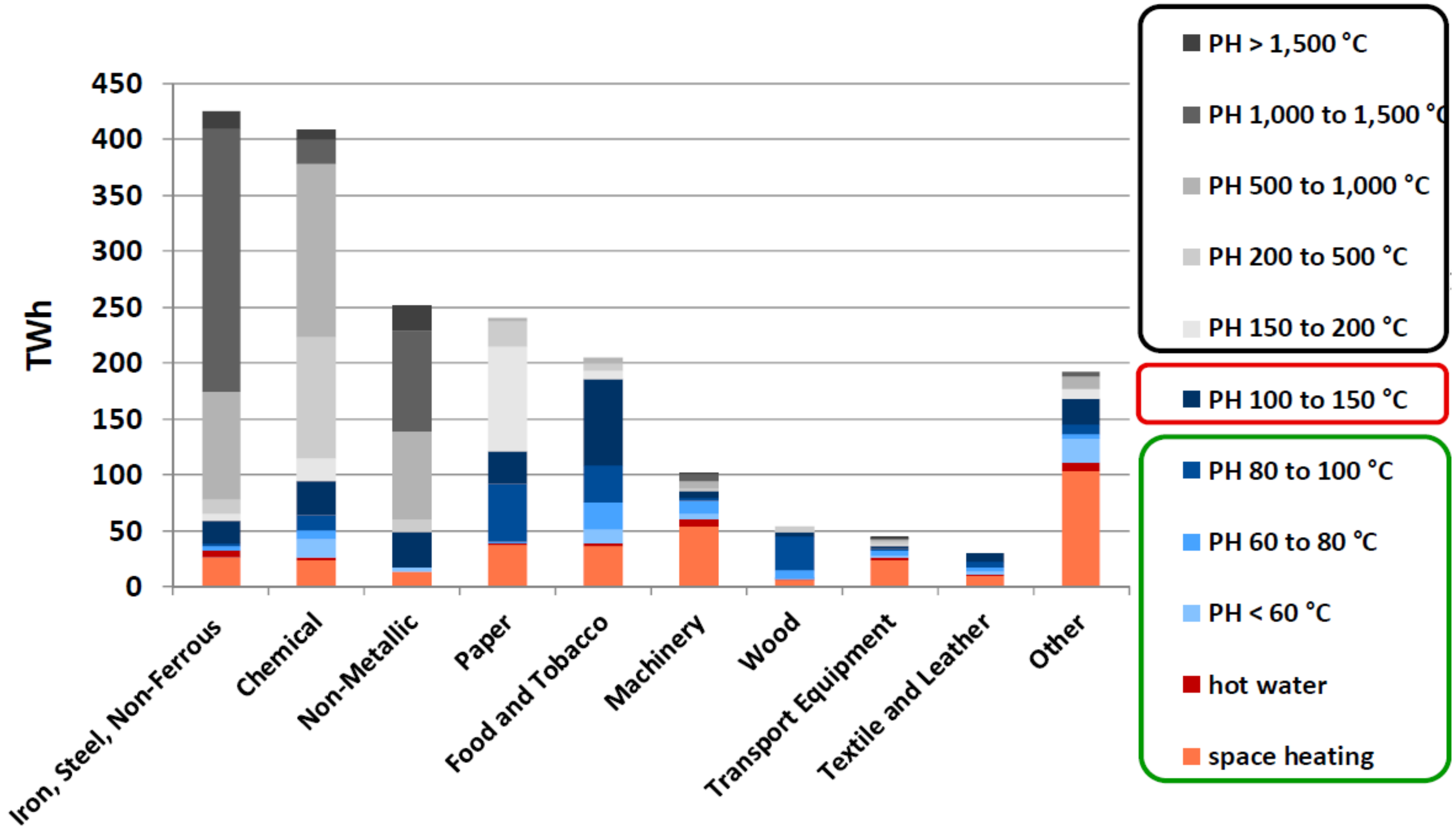
Energy sink:

Water, 110’C, 500m³/h

Water, 140’C, 500m³/h

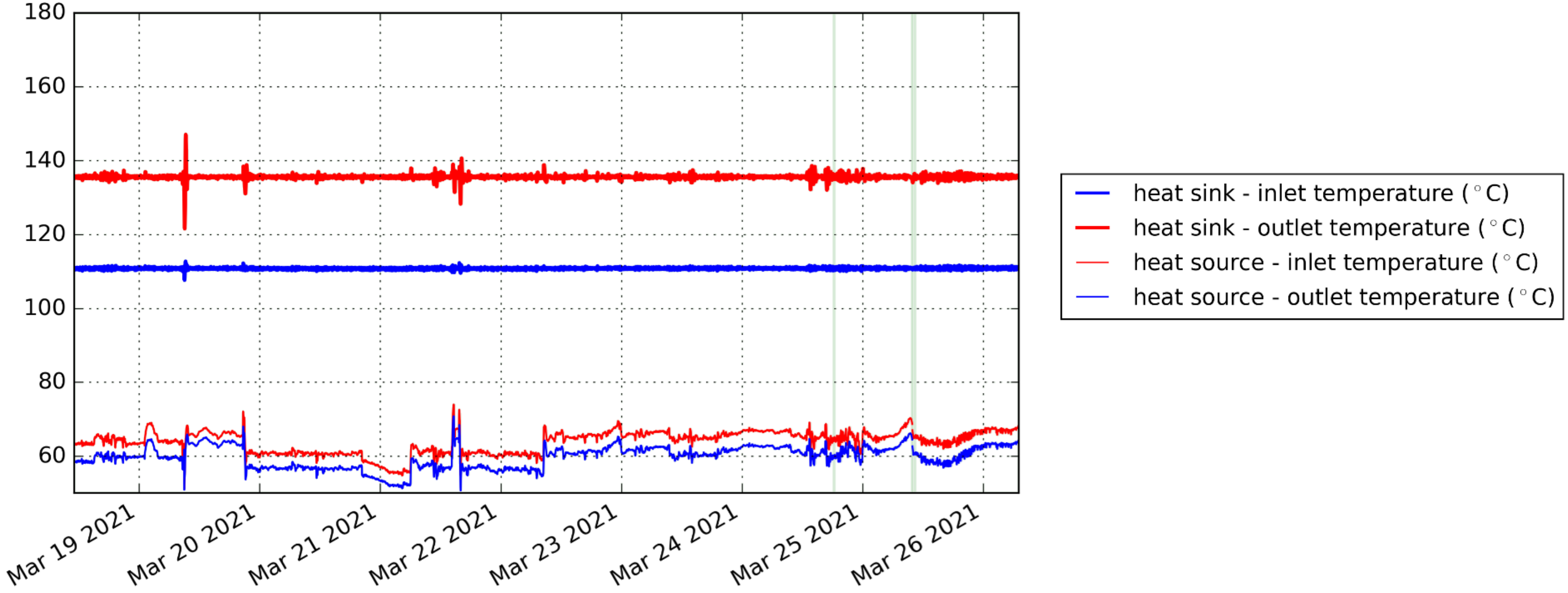
COP:
17.5MW supplied heat by 3.2MW electrical cons. = COP 5.5

Background



Wolf, S., et al. (2014). Analyse des Potenzials von Industriewärmepumen in Deutschland (in German) Forschungsbericht. Universität Stuttgart, Institut für Energiewirtschaft und Rationelle Energieanwendung

Performance: Agrana



Performance: Wienerberger