



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

Zühlsdorf, Benjamin; Bühler, Fabian; Bantle, Michael ; Elmegaard, Brian

*Published in:*

Book of presentations of the 2nd Symposium on High-Temperature Heat Pumps

*Publication date:*

2019

*Document Version*

Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

*Citation (APA):*

Zühlsdorf, B., Bühler, F., Bantle, M., & Elmegaard, B. (2019). Analysis of technologies and potentials for heat pump-based process heat supply above 150 °C. In B. Zühlsdorf, M. Bantle, & B. Elmegaard (Eds.), *Book of presentations of the 2nd Symposium on High-Temperature Heat Pumps* (pp. 26-37). SINTEF.

---

### General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

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

*Benjamin Zühlsdorf<sup>1</sup>, Fabian Bühler<sup>2</sup>, Michael Bantle<sup>3</sup>, Brian Elmegaard<sup>2</sup>*

<sup>1</sup> Danish Technological Institute, Energy and Climate, Aarhus C, Denmark,  
[bez@dti.dk](mailto:bez@dti.dk)

<sup>2</sup> Technical University of Denmark, Department of Mechanical Engineering, Kgs.  
Lyngby, Denmark

<sup>3</sup> SINTEF Energi AS, Department of Thermal Energy, Trondheim, Norway

### **Keywords:**

Cascade multi-stage steam compression, Decarbonization, High-temperature heat pump, Process heat, Reversed Brayton cycle, R718, R744.

### **Introduction**

The ambitions to reduce greenhouse gas emissions do inevitably require sustainable alternatives to fossil fuel-based combustions for supply of process heat to industrial processes. Electricity-driven heat pumps imply the general potential to operate emission free and do thereby represent a sustainable long-term solution for emission free process heat supply.

Currently available heat pump technologies are however limited to supply temperatures of 100 °C to 150 °C, while electric boilers and biomass boilers are often mentioned as alternatives in energy transition strategies. The overall feasibility for heat pump systems in such applications is among others limited by technical component constraints as well as limited thermodynamic performances, resulting in limited operating performances.

Zühlsdorf et al. [1] have therefore analyzed the possibilities for heat pump-based process heat supply at large capacities and temperatures above 150 °C. They evaluated the technical and economic feasibility of two heat pump systems for two case studies. The main results from [1] are summarized by this extended abstract. The article focused on large-scale applications and considered components as known from oil- and gas applications, as these are capable of operating in more challenging conditions and enable exceeding the limitations known from available refrigeration equipment [2]. In addition, the focus was on applications, in which the plant owners have access to electricity at low costs or the possibility to invest in own renewable electricity generators, such as wind farms and photovoltaics, as these are ensuring low levelized cost of electricity [3].

**Methods**

The study considered two different heat pump systems, namely a cascade multi-stage steam compression system and a reversed Brayton cycle. The cascade multi-stage steam compression system is shown in Figure 1 and consists of bottom cycles that are recovering the heat from the heat sources while providing heat to the evaporator of the top cycle, in which the steam from the evaporator is compressed in several stages. The steam is cooled by liquid injection after each compression stage. The system can supply steam at every pressure level to the system, ensuring an optimal integration into the process and thereby maximum performances.

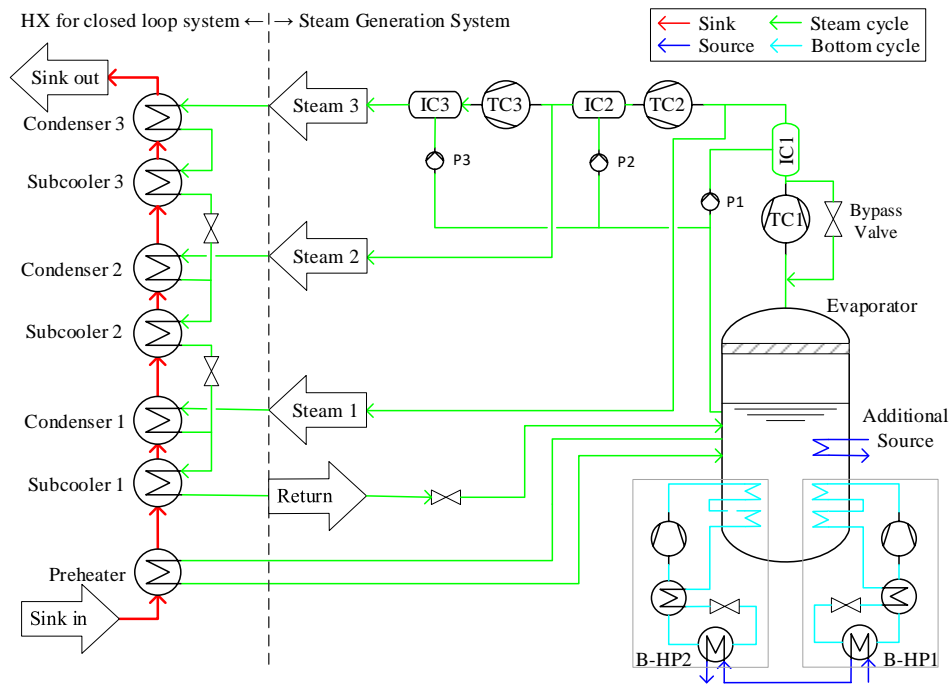


Figure 1: Flow sheet of a cascade heat pump with a multi-stage R-718 cycle for steam generation or closed loop heat supply at different temperature levels (B-HP = Bottom heat pump, IC = Intercooler, P = Pump, TC = Turbocompressor), [1]

The less complex layout of the reversed Brayton cycle is shown in Figure 2. The cycle consists of three heat exchangers, as well as a turbocompressor and a turboexpander, which are mounted on the same shaft. The cycle uses CO<sub>2</sub> as working fluid and operates completely in the gas phase.

The cycles were modelled with energy and mass balances. Design variables, such as pinch points in the heat exchangers or pressure levels were defined or optimized under consideration of common limitations. The investment cost of the equipment was estimated with cost correlations and validated with estimations obtained from manufacturers.

1.2. Analysis of technologies and potentials for heat pump-based process heat supply above 150 °C, Benjamin Zühlsdorf, DTI

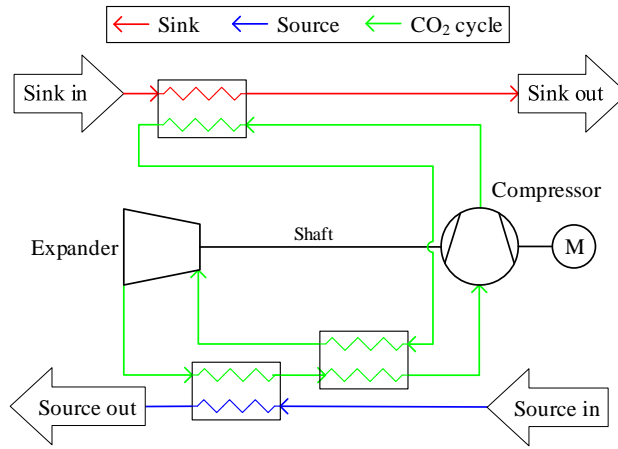


Figure 2: Flow sheet of reversed Brayton cycle, [1]

Both cycles were evaluated for two case studies. The first case study was alumina production in which 50 MW were supplied to heat thermal oil from 140 °C to 280 °C, while heat was recovered between 110 °C and 60 °C. The second case study was a spray dryer for milk powder production in which an air stream was heated up from 64 °C to 210 °C with a capacity of 8.2 MW, while a heat source at 50 °C was recovered.

Both technologies were evaluated in both cases for a set of economic boundary conditions. Three economic scenarios were considered that corresponded to the fuel cost in Norway, Germany and Denmark in 2020 and one scenario was considered corresponding to the acquisition and operation of own renewables.

### Results

The heat pump systems were designed and optimized for both case studies. Table 1 shows the COP and the total capital investment TCI for both cases and both technologies. It may be seen that the COP for the cascade system was estimated to be 1.9 in both cases, while it was 1.7 for the reversed Brayton cycle in the alumina production and 1.6 in the spray dryer case. The investment cost were relatively similar for the two technologies, while the economy of scale yielded considerably lower specific investment cost for the alumina production.

Table 1: COP and Total capital investment TCI for both cases and cycles [1]

	Alumina production		Spray dryer	
	Cascade multi-stage system	Reversed Brayton cycle	Cascade multi-stage system	Reversed Brayton cycle
Coefficient of performance COP, -	1.92	1.72	1.92	1.61
Total capital investment TCI, Mio. €	47.3	48.3	16.4	15.4
Specific total capital investment TCI <sub>spec</sub> , €/kW	946	966	1,997	1,868

Figure 3 shows the levelized cost of heat for both technologies and both case studies for all economic scenarios and compares them to the alternative heat supply technologies. The levelized cost of heat is divided into the contributions accounting for the investment, the fuel cost and an exemplifying CO<sub>2</sub> tax of 50 €/ton to indicate the impact of a potential tax. In the case of the alumina production, the levelized cost of heat reaches as low as 31 €/MWh to 33 €/MWh under consideration of own renewable electricity facilities, while it is between 44 €/MWh and 46 €/MWh for the spray dryer case. In the spray dryer case, the heat pump-based solutions are competitive with a biomass boiler and a natural gas boiler under consideration of the assumed CO<sub>2</sub> tax. In the alumina production case, the lowest levelized cost of heat are obtained for the heat pump systems.

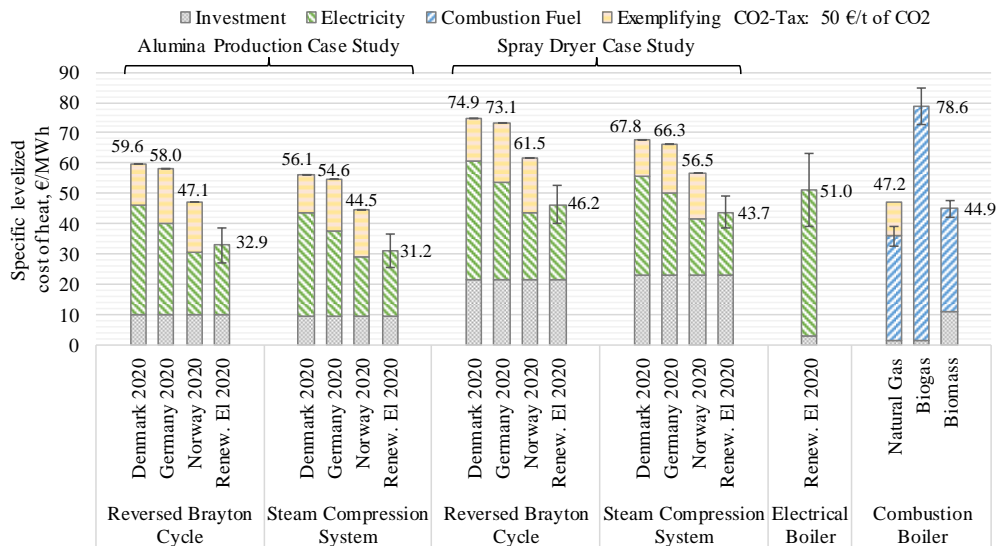


Figure 3: Specific levelized cost of heat  $c_h$  for both case studies including the reversed Brayton cycle, the multi-stage steam compression cycle, an electrical boiler and combustion-based boiler using natural gas, biogas and biomass. The cost scenarios are as defined in [1] while the ranges for the cost for electricity from renewables, natural gas, biogas and biomass are indicated by the black bars [1]

### Conclusions

The study analyzed a reversed Brayton cycle and a cascade multi-stage steam compression for large-scale process heat supply at temperatures above 150 °C. It was pointed out that these temperatures might be reached by components from oil- and gas industries and that low electricity prices, as typically accessible for energy intensive industries or obtainable from acquiring and operating own renewable facilities, may improve the economic performance considerably. The levelized cost of heat for the heat pump-based systems were competitive to the biomass boilers and natural gas boilers for the spray dryer case study and outperformed both for the alumina production case study. This study has accordingly demonstrated, that heat pump systems are a viable alternative for process heat supply in industrial processes at temperatures of up to 280 °C.

### References

- [1] Zühlsdorf B, Bühler F, Bantle M, Elmegaard B. Analysis of technologies and potentials for heat pump-based process heat supply above 150 °C. *Energy Conversion and Management: X* 2019;2:100011. doi:10.1016/j.ecmx.2019.100011.
- [2] Aga V, Conte E, Carroni R, Burcker B, Ramond M. Supercritical CO<sub>2</sub>-Based Heat Pump Cycle for Electrical Energy Storage for Utility Scale Dispatchable Renewable Energy Power Plants. The 5th International Supercritical CO<sub>2</sub> Power Cycles Symposium, San Antonio, Texas: 2016.
- [3] Philibert C. Renewable Energy for Industry - From green energy to green materials and fuels. International Energy Agency 2017:72. [https://www.iea.org/publications/insights/insightpublications/Renewable\\_Energy\\_for\\_Industry.pdf](https://www.iea.org/publications/insights/insightpublications/Renewable_Energy_for_Industry.pdf) (accessed January 15, 2019).

1.2. Analysis of technologies and potentials for heat pump-based process heat supply above 150 °C, Benjamin Zühlsdorf, DTI




**DANISH TECHNOLOGICAL INSTITUTE**

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

09.09.2019 – Copenhagen, Denmark  
2<sup>nd</sup> conference on high-temperature heat pumps

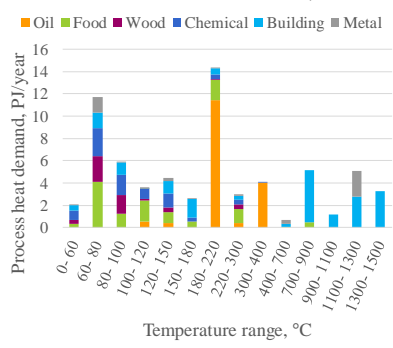
Benjamin Zühlsdorf, F. Bühler, M. Bantle, B. Elmegaard  
[bez@teknologisk.dk](mailto:bez@teknologisk.dk), +45 7220 1258



**DANISH TECHNOLOGICAL INSTITUTE**

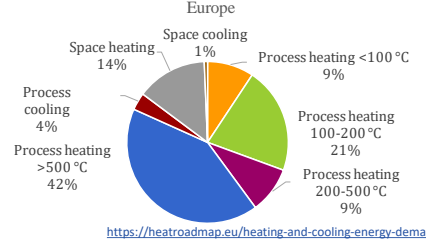
## Motivation and Potential

Process heat demand in Denmark, 2012



Temperature range, °C	Oil	Food	Wood	Chemical	Building	Metal
0-60	0.5	0.5	0.5	0.5	0.5	0.5
60-80	1.0	1.0	1.0	1.0	1.0	1.0
80-100	1.5	1.5	1.5	1.5	1.5	1.5
100-120	2.0	2.0	2.0	2.0	2.0	2.0
120-150	2.5	2.5	2.5	2.5	2.5	2.5
150-180	3.0	3.0	3.0	3.0	3.0	3.0
180-220	3.5	3.5	3.5	3.5	3.5	3.5
220-300	4.0	4.0	4.0	4.0	4.0	4.0
300-400	4.5	4.5	4.5	4.5	4.5	4.5
400-700	5.0	5.0	5.0	5.0	5.0	5.0
700-900	5.5	5.5	5.5	5.5	5.5	5.5
900-1100	6.0	6.0	6.0	6.0	6.0	6.0
1100-1300	6.5	6.5	6.5	6.5	6.5	6.5
1300-1500	7.0	7.0	7.0	7.0	7.0	7.0

Energy demand for heating and cooling in industry in Europe



Category	Percentage
Process heating >500 °C	42%
Process heating 200-500 °C	9%
Process heating 100-200 °C	21%
Process heating <100 °C	9%
Space cooling	1%
Space heating	14%
Process cooling	4%

<https://heatroadmap.eu/heating-and-cooling-energy-demand-profiles/>

\*Based on data from Bühler, F., Nguyen, T. V., & Elmegaard, B. (2016). Energy and exergy analyses of the Danish industry sector. *Applied energy*, 184, 1447-1459.\*

- **Alternatives:**
  - Electrical heater
  - Biomass/Biogas
  - Natural gas (+ compensation of emissions)
- **Role of high-temperature heat pumps?**



## Motivation and Potential

Challenges for HTHPs

- Limited performance ( $COP_{Lor}$ )
- High investment cost → Economic performance
- Component constraints

Motivation for electrification: Changing boundary conditions

- Decreasing LCOE from renewables
- Cost of emission increasing
- Limitations of biomass/biogas
- Political/industrial strategies to become carbon neutral

Possibilities

- Components from e.g., oil & gas industries operate in more challenging conditions (up to >400 °C)
- Combination of heat pumps and own renewable electricity utilities



## Agenda

- Considered case studies
  - Alumina production case study
  - Spray dryer case study
- Technical concepts
  - Cascade multi-stage compression cycle (R718)
  - Reversed Brayton cycle (R744)
- Economic Analysis
- Summary and outlook



1.2. Analysis of technologies and potentials for heat pump-based process heat supply above 150 °C, Benjamin Zühlsdorf, DTI

**DANISH TECHNOLOGICAL INSTITUTE**

## Considered Case Studies

Electricity supply → Power → Heat Pump → Heat → Process

- Focus on industries with:
  - Large capacities
  - Access to cheap electricity
  - High number of operating hours
  - Possibility to acquire own renewable electricity
  - Acceptance of process equipment

**Alumina production**

- $\dot{Q}_{\text{Demand}} = 50 \text{ MW}$
- $n = 8000 \text{ h/year}$
- Heat sink: Thermal oil
- Heat source: Air

$140 \text{ }^\circ\text{C} \rightarrow 280 \text{ }^\circ\text{C}$   
 $60 \text{ }^\circ\text{C} \leftarrow 110 \text{ }^\circ\text{C}$

**Spray dryer for milk powder production**

- $\dot{Q}_{\text{Demand}} = 8.2 \text{ MW}$
- $n = 7000 \text{ h/year}$
- Heat sink: Drying air
- Heat source: Moist excess air (fixed mass flow)

$64 \text{ }^\circ\text{C} \rightarrow 210 \text{ }^\circ\text{C}$   
 $20\text{-}25 \text{ }^\circ\text{C} \leftarrow 50 \text{ }^\circ\text{C}$

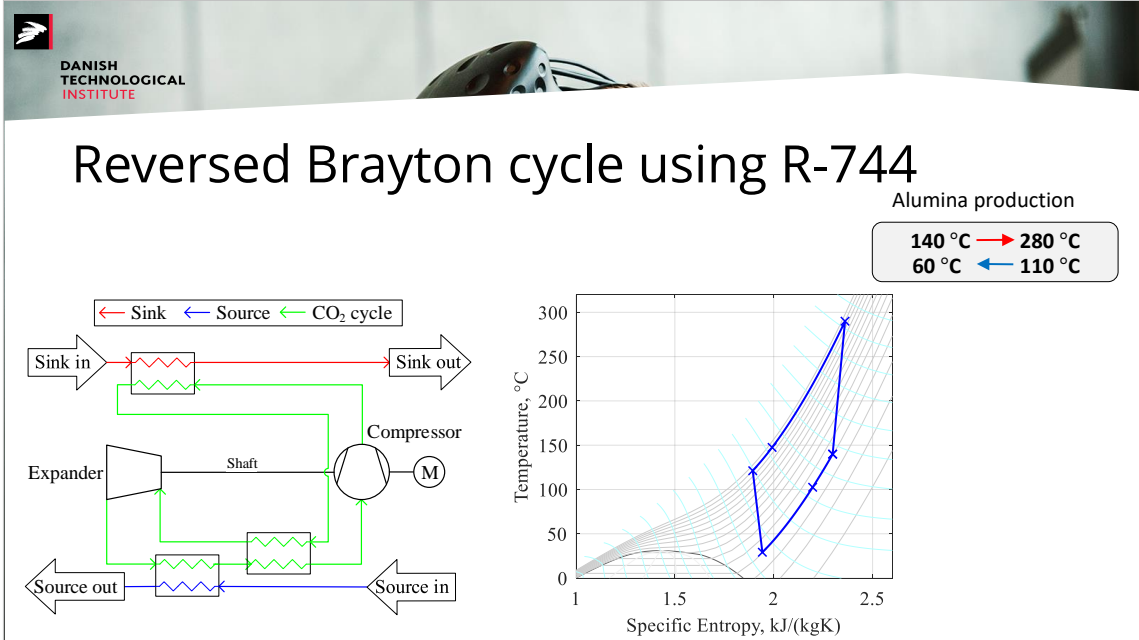
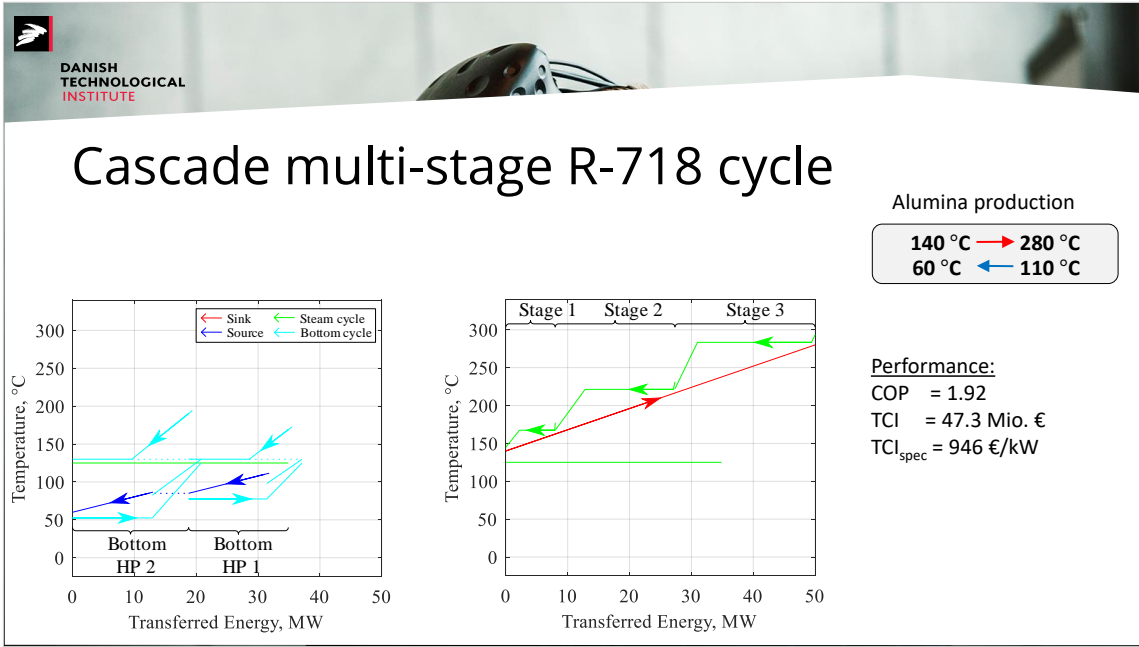
**DANISH TECHNOLOGICAL INSTITUTE**

## Cascade multi-stage R-718 cycle

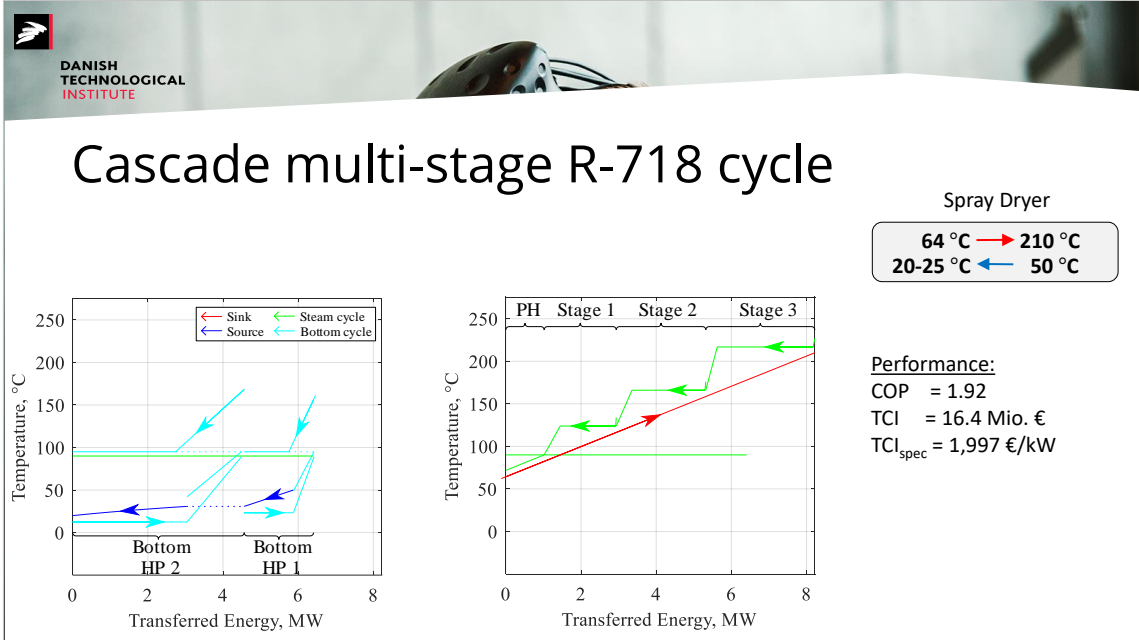
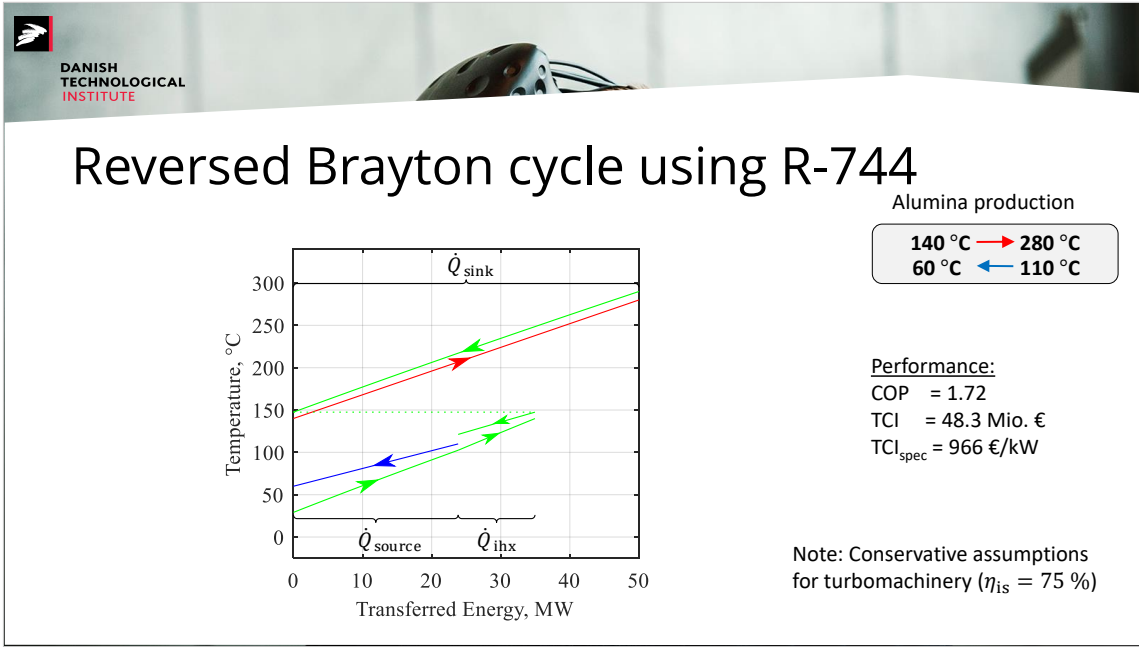
Alumina production

$140 \text{ }^\circ\text{C} \rightarrow 280 \text{ }^\circ\text{C}$   
 $60 \text{ }^\circ\text{C} \leftarrow 110 \text{ }^\circ\text{C}$

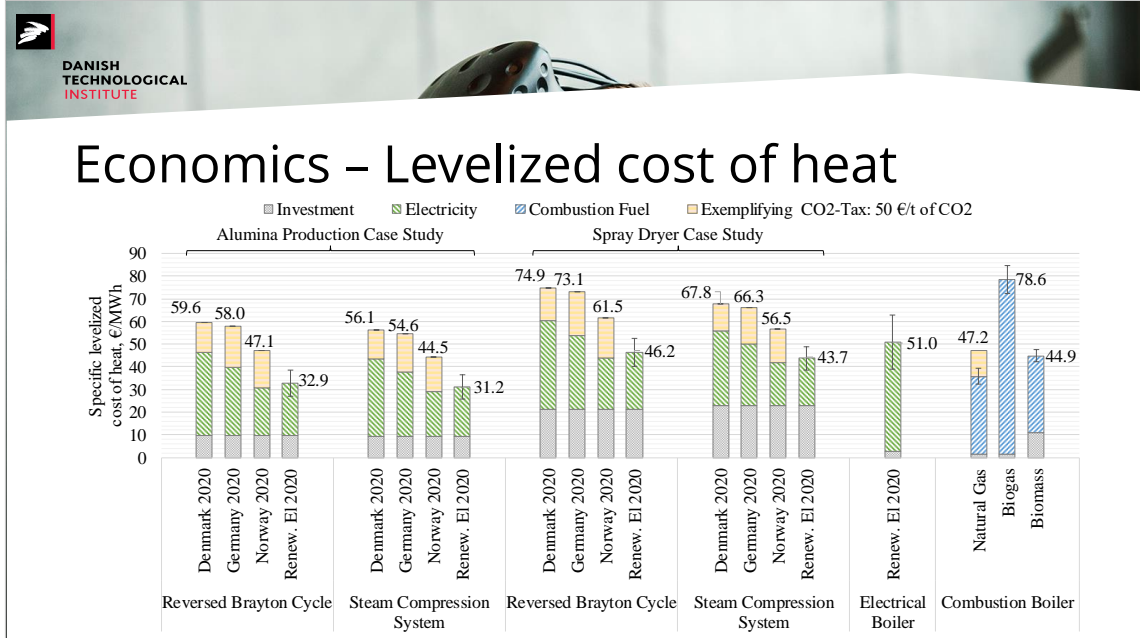
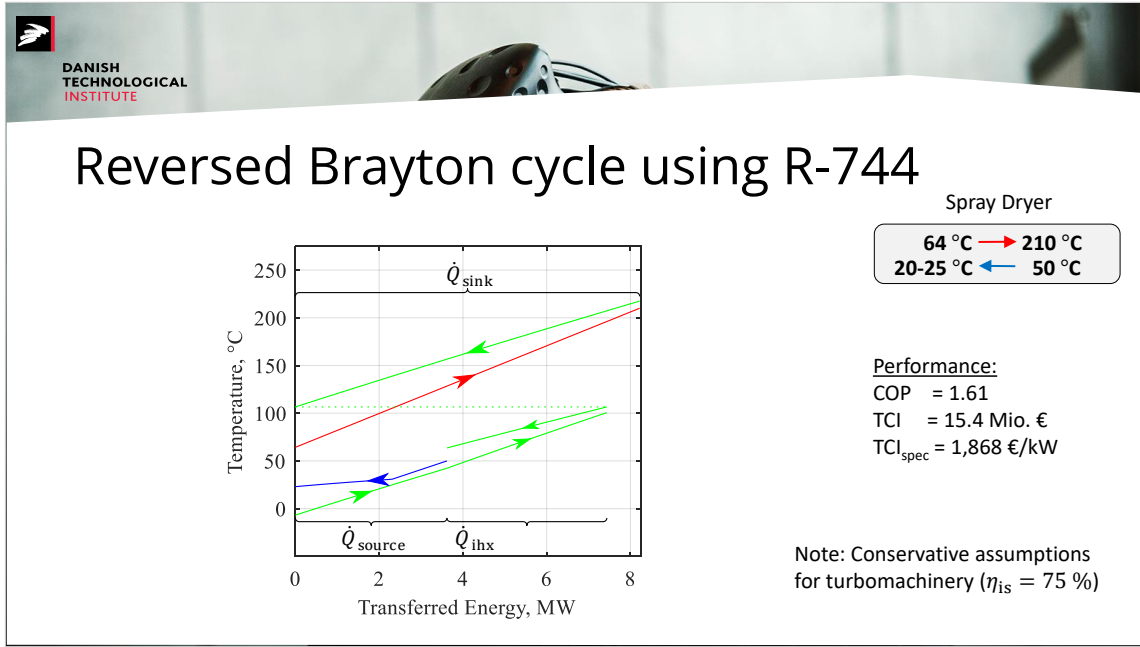
1.2. Analysis of technologies and potentials for heat pump-based process heat supply above 150 °C, Benjamin Zühlsdorf, DTI




1.2. Analysis of technologies and potentials for heat pump-based process heat supply above 150 °C, Benjamin Zühlsdorf, DTI



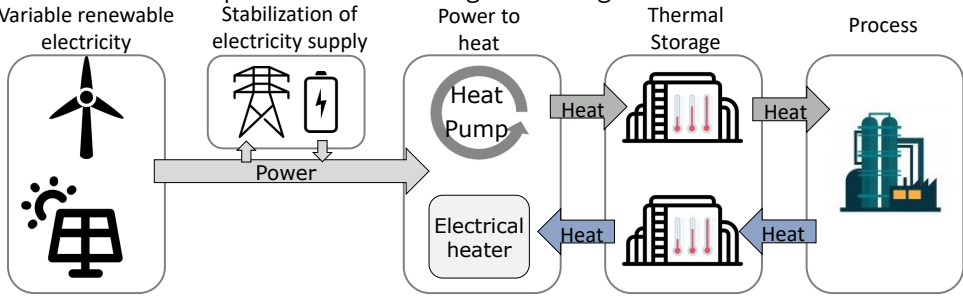
1.2. Analysis of technologies and potentials for heat pump-based process heat supply above 150 °C, Benjamin Zühlsdorf, DTI



 DANISH TECHNOLOGICAL INSTITUTE


## Discussion

- Different scenarios possible for balancing fluctuating renewables



The diagram illustrates a process flow for balancing fluctuating renewables. It starts with 'Variable renewable electricity' (represented by a wind turbine and solar panel icon). This leads to 'Stabilization of electricity supply' (represented by a power line and battery icon). A 'Power' arrow then points to 'Power to heat', which is split into two paths: 'Heat Pump' (circular arrow icon) and 'Electrical heater' (square icon). Both paths lead to 'Thermal Storage' (represented by two storage tank icons). Finally, 'Heat' arrows from the storage tanks lead to the 'Process' (represented by a factory icon).

- Large investments feasible?

 DANISH TECHNOLOGICAL INSTITUTE

## Conclusions

- Technical feasibility:
  - Supply temperatures of up to 280 °C analyzed
  - COPs between 1.6 to 1.9
- Economic feasibility:
  - Economy of scale → lower specific investment at increasing capacities
  - Levelized cost of heat strongly dependent on electricity cost
  - **Heat pump solutions competitive to natural gas and biomass boilers**
- Future work and potentials:
  - Component optimization
  - Optimization of investment cost
  - Demonstration