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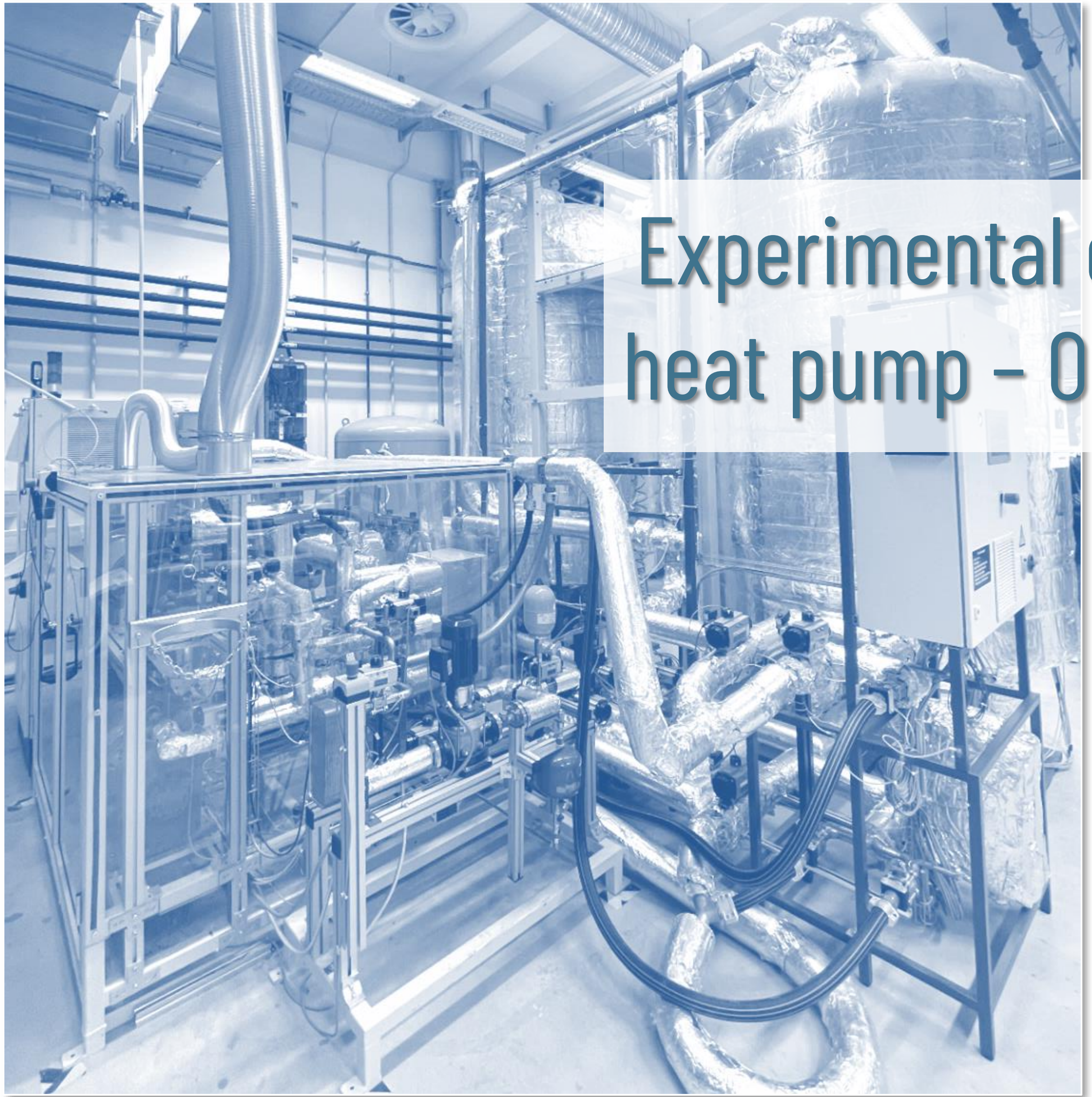

3rd International Workshop on Carnot Batteries, September 27-28, 2022, Stuttgart

Experimental characterization of a reversible heat pump – ORC pilot plant with sensible TES

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Agenda

I. Storage tasks for Carnot batteries

II. Reversible heat pump – ORC pilot plant

III. Experimental results

IV. Next steps at the pilot plant

V. Summary and outlook

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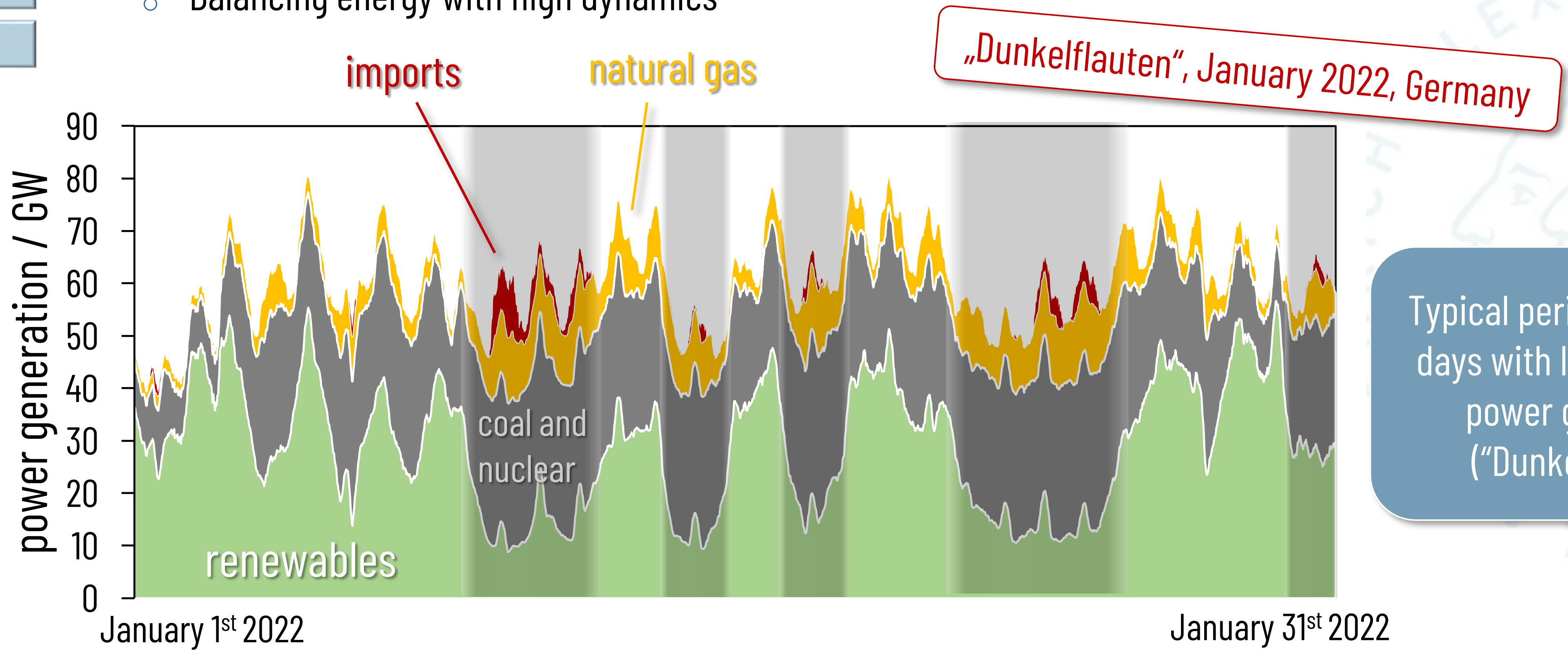
Storage tasks in renewable energy systems

- Current energy market developments underline the importance of grid-scale energy storages
- Preferred areas of application for Carnot batteries:
  - Bridging periods of low renewable power generation several hours to several days *("Dunkelflauten")*
  - Balancing energy with high dynamics



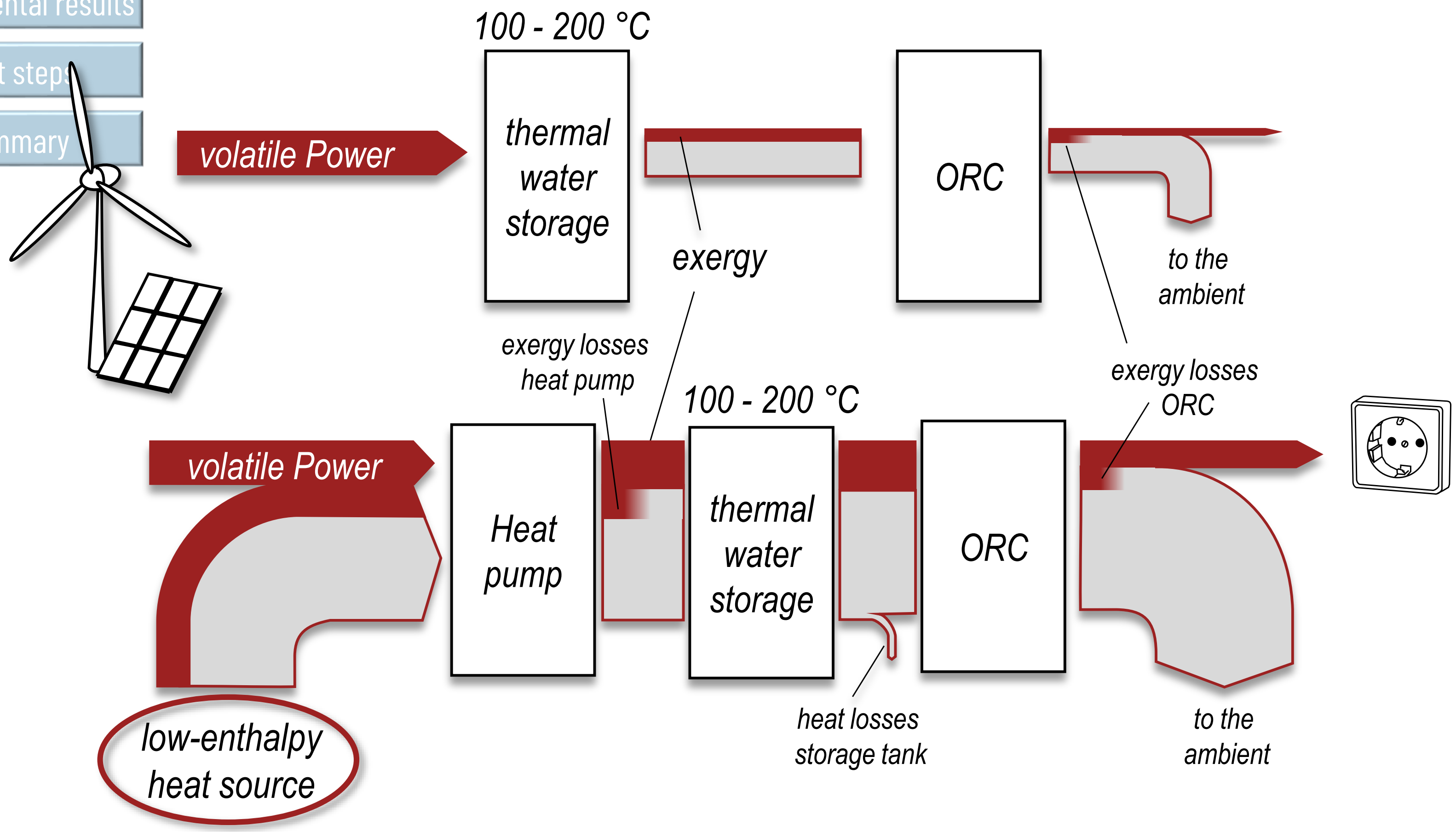
Typical periods of several days with low renewable power generation ("Dunkelflauten")

https://energy-charts.info/?l=de&c=DE

Heat pump – ORC systems

Carnot battery at Energy Campus Nürnberg:

Reversible heat pump – ORC system with sensible thermal energy storage

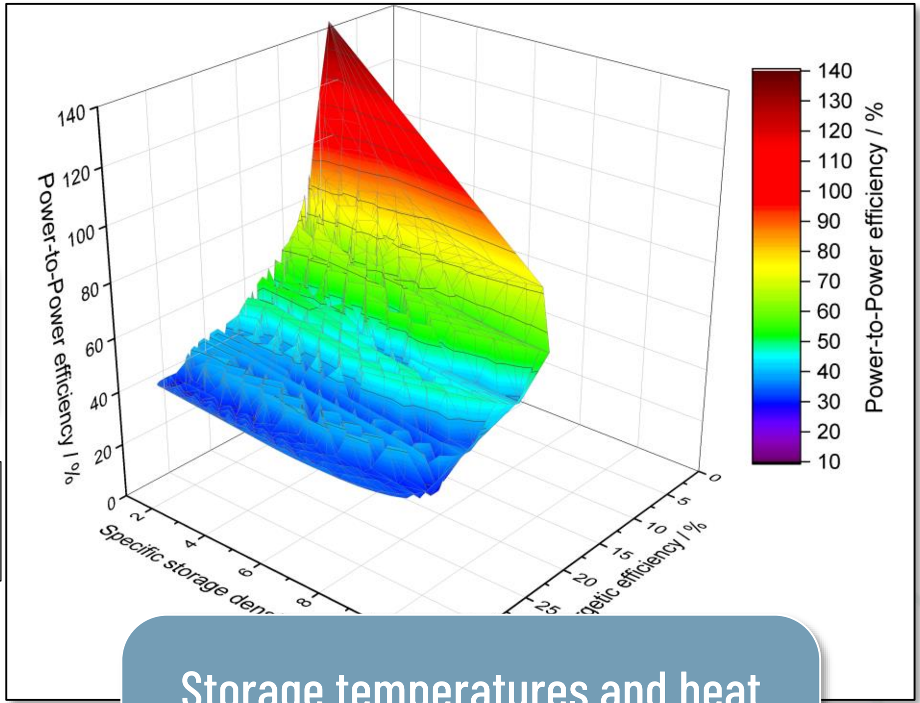


Advantages

- Simple and cheap storage upscale
- Component availability
- Reversible utilization of components
- Sector coupling
  (electricity, heating, cooling)

Thermal integration of low-enthalpy heat (< 100 °C) enables competitive power-to-power efficiencies

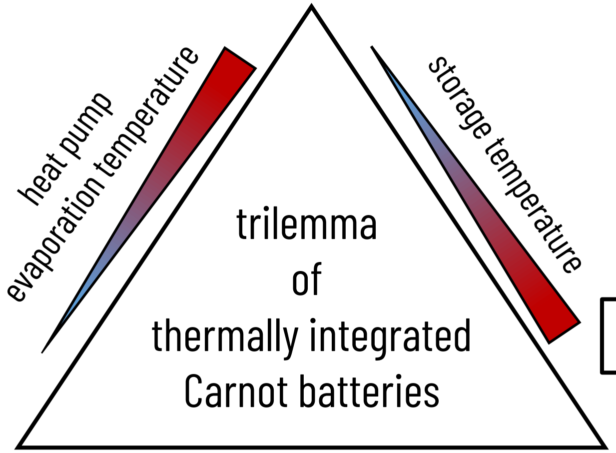
Optimization of Carnot batteries



$$\eta_{PTP} = \frac{E_{out}}{E_{in}} = COP_{hp} \cdot \eta_{orc}$$

η_{PTP}

power-to-power efficiency
(low storage spread and high heat pump evaporation temperature)



Storage temperatures and heat source availability determine the competing objectives

η_{II}

heat source utilization
(low heat pump evaporation temperature for high exergetic efficiency)

$E_{st,vol}$

storage size
(high storage spread for high volumetric storage density)

$$\eta_{ex} = \frac{Ex_{orc}}{Ex_{hp} + Ex_{hs}}$$

$$E_{st,vol} = \frac{E_{out}}{V_{st}}$$

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Reversible heat pump – ORC pilot plant

Specifications

- Charging max. **15 kW$_{el}$** (heat pump mode)
- Discharging max. **9 kW$_{el}$** (ORC mode)
- Working fluid: **R1233zd(E)**
- 2x 4m^3 sensible thermal energy storages **(~270 kWh$_{th}$)**
- Nominal storage temperature: 120 °C
- Fully **reversible operation** possible
- Auxiliary water cycles for heating and cooling
- Commissioned in May 2021

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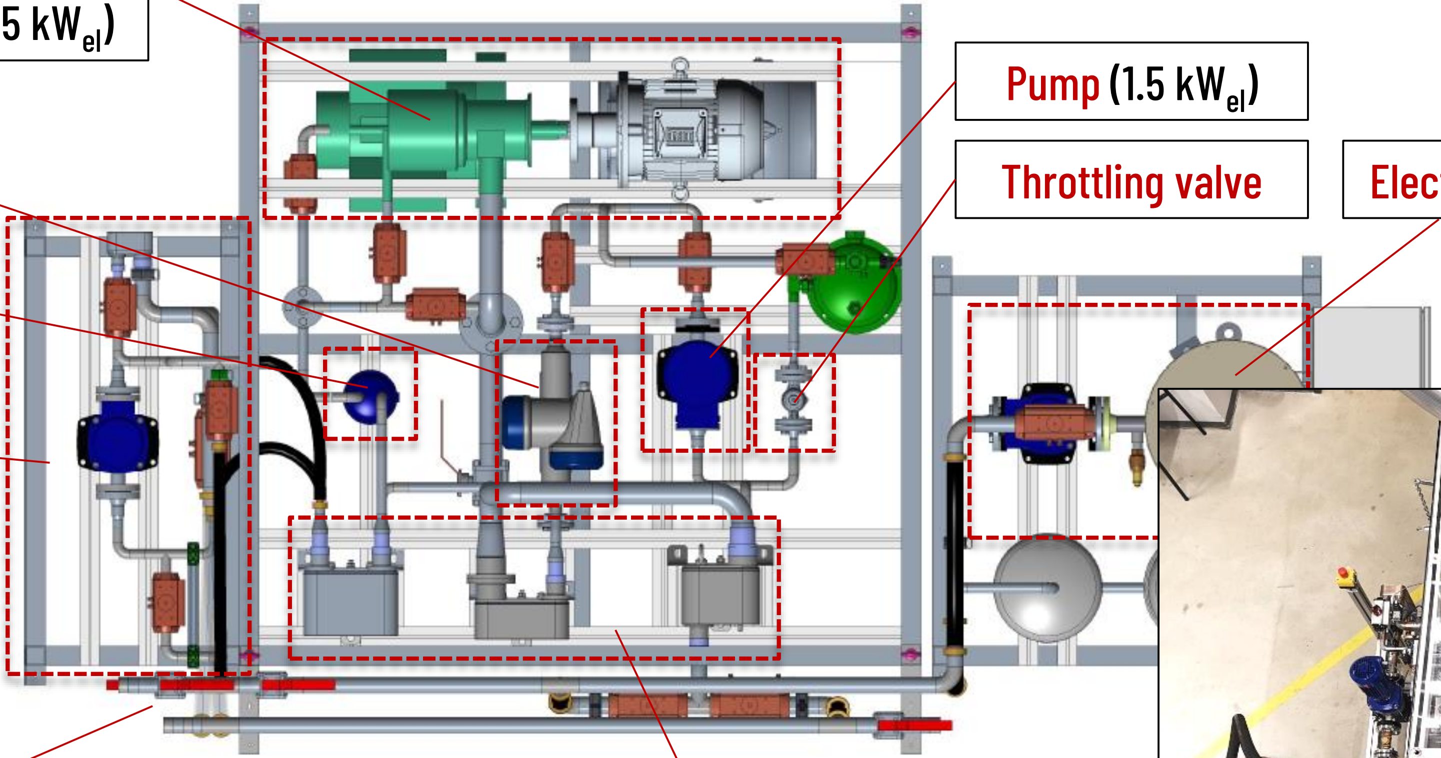
Reversible heat pump – ORC pilot plant



+ Storage (2x $4m^3$ ~ 270 kWh_{th})

+ Auxiliary cycles

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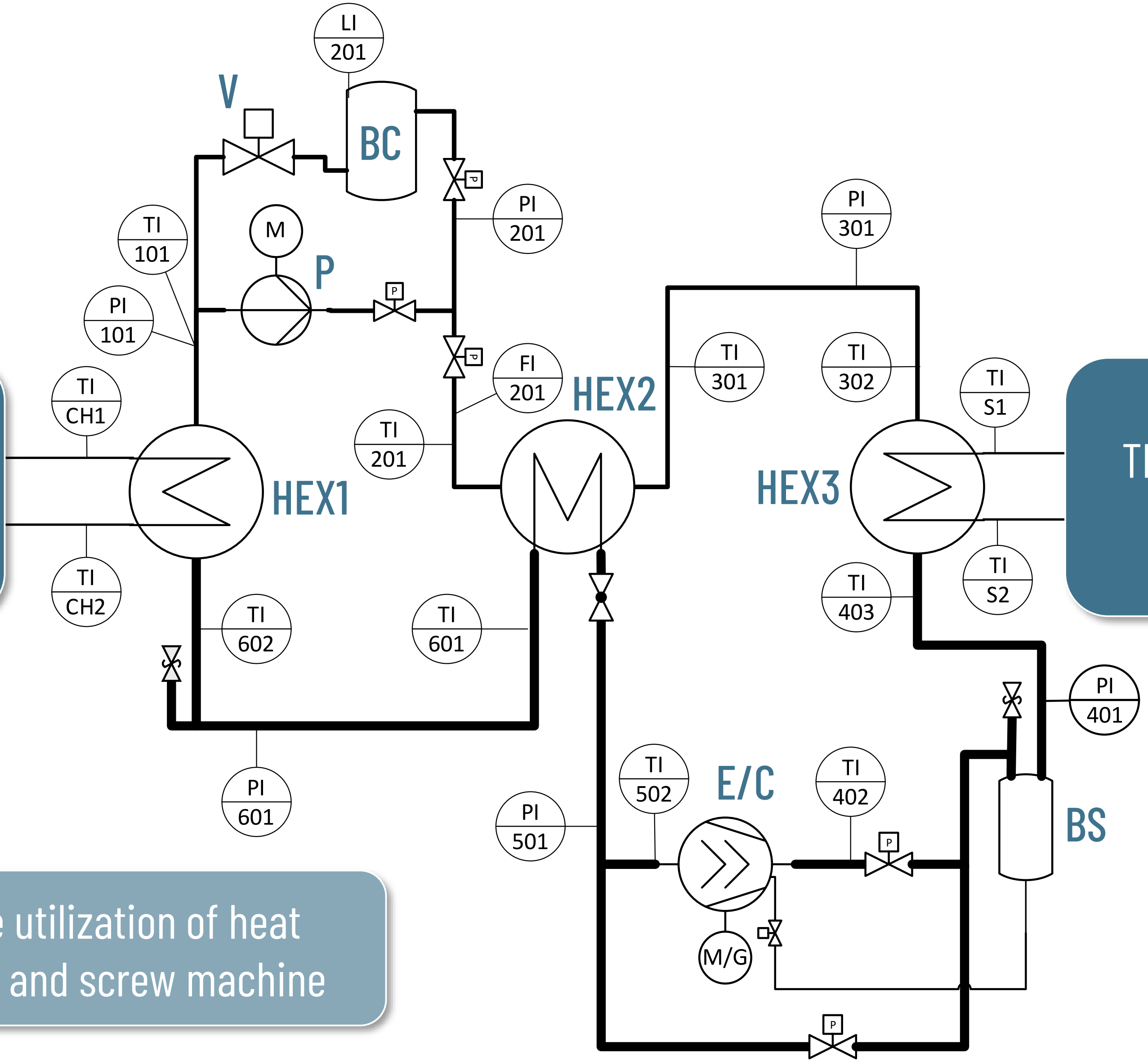
P&ID of the heat pump – ORC system

Auxiliary heating and cooling cycles



Thermal energy storage

- E: Expander
- C: Compressor
- BS: Oil Separator
- HEX1: Heat Exchanger
- HEX2: Heat Exchanger
- HEX3: Heat Exchanger
- V: Throttle Valve
- BC: Fluid Collector
- P: Pump

Reversible utilization of heat exchangers and screw machine

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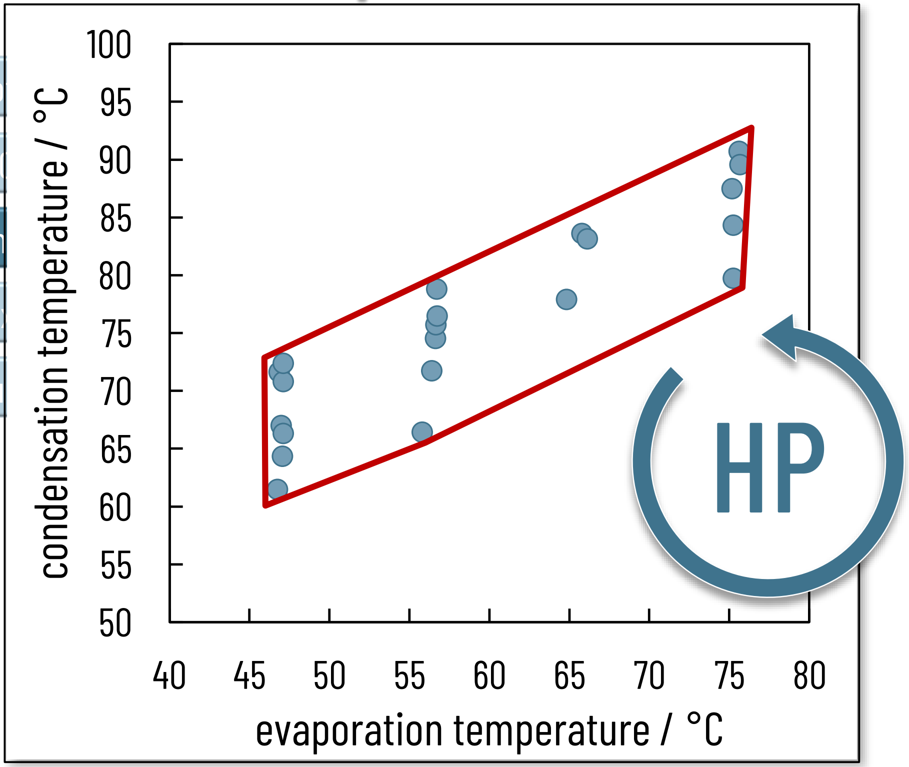
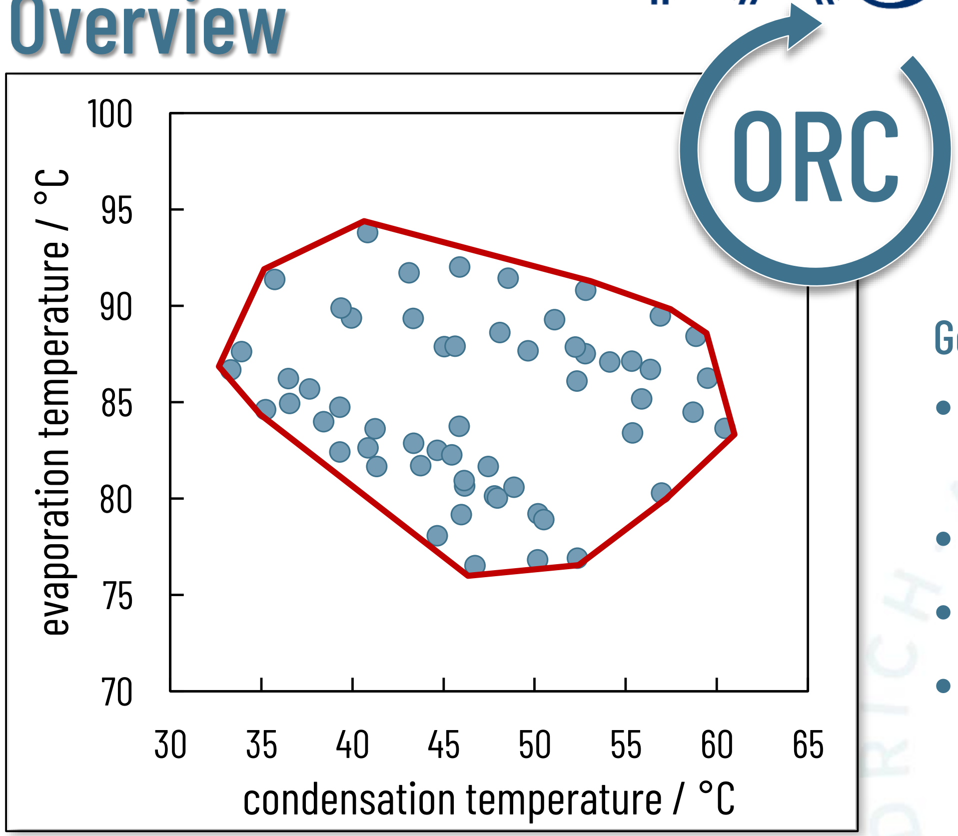
Experimental results – Overview





General methodology

- 81 stationary operating points (59 ORC, 22 HP)
- Defined stationarity criteria
- 15 minutes average values
- Auxiliary water cycles substitute storage

Parameter	Operating Range
Heat source temperature	50 – 80 °C
Heat source thermal power	12.6 – 22.7 kW_{th}
Mass flow working fluid	0.10 – 0.41 kg/s
Screw compressor speed	600 – 2200 rpm

Parameter	Operating Range
Upper storage temperature	100 – 110 °C
Storage thermal power	31.5 – 64.4 kW_{th}
Mass flow working fluid	0.14 – 0.36 kg/s
Screw expander speed	1000 – 3100 rpm

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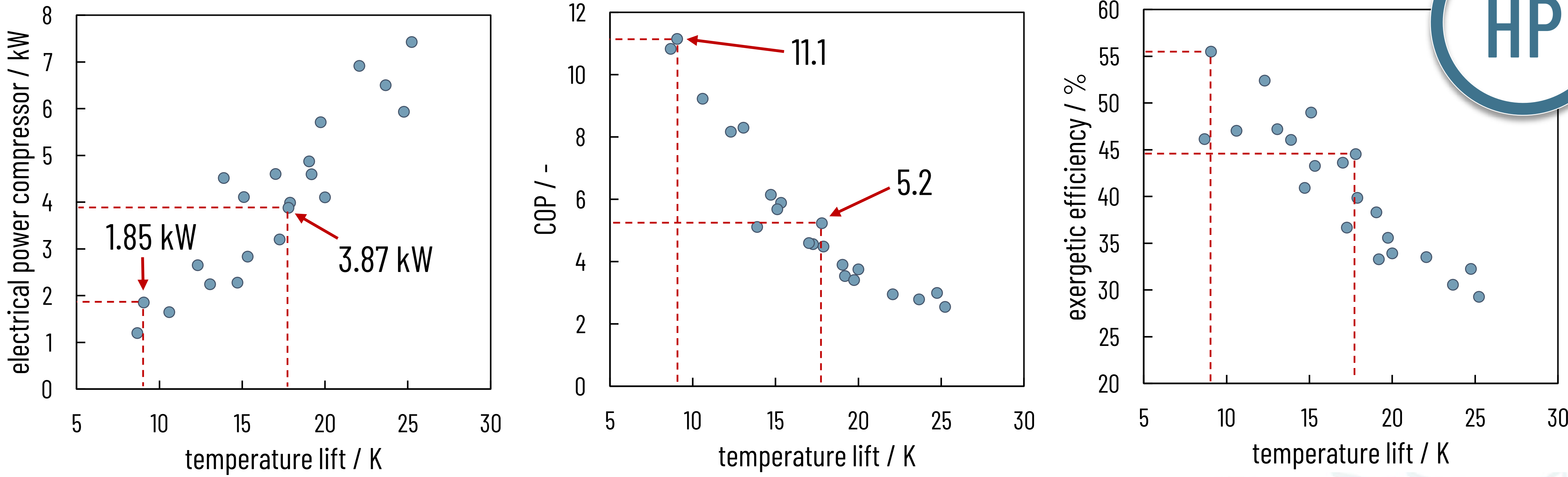
Experimental results – heat pump mode

HP



Outcomes

- Screw machine utilized in reverse operation *(compression)*
- COP decreases with increasing rotational speed *(and temperature lift)*
- Efficiency: 20.6 kW_{th} stored heat / 1.85 kW_{el} compressor power → **max. COP = 11.1** *(at 9.1 K temperature lift)*

Lessons learned

1. Heat pump results underline **trade-off between efficiency and sizing**
2. Nominal **motor power limits** the temperature lift / pressure ratio
3. Screw machine not ideally **lubricated** during compression

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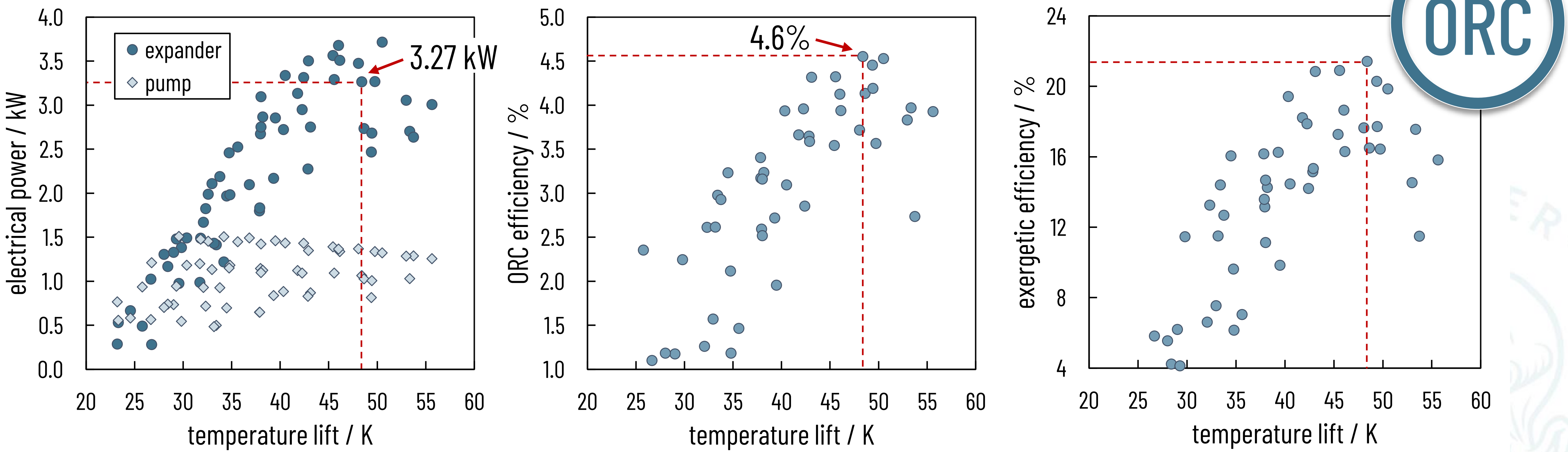
Experimental results – ORC mode



Outcomes

- ORC efficiency and power output increase with temperature gradient *(optimal rot. speed for given mass flow rate)*
- Efficiency: 49.9 kW_{th} storage heat / 3.27 kW_{el} expander power **max. 4.6%** *(at 48.4 K temperature gradient)*
- Discussion: Power-to-Power efficiency = 11.1 (COP) x 4.6% = 51%?

Lessons learned

1. High pump consumption (**optimize lubricant oil charge**, replace by more efficient pump)
2. Considerable subcooling (**optimize working fluid charge** in ORC mode)
3. Cooling capacity in the lab limits condensation pressure

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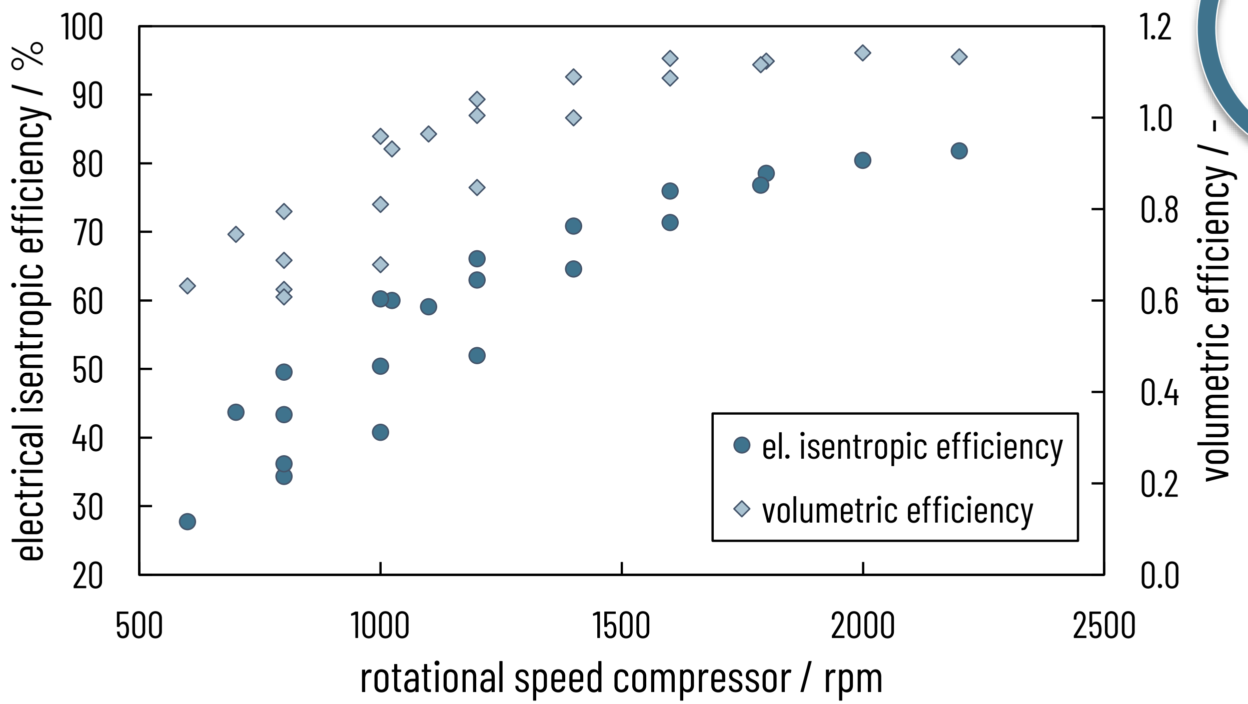
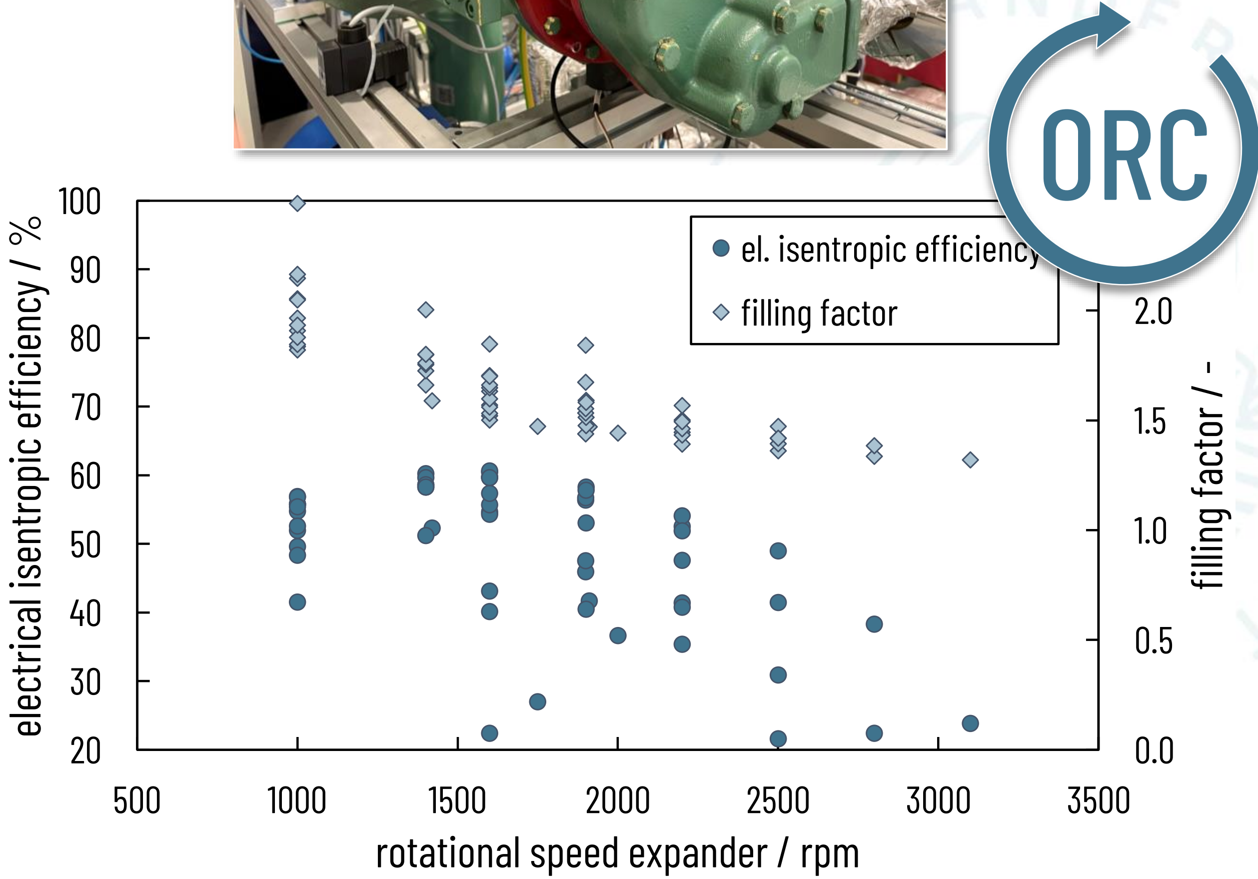
Reversible screw machine





- Filling factor decreases with decreasing pressure gradient and increasing rotational speed
- Max. electrical isentropic efficiency: 82% (HP), 61% (ORC)
- Non-optimized fluid management limits screw machine performance

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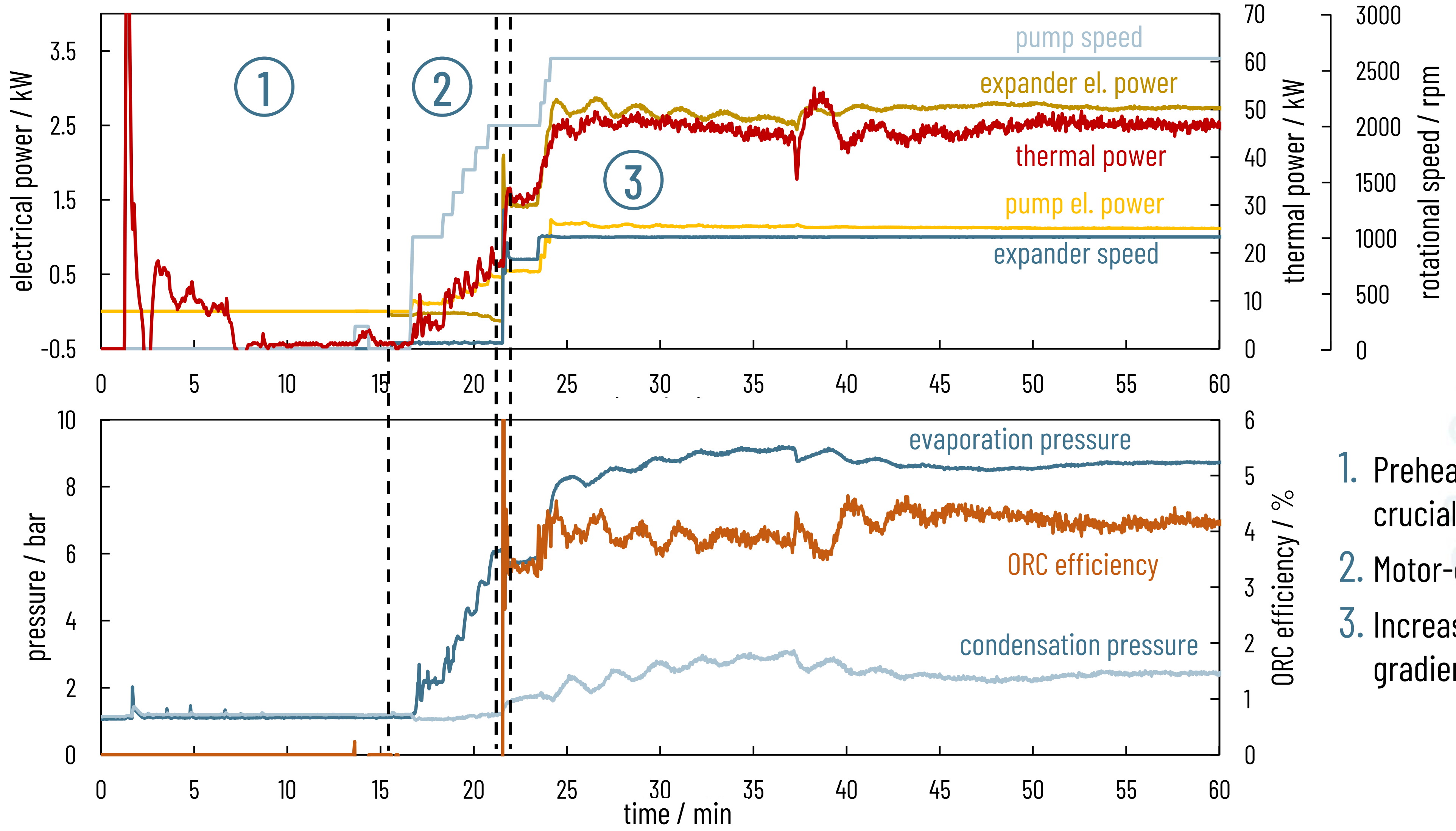
Experimental results – ORC start-up



ORC

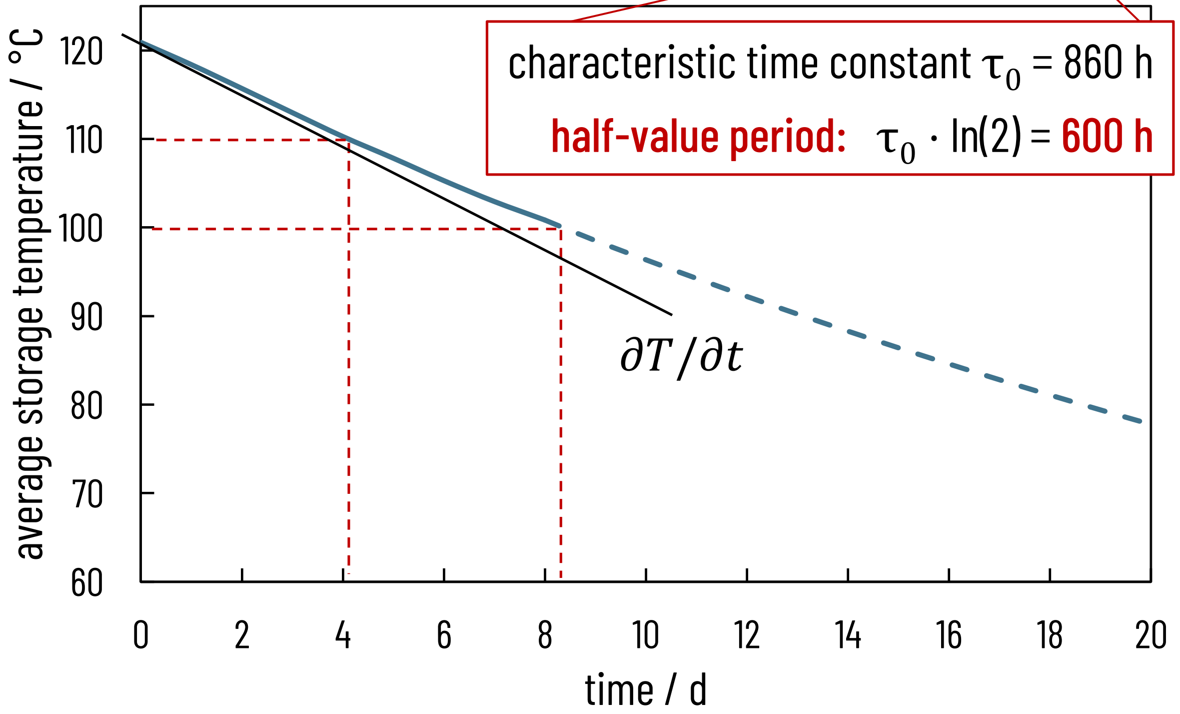
Improved start-up routine enables ORC operation after few minutes

1. Preheating of auxiliary hot water cycle and crucial parts of the cycle
2. Motor-driven screw expander at low speed
3. Increasing pump speed until pressure gradient is sufficient to drive expander

Impact of the thermal energy storage

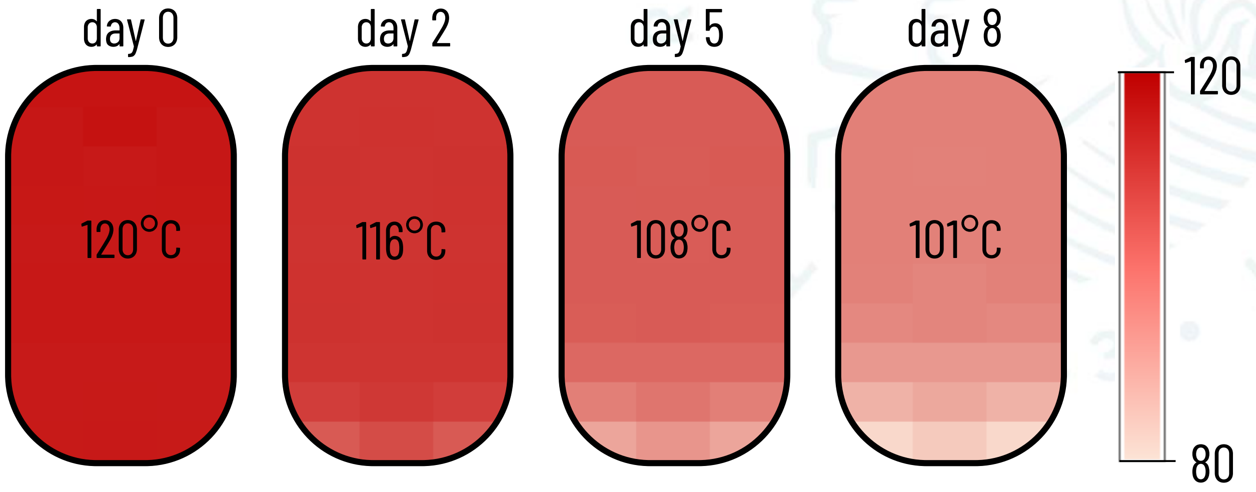
- Storage losses reduce ORC efficiency
- Storage temperature gradient increases with time

$$T(t) = T_{amb} + (T_0 - T_{amb}) \cdot \exp\left(\frac{t}{\tau_0}\right)$$



Next steps

- Operation of heat pump and ORC coupled with storage
- More detailed evaluation of storage losses



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Next steps at the pilot plant

Batteries

HP-(

Exper

1

Experimental characterization of the HP-ORC pilot plant

Experimental campaigns in HP and ORC mode to evaluate stationary and dynamic behavior with and without thermal energy storage

2

Optimization of the pilot plant

- Improvements on component level (e.g. screw machine)
- Optimize fluid management
- Implement effective plant control

4

New concepts on process level

- Experimental validation of fluid mixtures
- Improved process layouts
- Measures to enhance system dynamics

3

Control strategies

- Development of semi-empirical off-design model
- Derive and validate effective control strategies

Summary and outlook

Successful proof of concept of a reversible heat pump – ORC system

First experimental characterization shows good performance in both modes and indicates further potential

Main levers for improvement identified for both operating modes (e.g. fluid management, lubrication, components)

Storage losses quantified by means of a simplyfied model

Next steps

- Further experimental characterization
- Optimizations on component and system level
- Development of control strategies

Publications

Staub et al. (2018). Reversible heat pump-organic Rankine cycle systems for the storage of renewable electricity. Energies.

Steger et al. (2020). Design aspects of a reversible heat pump – Organic rankine cycle pilot plant for energy storage. Energy.

Weitzer et al. (2022). Organic flash cycles in Rankine-based Carnot batteries with large storage temperature spreads. Energy Conversion and Management,.