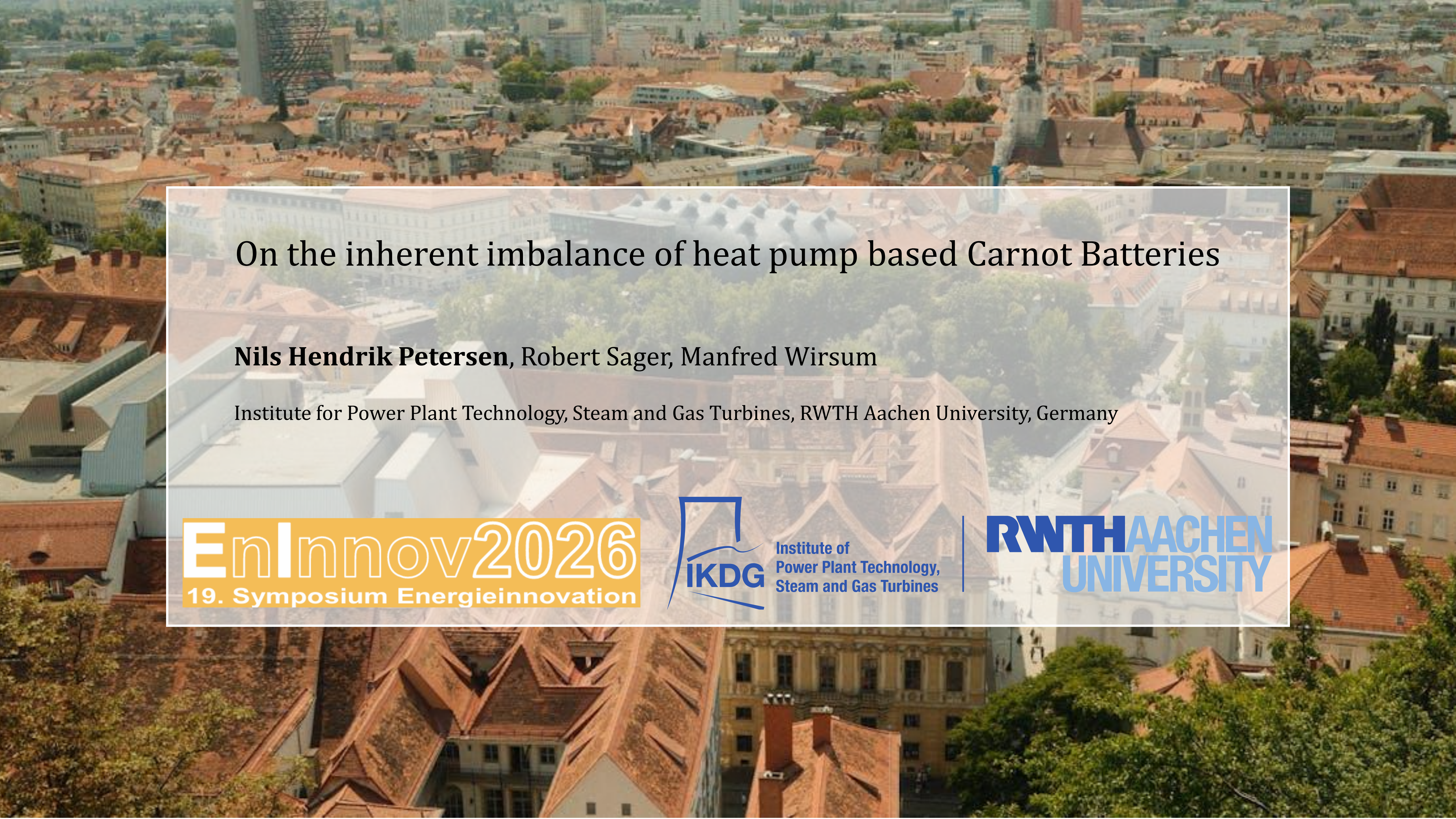

On the inherent imbalance of heat pump based Carnot Batteries

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EnInnov2026
19. Symposium Energieinnovation

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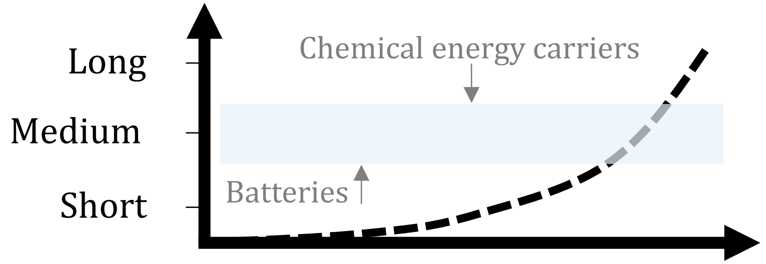
Current status and needs for Carnot Battery analysis

Challenges in the energy system

- Measures to integrate volatile renewable energy (among others)
  - Energy storage

Required discharge duration



➢ Medium-duration technology: **Carnot Battery**

Research question

- Heat pump-based CB utilize hot and cold storages

➢ Storage balancing is critical design task

- Two types exist: *operation* and *export imbalance*

➢ Systematic analysis of both types is still missing

» This study tries to close that gap by analysing *operation* and *export imbalance* for 3 CB concepts

CB: Carnot Battery

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Schematic overview of Carnot Battery

Charging cycle

- Electrical heater or heat pump

Discharging cycle

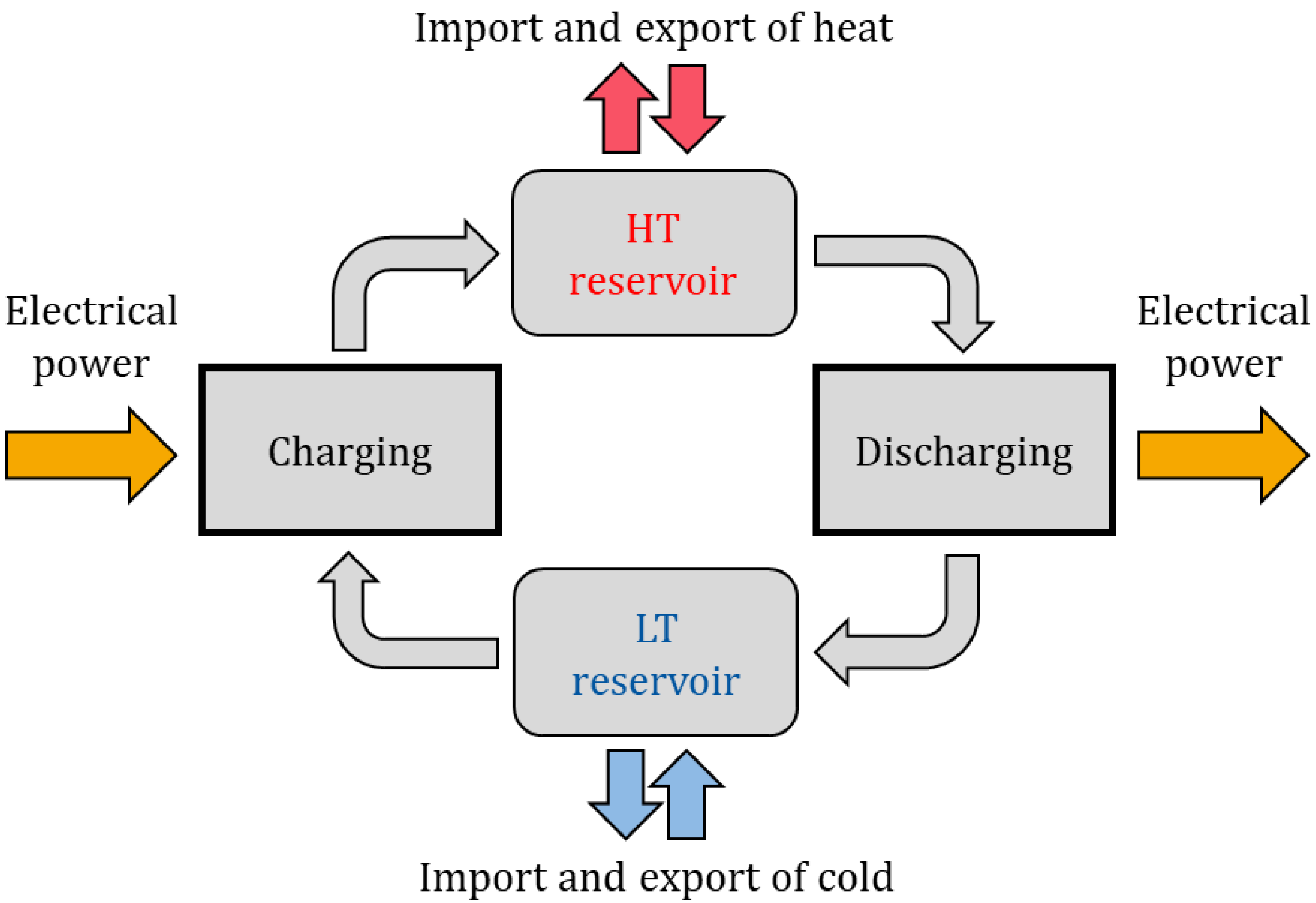
- Rankine- or Brayton-based cycle

Advantages

- Scalable components and storages
- Site-independent
- Flexible in terms of energy (electricity, heat, cold)

Disadvantages

- Moderate roundtrip efficiency
- Complex system



HT: High temperature | LT: Low temperature

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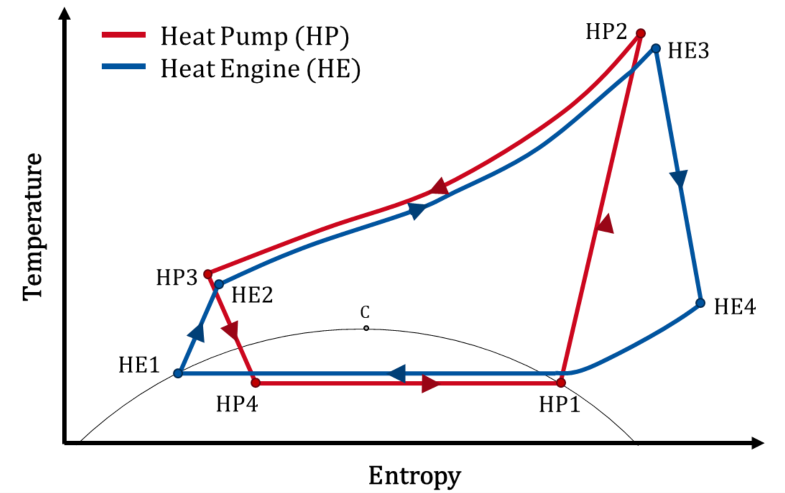
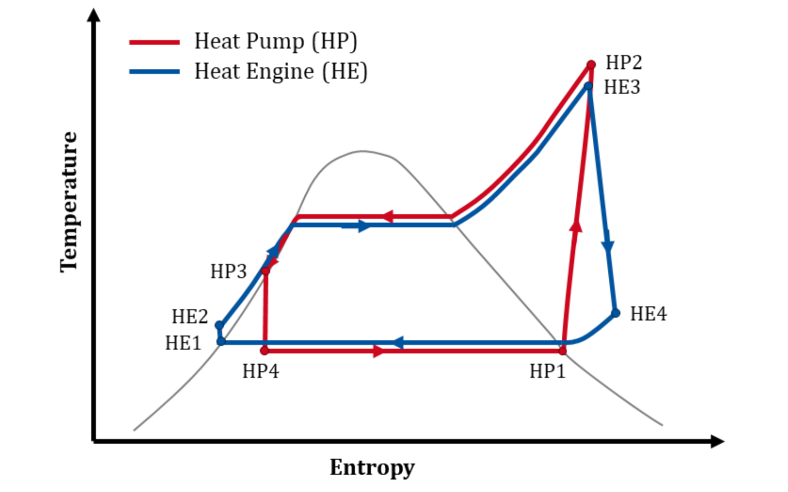
Schematic overview of investigated systems

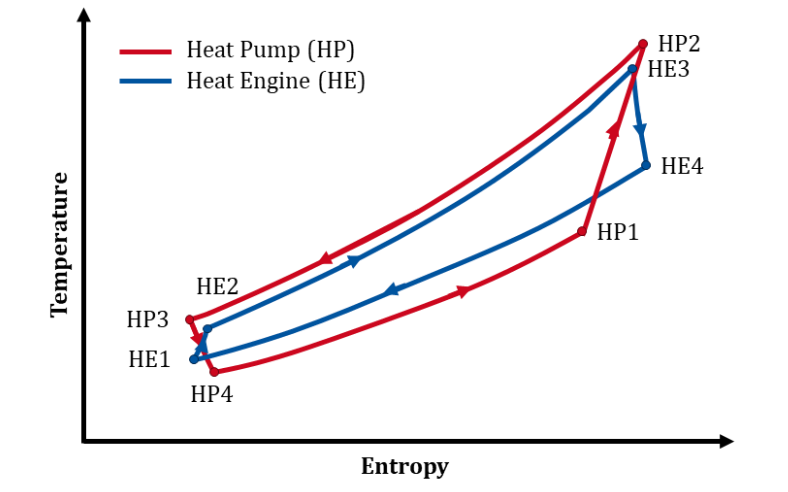
CO2-Transcritical



Water-Rankine



Air-Brayton



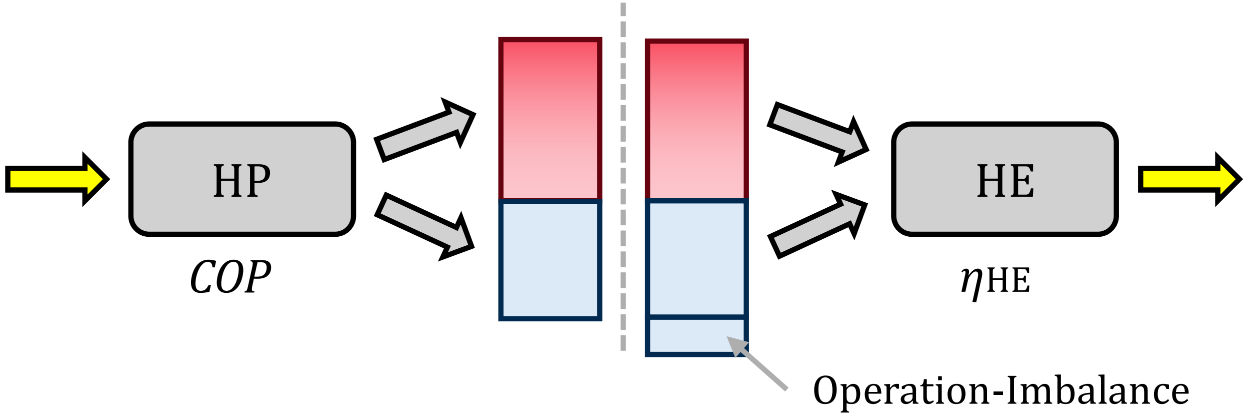
Medium_{hot}	Pressurized water
T_{hot} [K]	288-423
Medium_{cold}	Ice
T_{cold} [K]	270-266
RTE [%]	40-60[1),2)]
Layout Ref.	Everllence

T: Temperature | hot: Hot side | cold: Cold side | *RTE*: Roundtrip efficiency

Introduction of *operation* and *export imbalance*

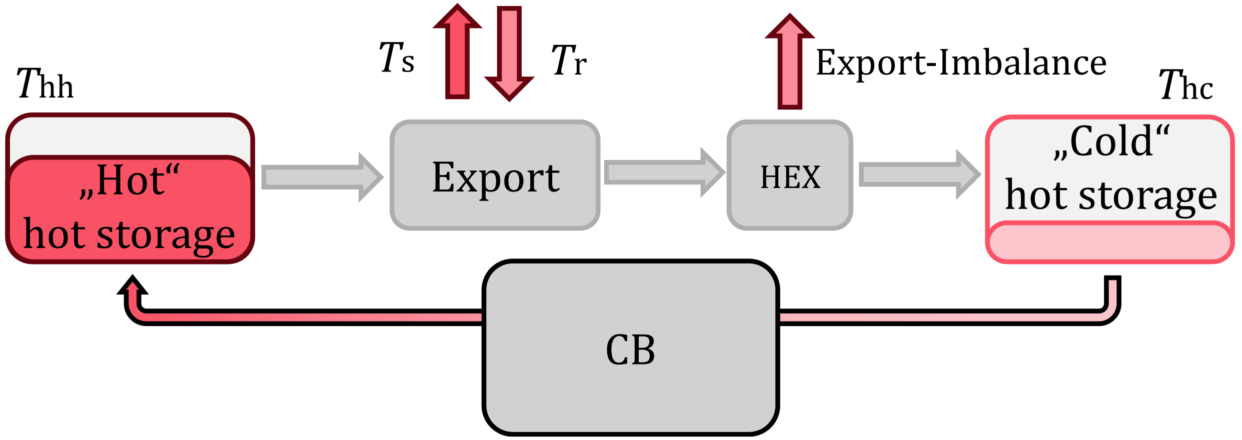
Operation-Imbalance

- $RTE = COP \cdot \eta_{HE} < 1$
  - Too much heat / not enough cold produced
  - Challenge for all CB concepts



Export-Imbalance

- Mismatch between storage and heat consumer temperature profile
  - Thermal export is temperature-dependent
  - Challenge for low-T CB concepts



RTE: Roundtrip efficiency | *COP*: *Coefficient of performance*, η_{HE}: Heat engine efficiency | CB: Carnot Battery | HP: Heat pump | HE: Heat engine | HEX: Heat exchanger | *T*: Temperature
s: Supply | r: Return

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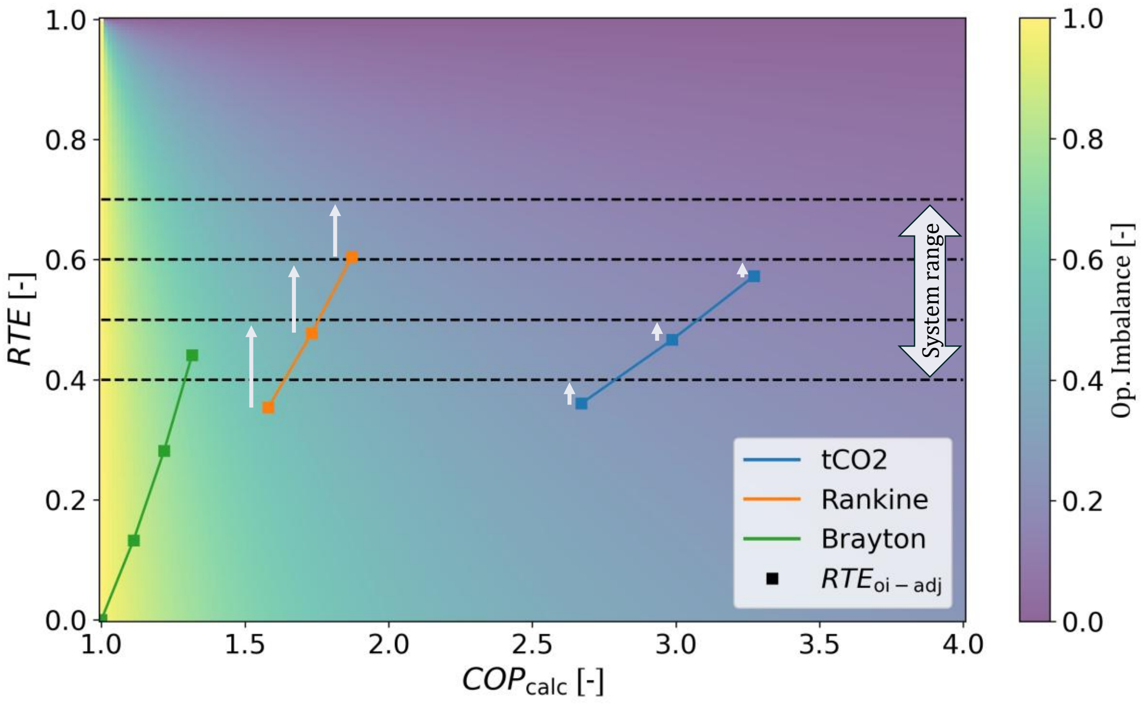
Results
The impact of *operation imbalance* reduces *RTE*



	tCO2	Water-Rankine	Air-Brayton
RTE [%]	40-60[1]	50-70[2,3]	40-70[4,5]

- quality factor: $\vartheta = \sqrt{RTE}^{*}$
  - ϑ used to calculate COP_{calc}
- Op. Imbalance $\sim \frac{1-RTE}{COP-RTE}$
  - subtracted from COP_{calc} to get $RTE_{oi\text{-}adj}$
- High op. Imbalance for low *RTE* and low *COP*
  - High-*T* CB suffer (Water-Rankine, Air-Brayton)
  - Low-*T* CB withstand (tCO2)

*Assuming equal distribution of losses

Not only low-*T* CB should consider thermal export, all CB systems must consider thermal export!

RTE: Roundtrip efficiency | *COP*: Coefficient of performance | calc: calculated | tCO2: transcritical CO2, CHEST: Water-Rankine | Brayton: Air-Brayton | oi-adj: operationa imbalance adjusted
theo: theoretical | eff: effective | *T*: Temperature | r: return | op: operation | ex: Export

$$\eta_{L,ch} = \frac{T_{m,h}}{T_{m,h}-T_{m,c}} \quad | \quad \eta_{L,dc} = \frac{T_{m,h}-T_{m,c}}{T_{m,h}}$$

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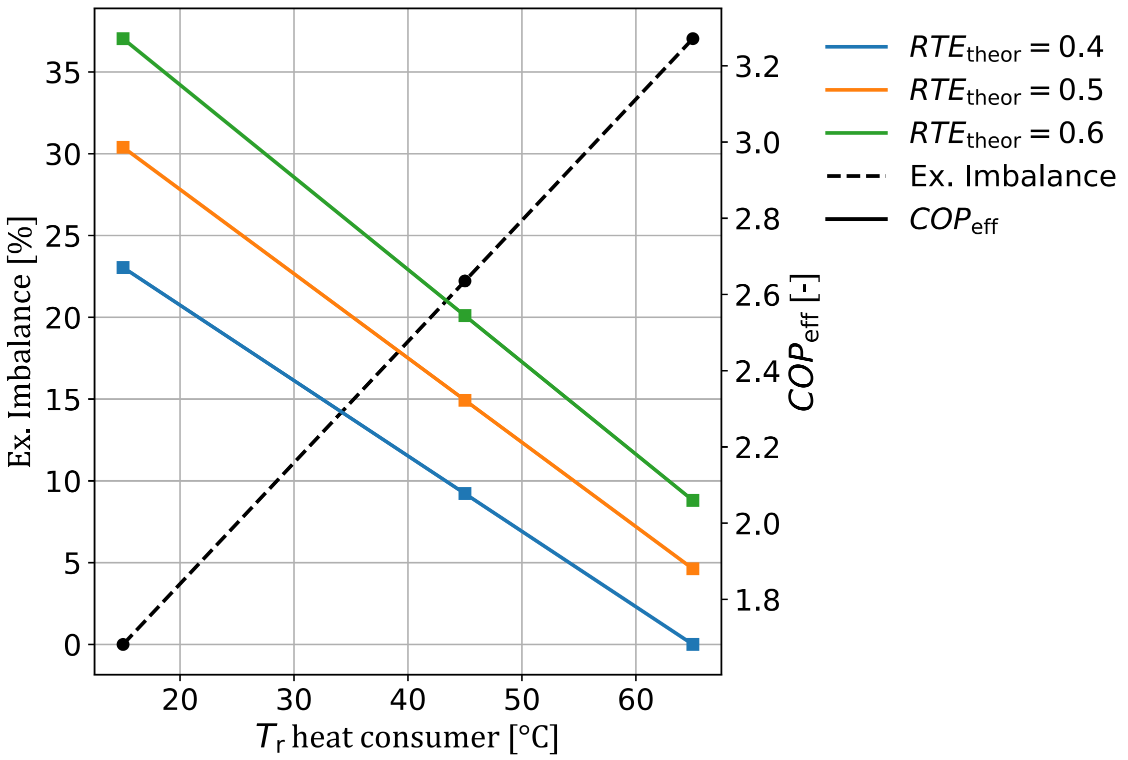
The impact of export *imbalance* reduces *COP*

	tCO2
$Medium_{hot}$	Pressurized water
T_{hot} [K]	288-423

- Pressurized water favors sensible heat transfer
  - Two district heating (DH) network T_r (45/65 °C)
- $\text{Ex. Imbalance} = \frac{\dot{Q}_{export}}{\dot{Q}_{storage}}$
  - Linear function of storage & DH temperature
- Ex. Imbalance is a challenge for low-*T* CB
  - Effective *COP* reduces for higher T_r
  - Reduction of 22-37 %



Ex. Imbalance can reduce the effective thermal export substantially if CB design does not match heat consumer

RTE: Roundtrip efficiency | *COP*: Coefficient of performance | calc: calculated | tCO2: transcritical CO2, CHEST: Water-Rankine | Brayton: Air-Brayton | oi-adj: operationa imbalance adjusted
theo: theoretical | eff: effective | *T*: Temperature | r: return | op: operation | ex: Export

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Summary & conclusion

Imbalance is not a secondary effect but a defining characteristic

Carnot Battery

Imbalance

Results

Conclusion & Outlook

1

Challenge: Integration of volatile renewable energy in the multi-day range

Limitation: Many different designs exist | imbalance effects unclear

2

Idea: Assess imbalance effects consistently

Method: Lorentz equations, quality factors and heat consumer temperatures

3

Op. IB: Significant for high-T CB ($RTE \rightarrow 0$), minor for low-T CB ($\Delta RTE < 10$ %)

Ex. IB: up to 35 % effective *COP* reduction

4

Summary: All CB **should** be installed with options for thermal export

Next: Expand to more CB concepts & integrate into dispatch optimization

T: Temperature | CB: Carnot Battery | *RTE:* Roundtrip efficiency | *COP:* Coefficient of performance | OP: Operation | IB: Imbalance | Ex: Export

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Thank you for your attention.

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