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# Advanced Organic Rankine Cycles for thermally integrated Carnot Batteries


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# Agenda

# Storage requirements in renewable energy systems (I)

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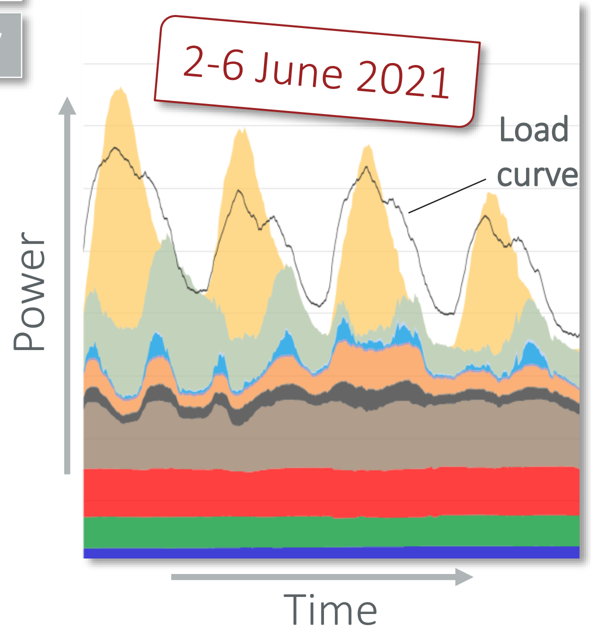
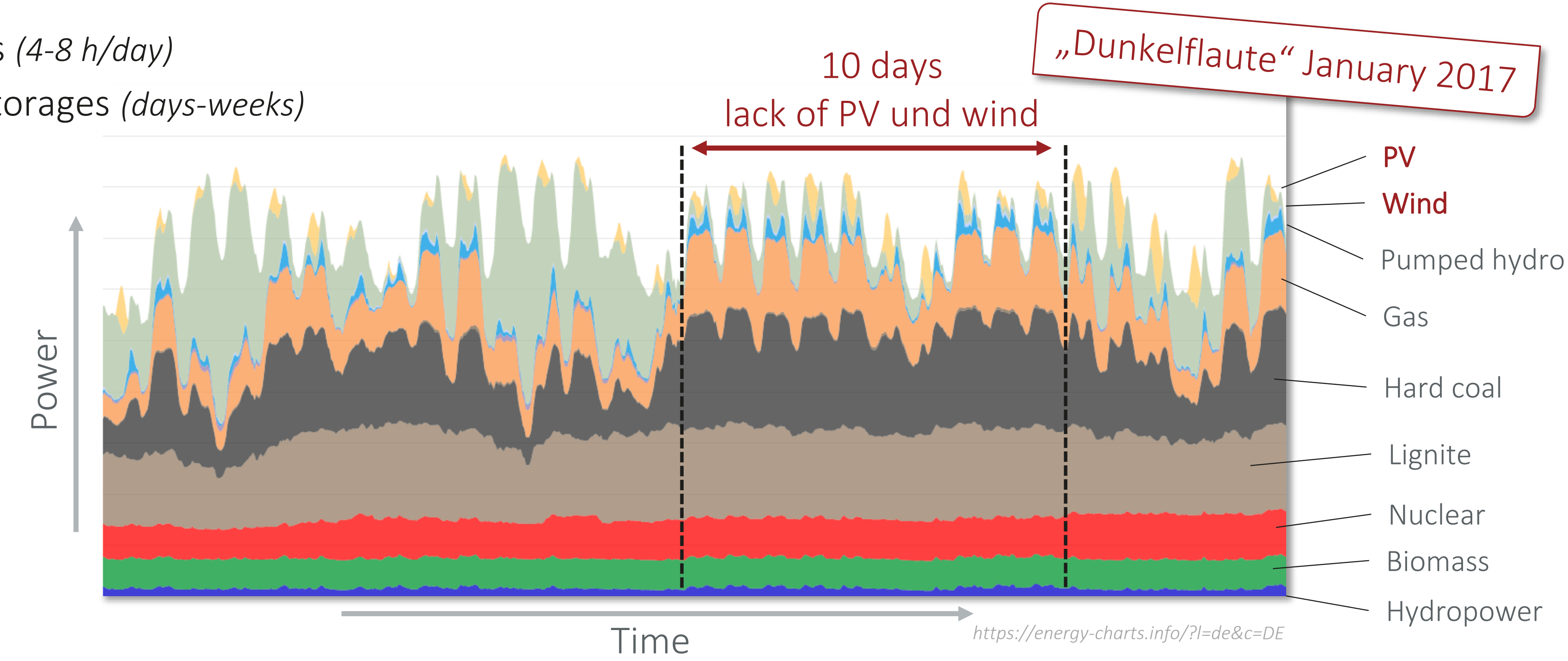
I
II
III
IV
V

- Defossilization requires **310 GW additional storage capacity** until 2050 *(in Europa, US, China and India; IEA 2014)*
- Grid-connected storages mostly by pumped hydro storage (130 GW) and compressed air storage (440 MW)
- Storage tasks include:
  - Base-load storages *(4-8 h/day)*
  - „Dunkelflauten"-storages *(days-weeks)*



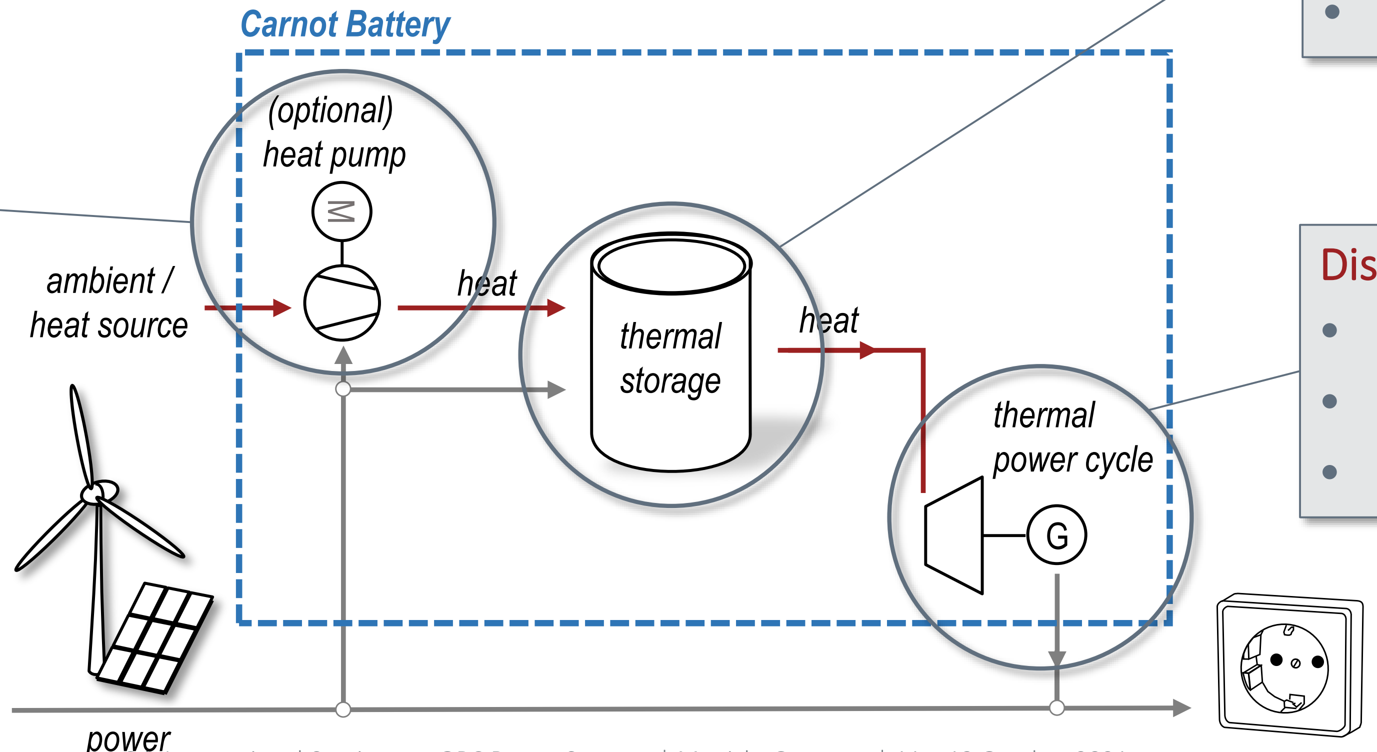
# Working principle of Carnot Batteries

- **Thermal storage** of surplus renewable electrical energy
- Discharging by means of thermal power cycles
- Similar charging and discharging cycles allow **reversible** utilization of components
- **Optional: Integration of low-temperature waste heat**

**Charging**
- Resistance heating
- Heat pump
- Reverse Brayton Cycle

**Storage**
- Hot water
- Packed bed
- Molten salts

**Discharging**
- Organic Rankine Cycle
- Clausius Rankine Cycle
- Brayton Cycle



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Advanced Organic Rankine Cycles for Thermally Integrated Carnot Batteries
Maximilian Weitzer, M. Sc.

# ORC-based Carnot Batteries

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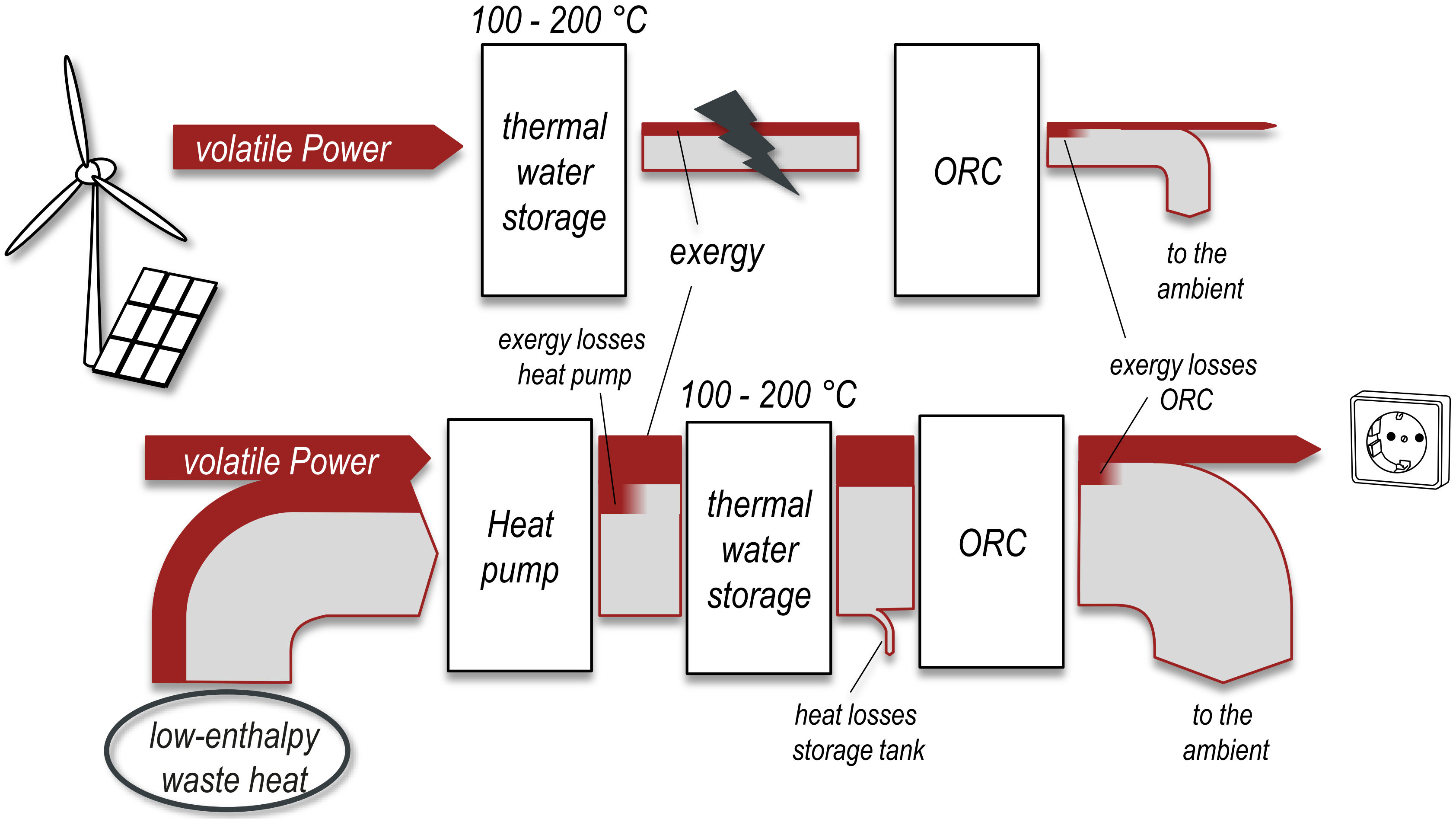
I
II
III
IV
V

- At EnCN:
  HP-ORC system with sensible hot water storage
- Advantages:
  - Simple and cheap storage upscale
  - Component availability
  - Geographical independence
  - Sector coupling
- Thermal integration of low-temperature heat (< 100 °C)
- PTP efficiencies > 100% possible
  *(due to „free“ waste heat))*



# The Carnot Battery trilemma

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

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

**trilemma**
of
**thermally integrated Carnot batteries**

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

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

**storage size**
*(high storage spread for high energy densitiy of sensible heat storage)*

$$E_{st,vol} = \frac{E_{out}}{V_{st}} = \rho_{st} \cdot \bar{c}_p \cdot \Delta T_{st} \cdot \eta_{orc}$$

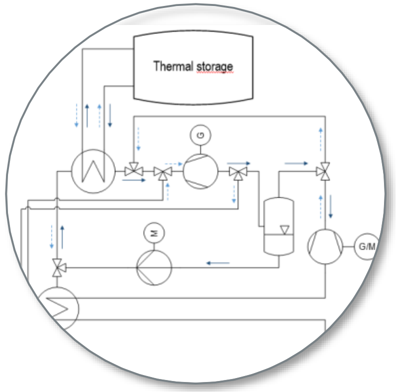
**Storage temperatures** and **waste heat availability** determine the competing objectives

Additional objective:
**Economic feasibility**

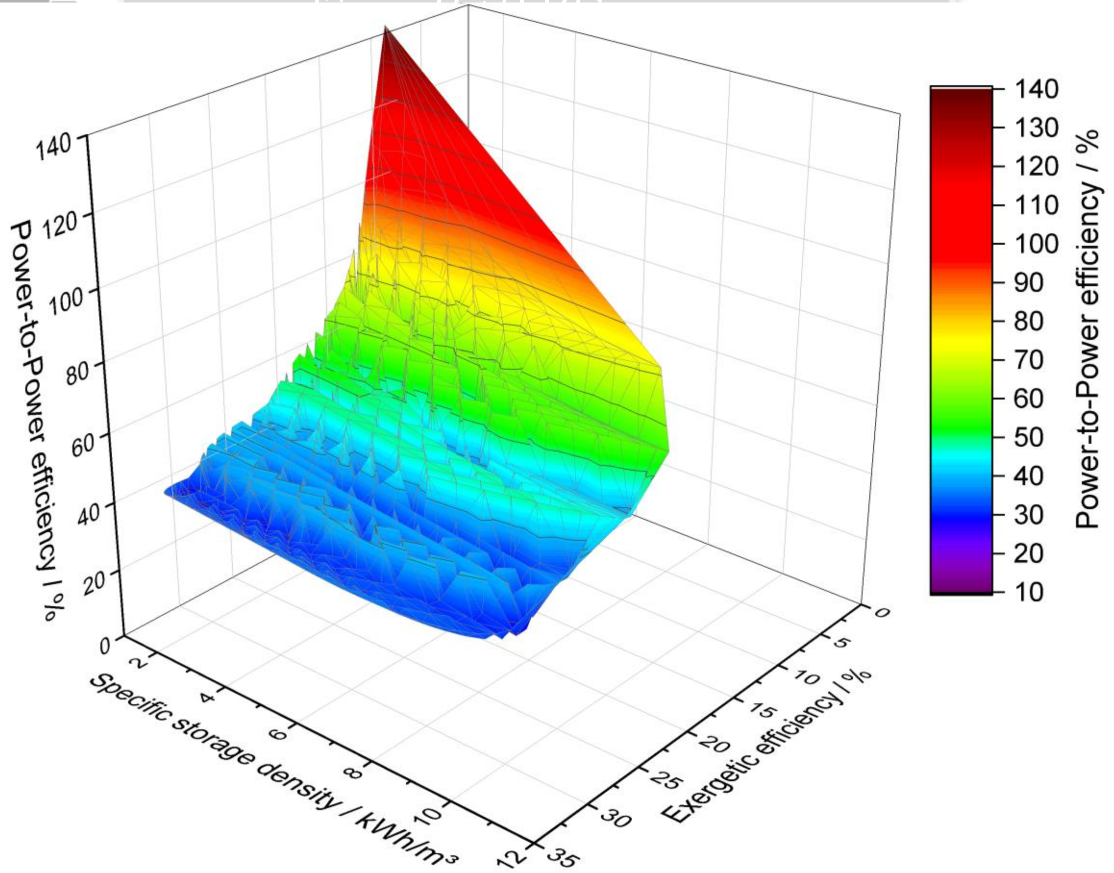
# The Carnot Battery trilemma

I
II
III
IV
V

## Advanced cycle layouts




$$\eta_{PTP} = \frac{E_{out}}{E_{i\ldots}} = \frac{\eta_{orc} \cdot Q_{st}}{Q_{\ldots}/COP_{\ldots}} = COP_{hp} \cdot \eta_{orc}$$




**Storage temperatures** and **waste heat availability** determine the competing objectives

Additional objective:
**Economic feasibility**

## Highly integrated applications

$\ldots_{ex} = \ldots$

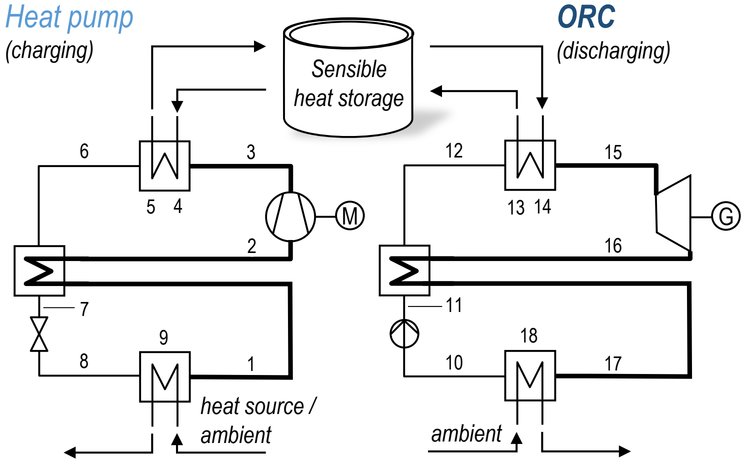
$$E_{st,vol} = \frac{E_{out}}{V_{st}} = \rho_{st} \cdot \bar{c}_p \cdot \Delta T_{st} \cdot \eta_{orc}$$

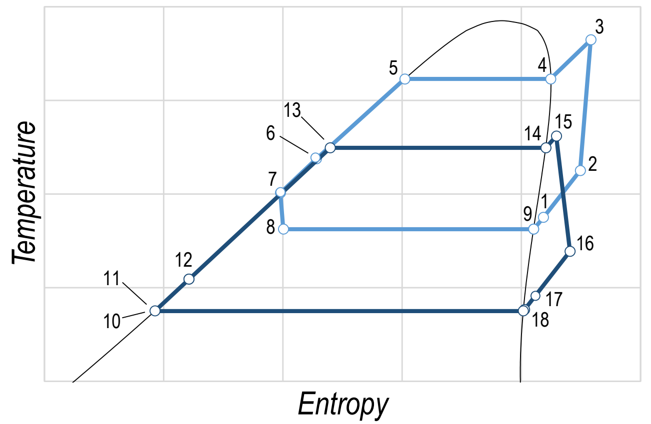
# Flash cycles in Carnot Batteries

I
II
III
IV
V

## Organic Flash Cycles

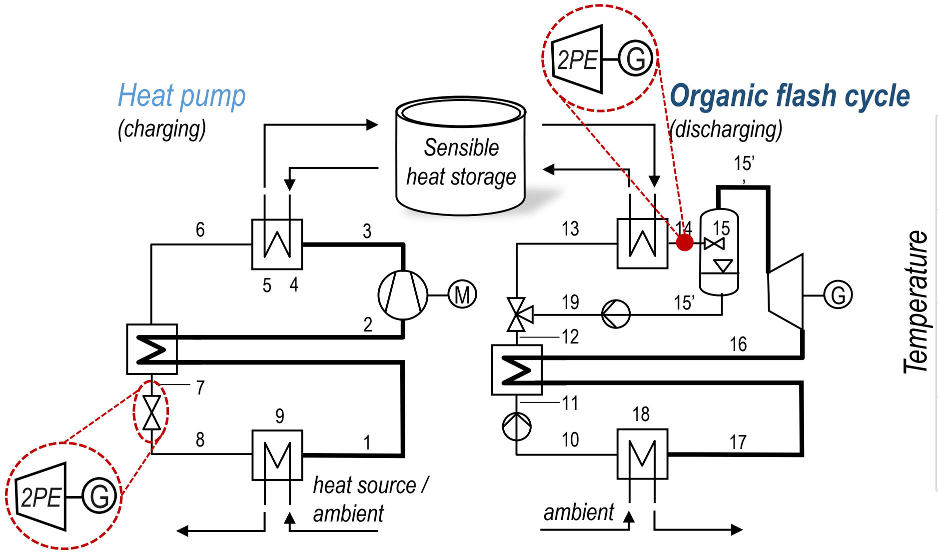
- Flash cycles widely used in geothermal power production
- Reduced exergy losses during heat transfer
- Flash evaporation by means of throttling valve

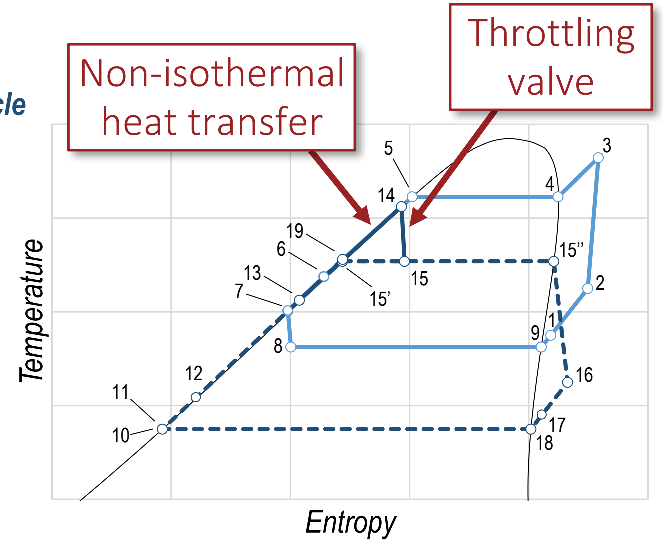



## Simulated process designs

1. HP-ORC *(Organic Rankine Cycle)*
2. HP-OFC *(Organic Flash Cycle)*
3. HP-OFC with two-phase expander









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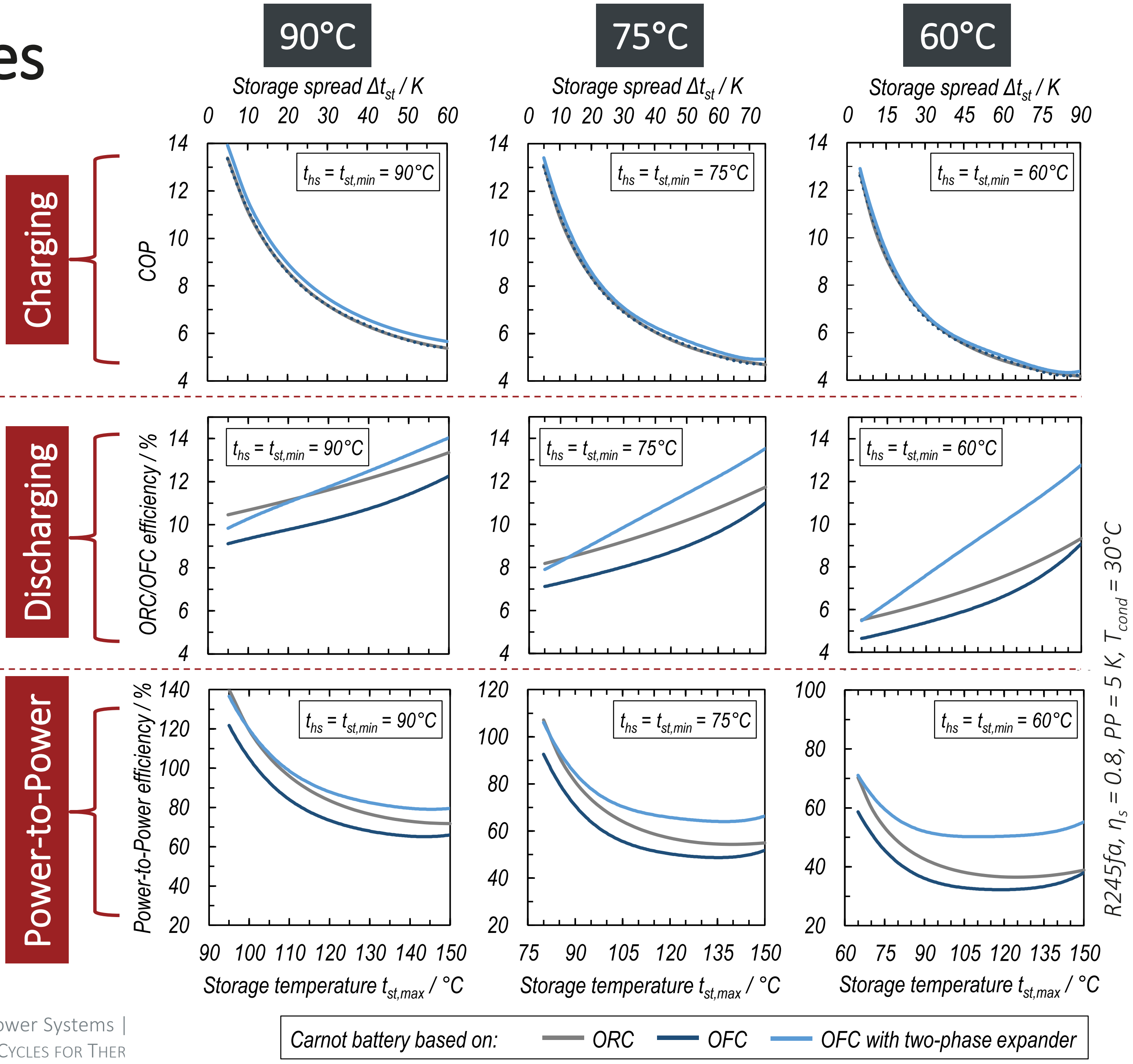
# Flash cycles in Carnot Batteries

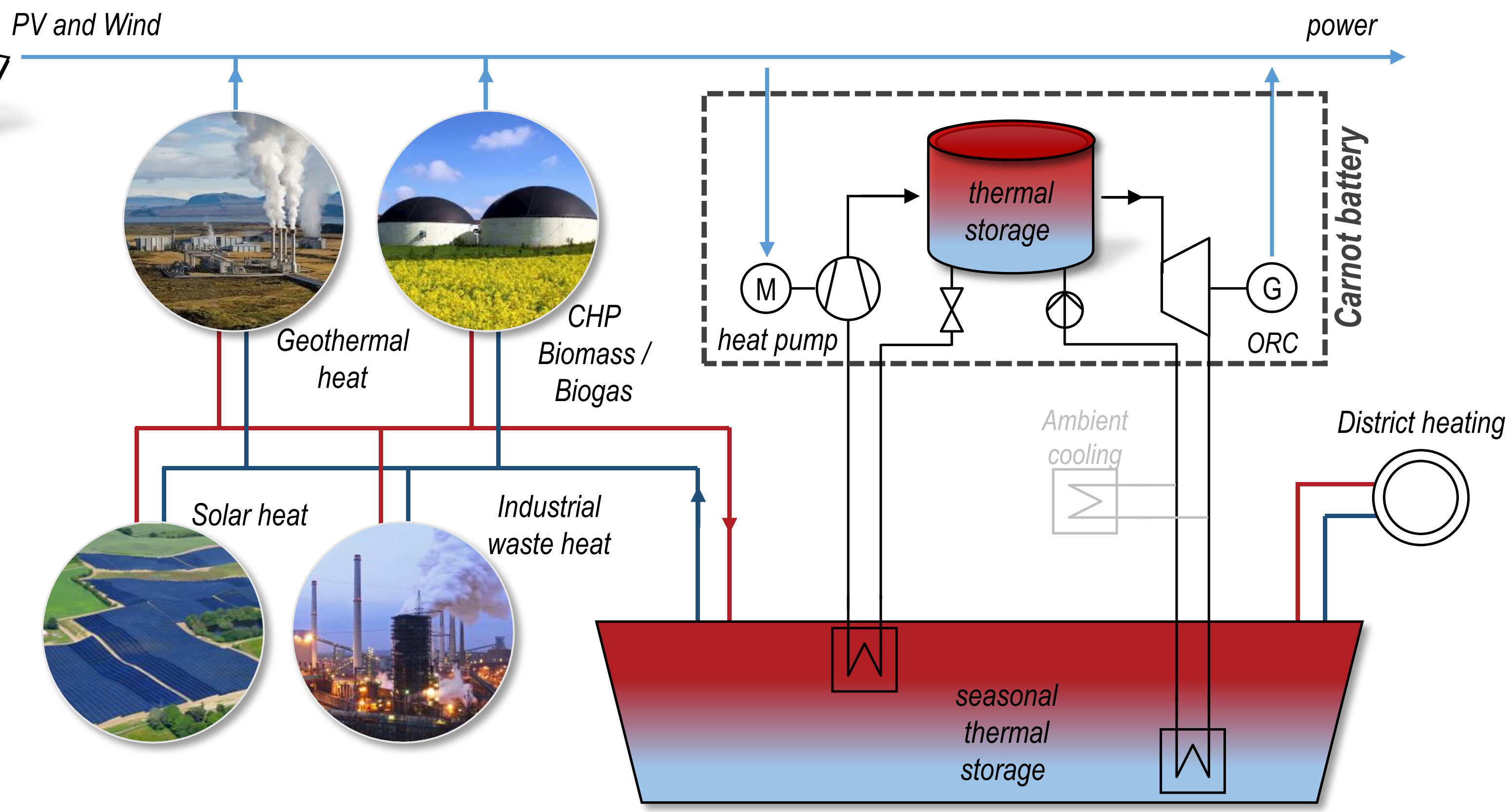
- COP reduces with increasing storage temperature
- Marginal improvement by two-phase expander

- ORC/OFC efficiency increases for higher storage temperatures
- Throttling losses outweigh improved heat transfer
- Two-phase expander generates additional power during flash evaporation

- OFC suffers from throttling losses
- ORC advantageous for nearly-isothermal storage
- **OFC with two-phase expander outperforms ORC above certain storage spread**



# Integrated applications (I) – sector coupling




- Low share of renewables in the heating and cooling sector *(GER: 13%)*
- Large thermal storages required for renewable heating
- Carnot Batteries can flexibly store and provide electrical and thermal energy
- Enhanced flexibility of CHP plants
- „Dunkelflauten“-storage

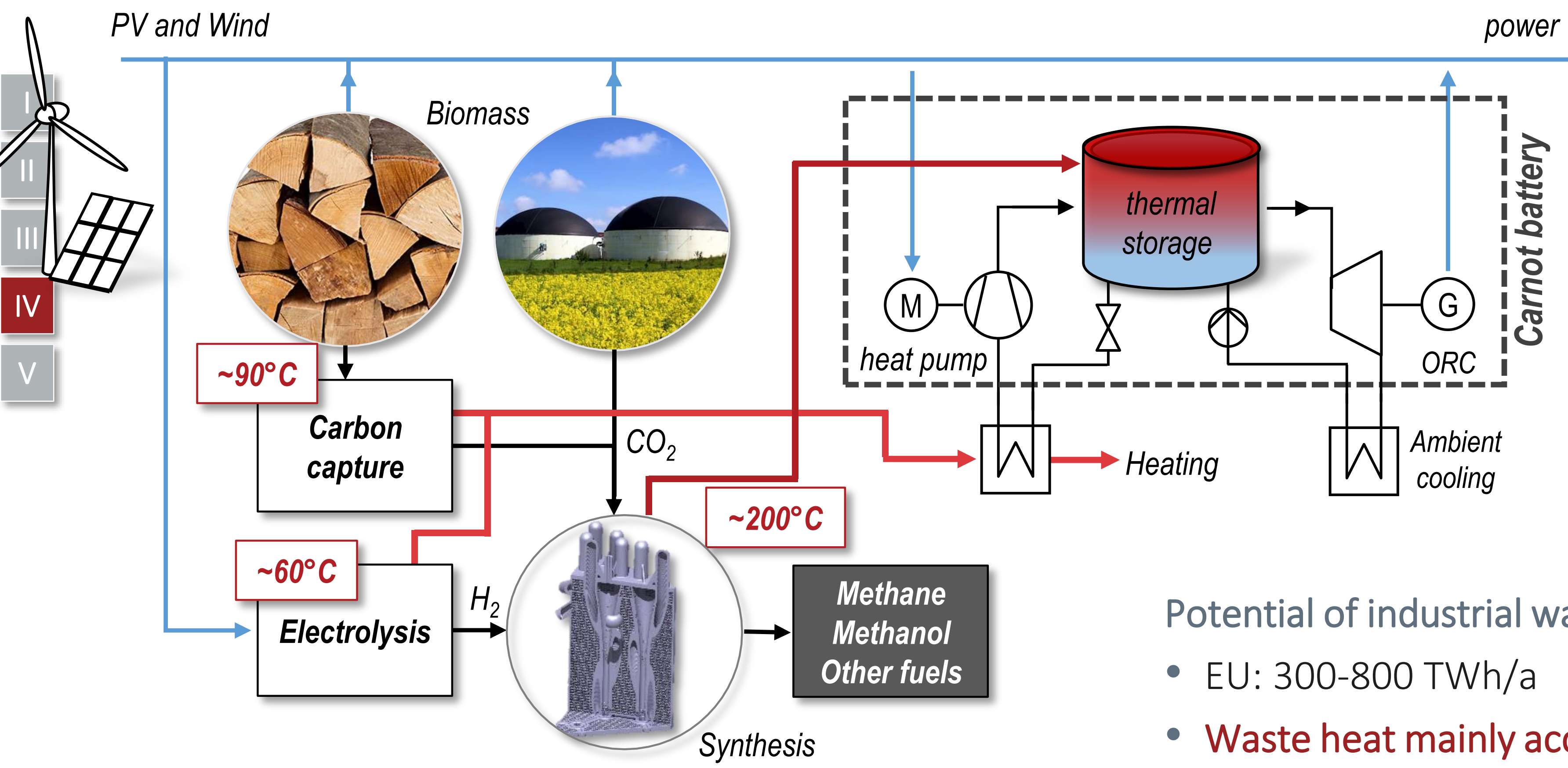
Role model Denmark

- Solar district heating, large heat pumps and pit storages
- > 64% connected to district heating *(> 62% renewable energy)*

Carnot Batteries enable sector coupling

Seasonal thermal storages required

# Integrated applications (II) – waste heat utilization




Focus: Power-to-Fuel processes

- Simultaneous PtX process and Carnot Battery charging
- Carnot Battery allows exploitation of waste heat at various temperature levels

Potential of industrial waste heat

- EU: 300-800 TWh/a
- Waste heat mainly accumulates at temperatures < 200°C
- e.g. steel, cement, glass, food, wood processing, paper and chemical industry

# Integrated applications (III) – Decentral polygeneration

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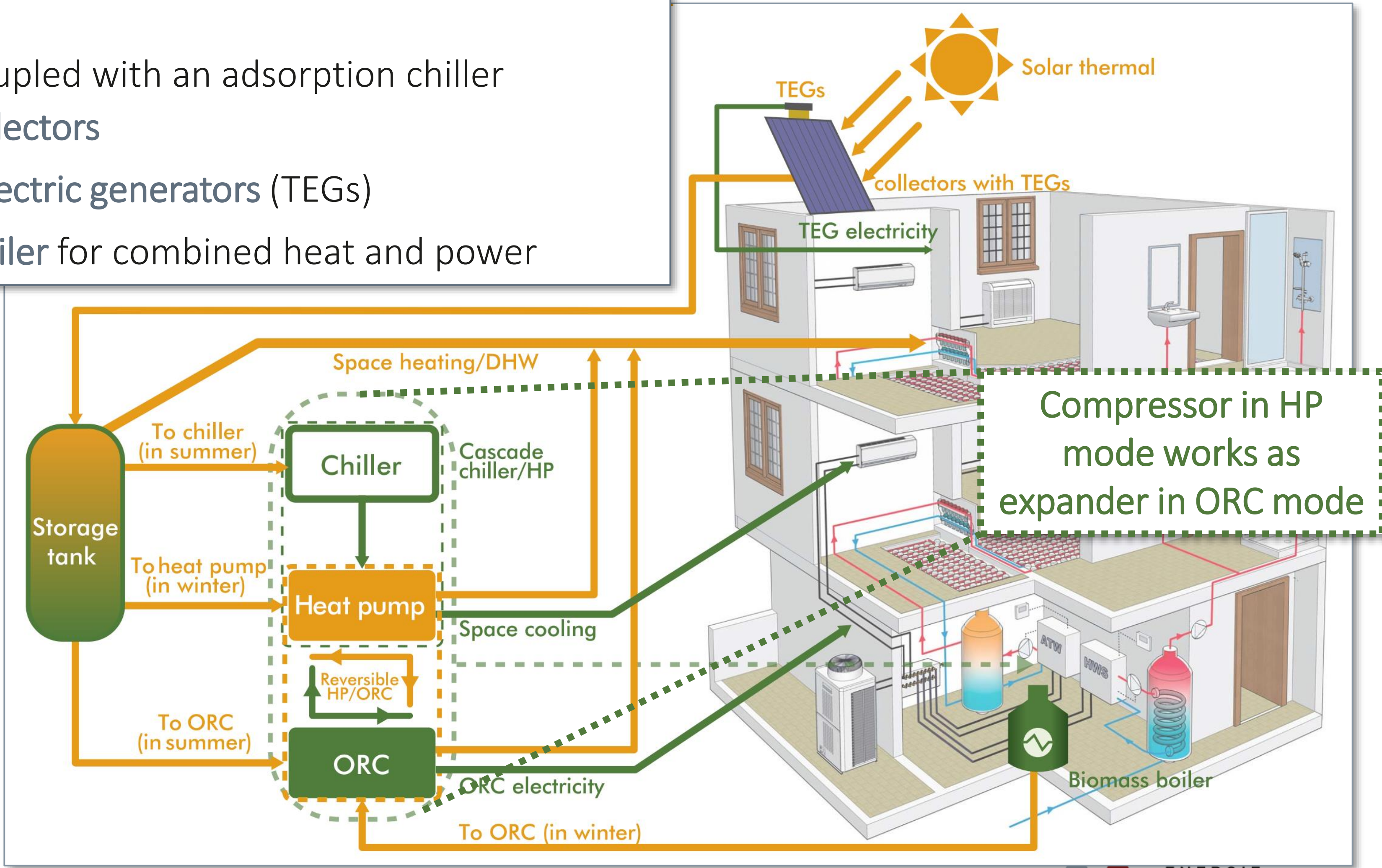
I
II
III
IV
V

## EU-Project SolBio-Rev

- Reversible heat pump/ORC system coupled with an adsorption chiller
- Heat supply by vacuum tube solar collectors
- Excess solar heat utilized in thermoelectric generators (TEGs)
- Additional heat supply by biomass boiler for combined heat and power

Energy sources:
solar heat
wood pellets

Supplying up to 70 % of the total energy demand in office buildings and multi-family houses





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# Key messages and outlook

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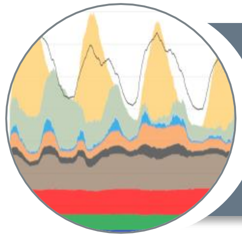
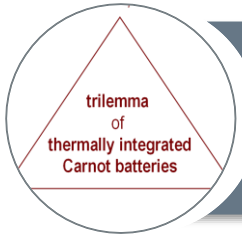
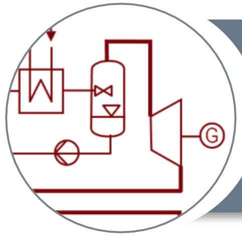


ORC-based Carnot Batteries offer base-load capable energy storage




The Carnot Battery trilemma can be dissolved by advanced cycle layouts and integrated applications



Flash cycles with two-phase expansion enable efficient Carnot Batteries with compact storage

Mid-scale Carnot batteries ideally support decentral, renewable energy grids

## Applications

- Upgrade **industrial waste heat**
  *(e.g. from Power-to-Fuel processes)*
- Flexible **sector coupling**
- **Cogeneration** for building applications
- **Seasonal energy storage**
  *(„Dunkelflauten“-storage)*

## Outlook

- Detailed experimental evaluation of ORC-based Carnot Batteries
- Dynamics and off-design behaviour
- Evaluation of two-phase expansion

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# Thank you for your kind attention!

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