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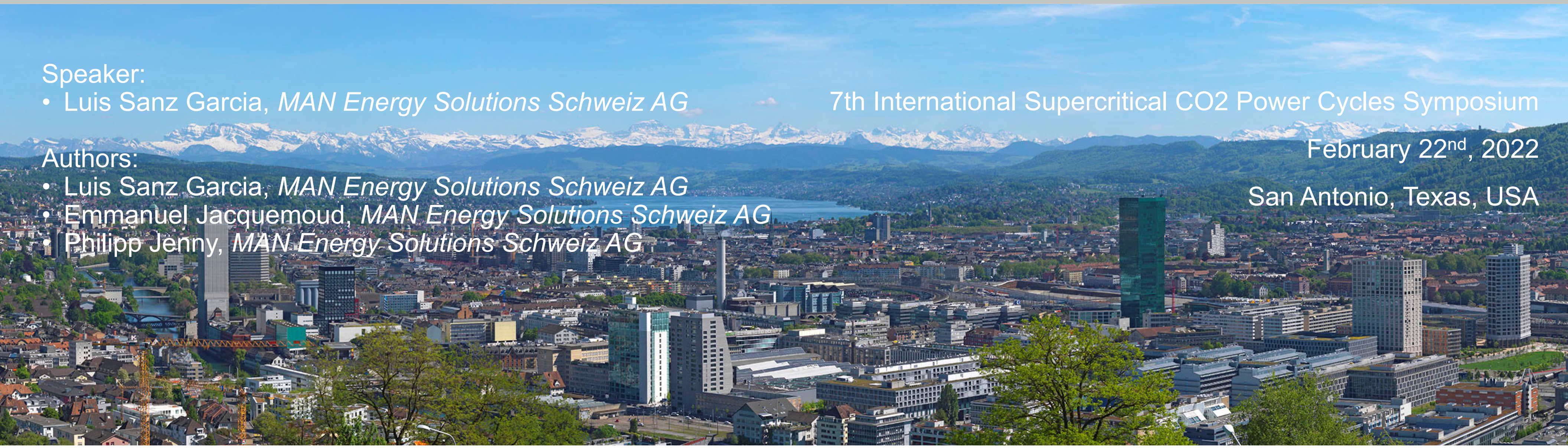
# Large Scale Tri-Generation Energy Storage for Heat, Cold and Electricity based on Transcritical CO2 Cycles

Paper #162

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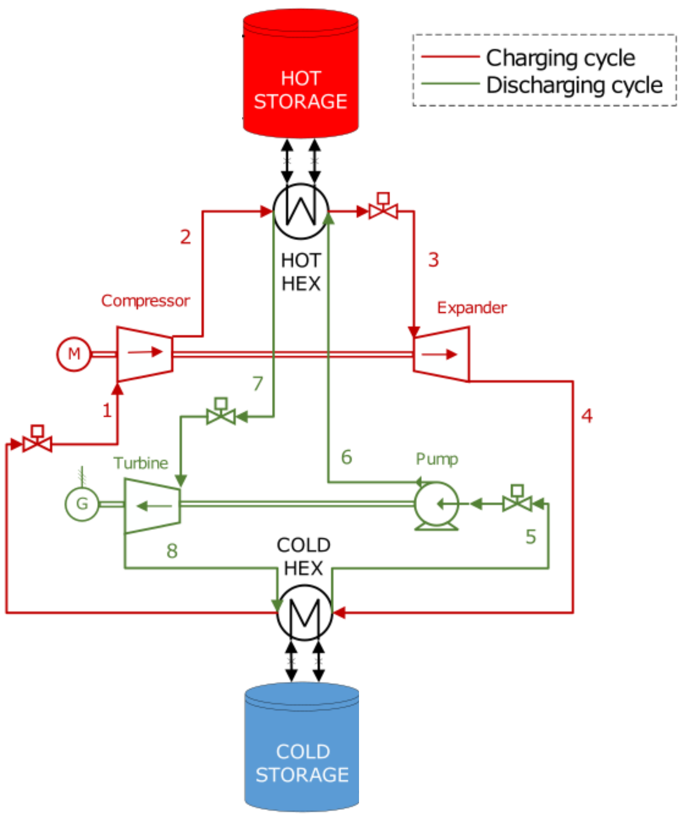
San Antonio, Texas, USA

# Agenda

# From an electricity storage system to a tri-generation energy system

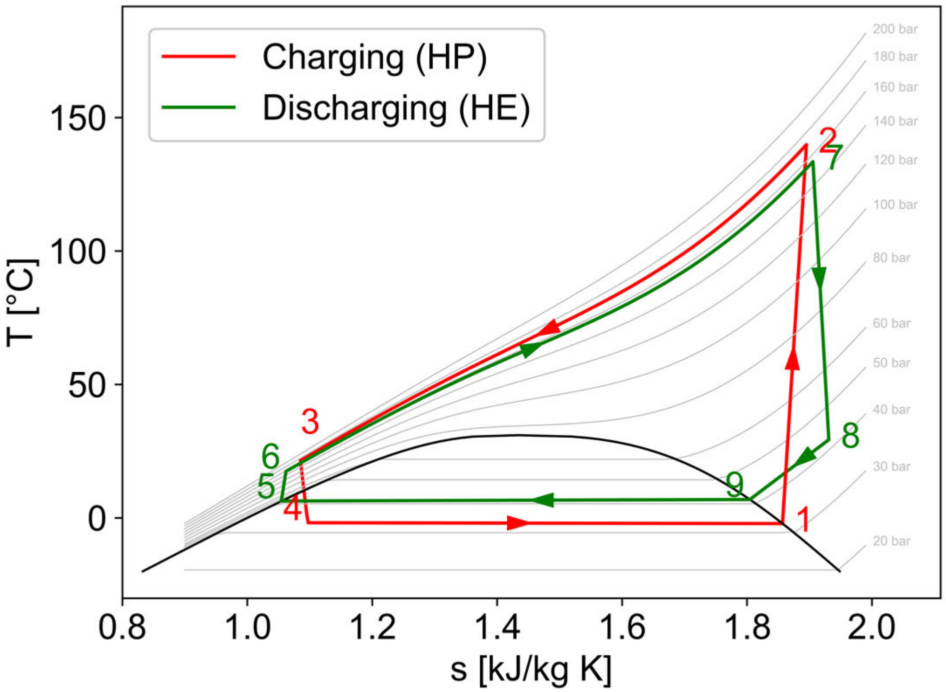


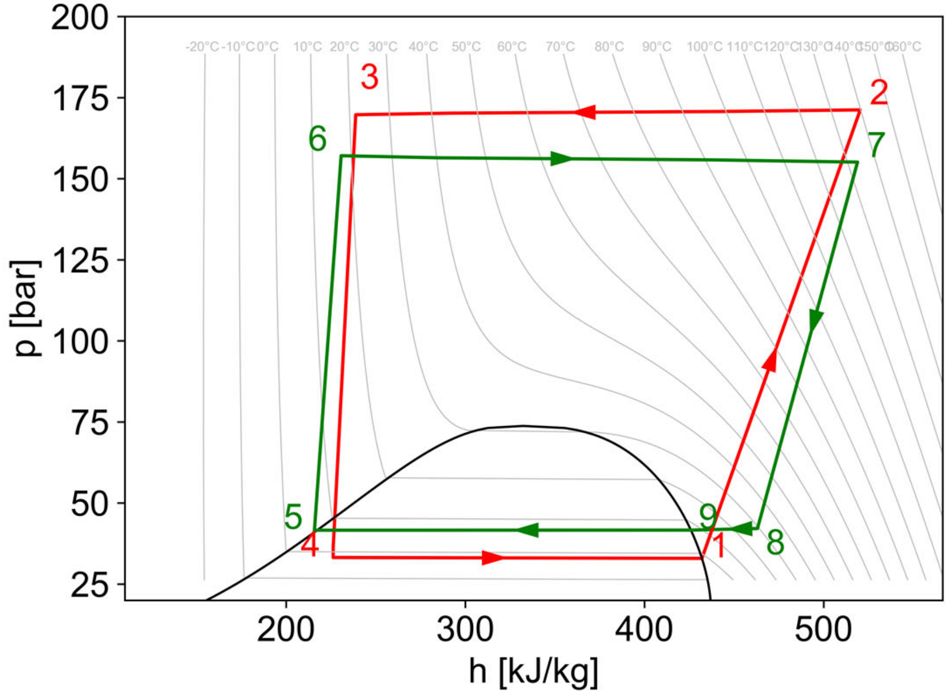

- $CO_2$ as working fluid
- Charging cycle: transcritical heat pump
- Discharging cycle: organic Rankine cycle
- Power range: 1-50 $MW_{el}$
- Typical cycle time: 12-24 h

| Thermal storage | Medium | Temp. range | Type | Setup |
|---|---|---|---|---|
| Hot | Water | 15-150°C | Sensible | Multi-tank reservoirs |
| Cold | Water / Ice | 0°C | Latent | Ice on coils |

Moderate temperature levels allows to combine the system with heating and cooling applications!

# Thermodynamic diagrams



# Working principle of the system

$E_{ch}^{tot}$

$$COP_{hot}^{ex} = \frac{Q_{hot}}{E_{ch}^{tot} \cdot \gamma^{th}}$$

$$\eta_{RT} = \frac{E_{dch}}{E_{ch}^{tot} \cdot \gamma^{el}}$$

$$COP_{cold}^{ex} = \frac{Q_{cold}}{E_{ch}^{tot} \cdot \gamma^{th}}$$

Thermal share $\gamma^{th}$ → amount of stored energy destined for thermal export

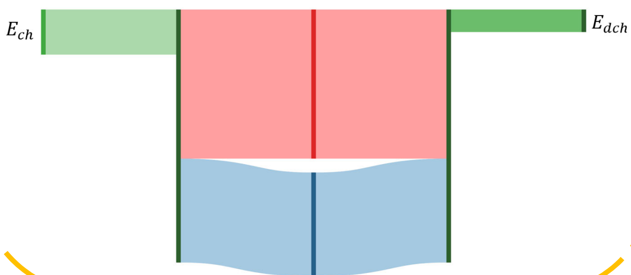
Electric share $\gamma^{el}$ → amount of stored energy destined for electricity export

$$\gamma^{th} + \gamma^{el} = 1$$

# Possible configurations

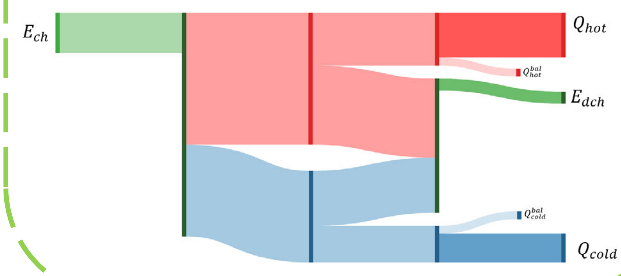
### Pure electricity storage (ETES)

- Charging cycle
- Discharging cycle
- Thermal storage
- $\gamma^{th} = 0$



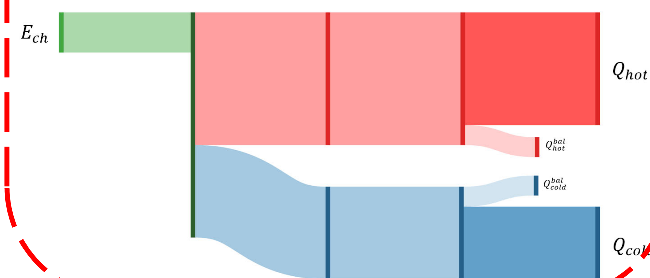

### Tri-generation energy system (3-TES)

- Charging cycle
- Discharging cycle
- Thermal storage
- Thermal export
- $0 < \gamma^{th} < 1$




### Heat pump unit (HPU)

- Charging cycle
- Thermal storage optional
- Thermal export
- $\gamma^{th} = 1$




**Highly flexible and adaptable to specific electric and thermal demands!**

# Sophisticated Model is needed to calculate and optimize System performance

Considered model:

- Thermodynamic library: Refprop v10.0
- Steady state
- Sequential calculation solver developed in python

Constrained optimization problem:

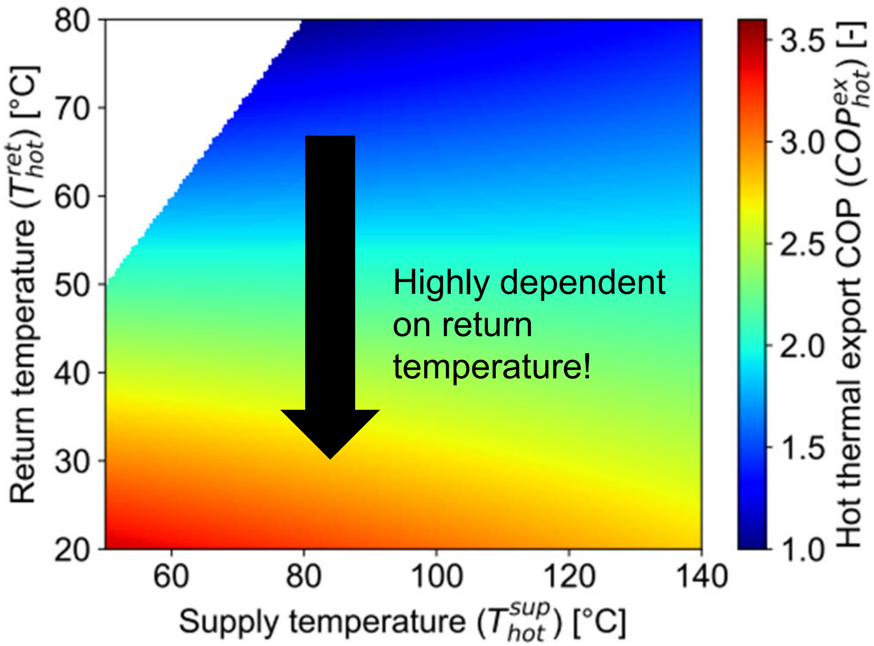
- Profit of the installation
- Performance
- other

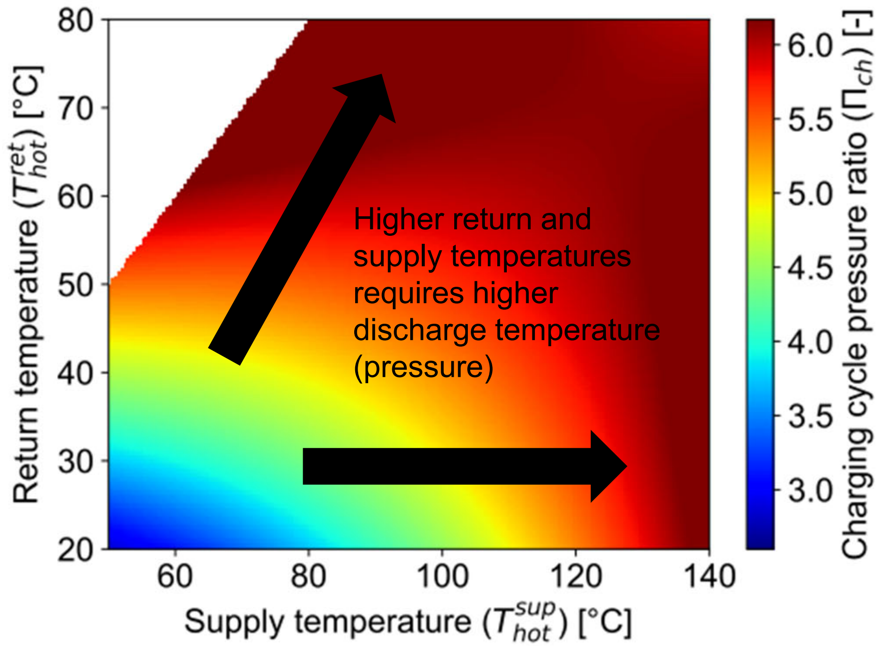
$$
\begin{aligned}
\underset{x}{\text{minimize}} \quad & f(x) + \sum_{i=1} Pen_i(x) \\
\text{subject to} \quad & l_b \leq x \leq u_b, \\
& x \in \mathbb{R}
\end{aligned}
$$

# System performance is heavily dependent on thermal boundary conditions

$$COP_{hot}^{ex} = \frac{Q_{hot}}{E_{ch}^{tot} \cdot \gamma^{th}}$$

$$\Pi_{ch} = \frac{P_{cond}}{P_{evap}}$$



# System profitability and operation is heavily dependent on economic boundary conditions

The operation of the cycle is determined by the profit one can obtain from running the system

Revenue

Costs

$$P_{cy}[€] = \underbrace{\left(E_{dch}^{el} \cdot C_{dch}^{el} + Q_{hot} \cdot C_{hot} + Q_{cold} \cdot C_{cold}\right)}_{\text{Revenue}} - \underbrace{E_{ch}^{tot} \cdot C_{ch}^{el}}_{\text{Costs}}$$

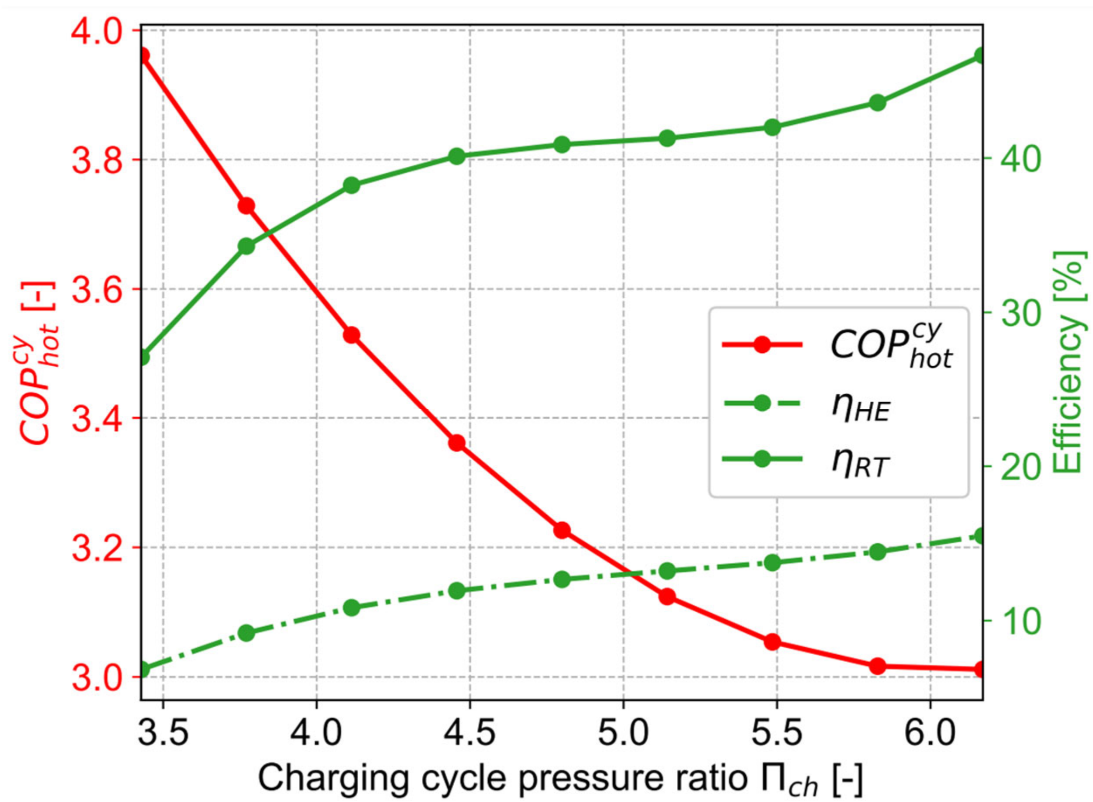
Dividing by purchased amount of electricity we obtain the normalized profit as a function of KPIs

$$\phi_{el} = \frac{C_{el}^{dch}}{C_{el}^{ch}} \qquad \phi_{hot} = \frac{C_{hot}}{C_{el}^{ch}} \qquad \phi_{cold} = \frac{C_{cold}}{C_{el}^{ch}}$$

$$\frac{P_{cy}}{E_{ch}^{tot} \cdot C_{ch}^{el}} \left[\frac{€}{€_{ch}}\right] = \frac{1}{E_{ch}^{tot} \cdot C_{ch}^{el}} \cdot \left(E_{dch}^{el} \cdot C_{dch}^{el} + Q_{hot} \cdot C_{hot} + Q_{cold} \cdot C_{cold}\right) - 1$$

$$= \left((1 - \gamma^{th}) \cdot \eta_{RT} \cdot \phi_{el} + \gamma^{th} \cdot \left(COP_{hot}^{ex} \cdot \phi_{hot} + COP_{cold}^{ex} \cdot \phi_{cold}\right)\right) - 1$$

# A compromise between electrical and thermal export is necessary




$$\eta_{RT} = COP_{hot}^{cy} \cdot \eta_{HE}$$

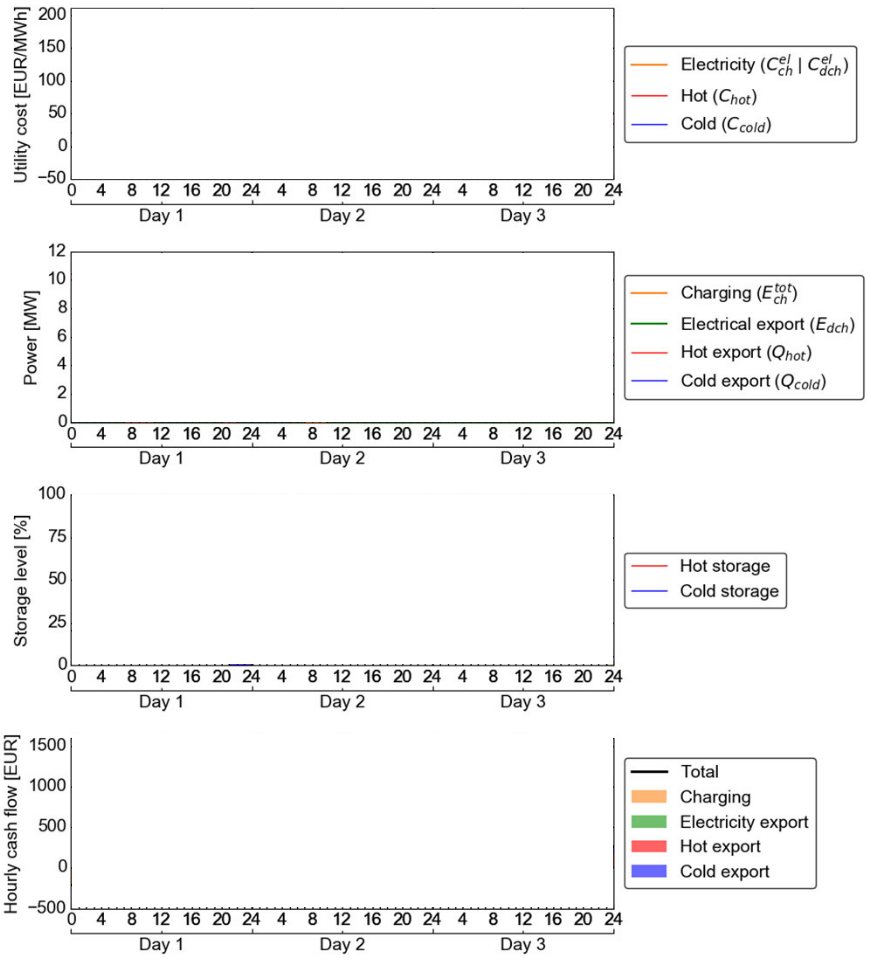
Charging cycle

Discharging cycle

- $\Pi_{ch}$ ↑ Favors electricity export
- $\Pi_{ch}$ ↓ Favors thermal export

$\Pi_{ch}$ can be optimized for the given set of thermal and economic boundary conditions of each cycle

# Highly adaptable and flexible system




| Day | Economic boundary conditions | Stored energy use | Storage levels |
|---|---|---|---|
| | | | |
| | | | |
| | | | |

| Day | Charging | Export | | | TOTAL |
|---|---|---|---|---|---|
| | | Electricity | Hot | Cold | |
| Day 1 | -1’726 | 2’768 | - | - | 1’042 |
| Day 2 | -1’88 | 2’370 | 4’071 | 3’885 | 10’138 |
| Day 3 | -1’303 | - | 5’824 | 5’200 | 9’720 |

High profit obtained from thermal export!

# Conclusions and interpretations

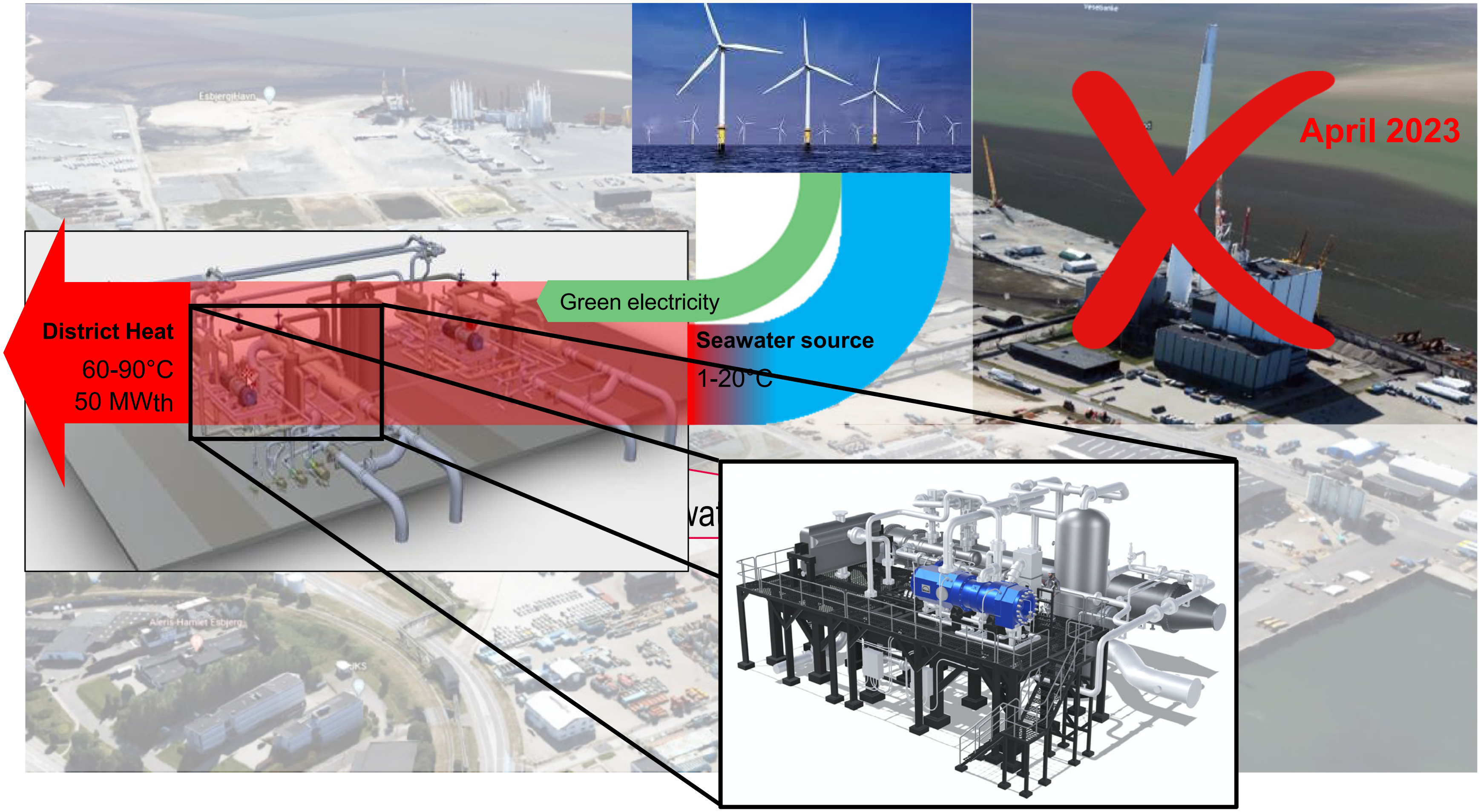
- The **moderate temperature conditions** of the system allows to not only store and export electricity, but also heat and cold.

- 3-TES system offers a **good compromise** between roundtrip efficiency and thermal export performance.

- The **large design and flexibility** of the system allows to adapt the system to the changing boundary conditions expected throughout the 30+ years the installation is expected to operate with the **same equipment.**

- The complexity to find a single customer requiring the three forms of energy in the produced quantities makes the 3-TES system particularly suitable for **sector coupling** applications.

# First MAN HPU cycle under construction in Denmark!



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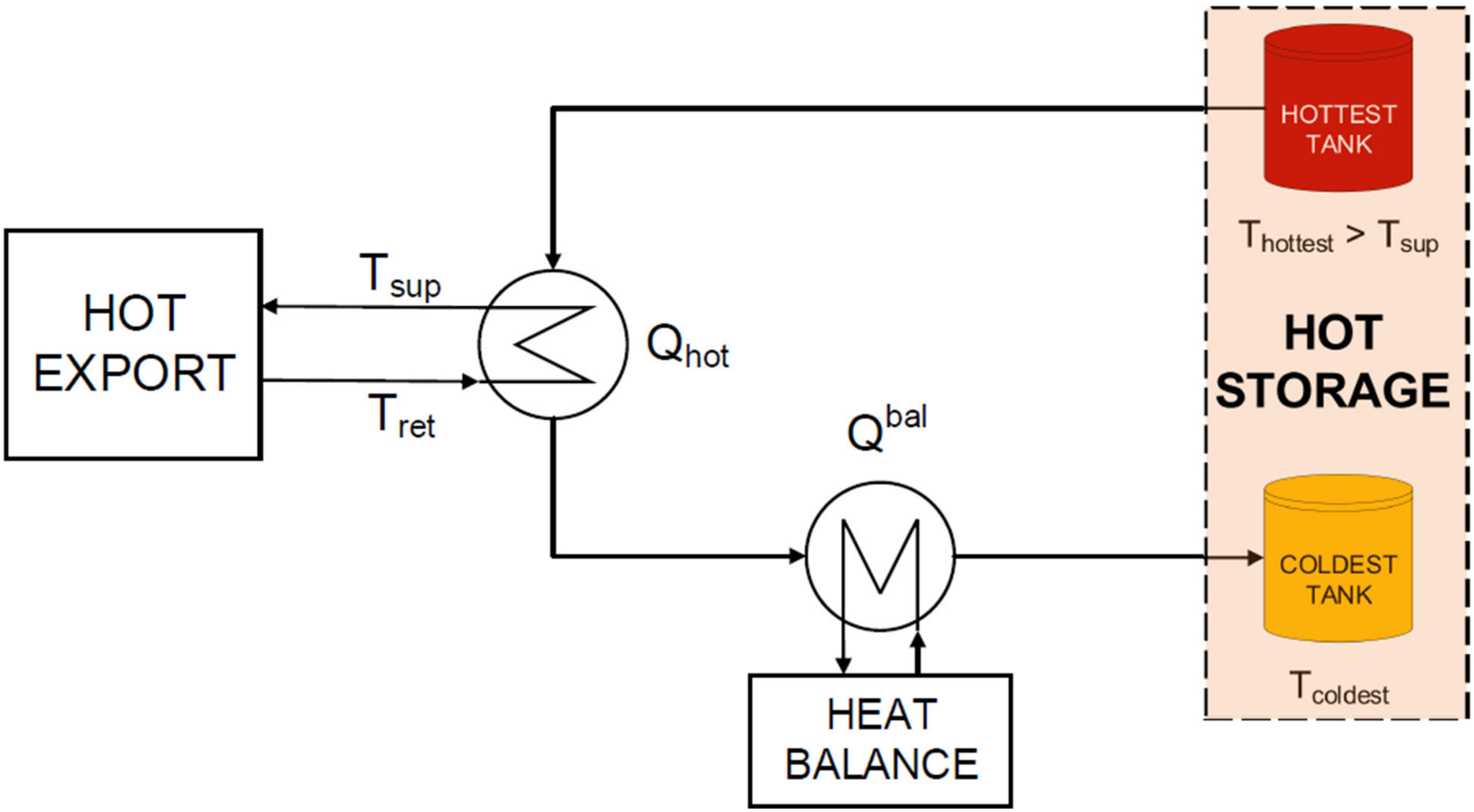
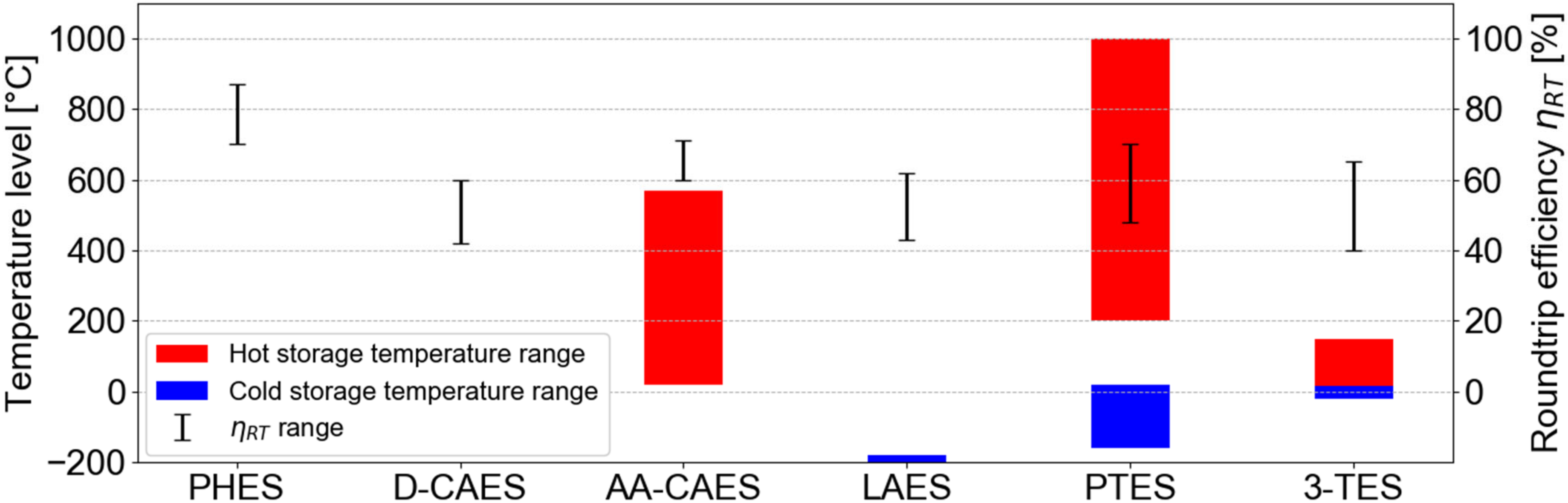
# Thank you for your attention!

# Impact of return temperature



# Excellent compromise between round-trip efficiency and thermal export



# First MAN HPU cycle under construction!

- Biggest ever $CO_2$ heat pump (50+ $MW_{th}$) installed in Esbjerg, Denmark.
- Replacement of CHP Coal fired plant.
- COP: 2.8 - 4.3
- Bid award January 2021
- Commissioning September 2022
- Heat production April 2023