Pumped Heat Electricity Storage: Potential Analysis and ORC Requirements

Institute of Combustion and Gas Dynamics
Chair of Thermodynamics

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Institut for Combustion and Gas Dynamics
Thermodynamics

Motivation

Rising share of renewable energy sources in power generation

↓

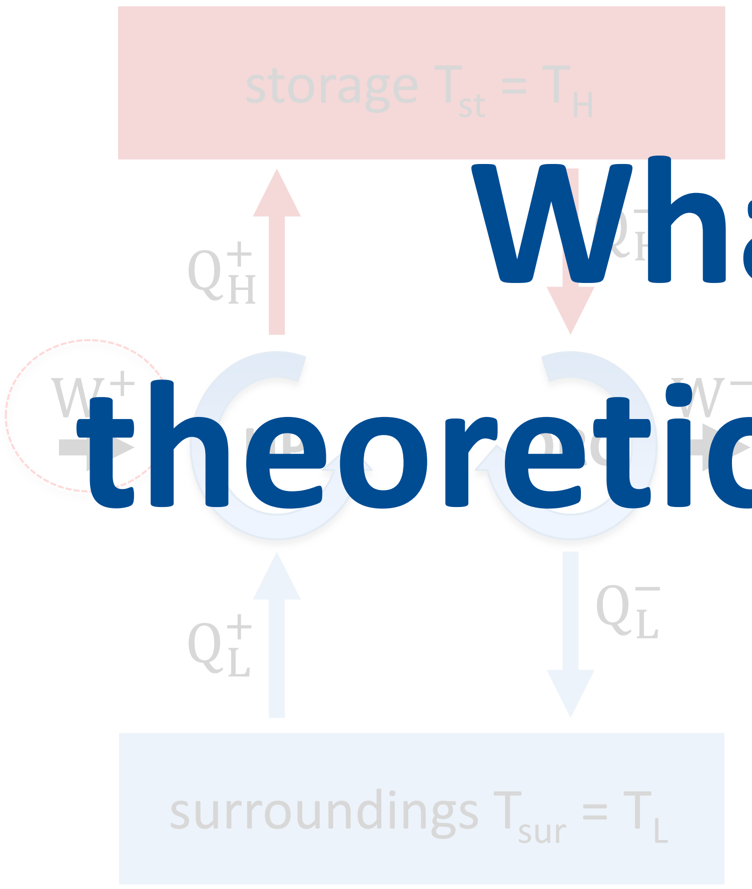
Increasing fluctuations within the electrical grid

↓

Large scale energy storage problem

Source: www.elektroplaggenborg.de

Source: Badische Zeitung



- **charging cycle:**
  vapor compression heat pump
- **discharging cycle:**
  organic Rankine-cycle
- **storage:**
  latent or sensible heat

What is the theoretical potential?

storage efficiency / roundtrip efficiency

$$\Psi = \frac{W^-}{W^+} = COP_{HP} \cdot \eta_{ORC}$$

Pre-studies: models

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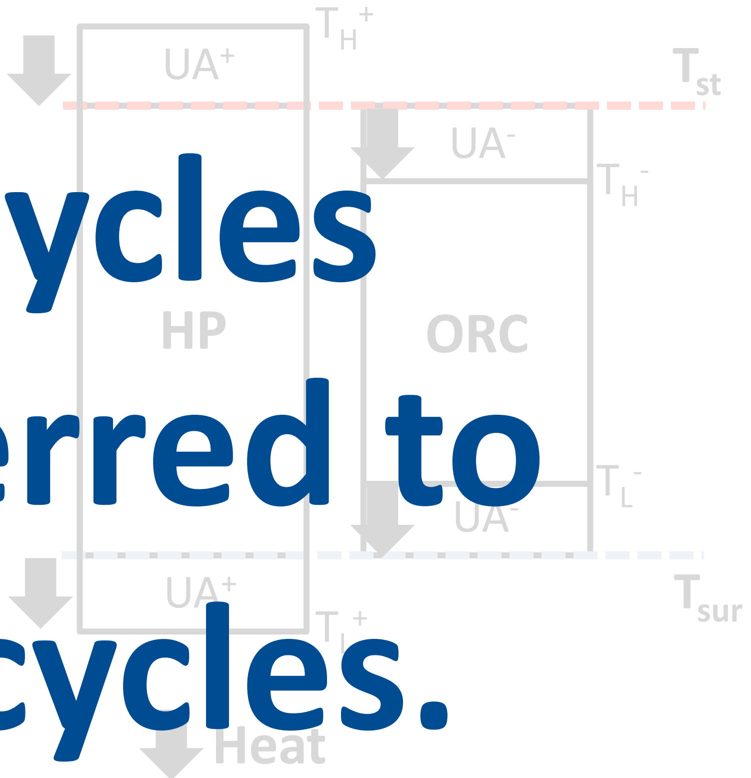
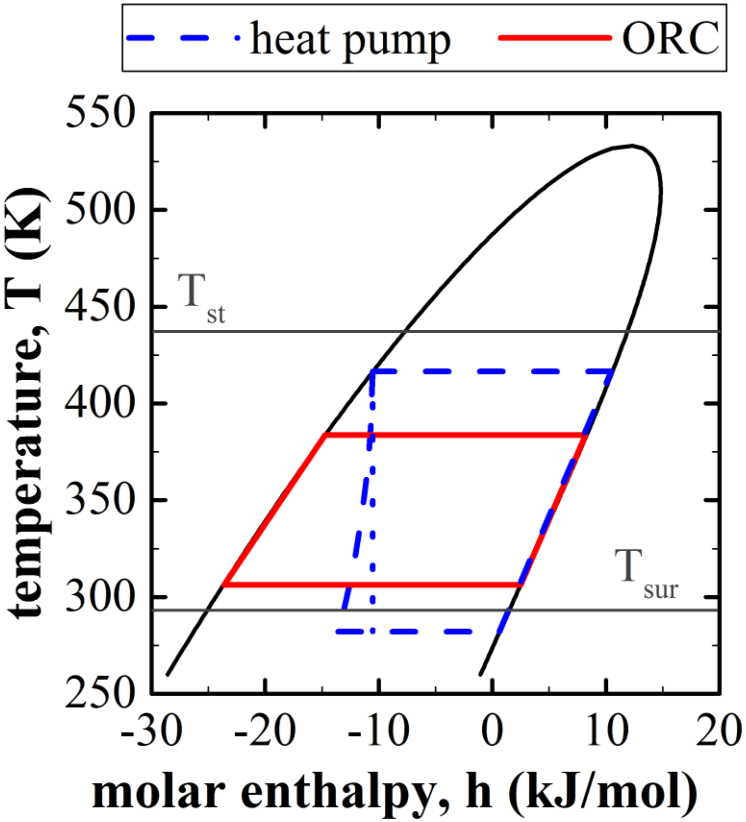
- Combining two full Carnot-cycles:
  - leads always to $\Psi = 1$
- Work of Thess[1]:
  - Carnot-cycles with irreversible heat transfer
  - maximum power output (ORC)
- Work of Roskosch and Atakan[2]:
  - Power output and efficiency lead to Pareto frontier
  - requiring 80 % of maximum power is a good compromise



Carnot-cycles are transferred to Rankine-cycles.

[1]Thess A. Thermodynamic efficiency of pumped heat electricity storage. Physical review letters 2013;111(11):110602.
[2]Roskosch D, Atakan B. Potential Analysis of Pumped Heat Electricity Storages Regarding Thermodynamic Efficiency. Proceedings of Ecos 2017;30.

Transfer to Rankine-cycles



- **Process temperatures from pre-study**
- **$U_{PC} = 10 \cdot U_{SP}$**
- **Heat pump & ORC**
  - full evaporation, condensation
  - ideal compressor and expander
- **For heat pump also**
  - expansion: throttle or expander
- **Now: Fluid properties get important**
  - How to select?
    - ➢ Inverse-Engineering-approach

Inverse-Engineering of fluid parameters

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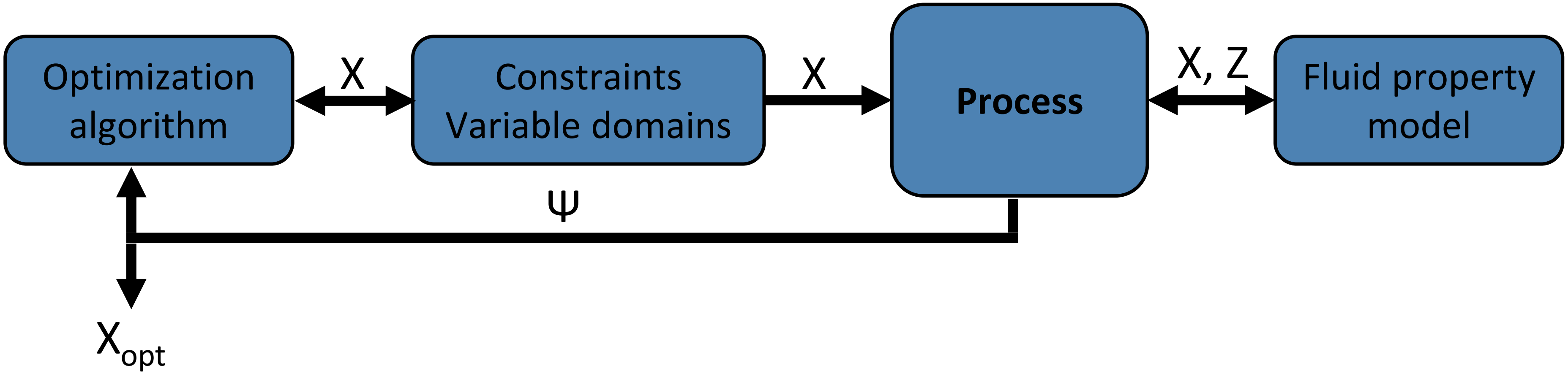


Fluid property model

- Peng-Robinson EOS
- ideal gas heat capacity
- $X=[T_c, p_c, \omega, c_{p,0}, dc_p/dT]$

Constraints

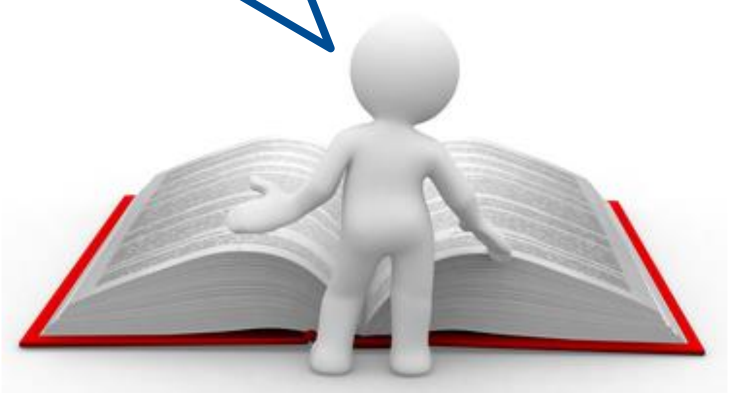
- Realistic range for every parameter
- 0.05 Mpa $\leq p_{sys} \leq 5$ Mpa
- no condensation in expander (ORC) and compressor (heat pump)

Why using optimal fluid parameters?

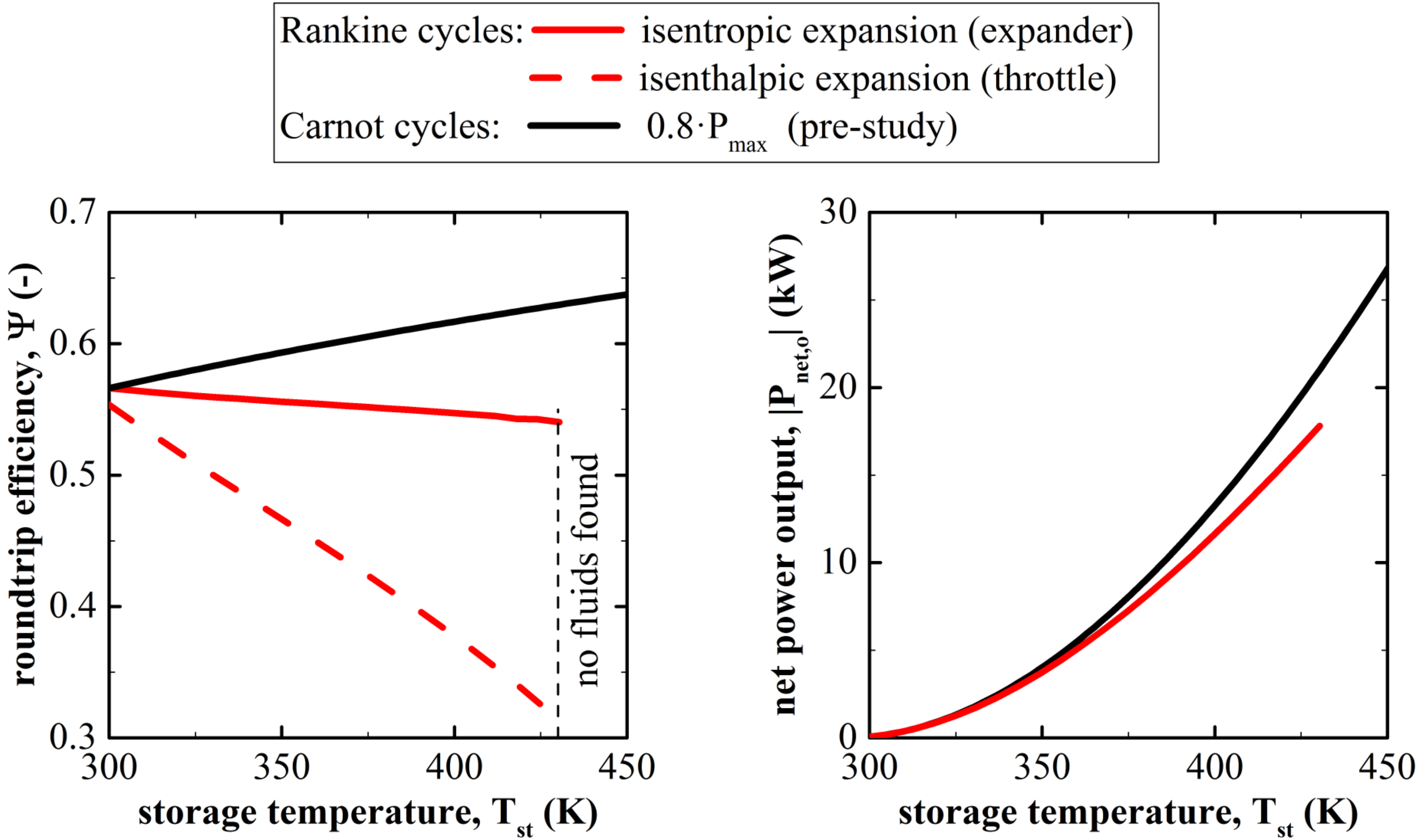
- Evaluation of promising operating and boundary conditions without the influence of a **specific** fluid
- better comparability of the result (e.g. storage temperature)
- finding limits in operating conditions with respect to available chemical compounds

I need:
- T_c = 1100 °C
- p_c = 3 Mpa
- ω = 0.01
- c_p = …

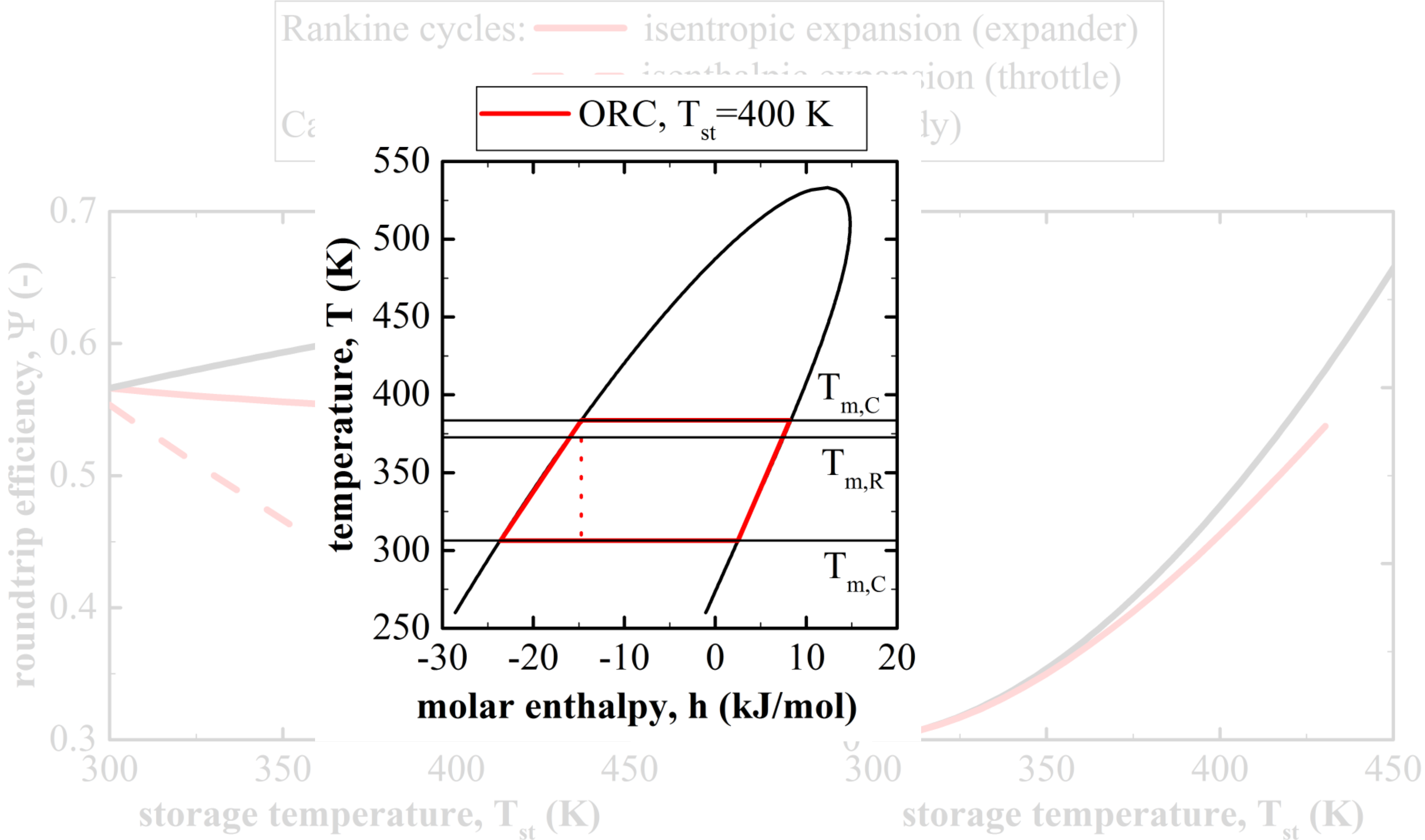
Such a substance doesn‘t exist!



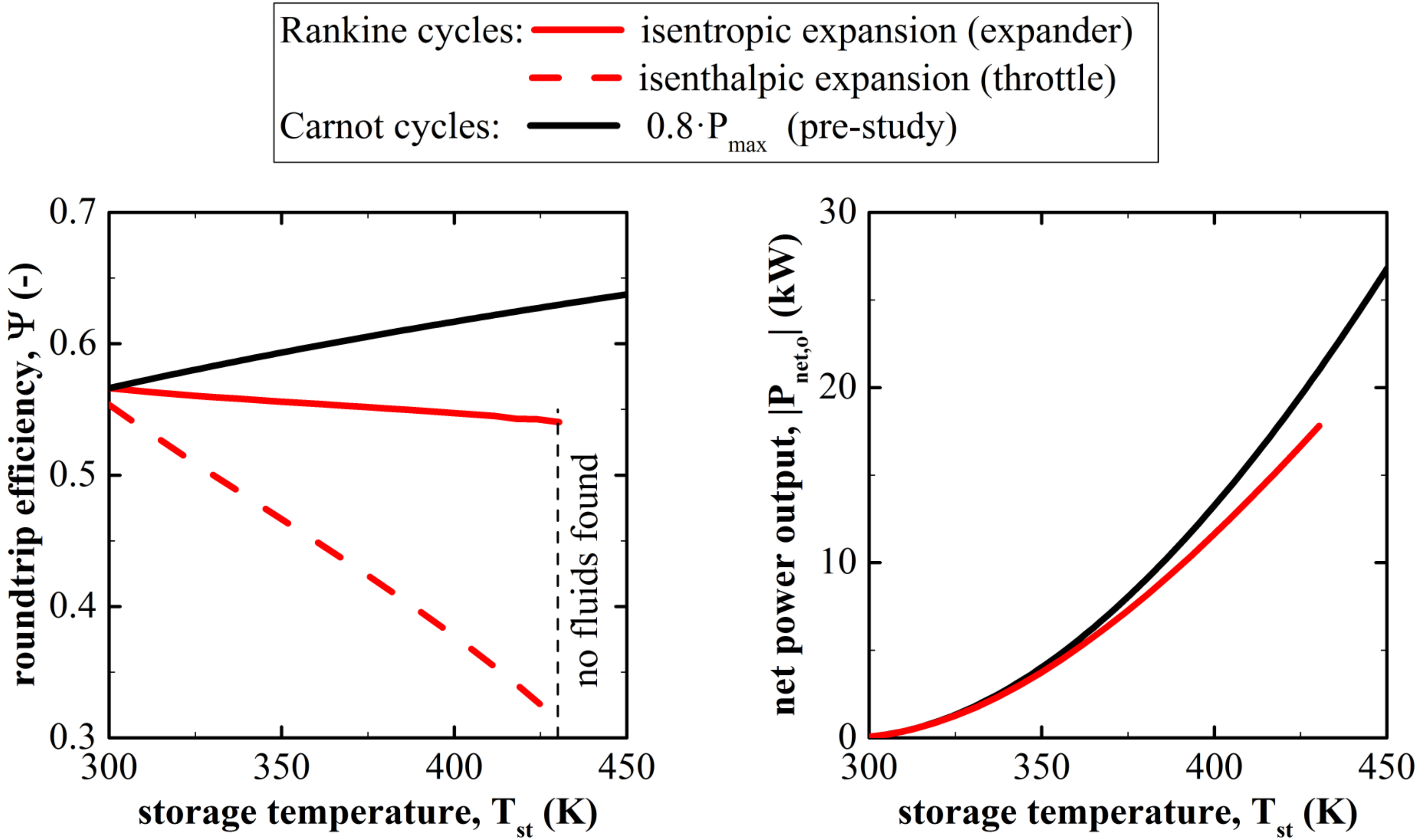
Results: efficiency and power output



Results: efficiency and power output



Results: efficiency and power output



Influence of superheating

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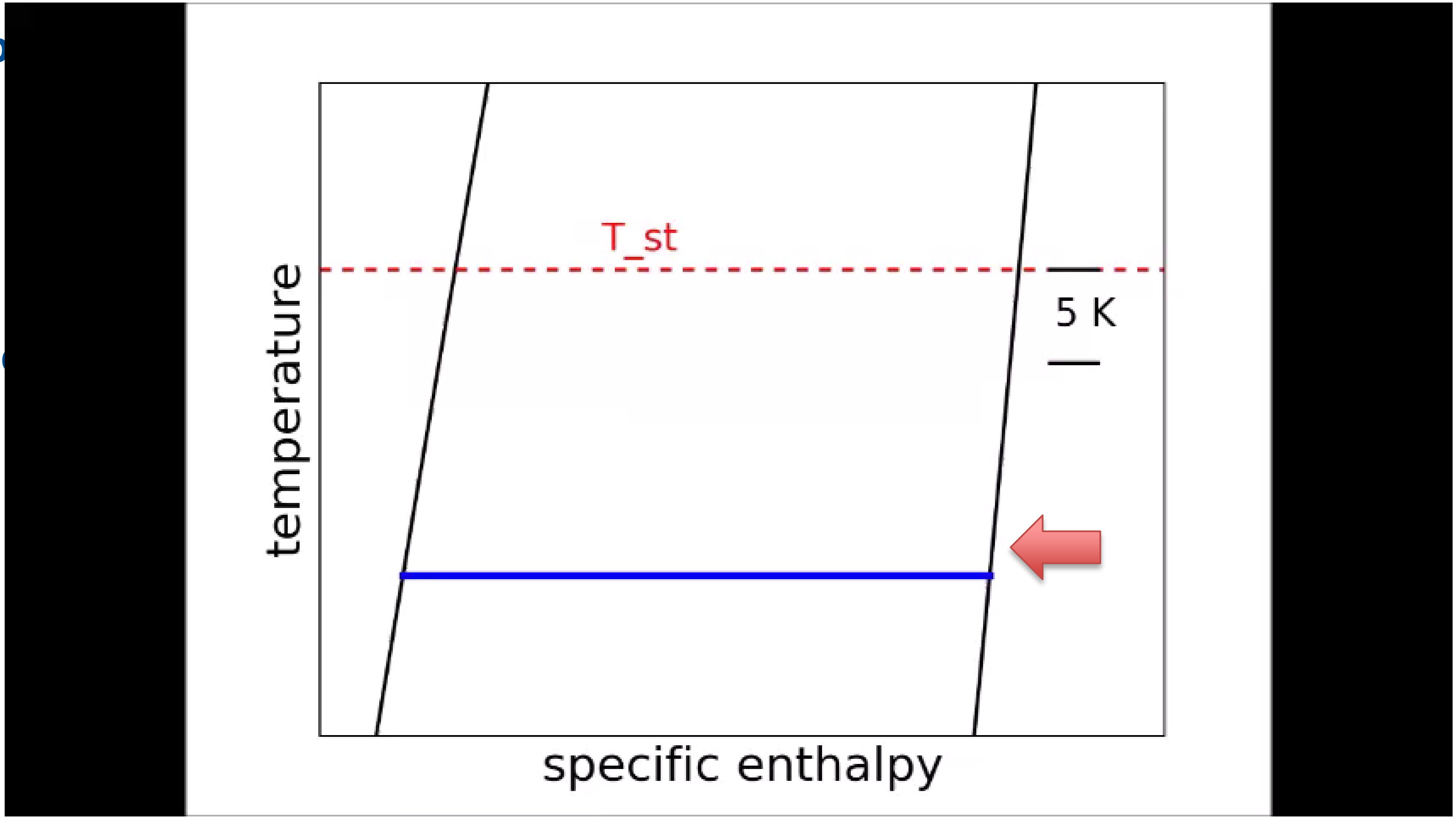
Co



M

decreased

Influence of superheating: Results

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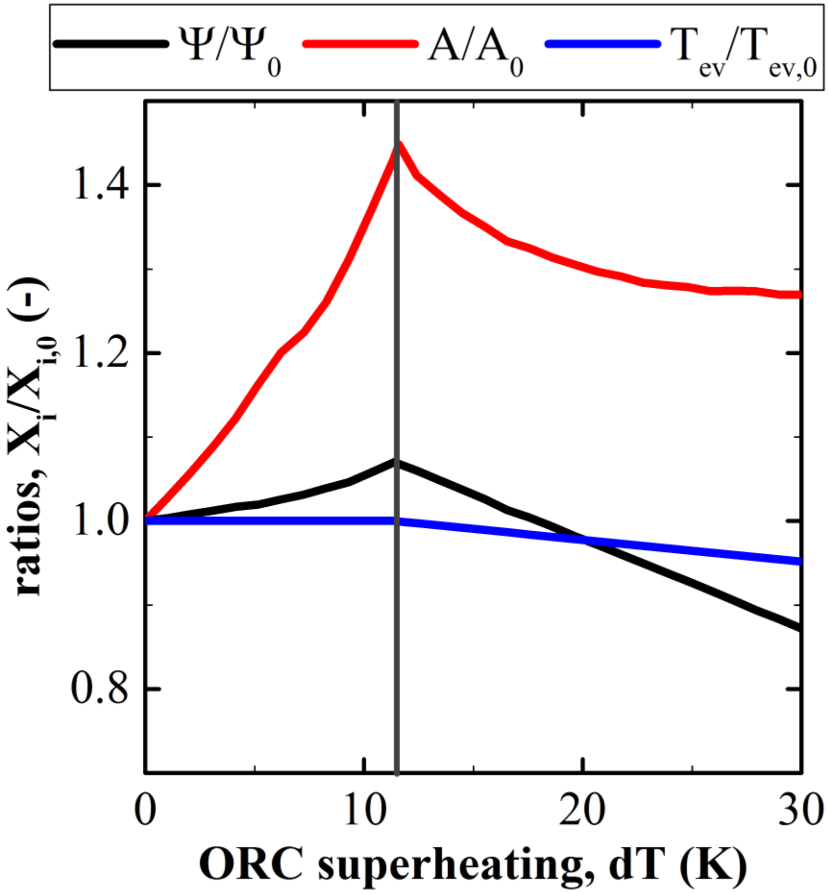


Constant evaporation temperature:

- Ψ increases slightly
- heat transfer area increases stronger

Reduced evaporation temperature:

- Ψ decreases

➢ **Superheating is not useful!**

Conclusions

- PHES is a promising application of an ORC and worth further investigations
- Carnot-cycles were transferred to Rankine-cycles using optimal fluids
- Contrary to Carnot-cycles: Ψ decreases with increasing $T_{storage}$
  - Expansion of the heat pump
  - boiling of the fluid (ORC)
- Superheating at expander inlet is not useful
- Above T_{st} = 430 K multistage cycles are probably needed

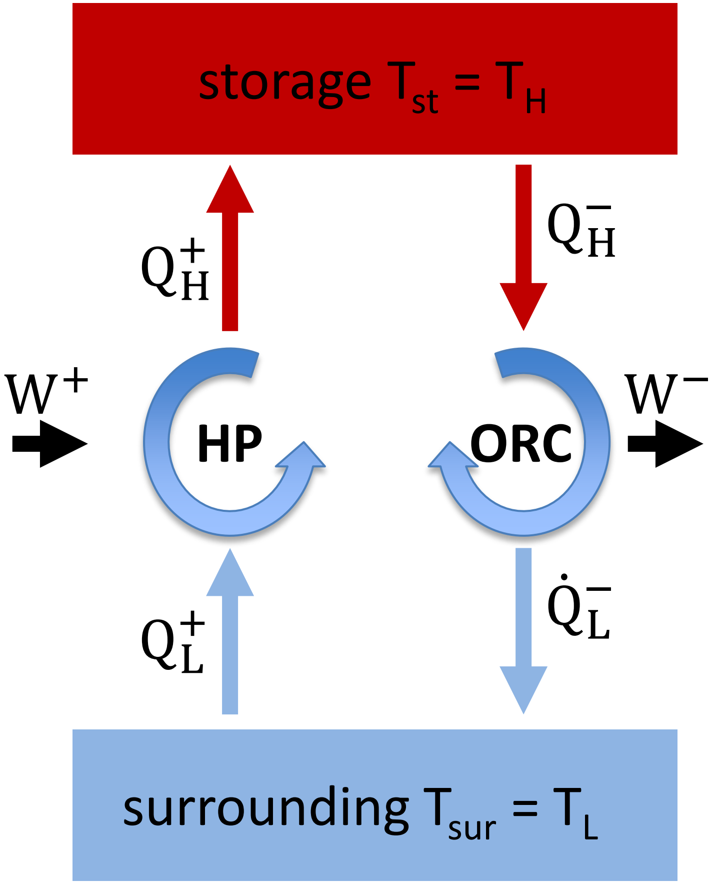
Outlook

- Expander instead of throttle in heat pump?
- Fluid boiling in ORC: Regenerative feed water heater?
- Influence of irreversibilities of the different components
- identifying efficient real fluids
- sensible heat storages
- storage modelling

Thank You!

Full Carnot-cycles: Ψ=1

PHES (T_{st}>T_{sur})



storage efficiency / roundtrip efficiency

$$\Psi = \frac{W^-}{W^+}$$

combining two Carnot-cycles

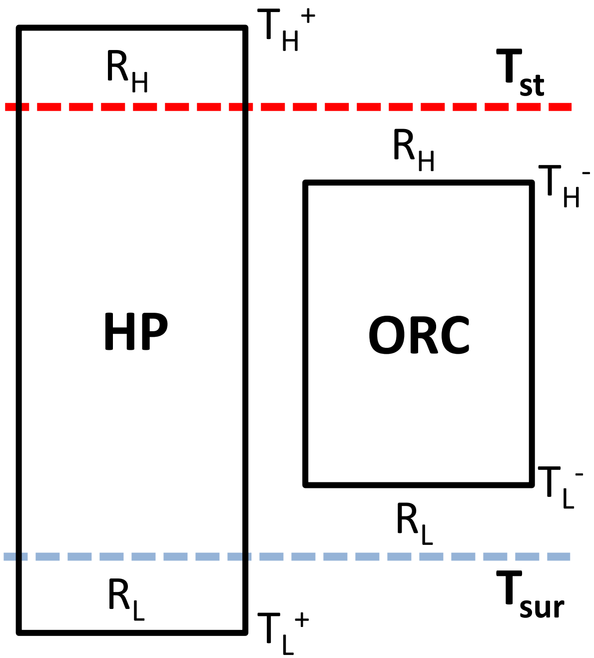
$$\Psi = \frac{W^-}{W^+} = \frac{\eta_{ORC} \cdot Q_H^-}{\frac{Q_H^+}{\epsilon_{HP}}} = \eta_{ORC}^c \cdot \varepsilon_{HP}^c$$

$$\Psi = \frac{T_H - T_L}{T_H} \cdot \frac{T_H}{T_H - T_L} = 1$$

Reduced power cycle (pre-study)

Boundary conditions

- $t_{charging} = t_{discharging}$.
- Same thermal resistances
  - $R_L^+ = R_L^- \qquad R_H^+ = R_H^-$.

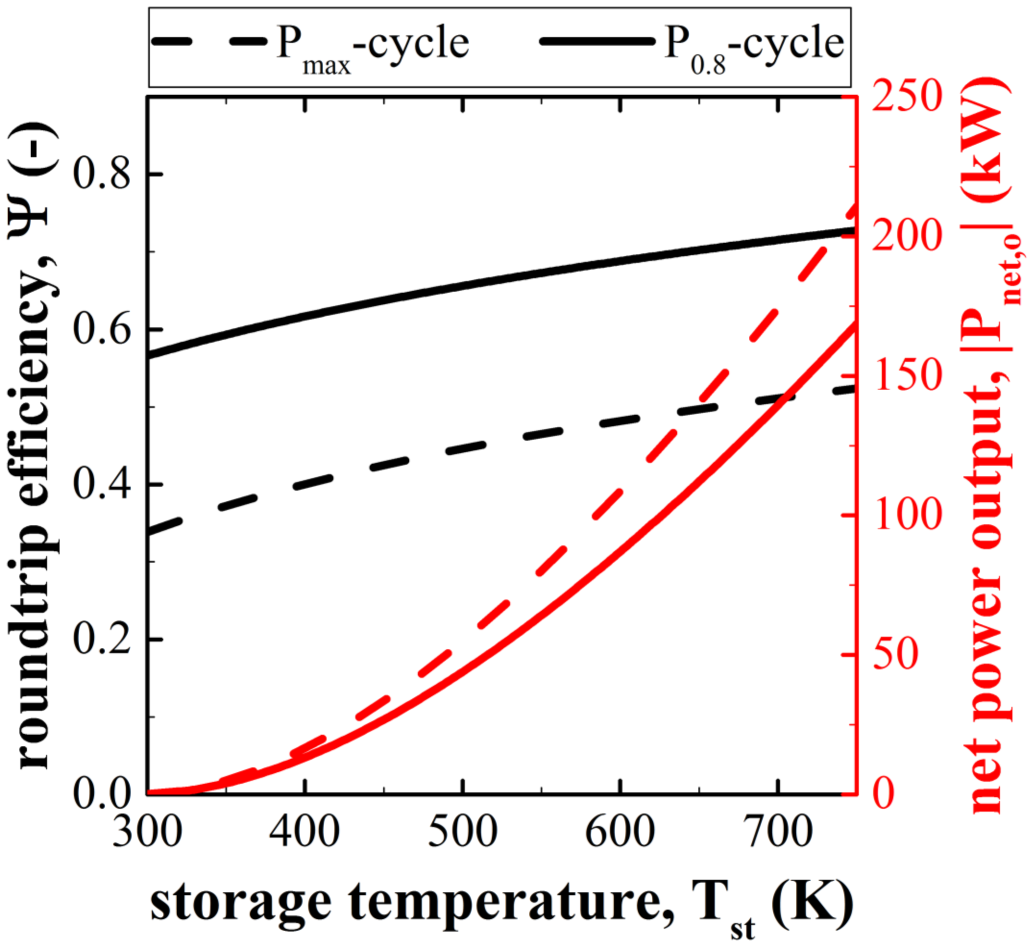


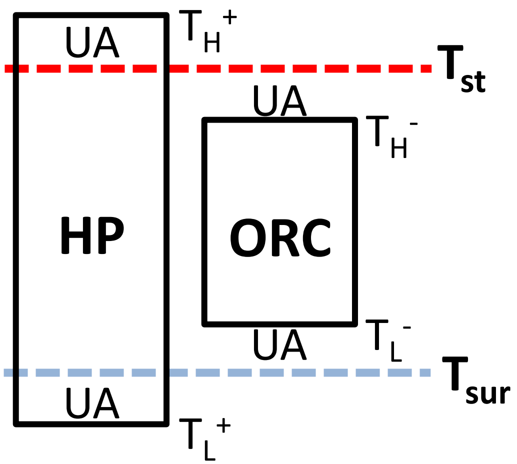
$$|P^-| = |\dot{Q}_H^-| \cdot \eta_{ORC} = \frac{(T_{st} - T_H^-)}{R_H} \cdot \left(1 - \frac{T_L^-}{T_H^-}\right)$$

$$\Psi_{PHES} = \varepsilon_{HP} \cdot \eta_{ORC} = \frac{T_H^+}{T_H^+ - T_L^+} \cdot \left(1 - \frac{T_L^-}{T_H^-}\right)$$

$$\frac{|\dot{Q}_H^-|}{T_H^-} = \frac{|\dot{Q}_L^-|}{T_L^-} \qquad \frac{|\dot{Q}_H^+|}{T_H^+} = \frac{|\dot{Q}_L^+|}{T_L^+} \qquad T_H^+ - T_{st} = T_{st} - T_H^-$$

Pre-studies: results

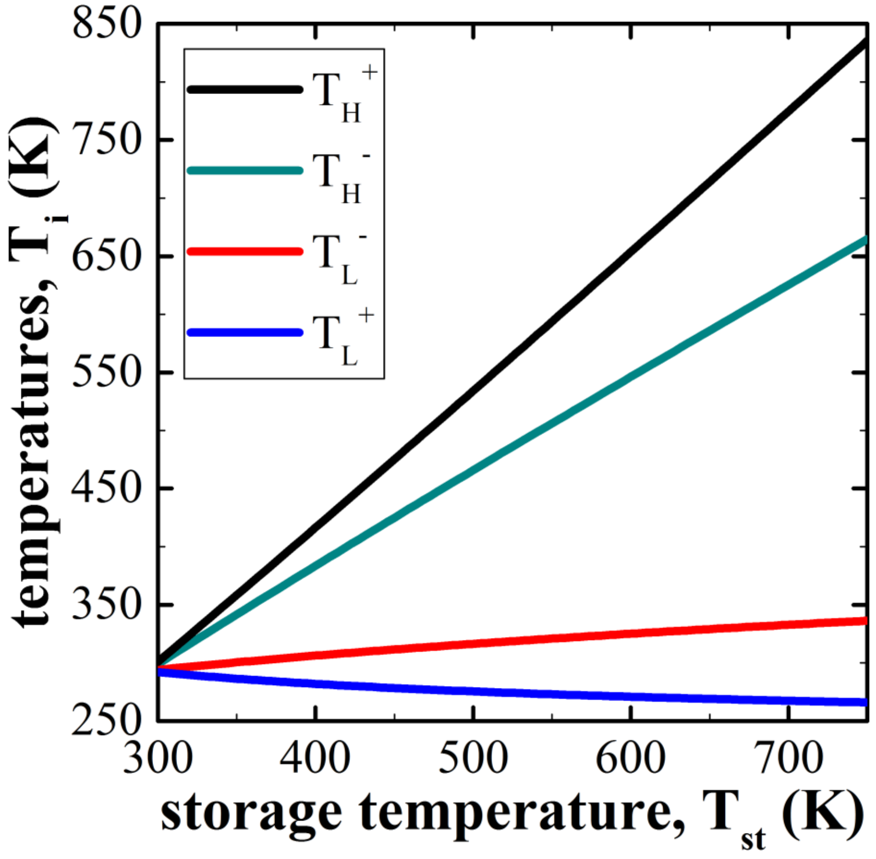


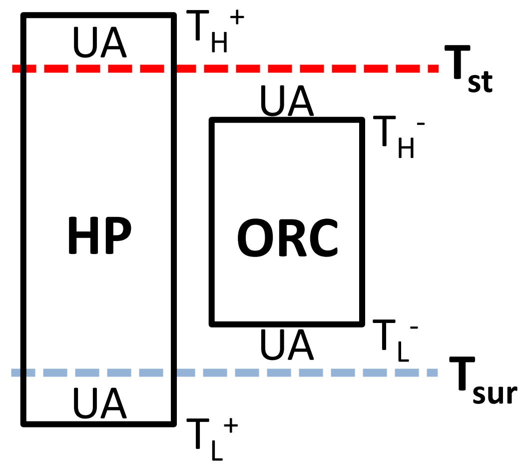


Boundary conditions

- $t_{charging} = t_{discharging}$,
- all heatexchangers:
  - $A = 4\ m^2$
  - $U = 1000\ Wm^{-2}K^{-1}$

Pre-studies: results

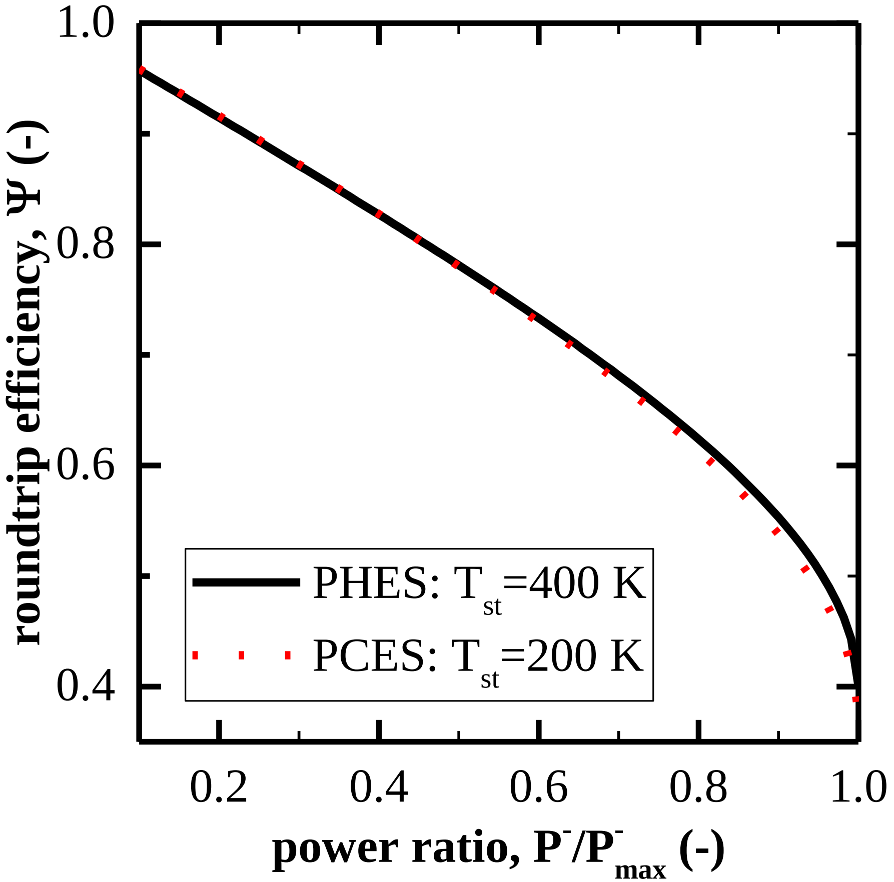


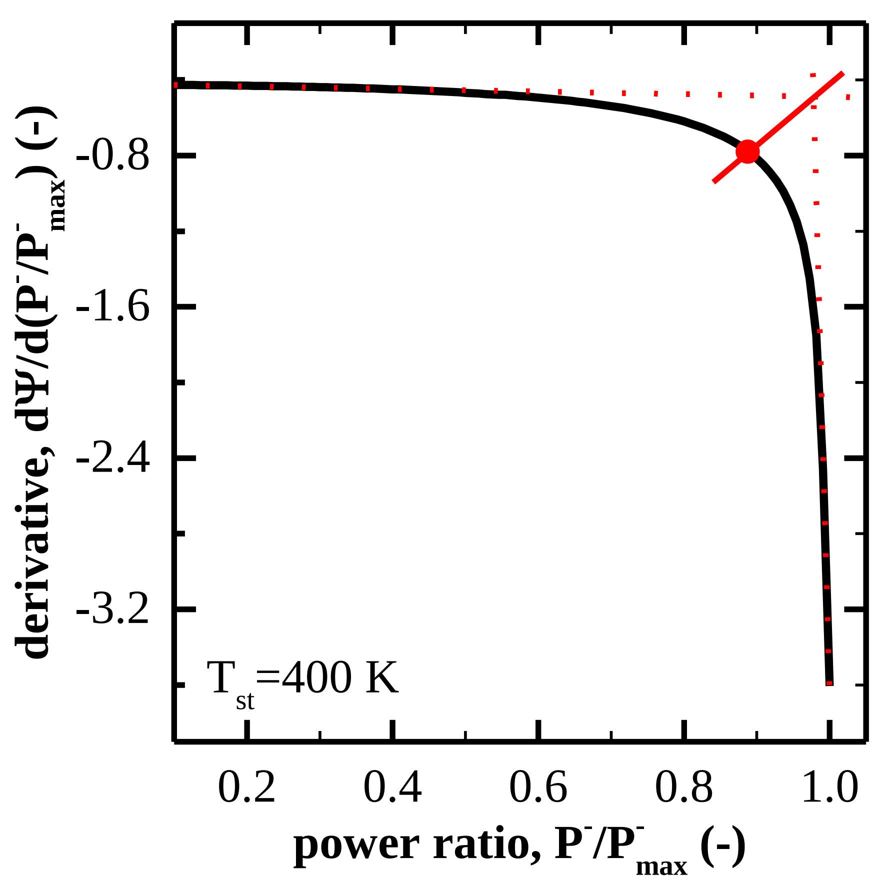


Boundary conditions

- $P = 0.8 \cdot P_{max}$
- $t_{charging} = t_{discharging}$,
- all heatexchangers:
  - $A = 4\ m^2$
  - $U = 1000\ Wm^{-2}K^{-1}$

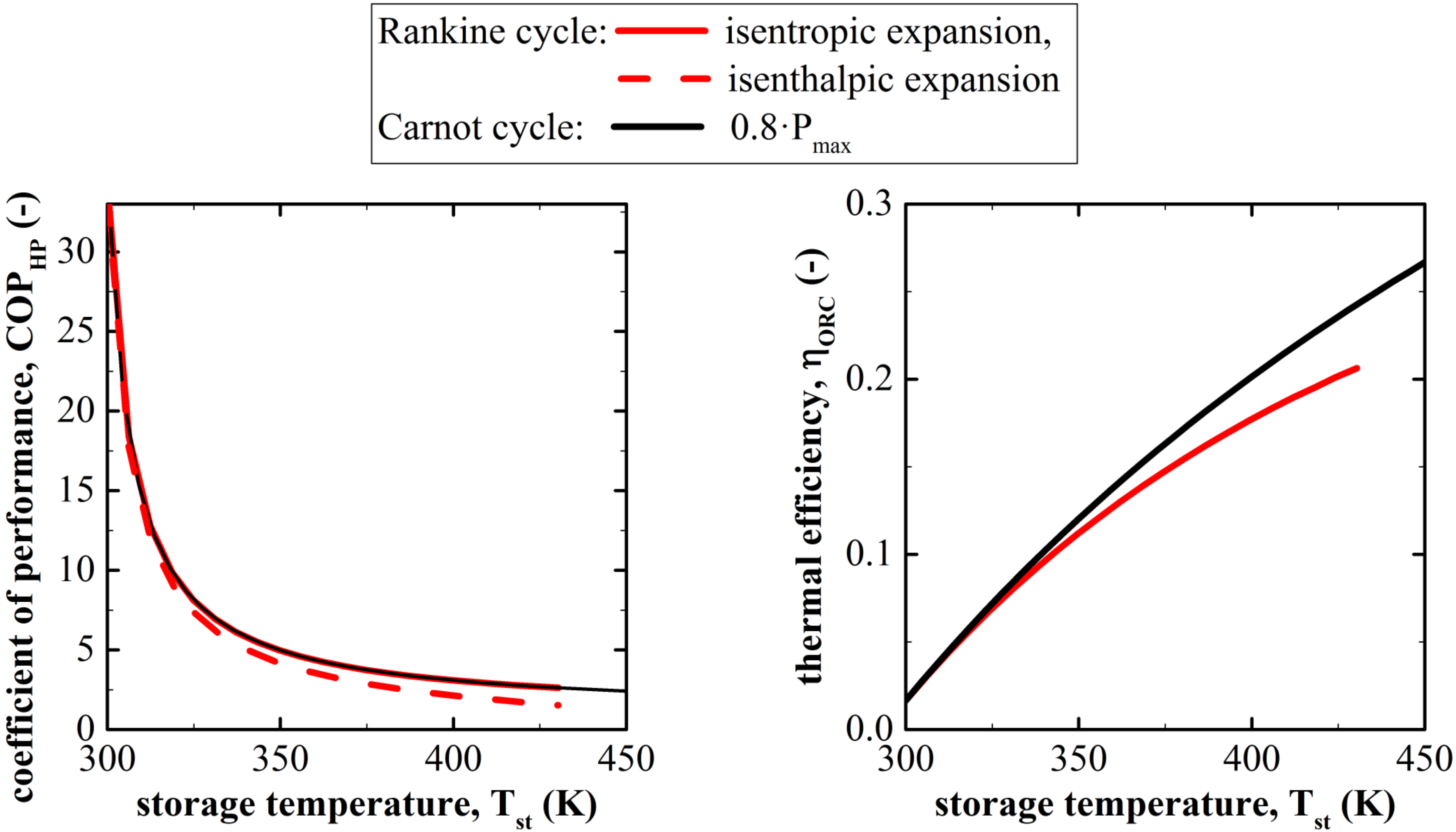
Roundtrip efficiency vs. power output

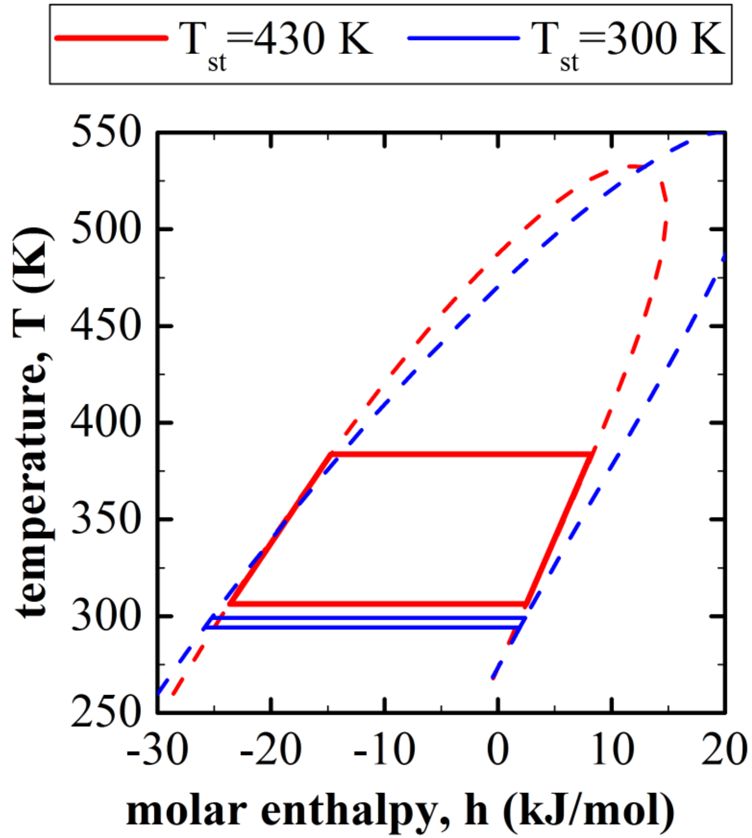




- Requiring P_{max} is very costly with respect to Ψ.

Single cycles




T_{st}=430 K
T_{st}=300 K
550
500
450
400
350
300
250
temperature, T (K)
-30
-20
-10
0
10
20
molar enthalpy, h (kJ/mol)

Variable ranges for fluid optimizing

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parameter	variable range
critical temperature, [K]	$305 \leq T_c \leq 700$
critical pressure, [MPa]	$3 \leq p_c \leq 10$
acentric factor	$0.1 \leq \omega \leq 0.7$
isobaric heat capacity (ideal gas) at 350 K, [J mol^{-1} K^{-1}]	$35 \leq c_{p,350} \leq 150$
slope of isobaric heat capacity at 350 K, [J mol^{-1} K^{-2}]	$0.09 \leq (dc_p/dT)_{350} \leq 0.45$
system pressures, [MPa]	$0.05 \leq p \leq 5.0$