Pumped Thermal Energy Storage: Thermodynamics and Economics

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SETO CSP Virtual Workshop: Pumped Thermal Energy Storage Innovations

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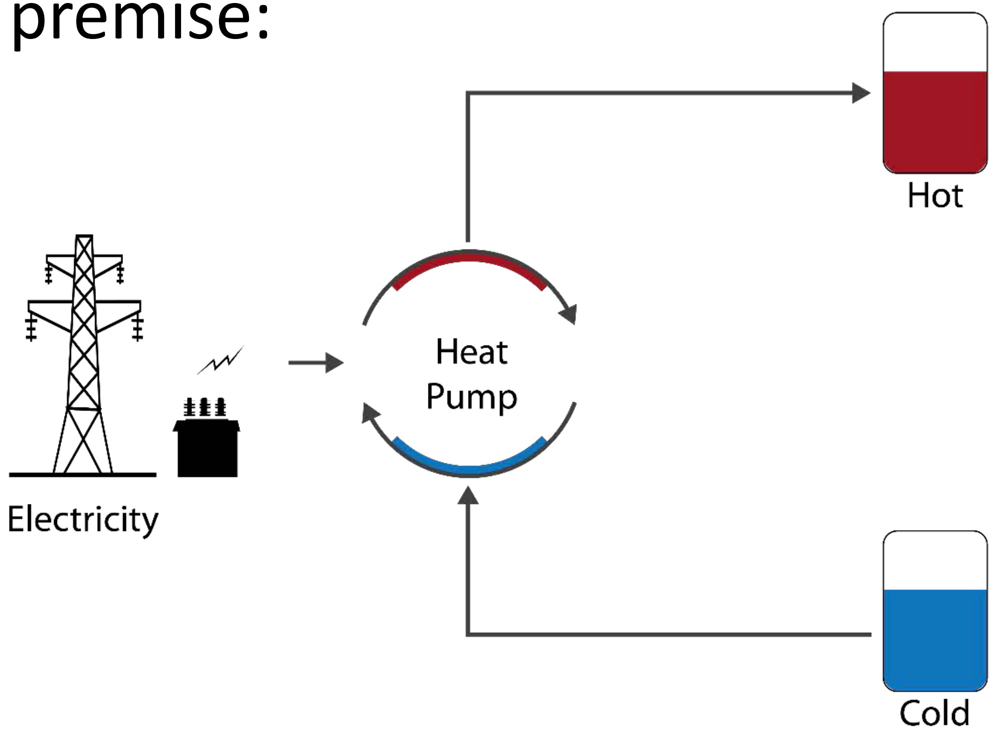
Crescent Dunes Solar Energy Facility, USA

Summary

- PTES background
- PTES variants
- PTES example: ideal-gas cycle with two-tank liquid storage
  - Choice of storage liquid
  - Heat exchanger design
  - Cost and *value*
- PTES example: supercritical CO_2 cycle
- Integrating solar heat with CSP
- Summary

Pumped Thermal Energy Storage (PTES)

- Basic premise:



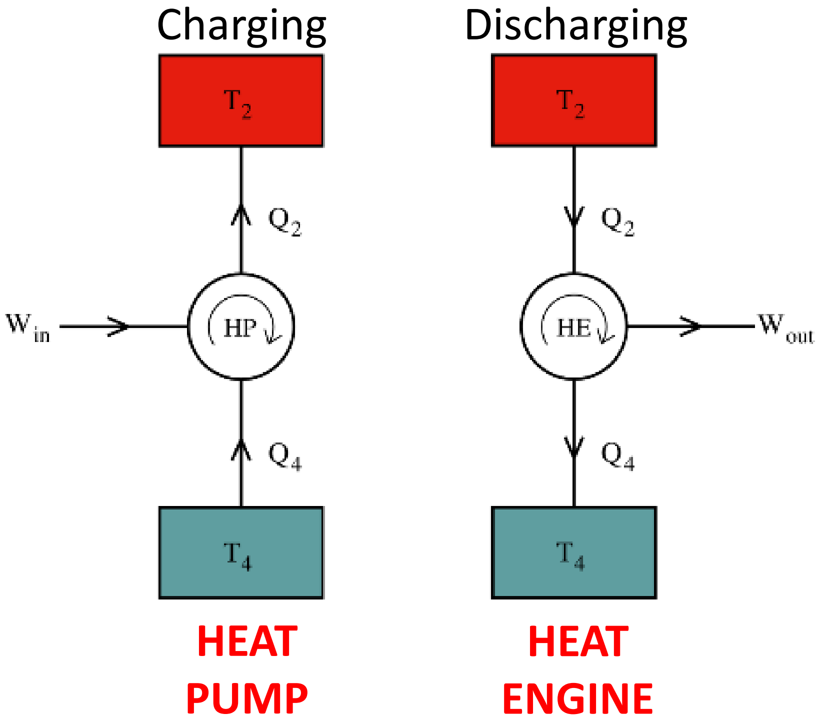
- Charge: heat pump or electric heater
- Discharge: some kind of heat engine (Brayton cycle, Rankine cycle etc.)
- Based on established thermodynamic cycles

The "Carnot Battery"

Sadi Carnot
(1796 – 1832)

- Carnot cycles are:
  - Reversible
  - Isentropic (no entropy generation)

Maximum Carnot Battery round-trip efficiency = 100 %



$$Q_2 = W_{in} \times COP \qquad W_{out} = Q_2 \times \eta$$

However ….

- A Carnot efficient engine has never been demonstrated
- A "non-Carnot" Battery has a round-trip efficiency of 40 – 70 %

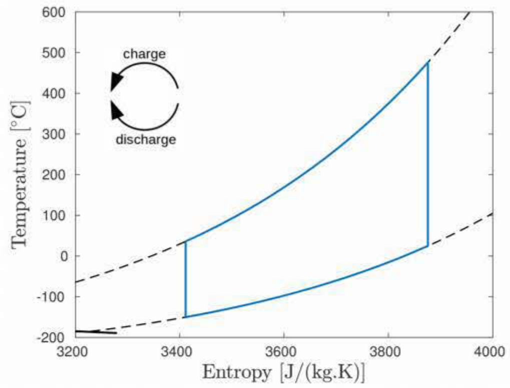
$$\chi = \frac{W_{out}}{W_{in}} = \eta \times COP$$

$$\chi = 1$$

(for a Carnot cycle)

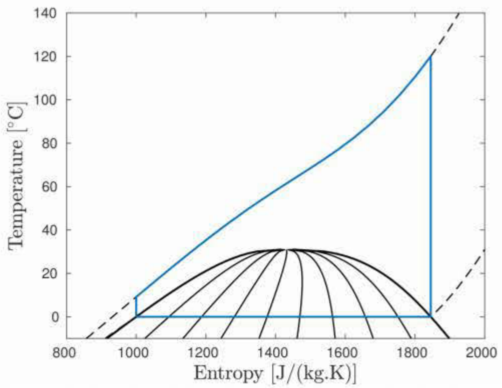
[1] A. White, G. Parks, and C. N. Markides, "Thermodynamic analysis of pumped thermal electricity storage," Applied Thermal Engineering, vol. 53, pp. 291–298, May 2013.
[2] J. D. McTigue, A. J. White, and C. N. Markides, "Parametric studies and optimisation of pumped thermal electricity storage," Applied Energy, vol. 137, pp. 800–811, Sept. 2015.

Many possible power cycle / thermal storage combinations



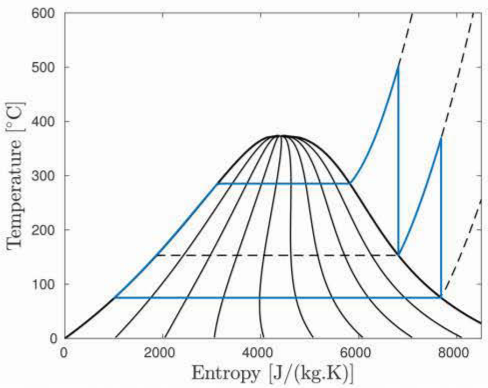
Brayton cycle

- High energy density
- Sensible heat storage
- Low work ratio (2~3)



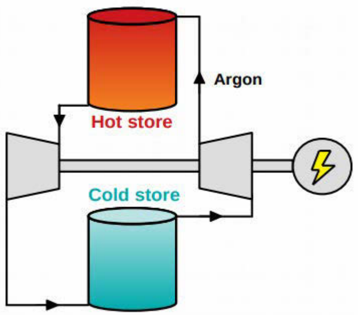
Transcritical

- Can operate at low temperatures (water, ice)
- Variable c_p



Rankine

- High work ratio (>20)
- Latent heat storage
- Very low vapour pressure at cold side (problem for heat pump)

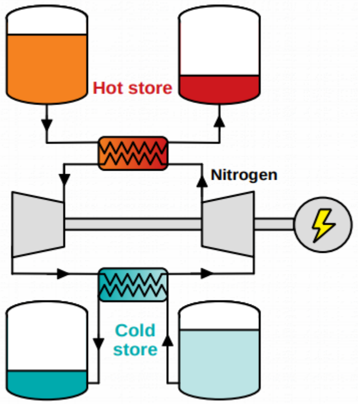


Solid stores

- Cheap storage materials
- Wide temperature ranges
- High energy densities

But...

- Difficult operation and high self-discharge losses



Liquid stores

- Easy to operate
- Low self-discharge losses
- High power density (pressurised cycle)

But...

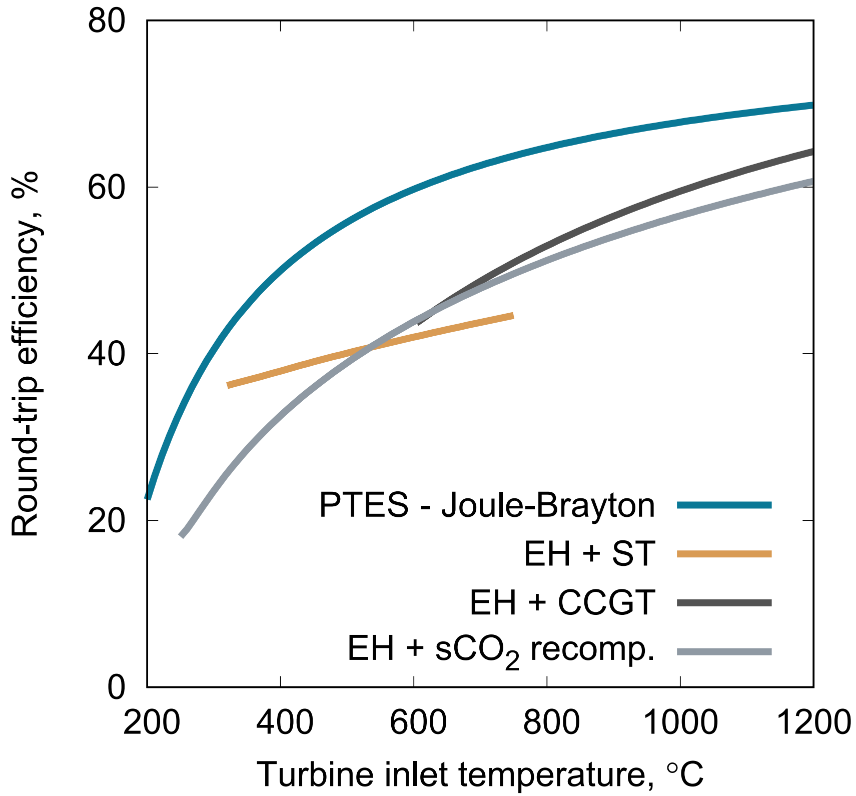
- Heat exchangers can be expensive

[3] A. Olympios et al., “Progress and prospects of thermo-mechanical energy storage – A critical review”, manuscript accepted by IOP Progress in Energy, 2020

PTES efficiency

What are the advantages/challenges of going to high temperatures?

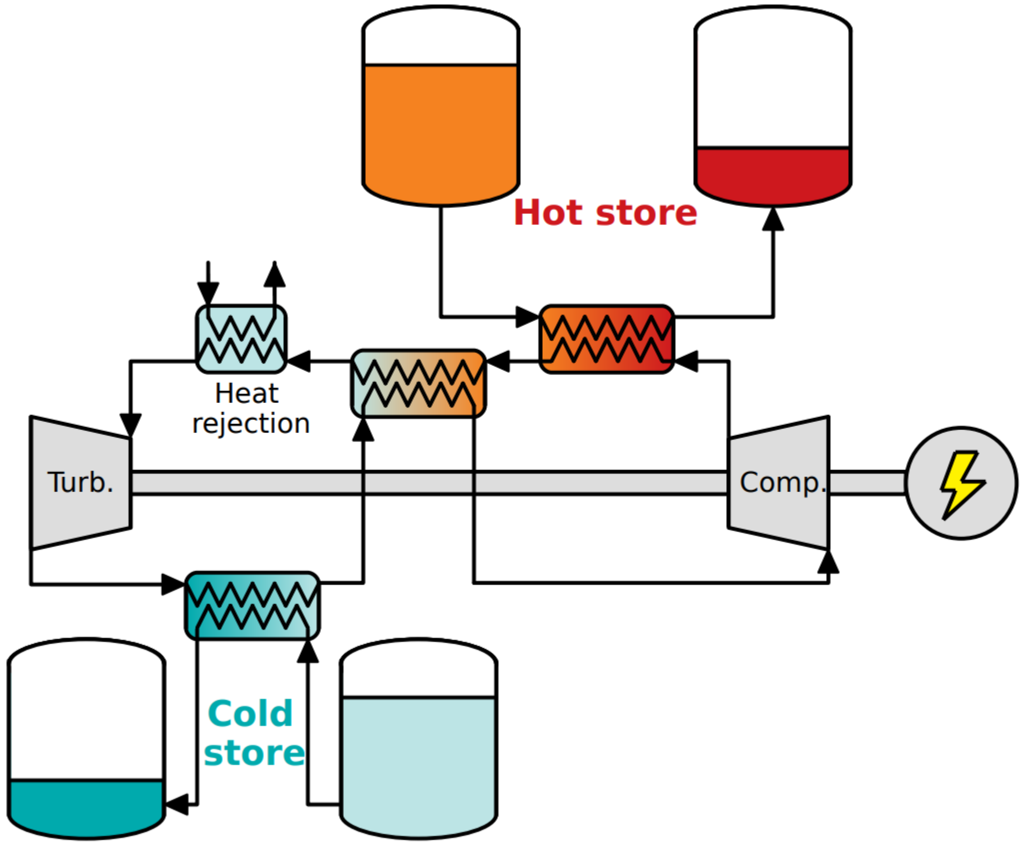
Material costs? Turbomachinery design?

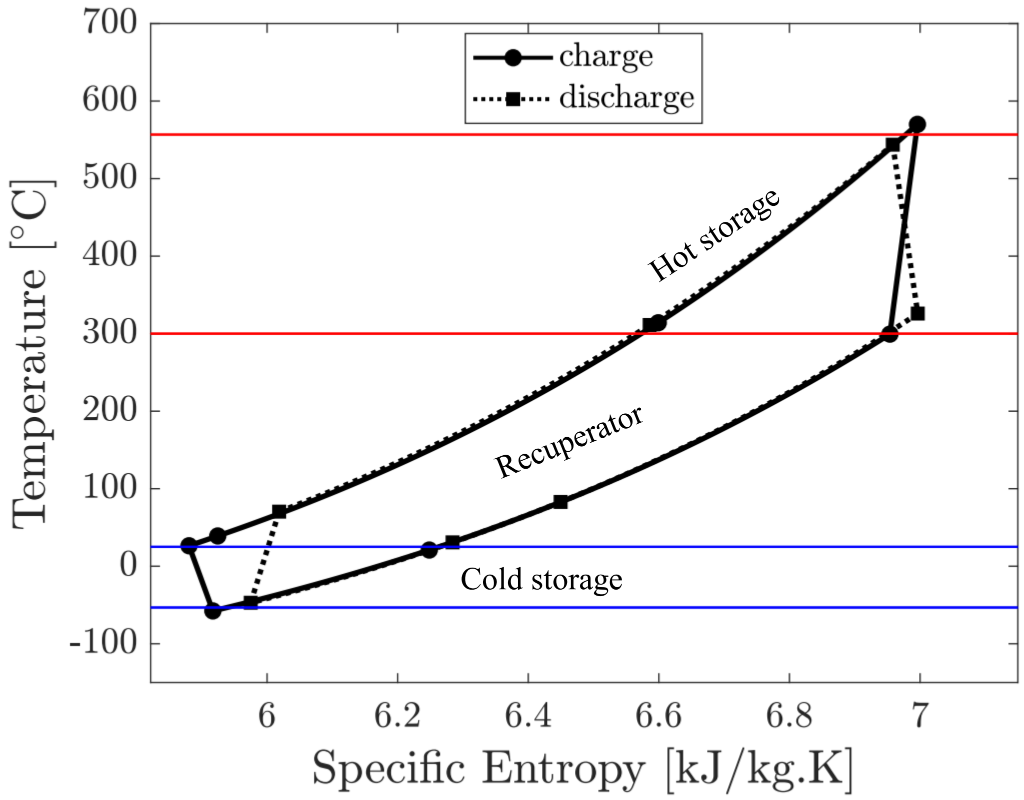


To what extent is the improved efficiency ‘worth it’?

EH = electric heater

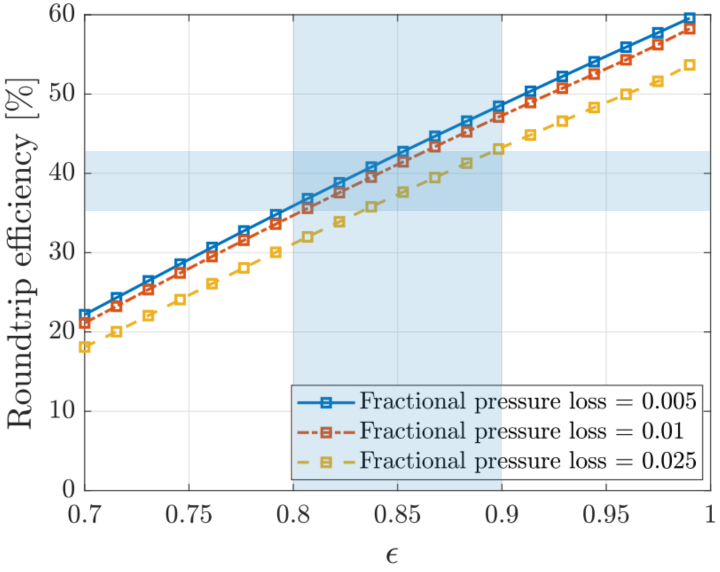
PTES with molten salt liquid storage

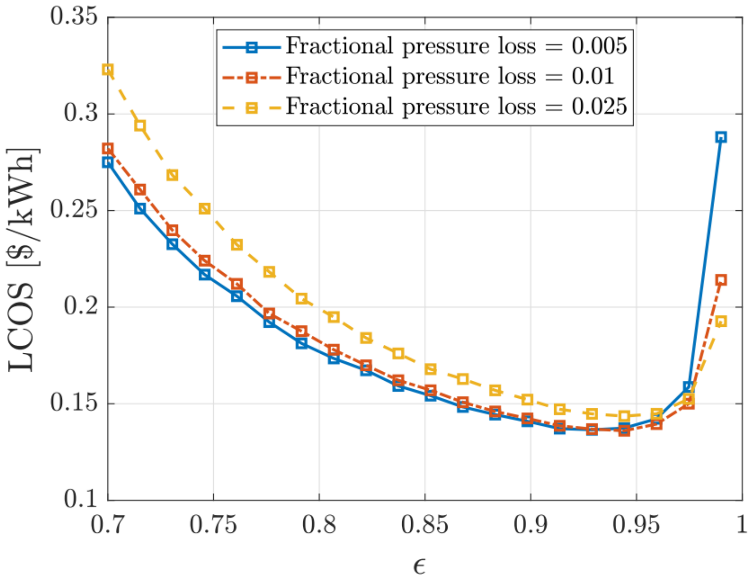




[4] J. D. McTigue, P. Farres-Antunez, K. Sundarnath, C. N. Markides, and A. J. White, "Techno-economic analysis of recuperated Joule-Brayton Pumped Thermal Electricity Storage (PTES) systems", manuscript in preparation, 2020

PTES with molten salt liquid storage





Consider heat exchanger efficiency:

Metrics

Round-trip efficiency:

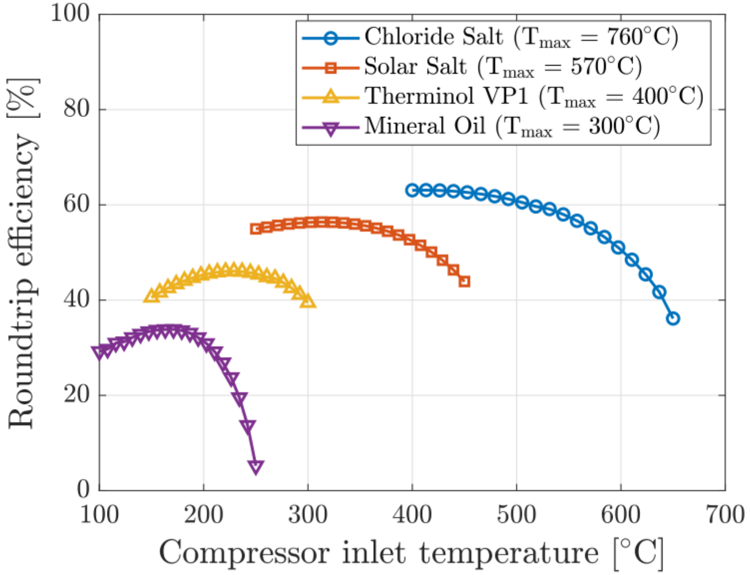
$$\eta_{RT} = \frac{W_{\text{out}}}{W_{\text{in}}}$$

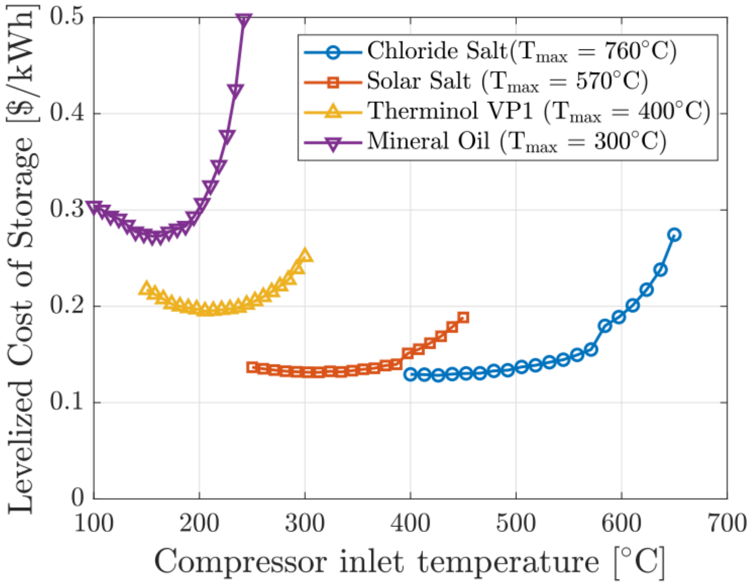
Levelized cost of storage:

$$\text{LCOS} = \frac{C_{\text{cap}} \cdot \text{FCR} + \text{O\&M} + P_{\text{el}} \cdot W_{\text{in}}}{W_{\text{out}}}$$

Performance and cost are very dependent on heat exchanger design

PTES with molten salt liquid storage



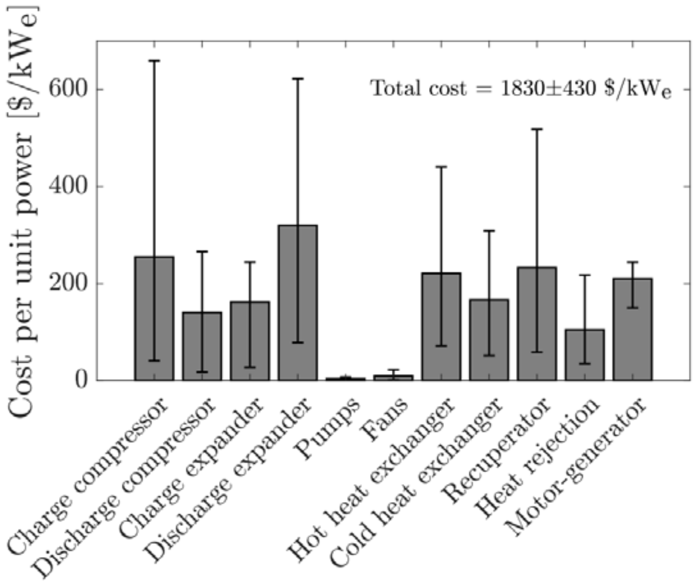


Higher top temperatures:

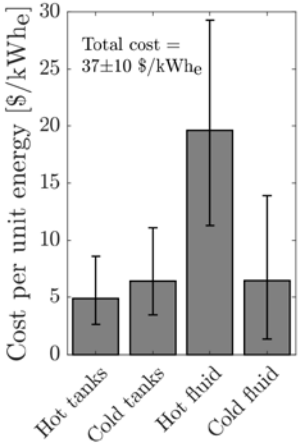
- Increased efficiency
- Increased costs – more expensive metals for heat exchangers
- Balance out in LCOS?
- Some design optimization required

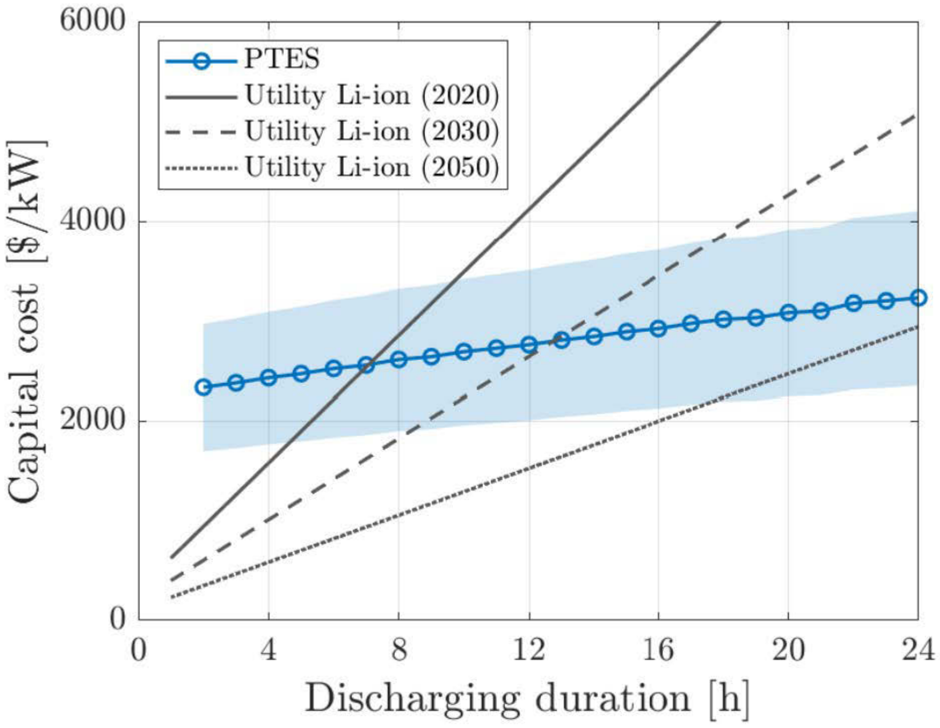
PTES with molten salt liquid storage

Cost of power components



Cost of energy components





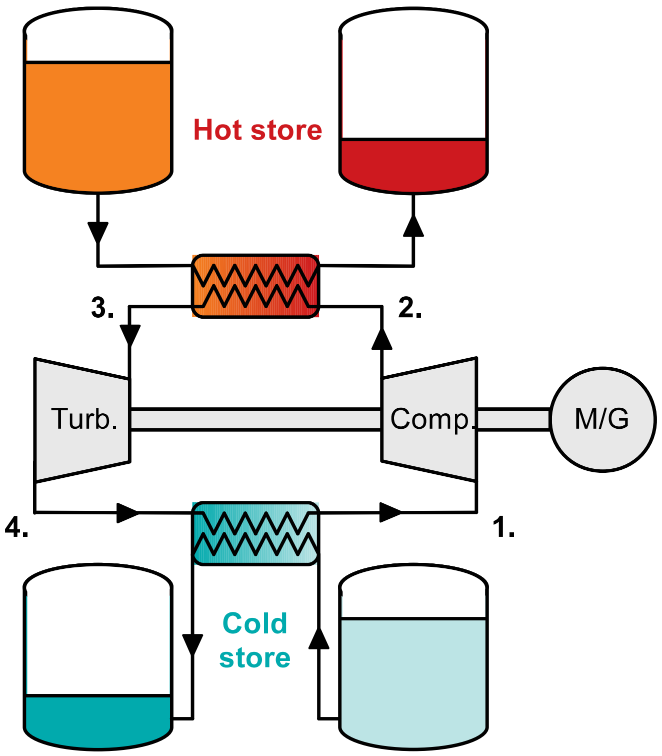
How to reduce power costs?

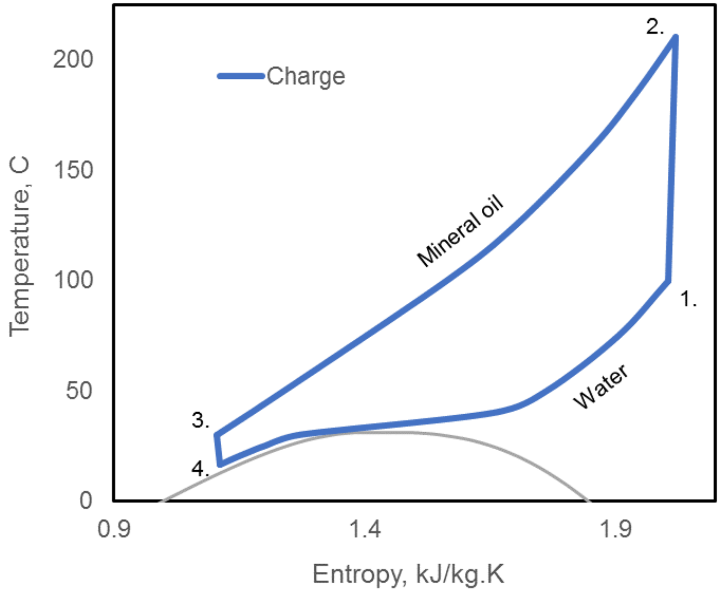
Novel, low-cost heat exchangers?

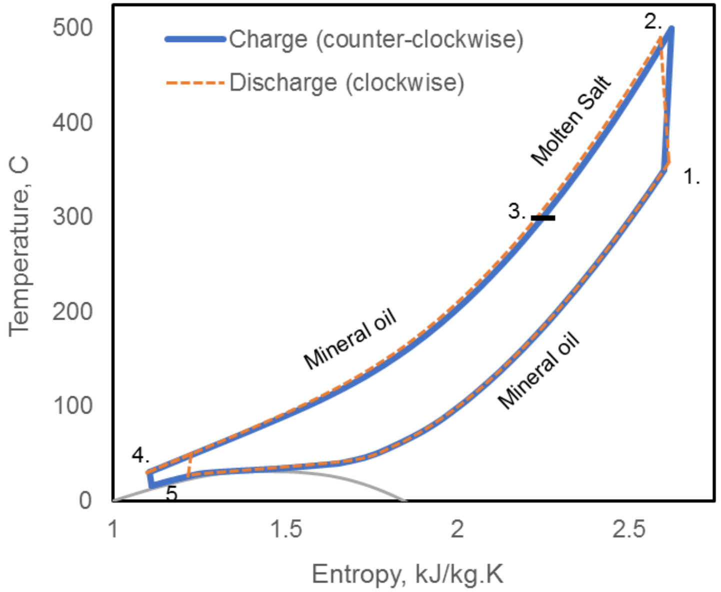
Alternative heat exchangers (packed beds, fluidized beds)

Reversible turbomachinery?

PTES with supercritical CO_2



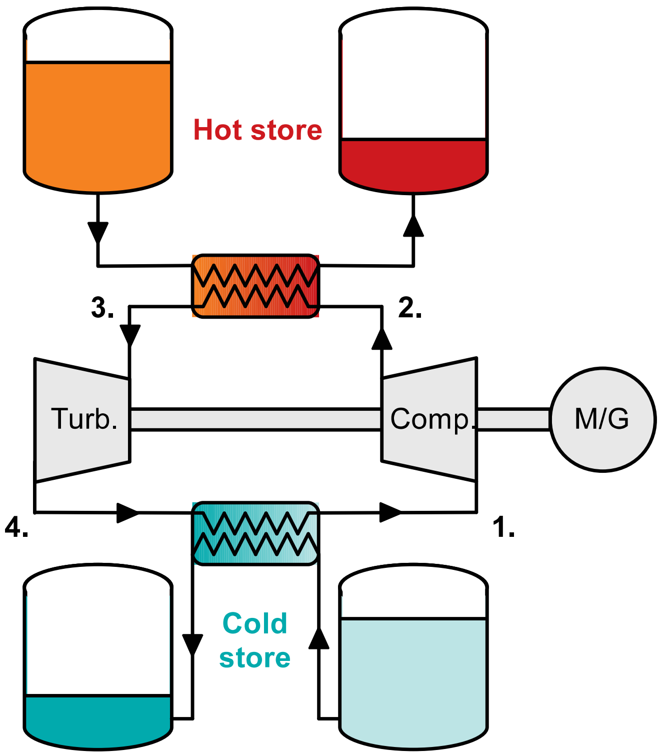


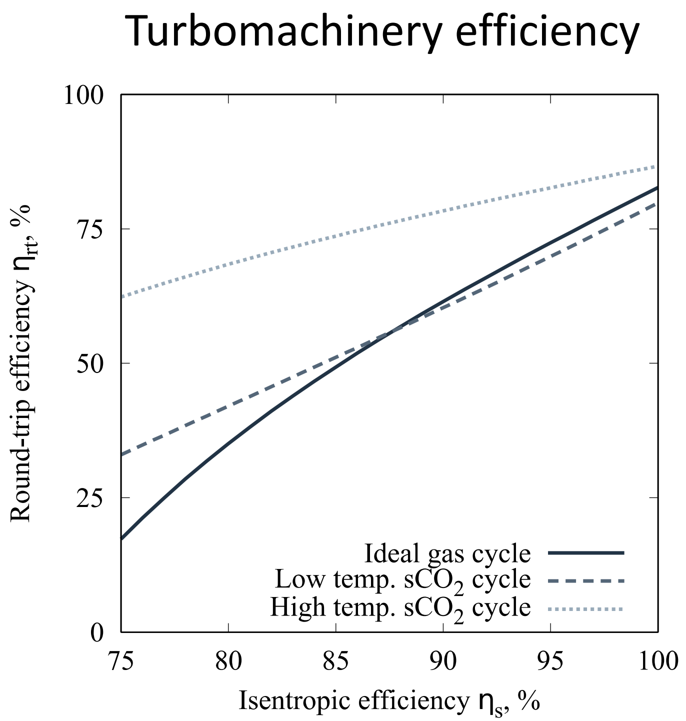


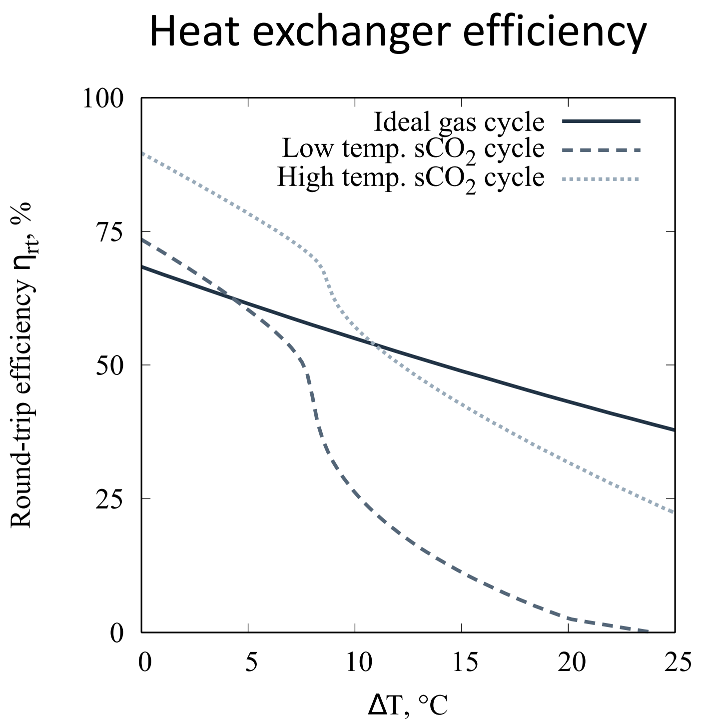
Numerous layouts and temperatures possible:

- Low temperatures *vs* high temperatures
- Supercritical *vs* transcritical
- Recuperation or storage?
- Recompression?

PTES with supercritical CO_2







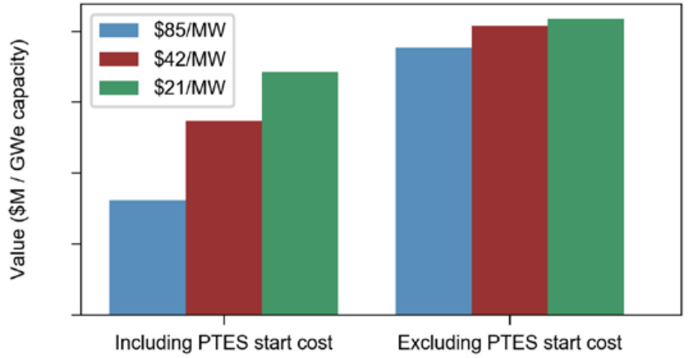
sCO_2-PTES performance is more sensitive to heat exchanger efficiency than ideal-gas PTES.

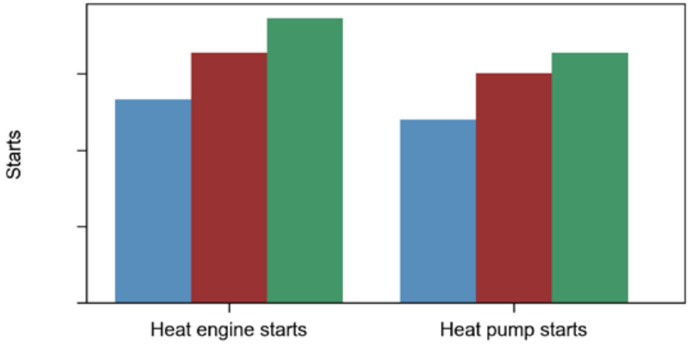
[5] J.D. McTigue, P. Farres-Antunez, K. Ellingwood, T. Neises, A.J. White, "Pumped Thermal Electricity Storage with Supercritical CO2 Cycles and Solar Heat Input", in: SolarPACES, Daegu, S. Korea, 2019.

Cost vs value

- System cost is only one side of the coin
- Quantify the *value* of PTES
- PTES services:
  - Capacity value
  - Grid inertia
  - Reducing renewable curtailment
  - Arbitrage
- Practical PTES limits:
  - What are start costs?
  - What are ramp rates?
  - What is the local generation mix, transmission constraints, etc.?
  - Optimize system sizing/design for these constraints rather than cost and efficiency?
  - These all affect operational profiles and value

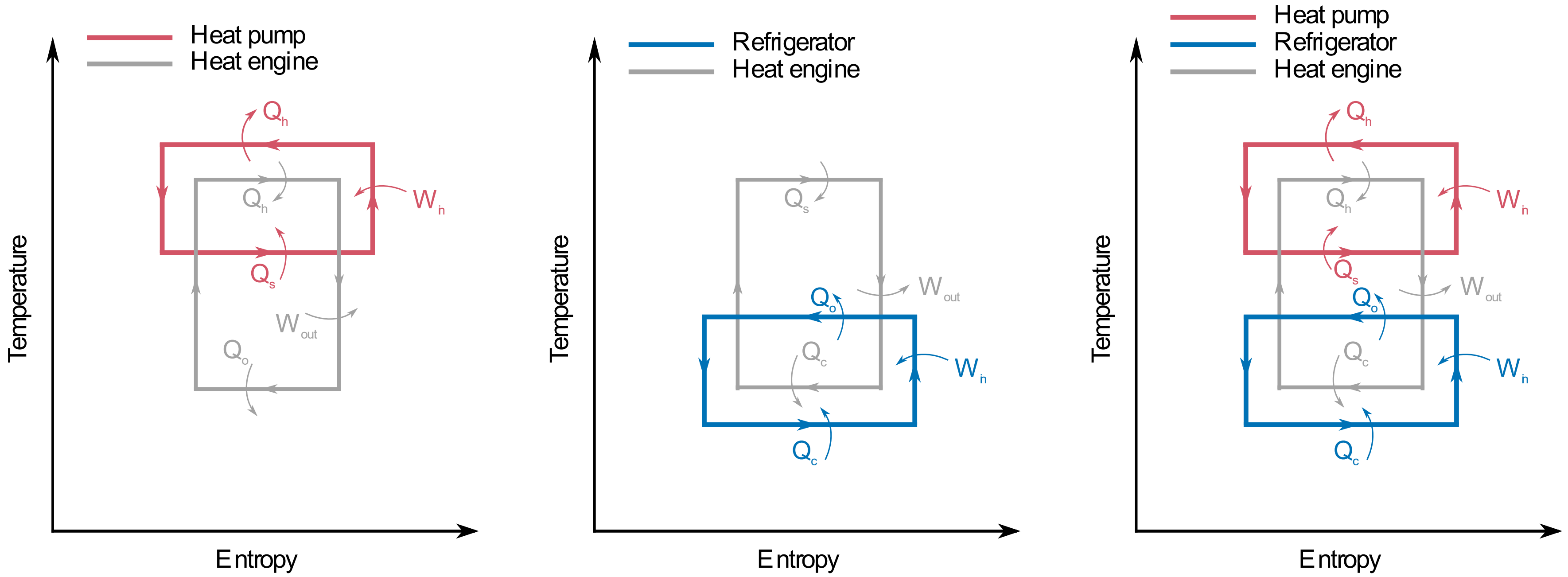
Effect of PTES start costs





Integrating PTES and solar heat

- PTES is suitable for hybridization
  - Electricity, and hot and cold thermal energy

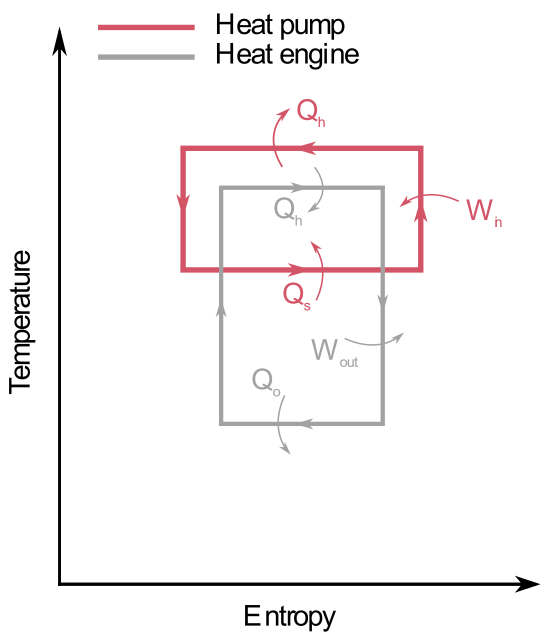


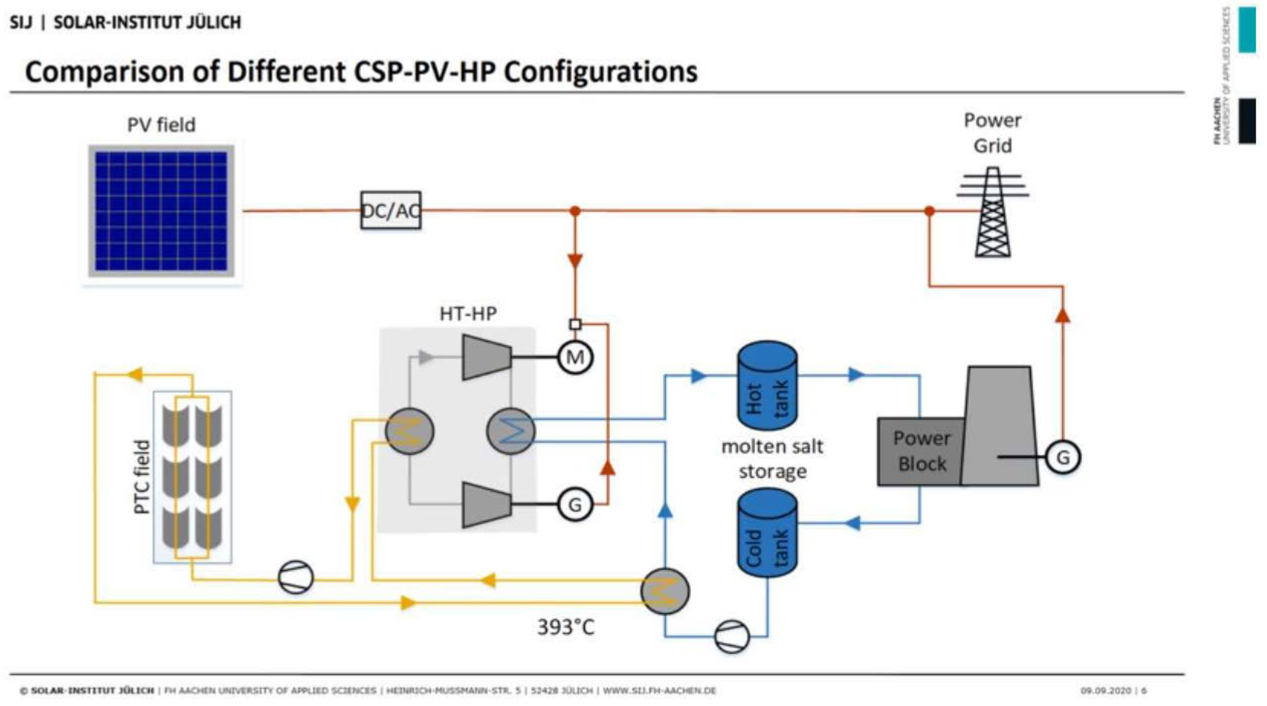
1. Provide multiple services
   a. Renewable power
   b. Electricity storage
2. Provide power when required
3. Improve energy density
4. Reduce thermal storage costs
5. Heat or cold to other loads

[6] J.D. McTigue, P. Farres-Antunez, A.J. White, “Integration of heat pumps with solar thermal energy”, in: Encyclopedia of Energy Storage, edited by Luisa F. Cabeza, manuscript in preparation .

Integrating PTES and solar heat

- An example from SolarPACES:
  - "Technical Assessment of Brayton Cycle Heat Pumps for the Integration in Hybrid PV-CSP Power Plants", Zahra Mahdi (mahdi@sij.fh-aachen.de), SolarPACES 2020

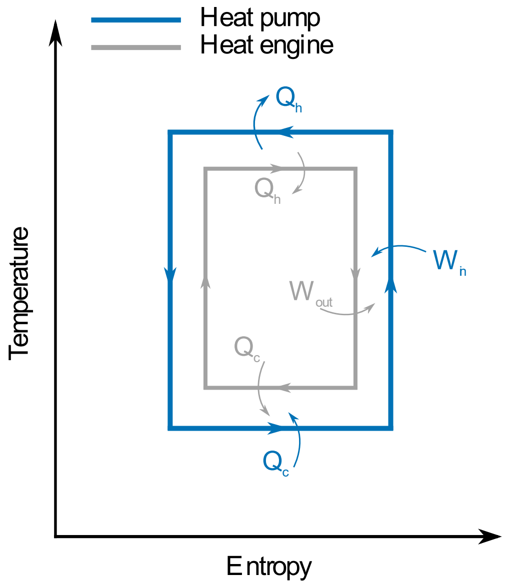


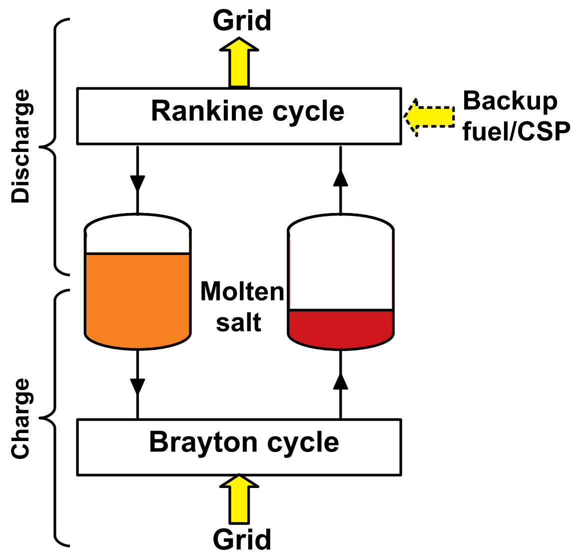


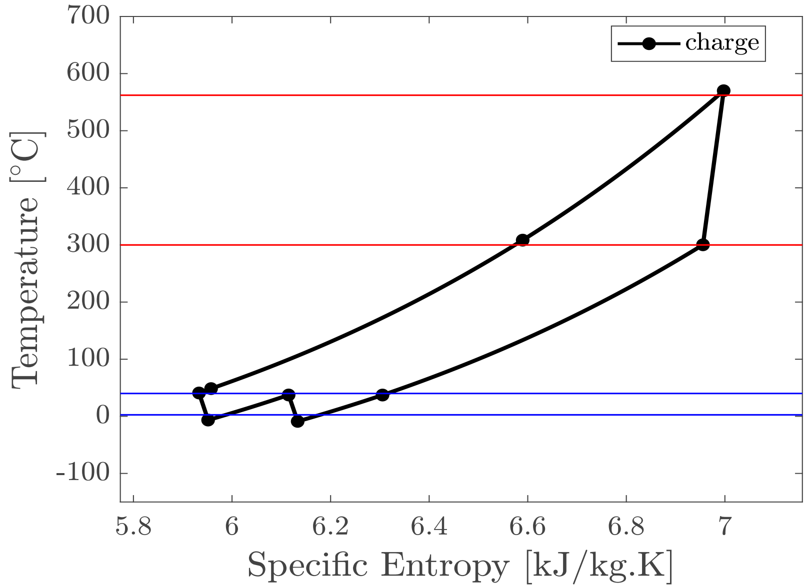
[7] Z. Mahdi, "Technical Assessment of Brayton Cycle Heat Pumps for the Integration in Hybrid PV-CSP Power Plants", SolarPACES, 2020

Integrating PTES and solar heat

- Retrofit an existing CSP system
  - Thermal storage and power block already in place
  - Grid connection, transmission lines, permits, etc.



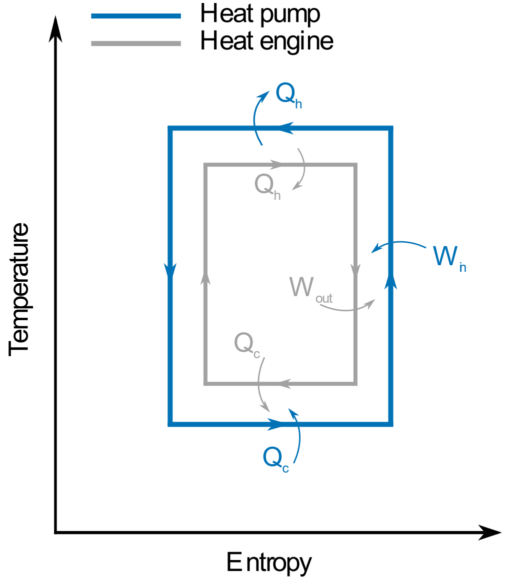


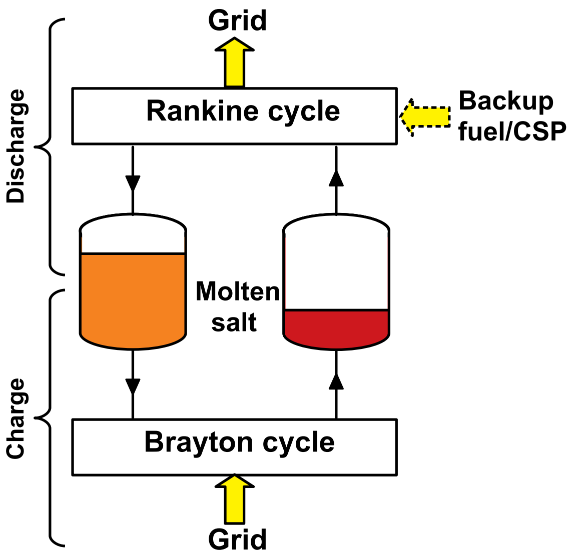


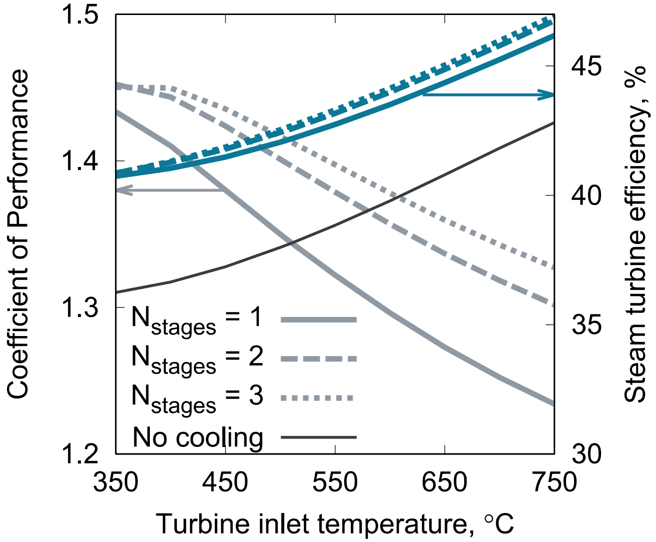
Heat pump also creates cold storage

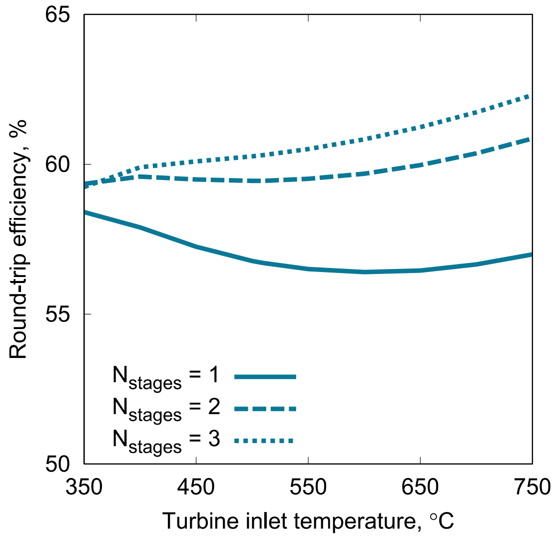
Integrating PTES and solar heat

- Retrofit an existing CSP system
  - Thermal storage and power block already in place
  - Grid connection, transmission lines, permits, etc.



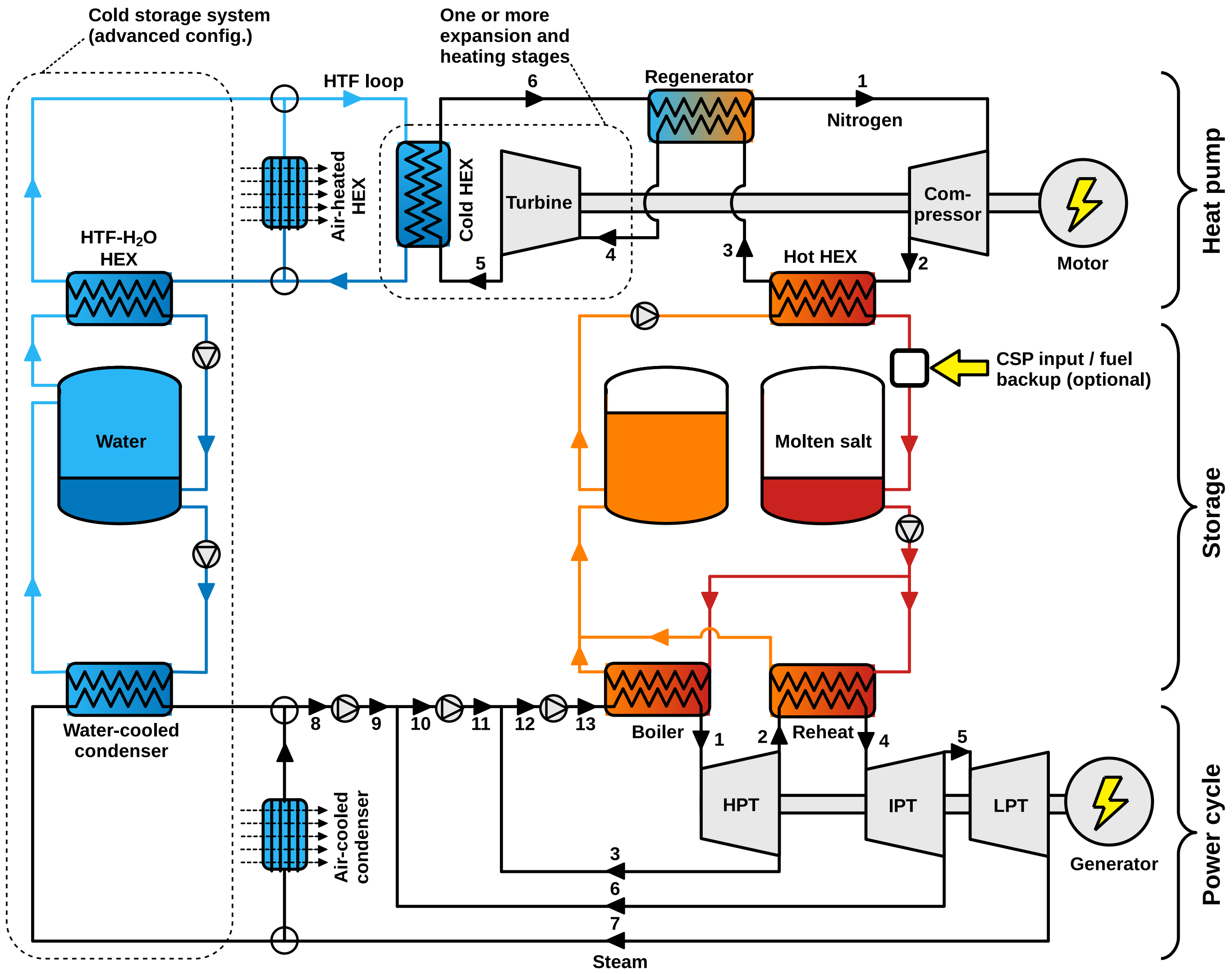






[8] P. Farres-Antunez, J.D. McTigue, A.J. White, "A pumped thermal energy storage cycle with capacity for concentrated solar power integration", in: Offshore Energy Storage Conf., Brest, France, 2019.

Integrating PTES and solar heat



- Different power cycles for charge and discharge
- Relatively complex: control systems, inventory management
- Limited available CSP sites

May be simpler, cheaper and more efficient to use the same power cycle in charge and discharge

Simpler, cheaper, less efficient solution: use an electrical heater

[9] P. Farres-Antunez, A.J. White, C. N. Markides, J.D. McTigue, "Analysis of a Brayton heat pump for bulk electricity storage in steam power plants", manuscript in preparation, 2020

Summary

- Numerous PTES designs – each may have a niche
- Some priorities
  - Heat exchanger design
  - Turbomachinery design
  - Novel approaches to reduce costs
  - Quantifying various value streams
- PTES suitable for hybridization
  - Benefits to integrating with CSP
  - Hybrid systems can be complex

Thank you

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