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Thermodynamic strategies for Pumped Thermal Exergy Storage (PTES) with liquid reservoirs

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UK Energy Storage Conference
Birmingham. 1st December 2016

Thermo-mechanical energy storage (TMES)

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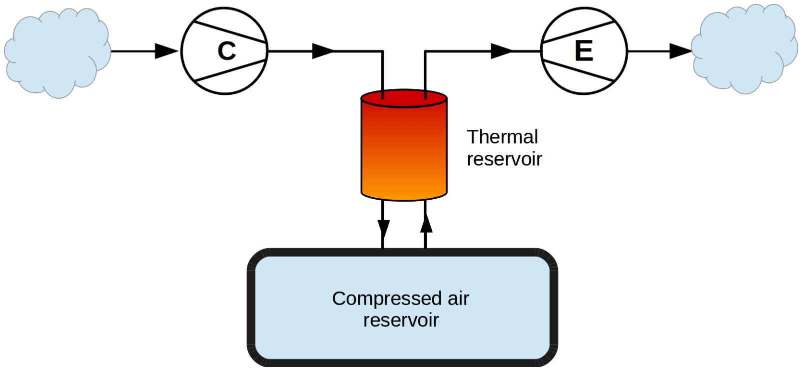
Compressed air energy storage (CAES)



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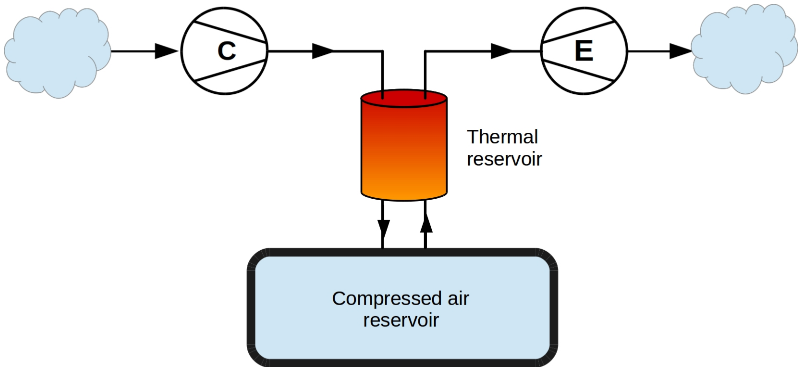
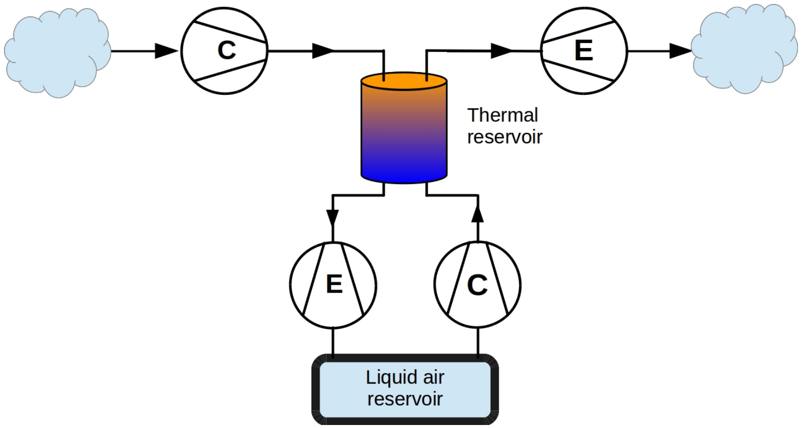


Liquid air energy storage (LAES)



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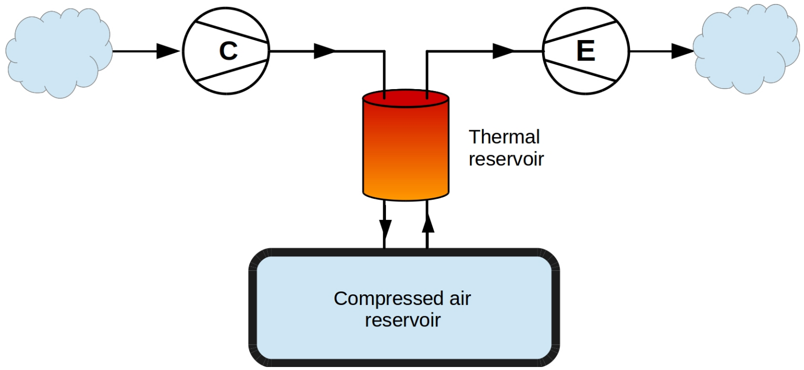

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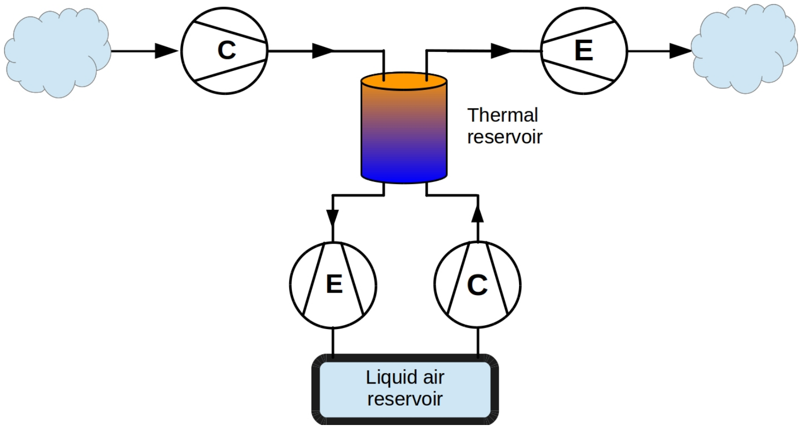
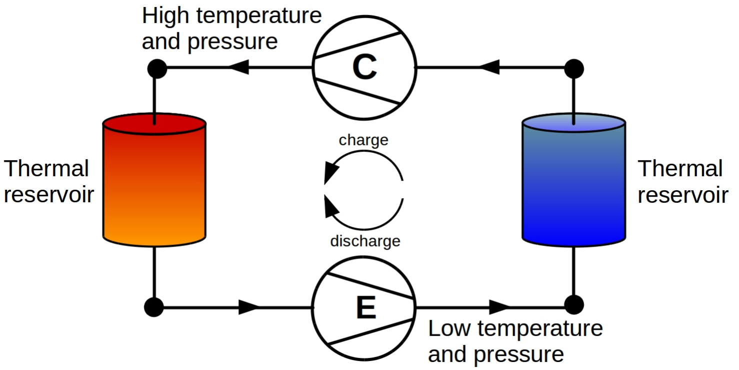


Pumped thermal exergy storage (PTES)



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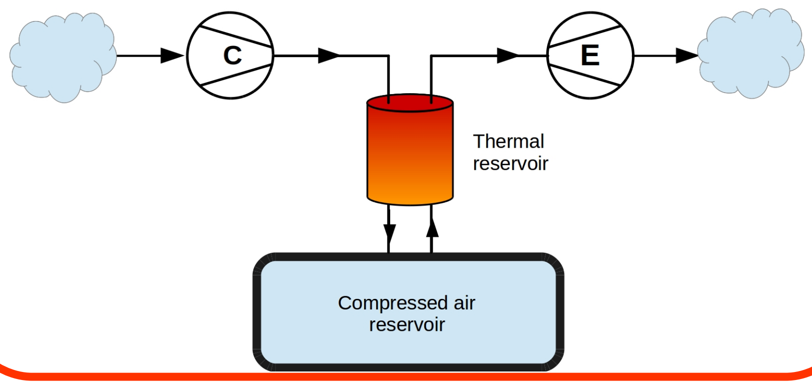

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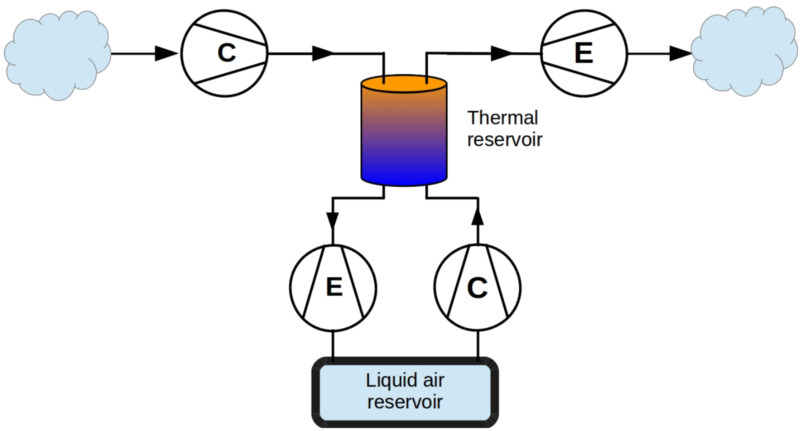
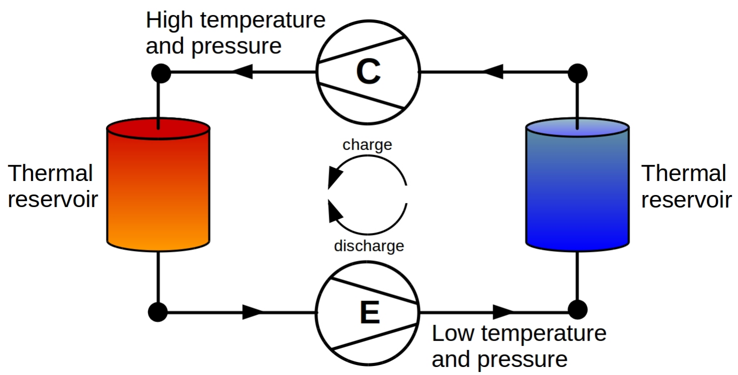


- High efficiency

Pumped thermal exergy storage (PTES)



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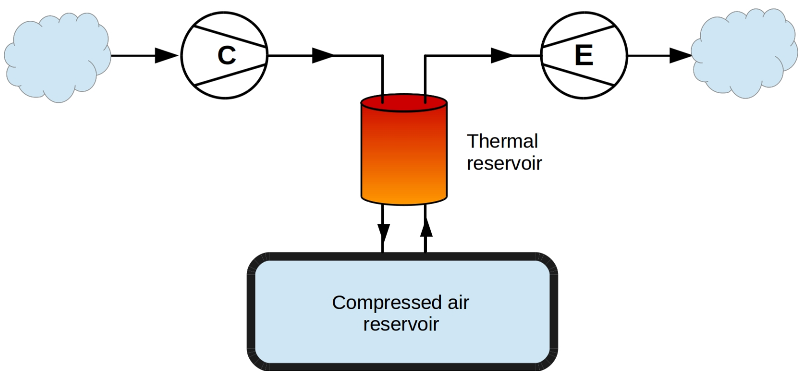

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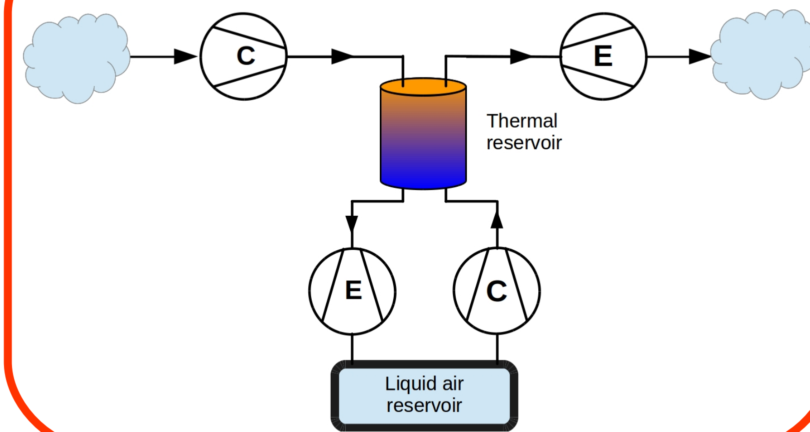

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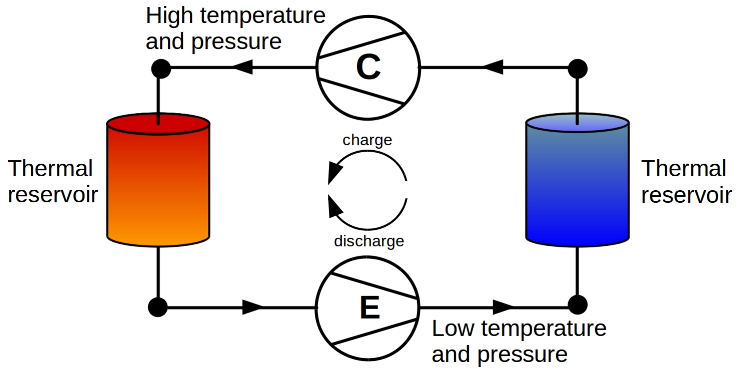
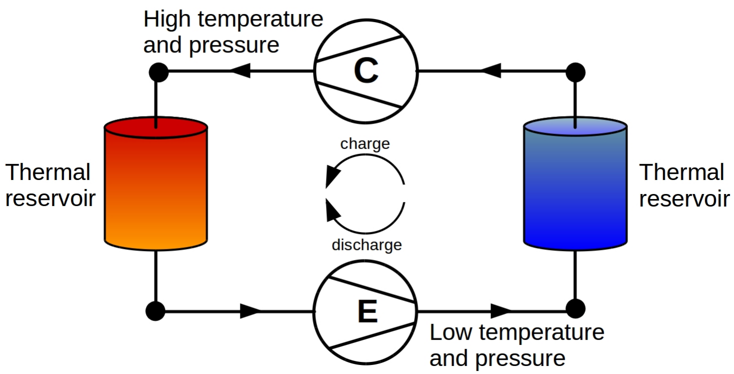


- High energy density
- Geographical independence

Solid and liquid storage media

Solid and liquid storage media

PTES with solid reservoirs



- Large heat transfer area
- Pressurised hot tank
- Thermal fronts

Solid and liquid storage media

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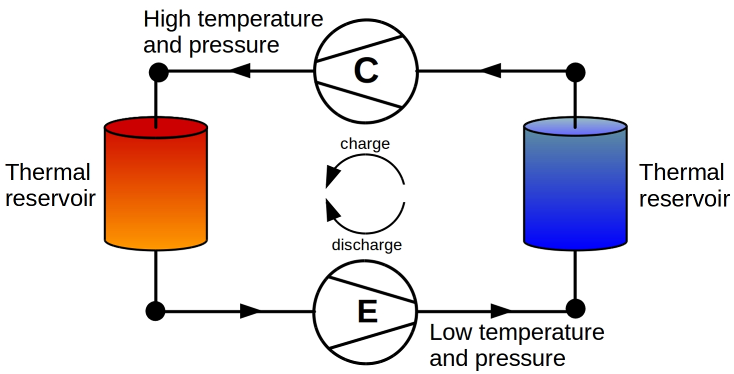

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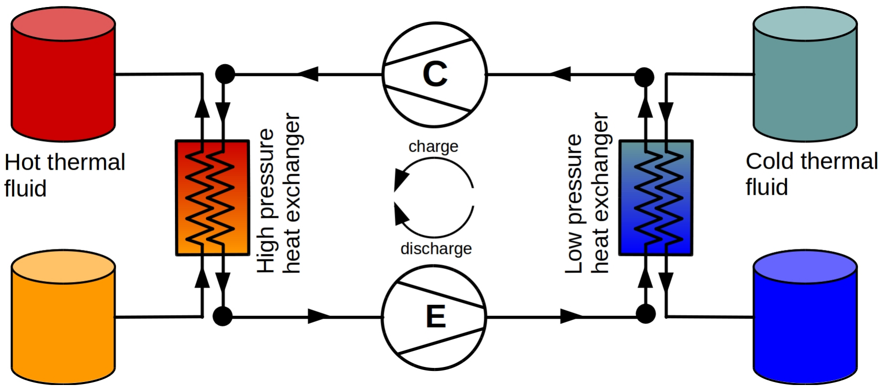

- Limited temperature ranges
- Unpressurised tanks
- Tanks at single temperature

Solid and liquid storage media

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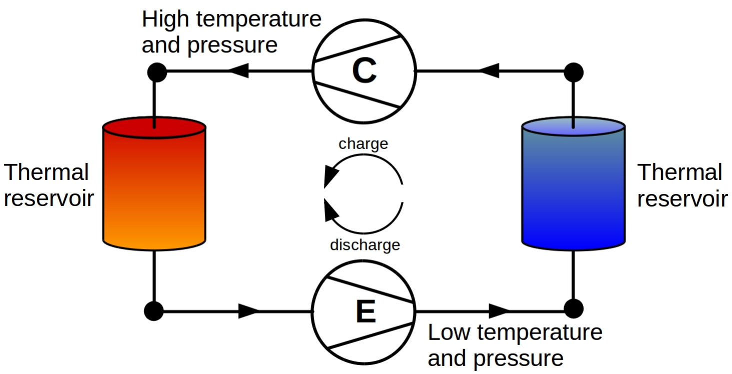

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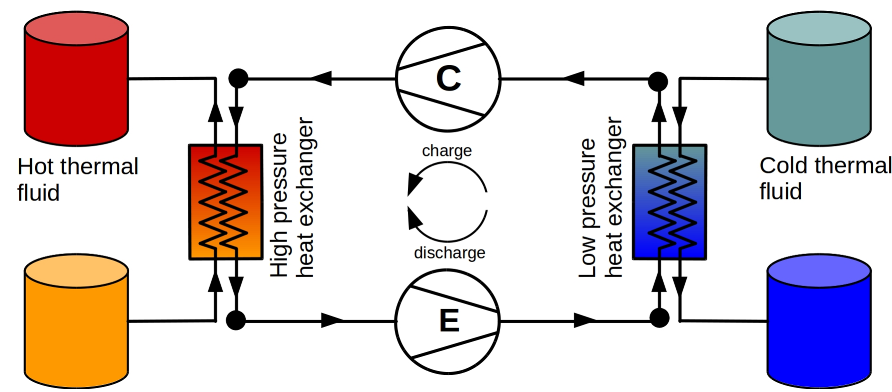

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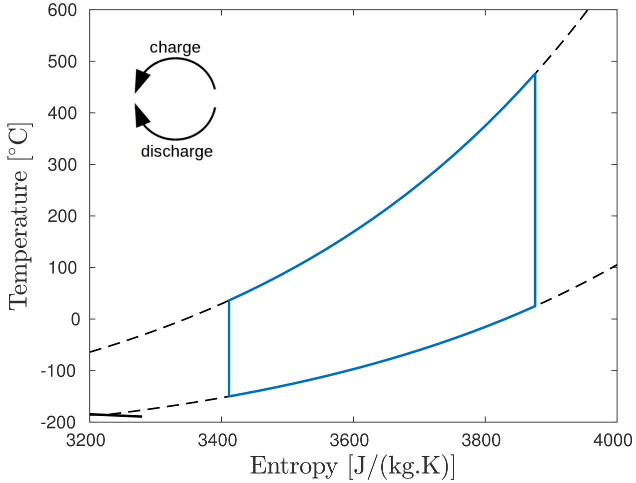
Different cycles

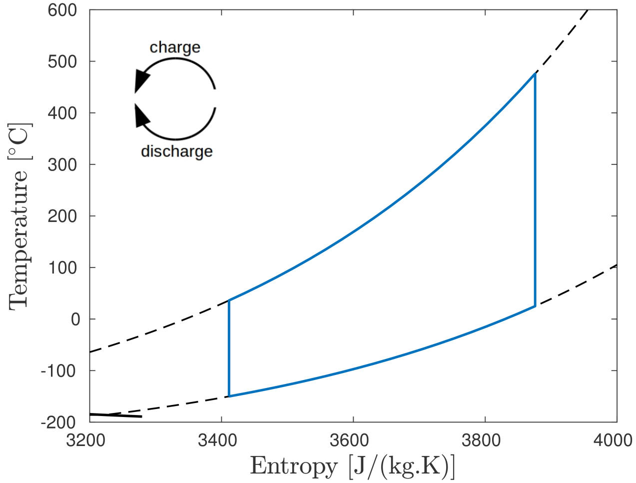
Different cycles

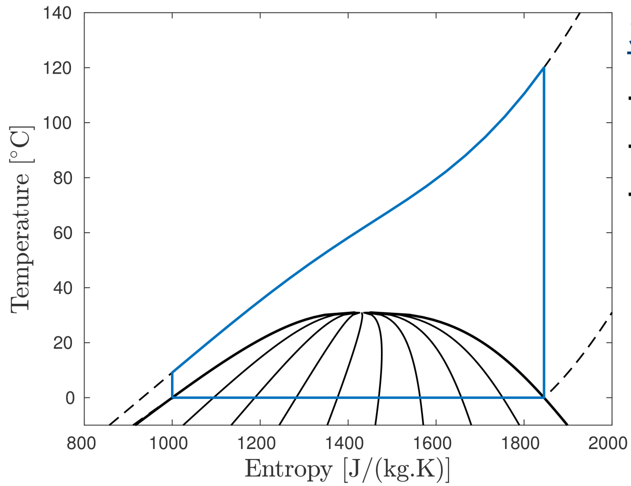


Gas cycle

- Sensible heat storage
- High energy density
- Low work ratio (~2.5)

Different cycles





Supercritical CO_2

- Sensible & latent heat
- Moderate work ratio (~5)
- Low energy density

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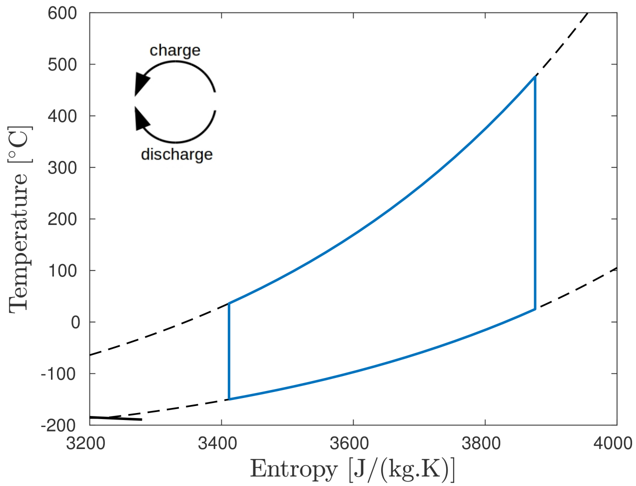

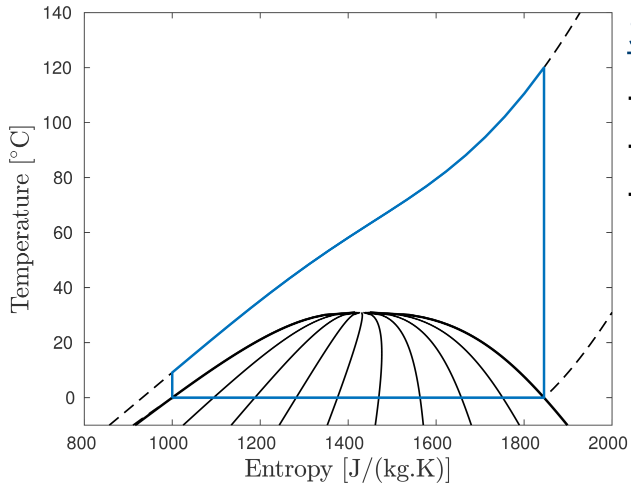

Supercritical CO_2

- Sensible & latent heat
- Moderate work ratio (~5)
- Lower energy density (x1/4)

Gas cycle

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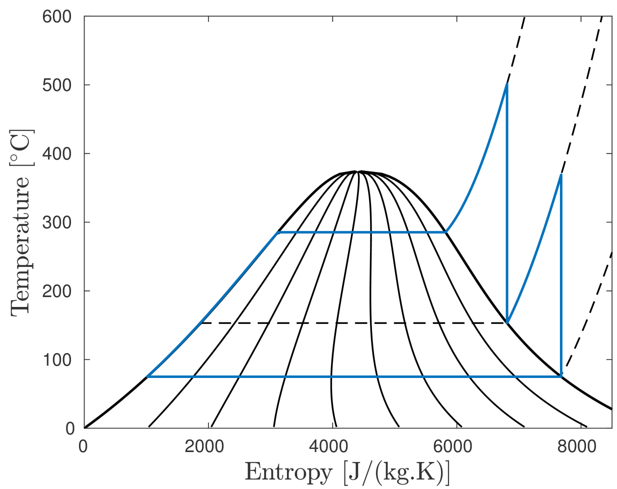
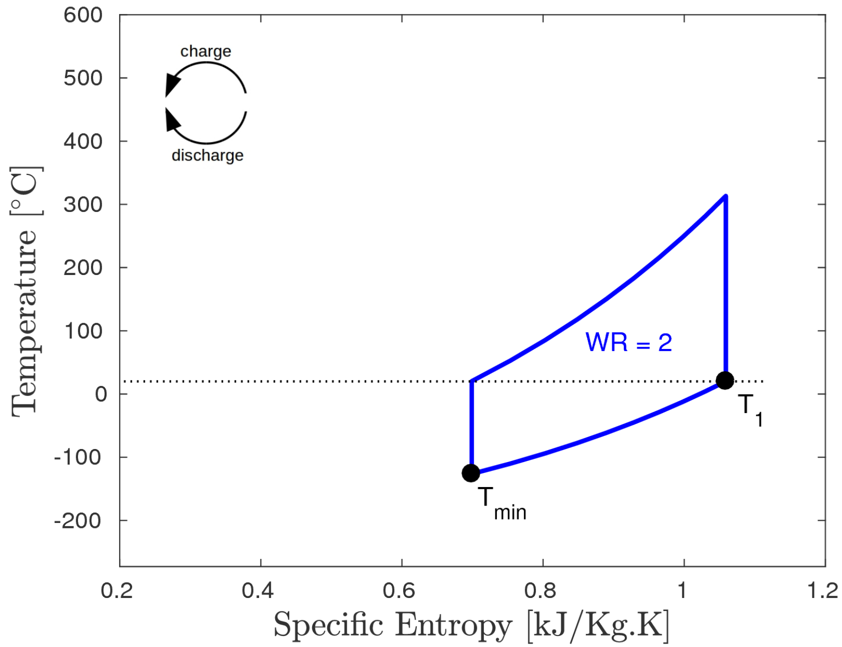


Steam cycle

- Very high work ratio (>100)
- Latent heat exchangers in development stage
- Requires additional Ammonia cycle for charging phase

Thermodynamic strategies



$$\text{Work Ratio} = \frac{\text{Compressor Work}}{\text{Expander Work}} = \frac{T_1}{T_{min}}$$

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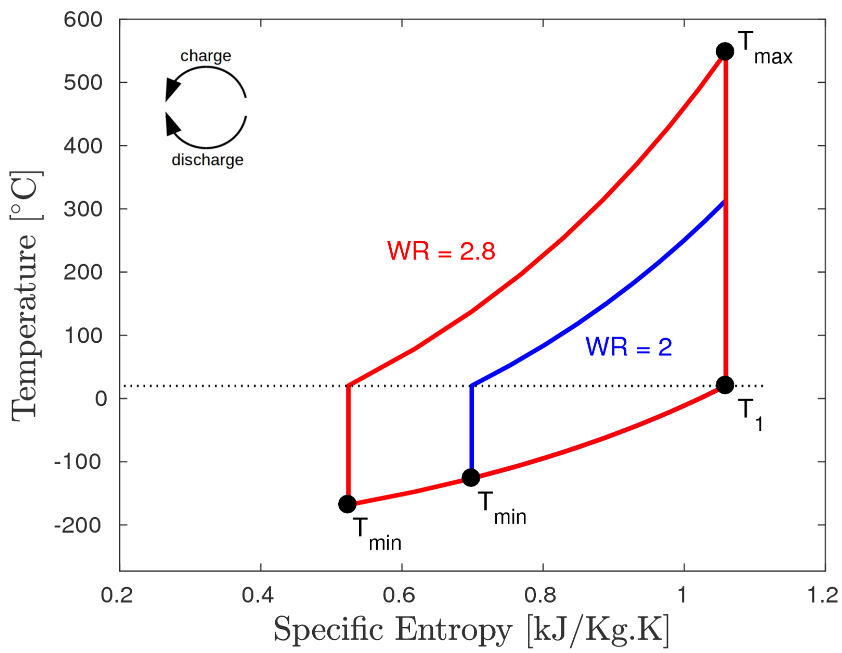
Thermodynamic strategies



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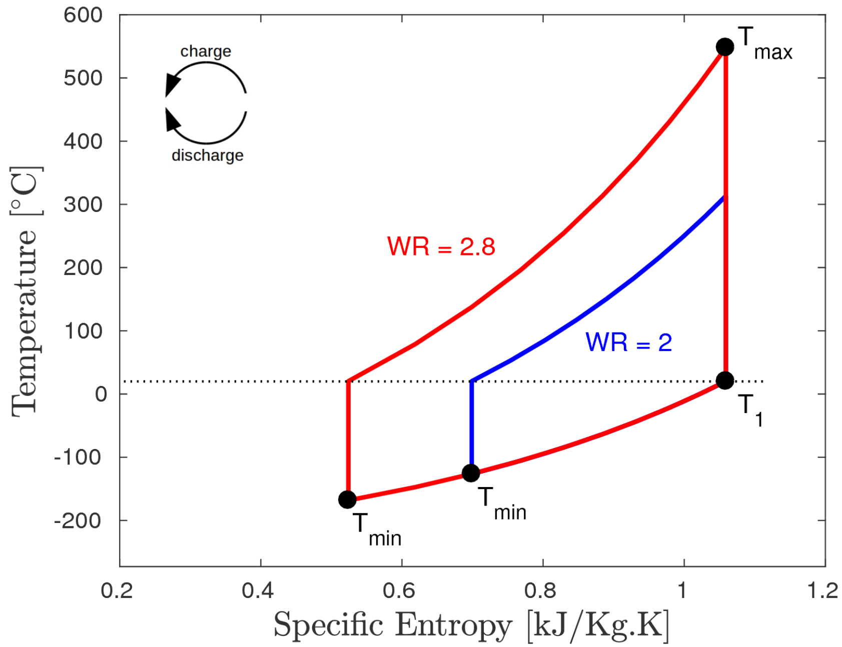
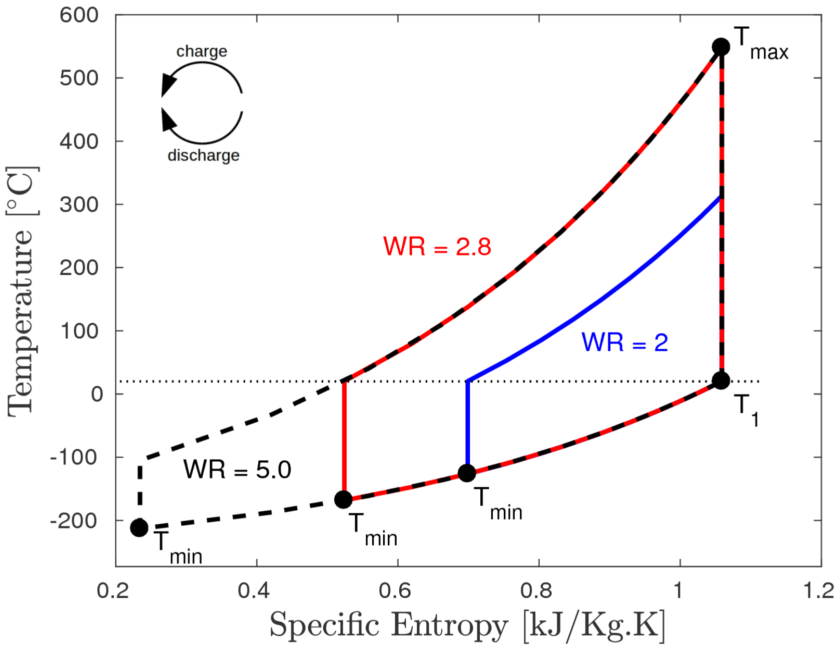


$$\text{Work Ratio} = \frac{\text{Compressor Work}}{\text{Expander Work}} = \frac{T_1}{T_{min}}$$

$$\frac{E}{m} \propto T_1 \left(1 - \frac{1}{\text{WR}}\right)\left(\frac{T_{max}}{T_1} - 1\right)$$

- Increasing the top temperature improves WR (→efficiency) and energy density
- A limit for Tmax exists due to constraints on compressor and energy storage materials (e.g. common molten salts)

Thermodynamic strategies



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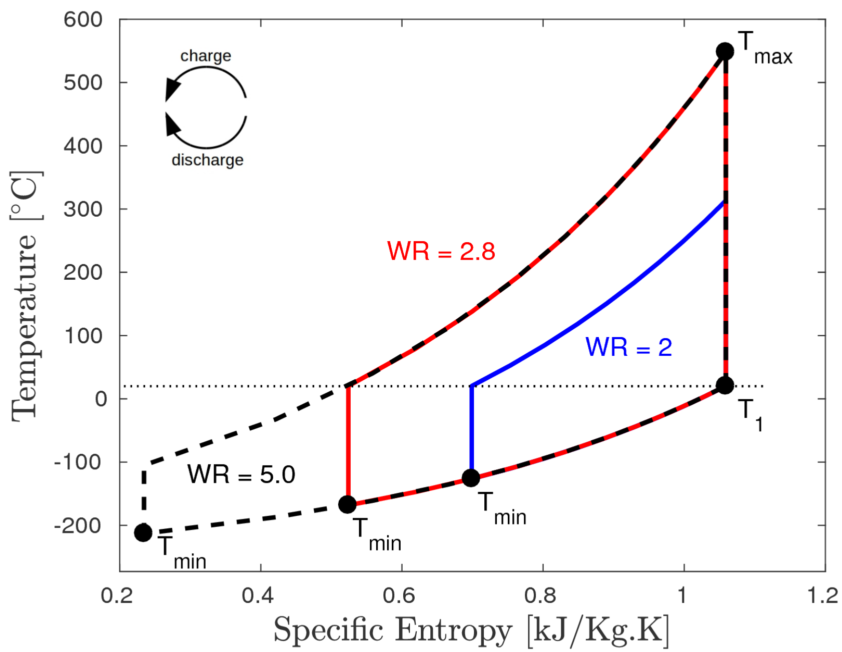
- We can continue to improve WR by lowering Tmin
- To do so, we require to incorporate a gas-gas regenerator:

Thermodynamic strategies



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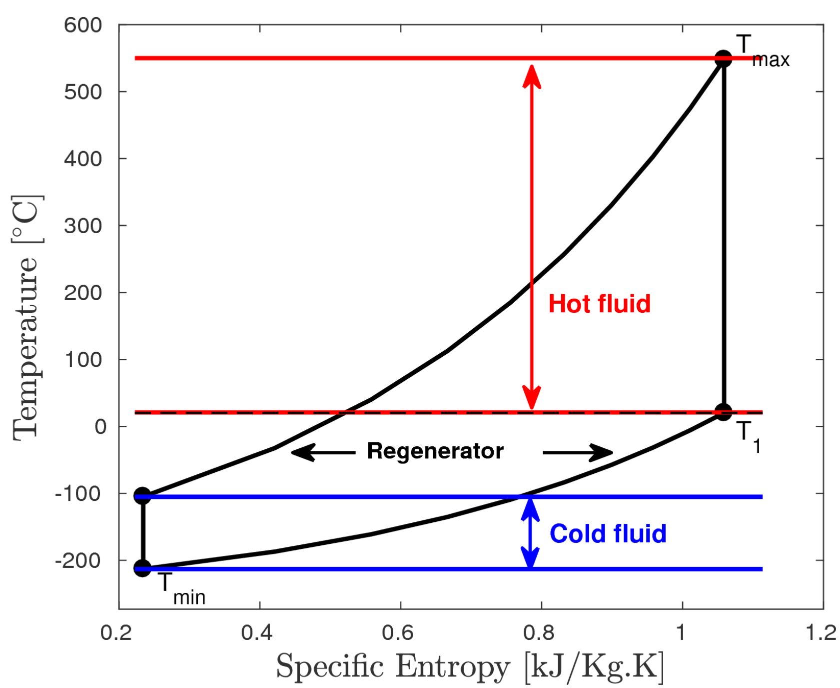

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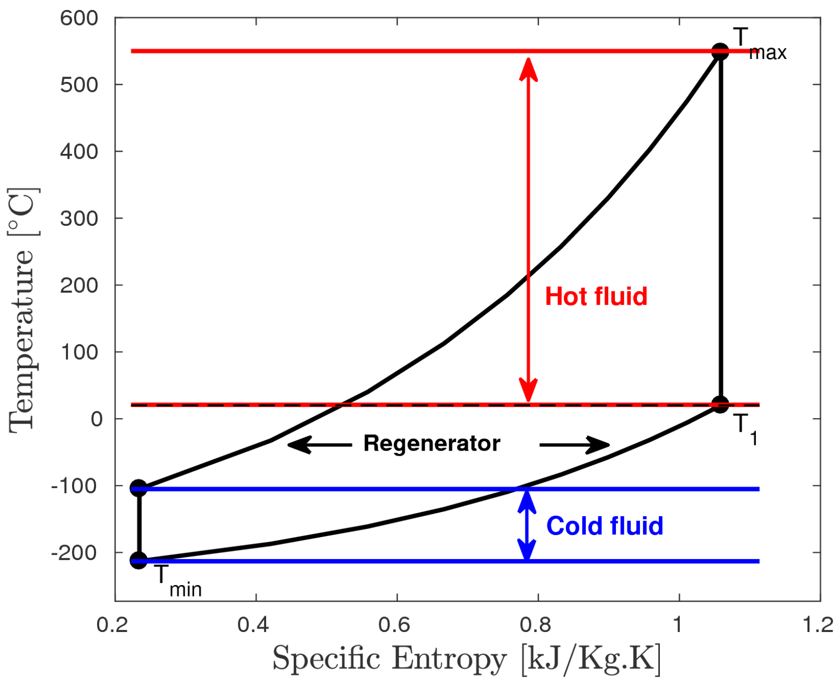

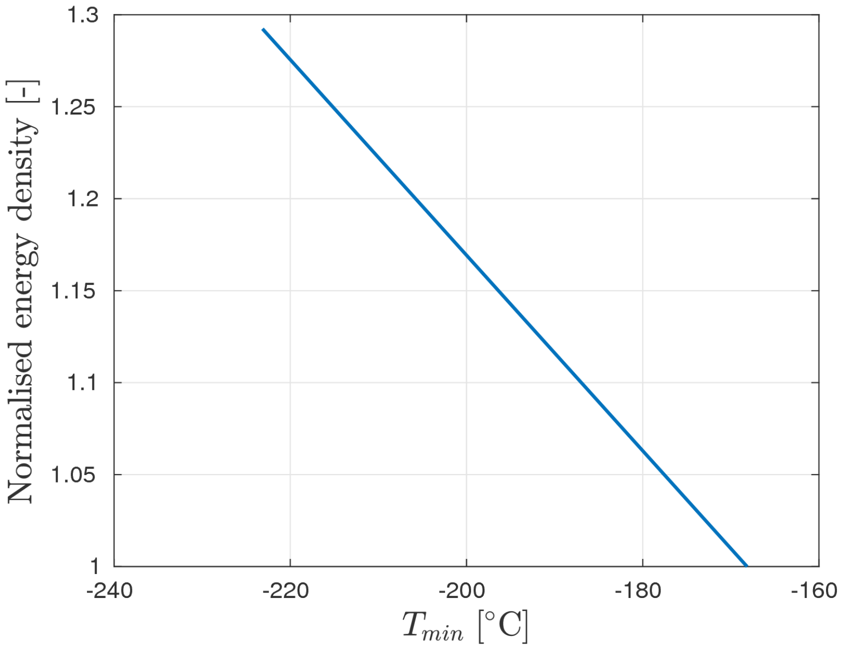

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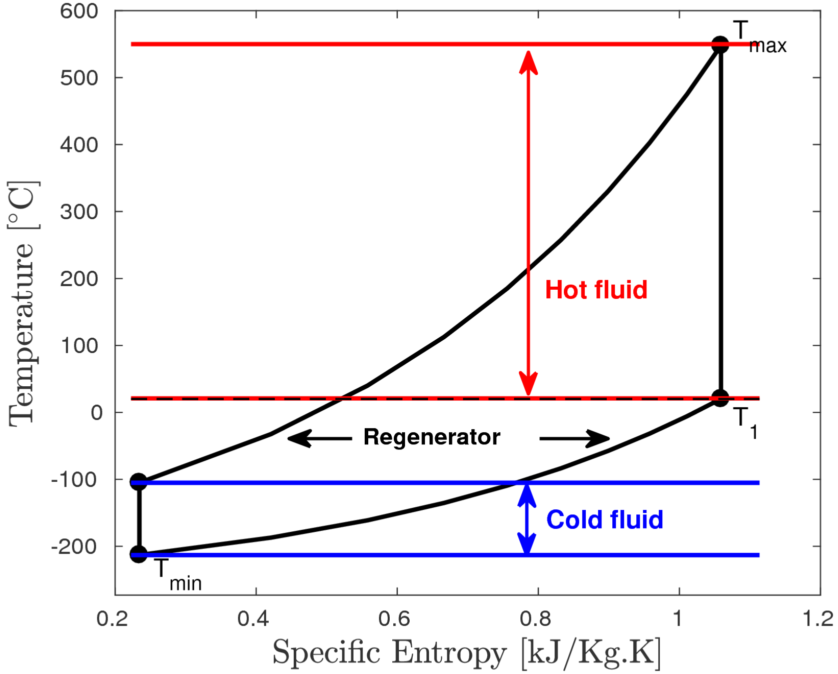
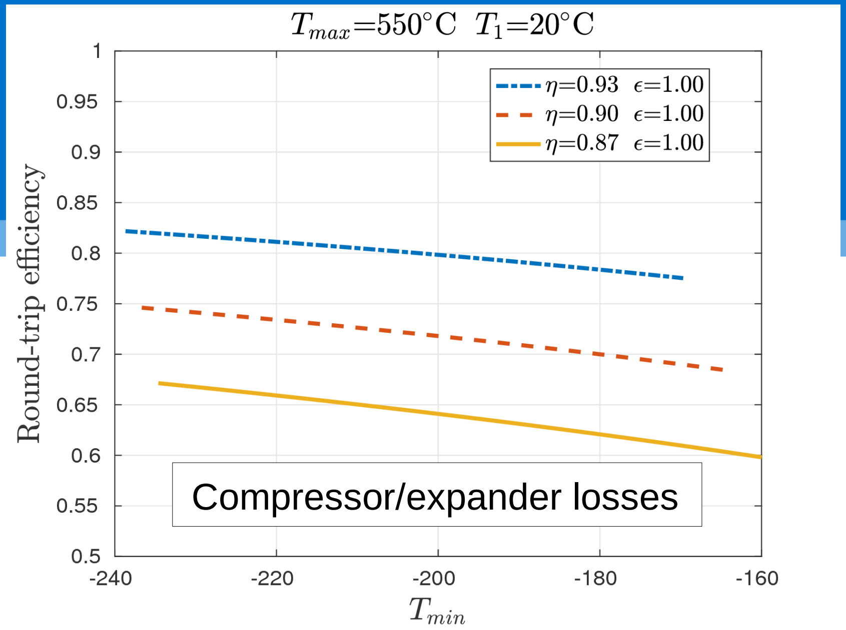
Same trend applies to power density!

Thermodynamic strategies





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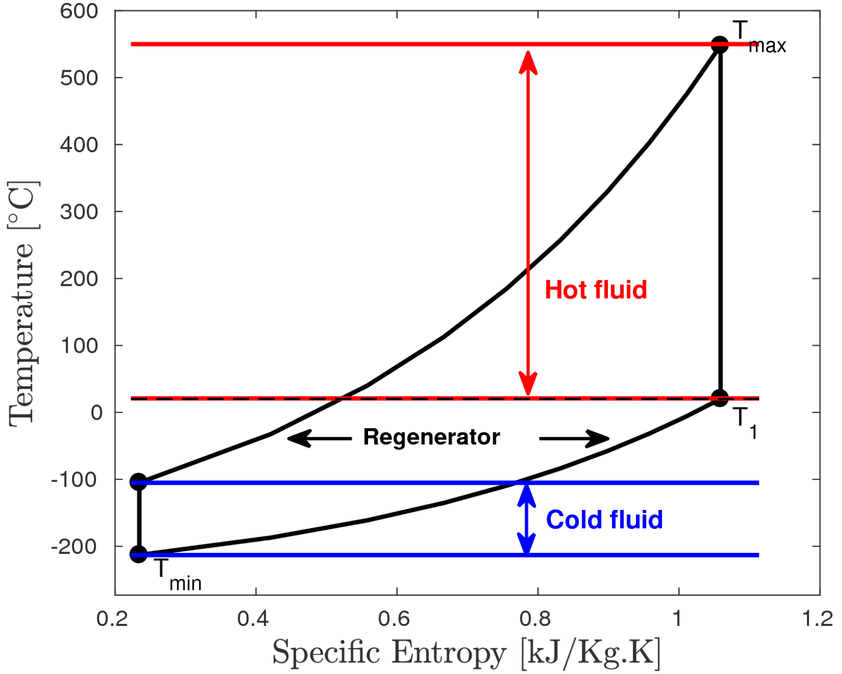
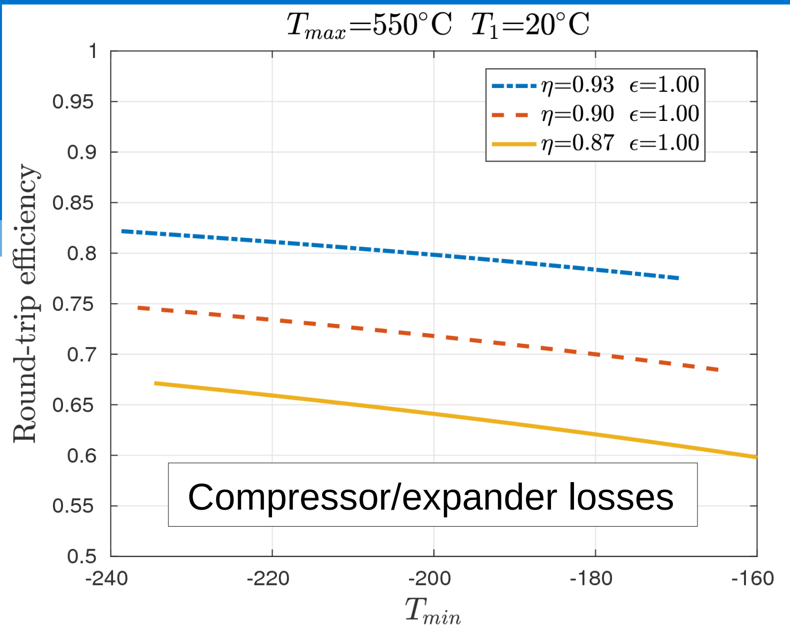
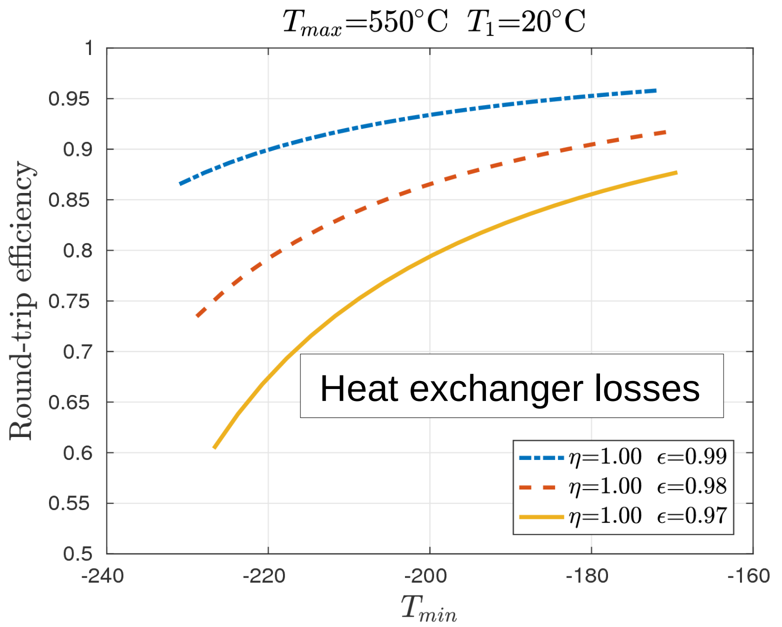
Thermodynamic strategies







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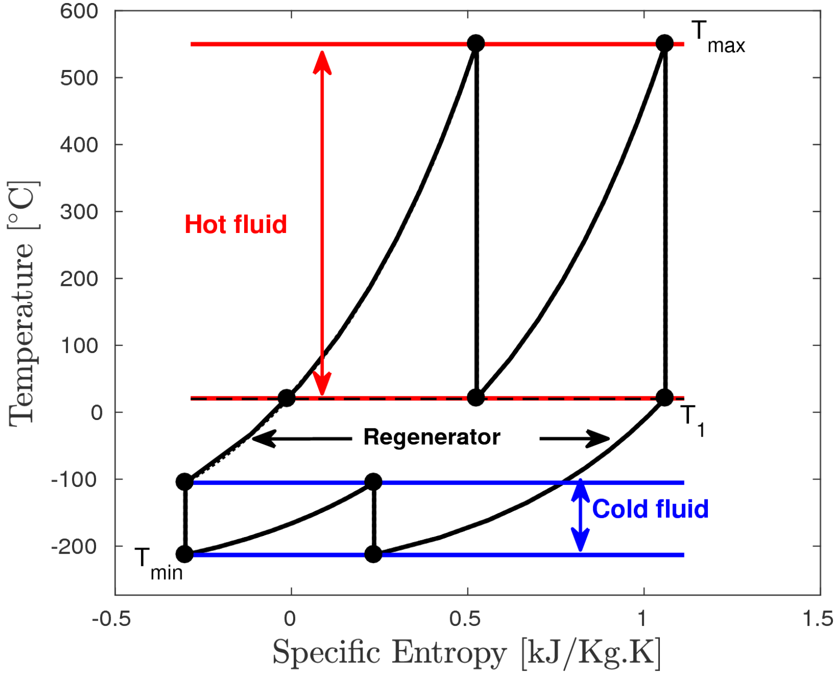
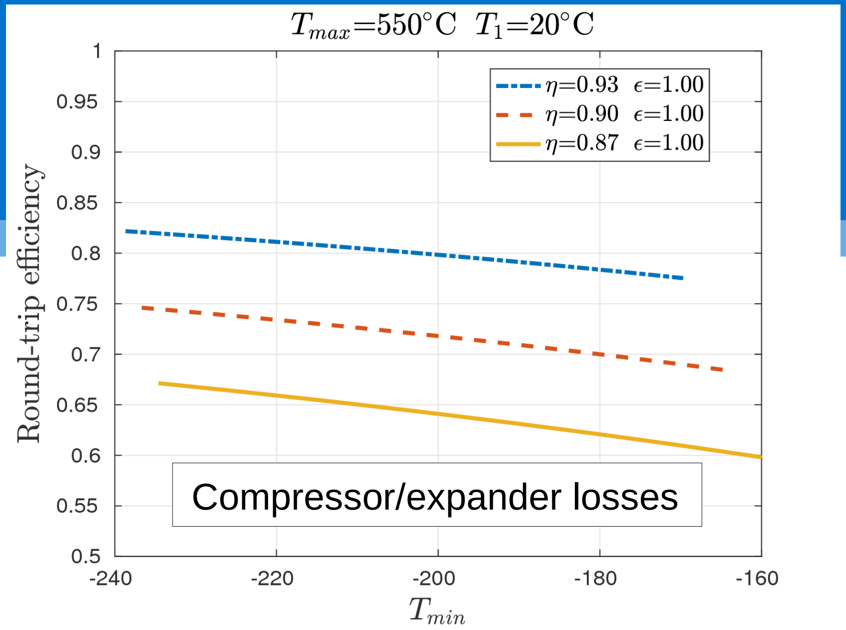
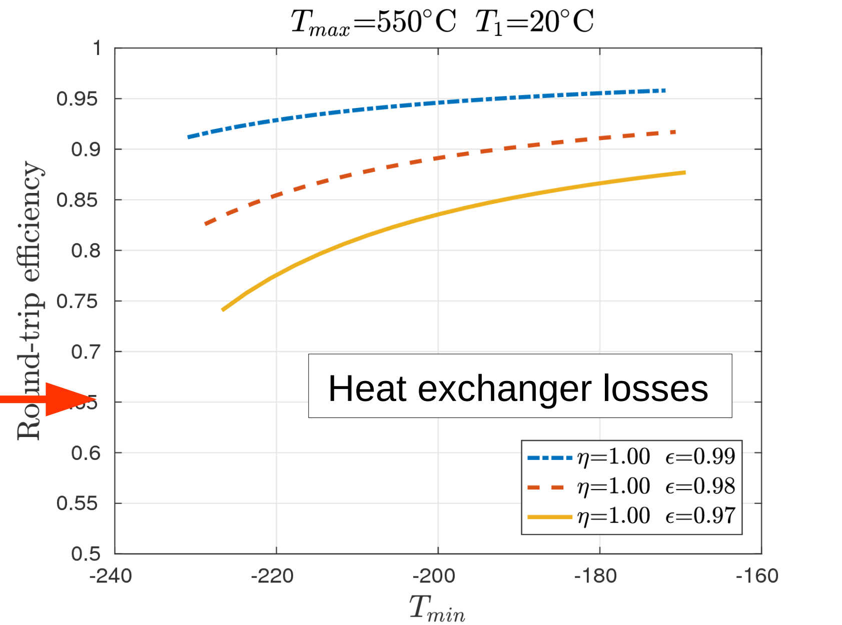


Two compressions





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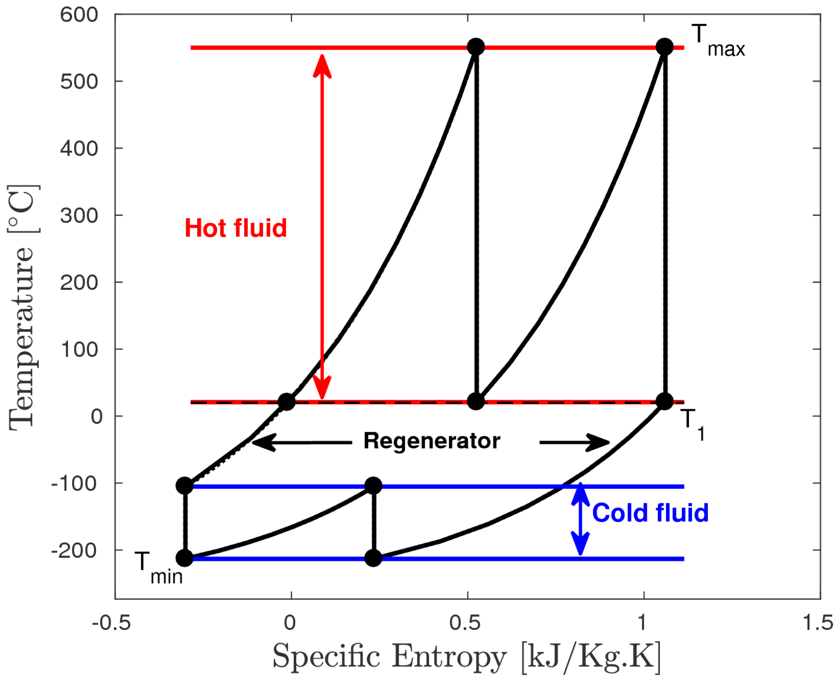
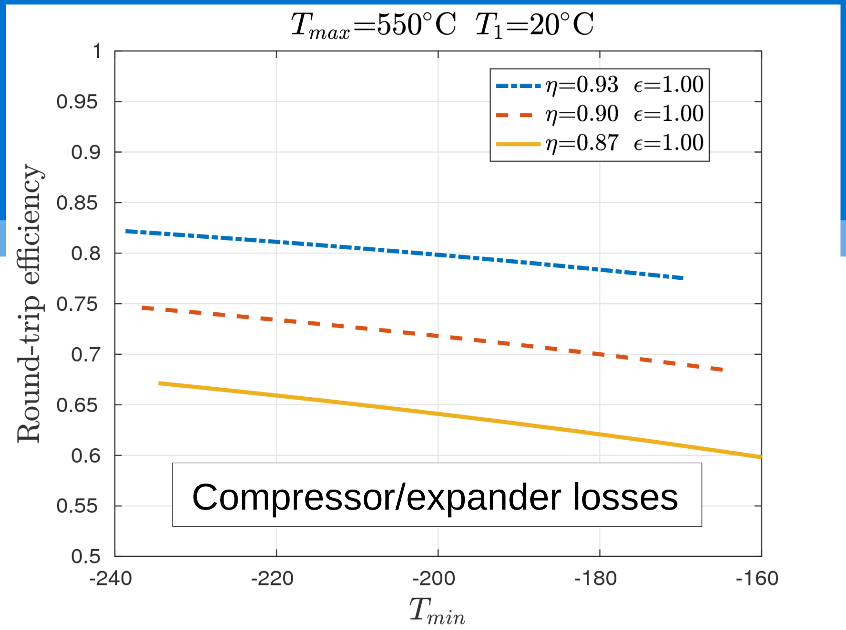
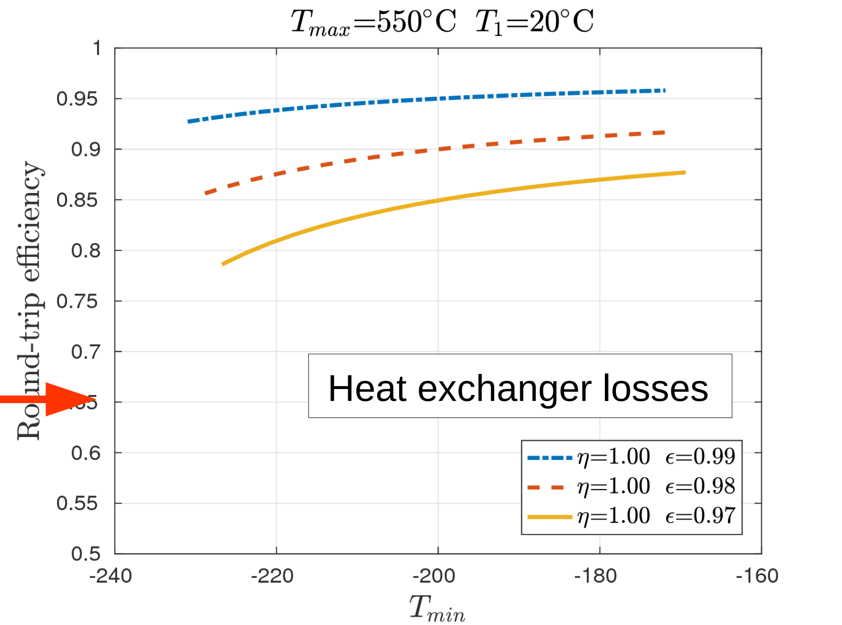
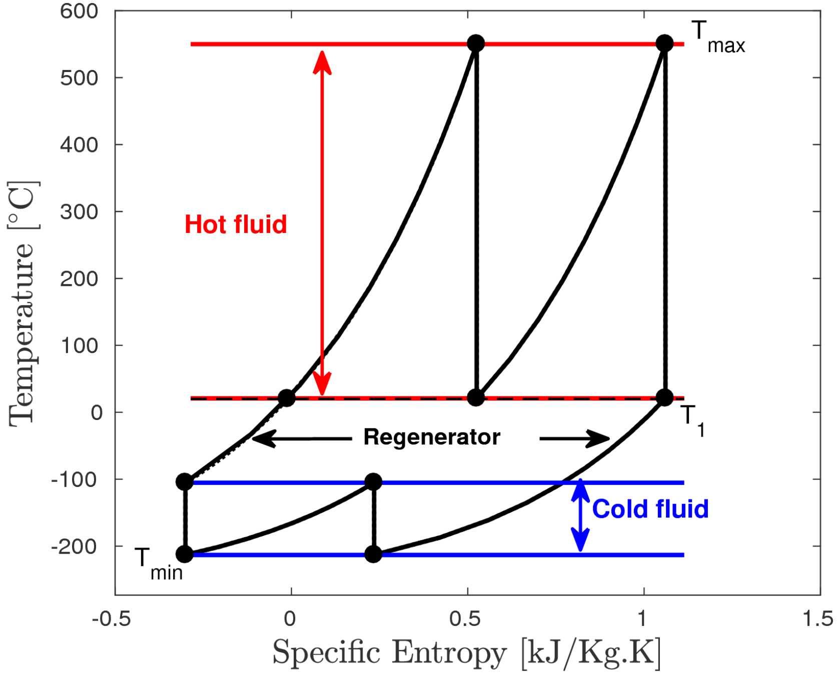


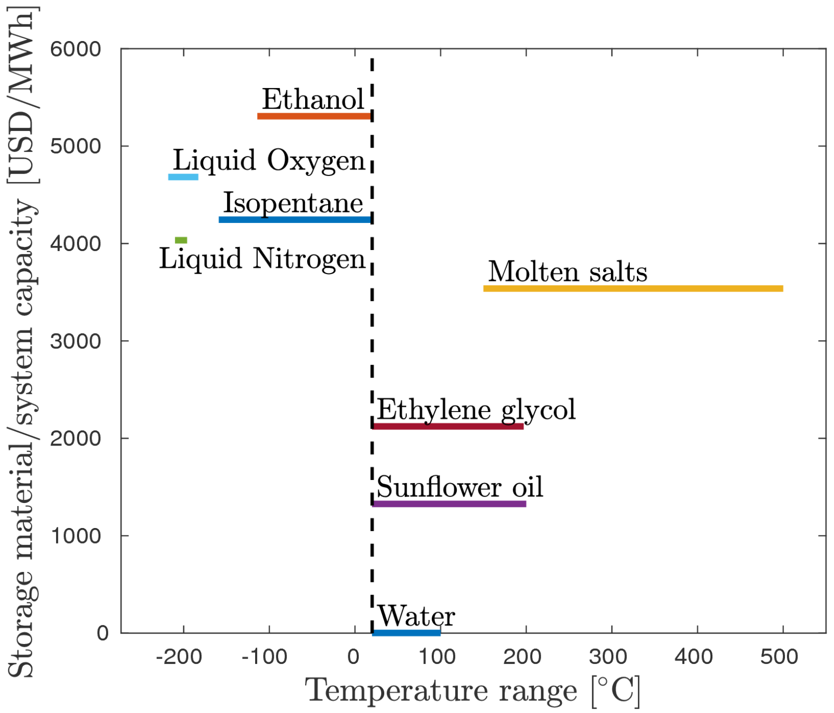




Three compressions

Thermodynamic strategies





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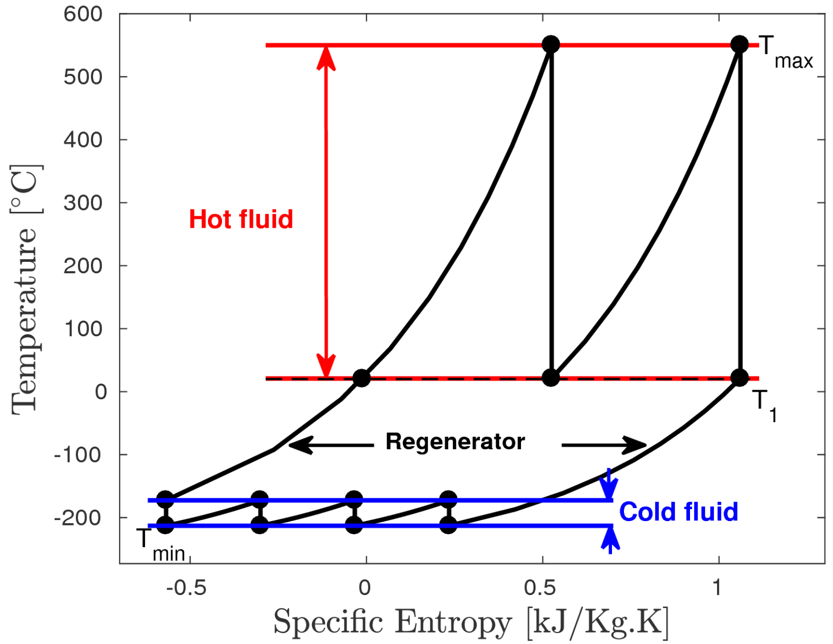

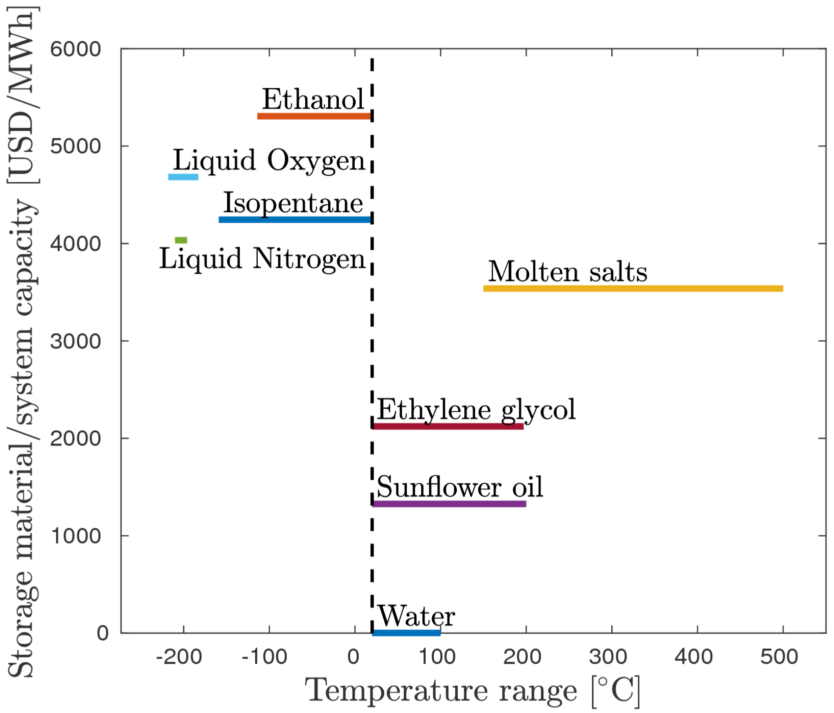

- Additional stages at cold side allow to use O2 and further increase WR

Can we build a HEX with +99% efficiency?

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Bejan (1996):

- Entropy generation is due to thermal resistance and pressure loss: $\dot{S} = \dot{S}_{\Delta T} + \dot{S}_{\Delta p}$
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We can apply the analysis to a counter-flow HEX, flat plate or shell-and-tube:

- $L_1 = L_2$ and $A_1 = A_2$
- Use standard heat transfer and flow-friction correlations
- Find an analytical expression: $\dot{S} = \mathrm{f}\left(A, D_h\right)$

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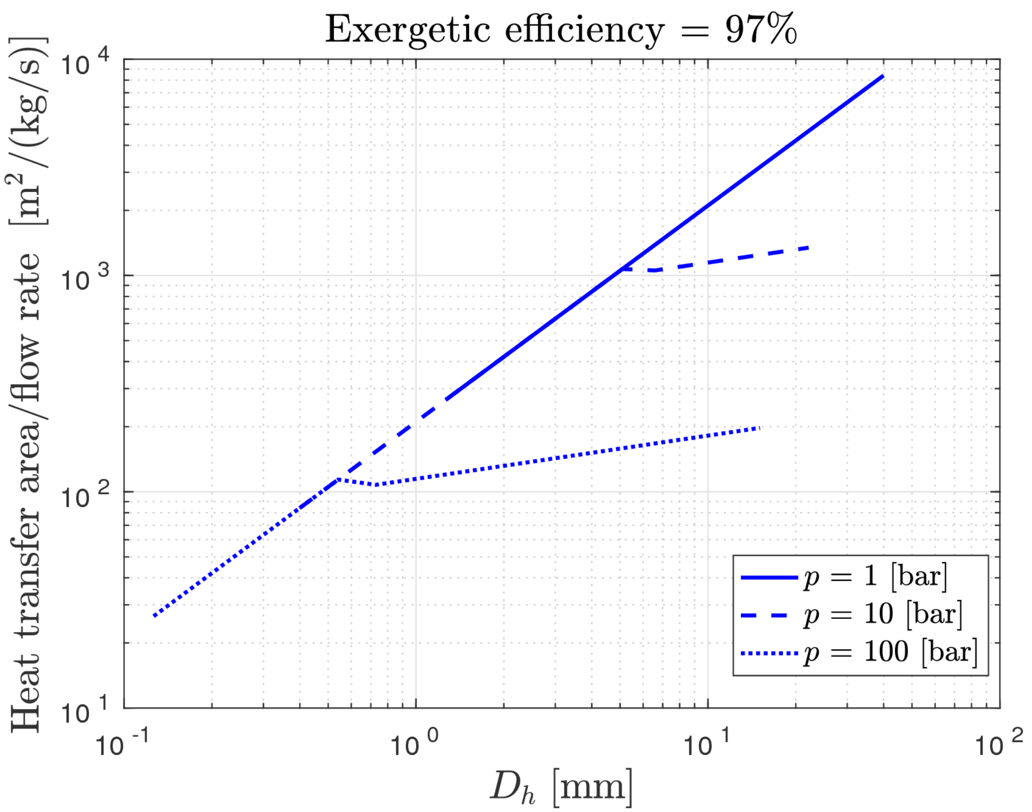

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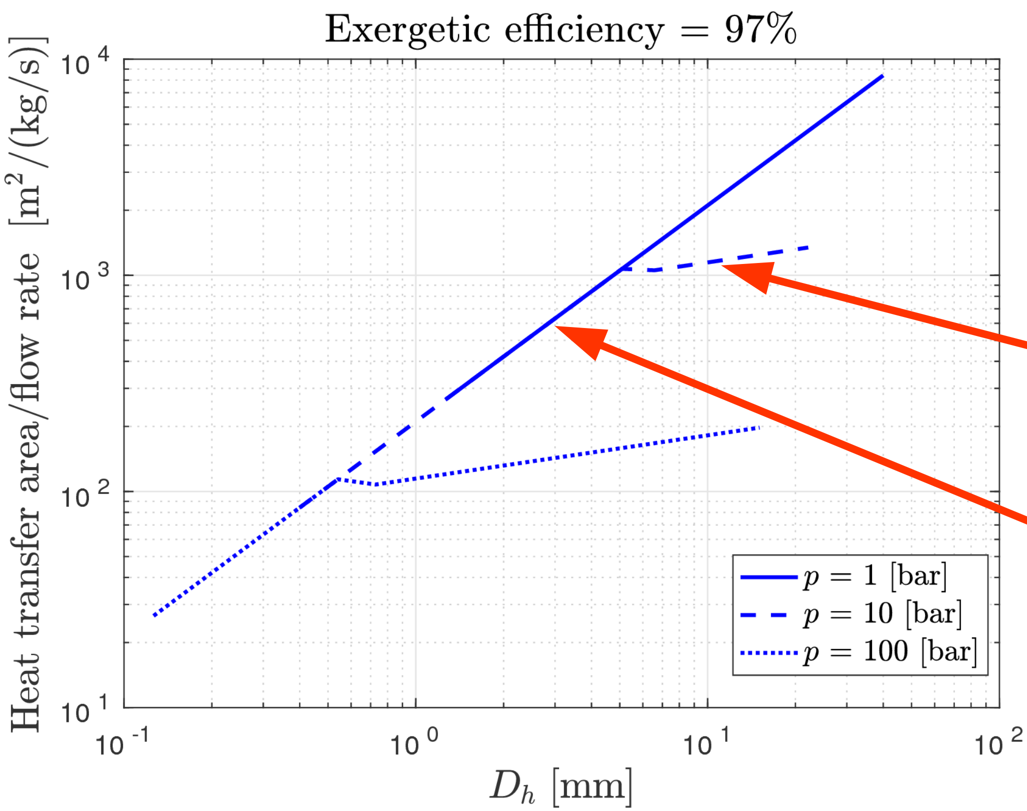

Turbulent regime

Laminar regime:

$$A \propto D_h$$

$$L \propto D_h^2$$

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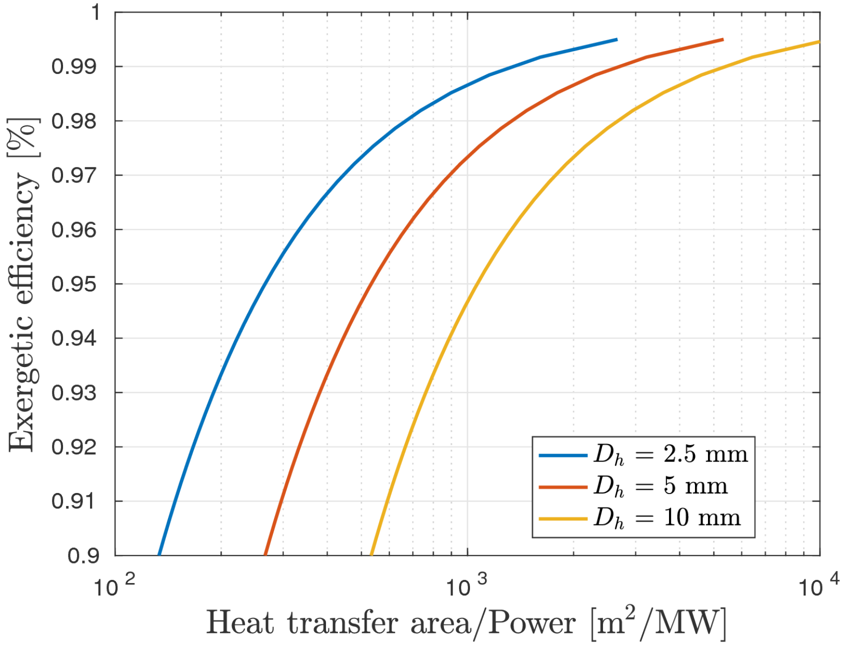

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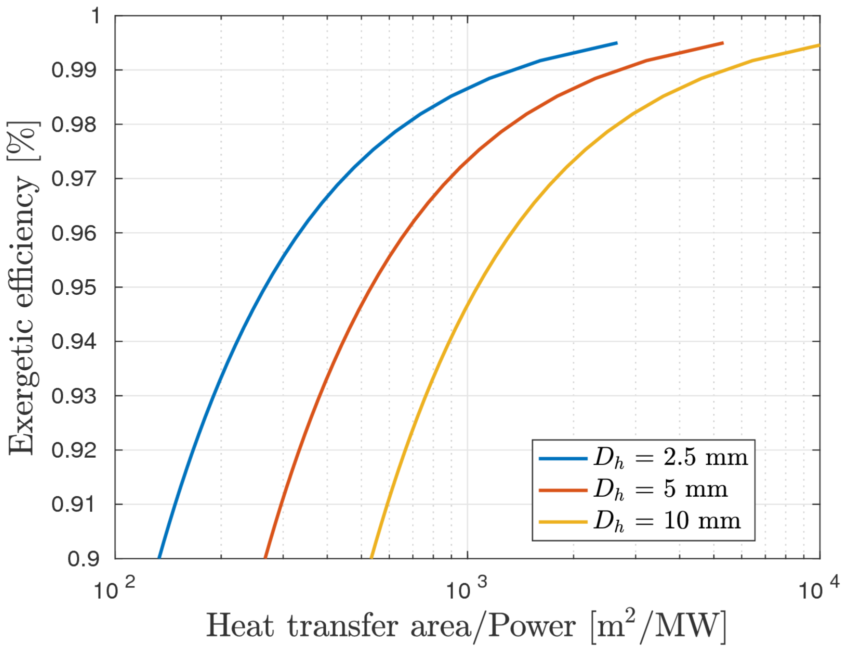

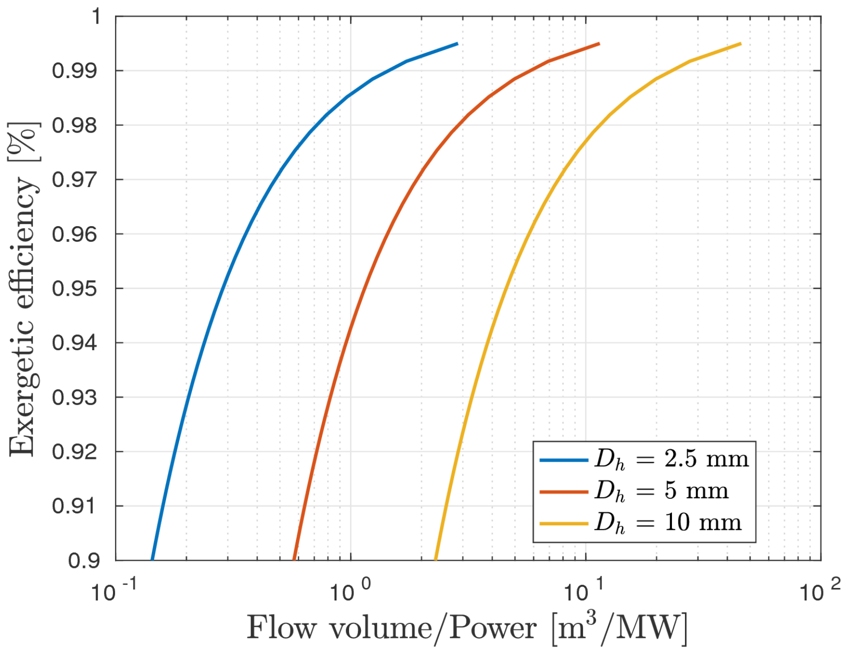

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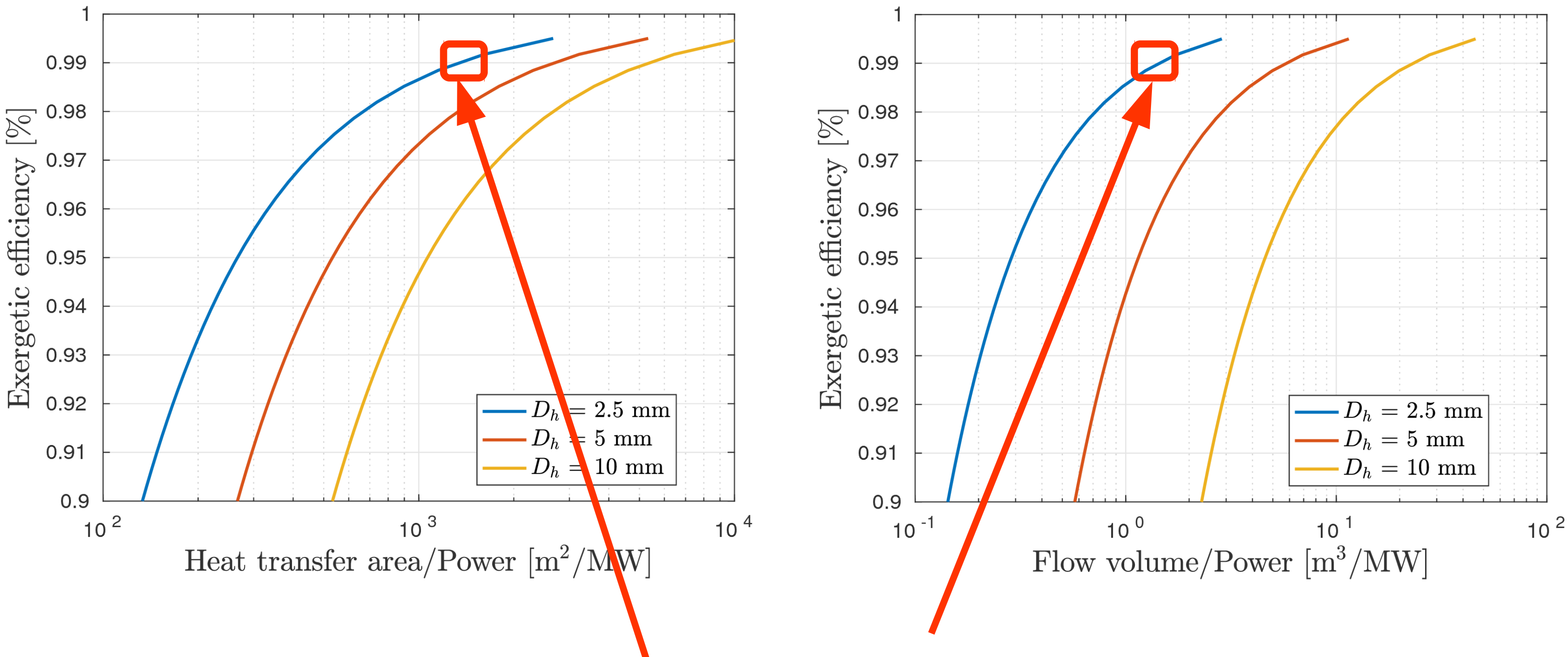

~1000m²/MW and
~1m³/MW at 99% efficiency

Concluding remarks

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  - Have lower self-discharge and a well-defined state-of-charge

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- Several strategies exist to improve Work Ratio

Concluding remarks

- PTES: high energy density and geographical independence
- Using liquid tanks allows to:
  - Pressurise working fluid
  - Have lower self-discharge and a well-defined state-of-charge
- Several strategies exist to improve Work Ratio
- Designing a HEX with ~99% efficiency is key to success

THANKS FOR LISTENING!

QUESTIONS?

Acknowledgements and references

Research Funding:

- Peterhouse, Cambridge

Funding to attend UKES2016:

- Peterhouse, Cambridge
- Cambridge University Engineering Department, Ford of Britain Fund

References:

[1] A.J. White, G. Parks, and C. Markides. Thermodynamic analysis of pumped thermal electricity storage. *Applied Thermal Engineering*, 53(2):291–298, 2013.

[2] Mehmet Mercangöz, Jaroslav Hemrle, Lilian Kaufmann, Andreas Z'Graggen, and Christian Ohler. Electrothermal energy storage with transcritical CO2 cycles. *Energy*, 45(1):407–415, 2012.

[3] W. D. Steinmann. The CHEST (Compressed Heat Energy STorage) concept for facility scale thermo mechanical energy storage. *Energy*, 69:543–552, 2014.

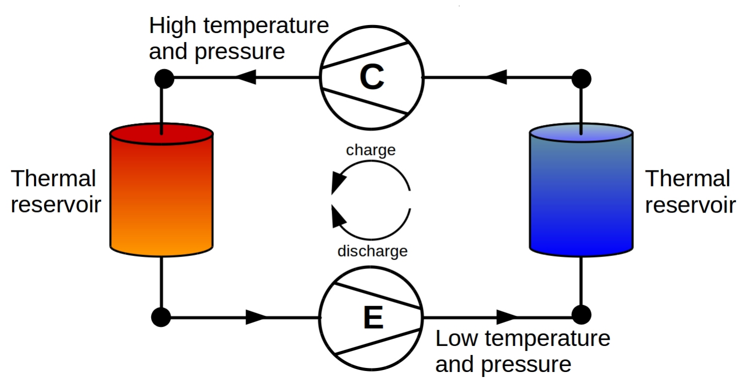
[4] Adrian Bejan. *Entropy Generation Minimization: The method of thermodynamic optimization of finite-size systems and finite-time processes*. CRC Press LLC, New York, 1996.

Extra slides...

What is Pumped Thermal Exergy Storage?

Heat pump — **Storage** — **Heat engine**

Electricity → **Thermal exergy** ↷ **Thermal exergy** → **Electricity**



Literature uses several names…

PTES: Pumped Thermal Energy Storage

PHES: Pumped Heat Electricity Storage

TEES: Thermo-Electrical Energy Storage

CHEST: Compressed Heat Energy Storage

SEPT: Stockage d'Electricité par Pompage Thermique

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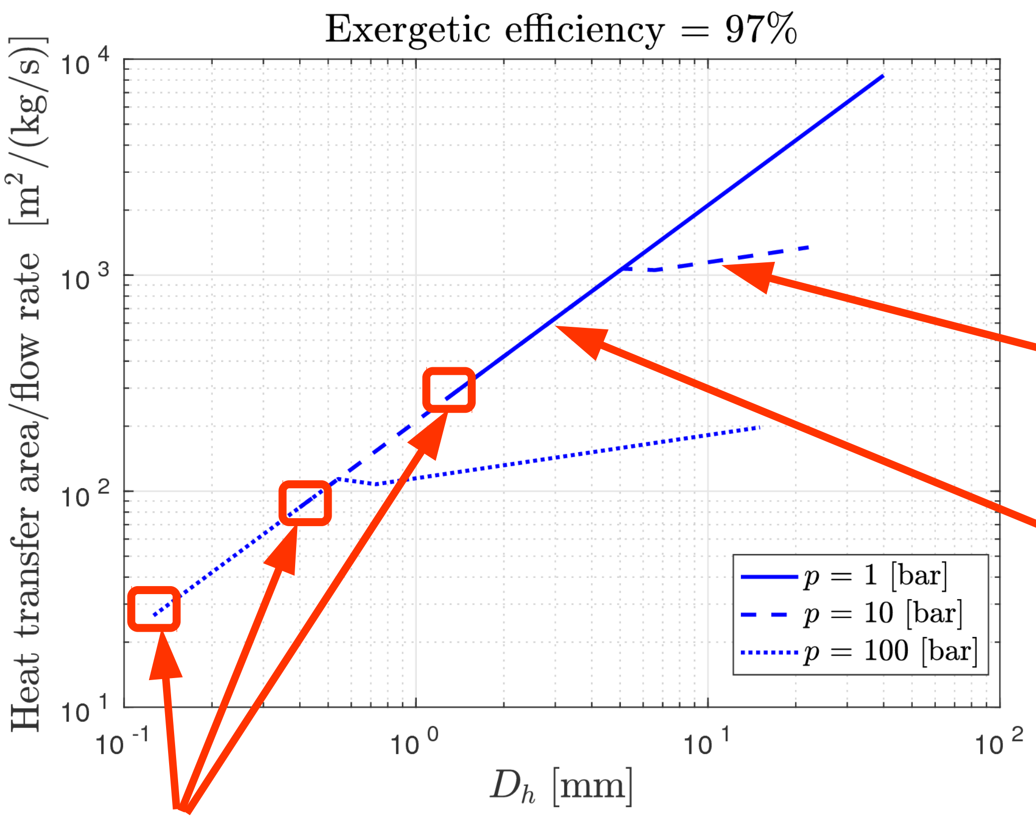

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$$L \propto D_h^2$$

Min. D_h limited by min. practical L

Higher pressures → Higher L and lower D_h