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)
Thermo-mechanical energy storage (TMES)

Compressed air energy storage (CAES)

Liquid air energy storage (LAES)

Pumped thermal exergy storage (PTES)
Thermo-mechanical energy storage (TMES)

Compressed air energy storage (CAES)

High efficiency

Liquid air energy storage (LAES)

Pumped thermal exergy storage (PTES)
Thermo-mechanical energy storage (TMES)

- Compressed air energy storage (CAES)
  - High efficiency

- Liquid air energy storage (LAES)
  - High energy density
  - Geographical independence

- Pumped thermal exergy storage (PTES)
  - High energy density
  - Geographical independence
Solid and liquid storage media
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PTES with solid reservoirs

- Large heat transfer area
- Pressurised hot tank
- Thermal fronts
Solid and liquid storage media

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PTES with liquid reservoirs

- Limited temperature ranges
- Unpressurised tanks
- Tanks at single temperature
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Different cycles
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Gas cycle
- Sensible heat storage
- High energy density
- Low work ratio (~2.5)
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Supercritical CO$_2$
- Sensible & latent heat
- Moderate work ratio (~5)
- Low energy density
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Gas cycle
- Sensible heat storage
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Supercritical CO$_2$
- Sensible & latent heat
- Moderate work ratio (~5)
- Lower energy density (x1/4)

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

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

![Graph showing thermodynamic strategies with specific entropy vs. temperature. The graph includes lines for WR = 2 and WR = 2.8, with points labeled T_min and T_max. The work ratio is defined as Work Ratio = Compressor Work / Expander Work = T_1 / T_min.]
Thermodynamic strategies

- 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)

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

\[ \frac{E}{m} \propto T_1 \left(1 - \frac{1}{WR}\right) \left(\frac{T_{\text{max}}}{T_1} - 1\right) \]
Thermodynamic strategies

We can continue to improve WR by lowering $T_{min}$

To do so, we require to incorporate a gas-gas regenerator:

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Thermodynamic strategies

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Same trend applies to power density!
Thermodynamic strategies

Compressor/expander losses
Thermodynamic strategies

- Compressor/expander losses
- Heat exchanger losses

Graphs showing temperature versus specific entropy for different conditions.
Thermodynamic strategies

Two compressions

Compressor/expander losses

Heat exchanger losses
Thermodynamic strategies

Three compressions

Compressor/expander losses

Heat exchanger losses
Thermodynamic strategies

![Diagram showing thermodynamic strategies with temperature and specific entropy plots.](image)

- **Temperature** [°C]: Graph shows temperature ranges from -200°C to 600°C.
- **Specific Entropy** [kJ/Kg.K]: Graph shows specific entropy values from -0.5 to 1.5.
- **Storage material/system capacity** [USD/MWh]: Graph lists various storage materials with their respective costs: Ethanol, Liquid Oxygen, Isopentane, Liquid Nitrogen, Ethylene glycol, Sunflower oil, Water, Molten salts.

The diagram illustrates the thermodynamic strategies for heat storage and regeneration.
Thermodynamic strategies

- 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: \( \dot{S} = \dot{S}_{\Delta T} + \dot{S}_{\Delta p} \)
- For a given mass flux, exists and optimal \( L/D_h \) that minimises \( \dot{S} \)
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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: \( \dot{S} = f(A, D_h) \)
Can we build a HEX with +99% efficiency?

Exergetic efficiency = 97%

Heat transfer area/flow rate $\left[\text{m}^2/\text{kg/s}\right]$ vs. $D_h$ [mm] for different pressures $p$.

- $p = 1$ [bar] (solid blue line)
- $p = 10$ [bar] (dashed blue line)
- $p = 100$ [bar] (dotted blue line)
Can we build a HEX with +99% efficiency?

Turbulent regime

Laminar regime:

\[ A \propto D_h \]
\[ L \propto D_h^2 \]
Can we build a HEX with +99% efficiency?
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~1000m²/MW and ~1m³/MW at 99% efficiency
Concluding remarks
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  - Pressurise working fluid
  - Have lower self-discharge and a well-defined state-of-charge
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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:


Extra slides...
What is Pumped Thermal Exergy Storage?

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
Can we build a HEX with +99% efficiency?

**Exergetic efficiency = 97%**

- **Turbulent regime**
  - Higher pressures $\rightarrow$ Higher $L$ and lower $D_h$

- **Laminar regime:**
  - $A \propto D_h$
  - $L \propto D_h^2$

Min. $D_h$ limited by min. practical $L$

Higher pressures $\rightarrow$ Higher $L$ and lower $D_h$