Pumped Thermal Energy Storage: Thermodynamics and Economics

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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 CO₂ 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”

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

Sadi Carnot (1796 – 1832)

Maximum Carnot Battery round-trip efficiency = 100%

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

\[
\chi = \frac{W_{\text{out}}}{W_{\text{in}}} = \eta \times \text{COP}
\]

(for a Carnot cycle)

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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

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

PTES with molten salt liquid storage

Consider heat exchanger efficiency:

**Metrics**

Round-trip efficiency:

\[ \eta_{RT} = \frac{W_{out}}{W_{in}} \]

Levelized cost of storage:

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

**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

![Graphs showing roundtrip efficiency and levelized cost of storage for different salts and oils at various compressor inlet temperatures.](image-url)
PTES with molten salt liquid storage

Cost of power 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.

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
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

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

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

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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

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