Pumped Thermal Exergy Storage
Past, Present and Future

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What is Pumped Thermal Exergy Storage?

- The literature uses several names…

- **PHES**: Pumped Heat Electricity Storage
- **TEES**: Thermo-Electrical Energy Storage
- **CHEST**: Compressed Heat Energy Storage
- **SEPT**: Stockage d'Electricité par Pompage Thermique
Possible embodiments of PTES
Possible embodiments of PTES (red = Isentropic’s PHES)

• Storage type:
  - hot / cold / combined
  - sensible heat / latent heat
  - packed bed / liquid tank / other (e.g., concrete)

• Thermodynamic cycle:
  - Rankine / Joule-Brayton / other (e.g., transcritical CO₂)

• Compression & expansion:
  - turbomachinery / reciprocating / other

• Heat exchange:
  - direct (packed bed) / intermediate HX
A (very) brief history of PTES

**1852:** Kelvin’s “Heat Multiplier”
A (very) brief history of PTES

1852: Kelvin’s “Heat Multiplier”

1924: “Thermodynamic” steam-based storage device (Marguerre)

1977: Forerunner of LAES (Smith)

1978: First solely thermal energy storage system (Cahn)

2007: (Oct): Isentropic’s PHES patent

2007: (Jan): PHES patent (Wolf)

Last Thursday: Isentropic’s SVS engine is “turned over”
Whole-system analysis (Strbac et al 2012)

- Savings from distributed storage are greater for a given storage cost
- Benefits are relatively insensitive to storage efficiency
Cost minimisation and endoreversible stuff (Thess, Guo et al)

A crude model of costs:

\[
\text{Total cost} = \text{Engine cost} + \text{Cost of heat exchange} + \text{Storage cost}
\]

\[
C = k_e \dot{W}_e + k_x A_x + k_s \frac{E_s}{\rho_e}
\]

\[
\frac{C}{\dot{W}_e} = k_e + k_x \frac{A_x}{\dot{W}_e} + k_s \frac{t_d}{\eta_e \rho_e}
\]

endoreversible analysis minimises this
A crude model of costs:

Total cost \( C \) = Engine cost \( k_e \dot{W}_e \) + Cost of heat exchange \( k_x A_x \)

\[
\frac{C}{\dot{W}_e} = k_e + k_x \frac{A_x}{\dot{W}_e}
\]

Endoreversible analysis minimises this.

Figure courtesy of Markides.
Endoreversible analysis: maximum power of CHE

Chambadal-Novikov efficiency:
\[ \eta_e^* = \frac{\dot{W}_p}{\dot{Q}_1} = 1 - \sqrt{\frac{T_0}{T_h}} \]

Maximum normalised power:
\[ \psi_e = \frac{\dot{W}_e}{(\alpha_h + \alpha_0)T_0} = \frac{(\sqrt{\frac{T_h}{T_0}} - 1)^2}{4} \]

Occurs at \( T_1 / T_2 = \sqrt{\frac{T_h}{T_0}} \) and \( \alpha_0 = \alpha_h \)
Endoreversible analysis: efficiency for hot storage

Round-trip efficiency:

\[ \chi = \text{COP}_p \times \eta_e = \frac{(k+1)\theta - k}{(k+1)\theta + 1} \]

where: \( \theta = \sqrt{\frac{T_h}{T_0}} \)
Endoreversible analysis: efficiency for hot storage

\[ \dot{Q}_4 = k \dot{Q}_1 \]
\[ \dot{Q}_1 = \alpha_h (T_h - T_1) \]
\[ \dot{Q}_2 = \alpha_0 (T_2 - T_0) \]

Storage temperature, °C

Round-trip efficiency, χ

Temperature ratio, T_s / T_0
Endoreversible analysis: efficiency for cold storage

\[ \dot{Q}_1 = \alpha_0 (T_0 - T_1) \]

\[ \dot{Q}_2 = \alpha_c (T_2 - T_c) \]

\[ \dot{Q}_3 = k \dot{Q}_2 \]
Endoreversible analysis: efficiency vs. power density

Round-trip efficiency, $\chi$

Normalised power output, $\psi_e$

Hot vs. Cold power outputs
Endoreversible analysis: combined hot & cold storage
Exergetic storage density (kWh / m³)

- liquid N₂
- PTES cold
- CAES
- PHS
- PTES hot

Storage temperature, °C
Isentropic’s “SVS” (Scaled Validation Model of PHES)

Hot and cold “layered” thermal stores for a 120 kW system

HOT (500 °C)

COLD (–150 °C)
Efficiency-cost optimisation (packed-bed reservoirs)

Isentropic's layered store concept

GA optimisation for different packed-bed thermal reservoirs (Josh McTigue, 2015)

Open symbols = layered stores

Efficiency (%)

Normalised cost per unit returned energy

R1: Hot (Argon)
R2: Cold (Argon)
Isentropic’s “SVS” : The Engine

- Double-acting “reversible” reciprocating compressor / expander

- HOT side
- COLD side (below gallery)
PTES is sensitive to all loss parameters (low “work ratio”)

\[ \chi = \text{fn} \left( P_i, T_i, \eta_j, \varepsilon_k, f_l \right) \]

- Heat exchange effectiveness
- Polytropic efficiencies
- Pressure loss factors

### Graphs

#### Liquid PTES

- \( \eta = 0.99 \)
- \( \eta = 0.95 \)
- \( \eta = 0.90 \)

#### 2-stage A-CAES

- \( \eta = 0.99 \)
- \( \eta = 0.95 \)
- \( \eta = 0.90 \)
Compression & Expansion Losses: Valve Losses

Early prototype piston / valve arrangement for a heat pump

P-V diagram from an ‘off-the-shelf’ compressor

“Isentropic”’s cunning valve design

P-V diagram from “Isentropic”’s device
Compression & Expansion Losses: Thermodynamic Losses

![Diagram showing isothermal and adiabatic losses for CFD Air and Helium, as well as experimental Helium, with Pe and Loss axes.]
Load-Integrated Energy Storage (LIES)

- Electricity in
- Low-grade heating

- Thermal reservoir
  - High temperature and pressure
  - Charge
  - Discharge

- Thermal reservoir
  - Low temperature and pressure

- Refrigeration and/or cooling

- Electricity out
More LIES

Optimised for work output

Lower discharge pressure
The UK’s Energy Storage Inventory (data from DOE)

- Installed capacity, GW
- PHS
- Mechanical
- Batteries


Values for each year:
- 1963: 0.0
- 1965: 0.5
- 1974: 1.0
- 1984: 2.5
- 2006: 2.0
- 2007: 2.0
- 2008: 2.0
- 2009: 2.0
- 2010: 2.0
- 2011: 2.0
- 2012: 2.0
- 2013: 2.0
- 2014: 2.0
- 2015: 2.0
- 2016: 2.0
PTES has good potential for distributed storage

High power density and efficiency go together for (hot + cold) storage

Possible scope for load integration (cooling / heating)

Low temperature PTES is probably best used for low-grade heat

High compression and expansion efficiencies need to be demonstrated

To reap the benefits of a whole-system approach it’s probably best to have a whole system