Thermal-Mechanical-Chemical Energy Storage Technology Overview

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SwRI is an Applied Research & Development Company

• Founded in 1947, based in San Antonio, Texas
• 501 (c)(3) nonprofit corporation
  • Internal Research
  • New Laboratories
• ~$600M Annual revenue from contract work for industry and government clients
• Over 2,600 employees
• 1,200-acre facility; 2.3 million square feet of laboratories & offices
• Flexible IP policy
• Machinery Department: 70 employees, 5 labs with turbomachinery trains up to 14 MW
Large-Scale Long-Duration Energy Storage is Needed to Enable Deep Renewable Penetration

- Variability, demand mismatch of wind and solar
- Studies show that storage on the order of ~1x daily energy production may be needed\(^1\)
- Storage at renewable plant or baseload plant absorbs ramps/transients
- The storage need for a large city ranges from ~ 25 GWh (4 hours storage in Phoenix) - 840 GWh (daily consumption in Tokyo)

Why Not Batteries?

- Batteries offer low $/MW but high $/MWh for significant durations above 2-6 hours
  - Energy and power both scale by adding cells
- Other concerns:
  - Rare-earth material sourcing (lithium, cobalt)
  - Degradation
  - No viable recycling option
  - Thermal management/runaway
- Other technologies offer promise of decoupling power with low-cost energy storage
Global Energy Storage Timeline

Data and Images from EASE/EERE (2017)
New Long-Duration Energy Storage Technologies are Needed

New Long-Duration Energy Storage Technologies are Needed

• New systems will need:
  • Lower cost than pumped hydro or batteries
  • Higher round-trip efficiency and fewer carbon emissions than gas-fired CAES
  • Longer duration than flywheels
  • Non-specific geology (no mountains or salt caverns)

• Many new system options are based on thermodynamic cycles:
  • Pumped heat energy storage (PHES)
  • Adiabatic or hydrogen-fired CAES
  • Liquid air energy storage (LAES)
  • Thermochemical
    • Hydrogen-based
    • Synthetic natural gas
    • Closed sulfur cycle

Example PHES Image Source: Tom (2019)

Diabatic CAES Image Modified from Kerth (2019)
Mechanical ES: Pumped Hydro

- Potential energy of water using reservoirs at different elevations
- Decades of commercial experience
- Mature turbomachinery
  - Reversible (Francis) pump-turbine
  - Ternary sets
- Technology Gaps/Development
  - Geography-specific concept -> siting limitations
  - High capital cost
  - Modular pumped hydro; subsurface; subsea; open-loop
- Expected Performance
  - 70-85%+ round trip efficiency
  - >40 year life

Data Source: Luo et al (2015)
Mechanical ES: Compressed Air Energy Storage

• Energy stored in large volumes of compressed air; supplemented with heat storage (adiabatic CAES)
• Centrifugal/axial machinery in existing concepts derived from gas turbine, steam turbine, integrally-geared compressor.
• TRL 9 for diabatic; 5-6 for adiabatic CAES
• Two existing plants at Huntorf & McIntosh
• Technology gaps/development
  • Site-specific; requires salt dome
  • Adiabatic CAES: heat exchange, storage concepts; reciprocating isothermal CAES; constant-head CAES; hydraulic compression; subsea CAES
• Expected performance
  • 40-50% for diabatic CAES, ~50-70% for adiabatic CAES

Diabatic (top) and Adiabatic (bottom) CAES

Image Source: Kere (2014)
Mechanical ES: Flywheels

• Store energy as rotating kinetic energy
  • Vacuum environment for loss minimization
• TRL 9, commercially available as UPS
• Technology gaps / development
  • High standby losses; Low power density
  • Improved strength:weight materials; minimize electrical losses; superconducting magnetic bearings
• Expected performance
  • 90-95% round-trip efficiency
  • Nearly infinite cycle lifetime
  • Very short response time

Mechanical ES: Gravitational

- Electricity used for elevation of solid mass
  - Subsurface with wind/hydraulic pump
  - On-surface with rail cars or towers
- High component TRL, including motor/generator and hydro pump/turbine
- System TRL 4-5, demonstrators/pilots funded
- Technology gaps/development
  - Overall system immaturity; Loss minimization
  - Sealing of hydraulic systems; position control
- Claimed Performance:
  - 80-90% Charge/Discharge Efficiency
  - 30-60% cost of pumped hydro
  - 1-10 s response

Image and Data Sources:
https://energyvault.ch/
https://www.gravitricity.com/
https://www.aresnorthamerica.com/grid-scale-energy-storage
https://heindl-energy.com/technical-concept/basic-concept/
Thermal ES: Storage Overview

- Sensible storage raises or lowers temperature of single-phase material
  - Molten salts, thermal oil, water, rocks, concrete, rocks, etc.
- Latent heat storage changes phase, typically liquid-solid transition
  - Ice, Phase change material (PCM)
- Direct (heat transfer and storage with same medium) or indirect systems
- Two-tank or thermocline storage
- Technology gaps/development
  - Corrosion and thermal/cyclic stability
  - Low-cost compact high-performance heat exchangers
  - Molten salts above 565 °C; salt pumps & tanks
  - Particle thermal storage & heat transfer
  - Encapsulated PCMs
  - Low-cost cold storage

Image Source: Shultz (2019)
Thermal ES: Pumped Heat

- Electricity drives heat pump to charge system, creating temperature difference; Heat engine discharges system for electricity out
- Working fluids: Argon, air, sCO₂
- Machinery is conceptually like a gas turbine, but some key differences.
- Two prominent designs
  - Thermoclines and reciprocating machinery: Isentropic UK / Newcastle Univ.
    - Packed bed stores (gravel)
  - Heat exchangers and turbomachinery: Brayton Battery / Malta Inc.
    - Hot store- molten salt
    - Cold store- refrigerant
- Technology gaps / development
  - Heat exchangers, machinery, cycle/system
- Predicted 50-70% RTE
Thermal ES: Liquid Air

- Similar to CAES but different process liquefies air for compact, portable storage
  - Claude cycle for liquefaction with thermal storage
- Utilizes existing technology for nitrogen storage, radial turbomachinery (at pilot scale).
- Technology gaps /development
  - Overall system efficiency and costs via turbomachinery and heat exchanger development; system / cycle variations & maturity
  - Water handling; Large-scale system development (5-50 MW); Synergy with waste heat, flywheels
- Expected Performance
  - 60-70% efficiency and 30-40 year lifespan
  - Storage losses as low as 0.05% by volume per day (Yang, 2006)
Thermochemical ES: Hydrogen

• Use excess grid energy to split water into H2 with electrolysis or reform methane
• Salt dome storage is mature, production and utilization under development.
• Technology gaps and development
  • High cost, low RTE
  • High temperature electrolysis
  • Feedstock availability required
  • High pressure storage – location and safety
  • H2 transport and compression challenges
  • Couple with CSP or other heat source instead of using surplus energy to drive electrolysis
• Expected Performance ~10-30% round trip efficiency, targeting 50%

\[
2H_2O \rightarrow 2H_2 + O_2
\]

Store
- H2 at high pressure
- H2O2, other carriers

Discharge
- Use for electricity/power generation: Hydrogen gas turbine / fuel cell
- Reaction heat release

Sell
- Use for refining
- Use for NG or Ammonia

https://www.turbomachinemag.com/fuel-switching/
Thermochemical ES: Sulfur

- **Principle**
  - Closed sulfur cycle include SO₂ Disproportionation, Sulfur combustion, and sulfuric acid decomposition

- **Turbomachinery Integration**
  - GT and heat exchangers for sulfur

- **Current TRL: 3-5**

- **Technology Gaps**
  - Overall system complexity and integration

- **Expected Performance**
  - High energy density

- **R&D Activities**
  - General Atomics development with CSP
  - Form Energy with ARPA-E DAYS

**Diagram:**
- **Charge**
  - Excess energy/heat for H₂SO₄ Decomp
  - \( 2H₂SO₄ \rightarrow 2H₂O + O₂ + 2SO₂ \)
  - SO₂ Disproportionation
  - \( 2H₂O + 3SO₂ \rightarrow 2H₂SO₄ + S \)

- **Discharge**
  - Sulfur combustion to run a steam turbine

- **Store**
  - Sulfuric Acid
  - \( H₂SO₄ \)

- **Store**
  - Sulfur piles

- **Other Reactions:**
  - \( H₂SO₂ \)
  - \( E \) or \( Q \)
  - \( O₂ \)
Development Needs for Energy Storage: Machinery & HX

• Most new thermodynamic systems are closed or semi-closed cycles requiring:
  • Very high machinery efficiency over a variety of temperatures, pressures, and scales (radial→axial)
  • Low leakage/makeup requirements; consider hermetic machinery
  • High pressures, densities, possibly temperatures
  • PHES: High-temp compressor; single machinery train for charge/discharge mode

• Integration of compression, expansion, and heat exchange functionality into machinery to improve cost and performance

• Hydrogen combustion, compression
  • Emissions, stability/range
  • High tip speeds or many stages

• Fast ramping and wide operating range

• Low-cost compact HX for gas-liquid and with fast transient capability
Development Needs for Energy Storage: Systems

- Control & operation experience of closed or semi-closed cycles
  - Inventory control for turndown; ambient conditions
  - Leakage management / recovery
  - Trip & settle-out scenarios
  - Charge/discharge mode system balancing

- Detailed plant design & cost optimization

- Integration/optimization with numerous generators and applications
  - Coal, Gas, Nuclear, Concentrating Solar, Waste Heat, Combined Heat & Power, Geothermal
  - Sector coupling with heating, cooling applications
  - Existing Brayton/Rankine cycles, advanced power cycles
  - Storage for time-shifting CCS

CSP Integrated with PHES (Image Source: U.S. DOE)
Current SwRI R&D – Pumped Thermal Energy Storage Demo

- Project funded by DOE/ARPA-E; Partnered with Malta, Inc.
- Advance PHES from concept to a kW-scale system demonstration in 27 months
  - Focus on system operation and integration
  - Evaluate control strategies for system startup, shutdown, and mode change
  - Gather performance data to verify system model (10 MWe, 10 hrs at rated power)

Charge Mode: Heat Pump
Discharge Mode: Heat Engine
Questions?

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References


