Thermal-Mechanical-Chemical Energy Storage Technology Overview

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TMCES Workshop

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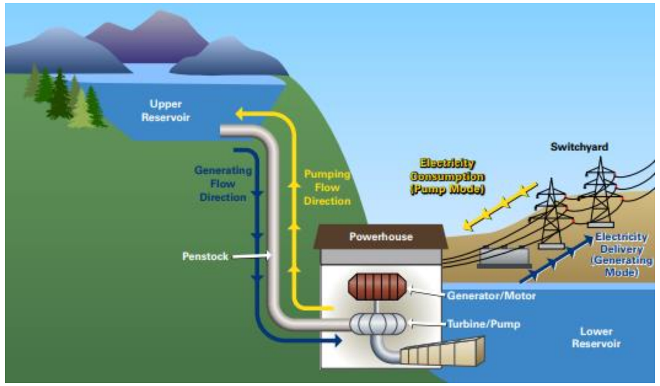
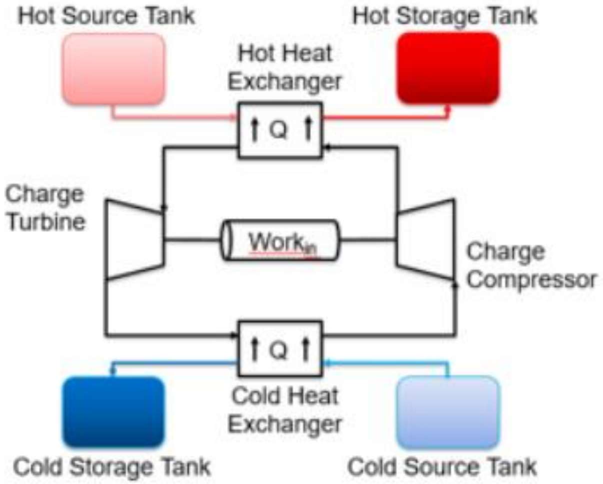
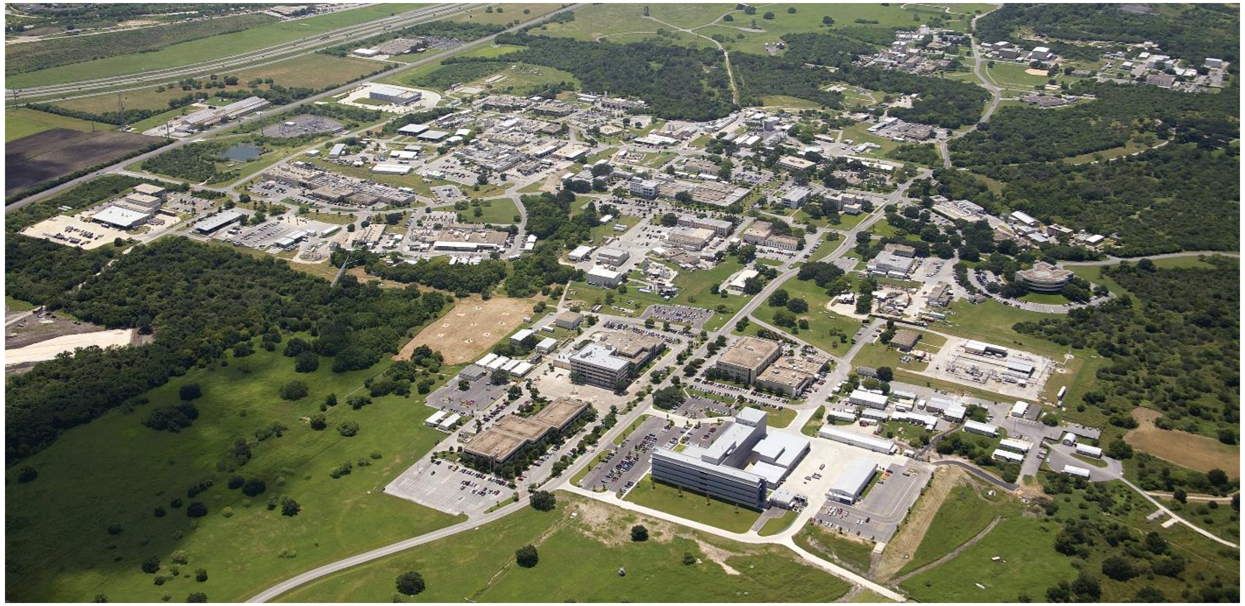
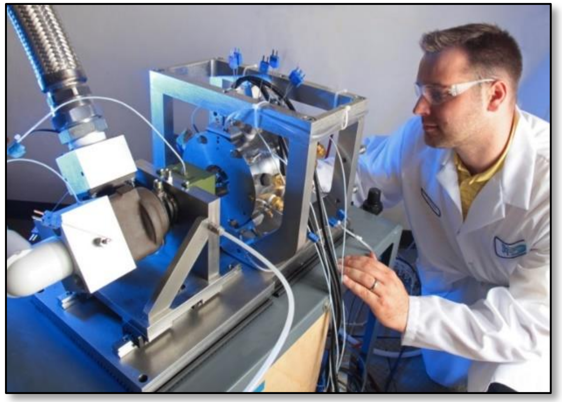


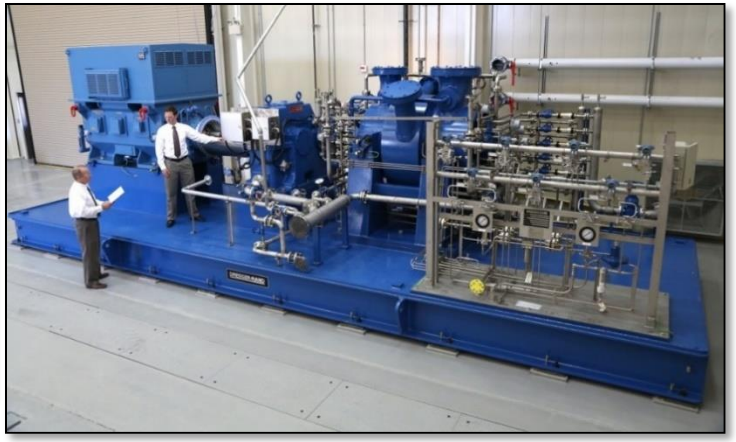


SwRI is an Applied Research & Development Company

- 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)

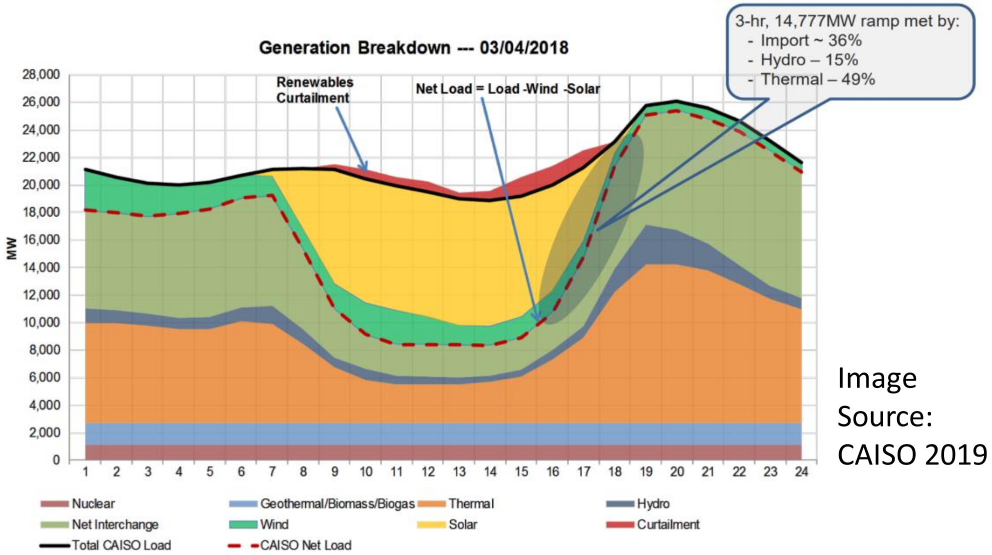


Image Source: CAISO 2019

1-35 of the world's largest pumped hydro system…

…or 23-763 of these molten salt tanks

[1]Solomon, A.A. *et al*, 2017.

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)[2]
  - Degradation[3]
  - No viable recycling option[4]
  - Thermal management/runaway[5]
- Other technologies offer promise of decoupling power with low-cost energy storage

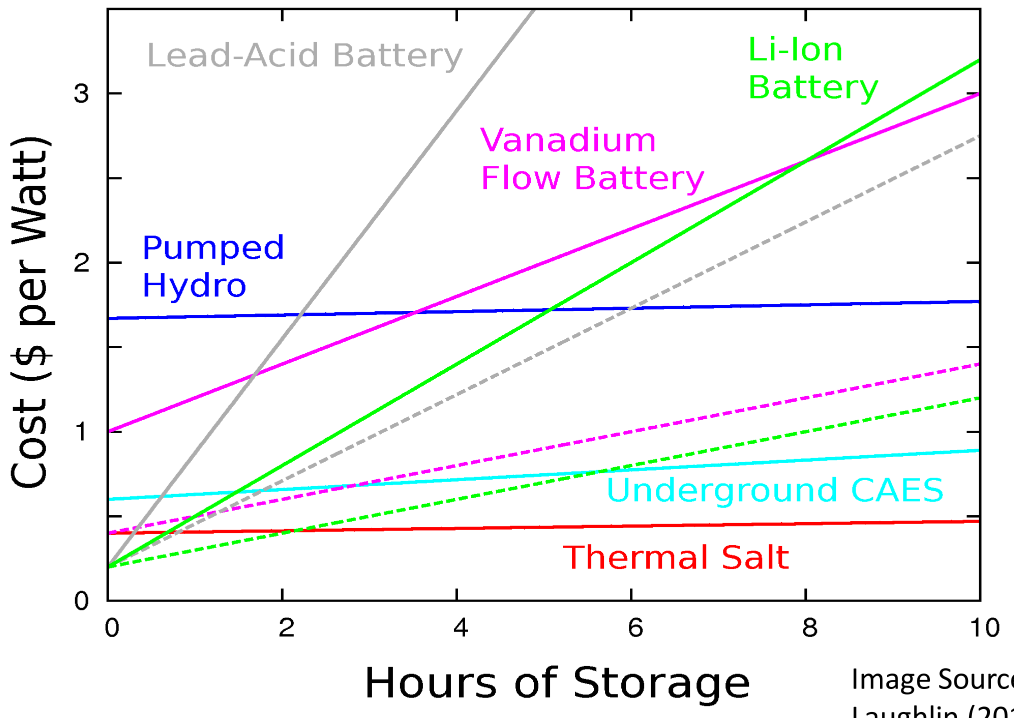
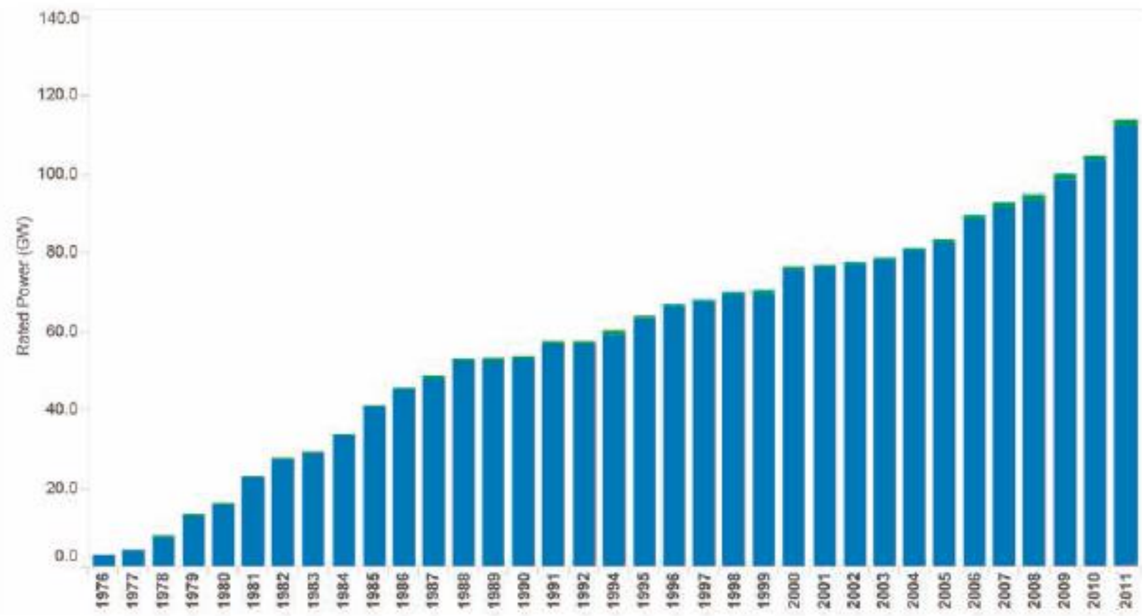


Image Source: Laughlin (2019)

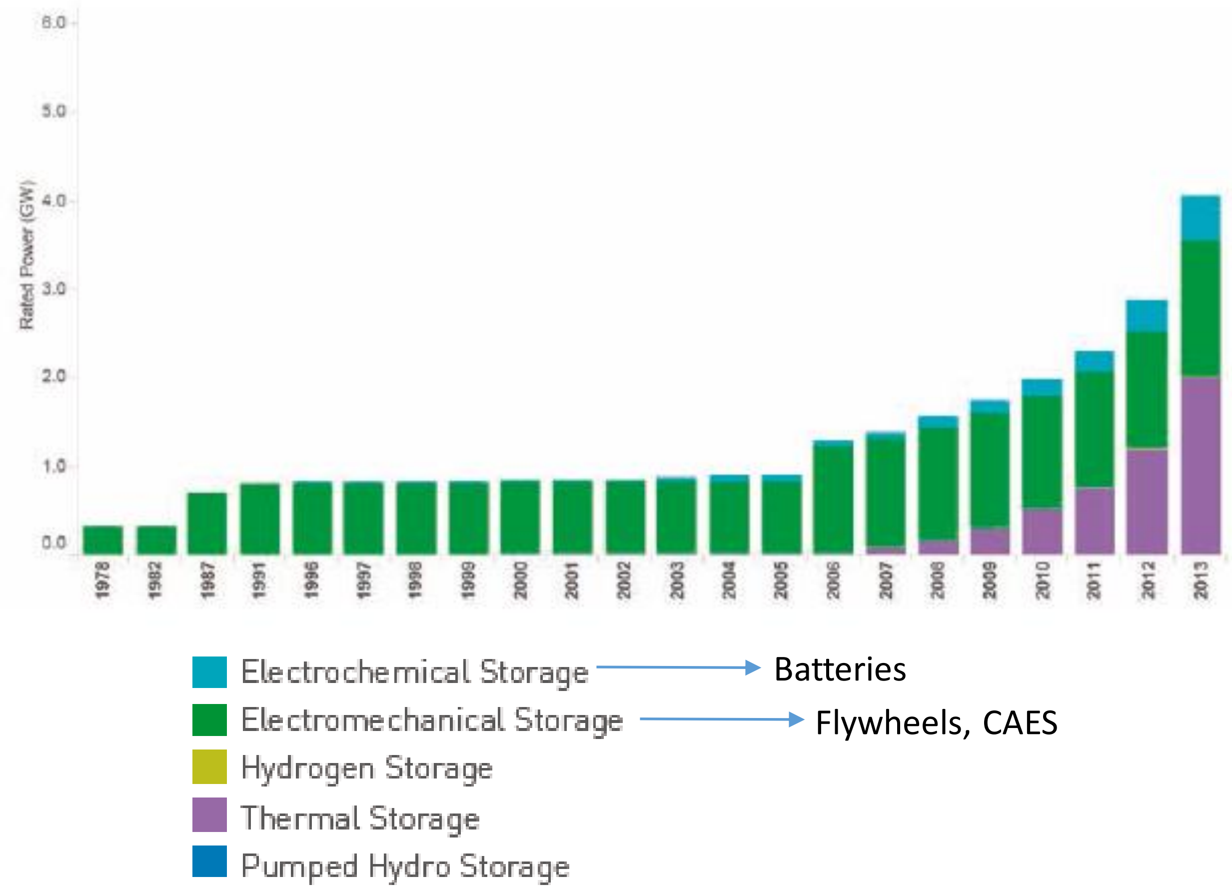
Image Source: S&P Global (2019)

Global Energy Storage Timeline

Global Energy Storage Project Installations

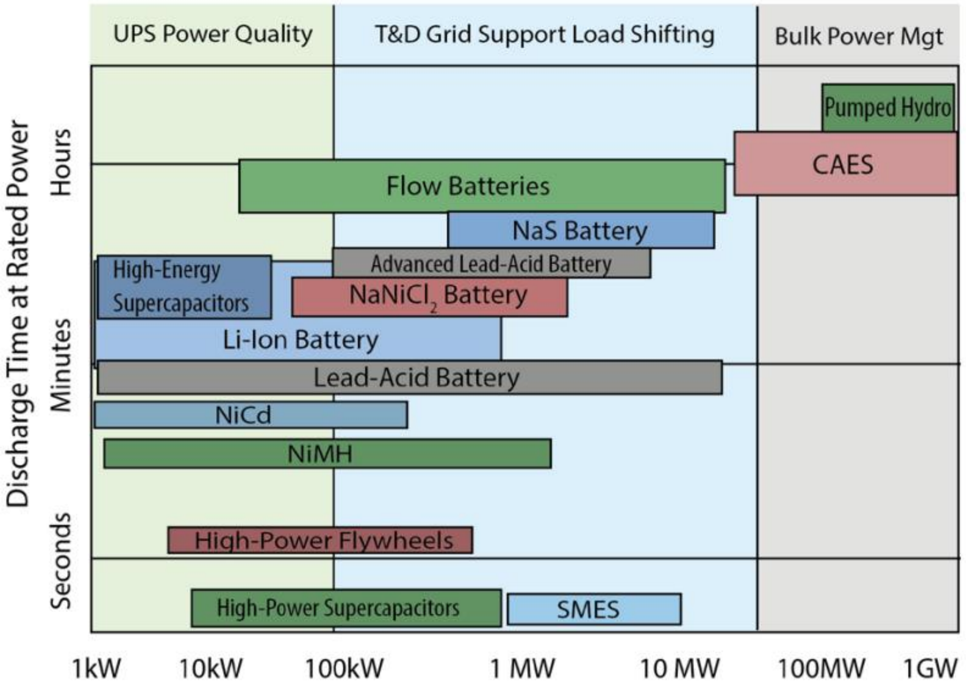


Global Energy Storage Project Installations – excluding PHS

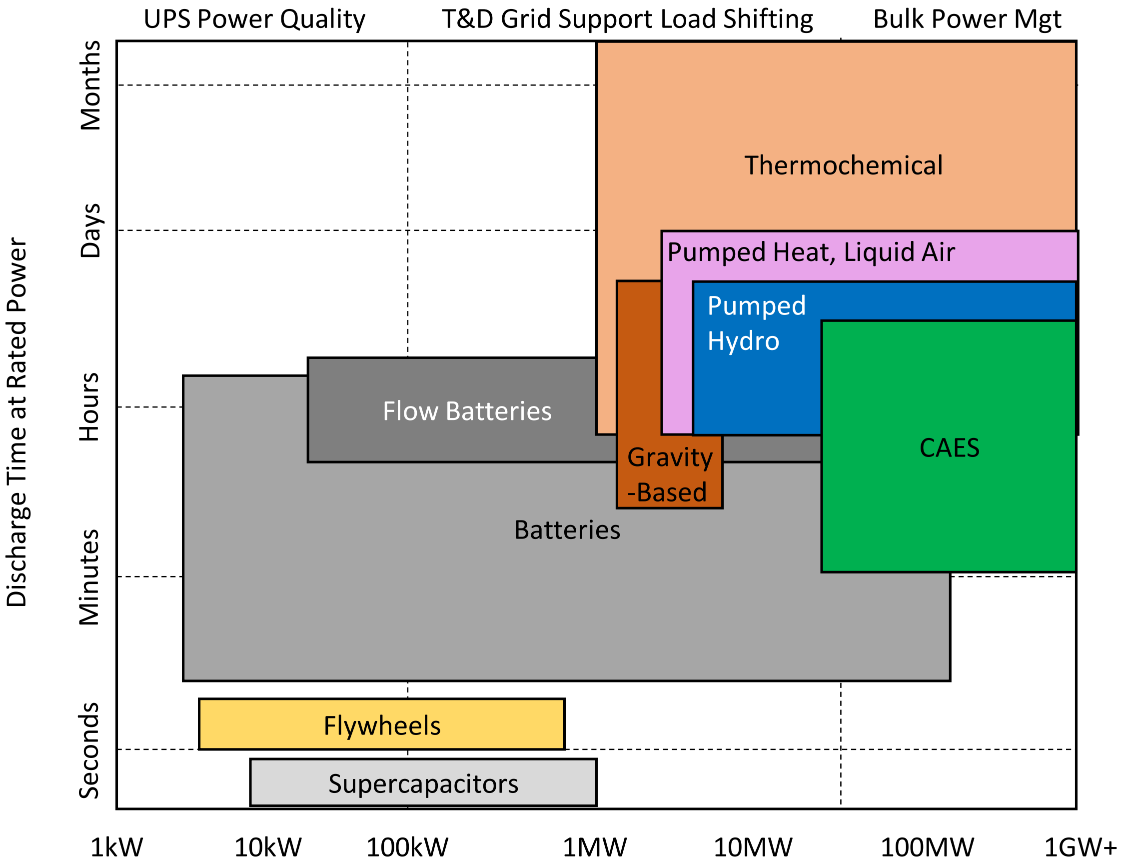


Data and Images from EASE/EERE (2017)

New Long-Duration Energy Storage Technologies are Needed



http://css.umich.edu/sites/default/files/U.S._Grid_Energy_Storage_Factsheet_CSS15-17_e2018.pdf



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

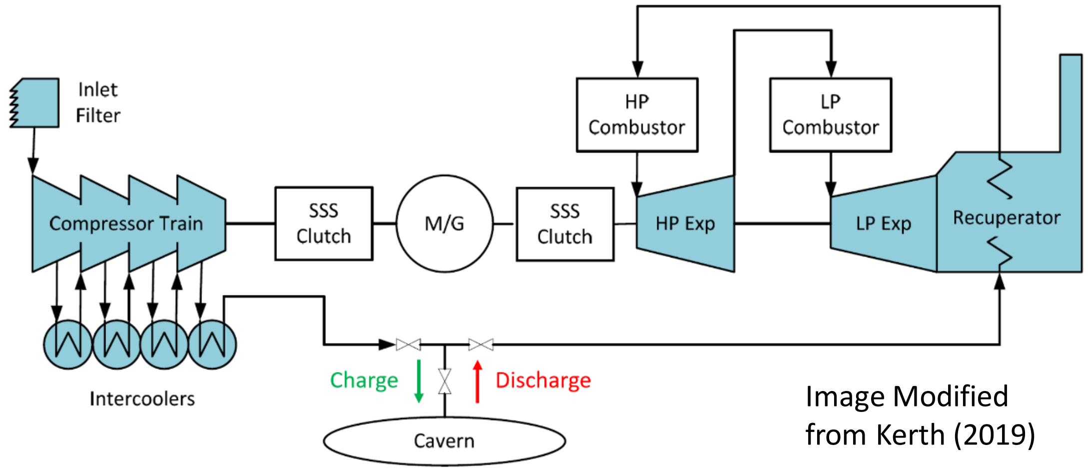
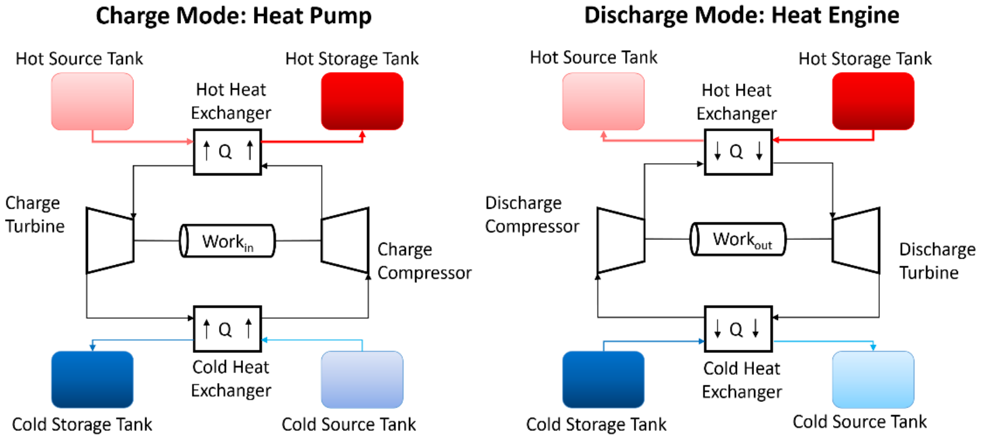


Image Modified from Kerth (2019)

Diabatic CAES



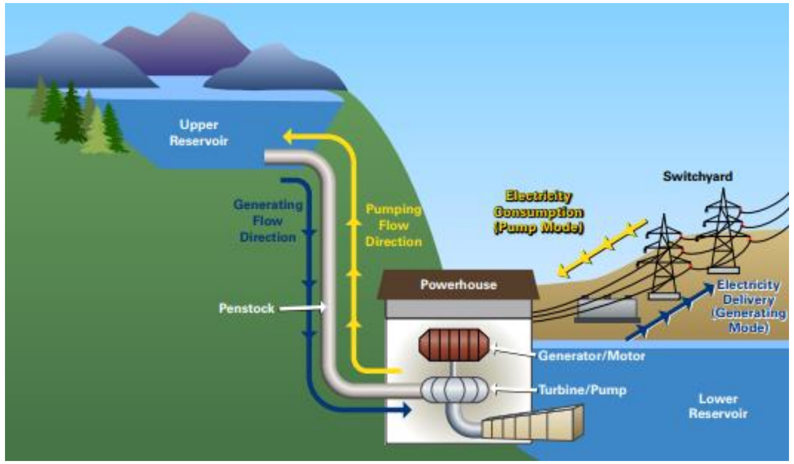
Example PHES

Image Source: Tom (2019)

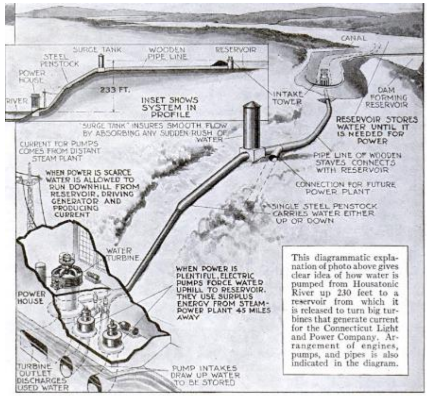
Mechanical ES: Pumped Hydro

- 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)



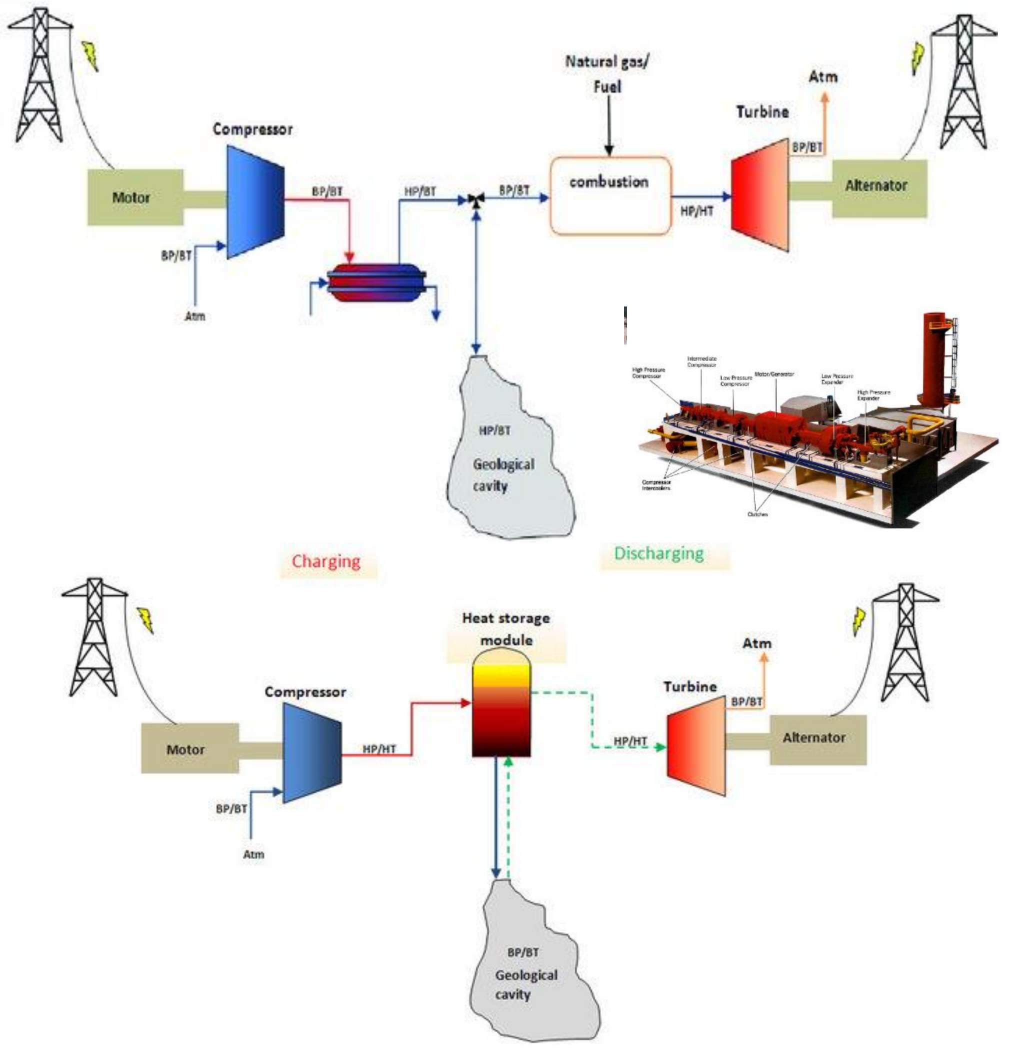
Francis Turbine Runner, 1942



World's First PSH System, 1930

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

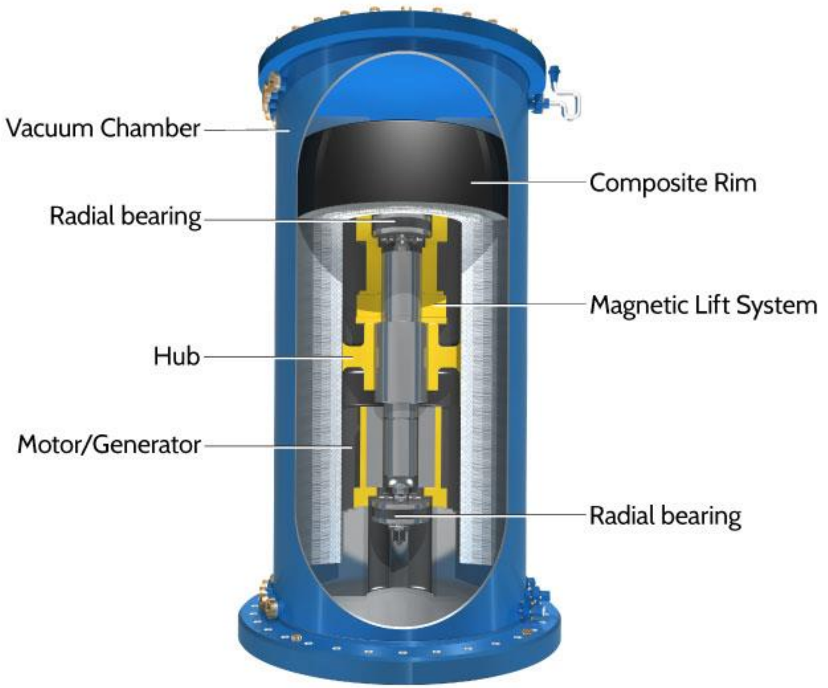


Diabatic (top) and Adiabatic (bottom) CAES

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



20 MW Flywheel Plant for NYISO

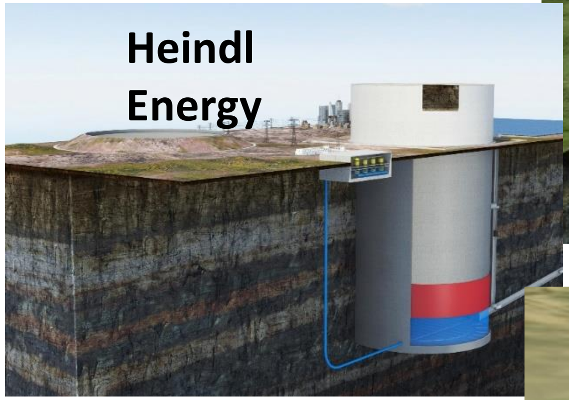
Image Sources: Beacon Power

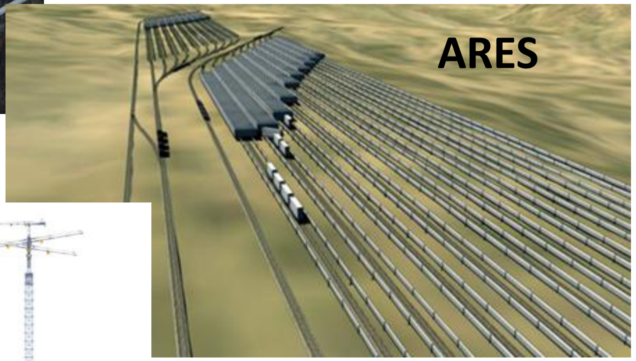
Data Source: Amiryar and Puleln (2017), Luo *et al* (2015)

SwRI

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





Energy Vault

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

CSP + Molten Salt TES

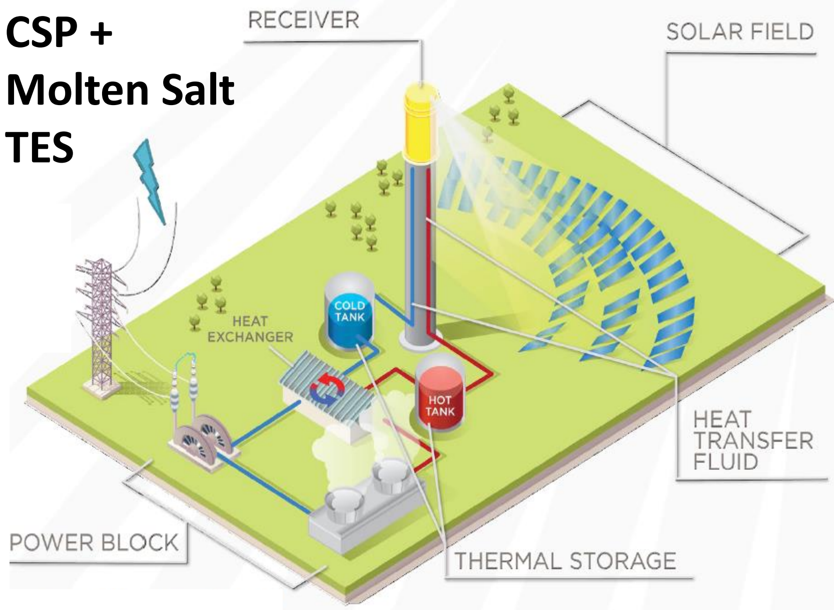
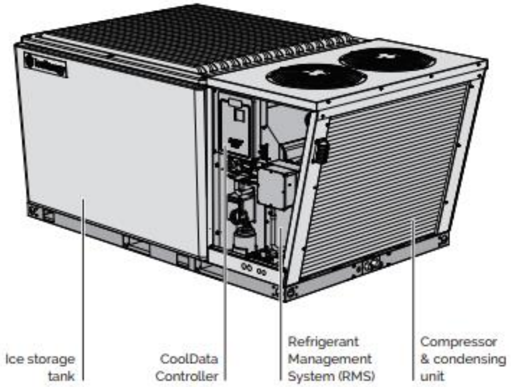
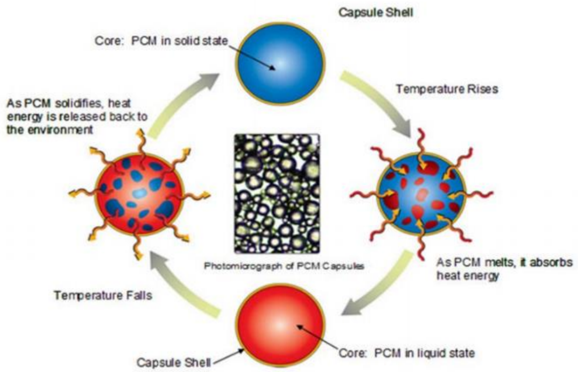


Image Source: Shultz (2019)

Ice storage



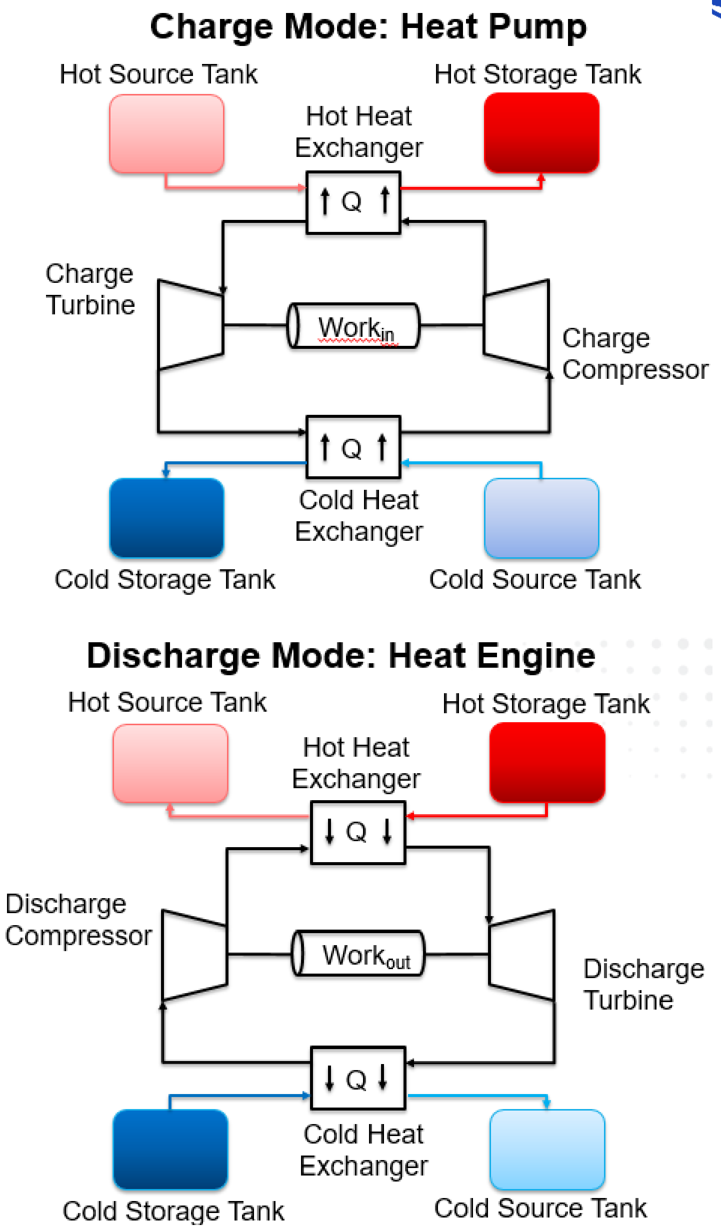
https://www.ice-energy.com/



Encapsulated PCM

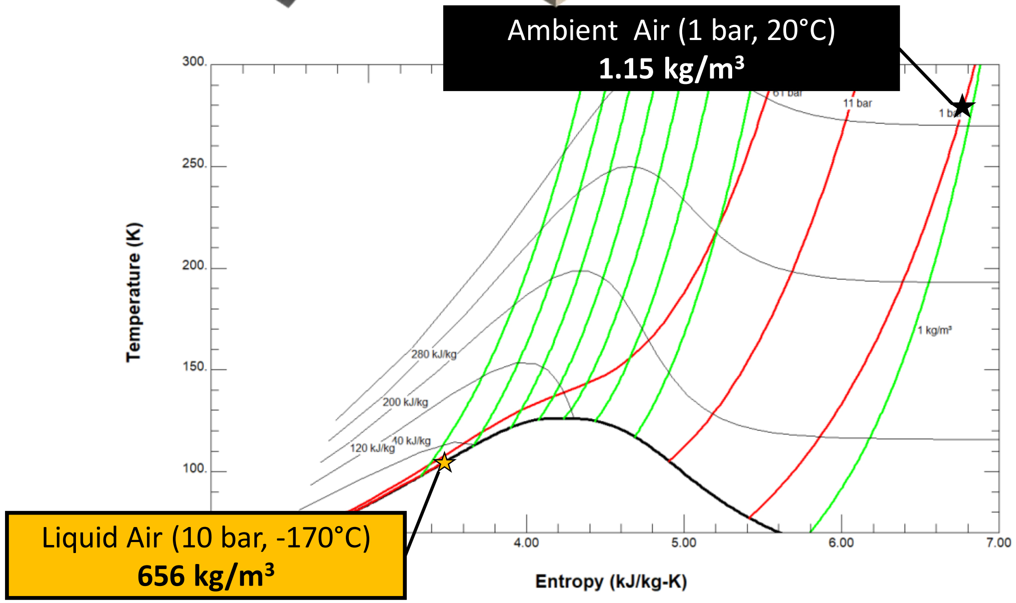
Thermal ES: Pumped Heat

- Electricity drives heat pump to charge system, creating temperature difference; Heat engine discharges system for electricity out
- Working fluids: Argon, air, sCO_2
- 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 in to 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%

H_2O E or Q

Charge

Water electrolysis

$2H_2O \rightarrow 2H_2 + O_2$

O_2

https://www.edie.net/news/6/Work-to-being-on-pioneering-salt-cavern-hydrogen-storage-scheme/

Store

H_2 at high pressure

H_2O_2, other carriers

E

Discharge

Use for electricity/power generation:

Hydrogen gas turbine / fuel cell

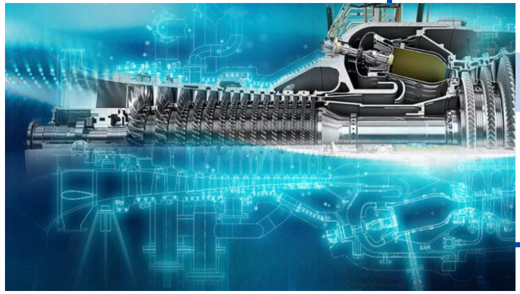
Reaction heat release

Sell

Use for refining

Use for NG or Ammonia

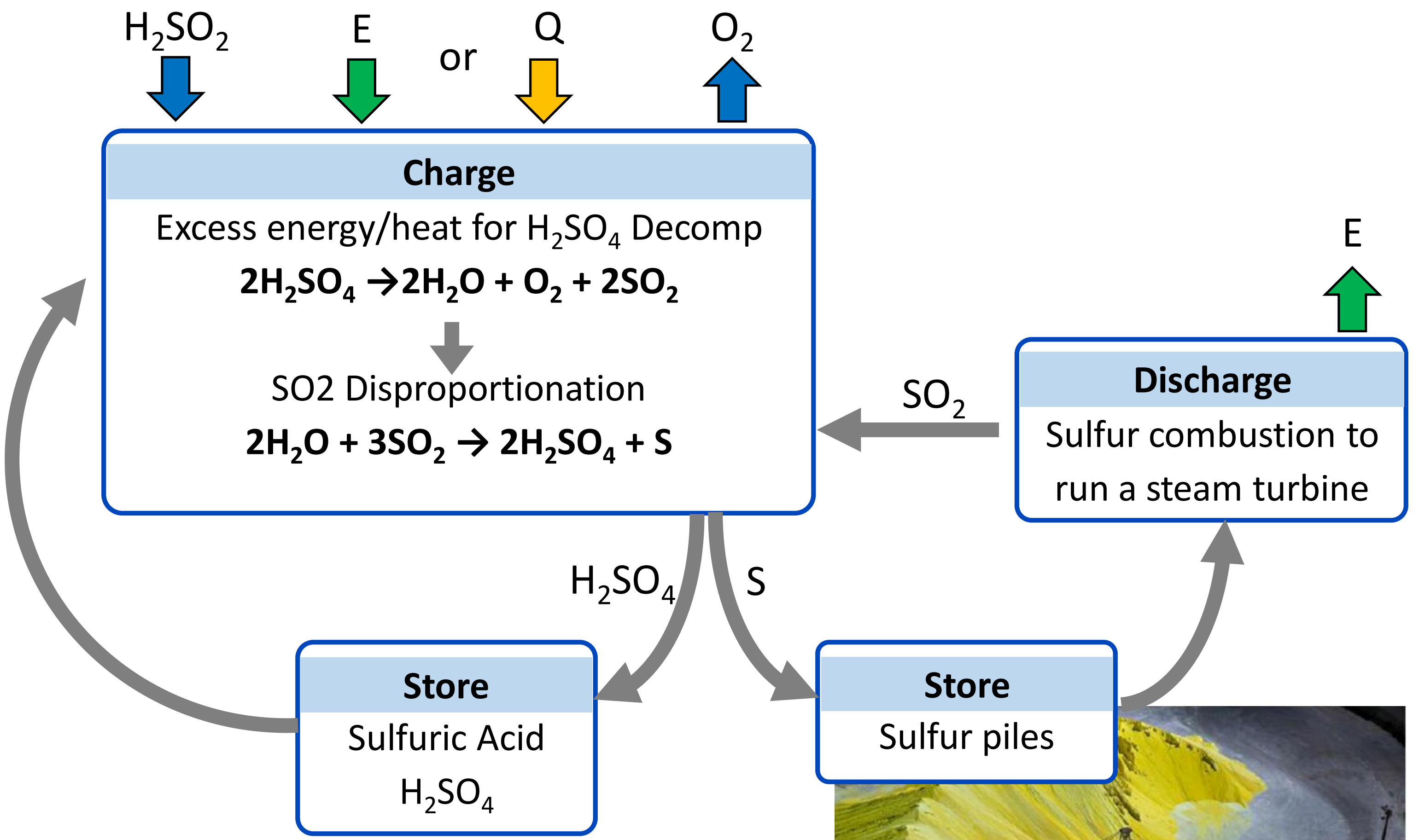
H_2



https://www.turbomachinerymag.com/fuel-switching/

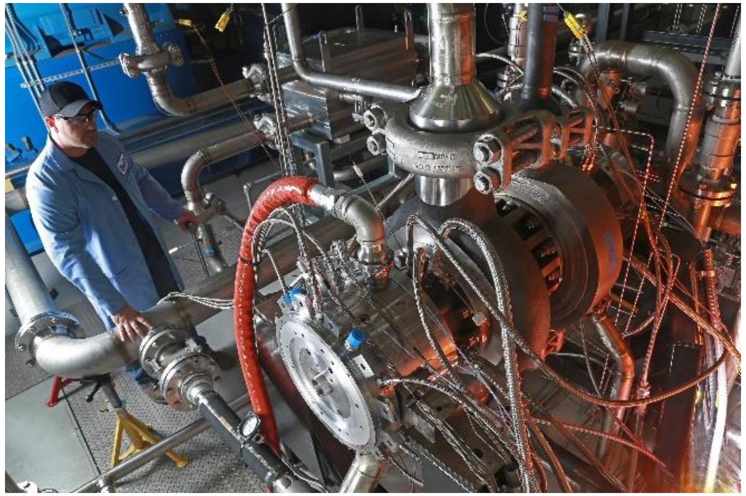
Thermochemical ES: Sulfur

- Principle
  - Closed sulfur cycle include SO_2 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

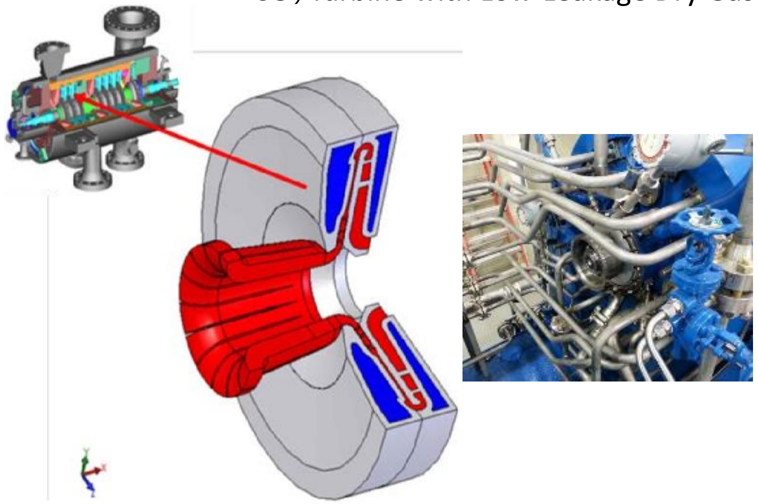


Development Needs for Energy Storage: Machinery & HX

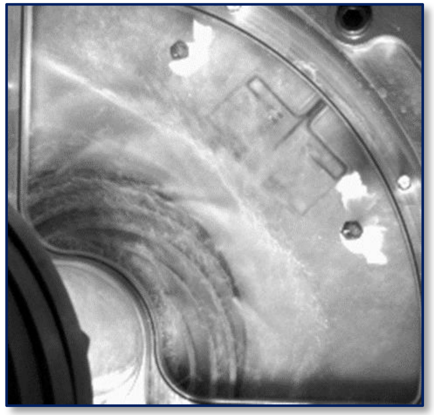
- Most new thermodynamic systems are closed or semi-closed cycles requiring:
  - Very high machinery efficiency over a variety of temperatures, pressures, and scales (radial→axial)
  - Low leakage/makeup requirements; consider hermetic machinery
  - High pressures, densities, possibly temperatures
 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



High-Efficiency High-Temperature 10 MWe 715 °C Supercritical CO_2 Turbine with Low-Leakage Dry Gas Seals (Moore 2019)



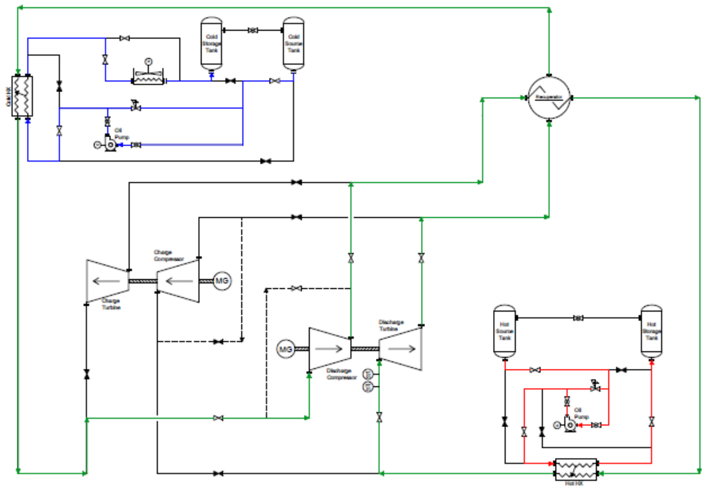
CO2 Compressor for CCS with Internally-Cooled Diaphragms (Moore 2014)

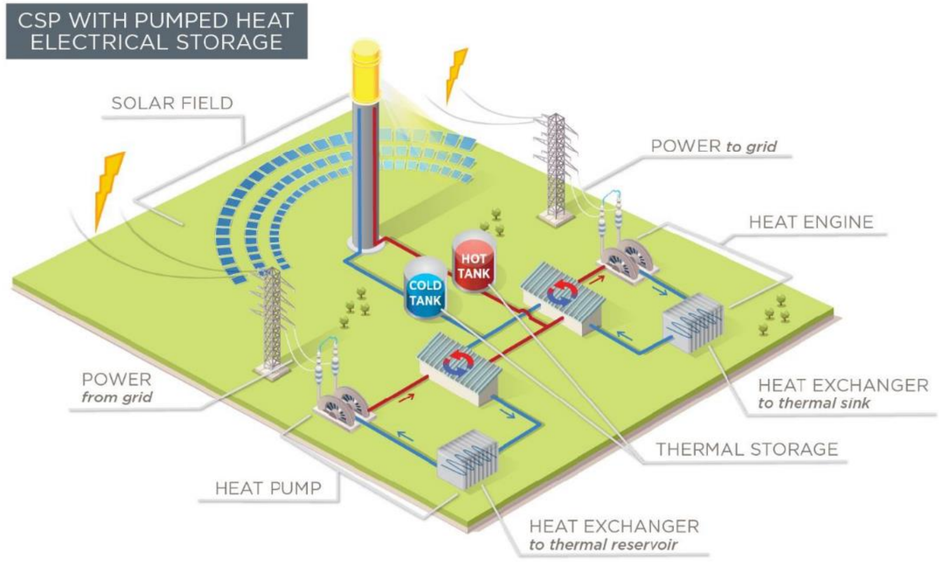


Wet Gas Compression Test (Musgrove 2016)

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

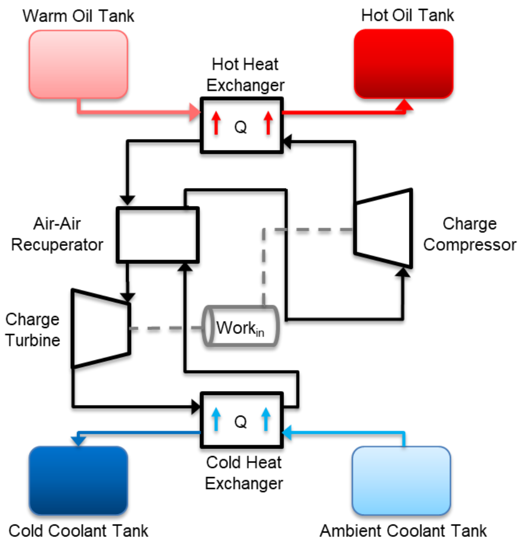




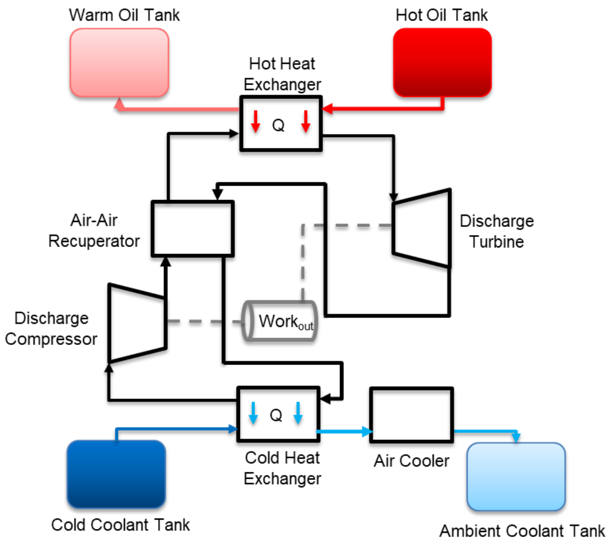
CSP Integrated with PHES (Image Source: U.S. DOE)

Current SwRI R&D – Pumped Thermal Energy Storage Demo

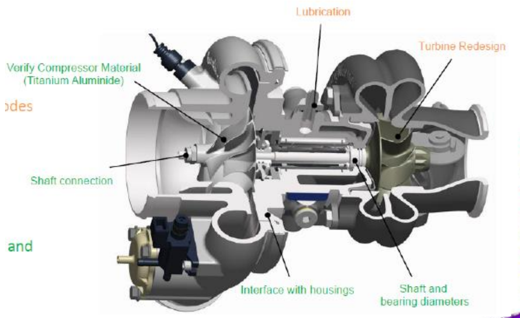
- Project funded by DOE/ARPA-E; Partnered with Malta, Inc.
- Advance PHES from concept to a kW-scale system demonstration in 27 months
  - Focus on system operation and integration
  - Evaluate control strategies for system startup, shutdown, and mode change
  - Gather performance data to verify system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

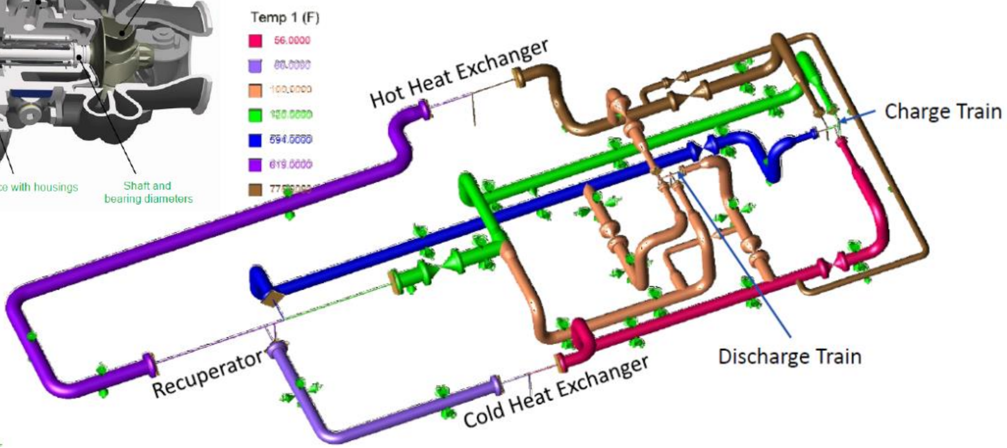


Charge Mode: Heat Pump



Discharge Mode: Heat Engine





Questions?

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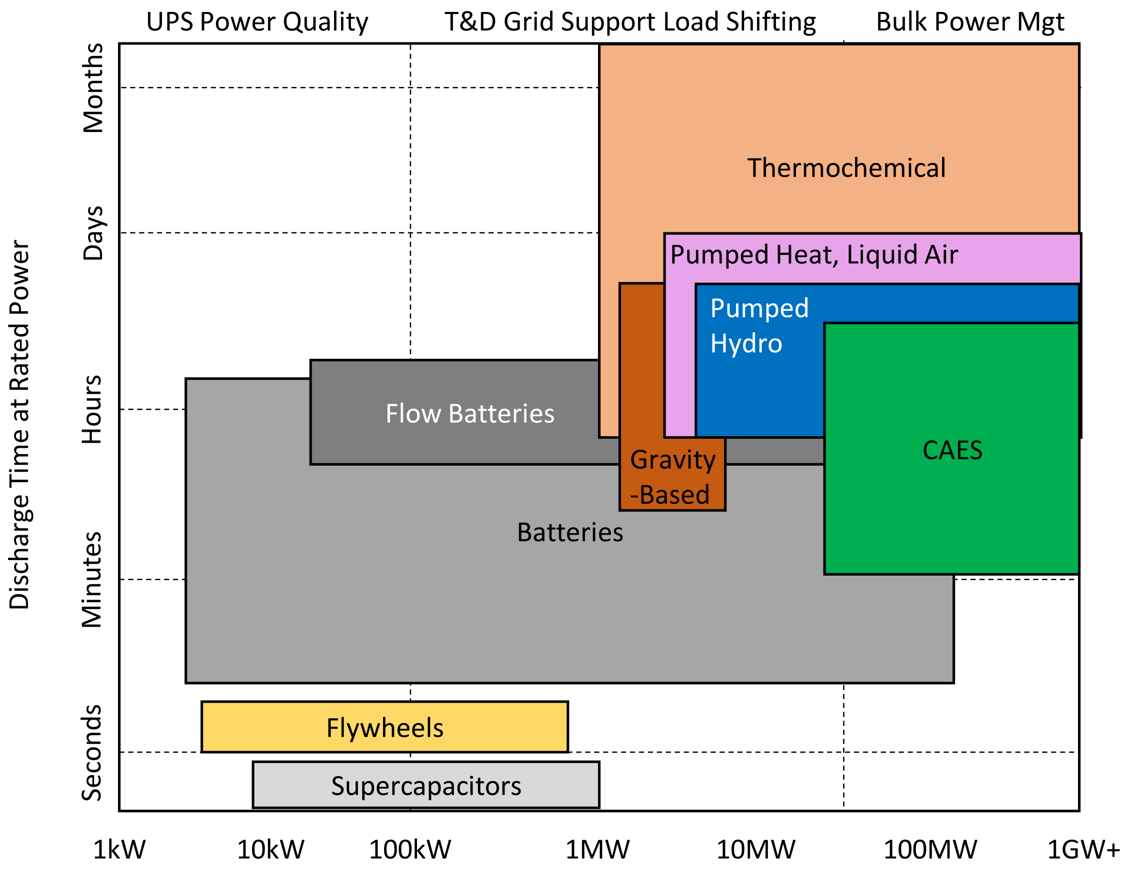

References

[1] Solomon, A.A., Child, M., Caldera, U., and Breyer, C., "How much energy storage is needed to incorporate very large intermittent renewables?" *Energy Procedia*, Vol. 135:283-293, Elsevier, 2017.

[2] Olivetti, E.A., Ceder, G., Gaustad, G.C., Fu, X., "Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals," *Joule 1*, 229-243, Elsevier, 2017.

[3] Mongird, K., Viswanathan, V., Balducci, P., Alam, J., Fotedar, V., Koritarov, V., and Hadjerioua, B. "Energy Storage Technology and Cost Characterization Report," PNNL-28866, U.S. DOE, July 2019.

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[5] Hering, G., "Burning Concern: Energy storage industry battles battery fires," S&P Global Market Intelligence, May 2019, https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/51900636 [accessed December 15, 2019].