# Thermal-Mechanical-Chemical Energy Storage Technology Overview and Research Activities

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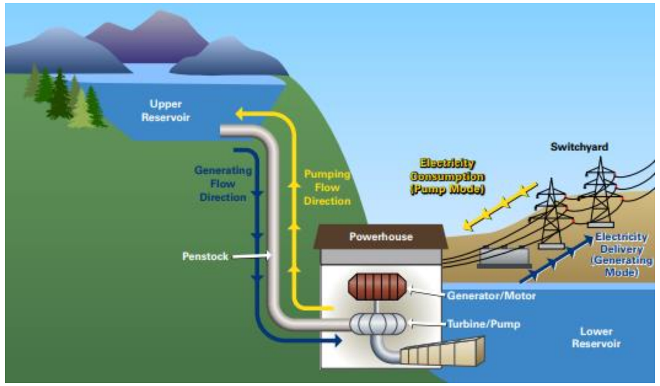
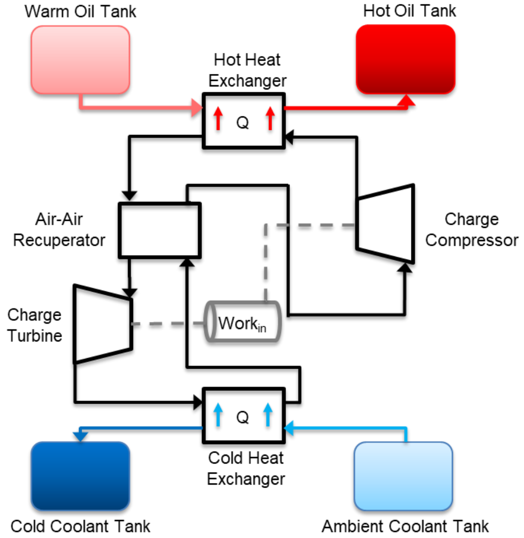
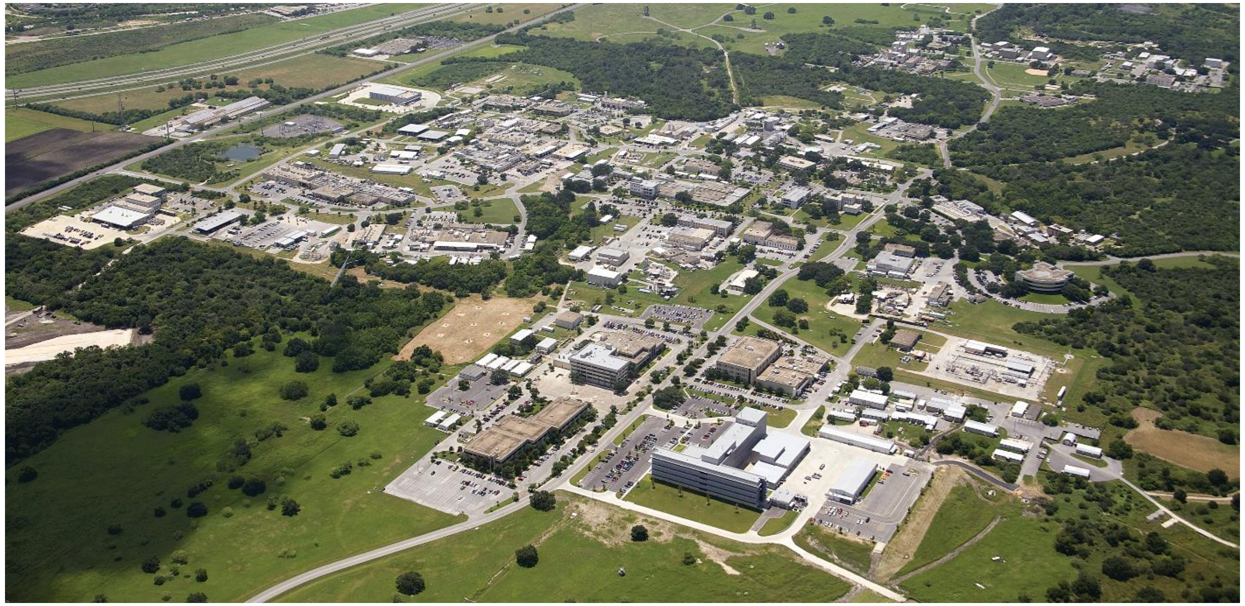
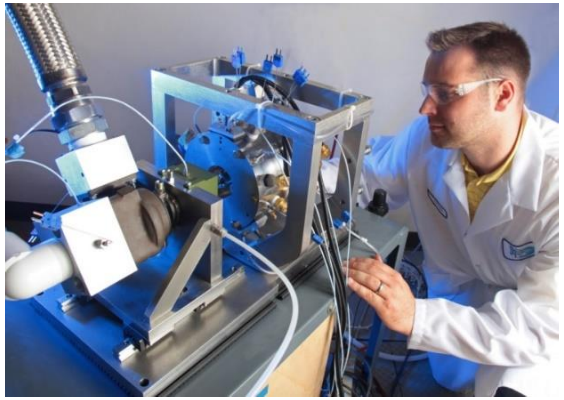


# SwRI is an Applied Research & Development Company

- Founded in 1947, based in San Antonio, Texas
- 501 (c)(3) nonprofit corporation
  - Internal research
  - New laboratories
- ~$680M annual revenue from contract work for industry and government clients
- Over 2,700 employees
- 1,500-acre facility; 2.3 million square feet of laboratories & offices
- Client-centric IP policy
- Machinery Department: 75 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
  - Typical hourly, daily, seasonal variability is ~50-100% of rated power
- 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)

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

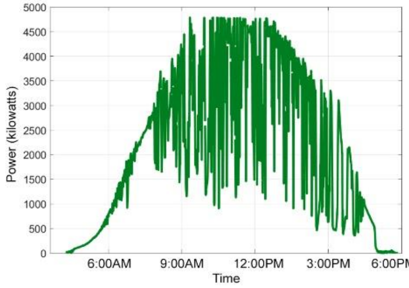



Image Source: EPRI 2018

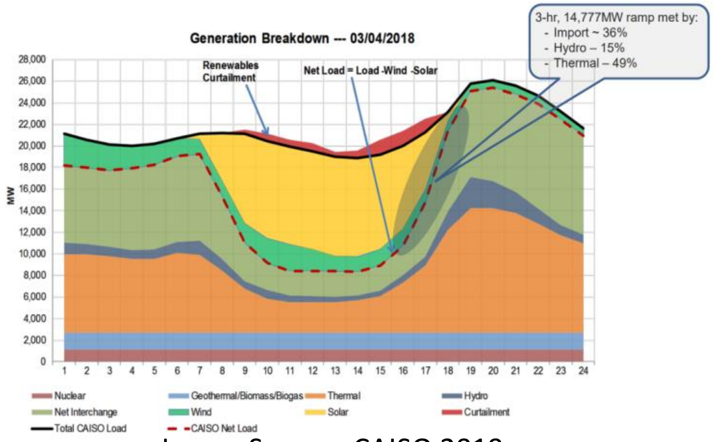



Image Source: CAISO 2019

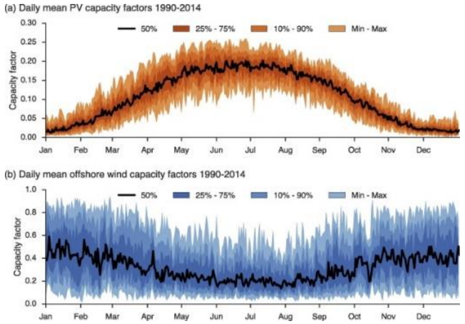


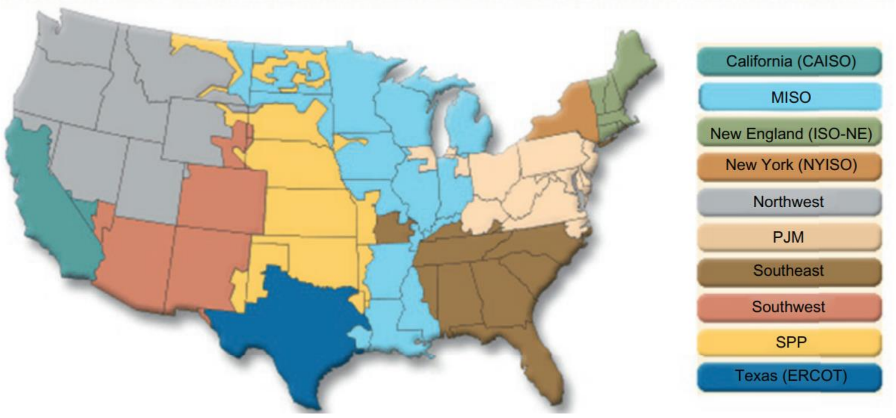

Image Source: Pfenninger 2017

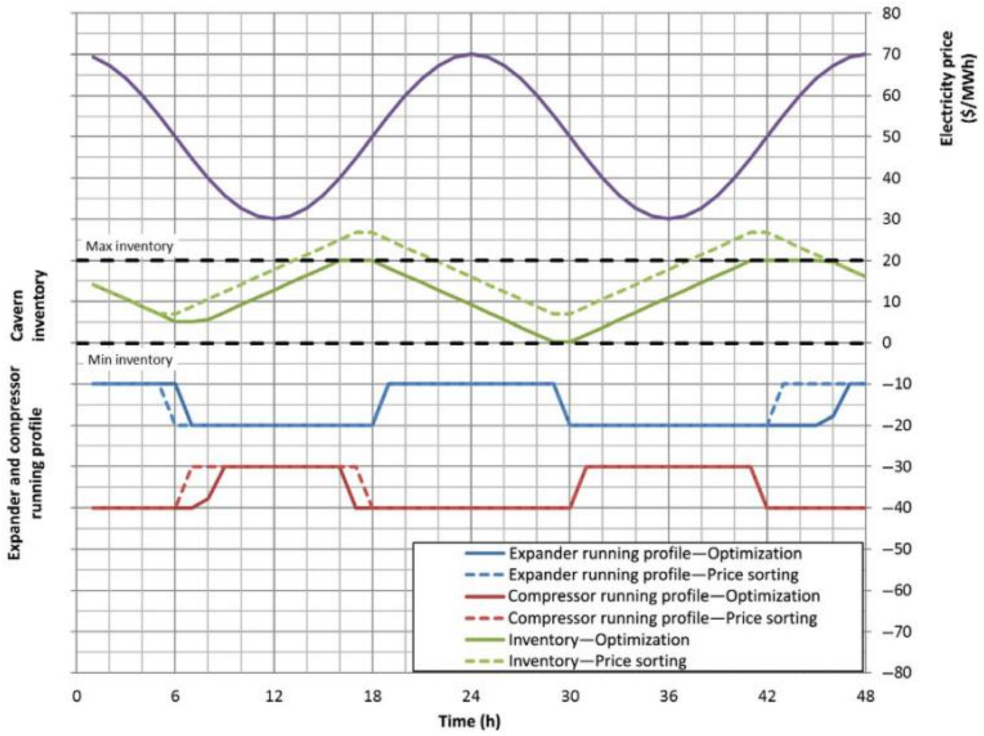
1-35 of the world's largest pumped hydro system…

…or 23-763 of these molten salt tanks

# Energy Storage Use Cases

- Many potential use cases for many markets
  - Arbitrage
  - Demand response
  - Peaker
  - Spinning reserve
  - Transmission & distribution upgrade deferrals
  - Behind-the-meter peak shaving
  - Reduced O&M for conventional generators
- Combinations of the above
- Many unknowns: future grid mix, regulatory, different markets, permitting, carbon/emission pricing, etc.

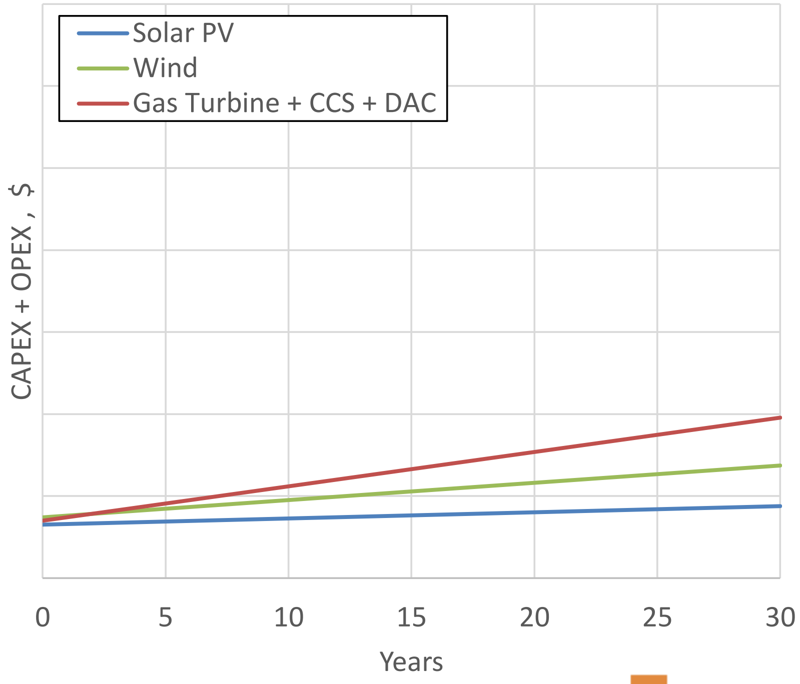


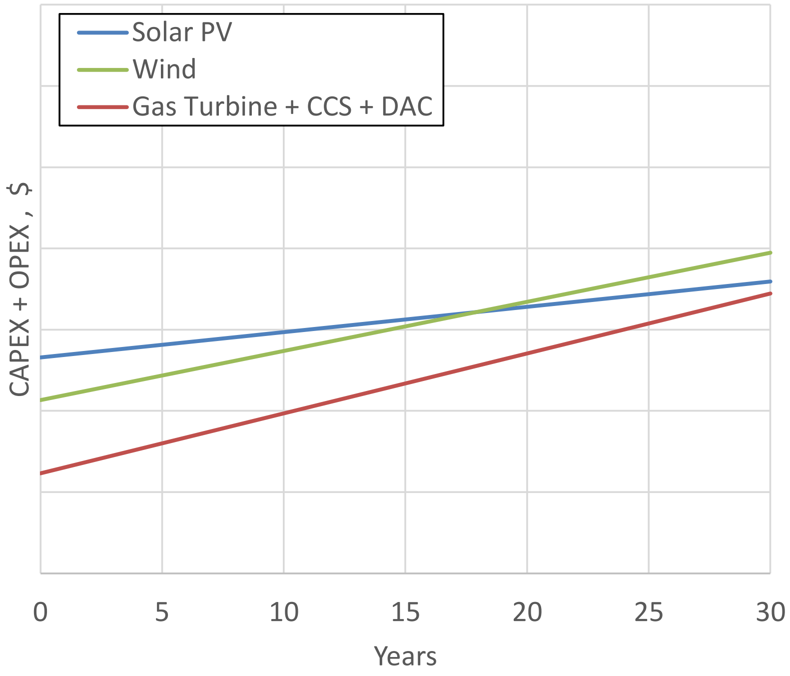

Voss *et al*, 2021

# Storage Cost Impacts to Renewable Power

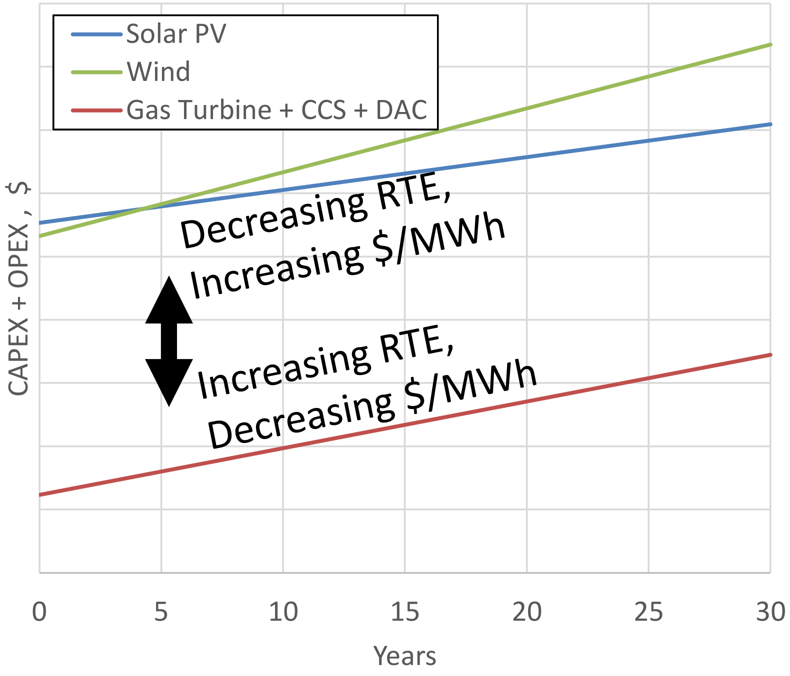
PV & Wind Look Cheaper Long-Term at Same Rated Power




Capacity Factor Requires Oversizing to Annual Power




Storage Cost Significantly Increase System Costs for Renewables!



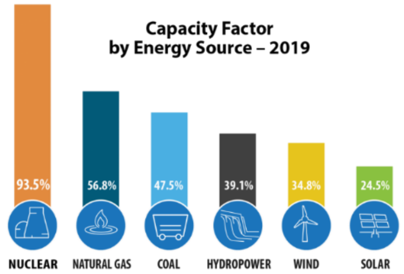




Image Source: U.S. EIA, 2021

- RTE Increases Oversizing
  - Assume 60%
- Storage Cost Depends on Duration
  - Assume 24 hours using non-battery storage

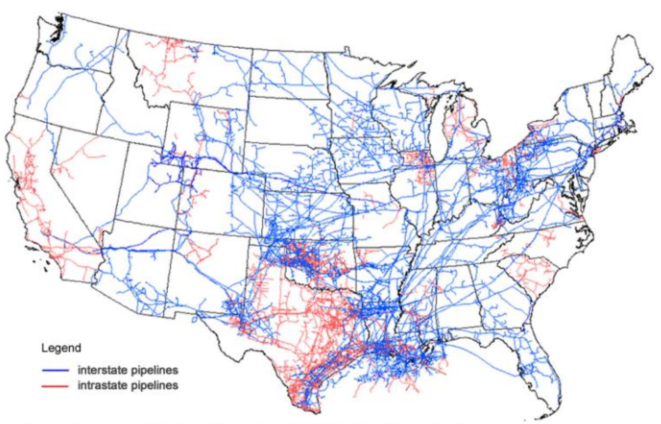
# Transport / Location

- Renewables generate electricity, needs transportation & distribution
- Transportation sector drives 26% of total energy use
- Energy transport efficiency and capital cost favors pipelines vs. electric transmission
- Electric input/output system locations may be driven by many factors, including permitting, existing infrastructure, energy security, safety, etc.

| Transport | Transport Losses per 100 Miles | Capital Cost, $/MW-mile |
| --- | --- | --- |
| Electric Transmission | 1.0-10% | $3.9M |
| Natural Gas Pipeline | 0.1-0.3% | $1.5-2M |
| Hydrogen Pipeline | 0.6-1.8% | $1.5-2M |
| Liquid Pipeline | 0.02-0.1% | $1.5-2M |

Data Sources: Brun (2020), Allison (2021), James (2018)

Map of U.S. interstate and intrastate natural gas pipelines




Source: U.S. Energy Information Administration, *About U.S. Natural Gas Pipelines*

# 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 power-energy decoupling with low-cost energy storage media
  - Potential for different charge/discharge rates

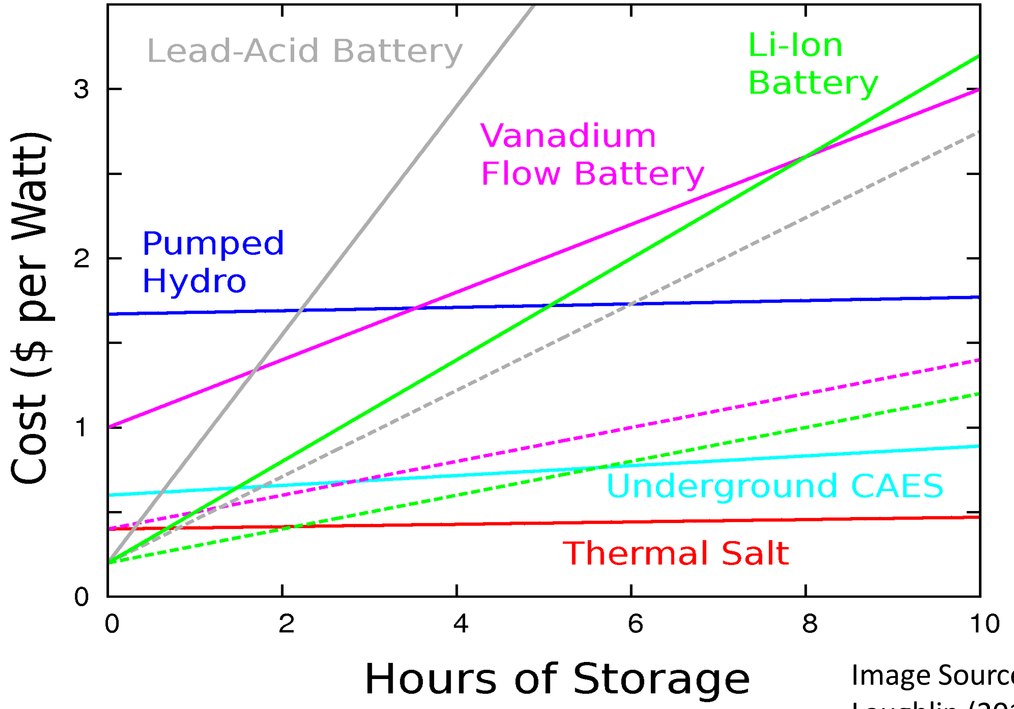
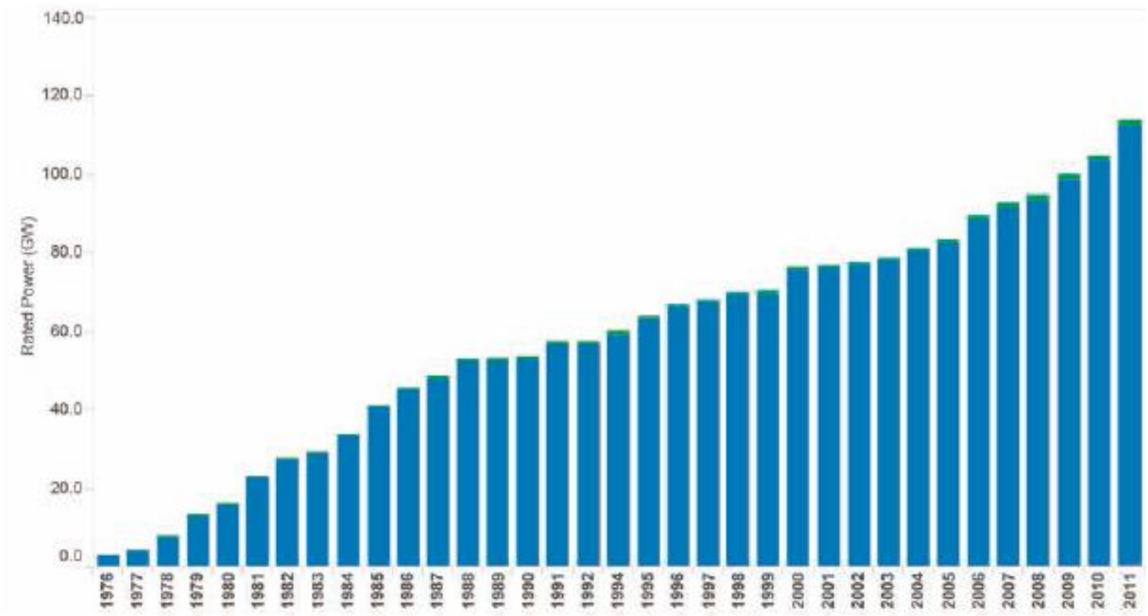



Image Source: Laughlin (2019)

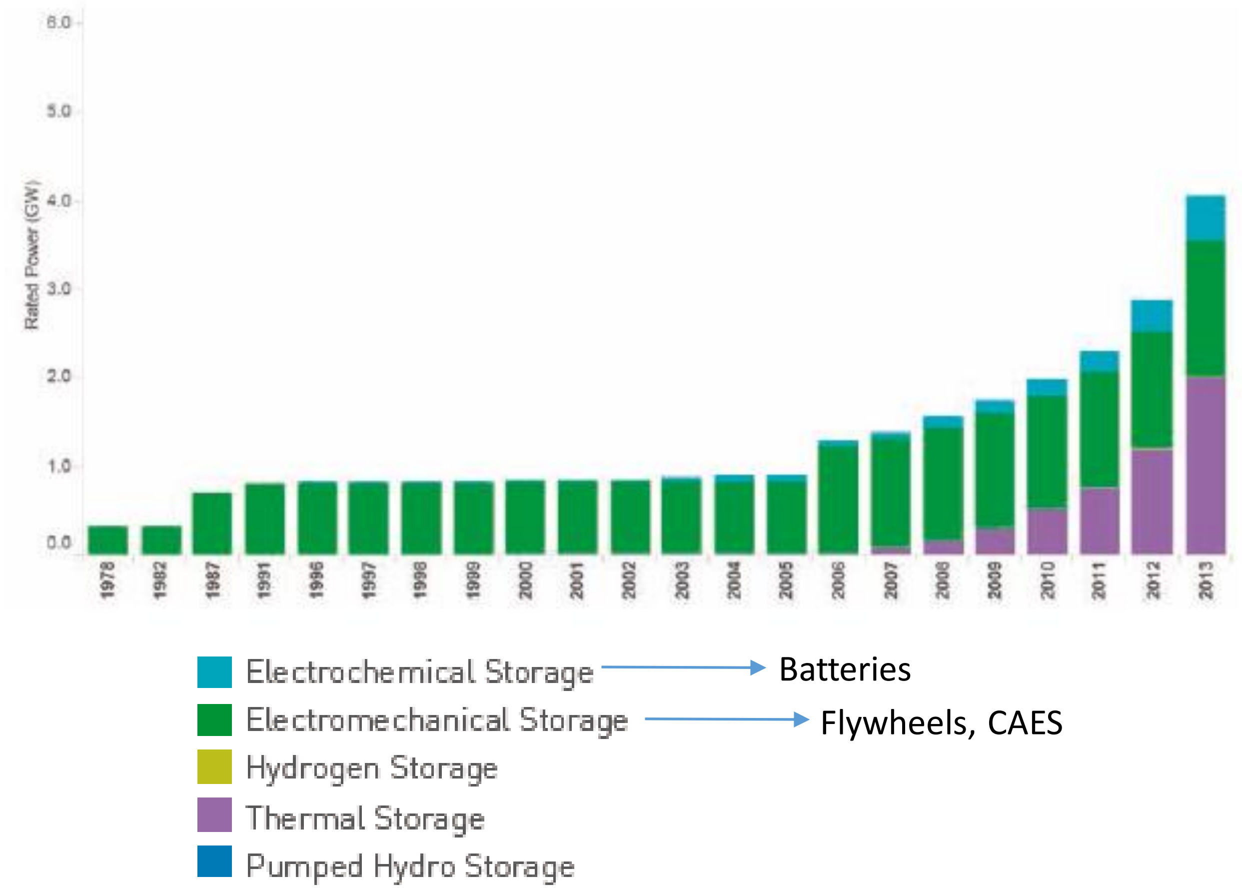
Image Source: S&P Global (2019)

# Global Energy Storage Technology Timeline

Global Energy Storage Project Installations

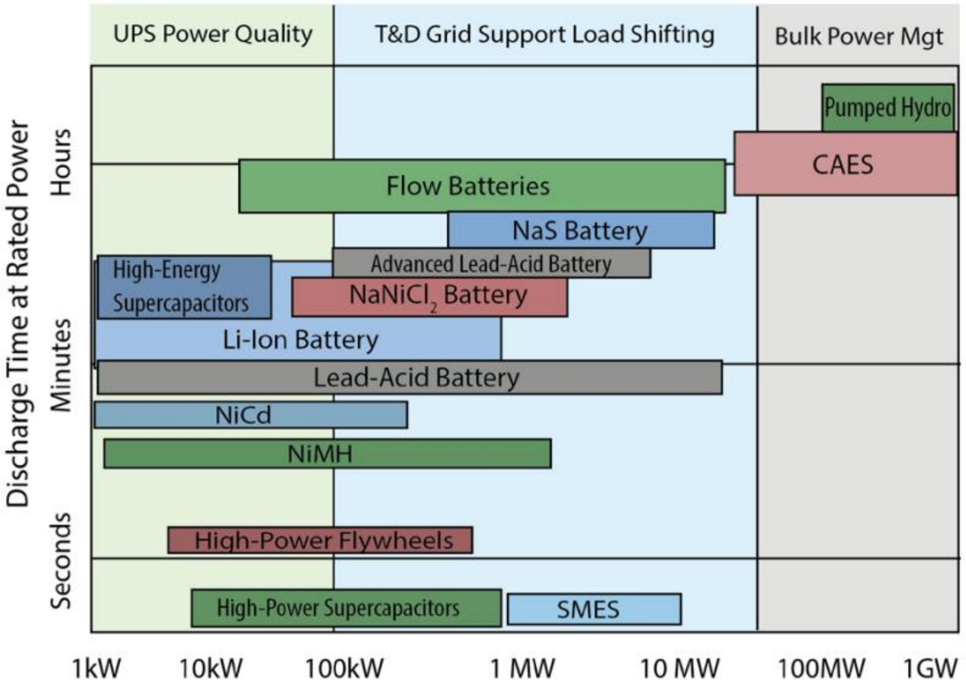



Global Energy Storage Project Installations – excluding PHS

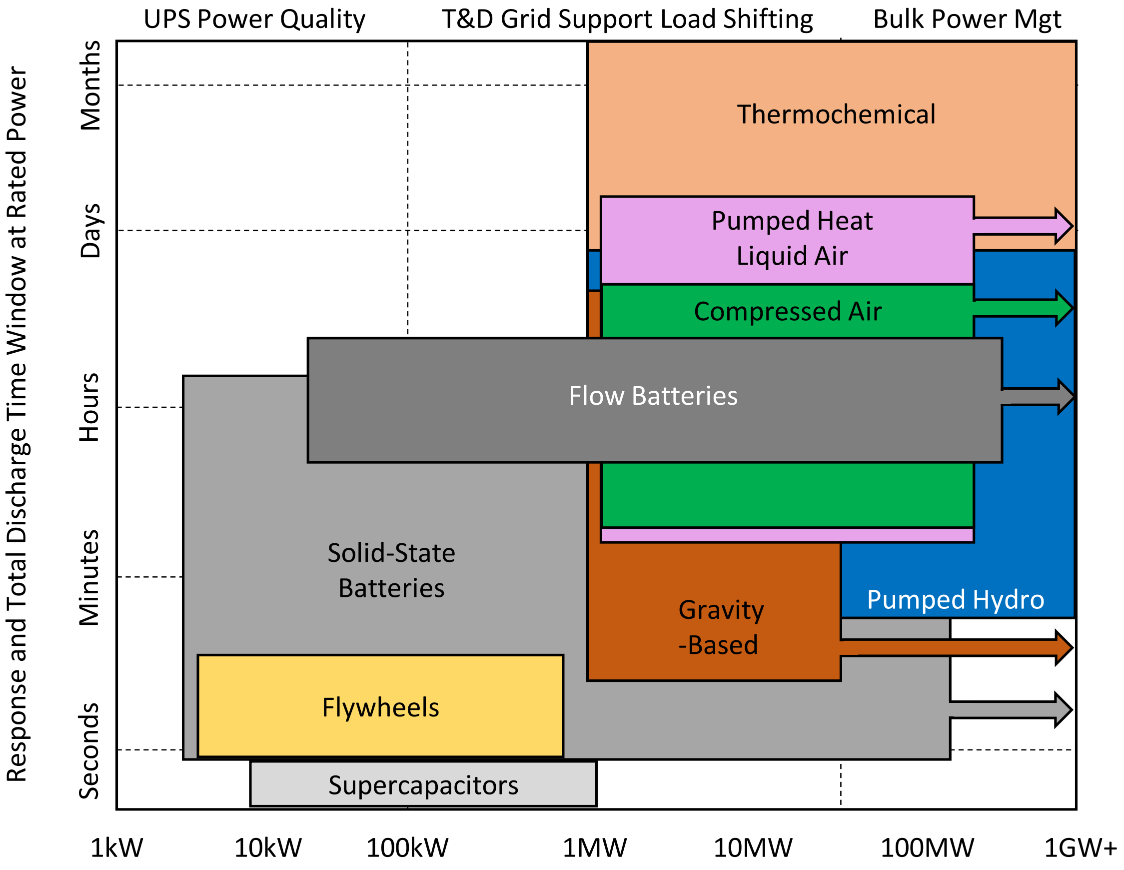



Data and Images from EASE/EERE (2017)

# 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

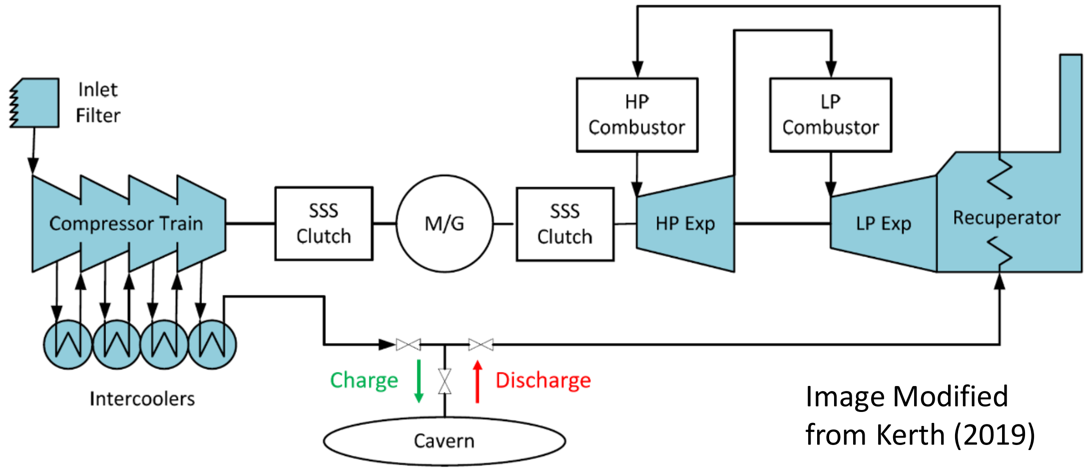
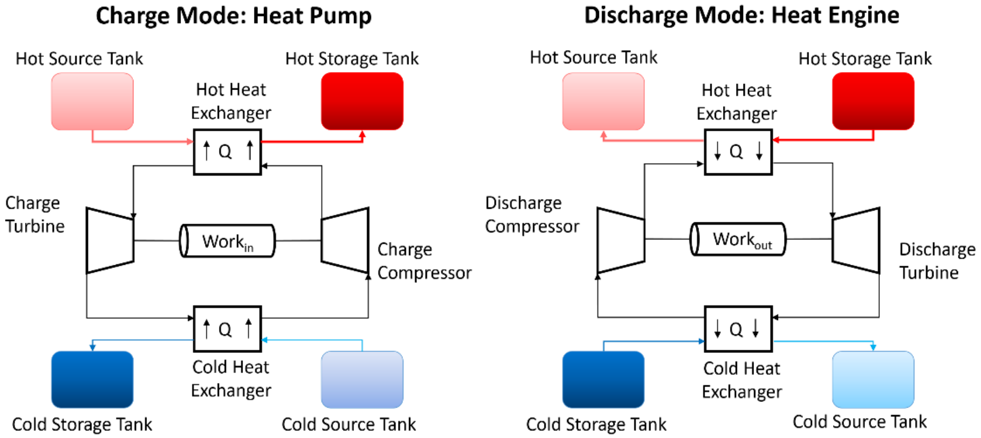



Image Modified from Kerth (2019)

Diabatic CAES

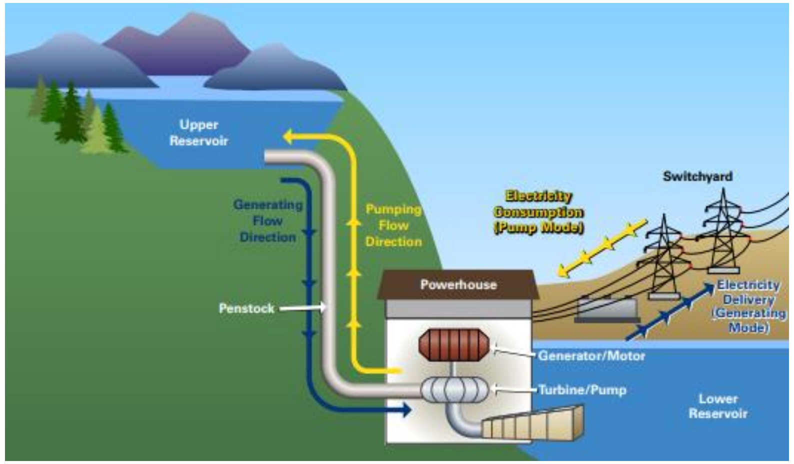



Example PHES

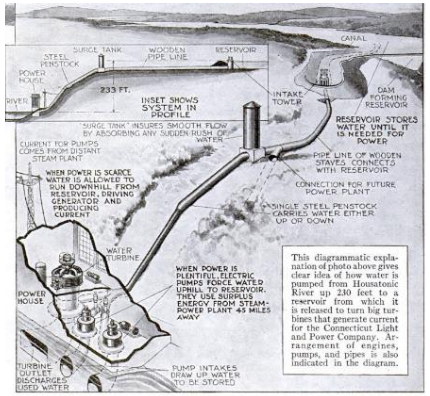
Image Source: Tom (2019)

# 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




Francis Turbine Runner, 1942

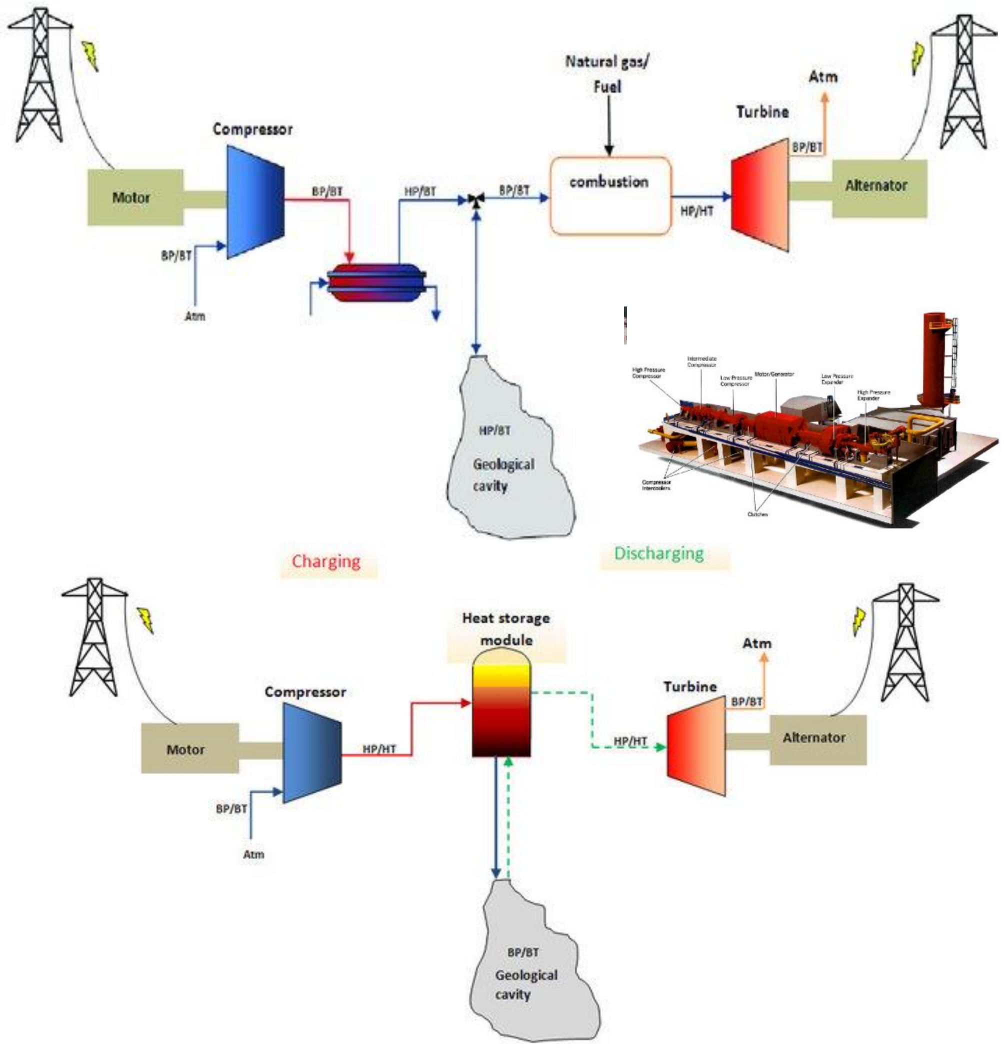


World's First PSH System, 1930

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

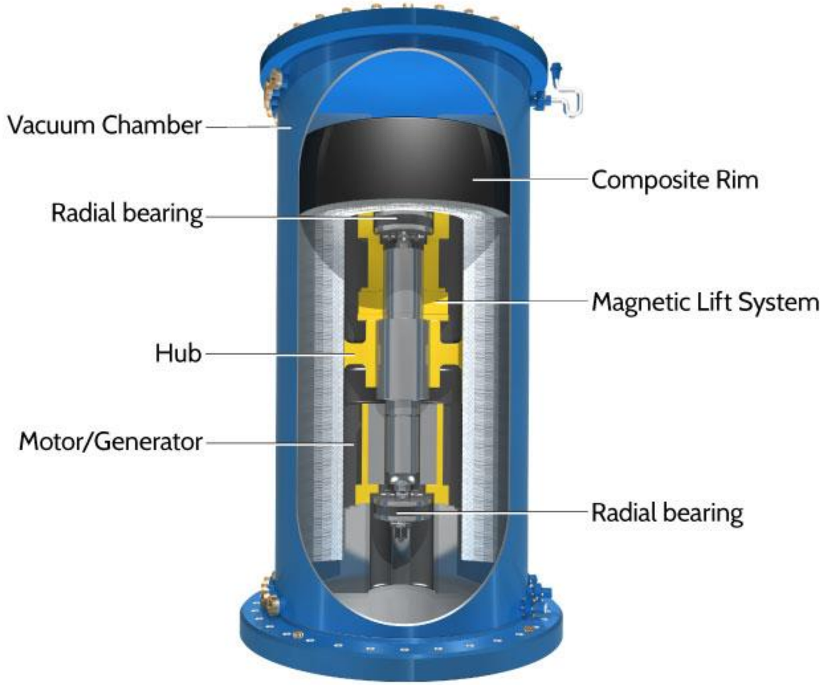



**Diabatic (top) and Adiabatic (bottom) CAES**

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



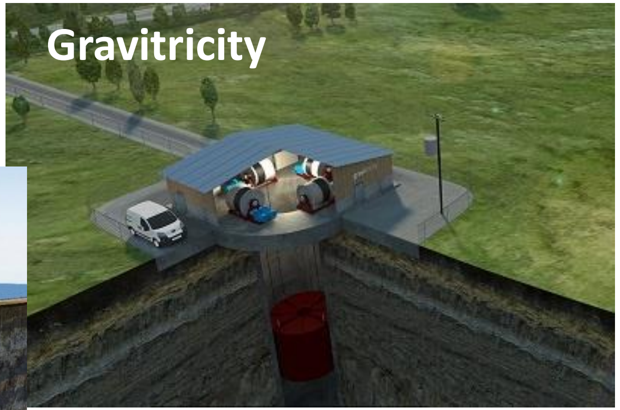

**20 MW Flywheel Plant for NYISO**

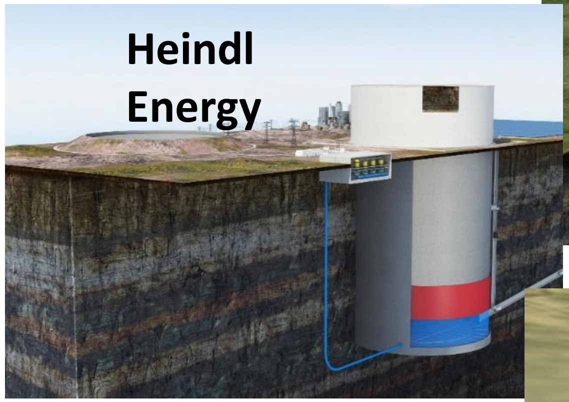
Image Sources: Beacon Power

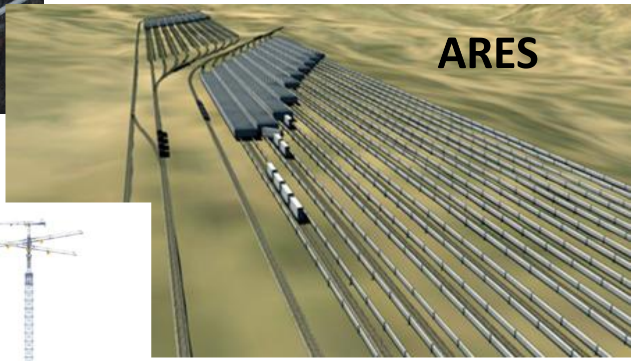
Data Source: Amiryar and Puleln (2017), Luo *et al* (2015)

# 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**

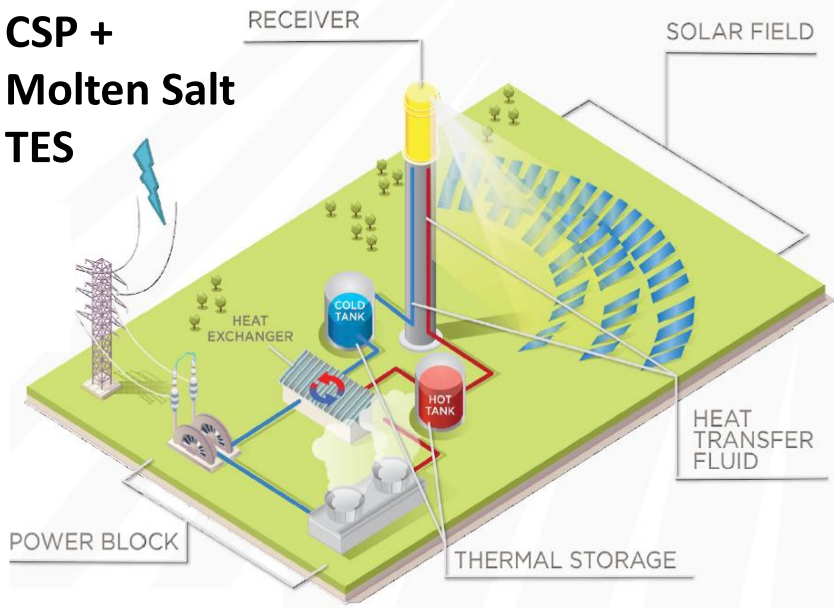
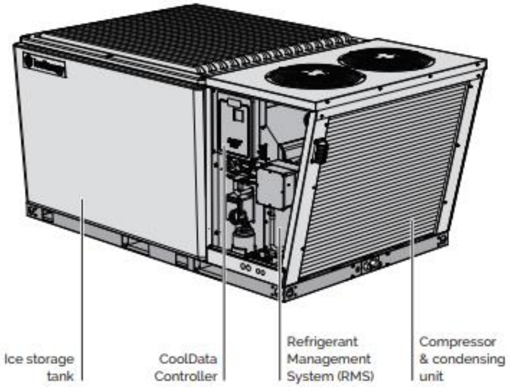
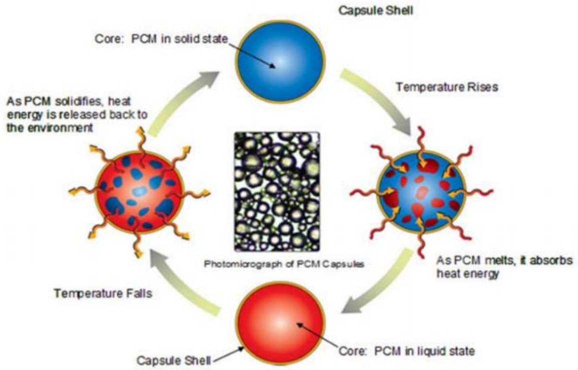



Image Source: Shultz (2019)

**Ice storage**



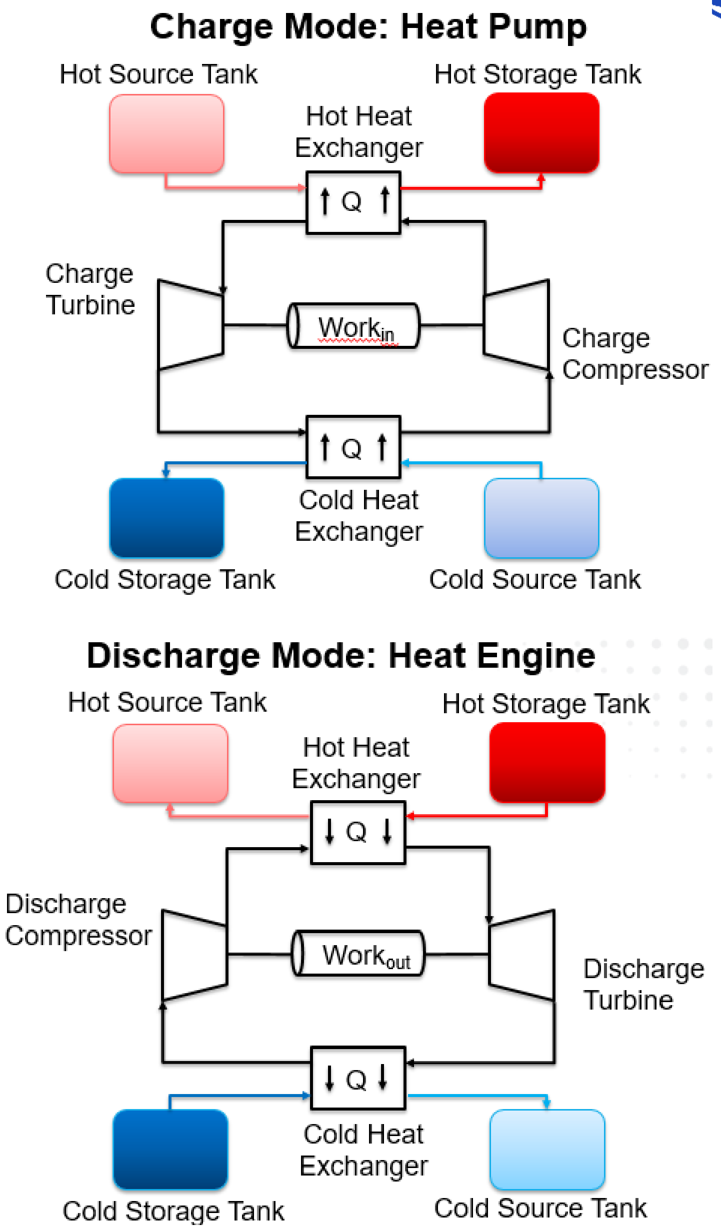

https://www.ice-energy.com/




**Encapsulated PCM**

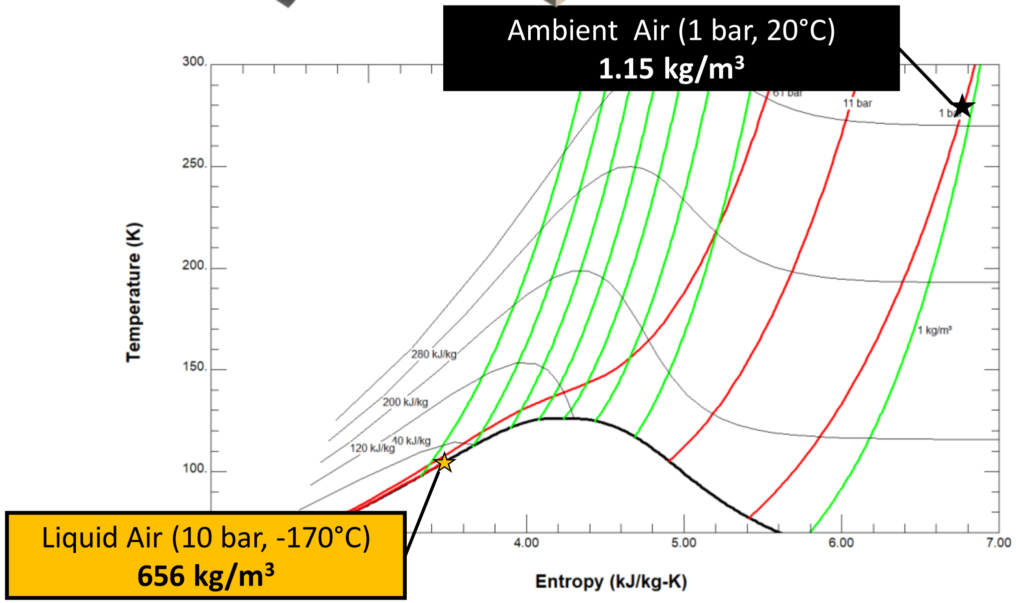
# Thermal ES: Pumped Heat

- Electricity drives heat pump to charge system, creating temperature difference; Heat engine discharges system for electricity out
- Working fluids: Argon, air, $CO_2$
- Machinery is conceptually like a gas turbine, but some key differences.
  - Closed cycle at higher pressure
  - No combustor
  - Charge mode temperatures very different
- Technology gaps / development
  - Low-cost TES, heat exchangers, machinery, cycle/system
  - Some variations store thermal energy through process fluid phase change and direct storage, e.g. $CO_2$
- Predicted 50-70% RTE



# Thermal ES: Liquid Air


- Similar to CAES but different process liquefies air for compact, portable storage
- Many variations: refrigeration cycles, thermal storage, heat input, cryogenic carbon capture, etc.
- 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 $H_2$ 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
  - Gas turbine combustion with low $NO_x$ emissions
  - Couple with CSP or other heat source instead of using surplus energy to drive electrolysis
- Expected performance ~10-30% round trip efficiency, targeting 50%
- Many hydrogen carriers including ammonia, methanol, synthetic methane, etc.

$H_2O$ E or Q

**Charge**

Water electrolysis

$$2H_2O \rightarrow 2H_2 + O_2$$

$O_2$

**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

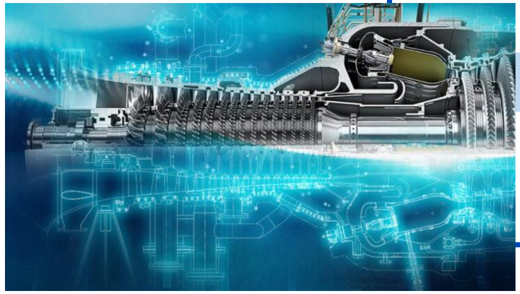
**Sell**

Use for refining

Use for NG or Ammonia

$H_2$

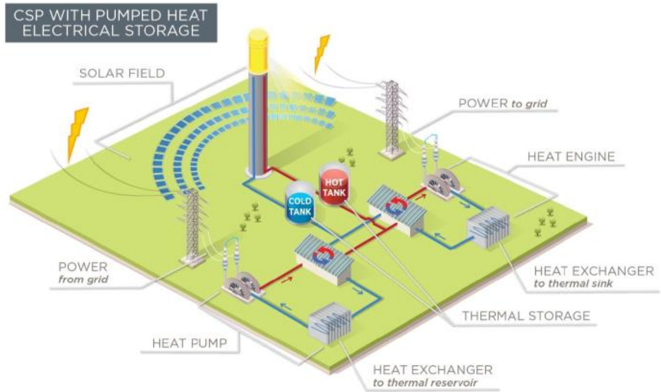
https://www.edie.net/news/6/Work-to-being-on-pioneering-salt-cavern-hydrogen-storage-scheme/

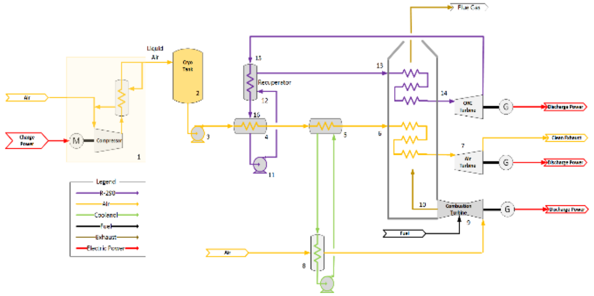


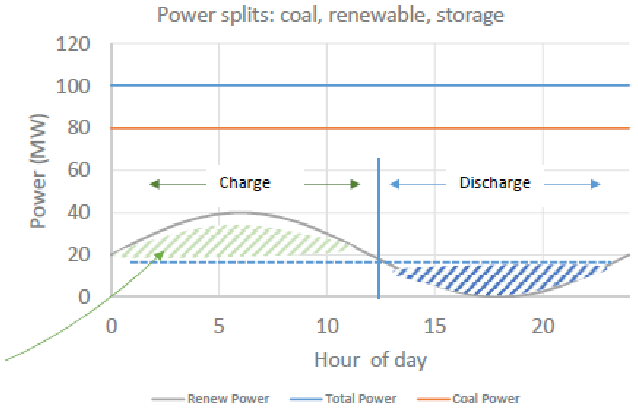
https://www.turbomachinerymag.com/fuel-switching/

# Integrated/Hybrid Energy Storage

- Best efficiencies/costs may be achievable by leveraging infrastructure and process of existing generation/industrial systems
  - Concentrating Solar Power + Pumped Thermal Storage
  - Natural Gas Pipelines + Hydrogen
  - Fossil Fuels + Stored Carbon Capture
  - Waste Heat + Liquid Air/Pumped Thermal
  - Sector Coupling + Thermal Storage
  - More…
- Storage can mitigate flexibility requirements on baseload generation
- Requires customization to match wide range of existing infrastructure

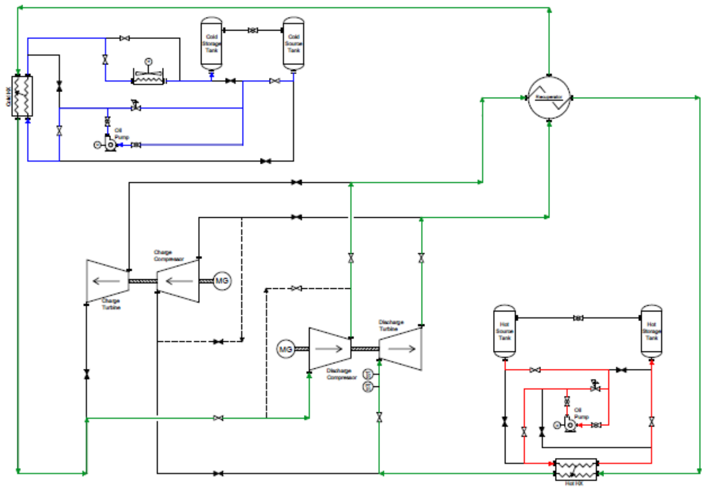


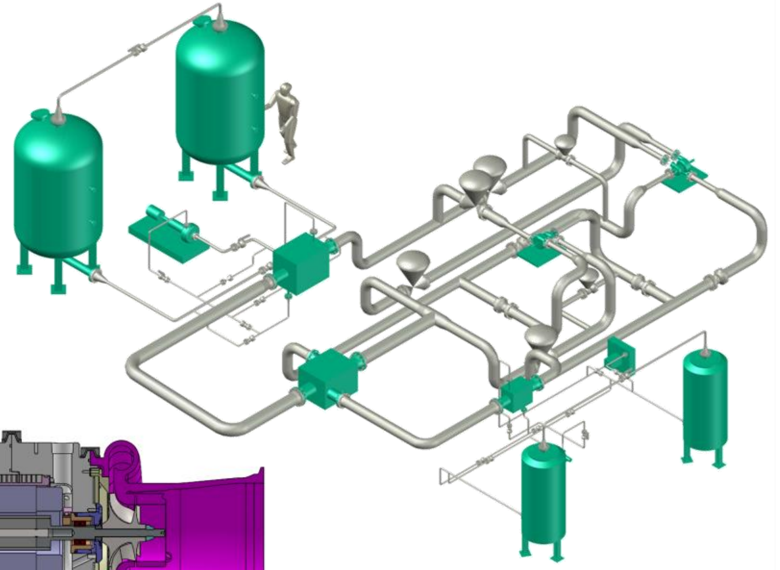



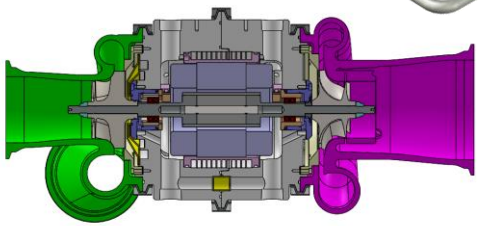


# Development Needs for Energy Storage: Systems

- Lab-scale and pilot-scale demonstrations to build commercial acceptance
- 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

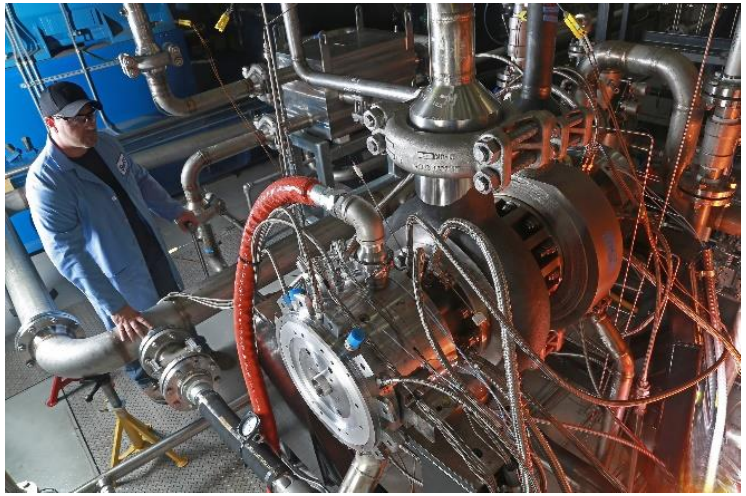




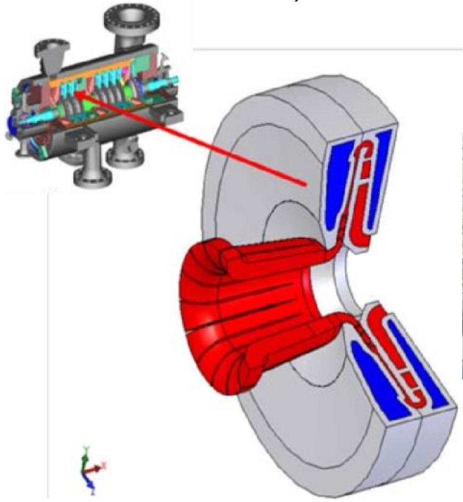


# Development Needs for Energy Storage: Machinery & HX

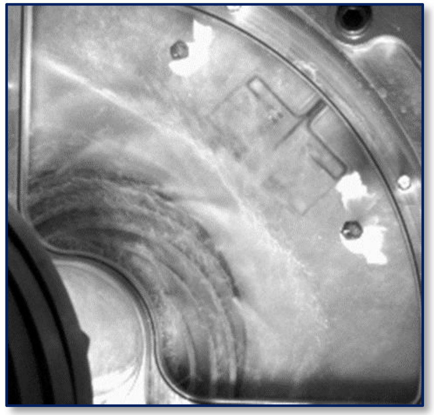
- Most new thermodynamic systems are closed or semi-closed cycles requiring:
  - Very high machinery efficiency over a variety of temperatures, pressures, and scales (radial → axial)
  - Low leakage/makeup requirements; consider hermetic machinery (bearings, seals)
  - High pressures, densities, possibly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

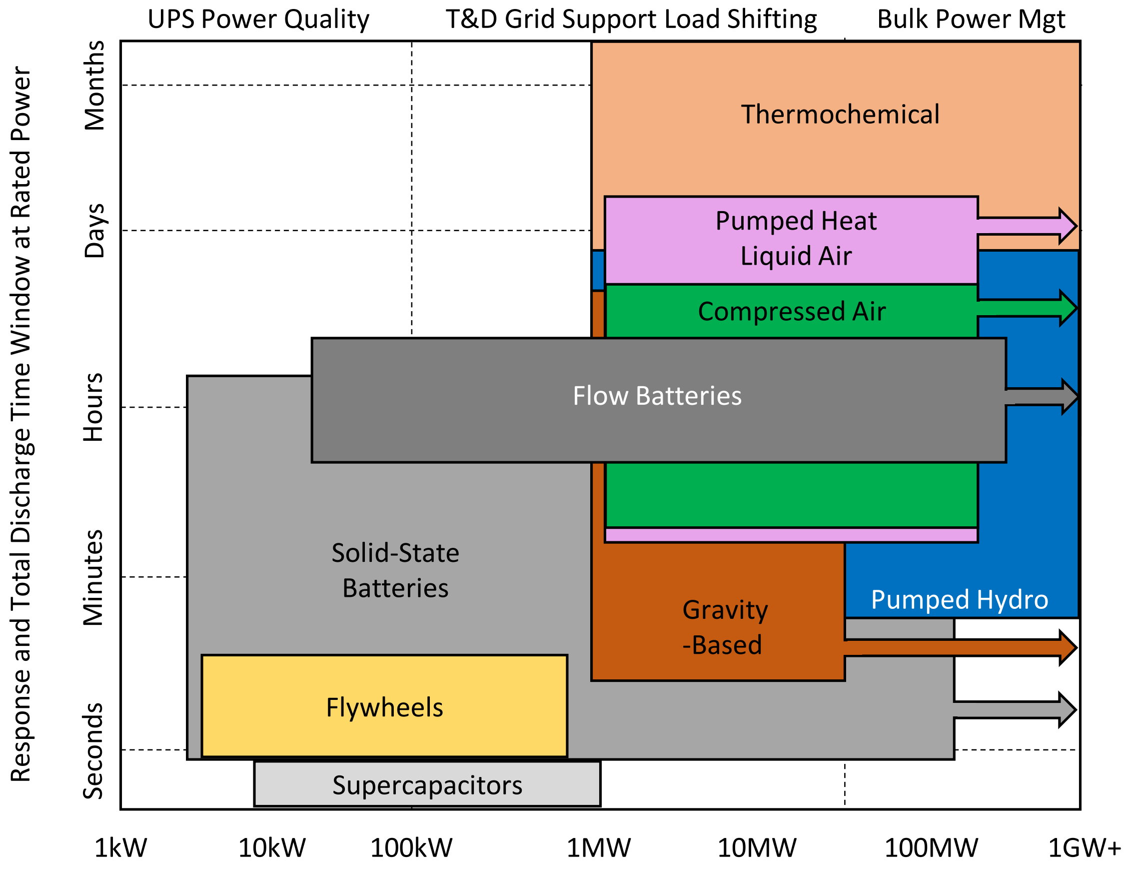


CO2 Compressor for CCS with Internally-Cooled Diaphragms (Moore 2014)



Wet Gas Compression Test (Musgrove 2016)

# Questions?

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