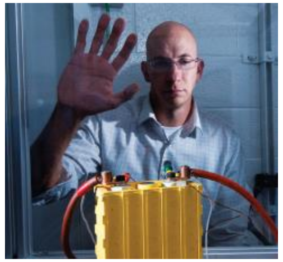
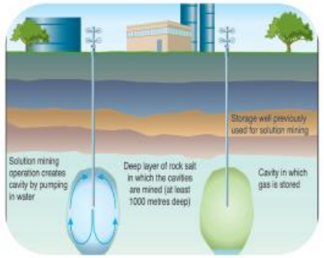
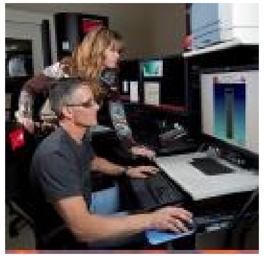
SAND2021-11897PE

Sandia National Laboratories

Long-Duration Energy Storage Technologies for NM







PRESENTED BY

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SAND2020-9626 PE

U.S. DEPARTMENT OF ENERGY NNSA

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Objective

Provide an overview of **large-capacity, long-duration energy storage** solutions that can enable higher penetrations of intermittent renewable energy with increased grid stability, reliability, and resilience for New Mexico

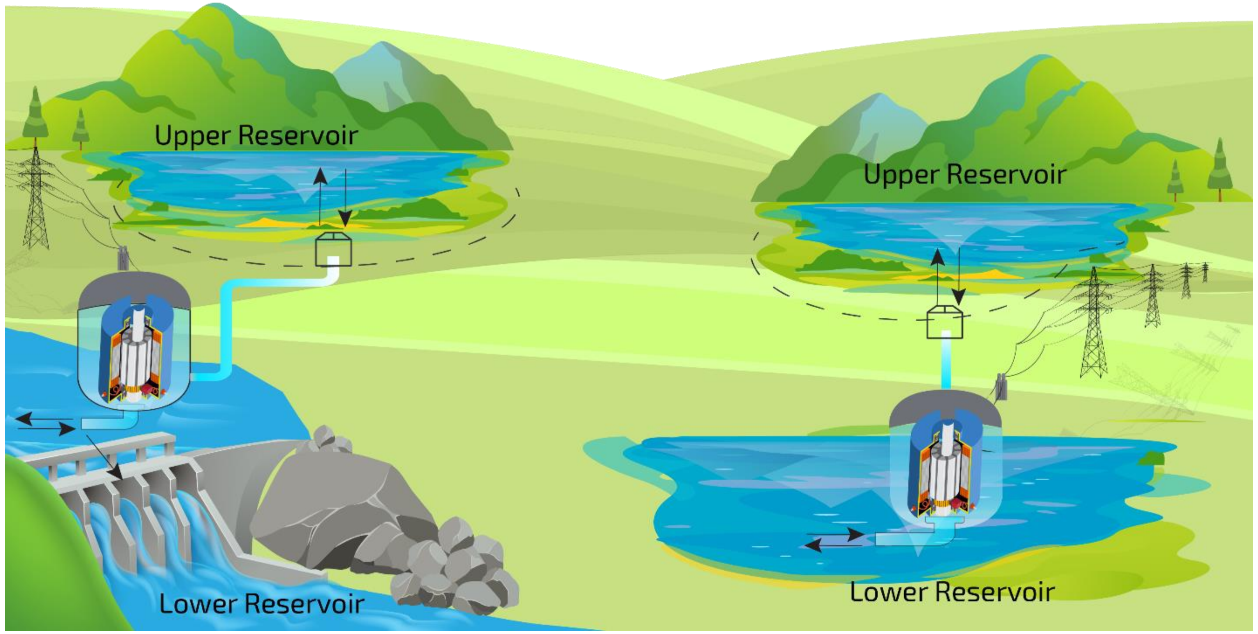
Summary of Energy Storage Technologies Evaluated

Storage Technology	Advantages	Challenges	Opportunities for NM
Compressed Air	• Demonstrated capability at large scales • Moderate round-trip efficiency • Good potential for long-duration storage	• Low number of demonstrations • Unique geologic resources • Well integrity • Repository integrity	• Suitable caverns and geologic repositories exist in NM for CAES
Electrochemical	• Mature technology • Modular deployment • Flow batteries can de-couple energy capacity from power capacity	• Short duration (~4 hrs), safety, and rare materials for Li-ion batteries • Limited cycles • High cost of large-capacity, long-duration systems	• Availability of renewable electricity for charging.
Flywheel	• Simple mechanical device • Provides spinning inertia • Large flywheels can store useful energy for days	• Can require significant power input • Requires tight tolerances and precision for very large flywheels	• Large flywheel design and manufacturing (>100 MWh)
Hydrogen	• Can be stored in large capacities for long periods of time • Can be used for both grid and transportation • Environmentally friendly	• Low round-trip efficiency of hydrogen production and storage • High cost of new infrastructure • Leakage and safety of hydrogen gas	• Hydrogen production from natural gas with CO_2 storage • San Juan County seeking to be hydrogen hub • Use of existing gas pipelines
Pumped Hydro	• Mature technology • Demonstrated large capacity (~GWh); >90% of U.S. grid energy storage • Good reliability with long-duration capabilities • Black start, Reactive Power and Grid Inertia capability • Low O&M costs	• Requires geologic elevation differences and water availability • Regulatory frameworks needs to encourage development • High initial capital cost	• Geographic availability • Modular pumped hydro systems allows synergy with local economies • Opportunity to utilize brackish/produced water
Other Gravimetric	• Simple technology • Can be sited widely with modular systems	• Very low energy density; requires many towers, many rail systems, or excavation of many mine shafts • Requires significant amounts of mass (volume) of storage material	• Geographic availability
Thermal	• Sensible heat storage (molten salt) is mature technology • Demonstrated large capacity with concentrating solar power (~GWh) • Low cost	• Heat loss • Large volumes required • Heat exchanger performance and cost • Latent and thermochemical storage are not mature	• Concentrating solar power and sensible thermal storage are a good fit for NM due to high solar irradiance and large areas of land

Bulk Storage Technologies

Pumped Hydroelectric and Gravimetric Storage

Pumped Hydroelectric Storage - Overview



SNL Energy Storage Handbook, 2020

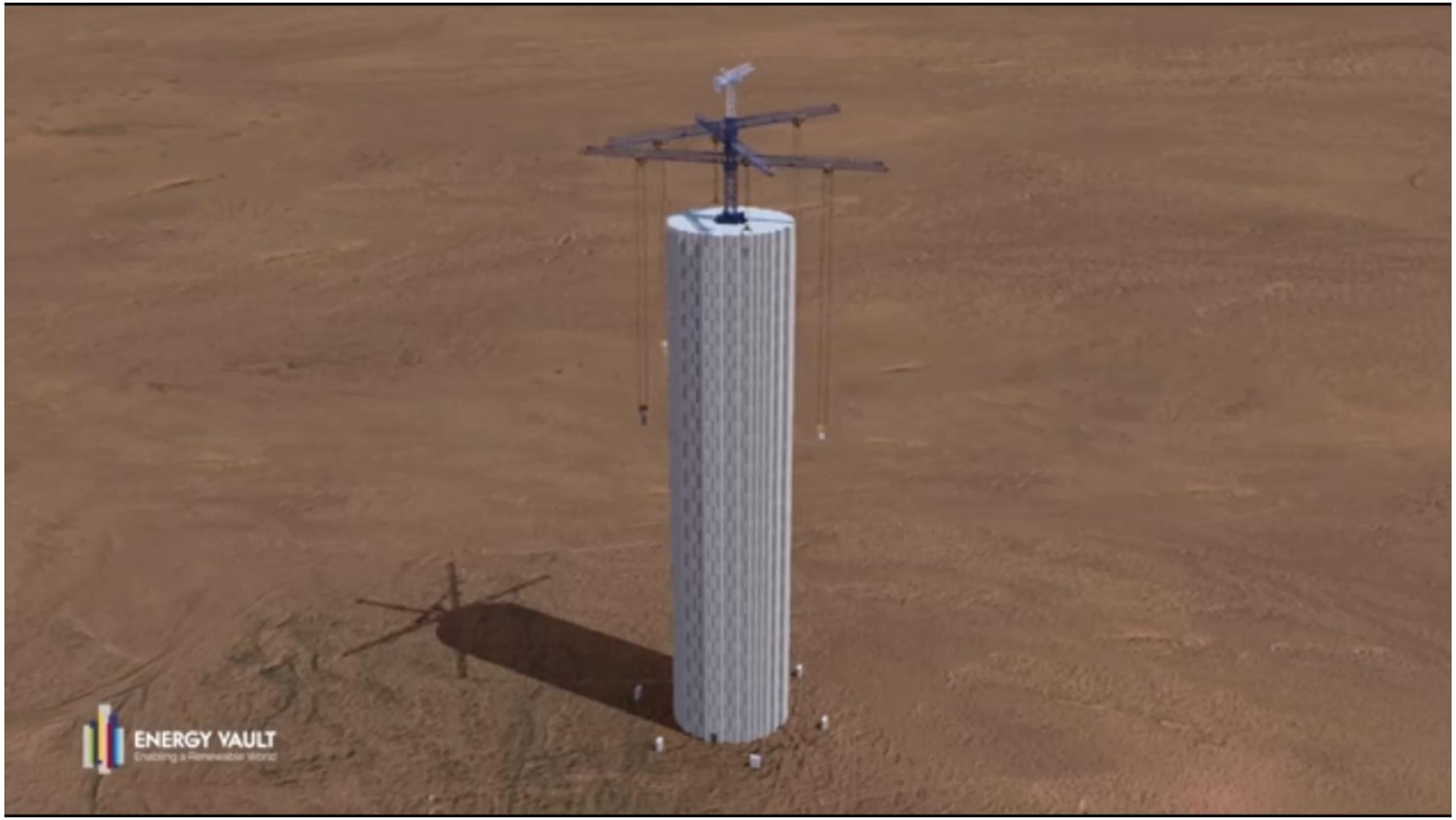
- ~23 GW of pumped hydro storage in U.S. as of 2018 (95% of energy storage on the grid)
- Expected to grow to ~150 GW by 2050
- As of January 2020, 74 active (FERC)-issued preliminary permits for proposed PHS projects (649 GW)

Pumped Hydro Storage - Specifications

Ho, *Applied Thermal Engineering*, 109 (2016) 958-969; Wang et al., *Energies*, 10, 991 (2017)

Metric	Value
Levelized Cost ($/$MWh_e$)	150 – 220
Round-trip efficiency	65 – 80%
Energy density (MJ/m^3)	~2 - 7
System life	>30 yrs (>10,000)
Toxicity/ environmental impacts	Water evaporation/ consumption
Restrictions/ limitations	Large amounts of water required; geographic limitations

Gravimetric Storage of Large Blocks

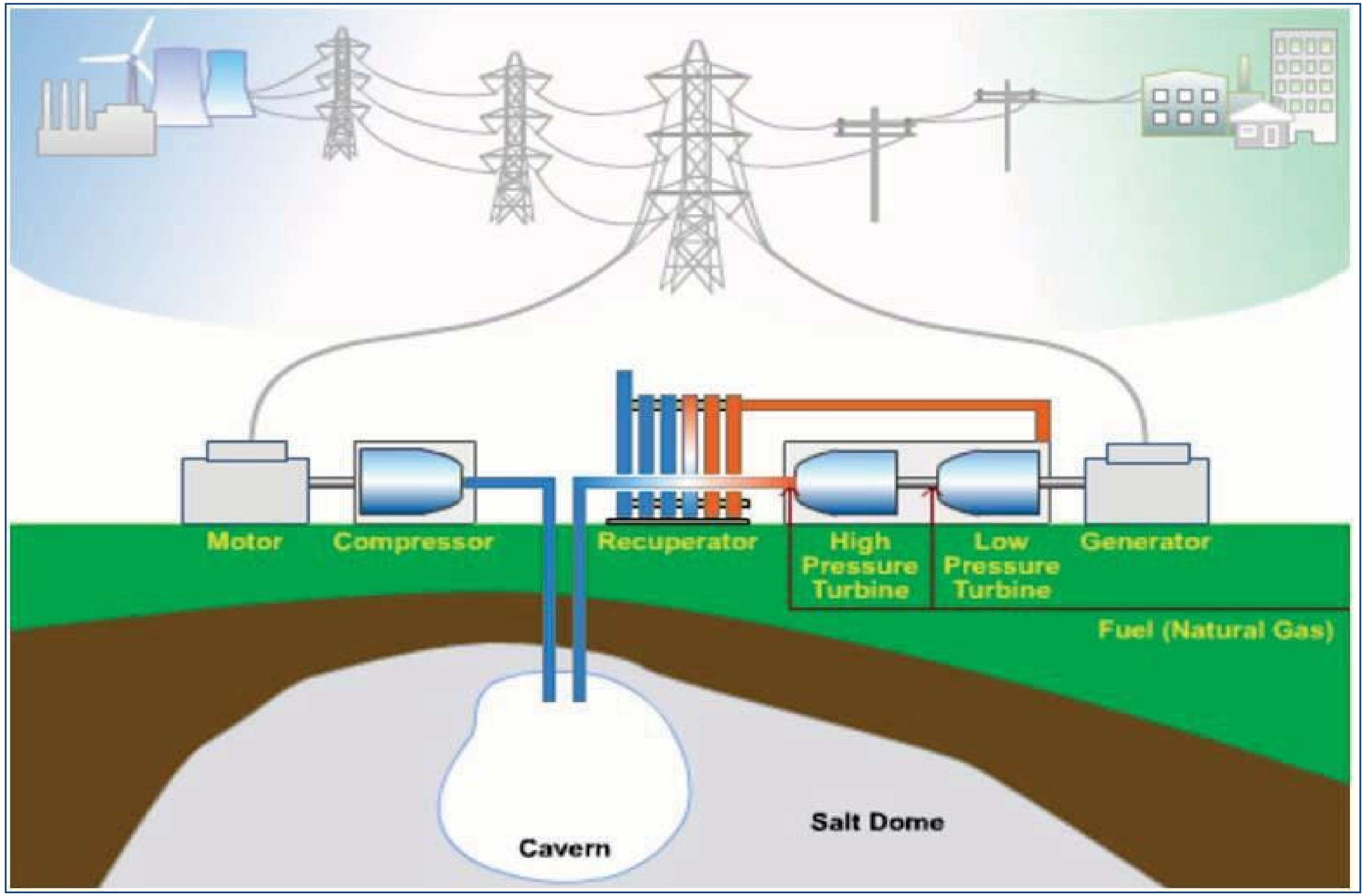


Source: https://www.youtube.com/watch?v=itbwXMMkBQw

- Gravimetric storage has relatively low energy density (~1 - 2 MJ/m^3 for every 100 m of elevation)
  - ~100 – 1,000 times less than thermal storage
  - ~1,000 – 10,000 times less the H_2 storage

Compressed Air Energy Storage

Compressed Air Energy Storage (CAES) - Overview



SNL Energy Storage Handbook, 2020

- Capacities of up to 400 MW and discharge times of 8 to 26 hours
- 1st generation commercial systems
  - PowerSouth Energy Cooperative (formerly Alabama Electric Cooperative) – 18 yrs
  - 290-MW, 4-hour CAES plant in Huntorf, Germany, since December 1978 (90% availability)

Compressed Air Energy Storage - Specifications

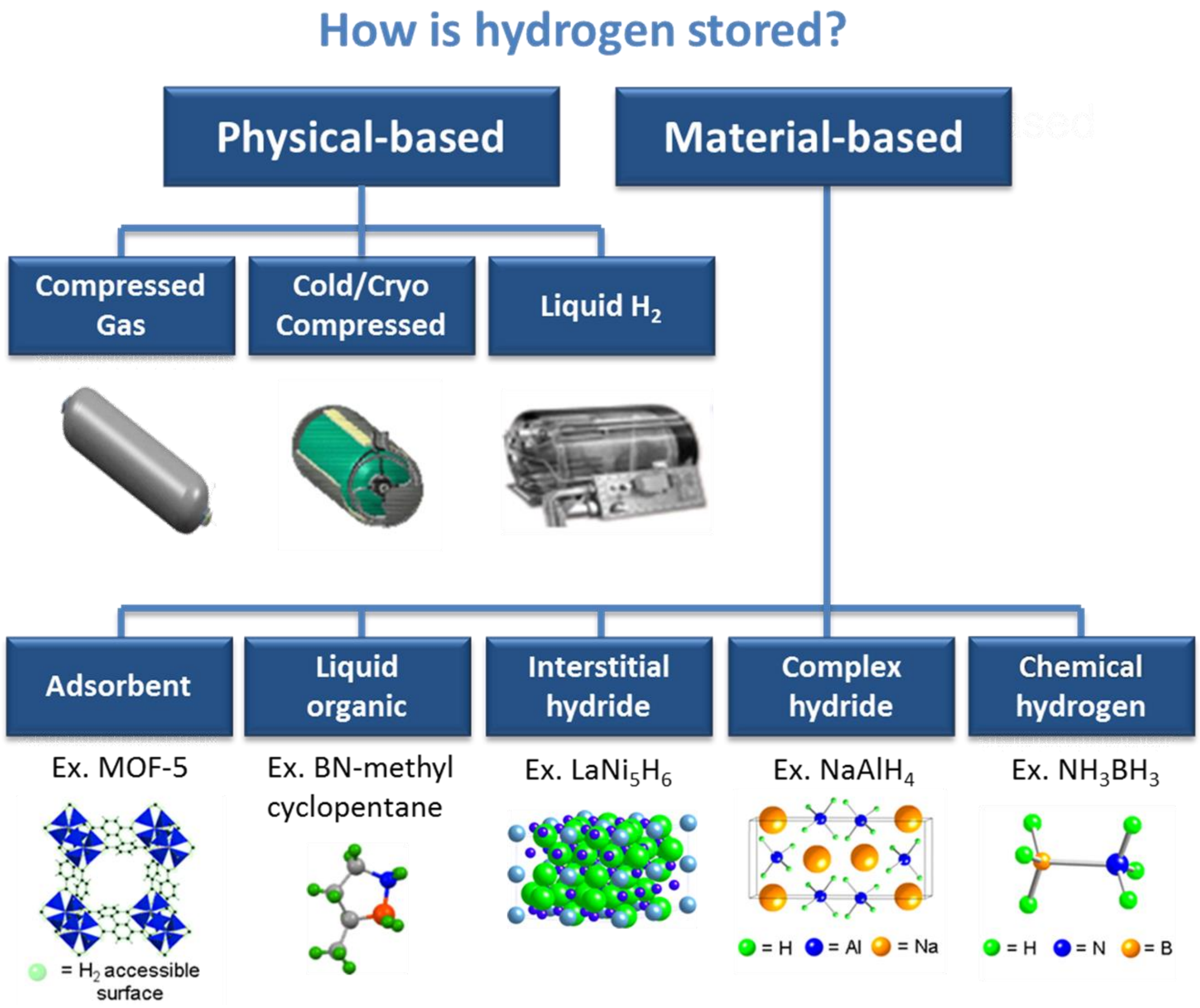
Ho, *Applied Thermal Engineering*, 109 (2016) 958-969; Wang et al., *Energies*, 10, 991 (2017)

Metric	Value
Levelized Cost ($/MWh$_e$)	120 – 210
Round-trip efficiency	40 – 70%
Energy density (MJ/m^3)	~7 - 22
System life	>30 yrs (>10,000 cycles)
Toxicity/ environmental impacts	Use of large subsurface caverns
Restrictions/ limitations	Unique geography required

Hydrogen and Liquid Fuels

Hydrogen Storage - Overview

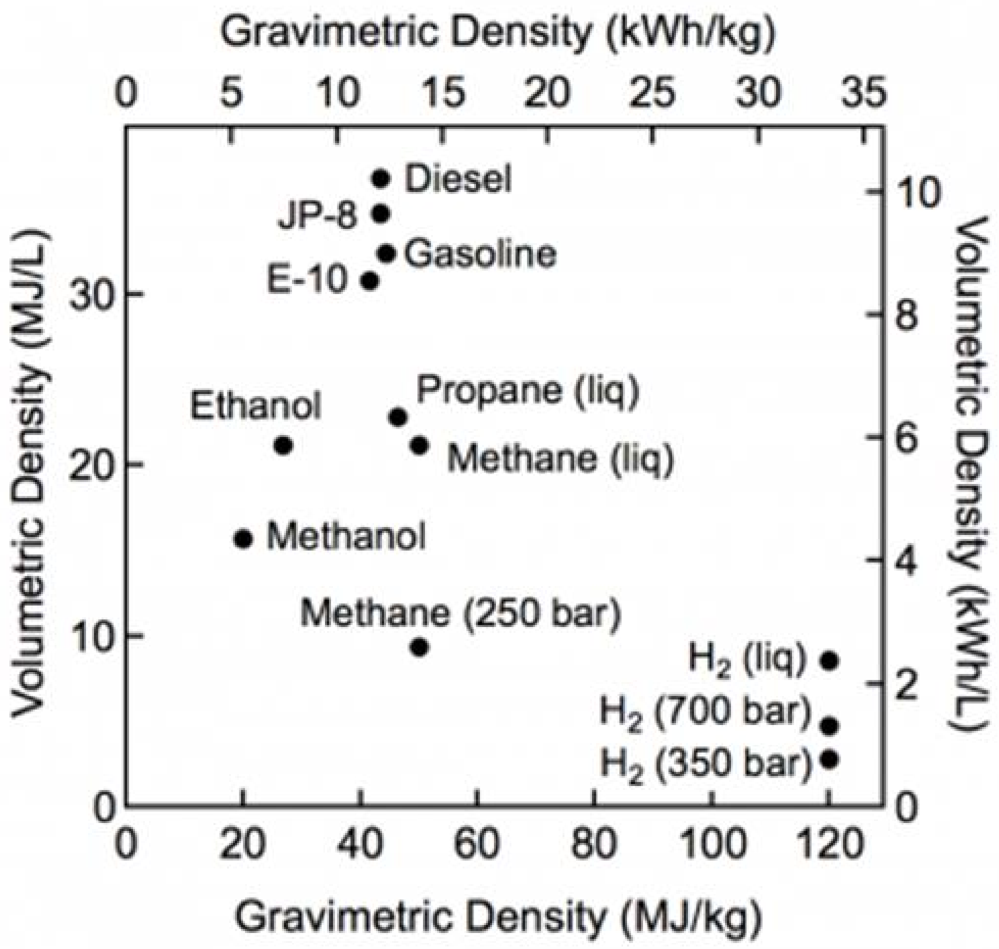
- Once generated from electrolysis (or another process), hydrogen can be stored in gaseous, liquid, or “bonded” forms.



Source:
https://www.energy.gov/eere/fuelcells/hydrogen-storage#:~:text=On%20a%20volume%20basis%2C%20however,based%20on%20lower%20heating%20values.

Hydrogen Storage – Specifications and DOE Target Metrics

- Challenges
  - Weight and volume
  - Efficiency
  - Durability
  - Cost
- Specific system targets include the following:
  - 1.5 kWh/kg system (4.5 wt.% hydrogen)
  - 1.0 kWh/L system (0.030 kg hydrogen/L)
  - $10/kWh ($333/kg stored hydrogen capacity)



Hydrogen Storage Storage - Specifications

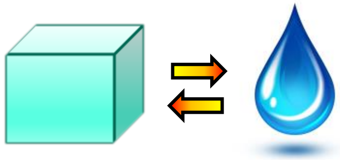
Mayyas et al., 2020, International Journal of Hydrogen Energy, 45, 16311-16325; Wang et al., *Energies*, 10, 991 (2017)

Metric	Value
Levelized Cost ($/MWh$_e$)	~160 - 250
Round-trip efficiency	~30%
Energy density (MJ/m^3)	~2000 – 10,000
System life	~20 years
Toxicity/ environmental impacts	Environmentally friendly, but potential flammability hazard if released
Restrictions/ limitations	Requires low electricity costs of ~$2/MWh

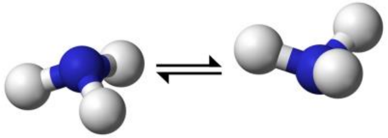
Thermal and Thermochemical Storage

Thermal Energy Storage - Overview

- Sensible (single-phase) storage
  - Use temperature difference to store heat
  - Molten salts (nitrates <600 °C; carbonates, chlorides 700 – 900 °C)
  - Solids storage (graphite, concrete, ceramic particles), >1000 °C



- Phase-change materials
  - Use latent heat to store energy (e.g., molten salts, metallic alloys)



- Thermochemical storage
  - Converting thermal energy into chemical bonds (e.g., decomposition/synthesis, redox reactions)

Molten-salt storage tanks at Solana CSP plant in Arizona. Credit: Abengoa

Falling particles for direct solar heating Sandia National Laboratories

Thermal Energy Storage - Applications

Sensible

Molten Salt Storage

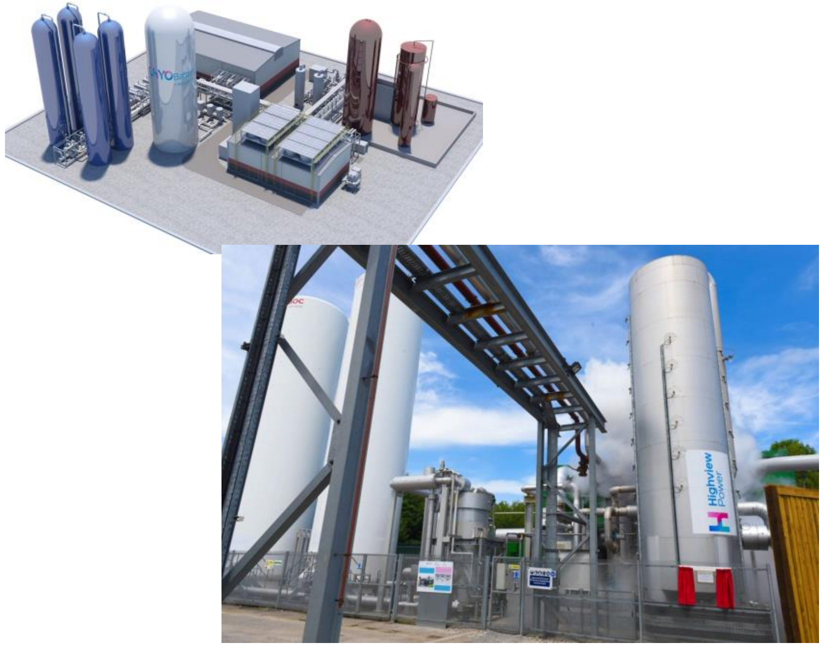
photo credit: Mary Grikas, Wiki commons, 10/9/15

Crescent Dunes CSP, Nevada
100 MW/1 GWh

https://en.wikipedia.org/wiki/Solana_Generating_Station

Solana CSP, Arizona
280 MW/1.7 GWh

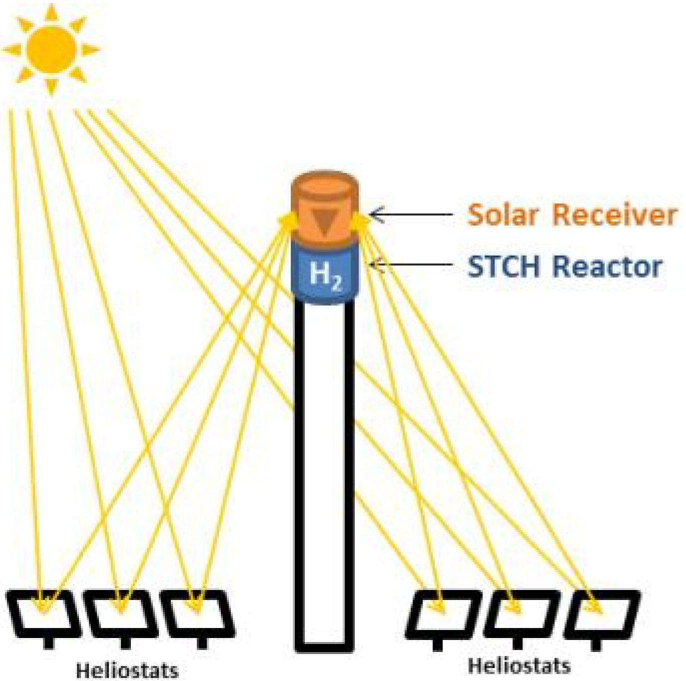
Latent



Images: Highview Power

Highview Power Liquid Air Energy Storage
50 MW/400 MWh
(Vermont - planned)

Thermochemical



https://www.energy.gov/eere/fuelcells/hydrogen-production-thermochemical-water-splitting

Solar thermochemical hydrogen production
(pilot demonstration)

Thermal Energy Storage (Sensible) - Specifications

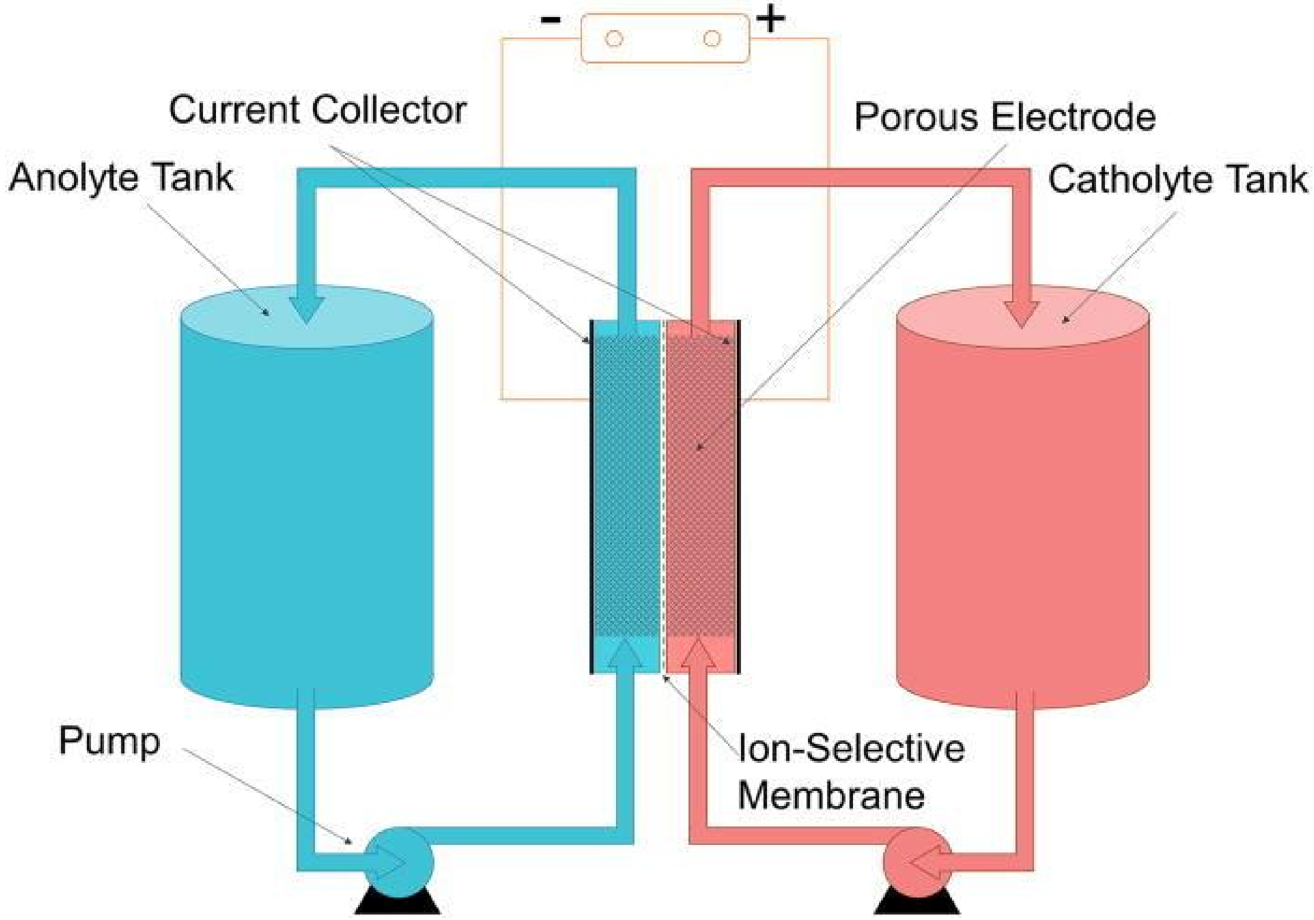
Ho, 2016, *Applied Thermal Engineering*, 109 (2016) 958-969; Siegel, 2012, *Wiley Interdisciplinary Reviews: Energy And Environment*, 1(2), 119-131.

Metric	Values	
	Solid Particles	Molten Nitrate Salt
Levelized Cost ($/MWh$_e$)	10 - 13	11 - 17
Round-trip efficiency	>98% (thermal in/out)	>98% (thermal in/out)
Energy density (MJ/m^3)	~400 - 900	~600 - 900
System life	30 yrs (>10,000)	30 yrs (>10,000)
Toxicity/ environmental impacts	N/A	Reactive with piping materials
Restrictions/ limitations	Particle/fluid heat transfer can be challenging	decomposes above ~600 °C

Electrochemical Storage

Flow Battery

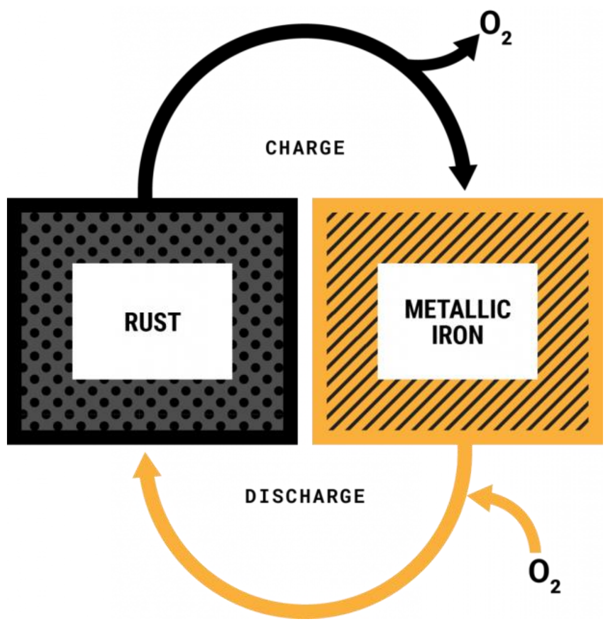
- Flow battery consists of two tanks of liquid electrolytes which are pumped past a membrane held between two electrodes to generate electricity through an external circuit
  - Lower energy density than Li-ion batteries
  - Large cycle life (~10,000)
  - Energy capacity determined by volume of storage tanks



https://en.wikipedia.org/wiki/Flow_battery

Iron-Air Battery (Form Energy)

- From Form Energy website:
  - "Reversible Rusting"
    - Iron and air electrodes and water-based electrolyte
  - $1/10^{th}$ cost of Li-Ion batteries
  - 100+ hour duration
  - Modular and scalable
  - Safe (no thermal runaway or heavy metals)



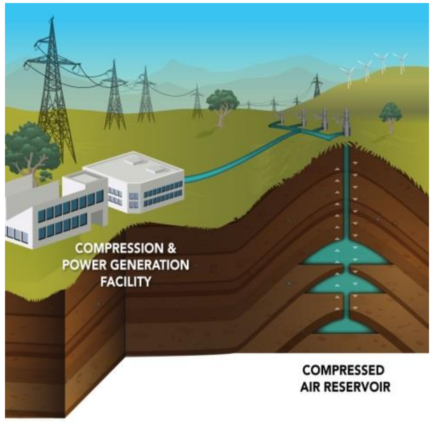
"~1 MW/acre"

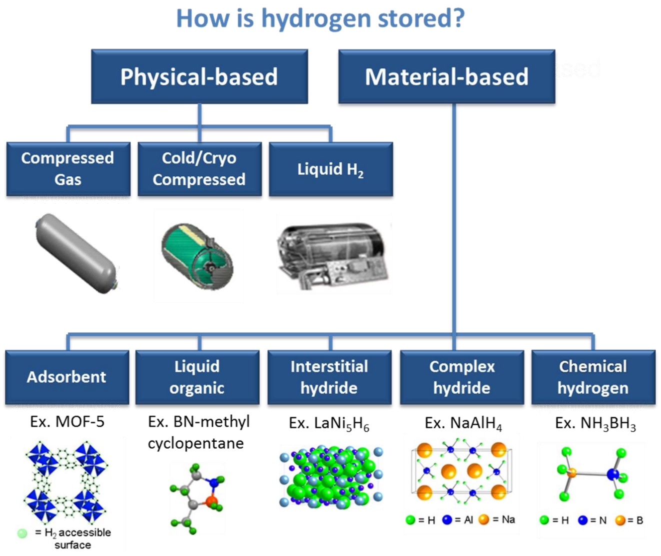
https://formenergy.com/technology/battery-technology/

Bulk Storage – Summary

Long-Duration Energy Storage Technologies

- Pumped Hydro and Gravimetric Storage Technologies
- Compressed Air Energy Storage
- Hydrogen and Liquid Fuels
- Thermal Storage
- Electrochemical Storage





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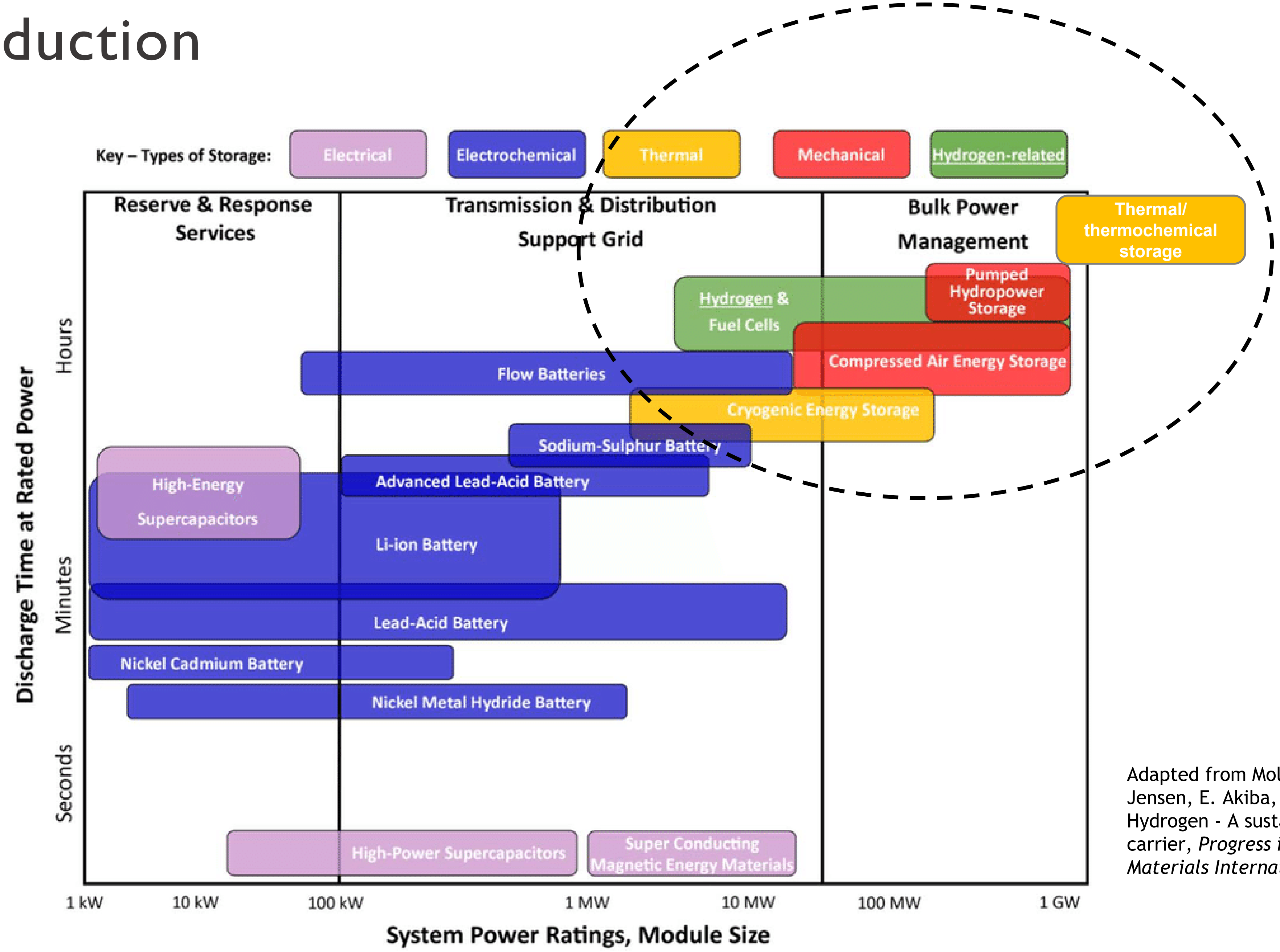
Backup Slides

Summary of Advantages and Challenges

Storage Technology	Advantages	Challenges
Pumped Hydro	▪ Mature technology ▪ Demonstrated large capacity (~GWh); >90% of U.S. grid energy storage ▪ Good reliability	▪ Unique geologic resources and water availability ▪ Improved turbines and electrical systems ▪ Small modular pumped hydro systems
Compressed Air	▪ Demonstrated capability at large scales ▪ Moderate round-trip efficiency ▪ Good potential for long-duration storage	▪ Unique geologic resources ▪ Well integrity ▪ Repository integrity
Hydrogen	▪ Can be stored in large capacities for long periods of time ▪ Can be used for both grid and transportation ▪ Environmentally friendly	▪ Low round-trip efficiency of hydrogen production and storage ▪ High cost ▪ Leakage and safety of hydrogen gas
Thermal (Sensible)	▪ Mature technology ▪ Demonstrated large capacity with concentrating solar power (~GWh) ▪ Low cost	▪ Heat loss ▪ Large volumes required ▪ Heat exchanger performance and cost
Thermochemical	▪ Large energy density ▪ Potential for long-duration storage	▪ Low maturity ▪ High cost ▪ Material durability and kinetics

Introduction



Adapted from Moller, K.T., T.R. Jensen, E. Akiba, and H.W. Li, 2017, Hydrogen - A sustainable energy carrier, *Progress in Natural Science-Materials International*, **27**(1), p. 34-40

Comparison of Large-Scale Battery and Thermal Energy Storage Capacity in the U.S.