First-principles techno-economic analysis of Long Duration Energy Storage

NETL – Research and Innovation Center

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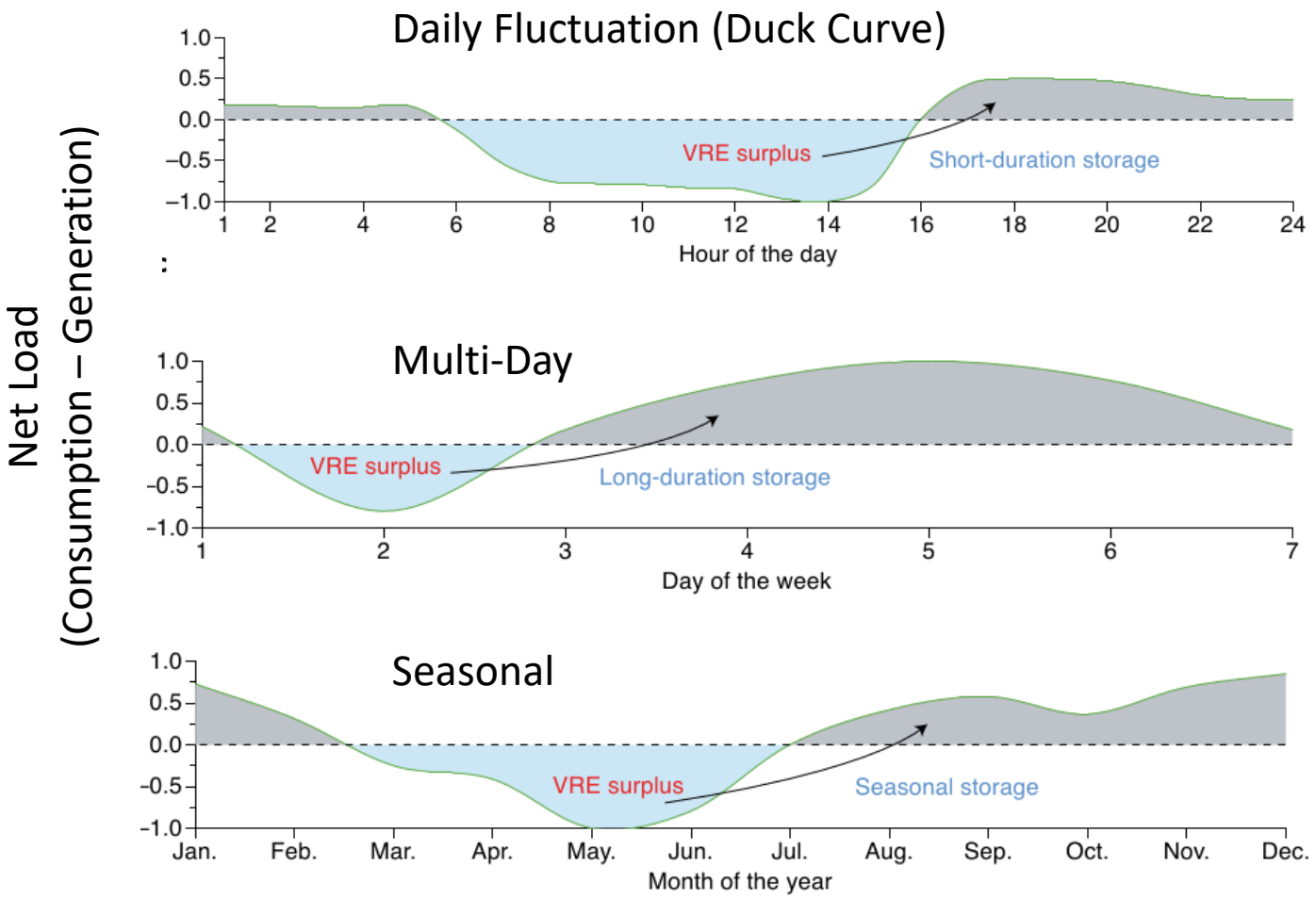
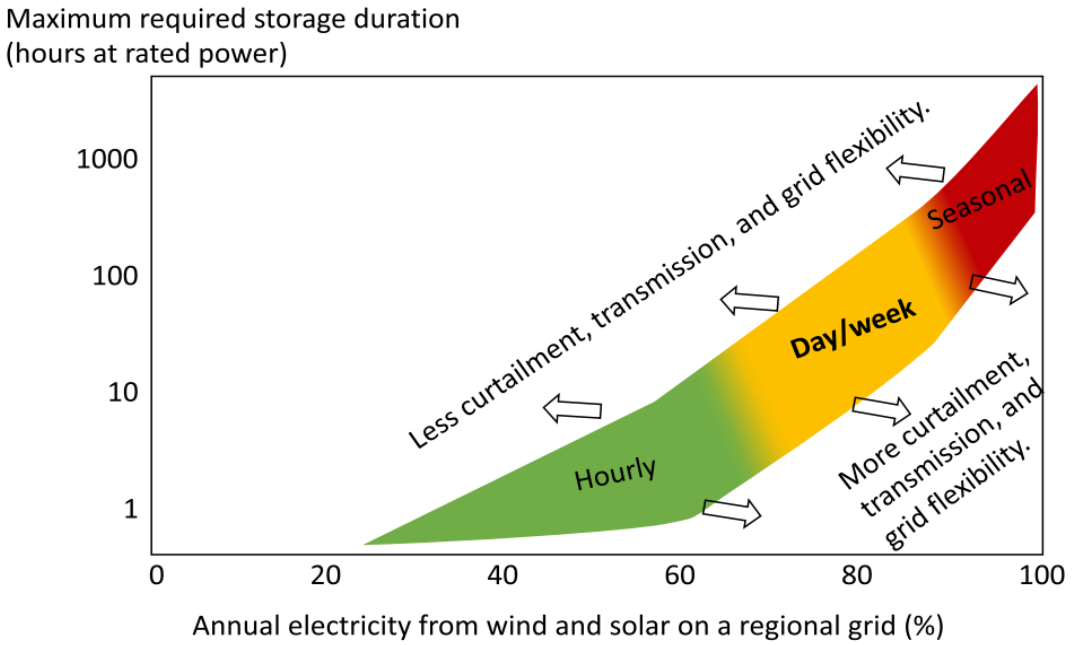
The need for energy storage

Variable Renewable Energy (VRE) fluctuations over many timescales

Guerra, Omar J. "Beyond Short-Duration Energy Storage." *Nature Energy (2021)* https://doi.org/10/gjwh76.



- Need multi day and seasonal storage at high renewable fraction



Albertus et al. "Long-Duration Electricity Storage Applications, Economics, and Technologies." Joule (2020):. https://doi.org/10/gg6vfx.

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Cost Projections

Oliver et al. "Projecting the Future Levelized Cost of Electricity Storage Technologies." *Joule* (2019): https://doi.org/10/gf8tkh.

Predictions with current technologies and learning curves (i.e. no research intervention)

Lowest Levelized Cost

<u>>100 hours</u>

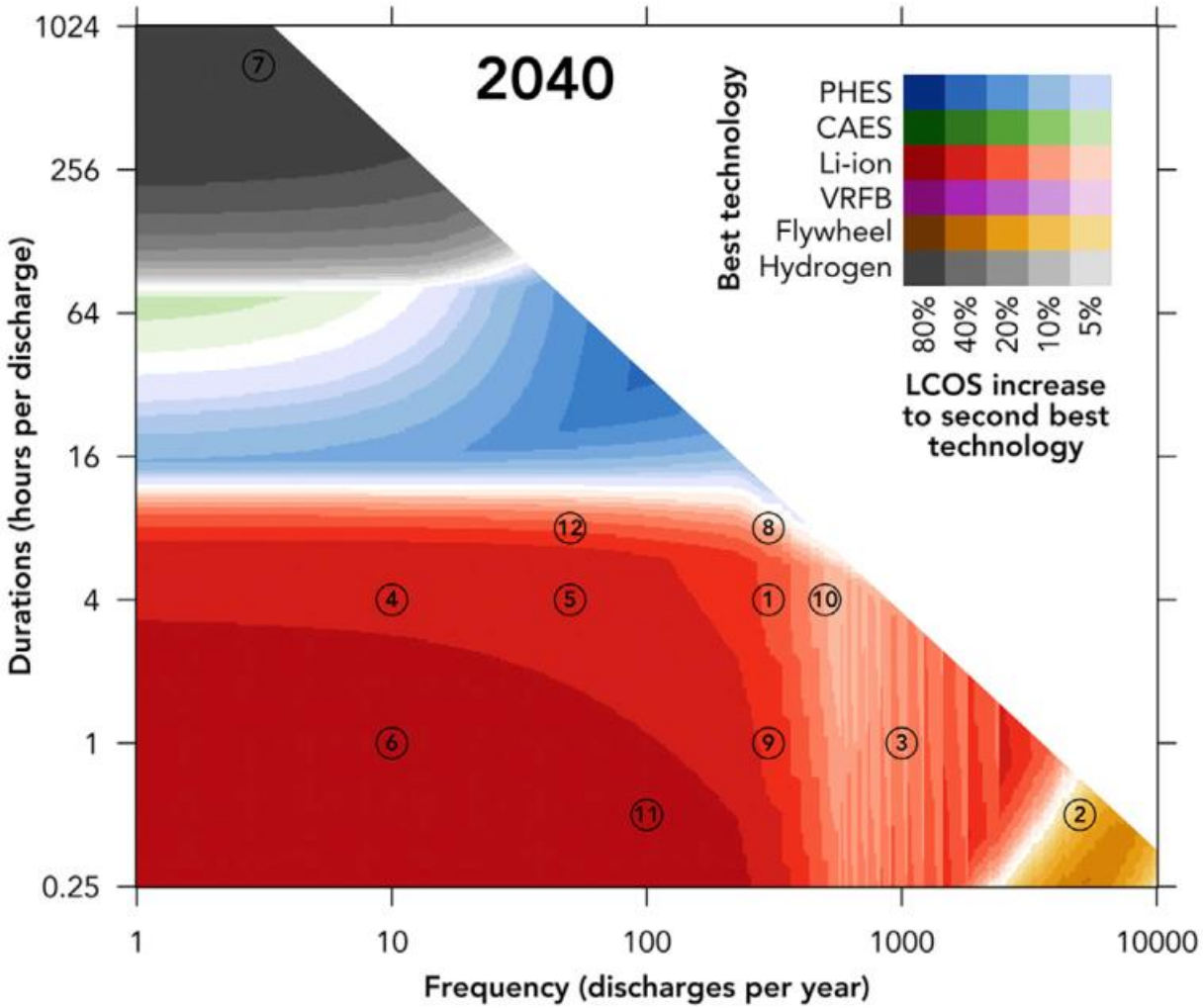
Hydrogen/synthetic fuel

<u>~10-100 hours</u>

No 'non-geologically-constrained' options

<u><10 hours</u>

Lithium-ion likely to dominate

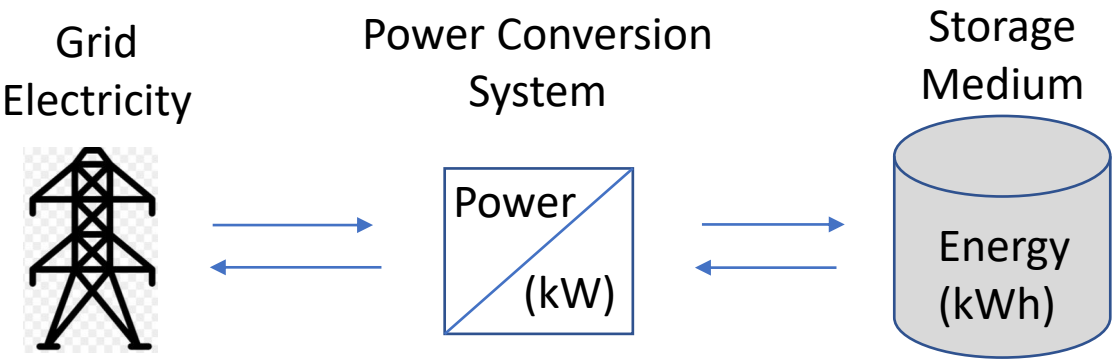


Pumped Hydro

Compressed Air (cavern)

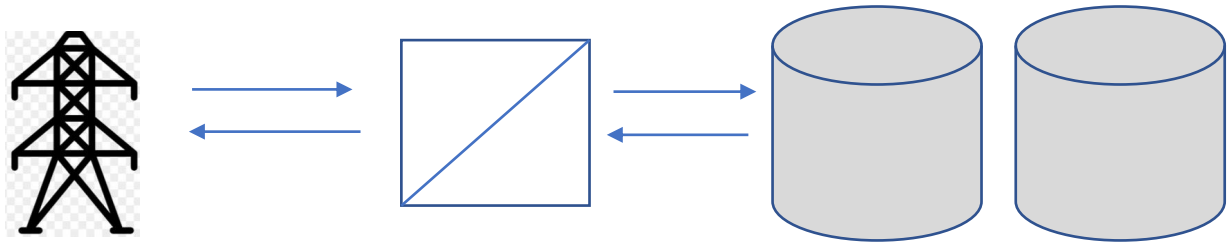
Vanadium Flow Battery

Energy Storage systems



What happens to cost for increasing duration?

$$\text{Duration [h]} = \frac{\text{Energy } [kWh]}{\text{Power [kW]}}$$



Input Electricity Cost

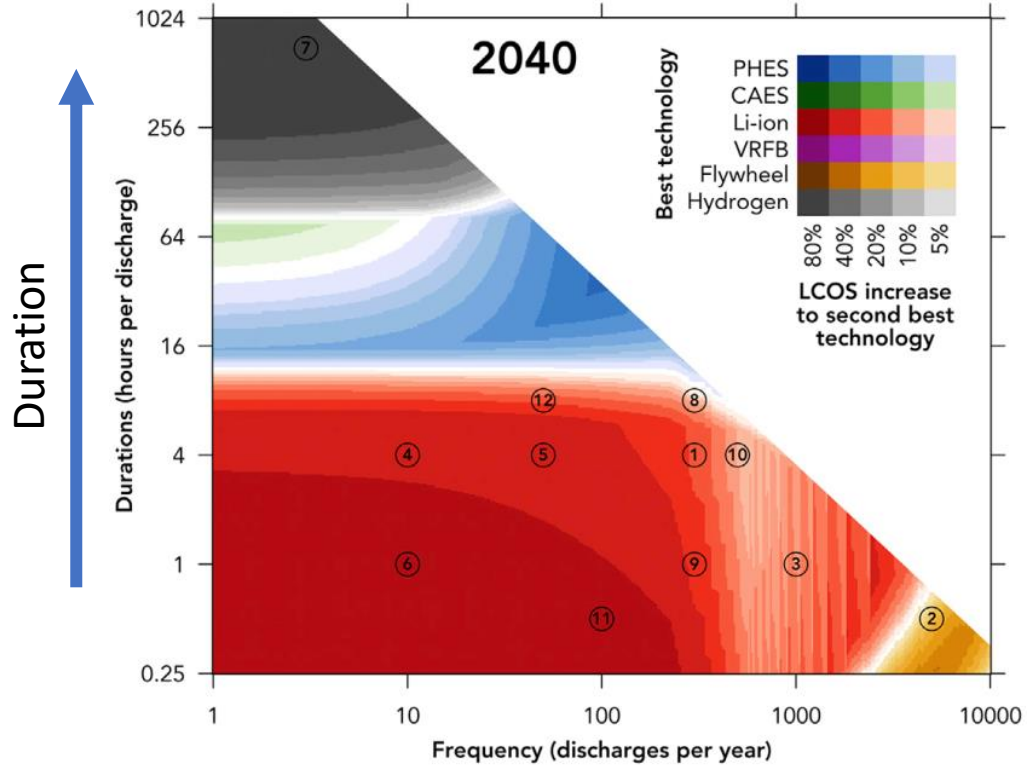
$C_{E,in}\ [\frac{\$}{kWh\ cycle}]$

Power Capital Cost

$C_{kW}\ [\$/kW]$

Energy Capital Cost

$C_{kWh}\ [\$/kWh]$



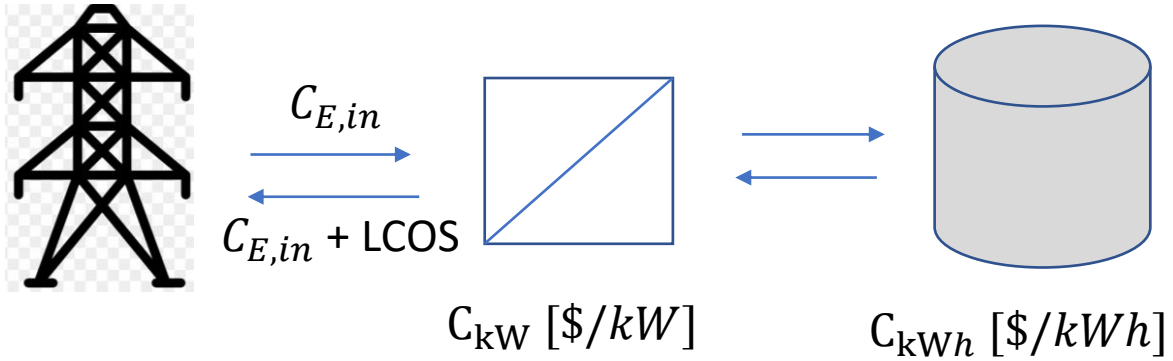
Levelized Cost of Storage

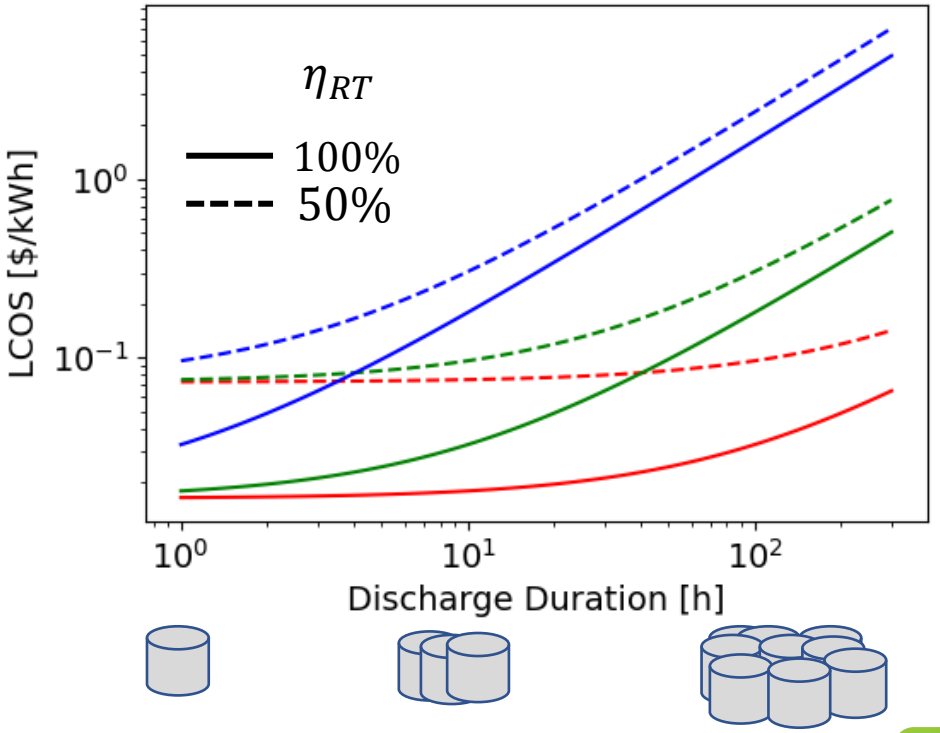
Extra cost of storing electricity

(η = efficiency)

Inefficiency Premium | Power capital | Energy capital

$$LCOS\left(\frac{\$}{kWh\ cycle}\right) = \left(\frac{1}{\eta_{RoundTrip}} - 1\right) C_{E,in} + \frac{\mathrm{C_{kW}}}{lifetime \cdot \eta_{out}} + \frac{\mathrm{C_{kWh}}}{lifetime \cdot \eta_{out}} \cdot \boldsymbol{duration}$$





$\frac{\mathrm{C_{kWh}}}{1000 \frac{\$}{kWh}}$

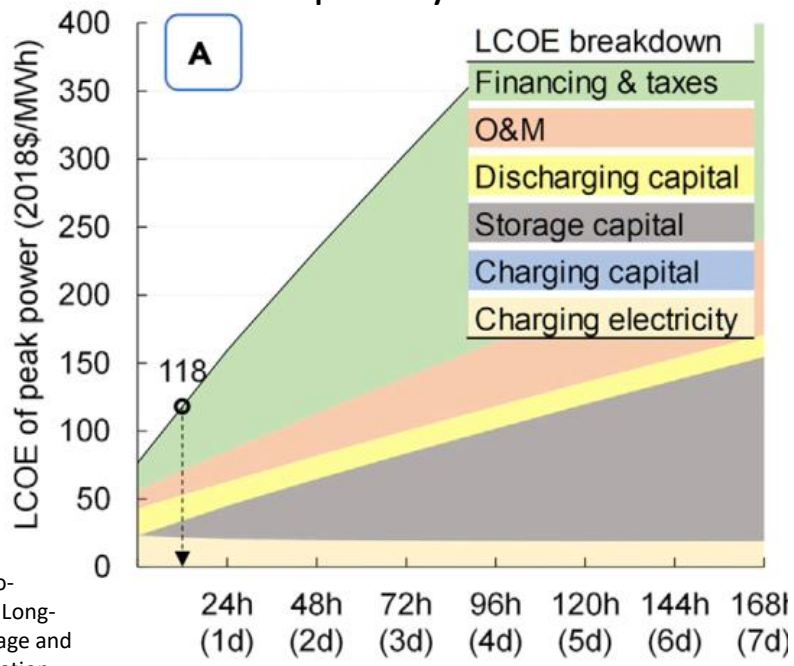
$100 \frac{\$}{kWh}$

$10 \frac{\$}{kWh}$

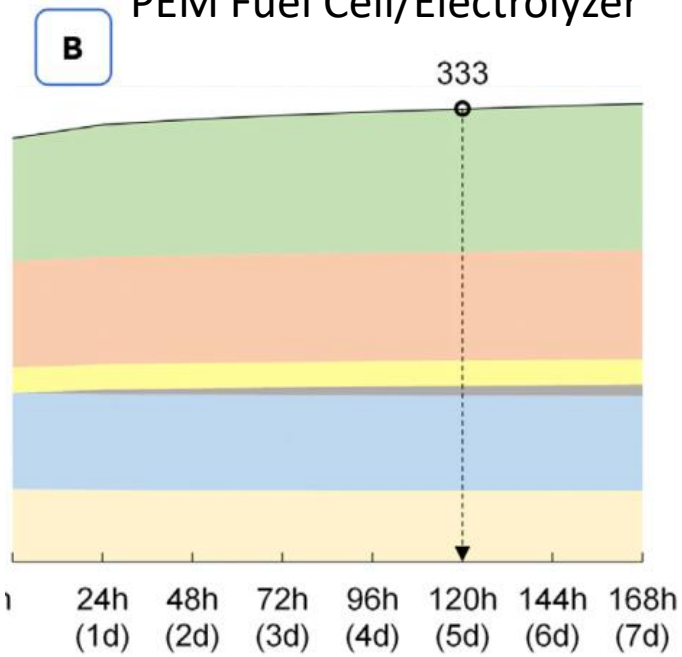
Energy capacity capital most important for long duration

$$LCOS\left(\frac{\$}{kWh}\right) = \underbrace{(1-\frac{1}{\eta_{RT}})PE + \frac{C_{kW}}{\eta_{out} lifetime}}_{\text{Vertical Offset}} + \underbrace{\frac{C_{kWh}}{\eta_{out} lifetime}}_{\text{Slope}} \cdot \textbf{duration}$$

Pumped Hydro



PEM Fuel Cell/Electrolyzer



- Pumped hydro: expensive land development $\propto kWh$
- Fuel Cell/Electrolyzer with Inexpensive salt cavern

For long duration: storage capital becomes more important

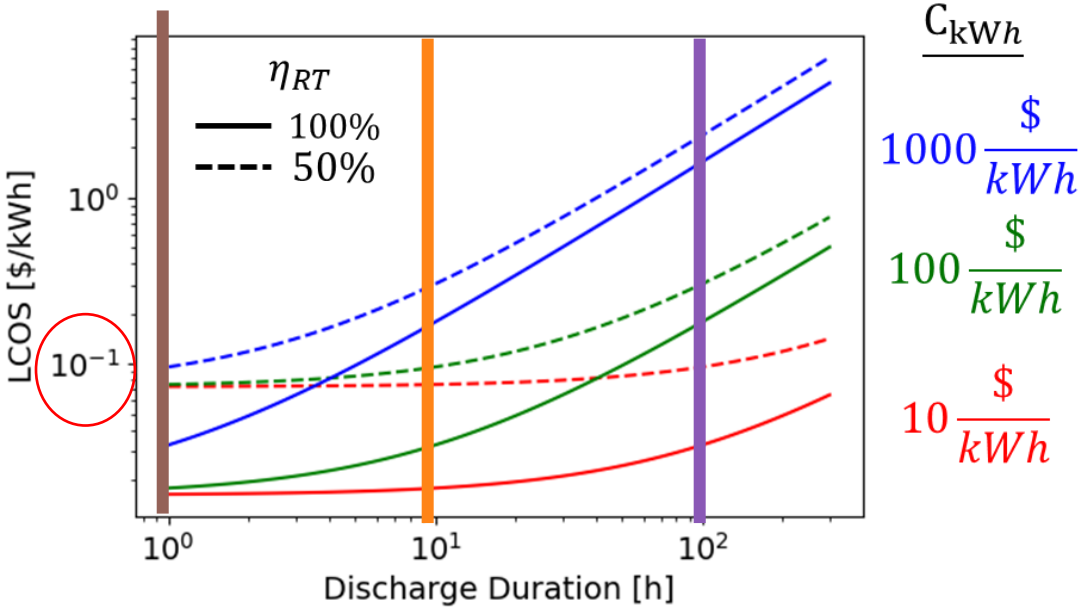
Key Figure of merit: $\frac{C_{kWh}}{\eta_{out} lifetime}$

C_{kWh} ($\$/kWh$) most able to vary over orders of magnitude compared to η_{out} and lifetime

Hunter et al. "Techno-Economic Analysis of Long-Duration Energy Storage and Flexible Power Generation Technologies to Support High-Variable Renewable Energy Grids." *Joule* (2021) https://doi.org/10/gk9mpf.

What C_{kWh} (energy capital cost) is needed?

What combination of C_{kWh}, C_{kW}, and η_{RT} are possible to achieve 0.1$/kWh LCOS?

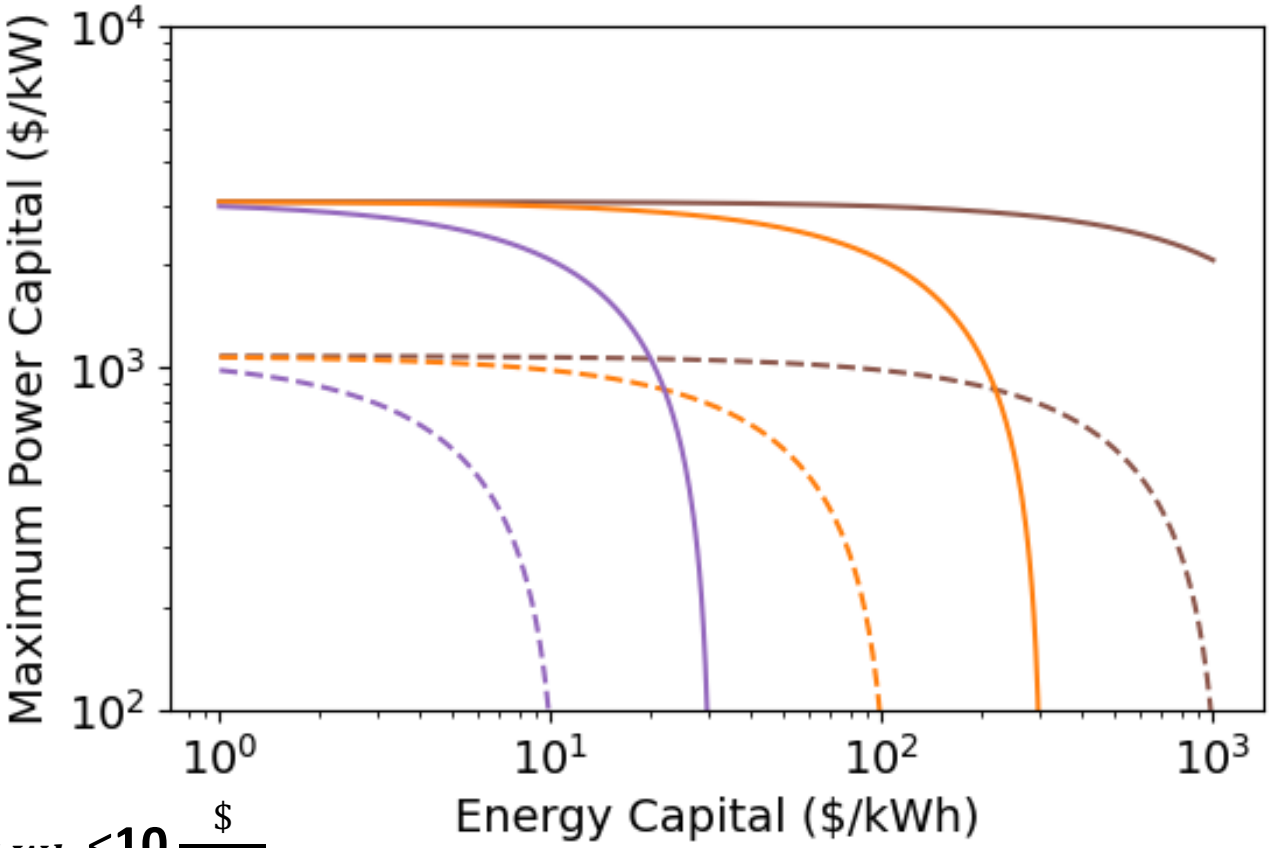


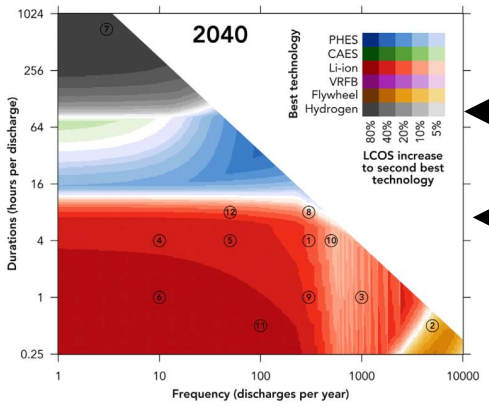
C_{kWh}

$1000 \frac{\$}{kWh}$

$100 \frac{\$}{kWh}$

$10 \frac{\$}{kWh}$





For 100 hours C_{kWh} <10 $\frac{\$}{kWh}$

For 10 hours C_{kWh} <100 $\frac{\$}{kWh}$

Technology Down Selection: Material Energy Capital Cost $C_{kWh,mat}$

$C_{kWh,mat}$ < ~10$/kWh as a criterion for long duration (~100 hours) fundamental viability

Accumulate many different **Material Cost** $C_{mat}[\frac{\$}{kg}]$

Define forms of energy and their **Energy Density** $\rho_E\ [\frac{kWh}{kg}]$

Stone
0.01 $\$/kg$

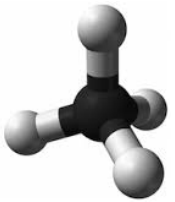
Steel
1 $\$/kg$

Vanadium oxide
20 $\$/kg$

Gravity
$\rho_E = g\Delta H$

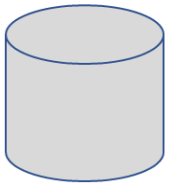
Sensible Thermal
$\rho_E = C_p\Delta T$

(Electro)Chemical
$\rho_E = \Delta G = \frac{n_e F \Delta V}{\mu}$



Combine to calculate $C_{kWh,mat}$

Storage Medium

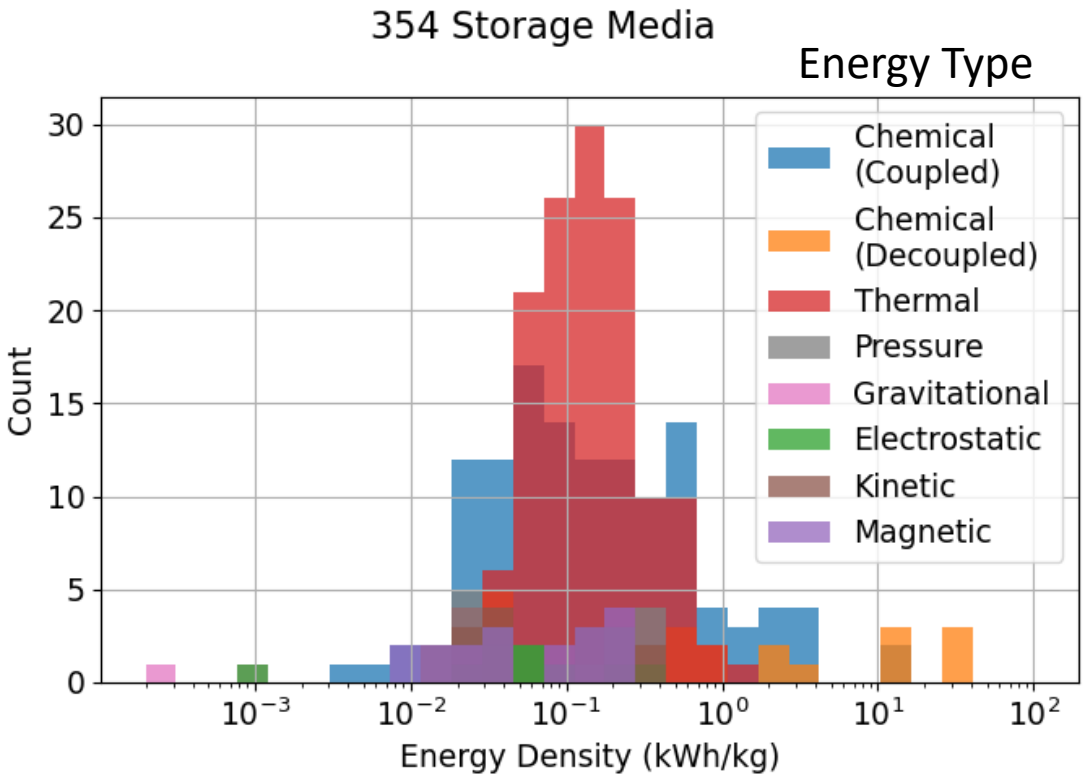


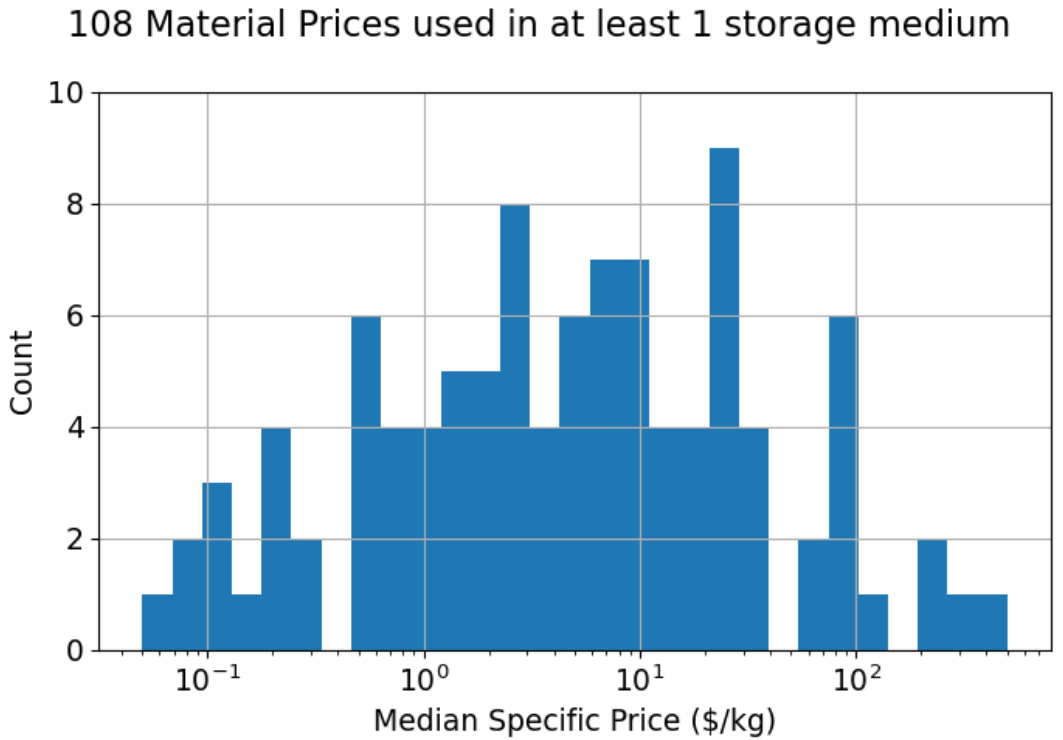
$$C_{kWh,total} > C_{kWh,mat}[\frac{\$}{kWh}] = \frac{C_{mat}[\frac{\$}{kg}]}{\rho_E\ [\frac{kWh}{kg}]}$$

Just testing for long-duration viability, candidates then need further examination.

- Balance of systems
- Efficiency
- Power costs
- Lifetime

Acumulate data for $\rho_E\ [\frac{kWh}{kg}]$ and $C_{mat}[\frac{\$}{kg}]$





Sources
- Physical properties in Scientific publications, used in ρ_E equations

Examples
- C_p for Thermal Storage in rocks
- ΔV for 1 mol Graphite (C_6) + 1 mol $LiCoO_2$ (Lithium ion battery)
- ΔG for Hydrogen Electrolysis/Fuel Cell

Sources
- Scientific publications
- USGS commodity data
- Internet Spot prices
- Alibaba web scraping

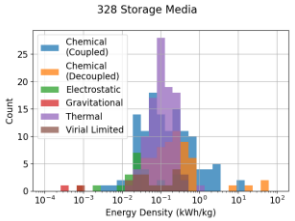
Examples
- Rocks
- Graphite
- $LiCoO_2$
- Salt cavern ($\frac{\$}{kg\ H_2}$)

All material energy capital cost data

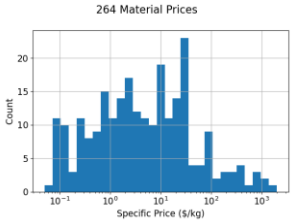
Each point is different storage medium

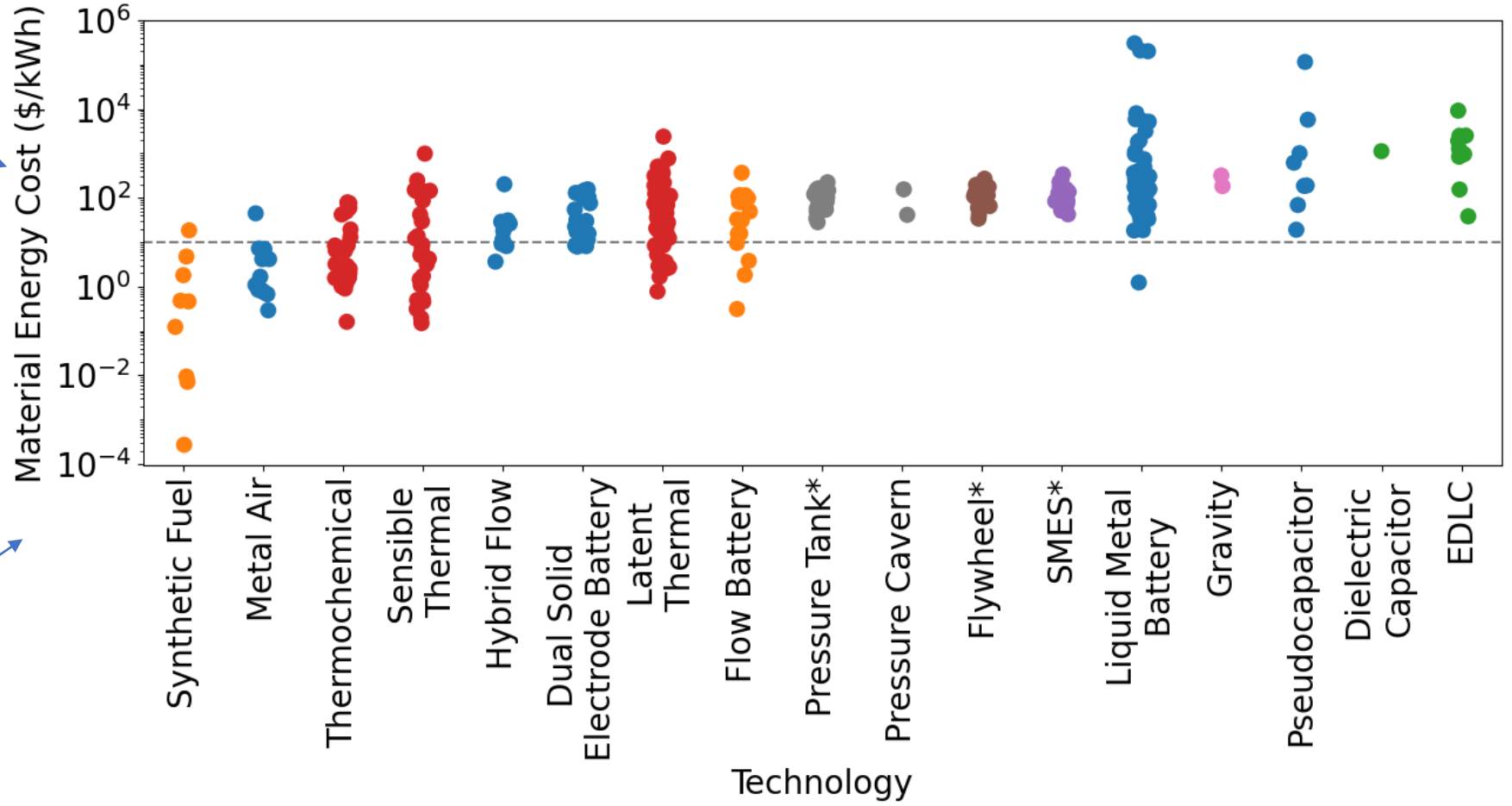
$$C_{kWh,mat}\left[\frac{\$}{kWh}\right] = \frac{C_{mat}\left[\frac{\$}{kg}\right]}{\rho_E\left[\frac{kWh}{kg}\right]}$$

$\rho_E\left[\frac{kWh}{kg}\right]$

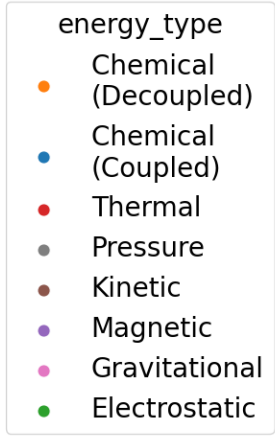


$C_{mat}\left[\frac{\$}{kg}\right]$



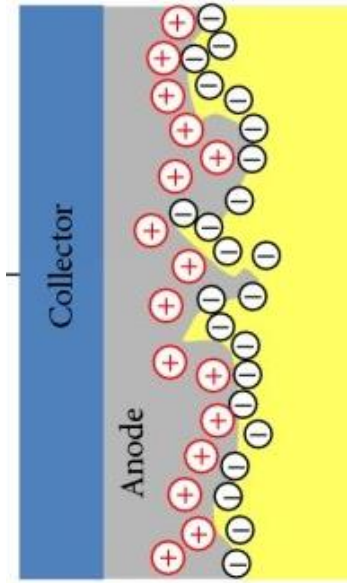


$10\frac{\$}{kWh}$

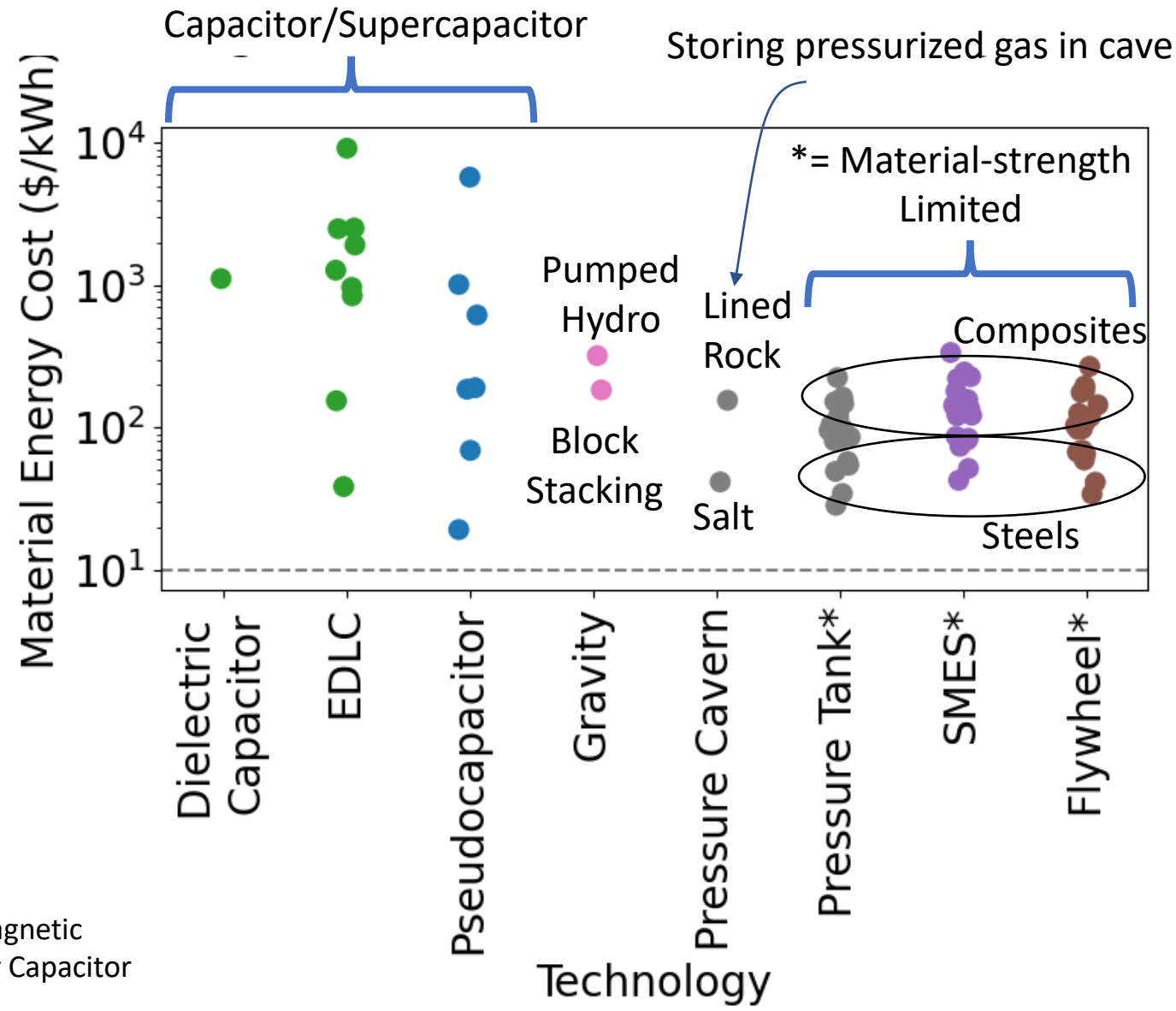


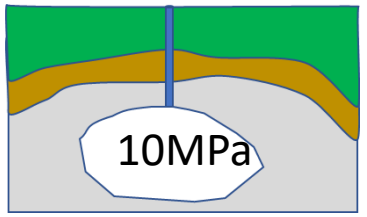
Eliminating technologies for long duration

Supercapacitors:
ρ_E Limited

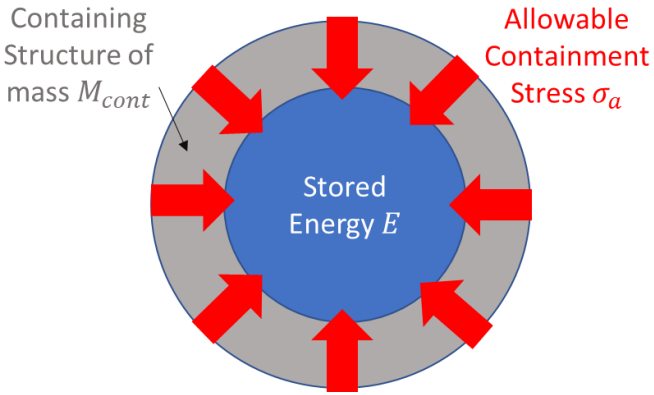


Saleem et al. 2016





Virial theorem



$$\rho_E = \frac{\sigma_a}{Q_{max}\rho_{m,cont}}$$

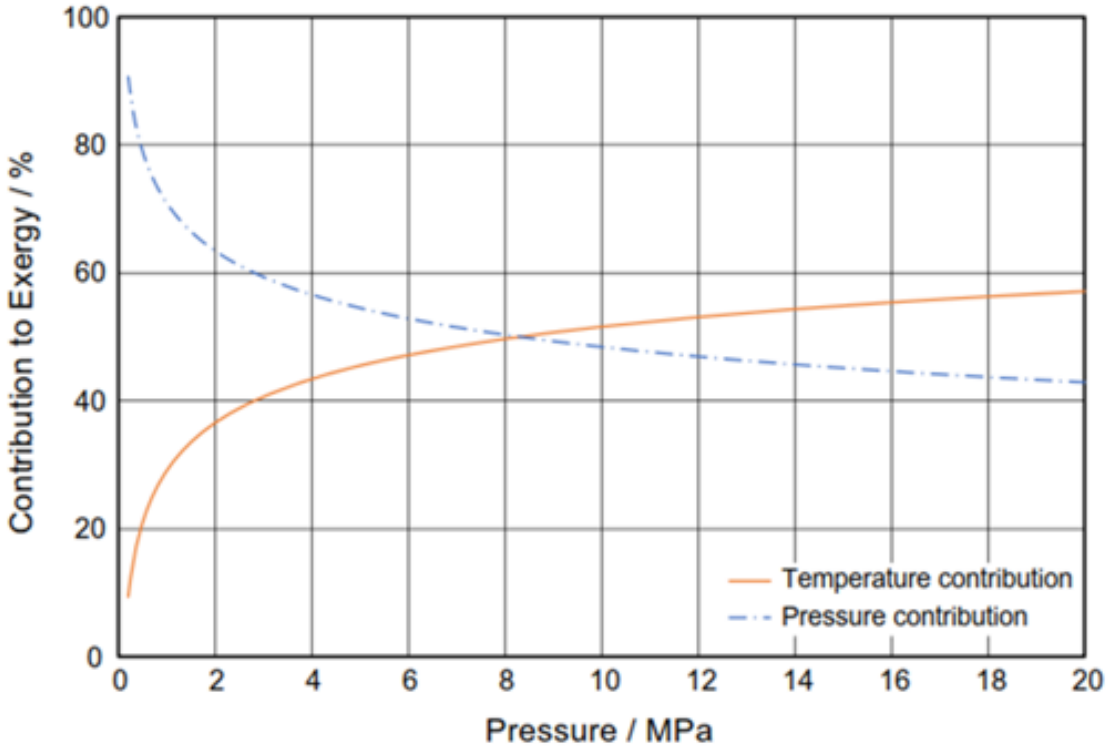
Best case scenario for these technologies

SMES = Superconducting Magnetic
EDLC = Electric Double Layer Capacitor

Thermomechanical storage

Thermomechanical = Storage through gas compression

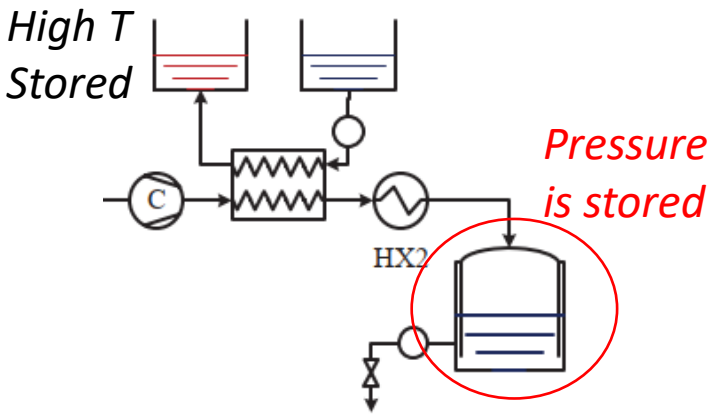
Compression creates **temperature and pressure** increase



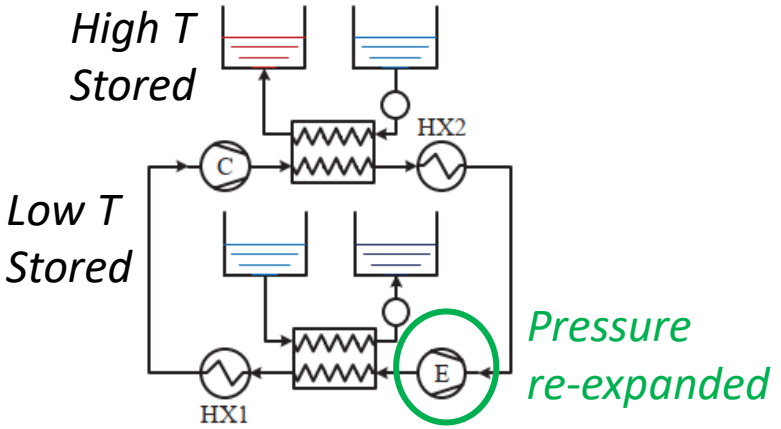
Budt et al., Applied Energy 2016

Two Main Variants:

Compressed Air (CAES)

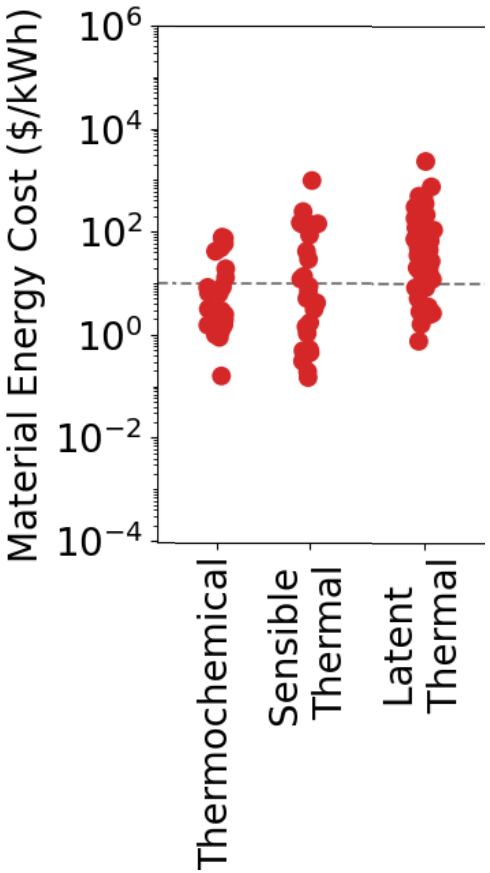


Pumped Thermal (PTES)



Xue, Haobai Thesis 2018.

Thermal storage is cheap enough

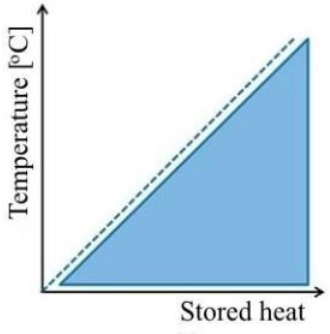


Thermal energy storage media with $C_{kWh,mat} < 10 \frac{\$}{kWh}$

Sarbu et al *Sustainability* (2018)

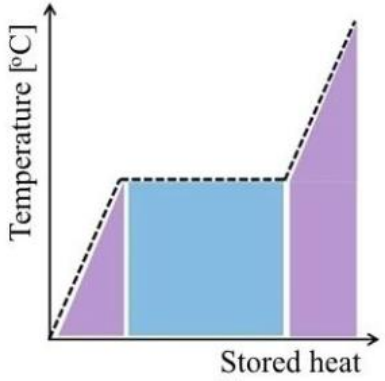
Sensible

$\rho_E = C_p \Delta T$



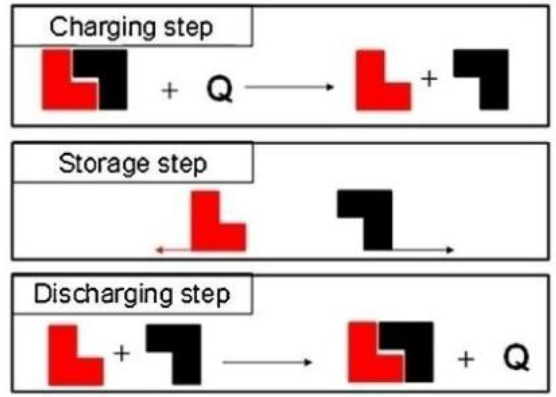
Latent

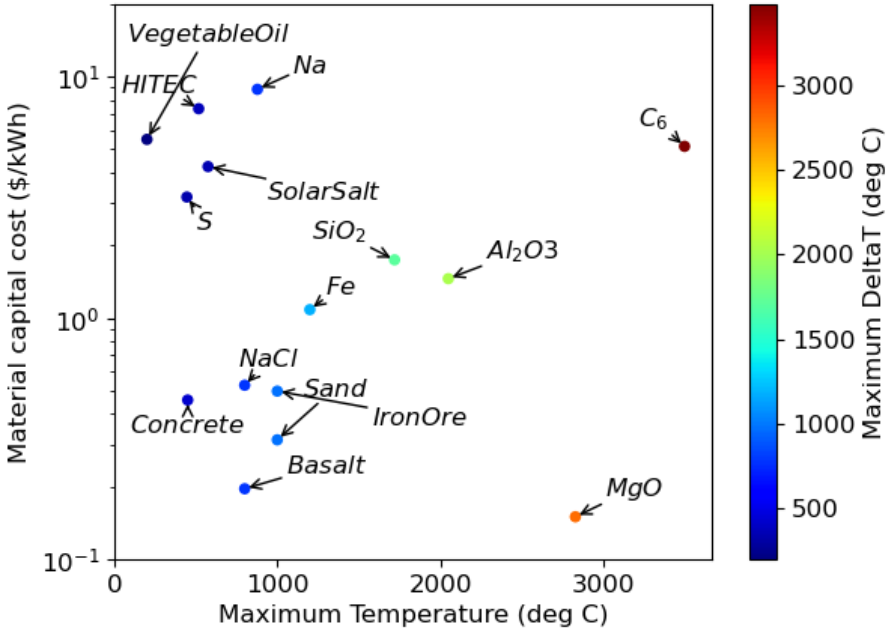
$\rho_E = \Delta H_f$

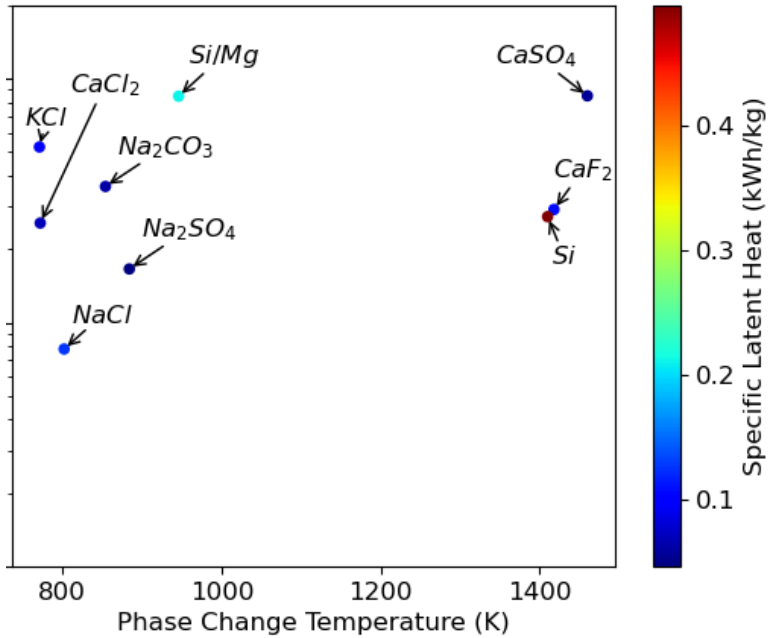


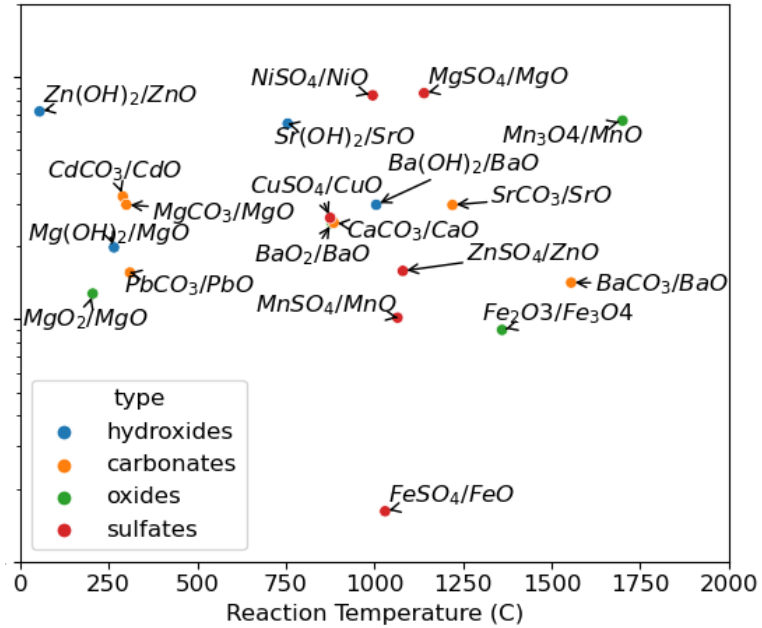
Thermochemical

$\rho_E = \Delta H_r$





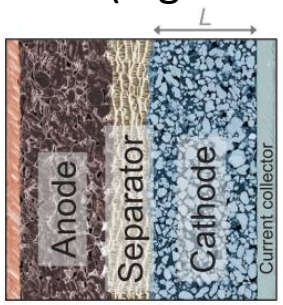




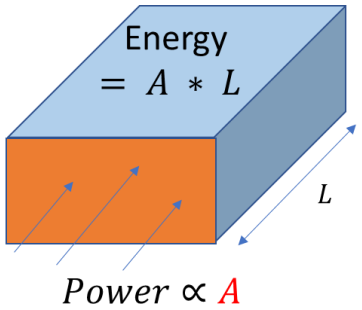
(Electro)Chemical technologies

Chemical energy with electrochemical transformation at electrode

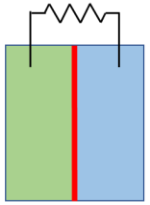
Coupled Energy/Power
(e.g. Lithium-ion battery)



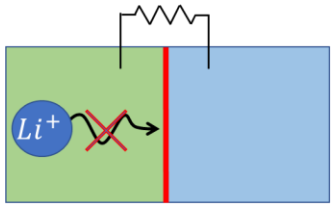
Christian et al. *Advanced Energy Materials* 2020



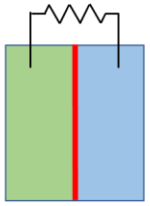
Option 1:
Thicker
Electrodes



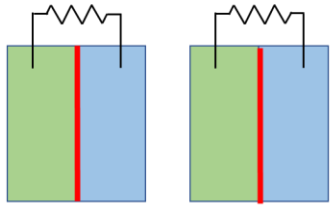
2X Duration
Diffusion losses

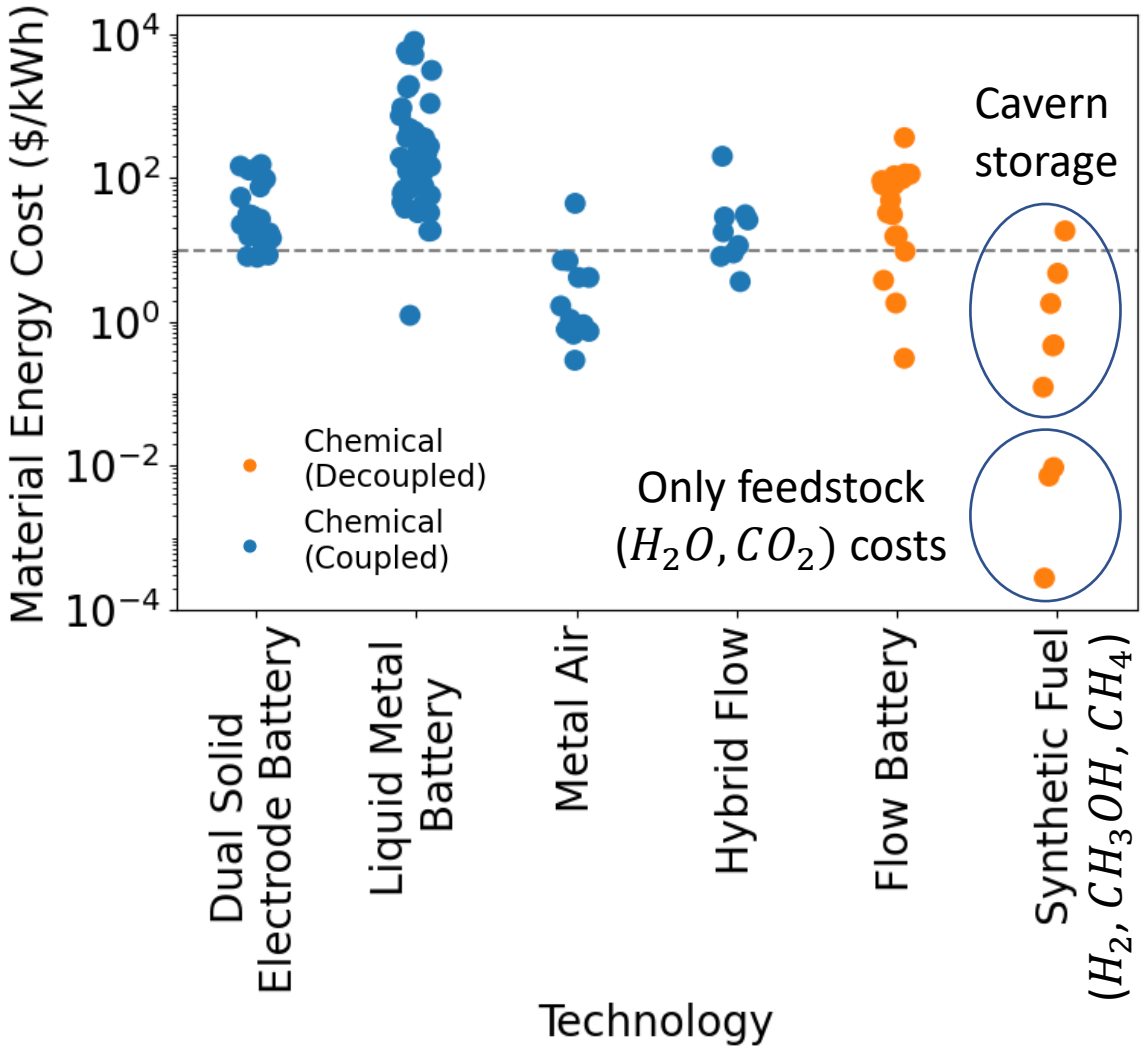


Option 2:
Overbuild
Power

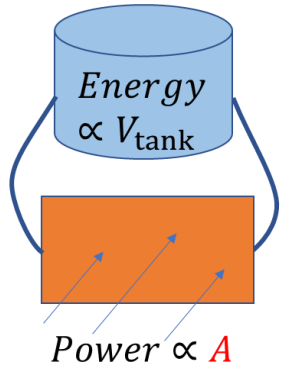


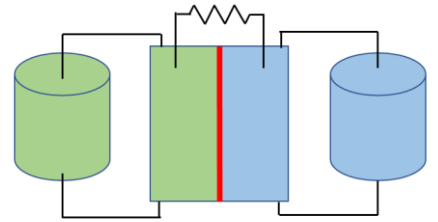
2X Duration
2X Power capital



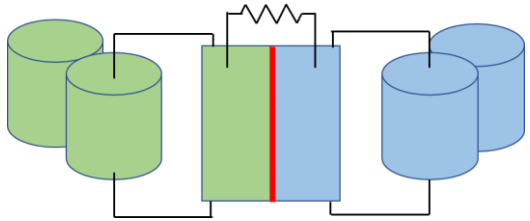


Decoupled System
(e.g. Vanadium Redox Flow Battery)

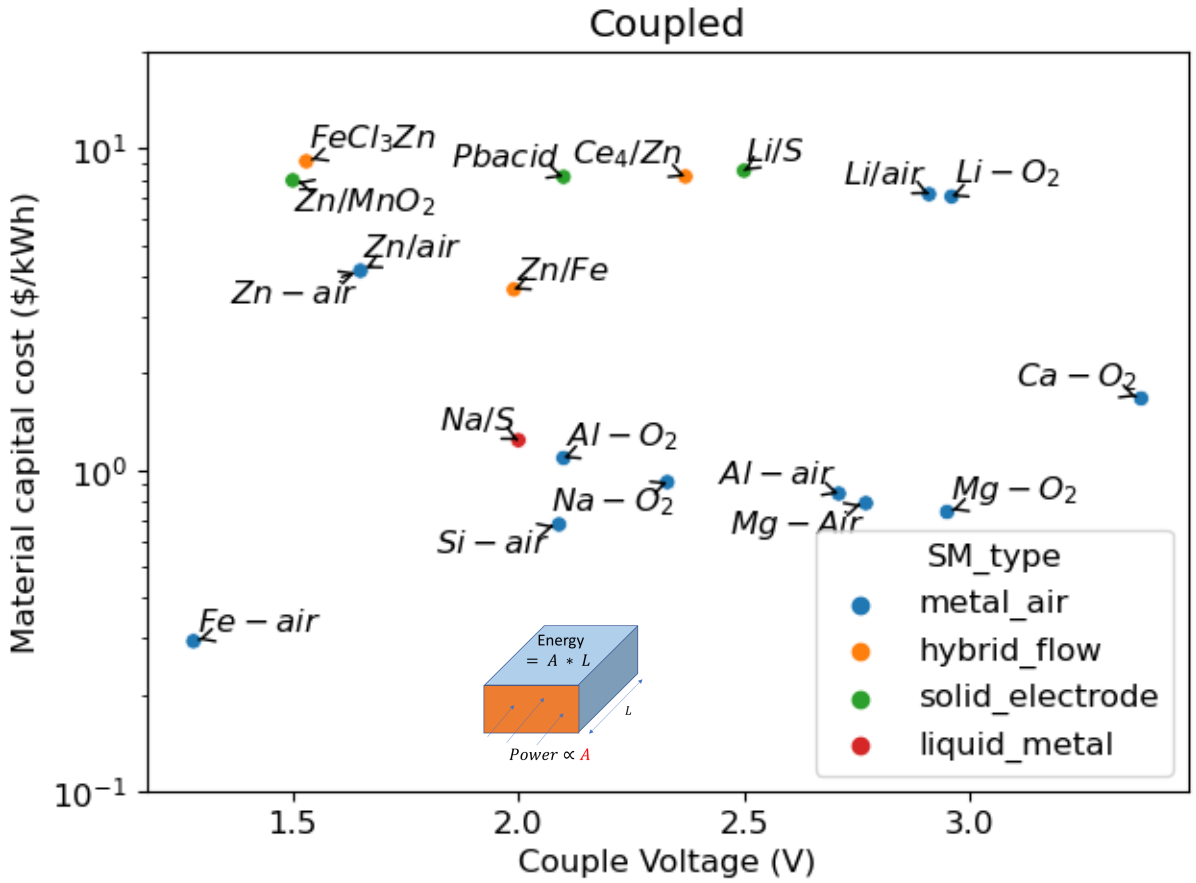


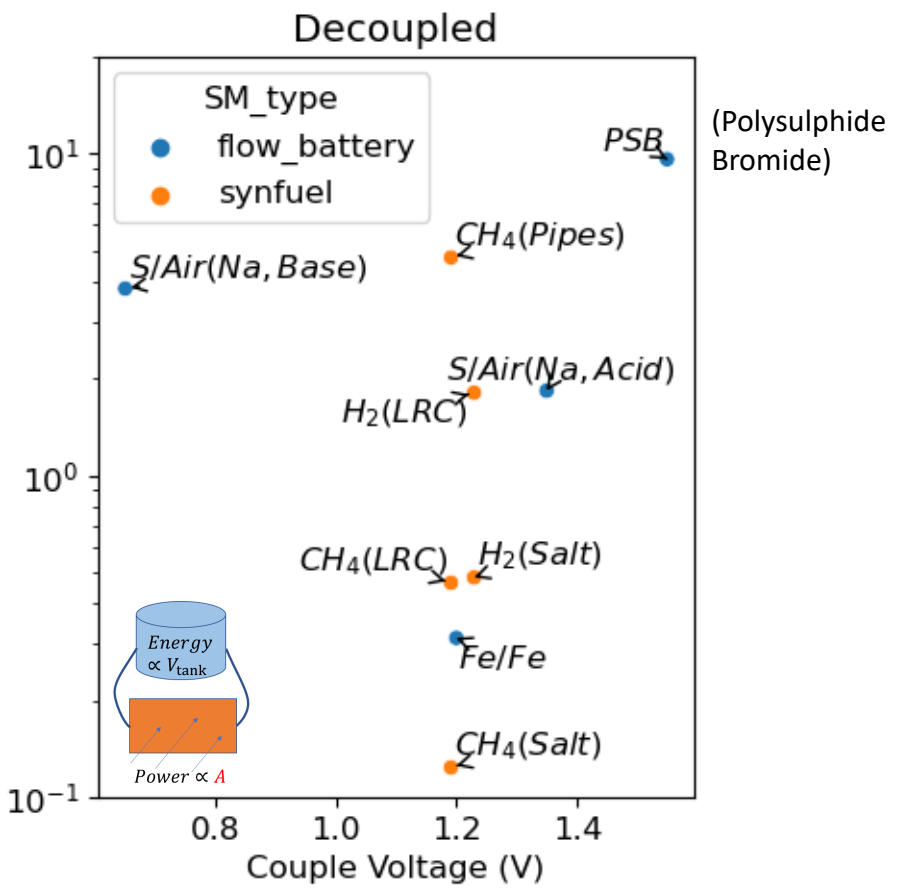


2X Duration
Same Power capital



(Electro)Chemical storage media $C_{kWh,mat} < 10 \frac{\$}{kWh}$



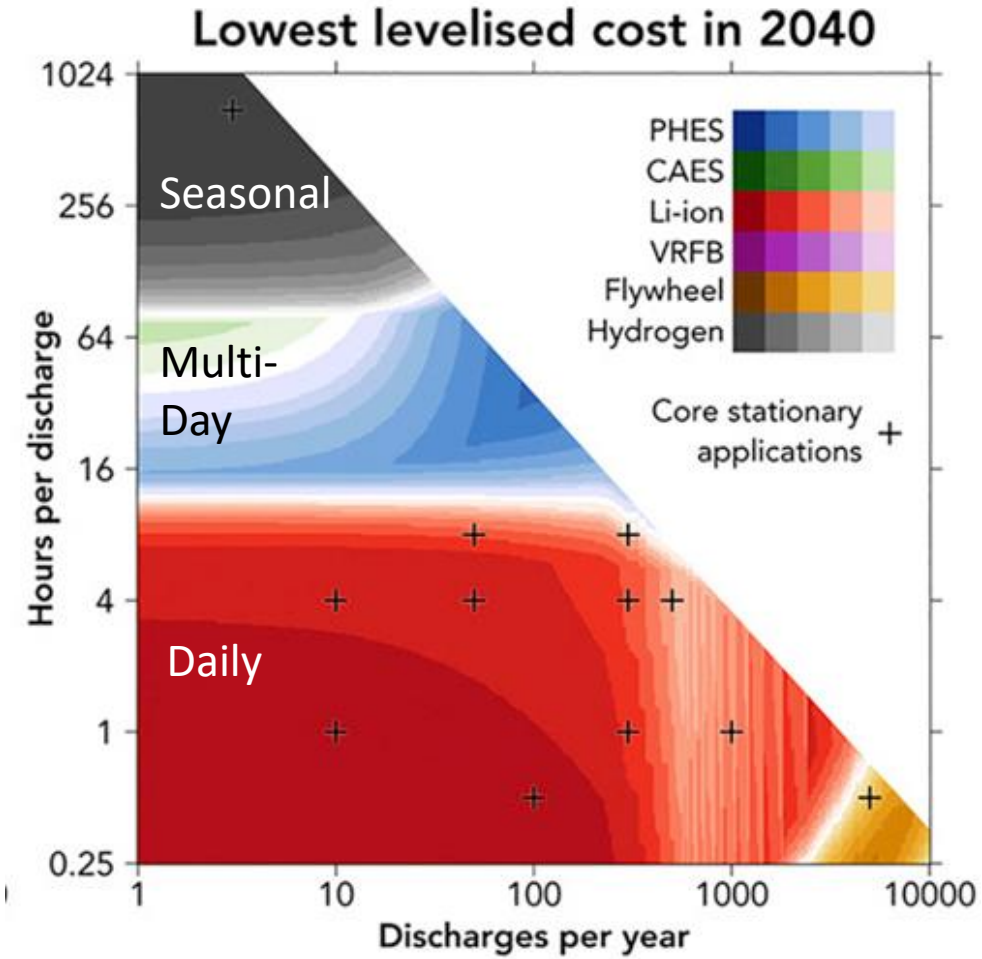


(Polysulphide Bromide)

- Coupled technologies are disadvantaged due to Energy/power inflexibility.
  - Metal air perhaps cheap/energy dense enough to get around this

- Inexpensive material flow batteries
- Synthetic fuel storage in caverns
  - LRC = Lined Rock Cavern
  - Salt = Solution-mined Salt Cavern

Promising Technologies



$$LCOS\left(\frac{\$}{kWh}\right) \propto \frac{\boldsymbol{C_{\mathbf{kWh}}}}{\eta_{out} lifetime} \cdot duration$$

Seasonal (>100 hours):$\mathrm{C_{kWh}} < \sim 1\ \$/kWh$

- Synthetic fuels with underground storage

Multi-day (10-100 hours): $\mathrm{C_{kWh}} < \sim 10\ \$/kWh$

- Pumped thermal energy storage (PTES) with cheap thermal storage
- Low cost material flow batteries
- Metal air batteries

Daily (<10 hours): Many discharges to payback capital, efficiency is key.

- Lithium ion likely to not be out-competed in near term

Oliver et al. "Projecting the Future Levelized Cost of Electricity Storage Technologies." *Joule* (2019): https://doi.org/10/gf8tkh.

Summary

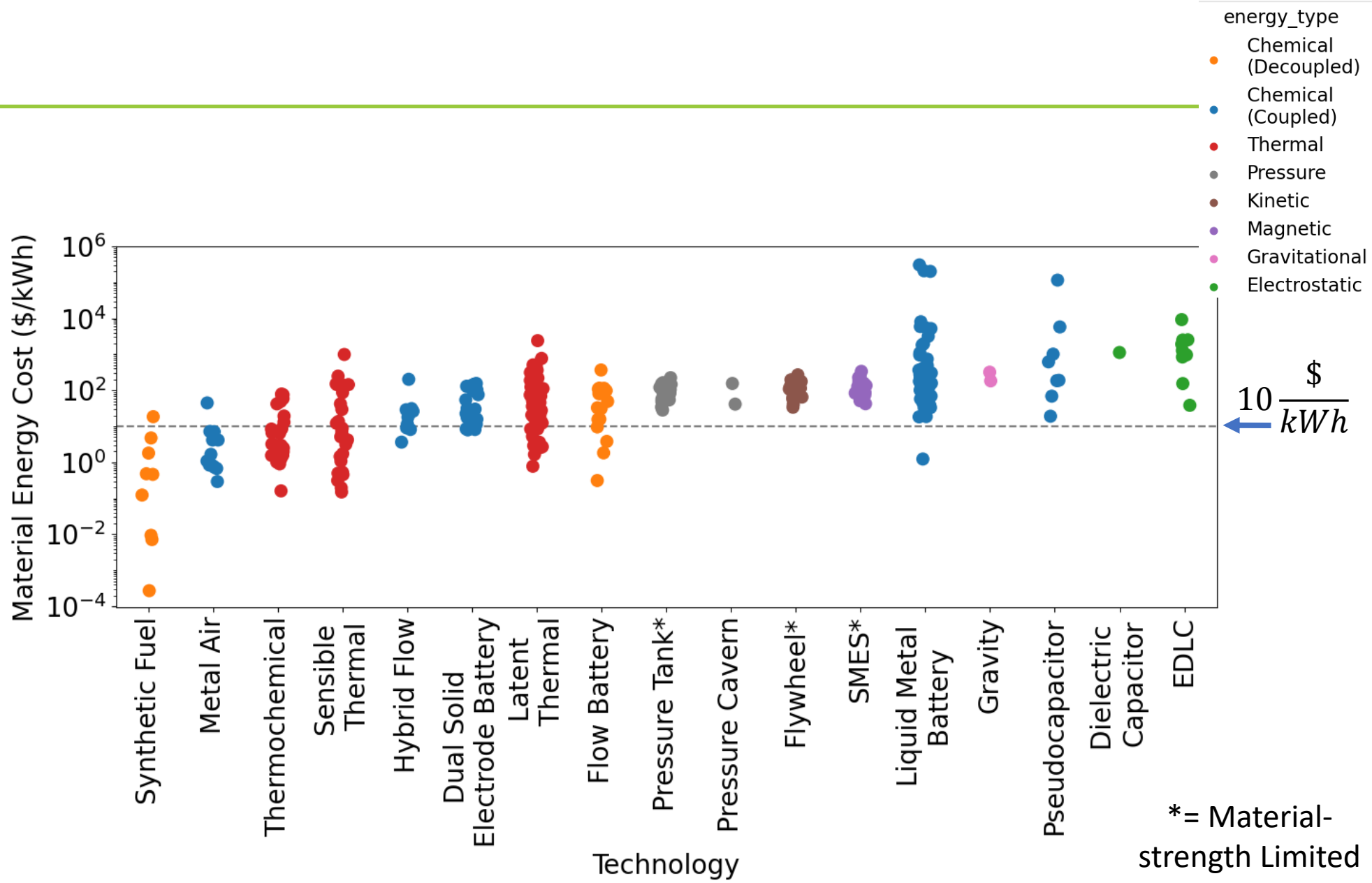
- Determined key long duration energy storage figure of merit

$$\frac{C_{kWh}}{\eta_{out} lifetime}$$

- Performed an extensive search for storage media with

$$C_{kWh} < 10 \frac{\$}{kWh}$$

Thank you!



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