Energy Storage: Days of Service Sensitivity Analysis

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Hydrogen and Fuel Cell Technical Advisory Committee

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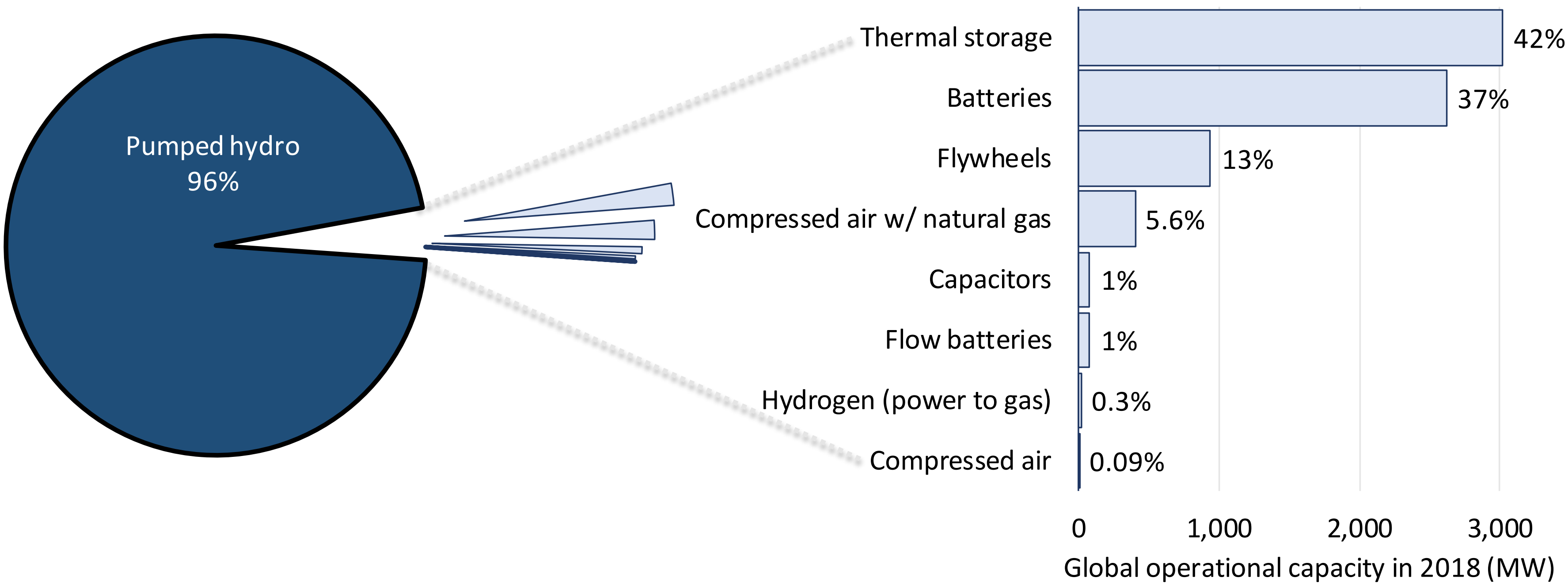
Screening Analysis Motivation:
Role of H_2 in Energy Storage Market



Global Energy Storage Inventory:

- **95% is pumped hydro serving diurnal operation**
- **Batteries typically provide few hours of storage**
- **Thermal storage is predominantly molten salt for concentrated solar**
- **Fly wheels provide very short duration storage (frequency regulation)**

Source: DOE Global Energy Storage Database: https://www.energystorageexchange.org/

Screening Analysis Scope

System	Energy storage options		Performance & cost metrics	
H_2 & fuel cell	Tank storage	Salt domes	Current status	Future potential
Battery, lithium ion	Battery		Current status	Future potential

Analyzed Components:

- Rectifier
- Electrolyzer
- Hydrogen compressors
- Hydrogen storage
  - tank storage
  - salt domes (geologic, 3 in USA)
- Batteries
  - lithium ion
- Power generation
  - fuel cell
- Inverter

Cost and performance parameters were extensively peer reviewed by battery and hydrogen technology experts.

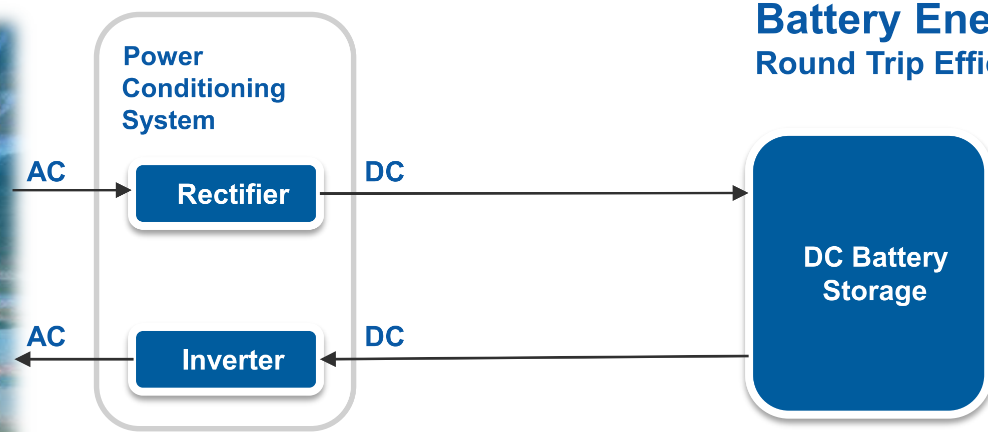
Current timeframe assumes 6¢/kWh electricity cost for storage recharging.

Future timeframe assumes 3¢/kWh electricity cost for storage recharging.

Diagrams of Storage

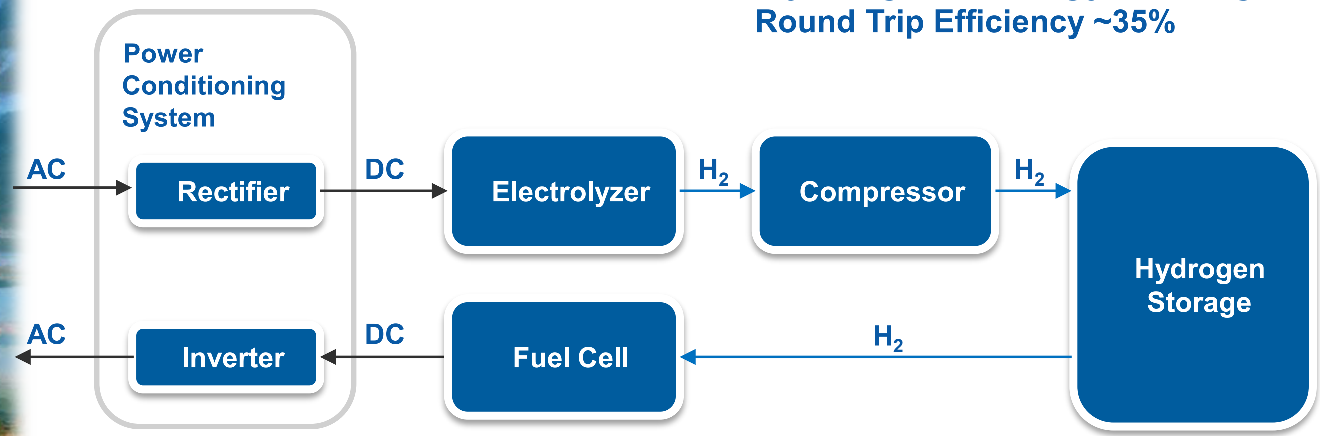
Battery Energy Storage

Round Trip Efficiency ~95%

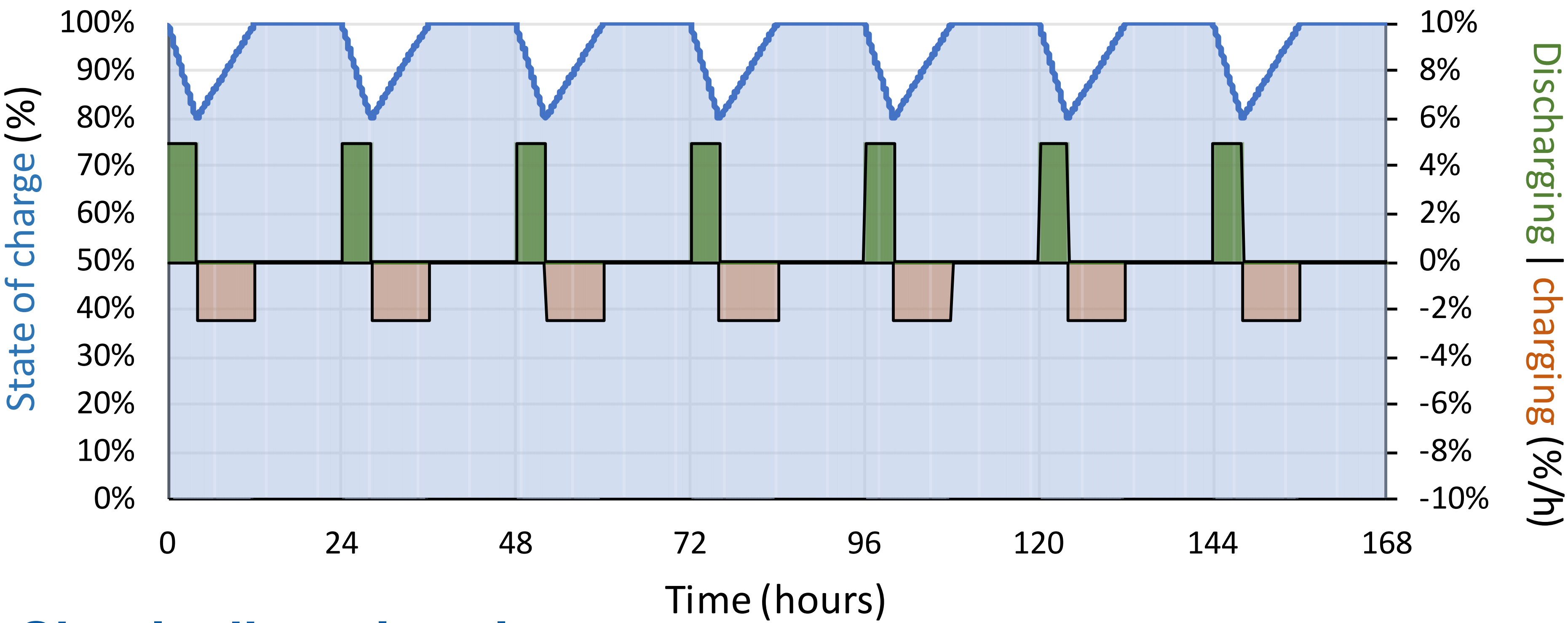


Hydrogen Energy Storage

Round Trip Efficiency ~35%



Simple Benchmark Profile



Simple diurnal cycle:

- ✓ 4 hours power generation
- ✓ 8 hours storage recharge
- ✓ 12 hours stand-by

Simple cycle provides a transparent and intuitive means of benchmarking energy storage systems.

Interest focus: long duration storage capability

Capital Cost Summary

Technology	Timeframe Assumption	Charging ($/kW)	Storage ($/kWh)	Discharging ($/kW)
Battery	Current	196	218	60
Battery	Future Potential	183	80	60
Hydrogen in tanks	Current	942	35	574
Hydrogen in tanks	Future Potential	432	18	300
Hydrogen in salt domes	Current	942	0.08	574
Hydrogen in salt domes	Future Potential	432	0.08	300

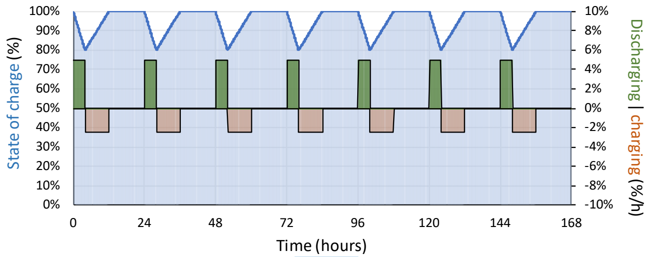
Preliminary

Charging capital: **Rectifier**, Electrolyzer, Compressor
Storage capital: **Batteries**, H2 storage tanks, salt dome
Discharging capital: **Inverter**, fuel cell

Hydrogen storage provides:

- lowest cost of stored energy
- more expensive charging and discharging capital
- lower round-trip efficiency

H2FAST Model Used For Levelized Cost Analysis

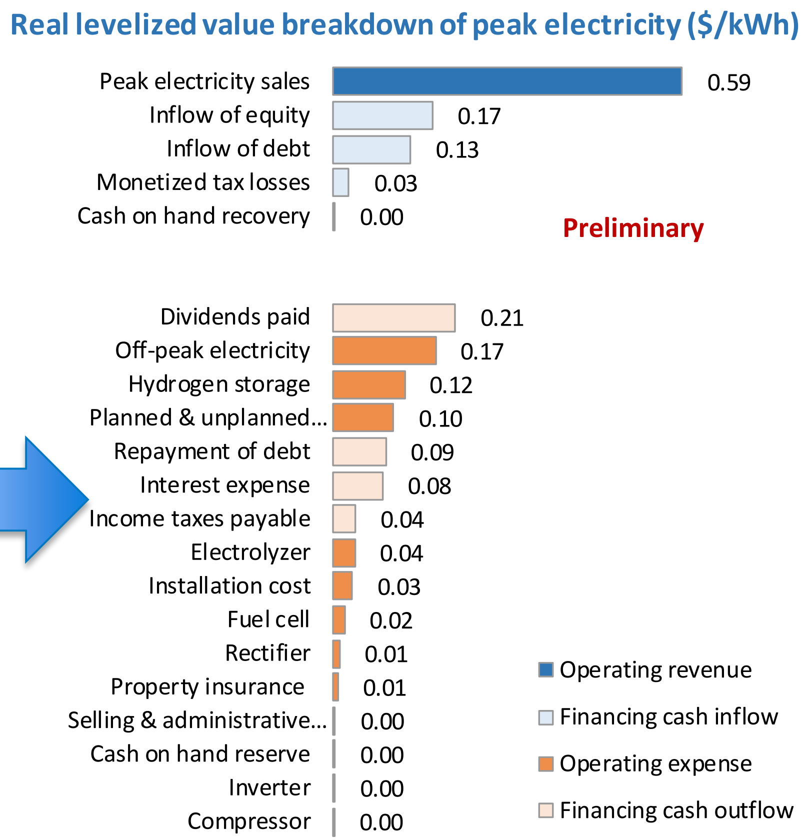


- Equipment sizing
- Cost estimation
- Efficiency estimation

- Energy Use
- Energy Costs
- Financial Assumptions

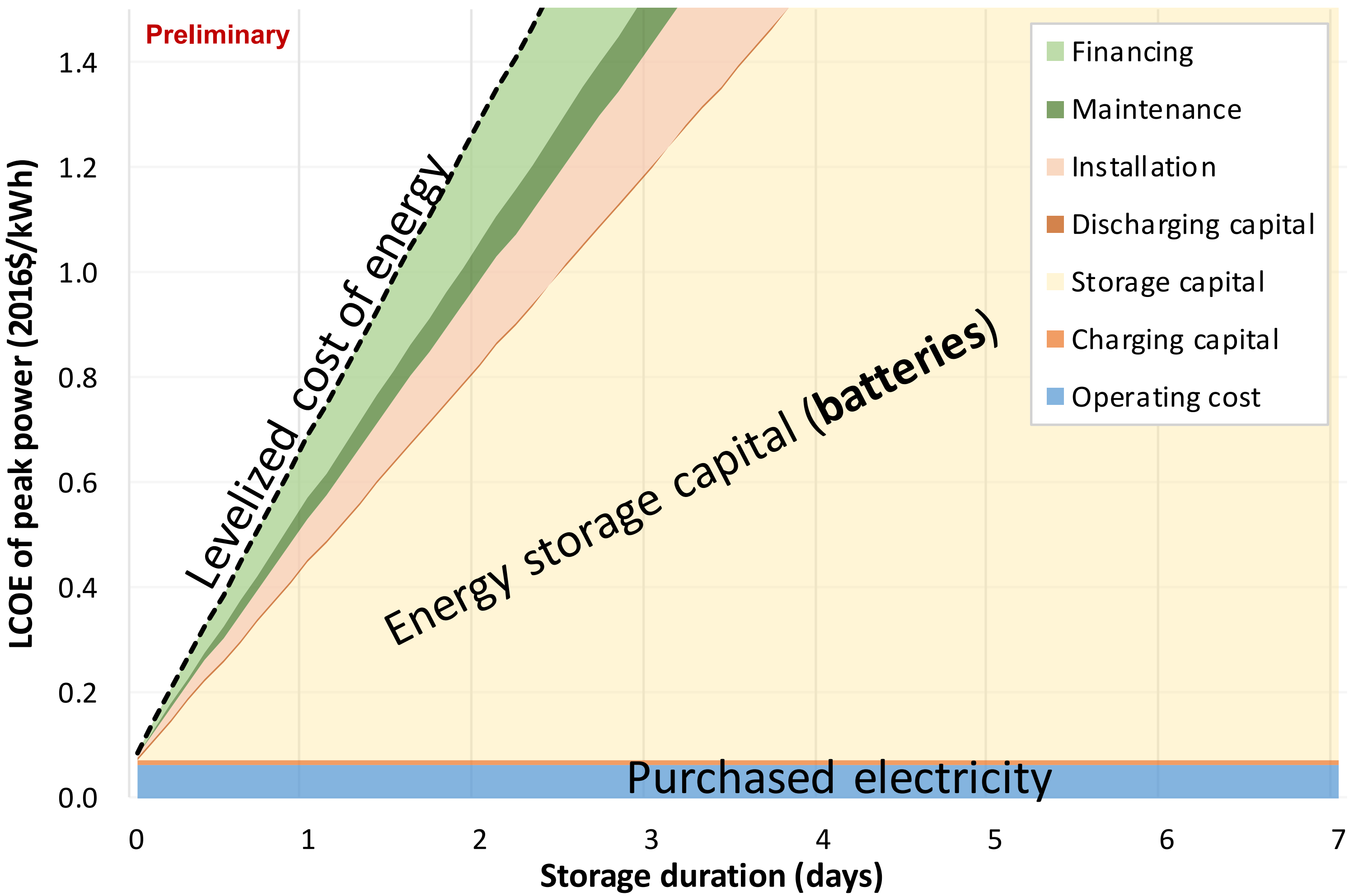
https://www.nrel.gov/hydrogen/h2fast.html

H2FAST



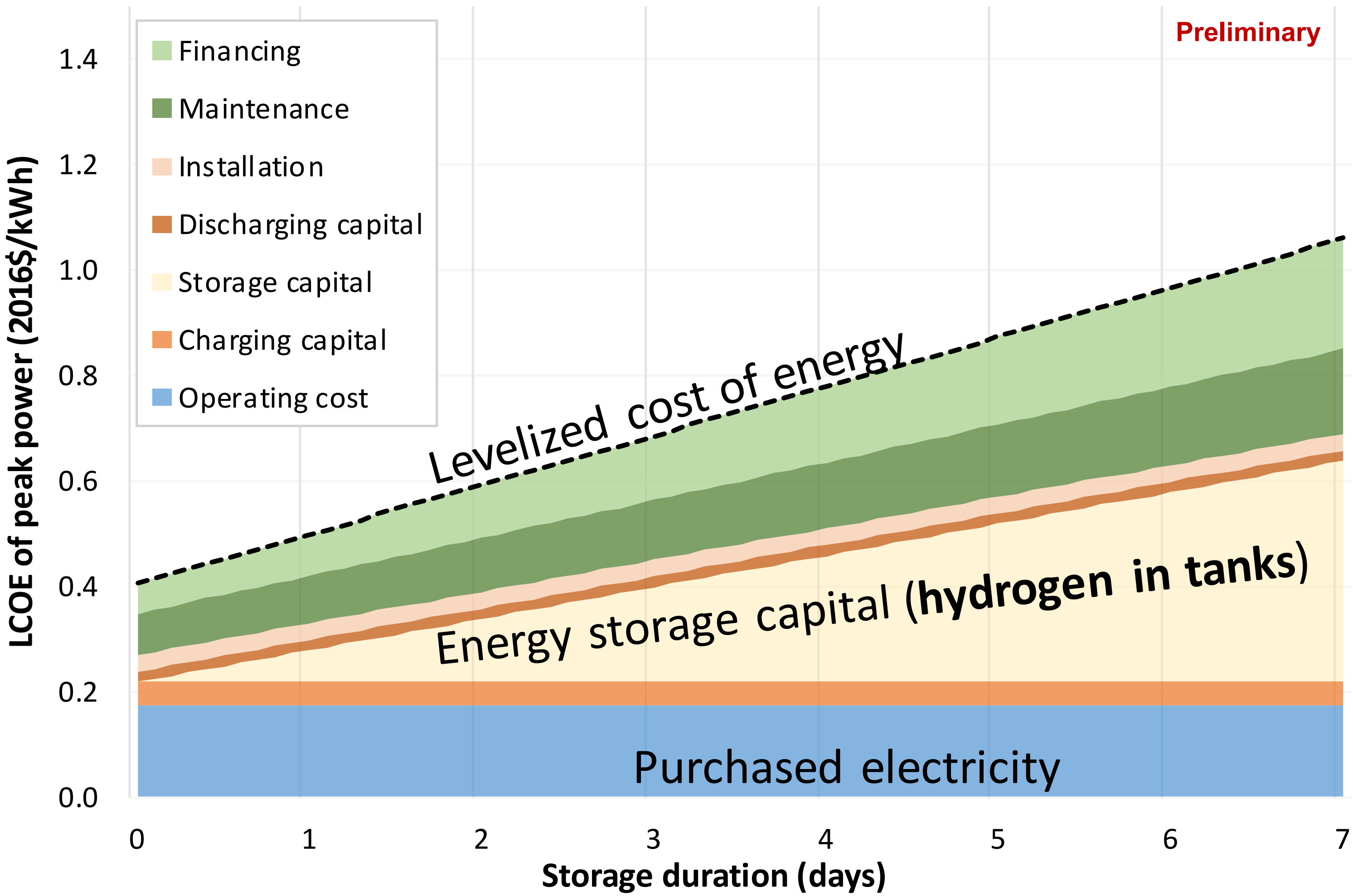
Techno-economic assessment is made based on minimal equipment sizing to achieve benchmark cycle. H2FAST model was used to evaluate levelized cost of peak power.

Levelized Cost of Energy vs. Duration of Storage Li-Ion Battery



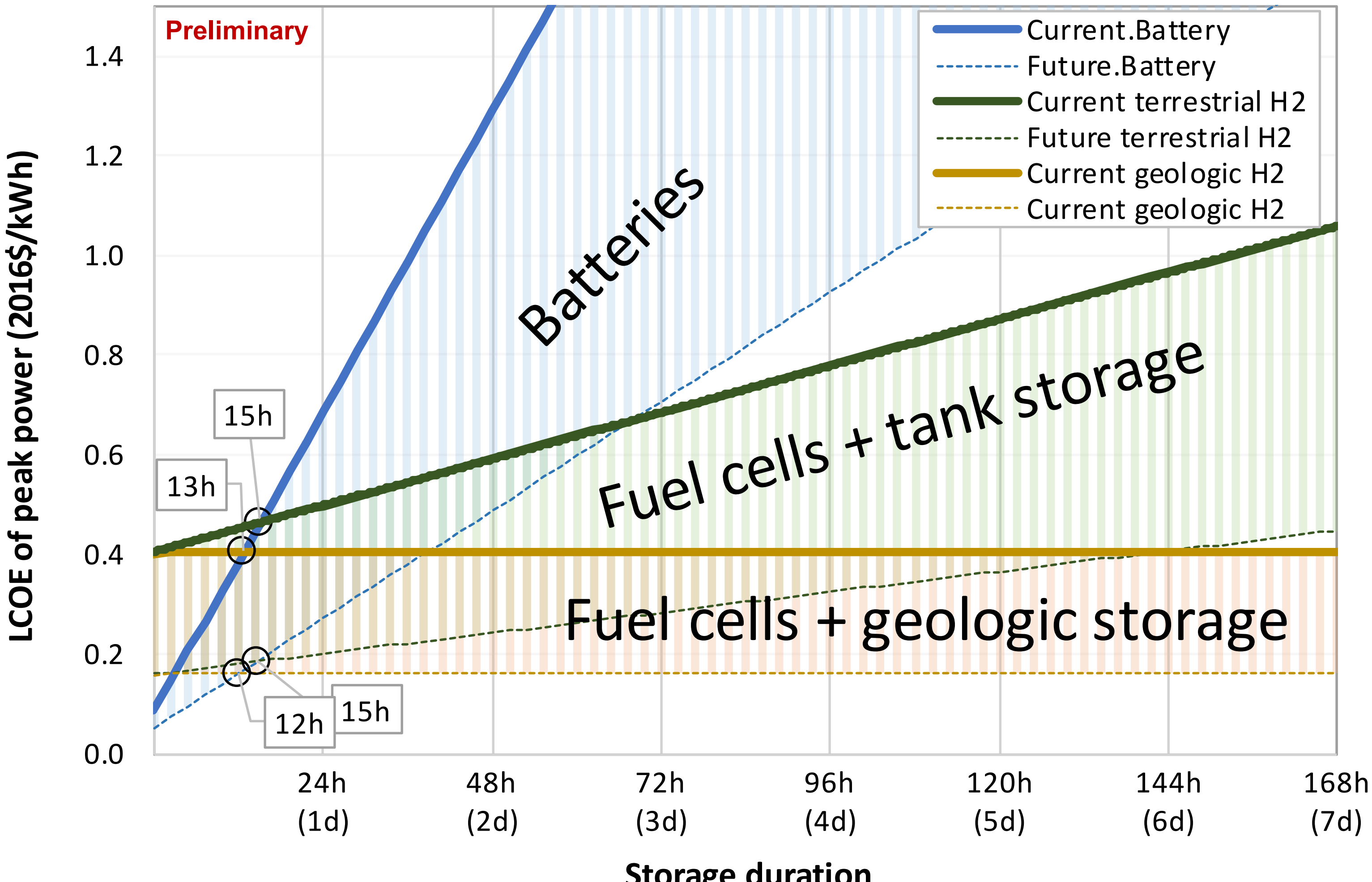
Excellent round-trip efficiency (95%) minimizes operating costs (purchase of electricity @ 6¢/kWh). Capital intensity is dominated by battery module cost.

Levelized Cost of Energy vs. Duration of H_2 Storage (FC + Tanks)



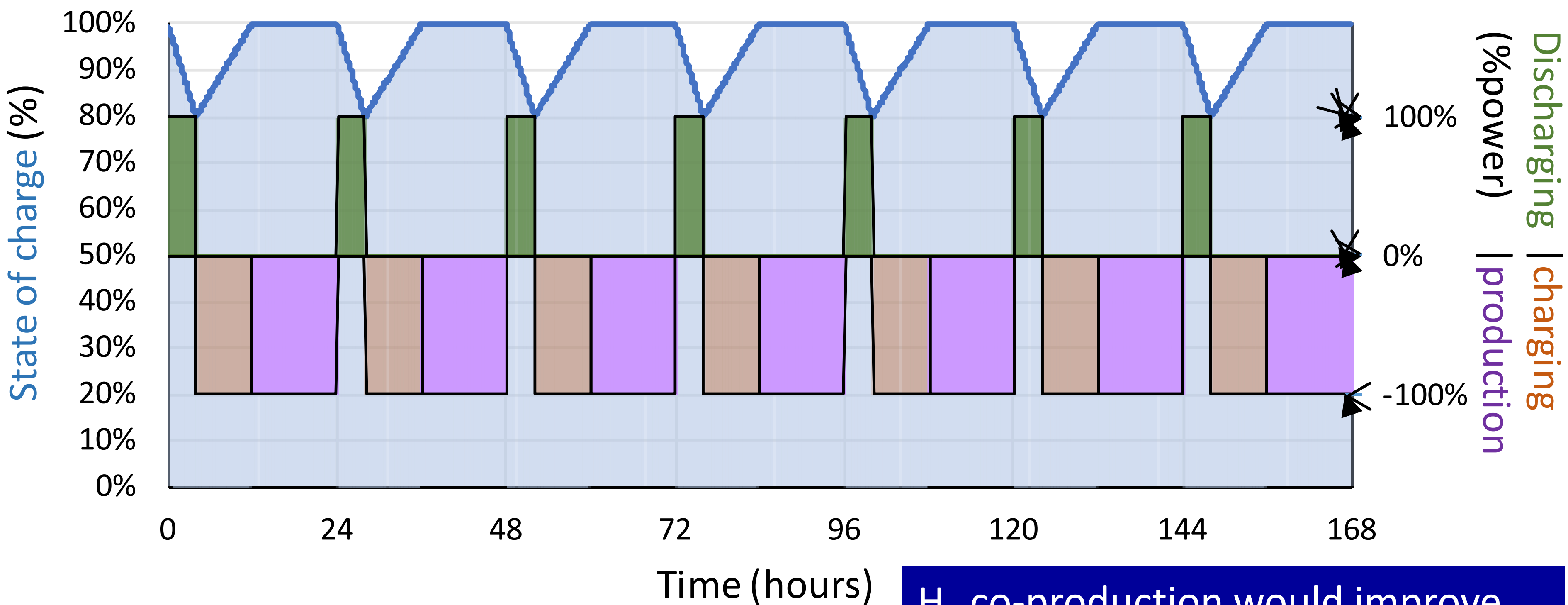
Lower round-trip efficiency (35%) induces higher operating costs. Lower capital cost for storage reduces total cost escalation for long duration storage.

Economic Performance Benchmark Current & Future Hydrogen and Batteries



- Below ~13h with current technology, batteries have economic advantage.
- Durations over ~13h favor hydrogen technologies.
- Windows of cost use 6¢/kWh electricity for current timeframe and 3¢/kWh for future timeframe.

Hydrogen Co-Production Opportunity



H_2 co-production would improve economics if H_2 price exceeds variable operating costs.
O_2 co-production may also bear value.

Simple diurnal cycle:

- ✓ 4 hours power generation
- ✓ 8 hours storage recharge
- ✓ 12 hours ~~stand-by~~ ▶ **hydrogen co-production**

Take-aways

1. **Hydrogen energy storage technologies have economic advantage for long-duration storage**
   - ✓ Above ~13h of storage with current tech

2. **Round-trip efficiency disadvantage over batteries can be overcome for storage durations greater than ~12h**

3. **Additional work is needed to understand the potential revenue (avoided cost) of long-duration storage**

4. **Energy storage system economics can be improved with H_2 co-production**

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- **National Renewable Energy Laboratory**

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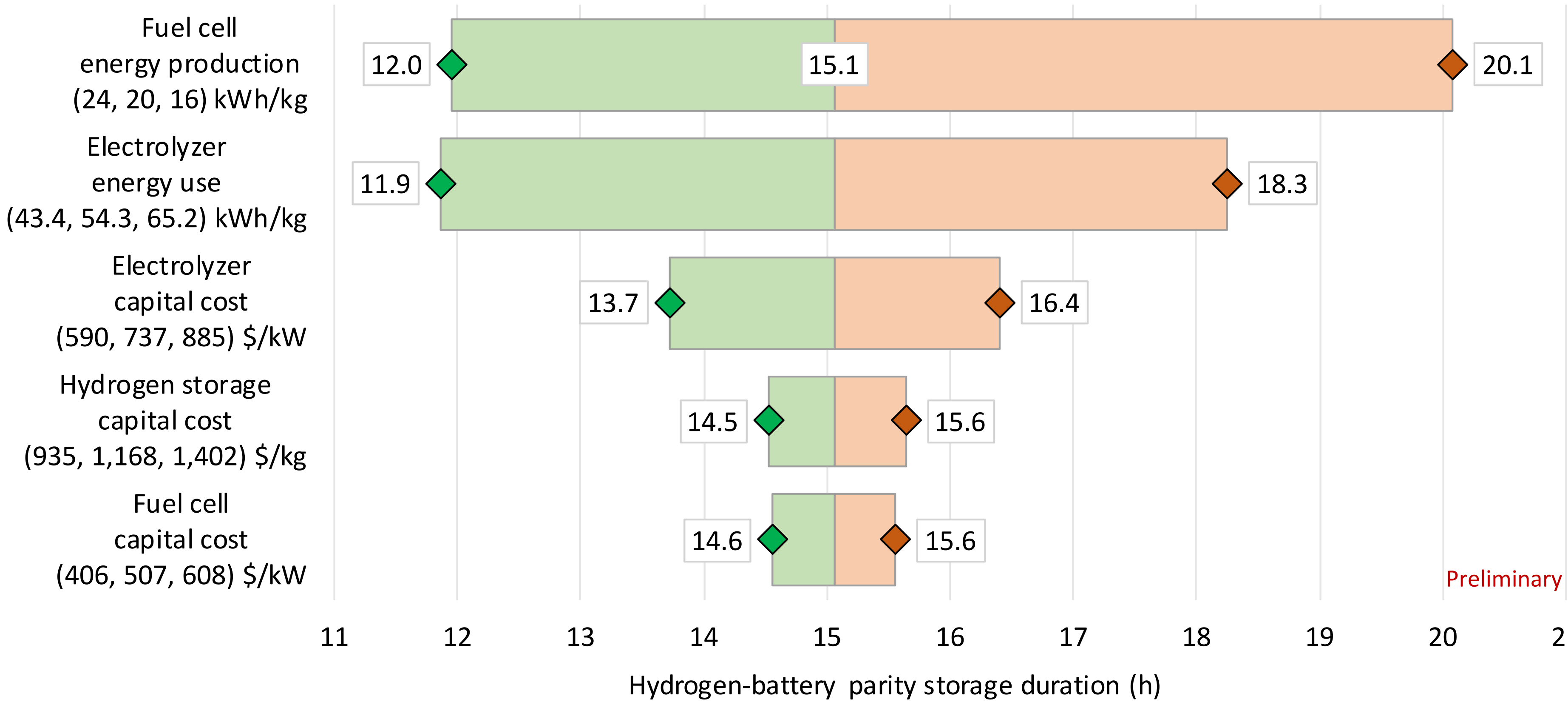
Backup Slides

Parity Duration Sensitivity vs. Techno-Economic Parameters (Current, H_2 vs. Batteries)



Round-trip efficiency improvements are most important

- Electrolyzer, compressor, fuel cell
- Above uses 6¢/kWh

Means of Improving Round Trip Efficiency

Increased efficiency can be traded for capital expenses

1. Increase electrolysis & fuel **cell active area**
2. Consider **solid oxide electrolysis** (SOEC)
3. Consider SOEC with **thermal storage** (store waste heat from power generation and use for thermal needs in electrolysis)
4. Consider **high pressure electrolysis** (reduce compression needs)
5. Consider compression energy recovery with **turbo expander**

Round trip efficiency is more important than capital cost.
Improving efficiency can be traded for increased capital cost.

Technoeconomic Parameter Details

Techno-Economic Parameters	Current status	Future potential	Reference
Rectifiers			
Rectifier efficiency	98.4%	98.4%	[2]
Rectifier cost ($/kW AC)	$ 196	$ 183	[3]
Total installation cost factor (% of equipment capital)	57%	57%	[3]
System O&M (% of capital cost)	1%	1%	assumption
Electrolyzers			
Electrolyzer power use (kWh DC/kg)	54.3	50.2	[3]
Electrolyzer cost ($/kW DC)	$ 737	$ 232	[3]
System life (years)	20	20	[4]
System O&M (% of capital cost)	8%	9%	[3]
Total installation cost factor (% of equipment capital)	57%	57%	[3]
Compressors			
Power use (kWh AC/kg)	1.42	1.42	[5]
Compressor cost factor A (equation form c=A*p^B; where p is power)	2290	2061	[5]
Compressor cost exponent B (equation form c=A*p^B; where p is power)	0.8225	0.8225	[5]
Total installation cost factor (% of equipment capital)	187%	187%	[5]
System O&M (% of capital cost)	4%	4%	[5]
Storage			
Terrestrial storage installed cost ($/kg)	1,168	600	[5], [6]
Terrestrial storage installed cost ($/kWh LHV)	35	18	assumes 33 kWh/kg H2
Terrestrial storage O&M (% of capital cost)	1%	1%	[5]
Geologic storage installed cost ($/kg)	2.69	2.69	[5]
Geologic storage installed cost ($/kWh LHV)	0.08	0.08	assumes 33 kWh/kg H2
Geologic storage O&M (% of capital cost)	4%	4%	[5]
Cushion gas (%)	17.1%	17.1%	[5]

Technoeconomic Parameter Details

Techno-Economic Parameters	Current status	Future potential	Reference
Fuel cells			
Fuel cell power production (kWh DC/kg)	20.0	23.3	[7]
Fuel cell cost ($/kW DC)	507	237	[8]
Total installation cost factor (% of equipment capital)	20%	20%	assumption
System O&M (% of capital cost)	6%	6%	[8]
Inverters			
Inverter efficiency (%)	98.6%	98.6%	[9]
Inverter installed cost ($/kW)	$ 60	$ 60	[10]
Total installation cost factor (% of equipment capital)	20%	20%	assumption
System O&M (% of capital cost)	1%	1%	assumption
Batteries			
Charging efficiency	98.3%	99.4%	[11]
Discharging efficiency	98.1%	99.4%	[11]
Cost ($/kWh)	217.5	80	[12], [13]
System life (years)	10	10	[14]
System O&M (% of capital cost)	1.0%	1.0%	assumption
Total installation cost factor (% of equipment capital)	20%	20%	assumption
System O&M (% of capital cost)	1%	1%	assumption
Feedstock			
Electricity cost ($/kWh)	0.060	0.030	assumption

Technoeconomic Parameter Details

Total tax rate (statefederallocal)	21.00%
General inflation rate	1.90%
Depreciation method	MACRS
Depreciation period	5 year
Leveraged after-tax nominal discount rate	10.0%
Debt/equity financing	1.50
Debt type	Revolving debt
Debt interest rate (compounded monthly)	3.70%
Cash on hand (% of monthly expenses)	100%

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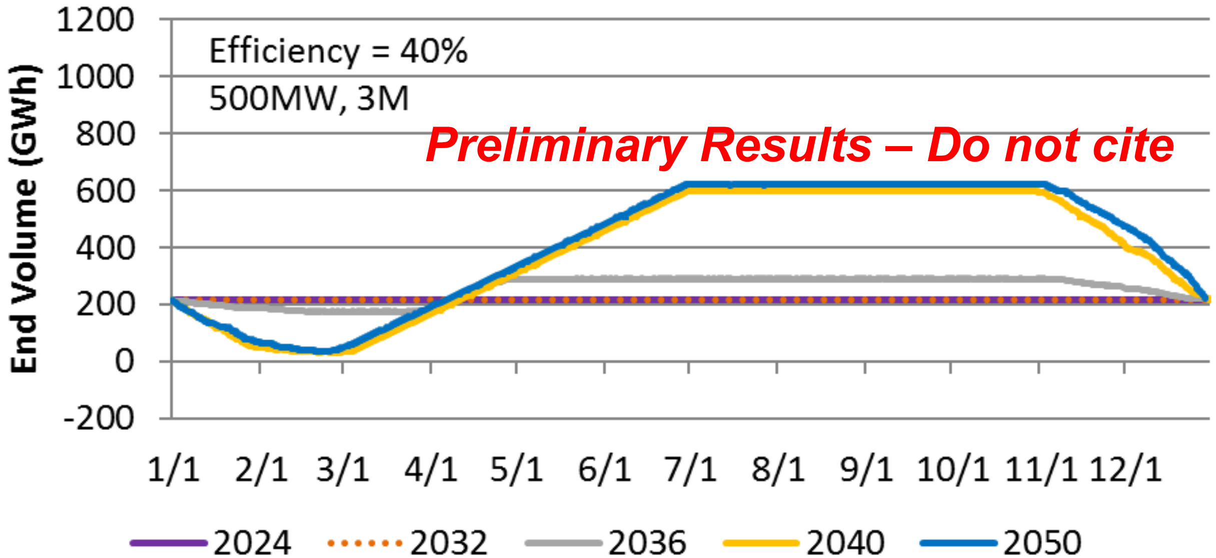
Long duration storage benefit

- Present work shows likely cost advantage of long duration hydrogen storage compared to other storage technologies

- Additional cost advantages may include revenue from hydrogen and avoided costs.

- Previous work has shown that market for multi-day storage is currently limited

- Using power system models, we can calculate the benefit (avoided cost) of operating the storage



Preliminary results from the EPRI-DOE H2@Scale CRADA Project show how storage can be used as renewable penetration increases.

To understand competitiveness of long duration storage, we can perform cost/benefit comparison using LCOE and avoided costs (LACE)