ENERGY STORAGE GRAND CHALLENGE
U.S. DEPARTMENT OF ENERGY

Storage Innovations 2030: Mapping a Path to $0.05/kWh

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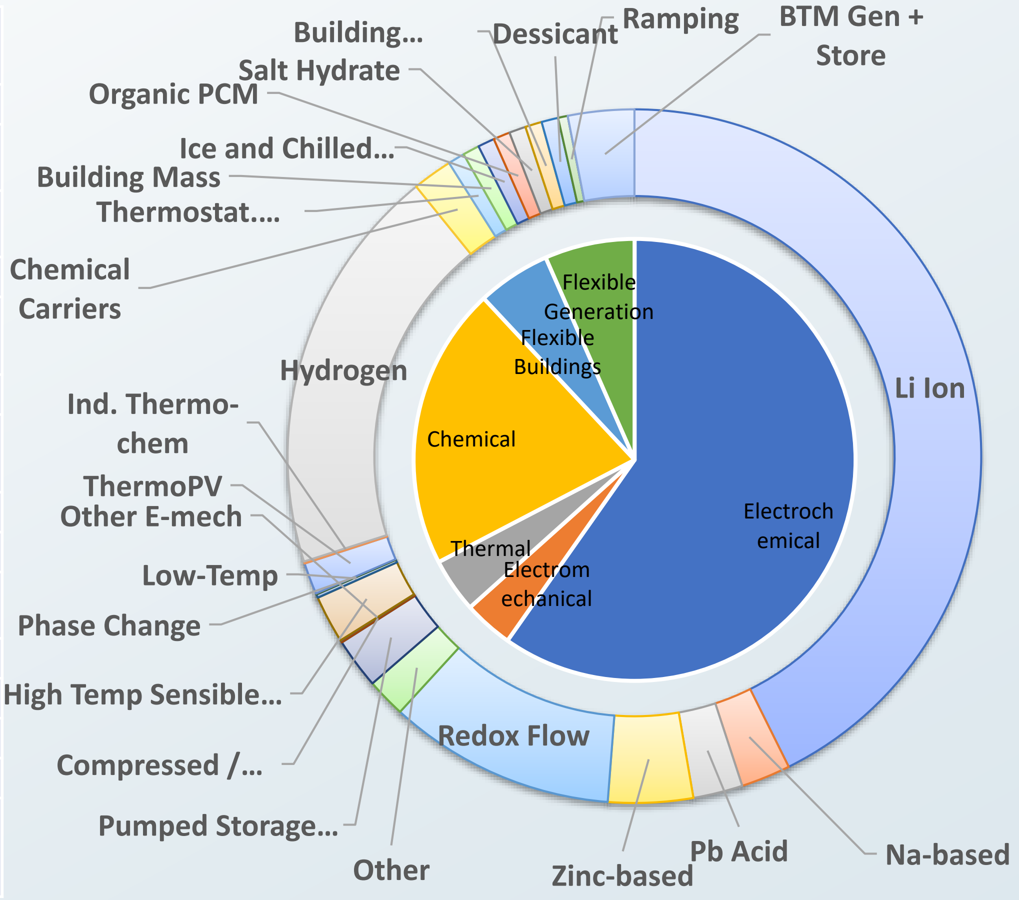
Methodology and Reports Update

DOE Has Supported 30+ Storage Technologies

Bidirectional Electric Storage	Electrochemical	Li-Ion & Li-Metal
		Na-Ion
		Na-Metal
		Lead Acid
		Zinc
		Other Metals (Mg, Al)
		Redox Flow
		Reversible Fuel Cells
		Electro-Chemical Capacitors
	Electromechanical	Pumped Storage Hydro
		Compressed Air
		Liquid Air
		Flywheels
		Geomechanical
		Gravitational
Crosscutting	Power Electronics	Power Electronic Systems
Thermal & Chemical	Thermal	High-Temperature Sensible Heat
		Phase Change
		Low-Temperature Storage
		Thermo-Photovoltaic
		Thermochemical
	Chemical	Chemical Carriers (e.g., Ammonia)
		Hydrogen
Flexible Generation & Loads	Flexible Buildings	Thermostatically Controlled Loads
		Building Mass
		Ice & Chilled Water
		Organic Phase Change Material
		Salt Hydrate
		Thermochemical
		Desiccant
	Flexible Generation	Ramping
		Behind-the-Meter Generation Plus Storage



SI 2030 Technologies

Find the results of SI 2030 and technology reports at https://www.energy.gov/oe/storage-innovations-2030.

Framework

Flight Paths

Lithium-Ion
Lead Batteries
Flow Batteries
Sodium Batteries
Zinc Batteries
Supercapacitors
CAES
PSH
Thermal Storage
Hydrogen Storage
Everything Else

Prize

We Implemented an 8-step Framework to Develop Intervention Portfolios

Identify individual innovation opportunities

Step 1: Assess R&D trajectory status quo
Step 2: Assess gaps with respect to improving technology cost/performance
Step 3: Define interventions that could be relevant to energy storage gaps
Step 4: Assess potential impacts of investment

Assess portfolios of interventions

Step 5: Implement Monte Carlo model
Step 6: Evaluate portfolios of interventions

Analyze modeled outcomes

Step 7: Conduct suitability evaluations
Step 8: Report on metrics

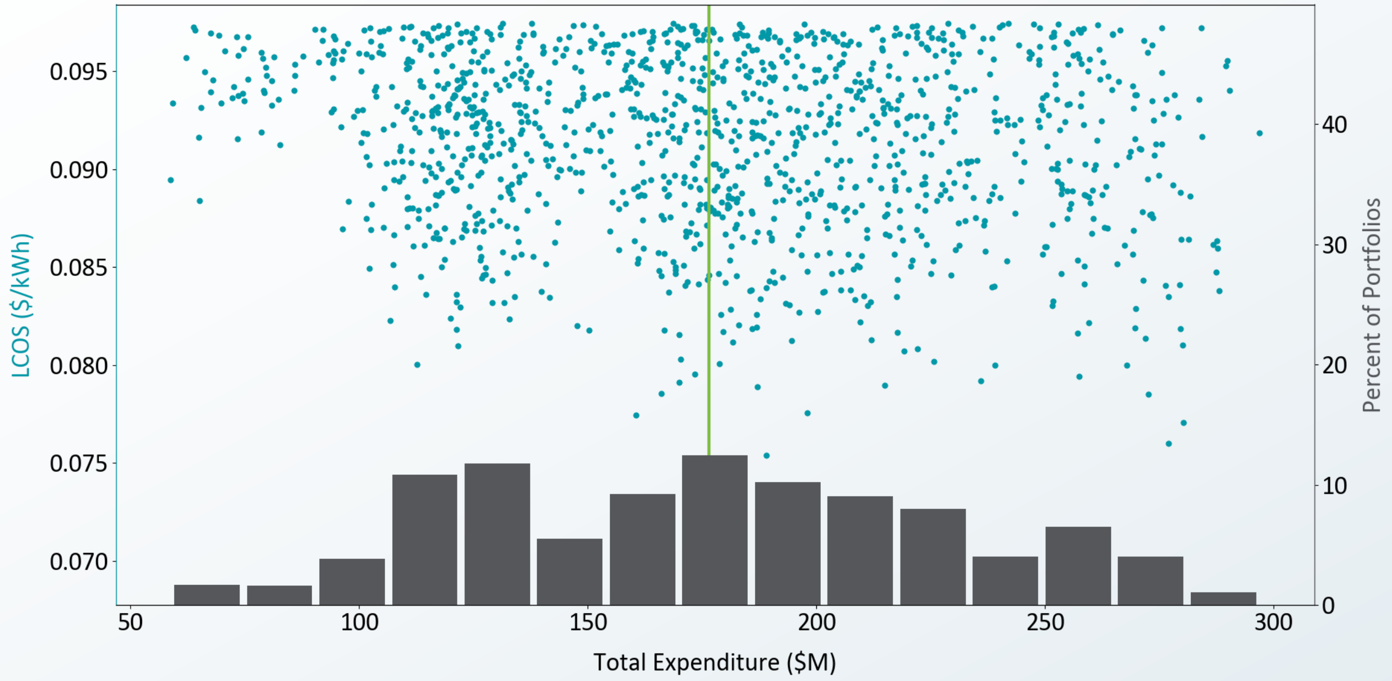
Innovations Defined and Assessed through Subject Matter Expert (SME) Interviews and Follow-on Data Sharing

- SME Interviews
  - 24 of 24 targeted groups interviewed for lead-acid batteries
  - SMEs represented industry groups, academia, and vendors
  - Follow-on forms (suitability, investment, and impacts); 17 forms returned
  - SMEs provided input covering lead acid suitability for ESGC goals, innovation areas, R&D budgets, and impacts

Lead-Acid Battery Taxonomy of Innovations

Innovation Category	Innovation
Raw materials sourcing	Mining and metallurgy innovations
	Alloying in lead sources
Supply chain	Supply chain analytics
Technology components	Re-design of standard current collectors
	AGM-type separator
	Minimizing water loss from the battery
Manufacturing	Manufacturing for advanced lead acid batteries
Advance material development	Novel active material
	Improving paste additives - carbon
	Improving paste additives - expanders or other
	Novel electrolytes
Deployment	Scaling and managing the energy storage system
	Demonstration projects
End of life	Enhancing domestic recycling

Monte Carlo Analysis Used to Evaluate Investment Impacts and Costs

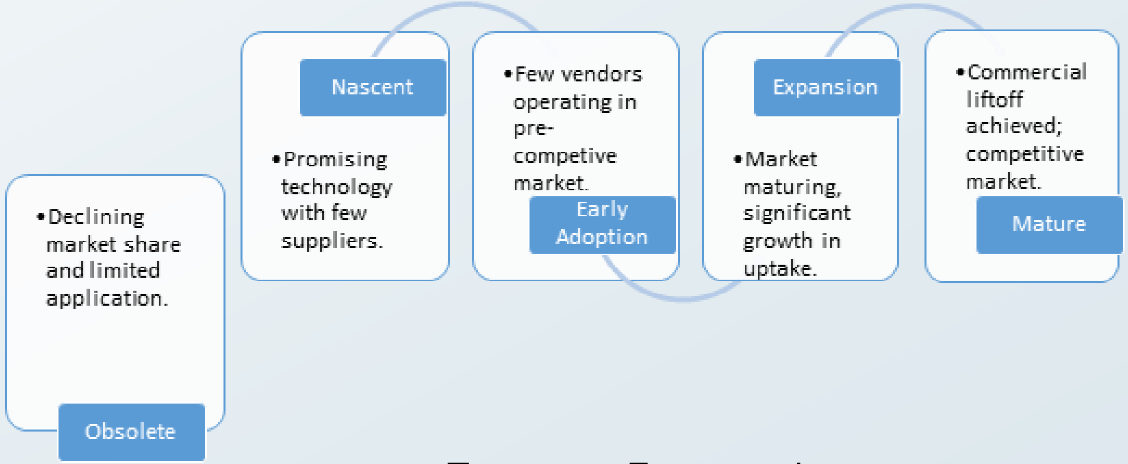


Top 10% of Portfolios for Lead-acid Batteries

- Iterates through each set of innovations and impacts
- Randomly select impact from the innovation's distribution
  - E.g., I1 has -40% impact on storage block cost
  - I3 has -17% impact on storage block cost
- Establish innovation coefficients to limit impact of multiple investments; some investments are in conflict (e.g., mining and metallurgy innovations, enhanced recycling techniques)

A Biannual Report to Inform Evolving Investment Opportunities: Refine List of Technologies

- SI 2030 Framework Study to be updated and published bi-annually
- Technology taxonomy framework established to systematically review and update the list of technologies
- Work more closely with industry groups
- Automate data collection process through online system
- Design website framework and layout
  - Links to current reports
  - Enable user to review and interact with key SI 2030 graphics and findings by technology
  - Advanced visualization techniques to present cross-technology results
  - Consider allowing users to query data to expand research base



Taxonomy Framework

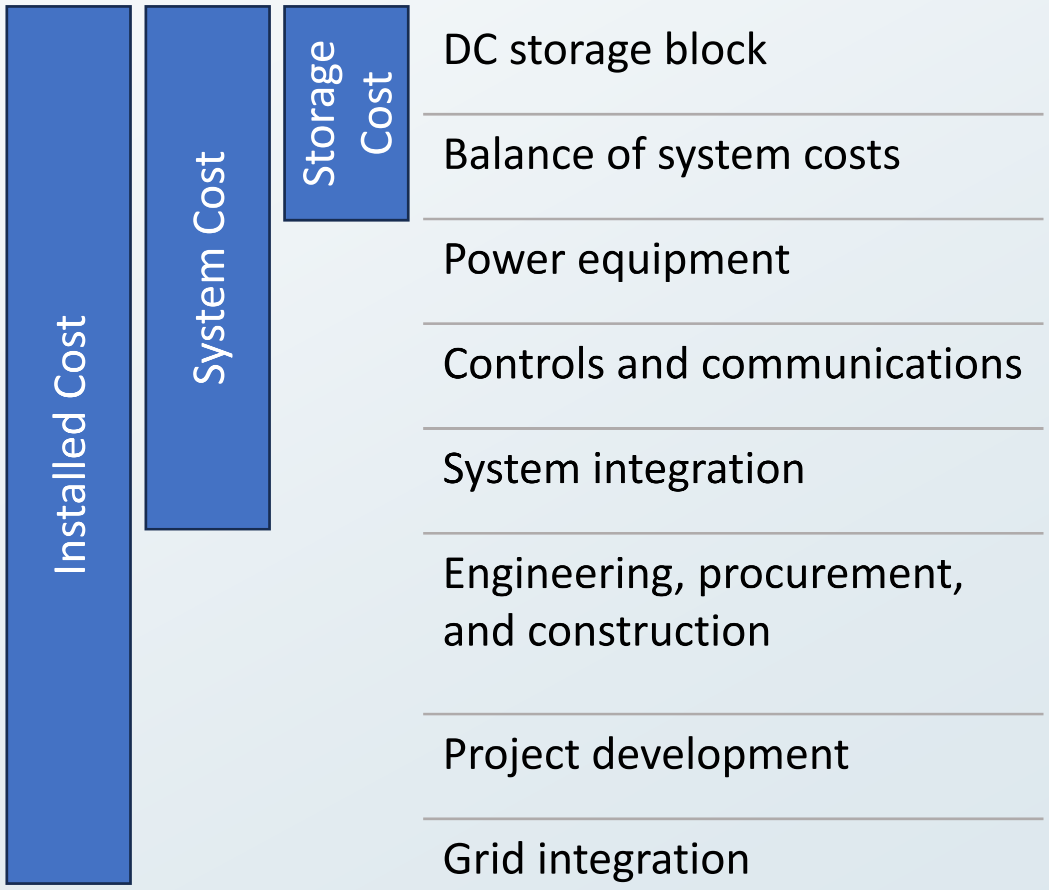
We Need Your Input

- Where do technologies fall in the taxonomy framework?
- What would you like to see on the SI 2030 Framework Study webpage?
- How can we expand the SME base without compromising the quality of the information being received?
- Would you be interested in data sharing to support industry collaboration, and how to structure such engagement opportunities?
- How can we improve the quality of the information we provide?
- What other information would be of most use?

Improved Accuracy and Realism

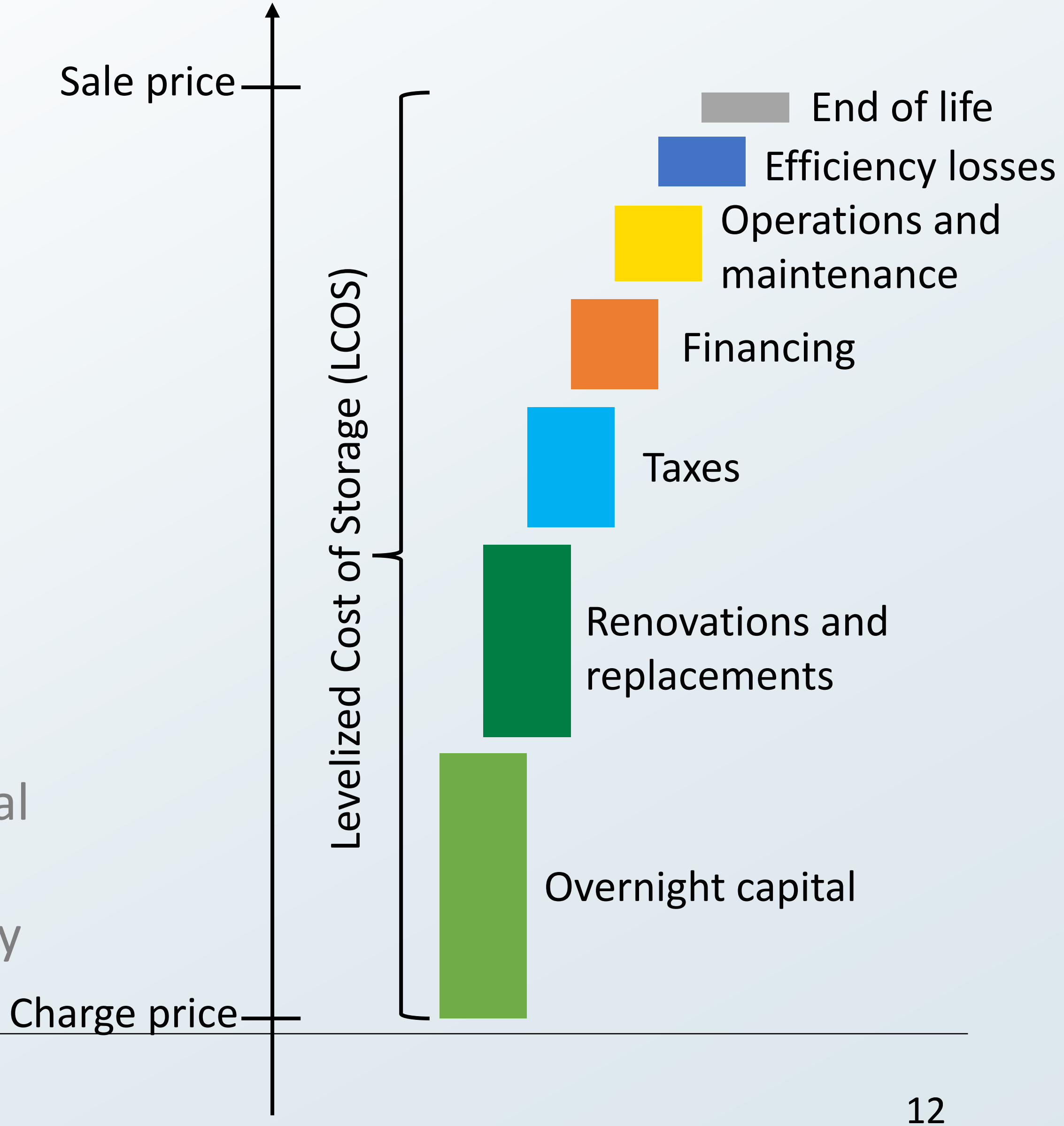
Challenges with levelized cost of storage

- Lack of standardization for inputs and formulation
    - E.g. whether to use installed cost, system cost, or storage cost
- Reduces trust in the metric
- Makes comparing results impossible



Solution: Combine the best parts of common formulations to meet criteria

1. Show how much cost is added to electricity by storing it
2. Consider the time value of money and inflation
3. Consider taxes
4. Consider financing costs
5. Consider of incentives like investment tax credits
6. Apply to all bidirectional electricity storage technologies
7. Inputs should be unambiguous
8. The full life cycle of the project should be included
9. Costs should be amortized over the longest practical project lifetime
10. The LCOS formula should be readily usable and easy to apply to a wide range of technologies



Comparison with other definitions

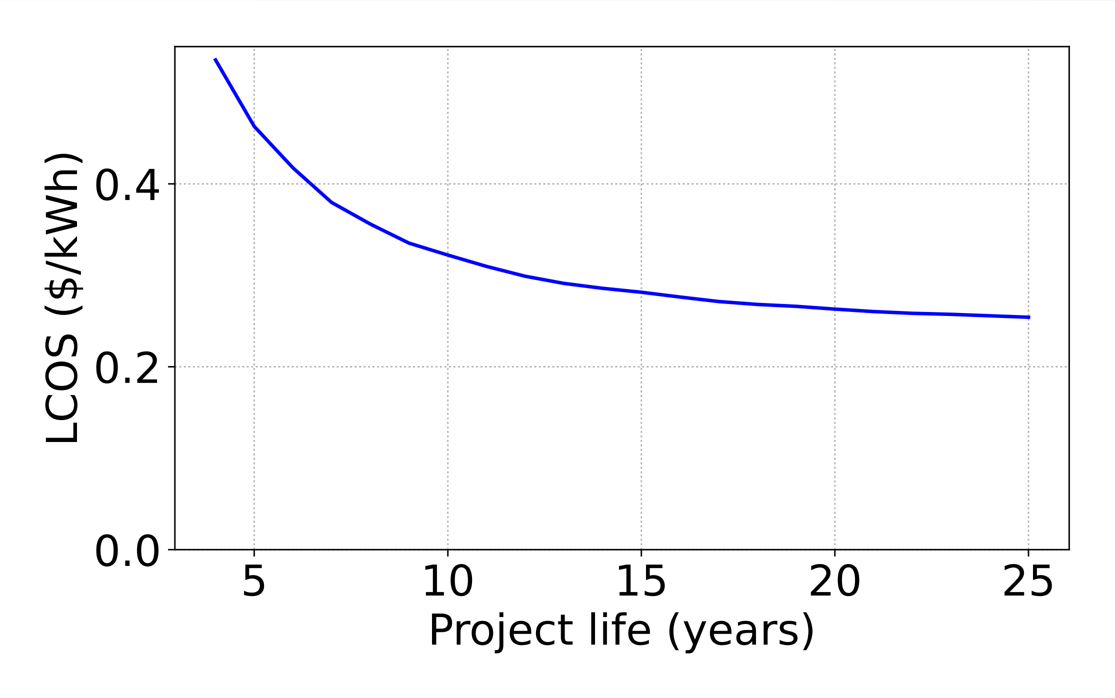
- Compared for an example Li-ion battery
- Spread is 16% when inputs are gathered by the same user
- DAYS is suggested for quick or early-stage estimates
- Proposed formulation is suggested for accuracy and consistency

Formulation	Result
DAYS	$0.241/kWh
LAZARD	$0.278/kWh
ESGC	$0.240/kWh
Proposed	$0.251/kWh

Sensitivity Analysis

LCOS is most sensitive to:

- Project life
- Which capital costs are included (31%)
- Renovations (29%)
- Escalation/discount rates (up to 25%)



LCOS of Li-ion for different project lives, considering renovations, replacements, and residual value

Accuracy also improved with tighter efficiency and cycle life limits

Originally, round trip efficiency was limited at 100%

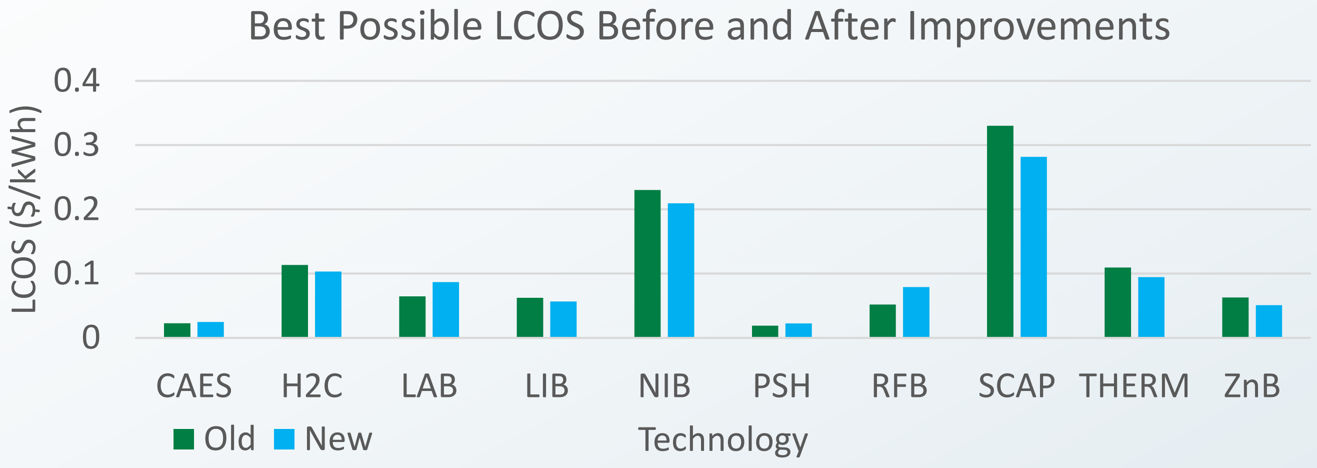
We installed tighter upper bounds based on thermodynamics, expert elicitation, and literature review

Technology	Efficiency Limit	Cycle Limit
Li-ion	97%	10,000
Na-ion	95%	10,000
Supercapacitors	98%	100,000
Hydrogen	86%	N/A
Thermal	65%	N/A
Pumped Storage Hydropower	87%	N/A
Flow Batteries	75%	7,000
Lead-acid	88%	9,000
Zinc	90%	7,000
Compressed air	80%	N/A

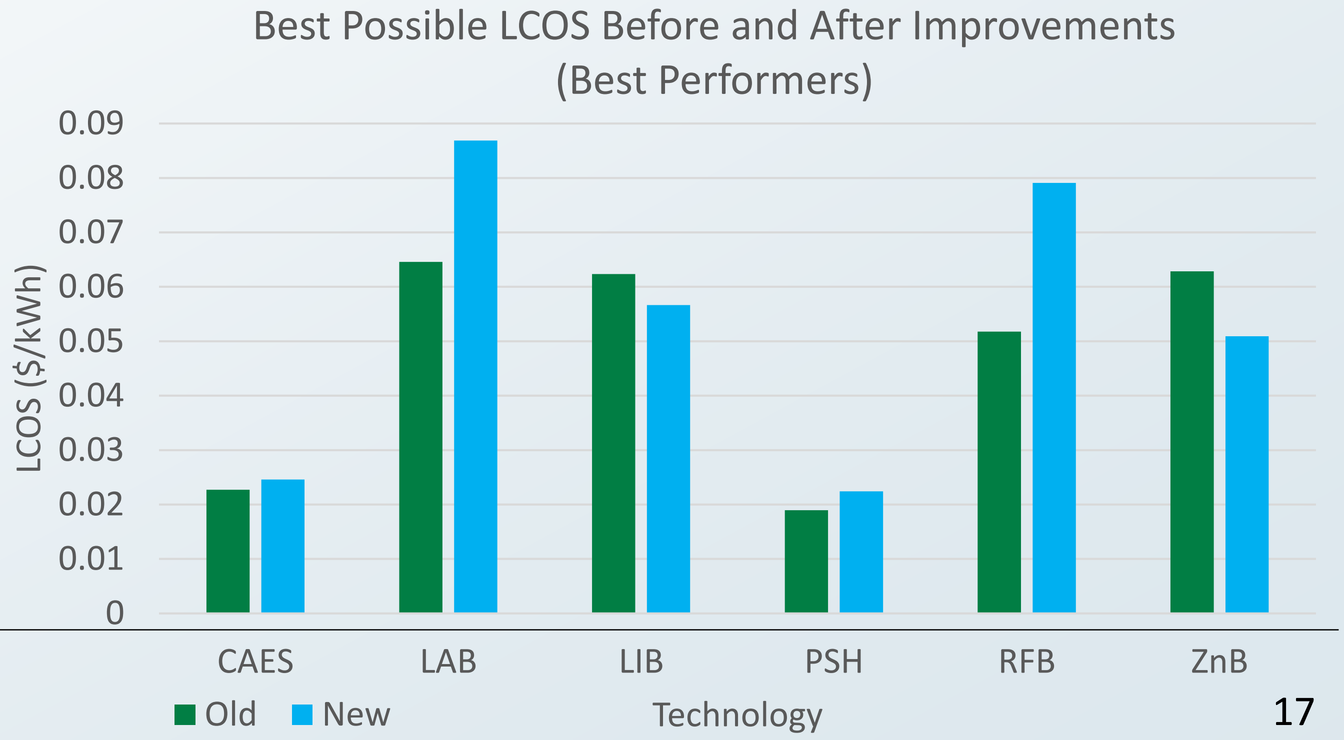
Revised Cross-Technology Results

Impacts of Revisions on LCOS

Best possible LCOS came down unless efficiency/cycle limits overrode

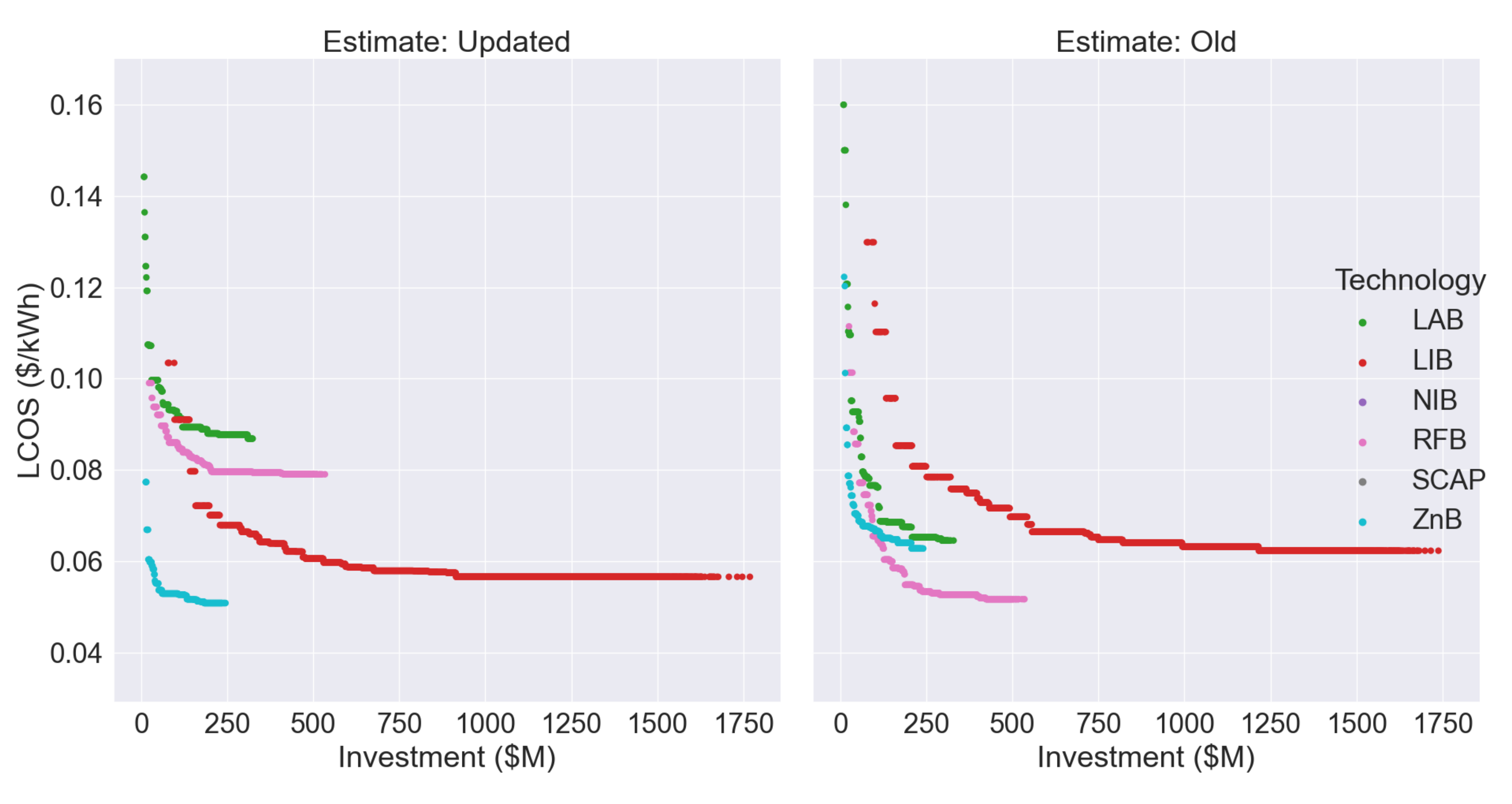


No technologies crossed $0.05/kWh as a result



Flow and lead acid batteries estimates were corrected by the new assumptions

- The old estimates allowed lead acid batteries to have cycle life over 22,000 cycles, the new estimates restrict to a maximum of 9000 cycles.
- Zinc and flow batteries were allowed to have unlimited cycle life and some innovation portfolios resulted in 28,000 cycles in the old estimates, and the updated estimates are limited to 7,000 cycles



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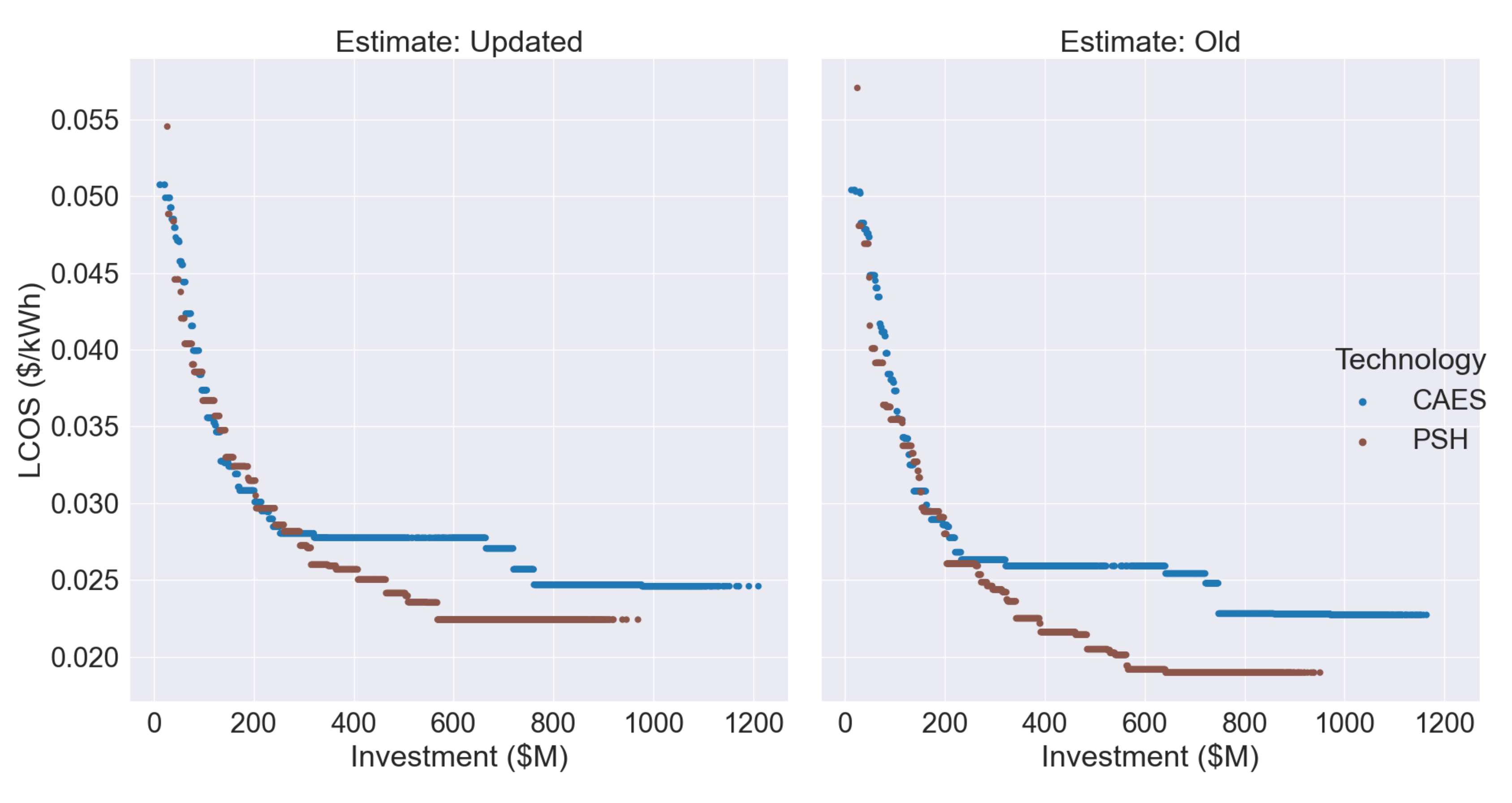
Pumped storage hydro is the least cost long duration storage technology

The new estimates of PSH and CAES are more expensive compared to our previous estimates due to the updated efficiency limits



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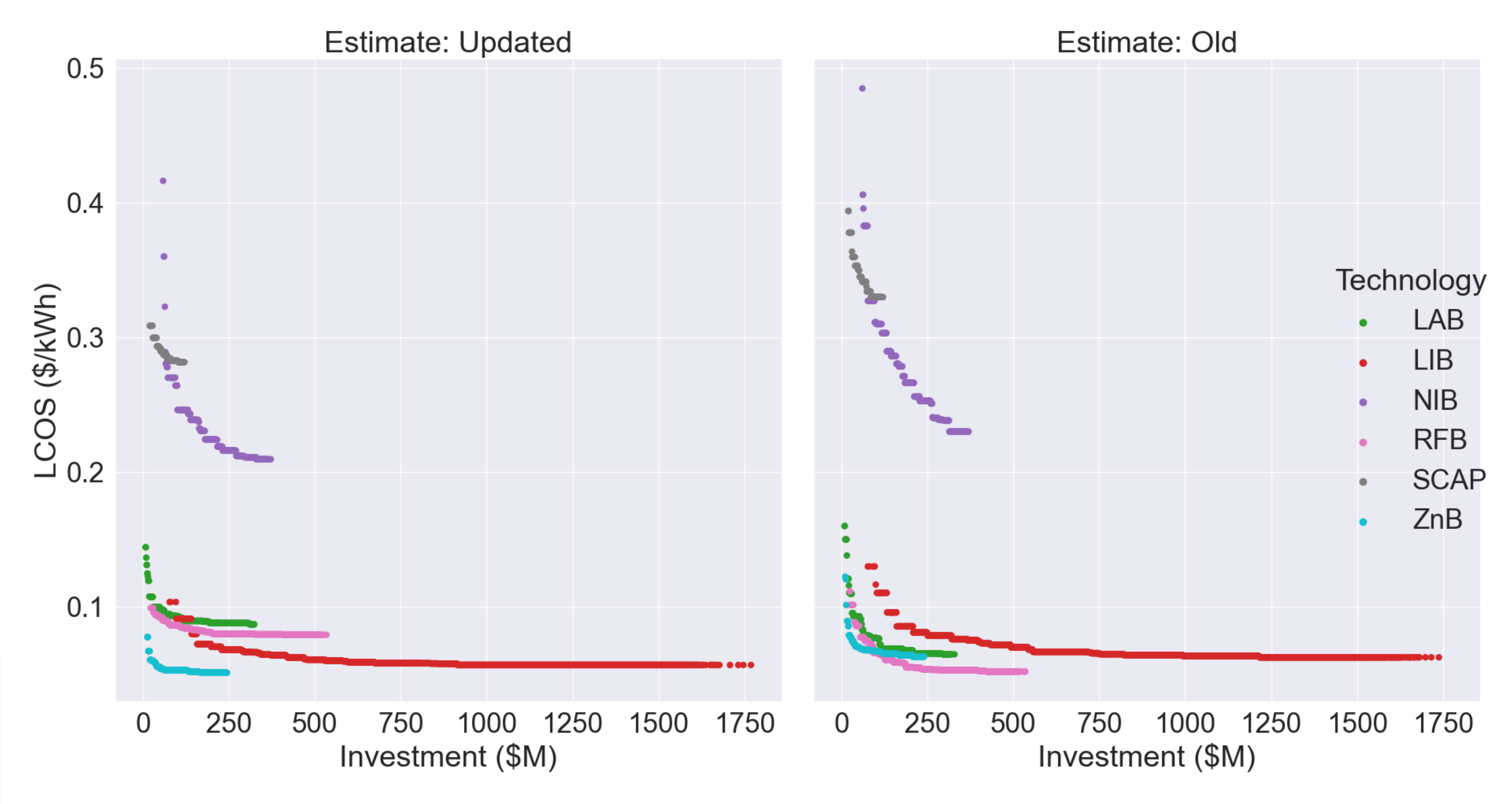
Base LCOS Comparision (updated vs. old)

Technology	Updated LCOS ($/kWh)	Old LCOS ($/kWh)
Lead Acid Battery	0.29	0.38
Pumped Hydro	0.07	0.08
Compressed Air	0.06	0.06
Zinc Battery	0.11	0.15
Redox Flow Battery	0.12	0.17
Li-ion Battery	0.11	0.14
Thermal Storage	0.14	0.13
Hydrogen-Tank	0.15	0.24
Hydrogen	0.11	0.13
Na-ion Battery	0.42	0.55
Supercapacitors	0.34	0.44

All electro chemical storage technologies



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Hydrogen and thermal storage