3[RD] ANNUAL ENERGY STORAGE GRAND CHALLENGE SUMMIT

Storage Innovations 2030: Exploring the Results

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ESGC Flight Paths Listening Sessions:

Collaborative Identification of Technology Pathways

July 25-27, 2023

Georgia Tech Global Learning Center

Atlanta, Georgia

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The Precursor: Pitch Sessions

- Brought together technology developers across the spectrum:
  - Presenters: Academic researchers, startups, established companies
  - Evaluators: Technology experts from across the national lab complex
  - *Question: Is your proposed LDES on a path to commercial viability?*

- 37 LDES technology pitches in total – at 5-10 minutes each
  - 9 during ESGC Summit at Argonne National Laboratory (Sept 2022)
  - 28 virtually (November 2022)

- Technologies for consideration were selected from pitch sessions and Congressional direction
  - Based on commercial viability by 2030

Listening Session Objectives:
Discussion on *precompetitive* research opportunities

- Engaged industry participants as broadly and comprehensively as practical
  - Focus on *Industry participation and discussion* equitably among participants
  - Prioritize technologies over products
  - Process notes:
    - Combination of Menti (real-time, internet-based survey) and open discussion
    - Extensive notes and Menti input capture
- Planned outcomes from flight paths effort:
  - Roadmap reports describing pre-commercial R&D pathways
  - Initiation of technology-specific industry consortia that will catalyze partnerships in areas that serve all participants.
  - Identification of research areas that USDOE can pursue
    - Led by national labs, academia, and/or industry

Ten 2-hour Listening Sessions Were Held

Workshop	Topic	Facilitators	Attendees
January 12, 2023	Flow Batteries	Vincent Sprenkle and Bin Li	41
January 24, 2023	Zinc Batteries	Erik Spoerke and Esther Takeuchi	47
January 26, 2023	Lithium-Ion Batteries	Eric Dufek and Noel Bakhtian	31
February 9, 2023	Thermal Energy Storage	Kyle Gluesenkamp, Zhiwen Ma, and Luke McLaughlin	82
February 16, 2023	Lead-Acid Batteries	Susan Babinec, Boryann Liaw, Tim Fister, and Pietro Papa Lopes	58
February 23, 2023	Pumped Storage Hydropower	Vladimir Koritarov and Scott DeNeale	54
March 2, 2023	Sodium Batteries	Erik Spoerke and Jagjit Nanda	48
March 9, 2023	Compressed-Air Energy Storage	Shabbir Ahmed and Dan Flowers	35
March 16, 2023	Supercapacitors	Thomas Mosier and Stanley Atcitty	33
April 13, 2023	Crosscutting Issues in LDES	Michael Starke and Charlie Hanley	52

Example Listening Session Questions

- What is the Technology Readiness Level and the Manufacturing Readiness Level of your particular technology?
- What are the most impactful impediments limiting the widespread deployment of your technology?
- What specific technical and/or market barriers are there for longer discharge durations (10-24 hours)?
- What would make public resources (e.g., state, regional, or federal testing sites, technoeconomic tools, technical expertise) more valuable for you?
- Can you identify specific "precompetitive" innovations or developments that would advance your technology?
- Is lack of a trained workforce currently a critical limitation for your success? What type of training or curricular development would you recommend for growing the workforce in this area?

Some Common Themes on Collaborative Efforts…
(from the cross-cut listening session*)

- Access to capital and financing
- Limited market opportunities
- Technology validation for industry acceptance
- Interconnection queues and permitting
- Integrating technologies
- Manufacturing supply chain
- Workforce development
- Standards and codes

*Thanks to Michael Starke, ORNL, for compiling

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Energy Storage 2030 – Framework Methodology and Expanded Results

Patrick Balducci[1], Thomas Mosier[2], Hill Balliet[2], Venkat Durvasulu[2], Ben Shrager[3]

Energy Storage Grand Challenge Summit
July 25, 2023

[1]Argonne National Laboratory [2]Idaho National Laboratory
[3]U.S. Department of Energy

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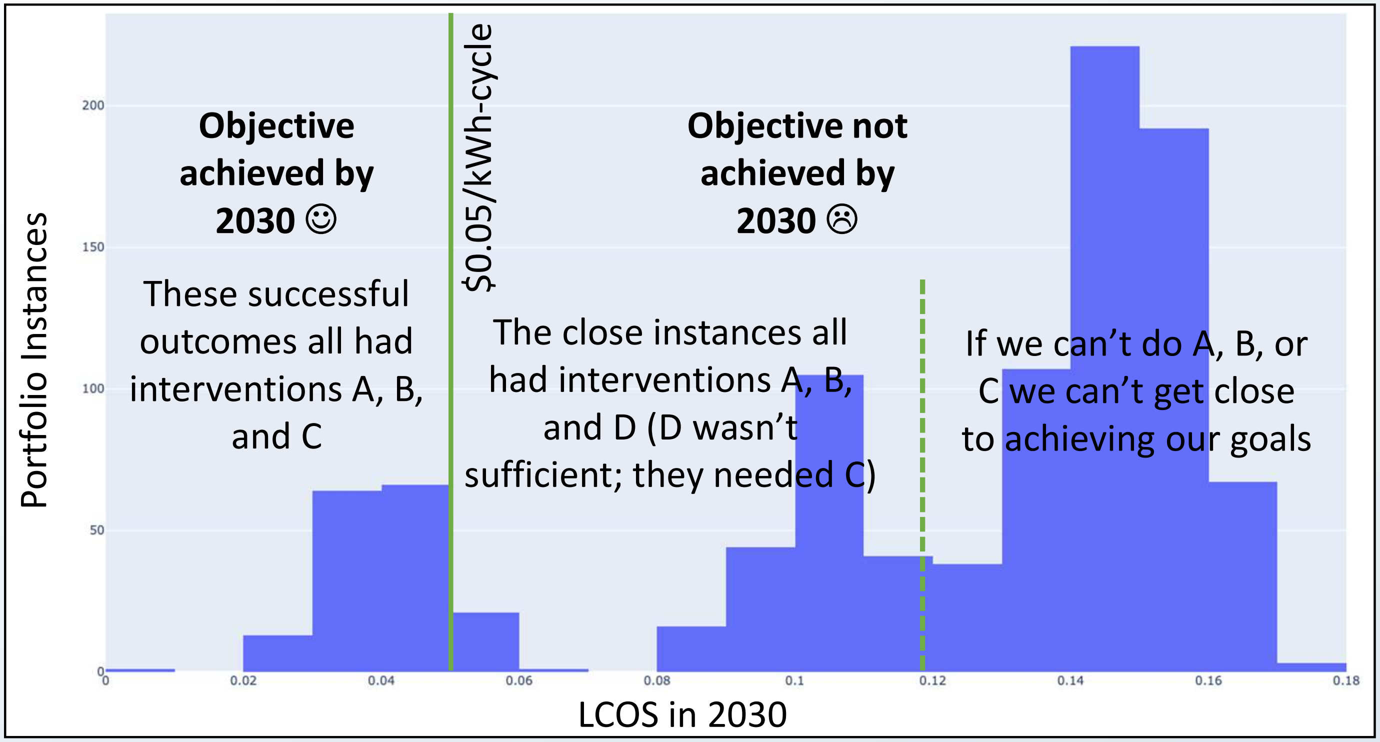
Objective - Identify Portfolios of Innovations That Efficiently Achieve Levelized Cost of Storage (LCOS) Reductions

"Portfolios" are sets of interventions by DOE (e.g., specific R&D activities, demonstrations, loans for scale-up)



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We are Implementing a Framework to Develop These 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

Simplified Example Technology: Step 1

- Baseline trajectories determined from Energy Storage Grand Challenge (ESGC) Cost and Performance report
- Power and duration set to match ESGC Roadmap for "Facilitating an Evolving Grid"
- LCOS approach defined and used for this study

Parameter	Value
Deployment life (years)	25
Battery power (kW)	10000
Battery duration (h)	10
Base total number of cycles	6508
Base round trip efficiency	0.74
Base storage block cost ($/kWh)	212.58

Levelized Cost of Storage

- **Storage block cost($/kWh)**
- **Balance of system cost ($/kWh)**
- Systems integration ($/kWh)
- Project development ($/kWh)
- Power Equipment ($/kW)
- Controls and communications ($/kW)

Capital cost

Operational cost

$$LCOS = \frac{\text{Total Cost (\$)}}{\text{Total Energy (kWh)}} \ \$/kWh$$

- **Fixed O&M ($/kW-yr)**
- **Variable O&M ($/kWh)**
- Electricity cost (Electricity cost/**round trip efficiency [RTE]**)

Technology	Base 2030 LCOS
Compressed air energy storage	0.06
Hydrogen cavern storage	0.13
Hydrogen tank storage	0.24
Lead acid battery	0.38
Lithium-ion battery	0.14
Sodium-ion battery†	0.55
Pumped hydro storage	0.08
Redox flow battery	0.17
Supercapacitor‡	0.44
Thermal energy storage	0.17
Zinc Battery	0.15
Compressed air energy storage	0.06

† Based on 2021 Value
‡ Based on 2025 Estimates

Steps 2-3: Interviews and Gap Analysis

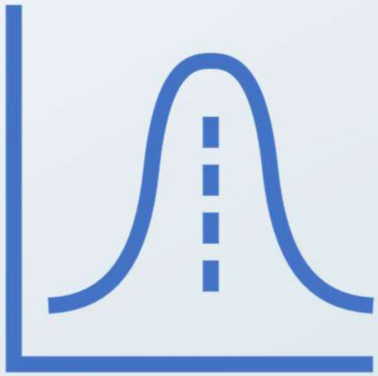
- Tier 1 categories (e.g., supply chain) common to all technologies whereas Tier 2 categories specific to individual technologies
- Innovations identified and defined from industry interviews
- Interventions (e.g., national lab funding, DOE grant, DOE loan, notice of technical assistance) examined through follow-on surveys

Innovation Category	Innovation
Raw materials sourcing	Mining and metallurgy improvements
Supply chain	Supply chain analytics
Technology components	Re-design of standard current collectors
	Minimizing water loss from the battery
Manufacturing	Advanced manufacturing

Step 4-5: Innovation Impact Assessment

- Innovation impacts collected through subject matter expert (SME) surveys
- Iterates through each set of innovations
  - E.g., I1, I3
- 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

	Storage Block Cost			
Innovation	Low	High	Mean	Std
I1	-0.1	-0.6	-0.2	0.1
I2	-0.1	-0.2	-0.1	0.05
I3	-0.1	-0.2	-0.15	0.01
I4	0	0	0	0.0



Step 6: Combine Innovations into Portfolios

- Some innovations are mutually exclusive or overlapping - e.g., re-design of standard current collectors and supply chain analytics while others are not
- Innovation coefficients established
- 15% improvement + (10% improvement * 0.16 coefficient) = 16.6% total improvement

Innovation	Mining and metallurgy improvements	Supply chain analytics	Re-design of standard current collectors	Minimizing water loss from the battery	Advanced manufacturing
Mining and metallurgy improvements	–	0.01	1	1	1
Supply chain analytics	0.01	–	0.16	0	0.19
Re-design of standard current collectors	1	0.16	–	1	1
Minimizing water loss from the battery	1	0	1	–	0.75
Advanced manufacturing	1	0.19	1	0.75	–

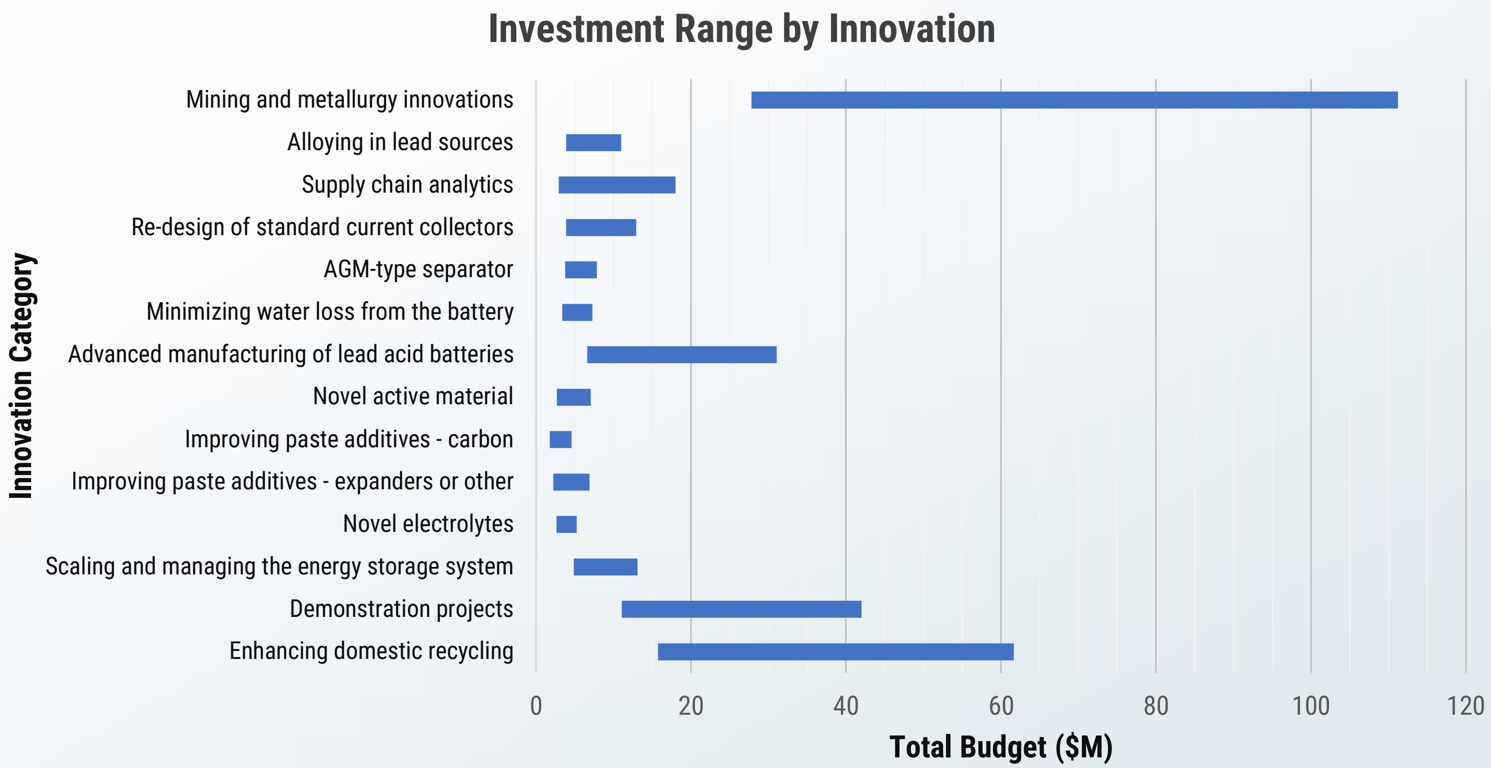
Step 7: Suitability Analysis

- SME surveys also gathered suitability scores and weighting values
- Scores were analyzed using multi-criteria decision analysis (MCDA) tool

Use Cases	Use case performance requirements		Score		
Facilitating an Evolving Grid	Services	Short duration load response	8	(1-10)	1=Not well suited.
		Medium duration load response	6	(1-10)	5=Neutral.
		Long duration load response	6	(1-10)	10=Exceptionally well suited.
		Power quality	8	(1-10)	
	Attributes	Long lifetime	5	(1-10)	
		Scalable	8	(1-10)	
		Flexible	8	(1-10)	

Technology Results

Recommended Investment by Innovation (Lead-acid)



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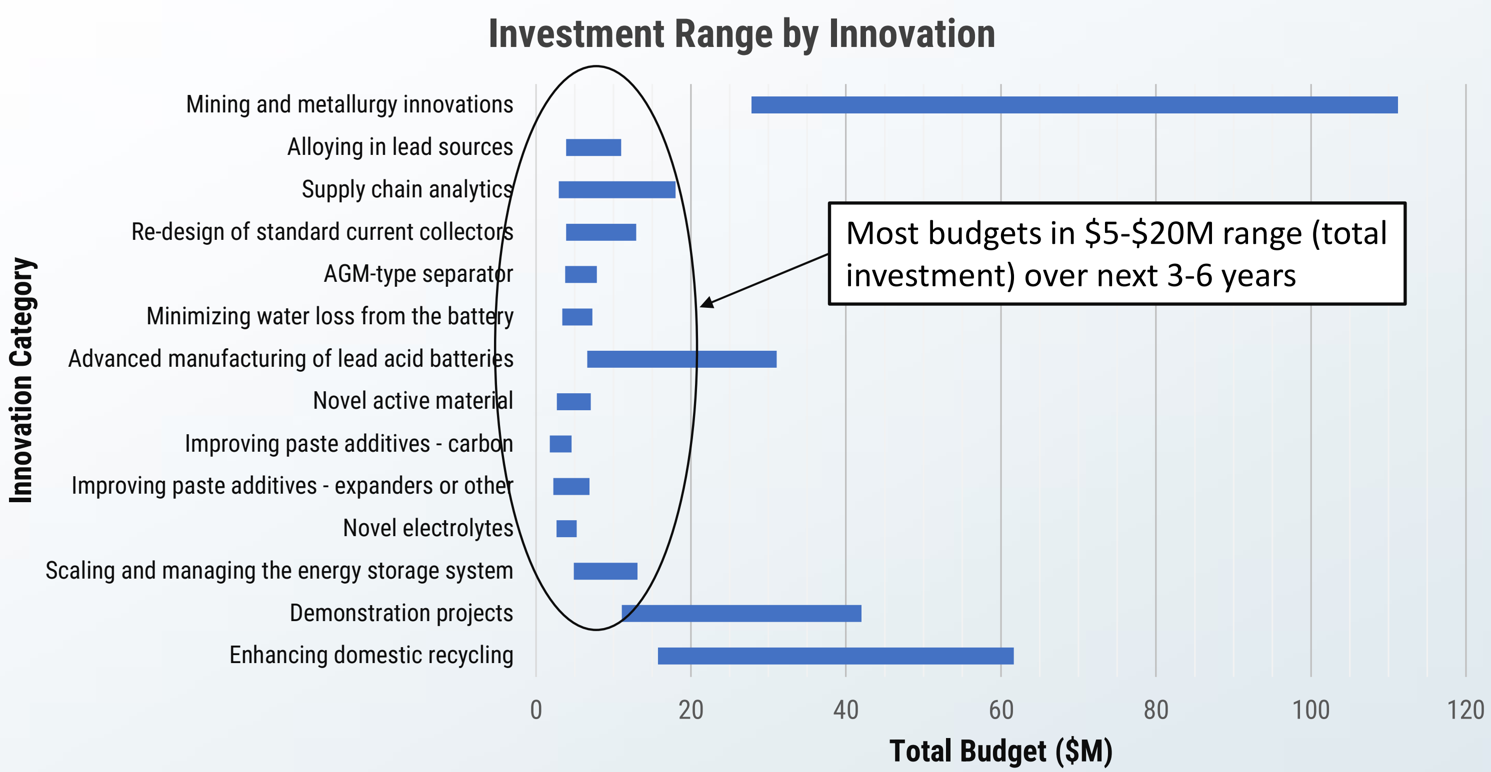

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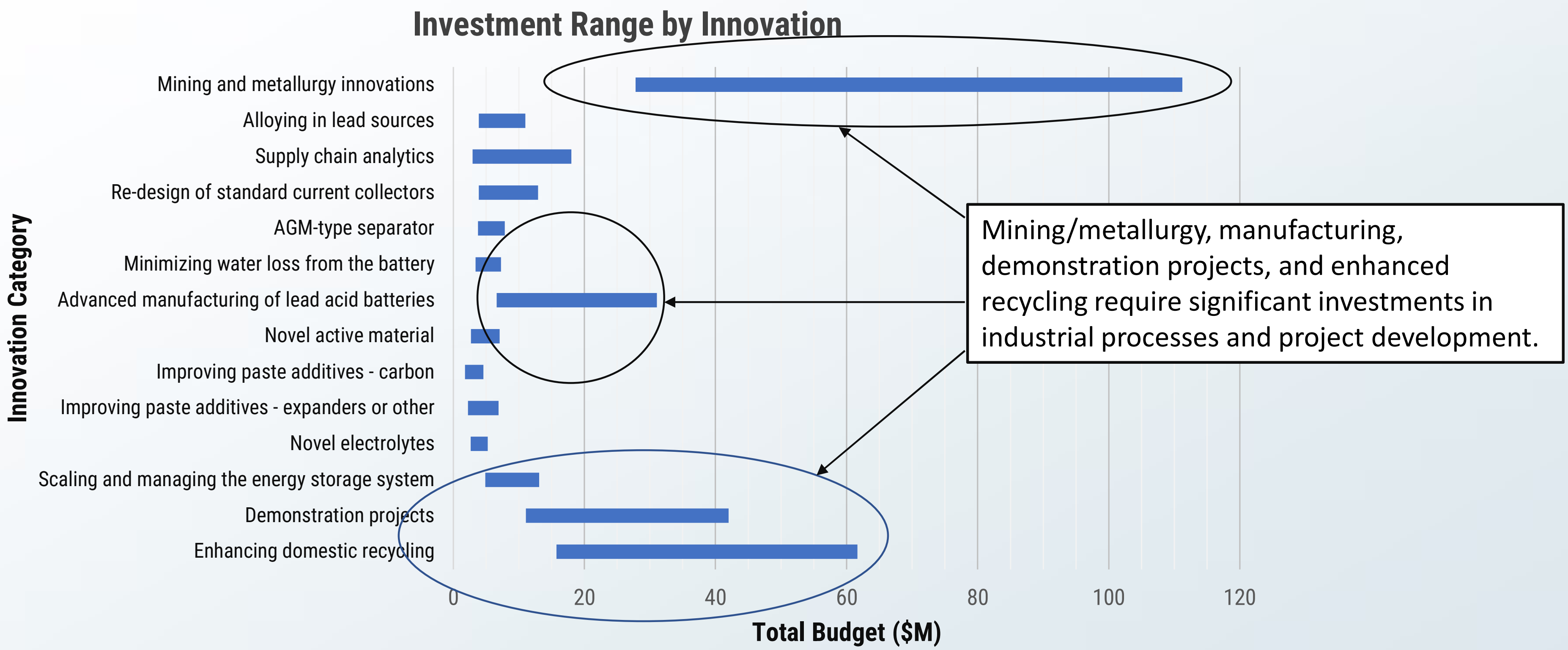
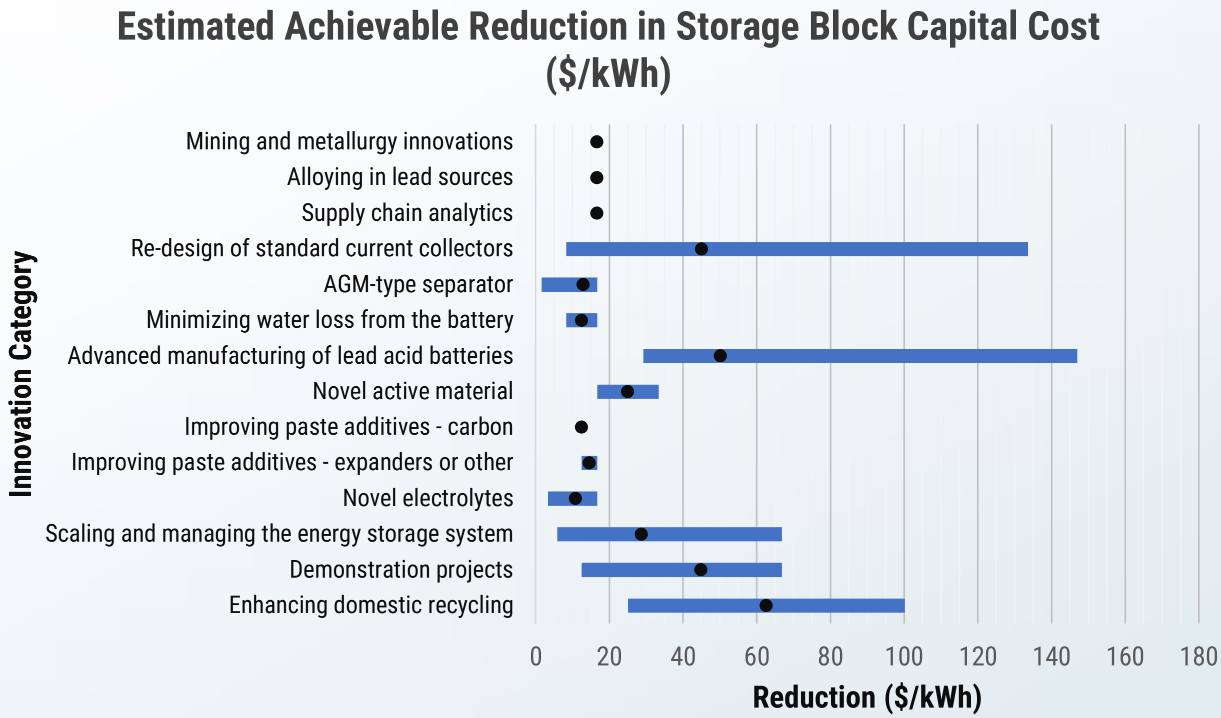
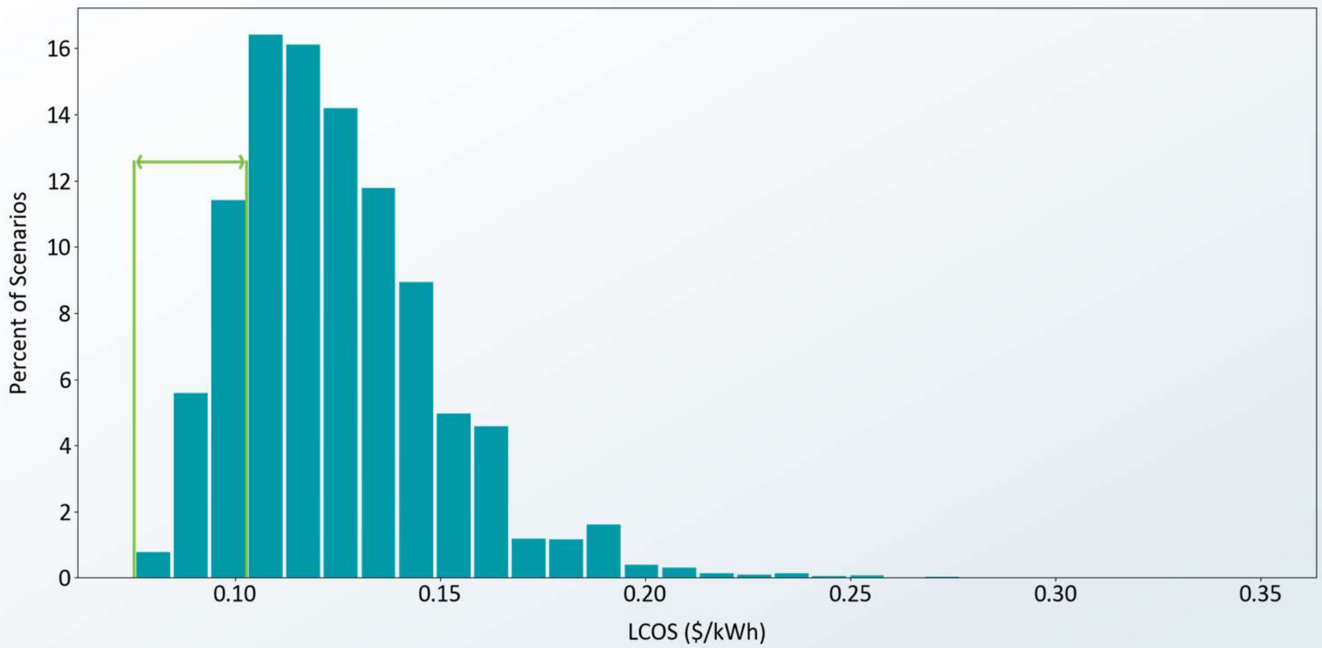


Estimated Reductions in Storage Block Capital Cost (%) (Lead-acid)



- Large variation in estimated cost reduction potential for multiple high-impact investments – e.g., re-design of standard current collectors and manufacturing advancements
- Significant potential reductions for high-cost efforts to restructure industrial processes or support demonstration projects
- Total reduction in storage block capital costs reflect a portfolio of investments

Some Innovation Portfolios Substantially Reduce LCOS



- LCOS for lead-acid with no additional investment in 2030 estimated at 38 cents/kWh
- The LCOS range with the highest concentration of simulated outcomes at prescribed investment levels is in the $.09-$.13 per kWh range
- The highest impact portfolios (top 10%) result in LCOS range of 7.5 – 9.7 cents/kWh (highlighted by green arrows)

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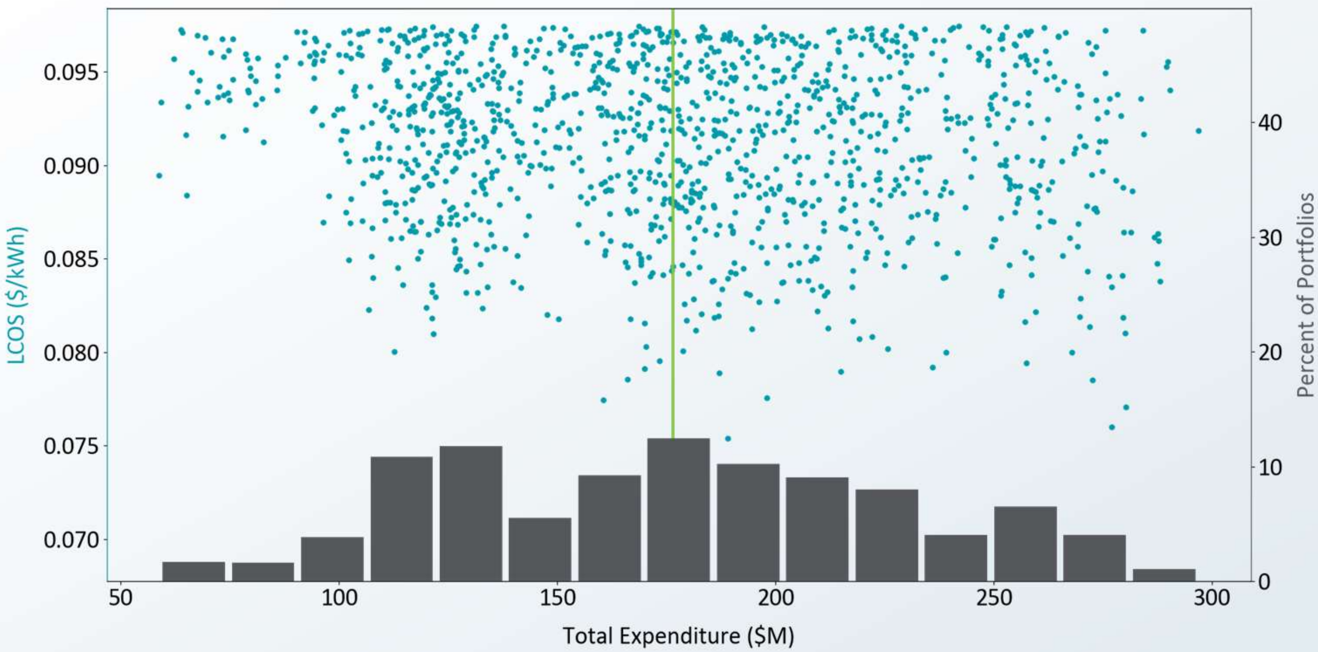
LCOS and Investment Requirements for top 10% of Portfolios



- The highest impact portfolios (top 10%) result in LCOS range of 7.5 – 9.7 cents/kWh
- 50 percentile budget of top 10% performing portfolios = $176.4 million
- Timeline for implementing top 10% of innovations: 5.2-8.7 years

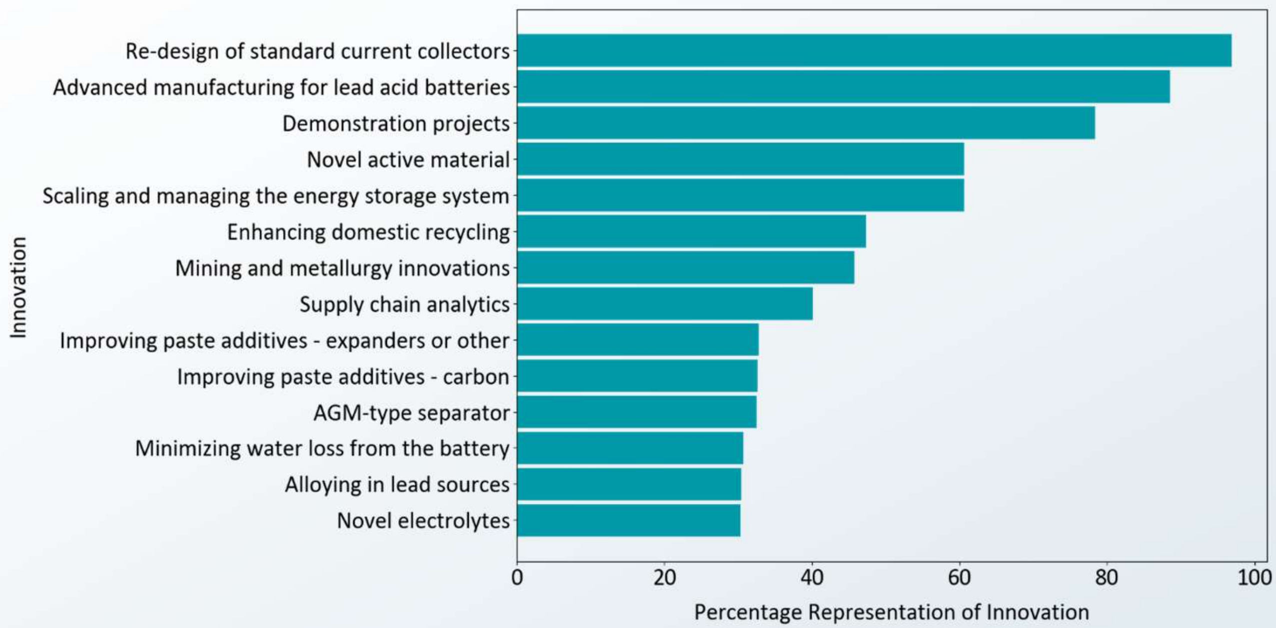
Investment Mechanism

Innovation	National Laboratory Research	R&D Grants	Loans	Technical Assistance
Enhancing domestic recycling	22%	31%	25% *	22%
Demonstration projects	16%	47%	32% *	5%
Scaling and managing the energy storage system	23%	41%	32% *	5%
Novel electrolytes	60%	27% *	0%	13%
Improved paste additives – expanders or other	37%	37%	7%	20% *
Improving paste additives – carbon	48%	29% *	5%	19%
Novel active materials	47%	30% *	7%	17%
Advanced manufacturing for PbA batteries	26% *	32%	18%	24%
Minimizing water loss from the battery	43%	39% *	0%	17%
AGM-type separator	37%	37%	5%	21%
Re-design of standard current collectors	25% *	46%	4%	25% *
Supply chain analytics	35%	29% *	12%	24%
Alloying in lead sources	40%	40%	7%	13%
Mining and metallurgy innovations	13%	33%	33%	20% *

*Preferred mechanisms.

- National lab research favored for fundamental research activities (e.g., novel active material, improving paste additives)
- R&D grants supported for larger, industry-focused efforts (e.g., enhancing domestic recycling, scaling/managing energy storage systems)
- Loans supported for industrial processes and demonstration projects that would require industry investment

Innovation Representation in the Top 10% of Portfolios



- There are basic research-focused innovations that appear to hold great promise for reducing cost and improving performance (e.g., re-design of standard current collectors, novel active material)
- Advanced manufacturing, demonstration projects, and scaling/managing the energy storage system required to achieve deep reductions in LCOS

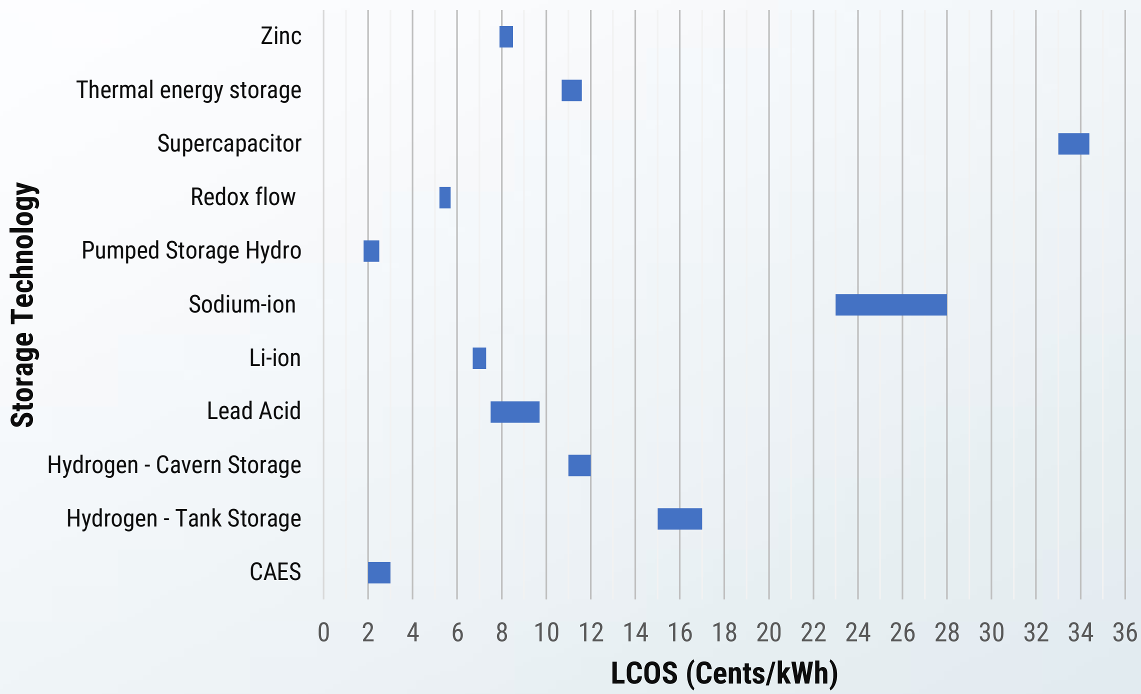
Investment Impacts by Innovation – Key Metrics

Innovation	Storage Block Cost Impact (%)	Cycle Life Improvement (%)	Round-trip Efficiency Impact (%)	Mean Investment Requirement (million $)	Mean Timeline (years)
Enhancing domestic recycling	-15% *	0% ‡	0% ‡	37.8 ‡	3.8 ‡
Demonstration projects	-24% *	75% *	11% *	26.6 ‡	3.7 †
Scaling and managing the energy storage system	-12% *	53% †	10% *	9.0 †	2.8 *
Novel electrolytes	6% †	87% *	4% †	3.9 *	3.0 *
Improving paste additives – expanders or other	8% ‡	52% †	5% †	4.5 *	3.1 †
Improving paste additives – carbon	8% ‡	63% †	3% †	3.3 *	3.1 †
Novel active materials	-15% †	102% *	7% *	5.0 *	3.7 †
Advanced manufacturing for PbA batteries	-25% *	219% *	6% *	18.4 ‡	5.5 ‡
Minimizing water loss from the battery	8% ‡	56% †	5% †	5.4 *	3.0 *
AGM-type separator	9% ‡	78% †	6% *	5.7 †	3.2 †
Re-design of standard current collectors	-21% *	125% *	5% †	8.2 †	3.0 *
Supply chain analytics	-10% †	0% ‡	0% ‡	10.5 †	2.3 *
Alloying in lead sources	10% ‡	31% ‡	0% ‡	7.7 †	4.3 ‡
Mining and metallurgy innovations	-10% †	0% ‡	0% ‡	65.7 ‡	4.2 ‡

Cells with asterisks (*) for top tier preferred mechanisms; daggers (†) to represent mid-tier; and double daggers (‡) for the lowest tier.

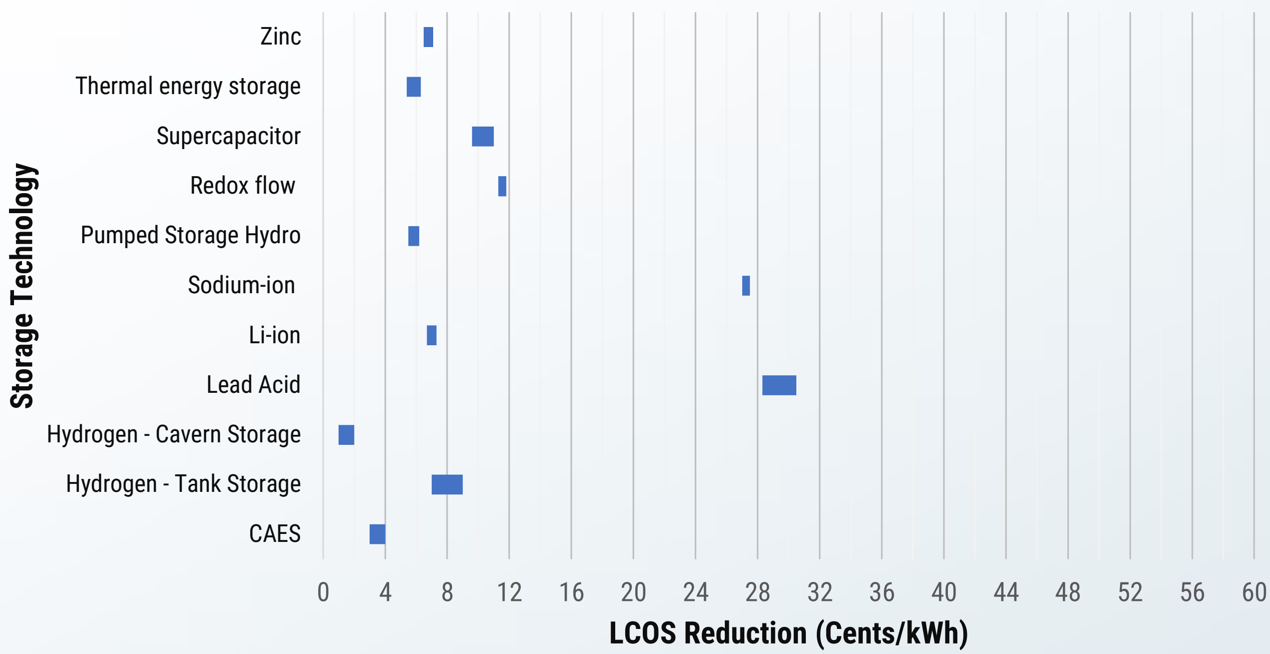
- Redesign of standard current collectors, novel active materials, demonstration projects, and advanced manufacturing for PbA batteries consistently yield top tier metrics
- LCOS improvements driven largely by gains in cycle life

Levelized Cost of Storage Top 10% of Portfolios in 2030



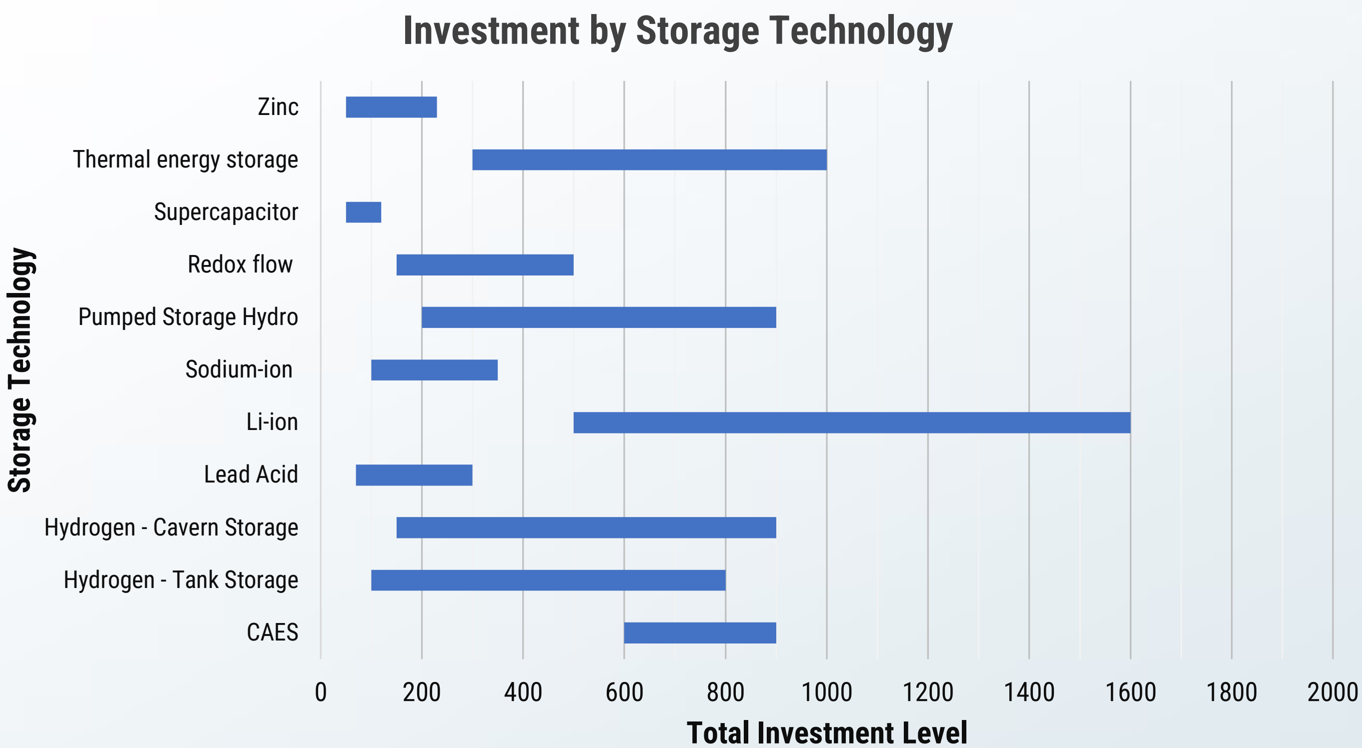
- Top 10% portfolios achieve 5 cents/kWh target for PSH and CAES
- Research team in next round of analysis establishing technical limits to all metrics

Levelized Cost of Storage Reductions



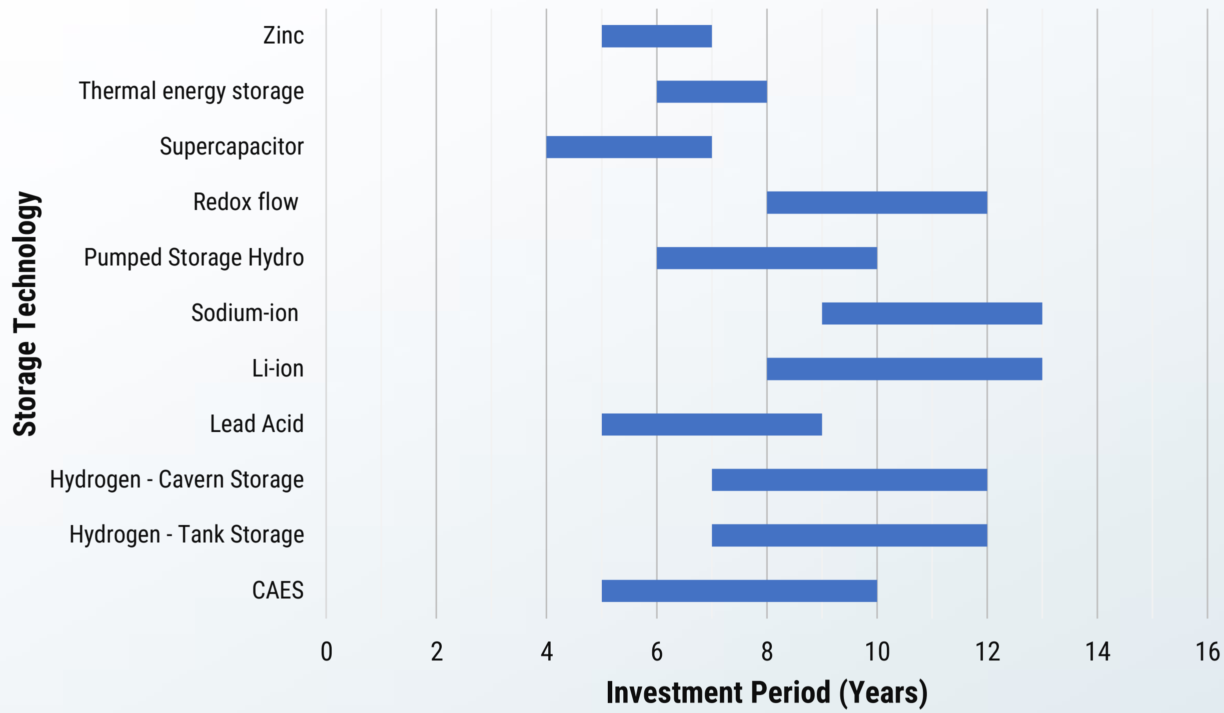
- LCOS reductions under 6 cents/kWh for more mature technologies, lower impact for mechanical energy storage
- Significant cost reductions viewed as achievable by SMEs for lead acid and sodium-ion technologies, followed by redox flow
- DOE should weigh the goals of investment – e.g., achieve 5 cents/kWh or achieve significant reductions in LCOS, invest in nascent technologies to clear hurdles and achieve commercial lift off or push more mature technologies to 5 cents/kWh

Investment Requirement



- Diminishing marginal returns evident as more mature technologies (e.g., PSH, Li-ion) generally require more investment to achieve deep LCOS reductions
- Investment requirements modest for several technologies – lead-acid, supercapacitors, zinc, sodium ion

Investment Period by Storage Technology



- Most investment time horizons extend beyond 2030 timeframe
- To meet ESGC target goals by 2030, more aggressive timelines must be considered

Top 3 Innovations by Technology

Technology	Innovation #1	Innovation #2	Innovation #3
CAES	Demonstration Projects	System Modeling and Design/Operation Optimization	Mechanical Compression/Expansion
Hydrogen	Liquid Hydrogen Carriers	Hydrogen Carrier Advancements	Demonstration Projects
Lead Acid	Re-design of Standard Current Collectors	Advanced Manufacturing for Lead Acid Batteries	Demonstration Projects
Li-ion	Rapid Battery Health Assessment	Controls to Improve Cycle Life	Impurity Reduction Techniques
Sodium-ion	Cathode-electrolyte Interface	In-operation Materials Science Research	Electrolyte Development
PSH	Hybrid PSH Projects	Testing Durability of New Materials and Structures	3D Printing at Large Scale
Redox flow	Novel Active Electrolytes	Manufacturing for Scalable Flow Batteries	Accelerate Discovery Loops for Battery Metrics and Materials
Supercapacitor	Cell Packaging	Hybrid Components	Automated Manufacturing
Thermal energy storage	Single-tank Storage	Heat-to-electricity Conversion Improvements	Large-scale Demonstrations
Zinc	Separator Innovation	Pack/system-level Design	Demonstration Projects

- Most technologies require both basic and applied research to achieve deep LCOS reductions
- Developing technologies (e.g., redox flow and sodium-ion) require technology improvement while advanced manufacturing, control systems, and demonstration projects favored for more mature technologies

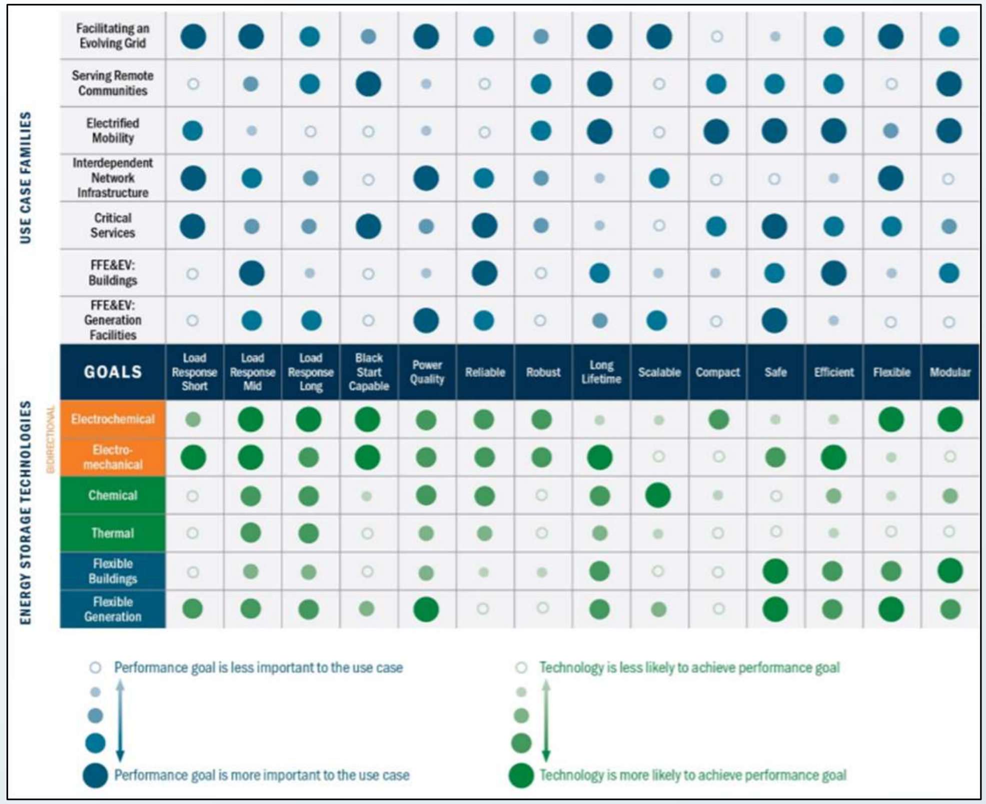
Impact measured by inclusion of innovation in top 10% portfolios.

Suitability Results

ESGC Roadmap Use Cases

ESGC Technology Development Activity 2

Identify a portfolio of energy storage technologies that have an ***R&D pathway*** *to achieve significant progress towards* ***ESGC cost targets by 2030****. Develop standardized metrics that facilitate technology-agnostic cost and performance evaluations.*



Current-year Suitability Ratings

100 = Perfect score. Traffic signal-style color coding with green being more positive than yellow, which is more positive than shades of red.

Limited confidence in results for sodium, supercaps, thermal, and hydrogen due to poor response rate.

	Lead Acid	Flow	CAES	Li-Ion	Sodium*	Supercaps*	Thermal*	Hydrogen*	PSH	Zinc
Facilitating an Evolving Grid	71.3	74.0	77.6	73.7	59.5	67.6	79.1	71.6	78.7	64.3
Serving Remote Communities	77.0	77.3	76.8	72.2	62.3	71.4	83.1	77.7	83.3	69.0
Electrified Mobility (Vehicles)	56.6	30.7	27.7	70.1	71.5	75.0	20.0	71.2	58.2	60.9
Electrified Mobility (Charging Infrastructure)	67.7	72.4	55.3	70.9	70.3	81.2	60.9	73.5	67.8	59.4
Interdependent Network Infrastructure	76.0	67.9	60.0	81.5	62.3	89.9	51.5	56.5	75.9	60.2
Critical Services	82.3	71.5	75.9	70.3	66.9	91.1	64.4	70.4	89.5	68.9
Facility Flexibility, Efficiency, and Value Enhancement (Buildings)	82.2	74.1	42.9	71.3	76.4	92.2	90.5	70.9	79.1	67.0
Facility Flexibility, Efficiency, and Value Enhancement (Generators)	82.2	80.2	80.1	71.3	76.1	95.0	56.0	63.9	90.1	71.3

We divided the electrified mobility use case into two cases covering vehicles and charging infrastructure.

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SMEs recognize need for improvement with vehicle-based technologies.

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PSH scores well for several use cases.

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Critical Services	82.3	71.5	75.9	70.3	66.9	91.1	64.4	70.4	89.5	68.9
Facility Flexibility, Efficiency, and Value Enhancement (Buildings)	82.2	74.1	42.9	71.3	76.4	92.2	90.5	70.9	79.1	67.0
Facility Flexibility, Efficiency, and Value Enhancement (Generators)	82.2	80.2	80.1	71.3	76.1	95.0	56.0	63.9	90.1	71.3

Low scores for more nascent technologies (e.g., sodium, zinc, and flow).

Current-year Suitability Ratings

100 = Perfect score. Traffic signal-style color coding with green being more positive than yellow, which is more positive than shades of red.

Limited confidence in results for sodium, supercaps, thermal, and hydrogen due to poor response rate.

	Lead Acid	Flow	CAES	Li-Ion	Sodium*	Supercaps*	Thermal*	Hydrogen*	PSH	Zinc
Facilitating an Evolving Grid	71.3	74.0	77.6	73.7	59.5	67.6	79.1	71.6	78.7	64.3
Serving Remote Communities	77.0	77.3	76.8	72.2	62.3	71.4	83.1	77.7	83.3	69.0
Electrified Mobility (Vehicles)	56.6	30.7	27.7	70.1	71.5	75.0	20.0	71.2	58.2	60.9
Electrified Mobility (Charging Infrastructure)	67.7	72.4	55.3	70.9	70.3	81.2	60.9	73.5	67.8	59.4
Interdependent Network Infrastructure	76.0	67.9	60.0	81.5	62.3	89.9	51.5	56.5	75.9	60.2
Critical Services	82.3	71.5	75.9	70.3	66.9	91.1	64.4	70.4	89.5	68.9
Facility Flexibility, Efficiency, and Value Enhancement (Buildings)	82.2	74.1	42.9	71.3	76.4	92.2	90.5	70.9	79.1	67.0
Facility Flexibility, Efficiency, and Value Enhancement (Generators)	82.2	80.2	80.1	71.3	76.1	95.0	56.0	63.9	90.1	71.3

Lead-acid scores well for use cases requiring consistent, reliable, and safe storage.

2030 Suitability Ratings

100 = Perfect score. Traffic signal-style color coding with green being more positive than yellow, which is more positive than shades of red.

Limited confidence in results for sodium, supercaps, thermal, and hydrogen due to poor response rate.

	Lead Acid	Flow	CAES	Li-Ion	Sodium*	Supercaps*	Thermal*	Hydrogen*	PSH	Zinc
Facilitating an Evolving Grid	81.4	90.7	84.0	83.6	81.6	68.3	81.8	77.4	82.9	75.6
Serving Remote Communities	86.0	89.5	80.9	81.8	83.3	73.3	84.1	87.0	84.5	80.6
Electrified Mobility (Vehicles)	65.5	32.0	30.1	84.8	85.5	80.1	20.0	81.7	64.8	75.8
Electrified Mobility (Charging Infrastructure)	77.8	87.0	58.3	85.7	85.0	82.1	62.0	81.5	70.5	77.0
Interdependent Network Infrastructure	81.2	82.5	63.3	88.7	83.3	86.8	54.8	58.3	78.4	73.3
Critical Services	87.4	85.3	79.6	80.2	86.0	90.3	66.8	78.5	90.4	80.1
Facility Flexibility, Efficiency, and Value Enhancement (Buildings)	86.9	88.5	47.3	83.9	86.2	92.3	91.7	78.5	80.5	78.7
Facility Flexibility, Efficiency, and Value Enhancement (Generators)	85.3	91.7	83.1	79.4	84.0	93.4	58.2	78.7	91.1	82.1

Significant improvement in electrified mobility (vehicles) for Li-ion, sodium-ion, and hydrogen.

2030 Suitability Ratings

100 = Perfect score. Traffic signal-style color coding with green being more positive than yellow, which is more positive than shades of red.

Limited confidence in results for sodium, supercaps, thermal, and hydrogen due to poor response rate.

	Lead Acid	Flow	CAES	Li-Ion	Sodium*	Supercaps*	Thermal*	Hydrogen*	PSH	Zinc
Facilitating an Evolving Grid	81.4	90.7	84.0	83.6	81.6	68.3	81.8	77.4	82.9	75.6
Serving Remote Communities	86.0	89.5	80.9	81.8	83.3	73.3	84.1	87.0	84.5	80.6
Electrified Mobility (Vehicles)	65.5	32.0	30.1	84.8	85.5	80.1	20.0	81.7	64.8	75.8
Electrified Mobility (Charging Infrastructure)	77.8	87.0	58.3	85.7	85.0	82.1	62.0	81.5	70.5	77.0
Interdependent Network Infrastructure	81.2	82.5	63.3	88.7	83.3	86.8	54.8	58.3	78.4	73.3
Critical Services	87.4	85.3	79.6	80.2	86.0	90.3	66.8	78.5	90.4	80.1
Facility Flexibility, Efficiency, and Value Enhancement (Buildings)	86.9	88.5	47.3	83.9	86.2	92.3	91.7	78.5	80.5	78.7
Facility Flexibility, Efficiency, and Value Enhancement (Generators)	85.3	91.7	83.1	79.4	84.0	93.4	58.2	78.7	91.1	82.1

Significant improvement envisioned for nascent technologies, with particularly strong performance predicted for flow batteries.

2030 Suitability Ratings

Limited confidence in results for sodium, supercaps, thermal, and hydrogen due to poor response rate.

100 = Perfect score. Traffic signal-style color coding with green being more positive than yellow, which is more positive than shades of red.

	Lead Acid	Flow	CAES	Li-Ion	Sodium*	Supercaps*	Thermal*	Hydrogen*	PSH	Zinc
Facilitating an Evolving Grid	81.4	90.7	84.0	83.6	81.6	68.3	81.8	77.4	82.9	75.6
Serving Remote Communities	86.0	89.5	80.9	81.8	83.3	73.3	84.1	87.0	84.5	80.6
Electrified Mobility (Vehicles)	65.5	32.0	30.1	84.8	85.5	80.1	20.0	81.7	64.8	75.8
Electrified Mobility (Charging Infrastructure)	77.8	87.0	58.3	85.7	85.0	82.1	62.0	81.5	70.5	77.0
Interdependent Network Infrastructure	81.2	82.5	63.3	88.7	83.3	86.8	54.8	58.3	78.4	73.3
Critical Services	87.4	85.3	79.6	80.2	86.0	90.3	66.8	78.5	90.4	80.1
Facility Flexibility, Efficiency, and Value Enhancement (Buildings)	86.9	88.5	47.3	83.9	86.2	92.3	91.7	78.5	80.5	78.7
Facility Flexibility, Efficiency, and Value Enhancement (Generators)	85.3	91.7	83.1	79.4	84.0	93.4	58.2	78.7	91.1	82.1

Li-ion and sodium-ion performing well for use cases requiring efficient, flexible, and scalable solutions.

Percentage Point Change in Performance

Limited confidence in results for sodium, supercaps, thermal, and hydrogen due to poor response rate.

100 = Perfect score. Traffic signal-style color coding with green being more positive than yellow, which is more positive than shades of red.

	Lead Acid	Flow	CAES	Li-Ion	Sodium*	Supercaps*	Thermal*	Hydrogen*	PSH	Zinc	Average
Facilitating an Evolving Grid	10.10	16.70	6.40	9.90	22.10	0.70	2.70	5.80	4.20	11.30	8.99
Serving Remote Communities	9.00	12.20	4.10	9.60	21.00	1.90	1.00	9.30	1.20	11.60	8.09
Electrified Mobility (Vehicles)	8.90	1.30	2.40	14.70	14.00	5.10	-	10.50	6.60	14.90	7.84
Electrified Mobility (Charging Infrastructure)	10.10	14.60	3.00	14.80	14.70	0.90	1.10	8.00	2.70	17.60	8.75
Interdependent Network Infrastructure	5.20	14.60	3.30	7.20	21.00	(3.10)	3.30	1.80	2.50	13.10	6.89
Critical Services	5.10	13.80	3.70	9.90	19.10	(0.80)	2.40	8.10	0.90	11.20	7.34
Facility Flexibility, Efficiency, and Value Enhancement (Buildings)	4.70	14.40	4.40	12.60	9.80	0.10	1.20	7.60	1.40	11.70	6.79
Facility Flexibility, Efficiency, and Value Enhancement (Generators)	3.10	11.50	3.00	8.10	7.90	(1.60)	2.20	14.80	1.00	10.80	6.08
Average	7.03	12.39	3.79	10.85	16.20	0.40	1.74	8.24	2.56	12.78	7.60

Less improvement predicted for mechanical energy storage.

Cross-Technology Results

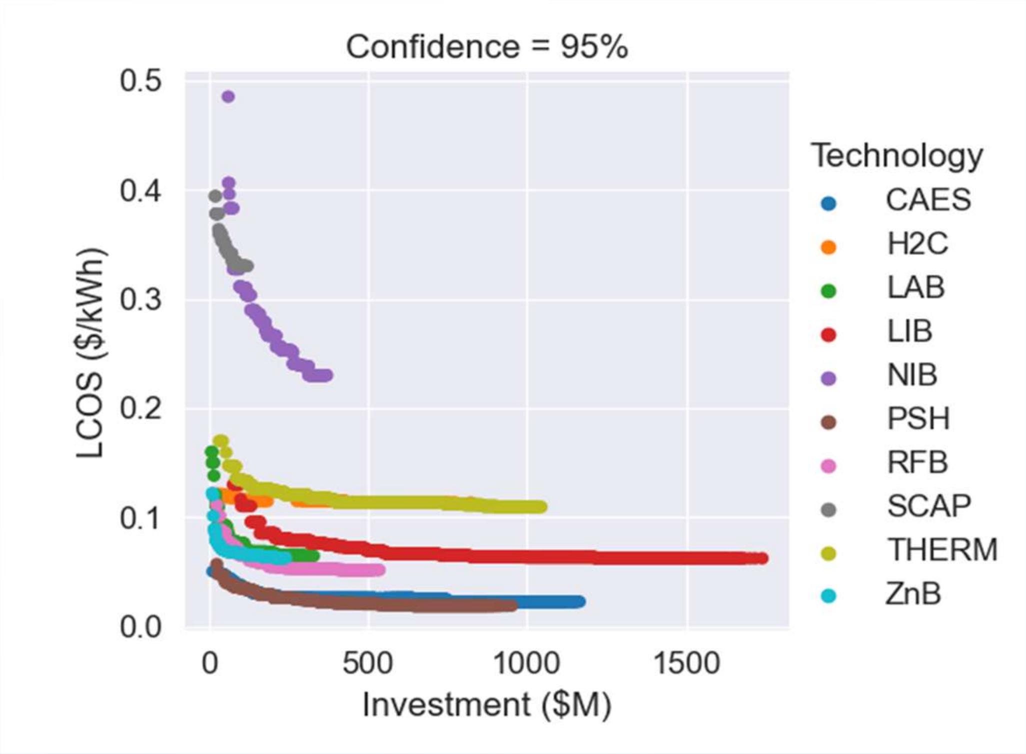
Cross-Technology Results Disclaimer

- These results do not indicate that any technologies have "won" or "lost"
- Picking a technology requires a deep understanding of the specific use case – cost does not nullify suitability
- Because there are so many roles for energy storage and research is inherently uncertain, investment in a diverse set of technologies is most likely to lead to a successful clean energy transition

Cross-Technology Results

- Diminishing marginal returns on investment
- More mature technologies have longer, flatter tails

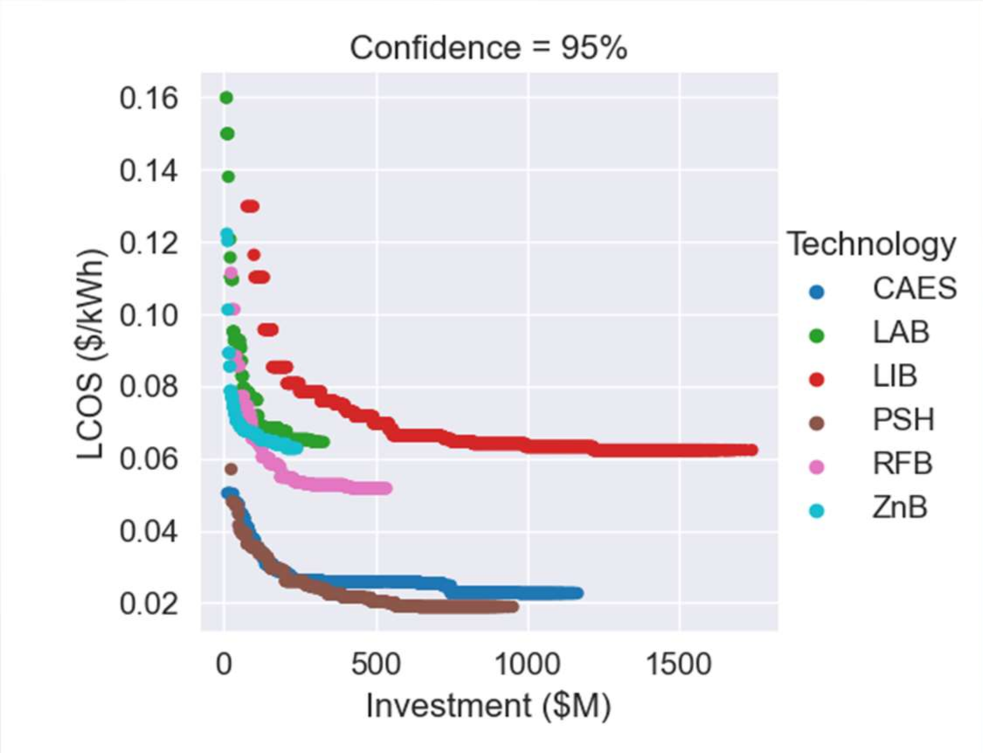
Parameter	Value
Duration	10 hours
Power	100 MW
Cycle Frequency	1 per day



Zooming in on the Cheapest Technologies

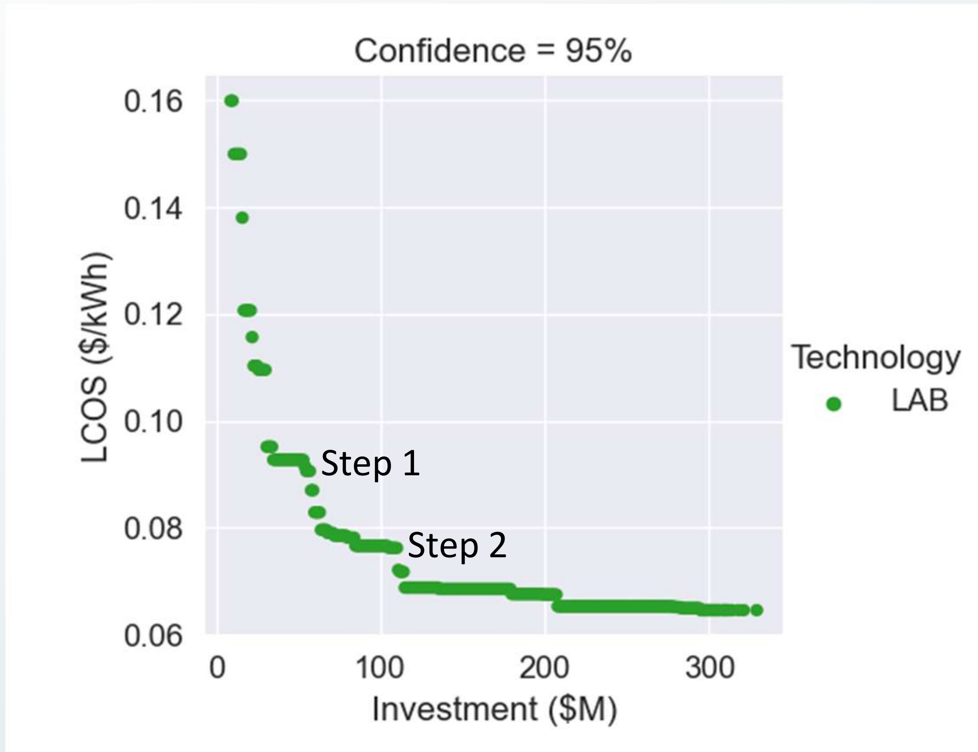
- Diminishing marginal returns on investment
- Cheapest technologies with investment are often cheap already

Parameter	Value
Duration	10 hours
Power	100 MW
Cycle Frequency	1 per day



Innovations Drive Steps in the Curves

- Many cheap innovations start the curve
- Steps are high-budget, complementary innovations
    - Step 1 = Advanced manufacturing
    - Step 2 = Demonstration projects



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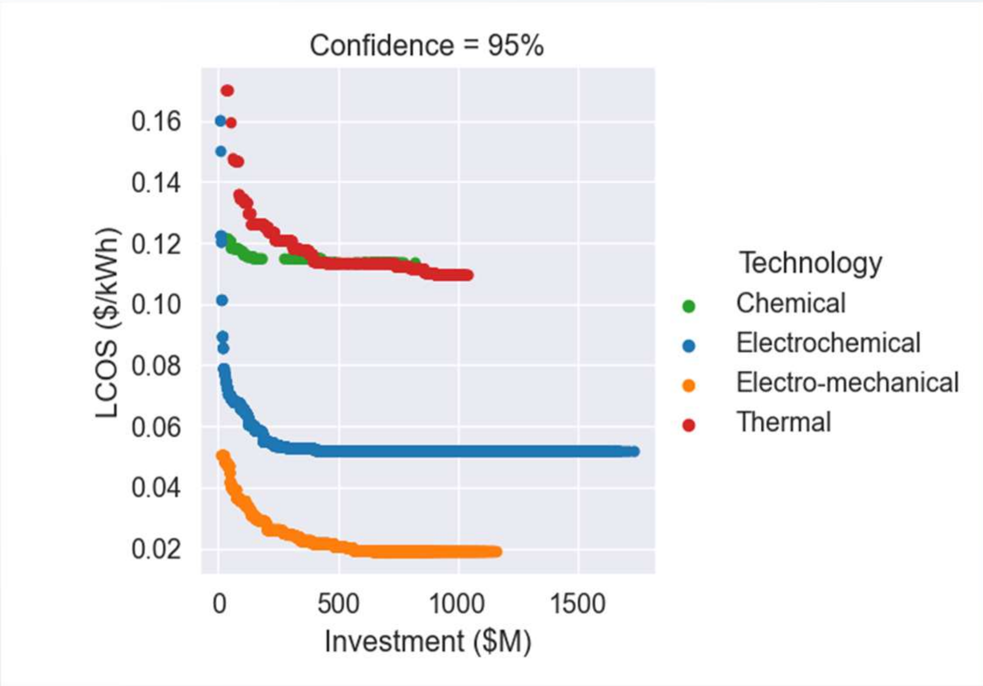
By Category of Storage Technology

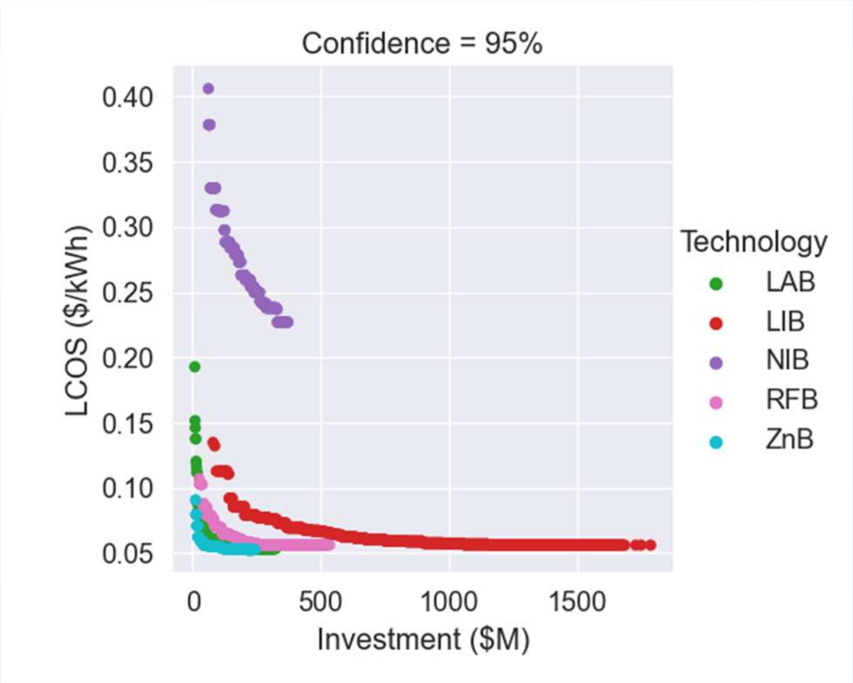
- Electro-mechanical is promising for cost
- Other types have benefits like multi-market output, energy density, and modularity

Parameter	Value
Duration	10 hours
Power	100 MW
Cycle Frequency	1 per day



EV Infrastructure Use Case

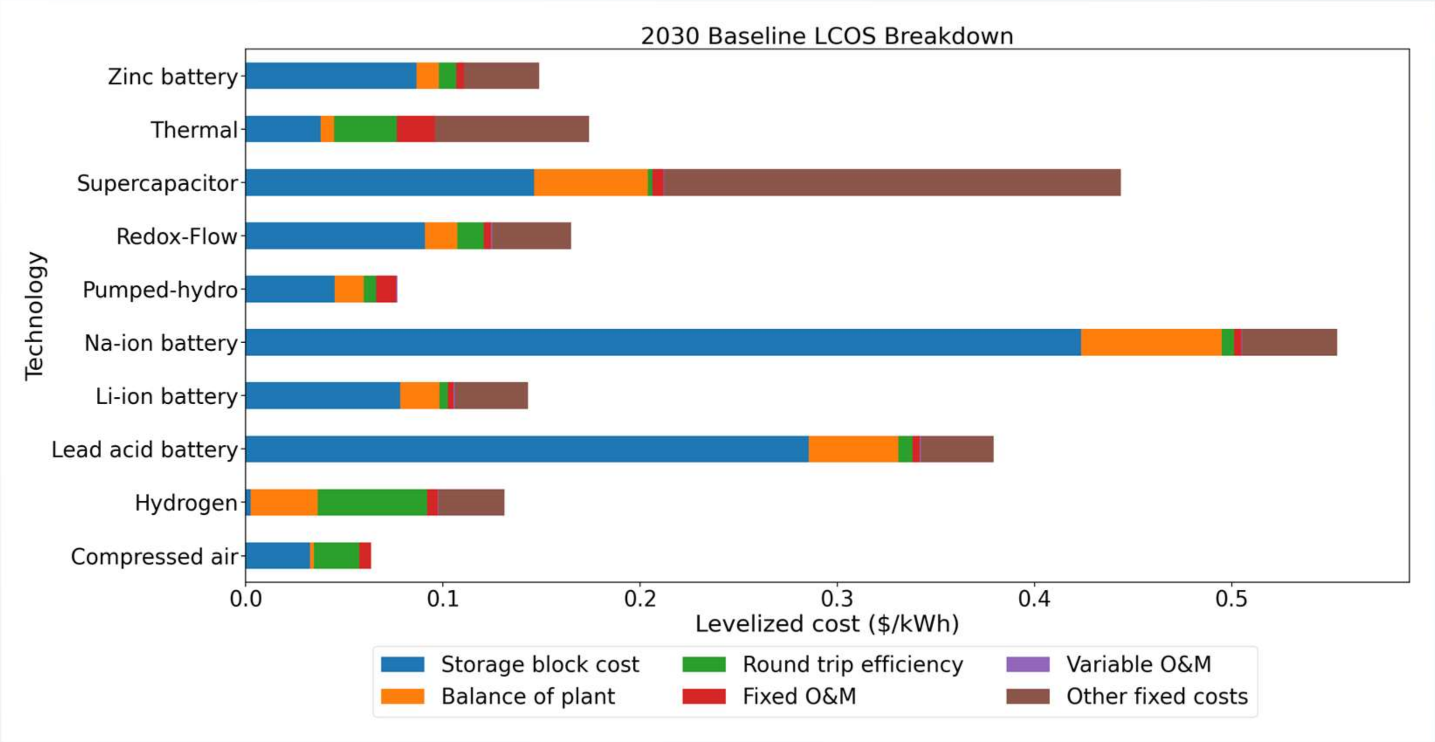
- Considers electrochemical only
- Significant cost reduction potential in this category



Parameter	Value
Duration	2 hours
Power	1 MW
Cycle Frequency	2 per day

Contributions of Parameters to LCOS

- Storage block costs are large
- "Other" is dominated by power equipment and project development



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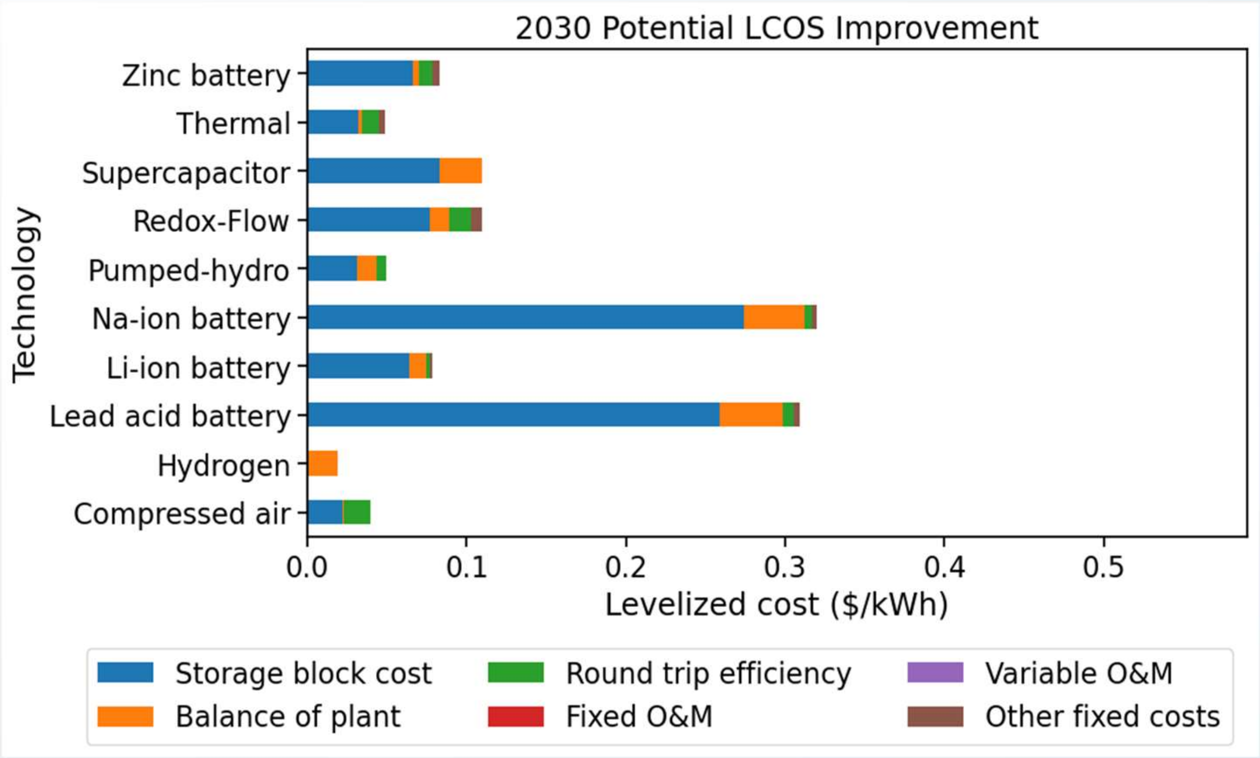
Potential Improvement by Parameter

- Storage block cost has highest reduction potential
- RTE improvement is limited because of relative maturity
- Balance of plant, O&M are limited by absolute contribution to LCOS



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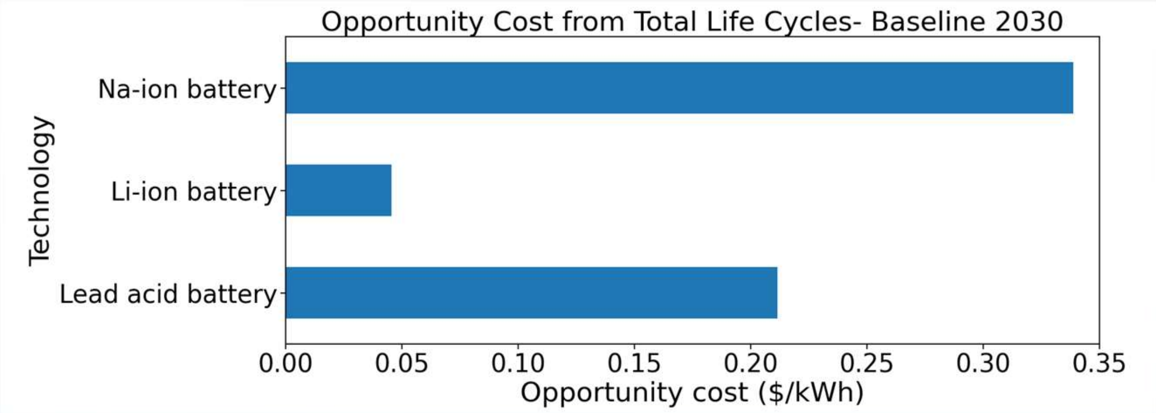
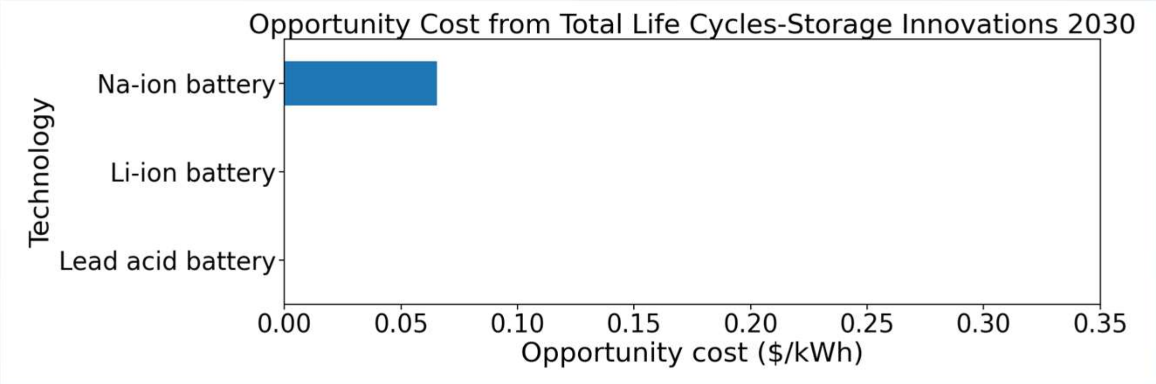
Opportunity Cost of Cycle Limits

- Assuming calendar life is fixed by chemistry / physics
- If cycle life could be maximized, how much would LCOS improve?
- Other technologies are already calendar-life limited





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Conclusions and Next Steps

Conclusions

- Research team successfully implemented an 8-step framework and LCOS framework for evaluating targeted investments in 10 storage technologies
- The top 10% of innovation portfolios achieve LCOSs as low as 2-3 cents/kWh (PSH) and as high as 33-34 cents/kWh (supercapacitors)
- Investment requirements modest for several technologies (e.g., lead-acid, zinc, sodium ion); diminishing marginal returns evident as more mature technologies (e.g., PSH, Li-ion) require high levels of investment to achieve LCOS reductions and marginal returns fall for all technologies as investment portfolios expand
- DOE should weigh the goals of investment – e.g., achieve 5 cents/kWh or achieve significant reductions in LCOS, invest in nascent technologies to clear hurdles and achieve commercial lift off or push more mature technologies to 5 cents/kWh

Next Steps

- Near-term steps
  - Set technically feasible limits
  - Continue cross-technology innovation value assessment
  - Publish journal articles covering LCOS framework and framework study methodology and results
- Update report annually or biannually, building off published data in the ESGC Technology Cost and Performance Assessment and identifying new technologies and evolving RD&D innovation pathways
  - Automate data collection process through web-based system
  - Work with industry groups (e.g., Battery Council International, Long Duration Energy Storage Council) to improve response rates
  - Explore data visualization techniques and use in website and web-based database to convey results in a more compelling manner

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Technology Strategy Assessment: Lithium-ion Batteries

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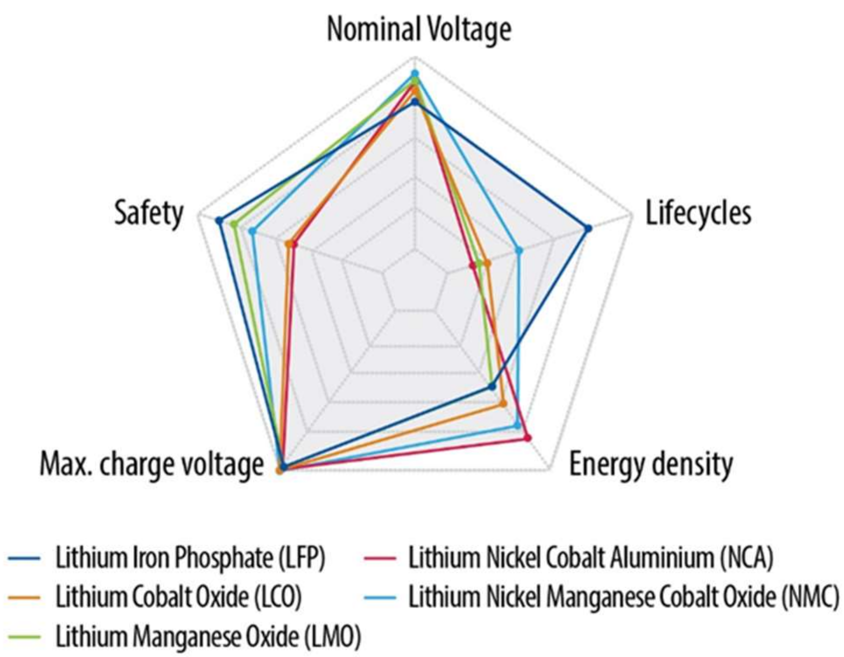
Lithium-ion Batteries

- Broadly commercialized for consumer electronics, electric vehicles and growing grid-scale energy storage
- Multiple chemistries with difference performance, safety and life considerations
- Represent 90% of new battery-based grid deployments.
- Most use cases less than 10 hours. Large energy storage (typically 8-10 hours or longer)
- Baseline LCOS estimates for 100 MW LFP installation: ~$0.14 per kWh per cycle



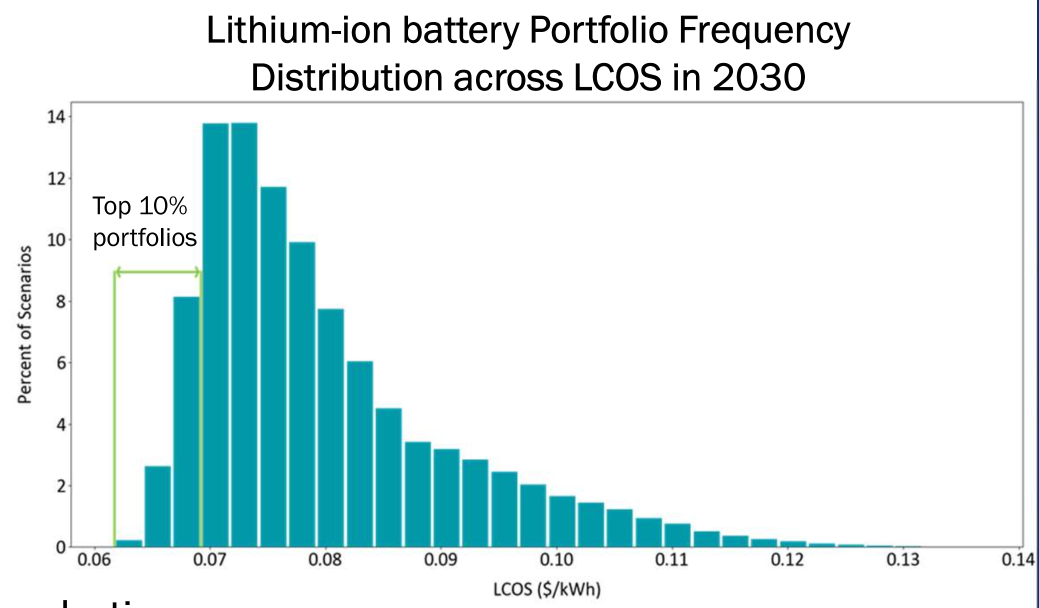
Lithium-Ion Battery R&D Opportunities

- Findings are based on Lithium-ion Batteries Flight Paths listening session, and interviews with 22 experts and developers.
- Stakeholder inputs identified potential Lithium-ion battery innovation opportunities
- ESGC Roadmap goal: LCOS of $0.05/kWh by 2030

Innovation Category	Innovation
Raw materials sourcing	Cathode materials mining
	Domestic sourcing of lithium
Supply chain	Anode materials production
	Mining permitting
	Co-locating manufacturing and mines
Technology components	Sensor and monitoring technologies
Advanced materials development	Solid-state electrolyte improvements
	Anode innovations
	Electrode and electrolyte innovations
	Atomic-level cell dynamics studies
	Fundamental materials research
Manufacturing	Foundational manufacturing RD&D
	Manufacturing process scale-up
	Data-driven manufacturing improvements
	Manufacturing workforce development
Deployment	Controls to improve cycle life
	Deployment policies
	Demonstration
	Deployment efficiency
End of life	Recycling defective cells
	Recycling degraded cells
	Impurities reduction technique
	Rapid battery health assessment

Analysis of Lithium-ion Battery R&D Opportunities

- Information provided by industry experts was used to define R&D investment requirements and timelines, as well as potential impacts on cost and performance resulting from each innovation
- Monte Carlo simulation tool then combined each innovation with 2-7 other innovations to find out their combined impact on LCOS
- More than 80% of the portfolios achieve at least 37% reduction in LCOS ($0.09 per kWh-cycle)
- Innovations most often in Top 10% portfolios:
  - Rapid health assessment and advanced controls
  - Advanced manufacturing processing and impurity reduction
  - Electrode & electrolyte innovations
  - Domestic supply chain development



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Technology Strategy Assessment: Lead Acid

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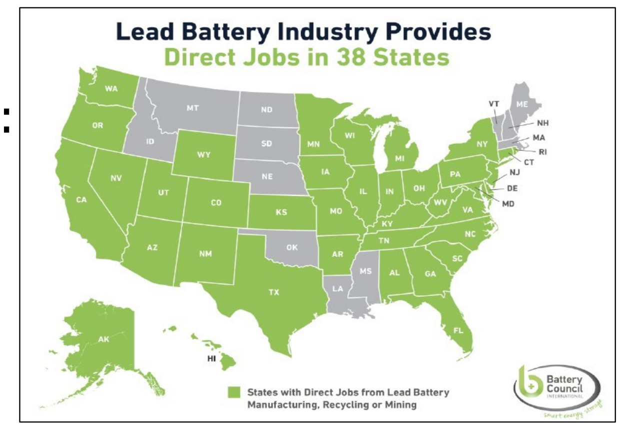
Lead Acid Overview

- WHY LEAD ACID? Mature tech & comprehensive suite of attributes:
  - Super low-cost & globally abundant raw materials
  - Mature supply chain & 99% recycle (1.5 million tons/yr)
  - Intrinsically safe, water-based system

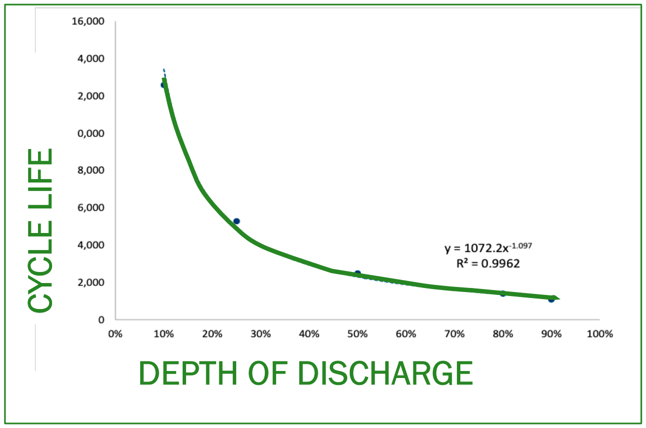
- MARKET: Mature in transportation & back-up power:
  - **Global:** 600 GWh / $80 Billion / 70% of total market
  - **US:** 206 GWh / $28 Billion / 25,000 jobs / 38 states

- PERFORMANCE/COST: today's designs cannot meet LDES requirements:
  - Full grid system - $532/kW
  - Storage block & balance of plant only - $262/kWh
  - **High LCOS: 42¢/kWh-cycle:**
    - Poor cycle life
    - Low utilization of available capacity



Lead Acid R&D Opportunities

- KEY CHALLENGES - R&D THEMES
  - Trade-off between cycle life & capacity utilization
  - High manufactured cost despite low raw materials cost
  - Ineffective & inefficient testing methods and protocols



- PRE-COMPETITIVE RESEARCH & ISSUES ADDRESSED:

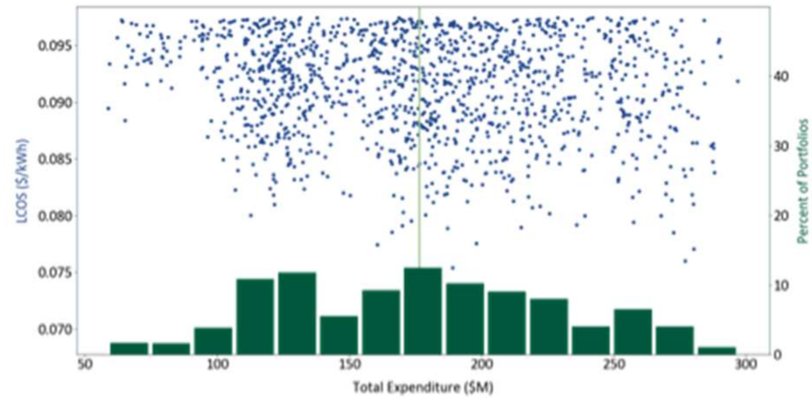
Precompetitive R&D Focus	Cycle life	Manuf. Cost	Calendar life	LCOS	Product develop time
Effective understanding degradation mechanisms	X		X	X	
More robust & efficient electrodes	X			X	
Material & energy utilization	X	X		X	
New manufacturing approaches		X		X	
New testing methods – AI/ML					X
Use case & duty cycle definitions		X		X	X

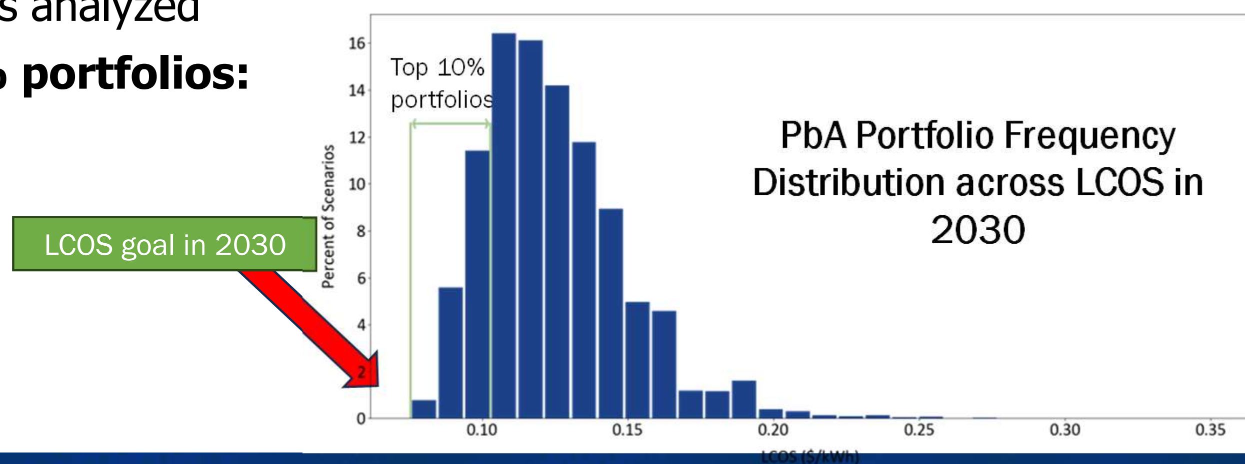
Framework Analysis of R&D Opportunities

- Information provided by industry experts defined R&D investment requirements, timelines, and resulting potential impacts on cost & performance
- Monte Carlo simulation tool then combined each innovation with 2-7 other innovations to find out their combined impact on LCOS
  - *Multiple Innovations required for target LCOS*
- Thousands of PbA innovation portfolios analyzed

Innovations most often in Top 10% portfolios:

- Improved current collectors
- Advanced manufacturing
- Demonstration projects
- Novel active materials
- Better system design





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Technology Strategy Assessment: Redox Flow Batteries

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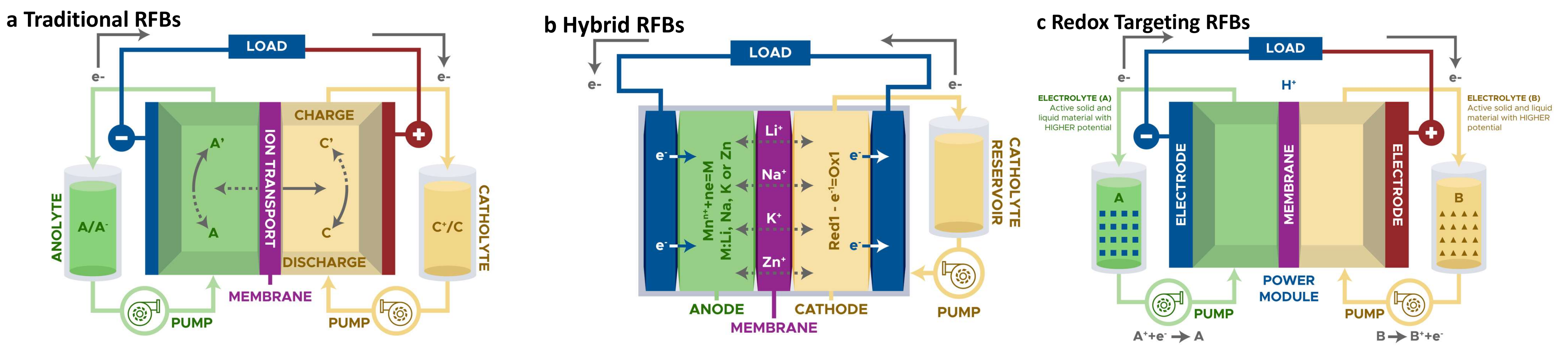
Redox Flow Batteries (RFB)

- Potential for more flexible power and energy configurations
- Systems ranging from residential (kW) to utility scale (MW)
- Largest: 100MW/400MWh Vanadium Flow in Dalian, China
- Typical peak discharge durations (4 – 8 hours)
- 2030 projected LCOS: $0.16/kWh for 100 MW/10-hr system



Redox Flow R&D Opportunities

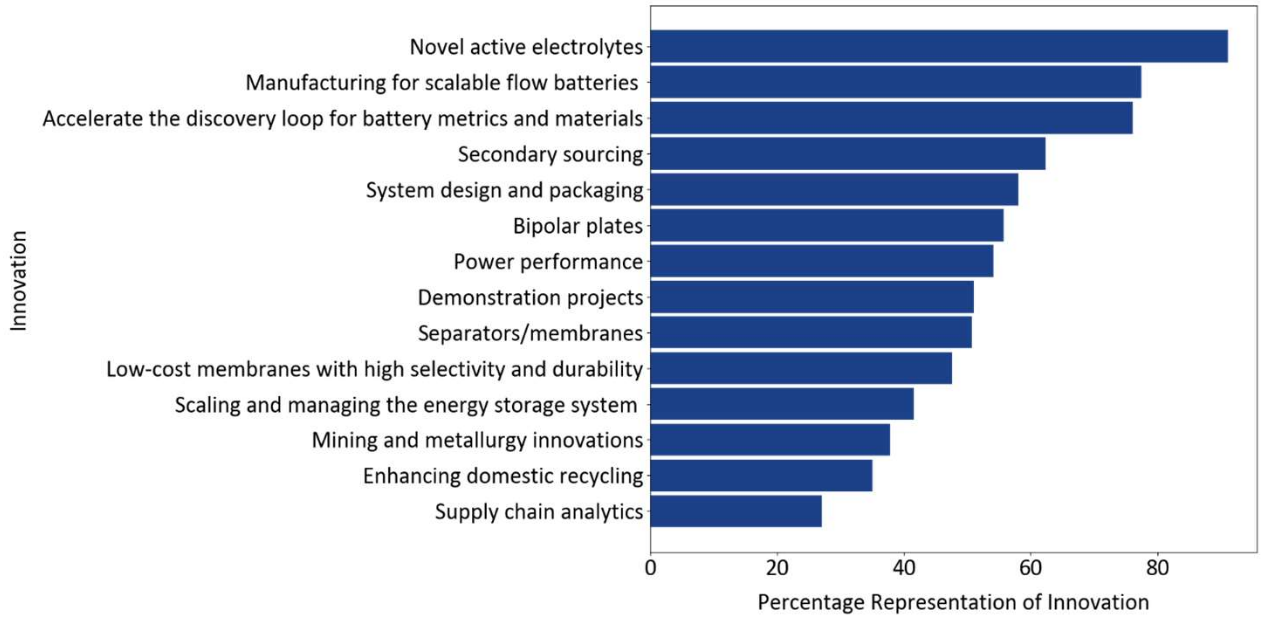
- Findings are based on
  - RFB Flight Paths listening session (Jan 12, 2023) with 16 commercial flow battery developers
  - Framework: interviews, survey of 20 RFB organizations.
- Identified both technical and non-technical innovations needed to meet
- ESGC LCOS goal of $0.05/kWh by 2030

	Technical Innovations	Non-Technical Innovations*
Flight Paths	• Membranes • Electrolytes • Manufacturing/Supply Chains • Power electronics • Electrodes, Bipolar plates	• Interconnection queue • Bankability • Standardization • Tax credits
Framework	• Manufacturing for scalable flow batteries • Novel active electrolytes • Separators/membranes • Secondary sourcing • Supply chain analytics • Accelerate the discovery loop for battery metrics and materials	• Regulatory hurdles • Electrolyte leasing option • Standardization of RFB system • Start-up vs big company • Leak proof design

Analysis of RFB R&D Impacts

- Information provided by industry experts was used to define R&D investment requirements and timelines, as well as potential impacts on cost and performance resulting from each innovation
- Monte Carlo simulation tool then combined each innovation with 2-7 other innovations to find out their combined impact on LCOS

Innovations in the top 10% of RFB portfolios to approach $0.05/kWh LCOS



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Technology Strategy Assessment: Zinc Batteries

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Zinc Batteries Overview

- Low-cost, high energy density, safety, and global availability have made Zn-based batteries attractive for more than 220 years!
- *Diverse* Zn-batteries offer a range of properties to meet growing demand across varied applications:

✓ Renewables integration (including microgrids)

✓ Backup power (assurance for data centers, telecom, etc.)

✓ Grid stability and resilience

✓ Behind-the-meter applications for residential and commercial applications (Lower energy cost, power quality, etc.)

Zn-MnO_2

URBAN ELECTRIC POWER

1 MWh UEP alkaline battery backup system for the San Diego Supercomputer Center (CA).

ZĒLOS

Zn-Ni

ZincFive

ZAF Energy Systems

Æsir Technologies, Inc.

ENZINC

Zn-Air

ZINC8

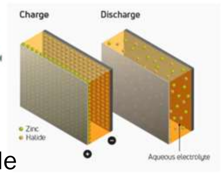
ZAF Energy Systems

e-zinc

Zn-Br

eos

35 MWh EOS Zn-Br system planned to provide 10 hour storage for solar-plus-storage microgrid with Indian Energy (CA).



redflow

Zn-Br flow battery installation

Zn-ion

SALIENT ENERGY

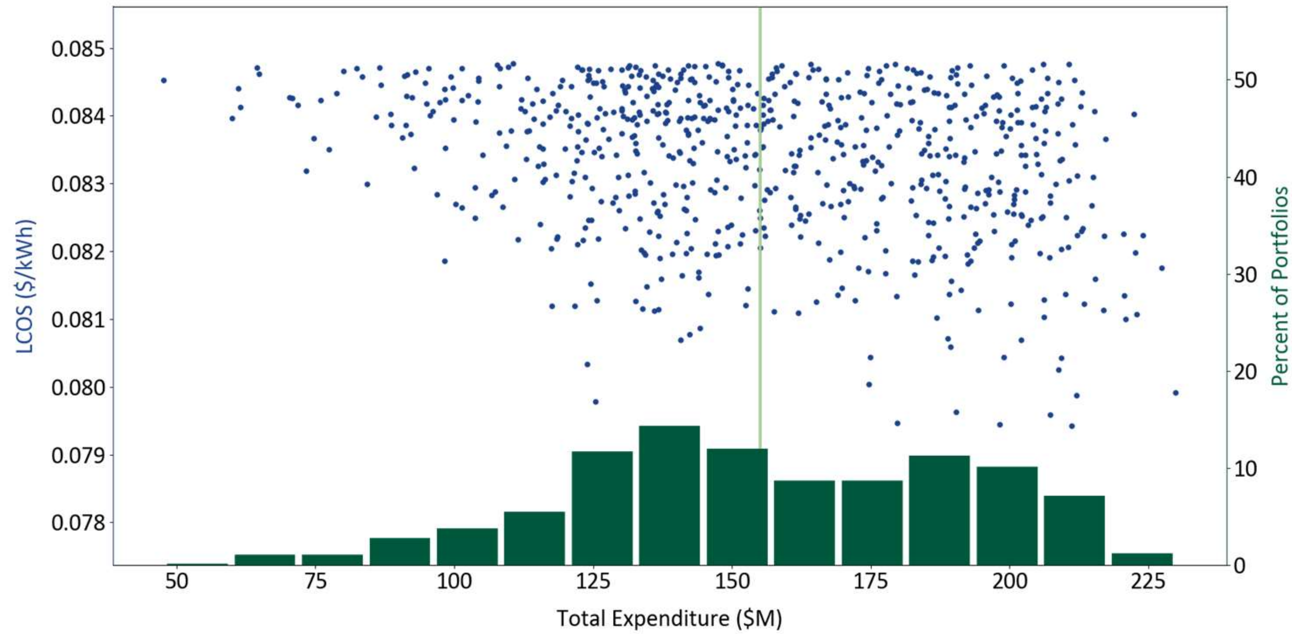
enerpoly

Highlighted Zinc Battery R&D Opportunities

	R&D Technical Innovations	Non-Technical Advances
Flight Paths	• Cathodes • Separators • Electrolytes	• Education (public relations for Zn batteries) • Zn-Specific Codes, Standards, Requirements, and Validation (not force-fit to Li-ion) • Demonstrations/Validation Resources • Industry Cooperation (consortium/engagement with DOE/U.S. Department of Defense)
Framework	• Separators • Cathodes • Zn Anodes • Electrolytes	• Improved/Supported Manufacturing • Pack/System-Level Design • Demonstration Projects • Inactive Materials Cost Reductions

Collective assessments from Flight Paths Listening Session input and Framework Study Data Analyses highlight priorities for both technical innovations and non-technical advances across diverse Zn-battery chemistries.

Simulating Impact Realization Through Innovation



Monte Carlo simulation predictions from thousands of innovation portfolios that fall within the top 10% of LCOS impact. The highest impact portfolios indicate possible lowest LCOS ~0.08/kWh, most commonly predicted with $120-150M in expenditures. Timeline to achieve these goals is predicted on the order of 5-7 years.

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Technology Strategy Assessment: Sodium Batteries

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Sodium Batteries Overview

- Sodium (Na) is >1000X more abundant than Lithium – just in the Earth's crust
  - 6th most abundant element in Earth's crust and 4th most abundant in the oceans
    - 93% of soda ash (Na_2CO_3) reserves are in the U.S. (Hirsh, et al. Adv. Energy. Mater., 2020, 10(32), 202001274.

Sodium Metal Anode (e.g., Molten Sodium)

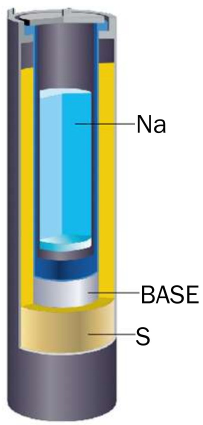


Image from NGK Insulators

"Mature" High-Temperature NaS and Na-$NiCl_2$ deployments support:

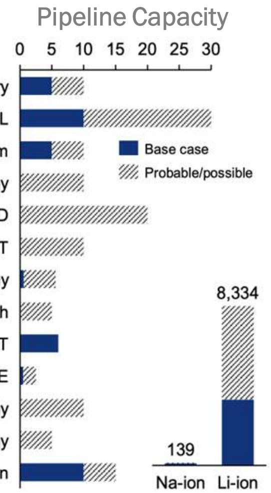
- Renewables Integration
- Grid Services
- Microgrids
- Behind-the-Meter Applications
- Select Mobility

Emerging systems show promise

- Low-temperature molten salt
- Molten Na flow batteries
- Solid State Na batteries

Sodium Ion Batteries (NaIBs)

Producer	Production details
HiNa Battery	First Na-ion production at GWh scale last year
CATL	Planned GWh-scale production this year
Zoolnasm	Building a factory in Jiangsu, China
Farasis Energy	Partnered with the **JMEV** to develop Na-ion EVs
BYD	May launch a Na-ion-based EV this year
SVOLT	Expects to develop Na-ion cells this year
Natron Energy	**Clarios** will manufacture cells this year
Li-Fun Tech	Planned production in 2023
TIAMAT	**Neogy** will mass produce Na-ion cells
AMTE	Building a factory in Scotland, UK
EVE Energy	Developing cells further before production
Godi Energy	Planning a 5 GWh Li-ion factory before Na-ion
Faradion	Planning double-digit production under **Reliance**



Immature technology/manufacturing has limited demonstrations and deployments. Significant NaIB manufacturing capacity is projected to 40-100 GWh by 2030.

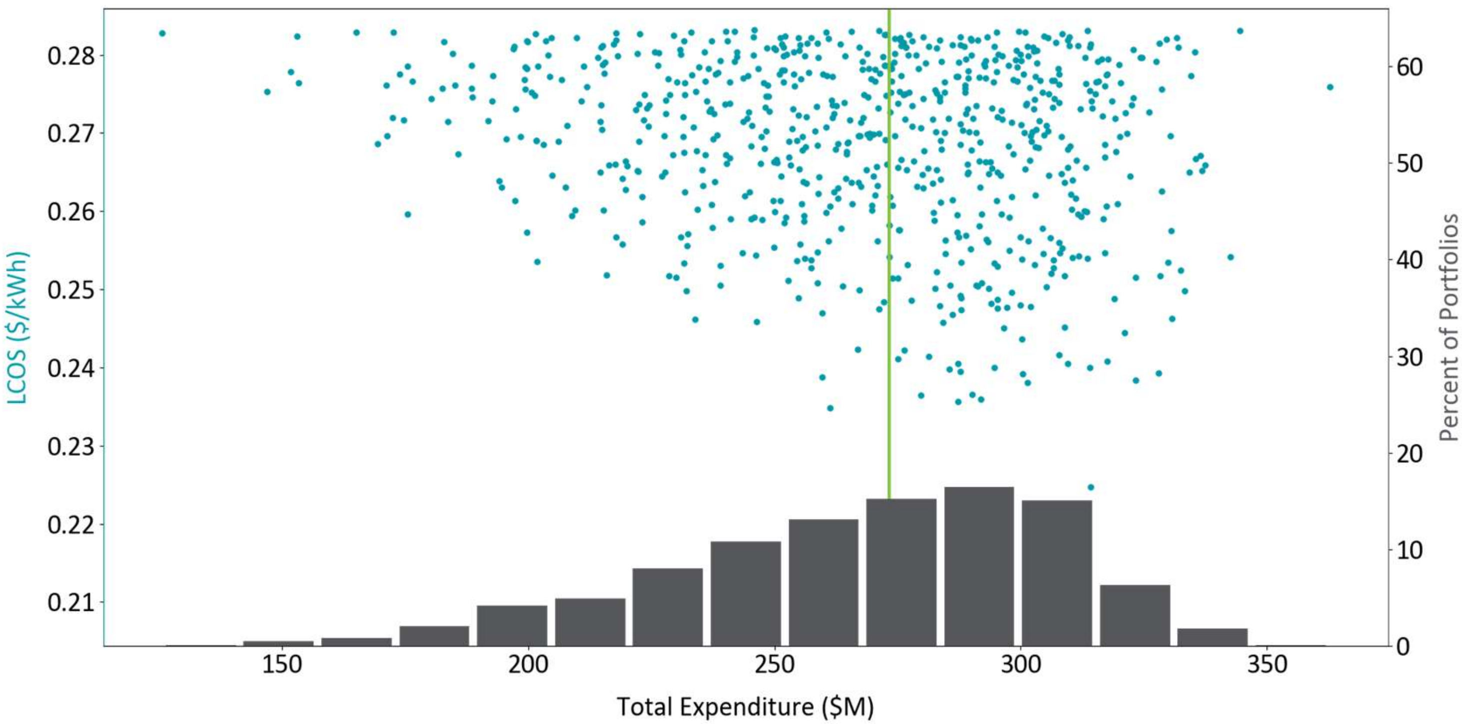
Natron High-Power, High Cycle Life Prussian Blue NaIBs are used for "critical power applications.

Faradion NaIBs deployed for 10kW stationary-storage demonstrations.

Highlighted Sodium Batteries R&D Opportunities

	R&D Technical Innovations	Non-Technical Advances
Flight Paths Listening Session (NaS, NaMH, SSSB, NaIBs)	• Cathodes • Electrolytes • Power Electronics/Integration • Manufacturing Advances • Lower Temperature	• Battery Ecosystem Development (Supply Chain, Manufacturing, End of Life, Workforce) • Education (Public Relations for Na Batteries) • Na-Specific Codes, Standards, Requirements, and Validation (not force-fit to Li-ion) • Demonstrations/Testing/Validation Resources • Lifecycle Analyses
Framework Study (NaIBs only)	• Cathodes • Electrolytes • In-Operations Materials R&D • Anodes • Controllers/Battery Management Systems	• High-Volume Manufacturing • Multi-Scale Demonstration Projects • Lifecycle Analyses

Simulating Impact Realization Through Innovation



Based on early stage commercial and performance data, Monte Carlo simulation predictions from innovation portfolios reveal that the top 10 highest impact portfolios could achieve possible LCOS ~$0.23-$0.28/kWh, based on $125M-$362M in industry expenditures. Timeline to achieve these goals is predicted on the order of 9-13 years.

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Technology Strategy Assessment: Pumped Storage Hydropower

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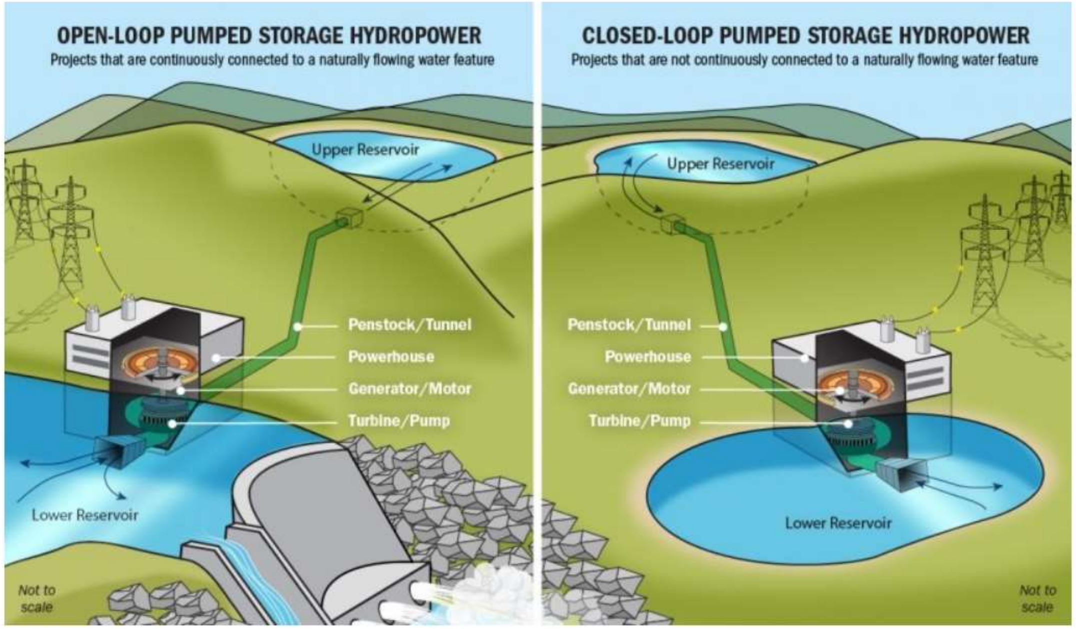
Pumped Storage Hydropower (PSH)

- First grid-scale energy storage
- Proven and reliable commercial technology (22 GW in the US, over 160 GW globally)
- Unit capacity from <1 MW up to 500 MW
- Plant capacity up to 3,000 MW (Bath County, VA)
- Large energy storage (typically 8-10 hours or longer)
- Baseline LCOS estimates: $0.12-$0.14 per kWh



PSH R&D Opportunities

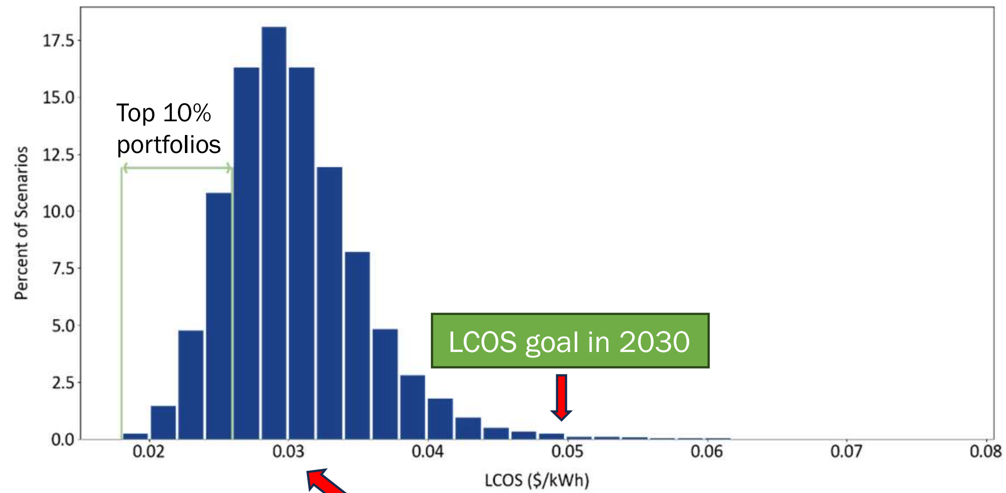
- Findings are based on PSH Flight Paths listening session (Feb 23, 2023), and interviews with 17 PSH industry experts and developers.
- Stakeholder inputs identified potential PSH innovation opportunities
- ESGC Roadmap goal: LCOS of $0.05/kWh by 2030

Innovation Category	Innovation
Supply chain	Standardized design in modular projects
Technology components	Design and implementation of modular PSH
	Design, components, and materials related to electromechanical equipment (e.g., pumps, turbines, generators)
	Underground PSH
	Designs that avoid the need for underground powerhouses
	Underwater PSH
	Tunnel boring/drilling technologies
	Cost-effective technologies for underground geology characterization
	Expanded use of computerized digital twin models for equipment design and testing
Manufacturing	3D printing technology on large scales
	Advanced manufacturing techniques
Advanced materials development	Development of new materials
	Metallurgical innovations to enable the use of seawater
	Testing the durability of new materials and structures
Deployment	Hybrid PSH projects
	Innovations related to single-stage pumping limits

Analysis of PSH R&D Opportunities

- Information provided by industry experts was used to define R&D investment requirements and timelines, as well as potential impacts on cost and performance resulting from each innovation
- Monte Carlo simulation tool then combined each innovation with 2-7 other innovations to find out their combined impact on LCOS
- Thousands of PSH innovation portfolios were analyzed
- Innovations most often in Top 10% portfolios:
    - Hybrid PSH projects
    - Testing the durability of new materials and structures
    - Large scale 3D printing technology
    - Innovations related to improving PSH single-stage pumping limits
    - Efficient underground geology characterization

PSH Portfolio Frequency Distribution across LCOS in 2030



Majority of the analyzed thousands of PSH innovation portfolios had LCOS below the target value. Average LCOS results were around $0.03/kWh.

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Technology Strategy Assessment
Compressed Air Energy Storage [CAES]

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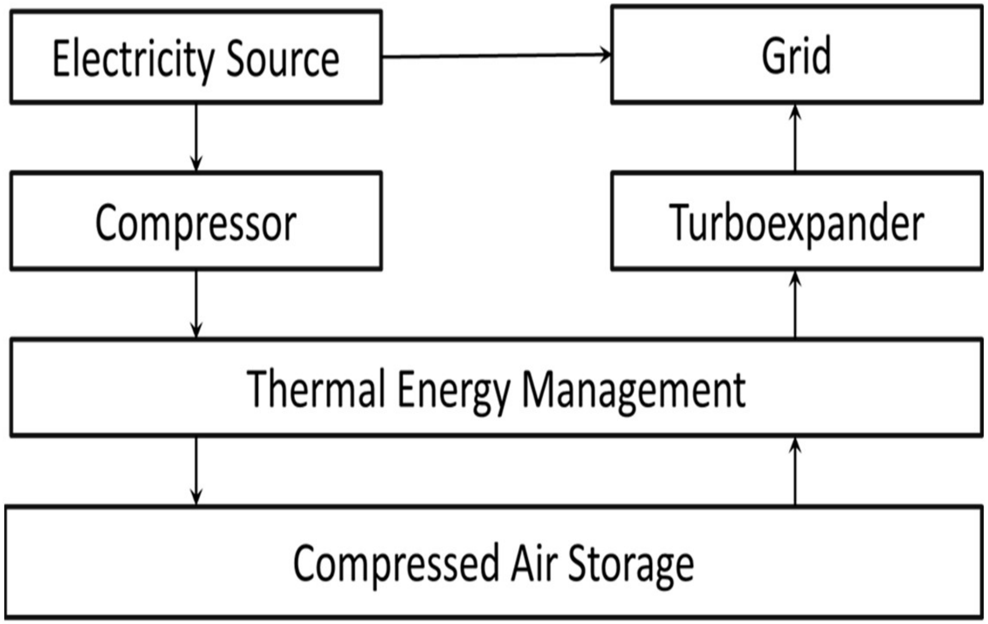
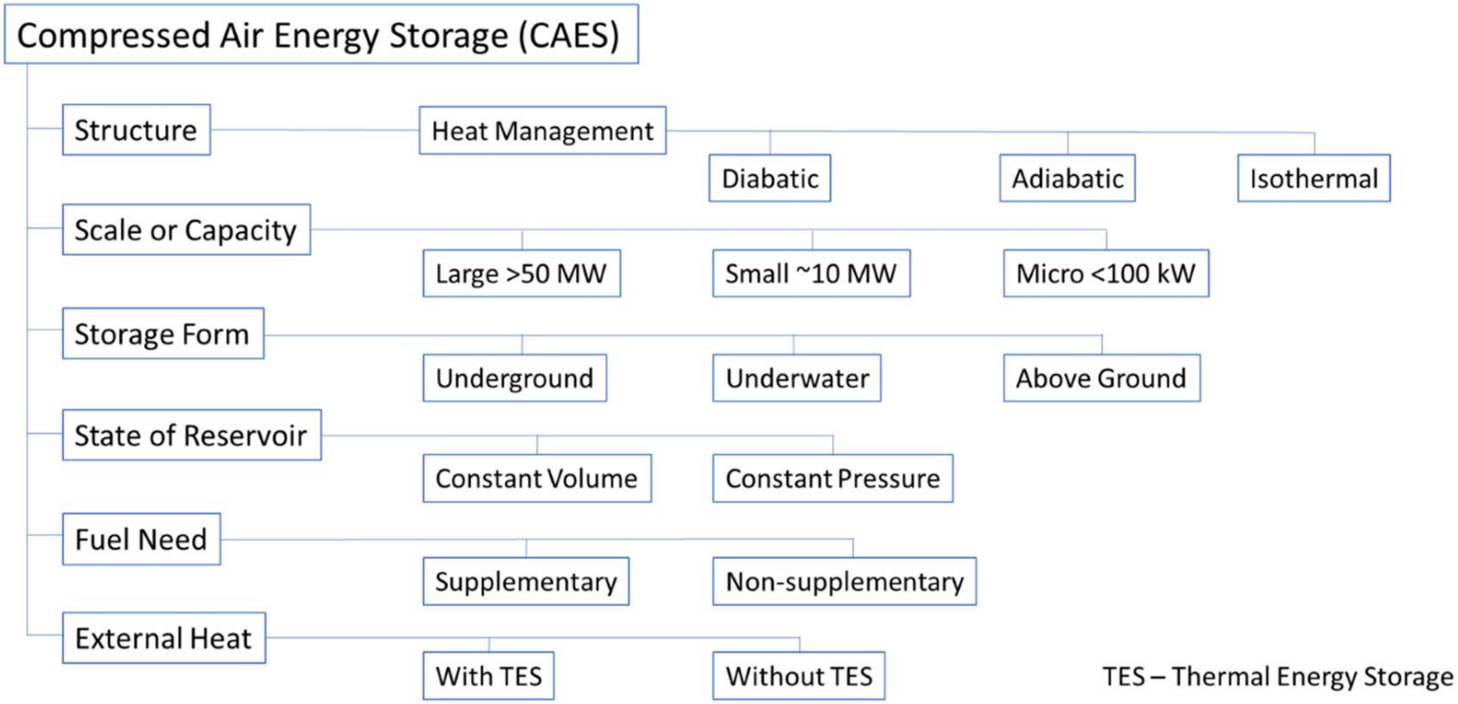
Compressed Air Energy Storage (CAES) Overview

- Converts electricity → potential energy by compressing air
- Technology is simple, easily deployable, and eco-friendly
- Essential equipment include compressor, heat exchanger, storage volume, expander
- Round-trip efficiency (RTE) increased with Thermal Energy Storage (TES)
- Advanced systems offer process variability



- Compressed air was used to provide energy in late 19th century in Buenos Aires, Paris
- Commercial CAES systems have capacities of up to ~300 MW or ~400 MWH

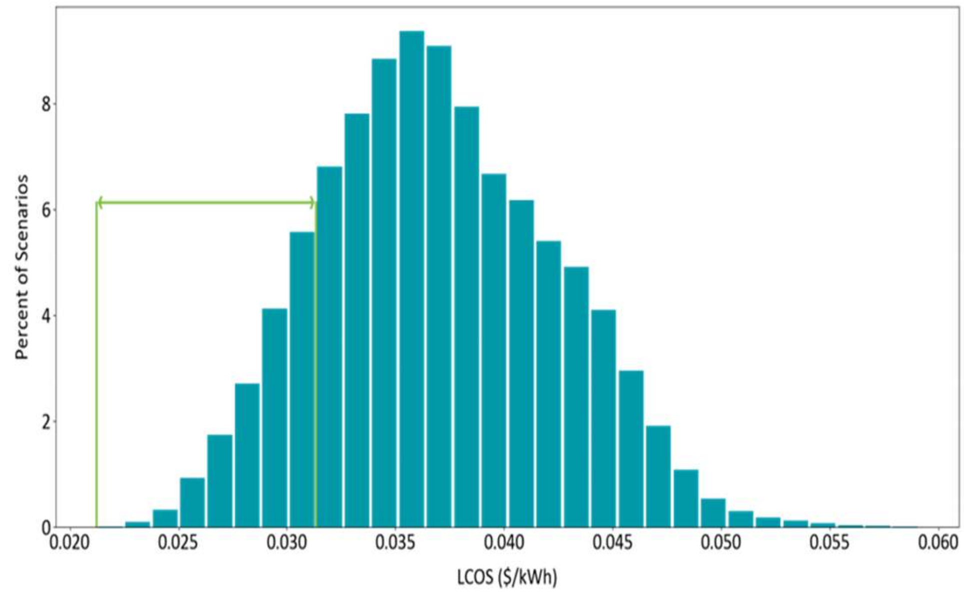
CAES system combinations can be quite diverse



- Each path and combination offers its own attractive features, challenges
- Some are at low Technology Readiness Level

Precompetitive R&D will promote performance and deployment

- Standardization and definition of metrics
  - RTE, kW, kWh
- TEA and optimization
  - Process diagrams, CapEx, OpEx, LCOS
- Location, characteristics, and readiness of geologic storage
  - Capacity, readiness needs
- Air/Heat storage options and RD&D needs
  - T,P range, suitable materials, volumes
- Compression-expansion, H-Ex hardware
  - Efficiency, compatibility, response time
- Durable materials
  - Elevated T,P and cycling tolerance



Top 10% of portfolios can operate with LCOS of $0.03/kWh.

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Technology Strategy Assessment: Thermal Energy Storage (TES)

Luke McLaughlin – Sandia National Laboratories
Kyle Gluesenkamp – Oak Ridge National Laboratory
Hill Balliet – Idaho National Laboratory
Zhiwen Ma – National Renewable Energy Laboratory

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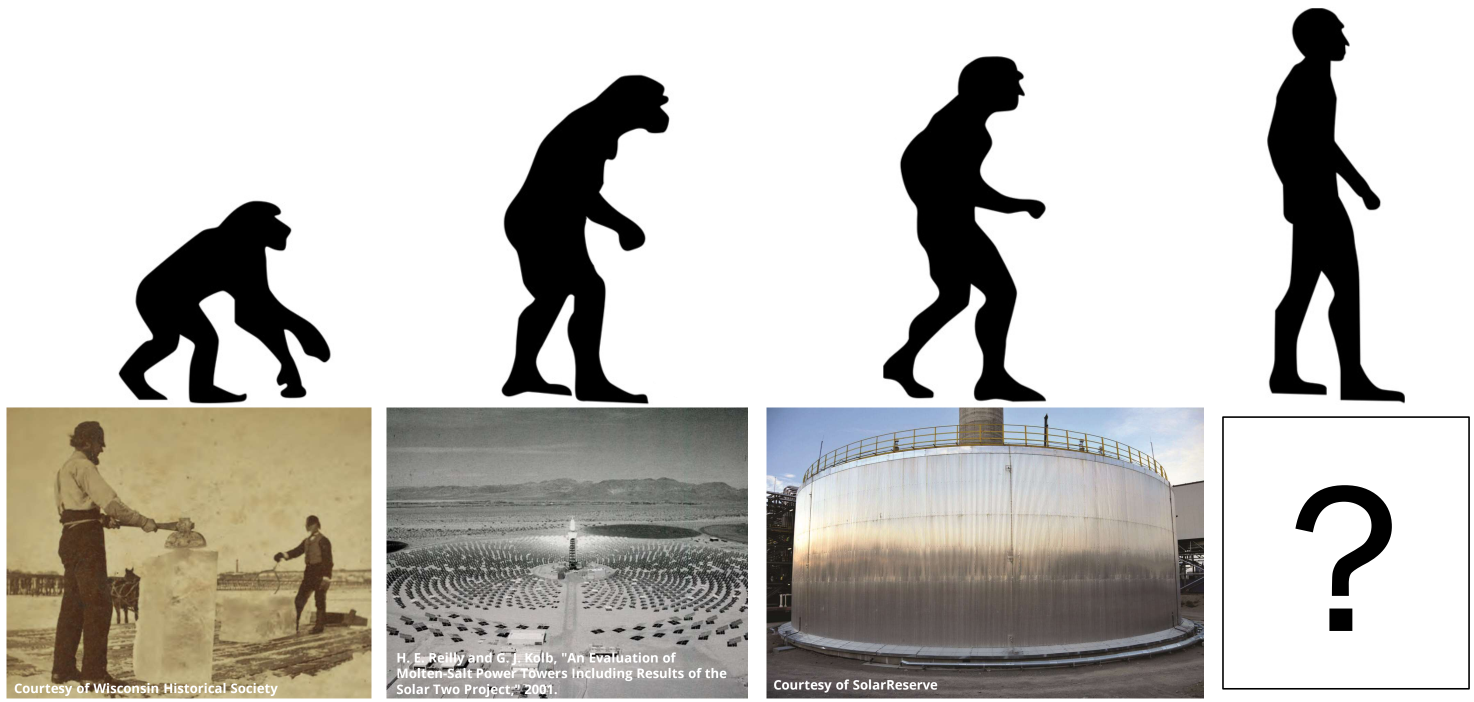
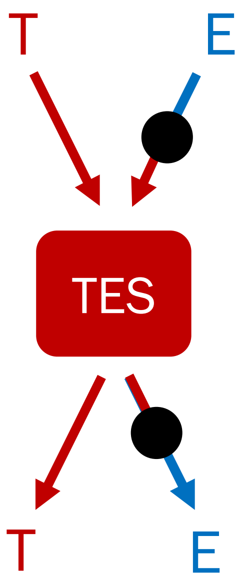
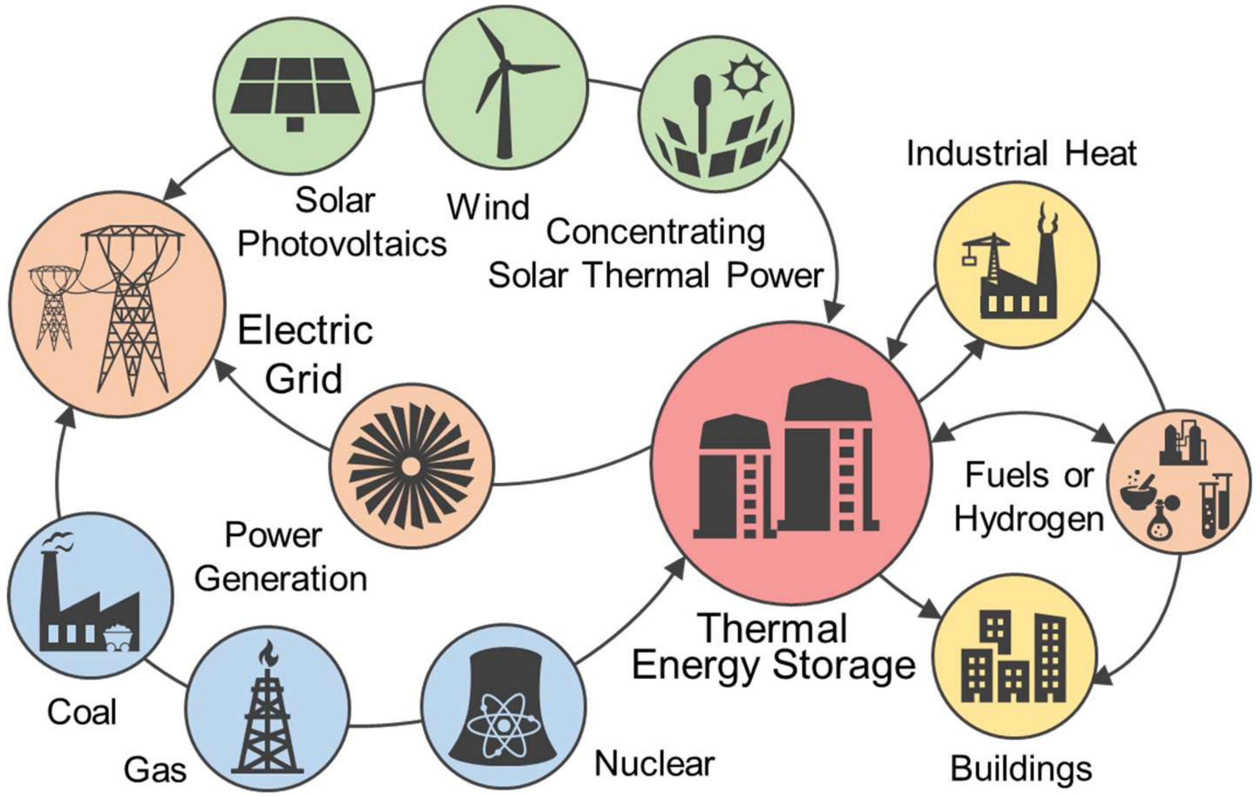
TES Overview

TES: Low cost potential, long operational lives, high energy density, synchronous power generation capability, heat and electricity output

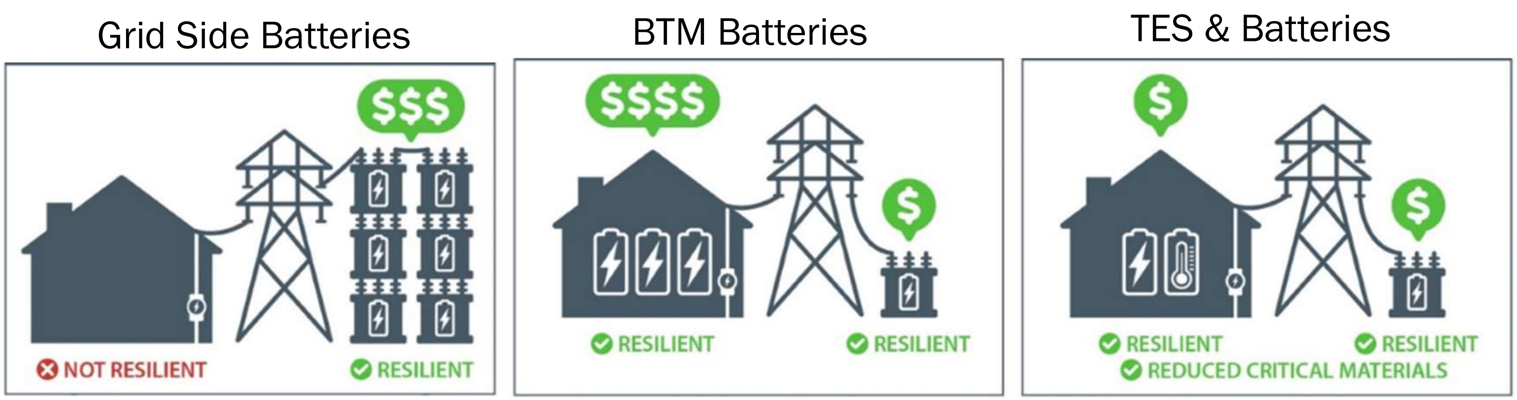


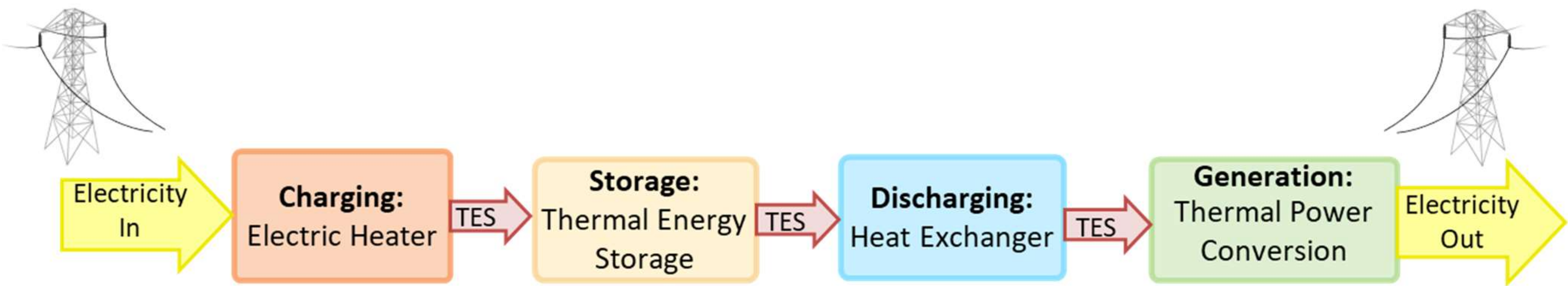
TES Overview





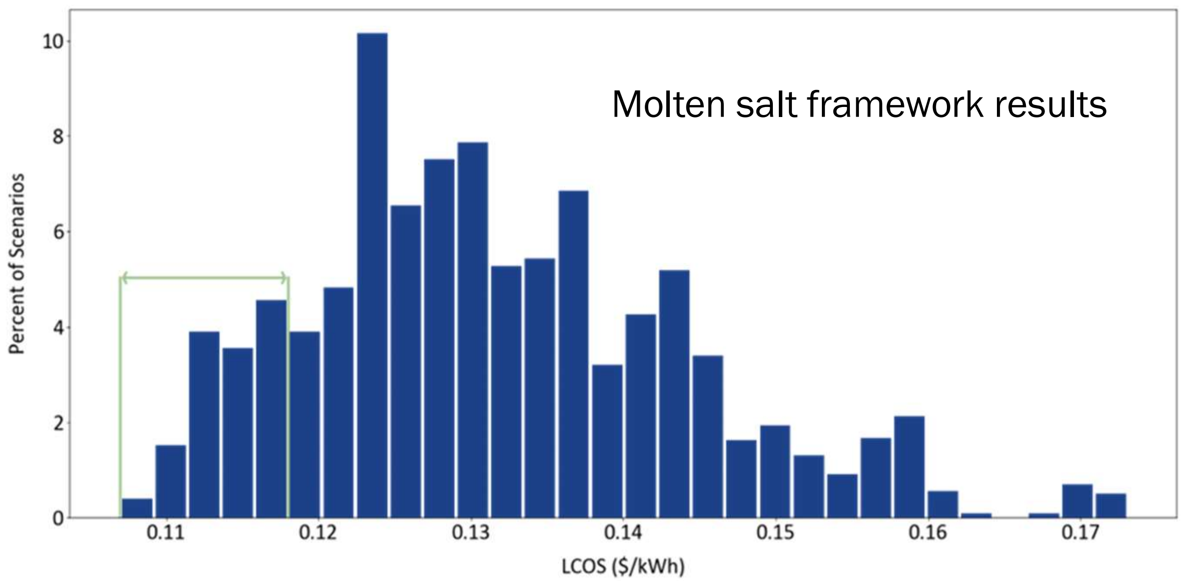
TES Overview





TES Paths to $0.05/kWh

Molten salt is unlikely to reach $0.05/kWh



Technologies with <$0.05/kWh Pathway: E-to-E, T-to-T, E-to-T, and T-to-E

- High temperature solid media TES
- Earth abundant storage media
- Advanced power cycles
- High temperature heat pumps
- Low-cost high-performance PCMs
- Plug & play TES systems

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Technology Strategy Assessment: Supercapacitors

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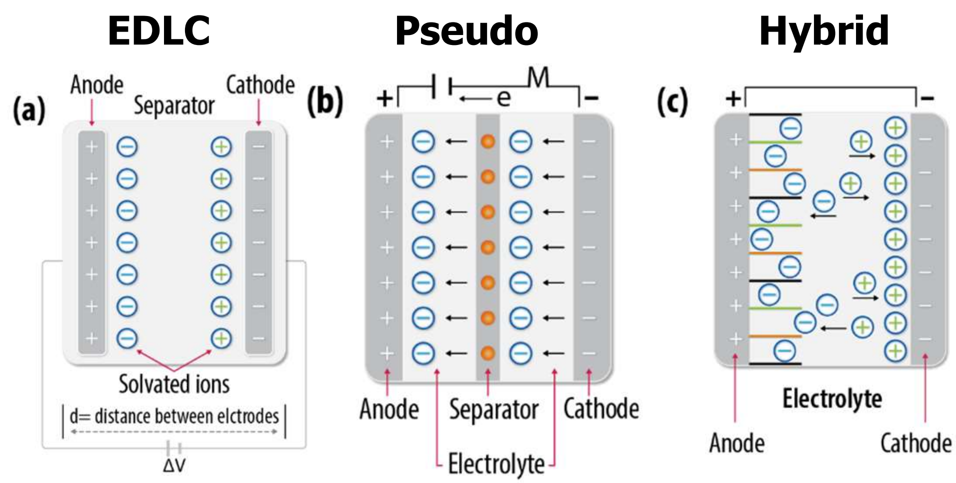
Supercapacitors: high cycle life and well suited for short duration applications

- Not well suited for standalone long duration energy storage (LDES)
- Better use is as hybrid LDES and supercapacitor system, where supercapacitor performs at least:
  - 40 cycles/day
  - 1 MW block
  - 45 second duration
- Current LCOS ~$0.44/kWh
- Best performing innovation portfolios achieve LCOS of ~$0.33/kWh (25% reduction)

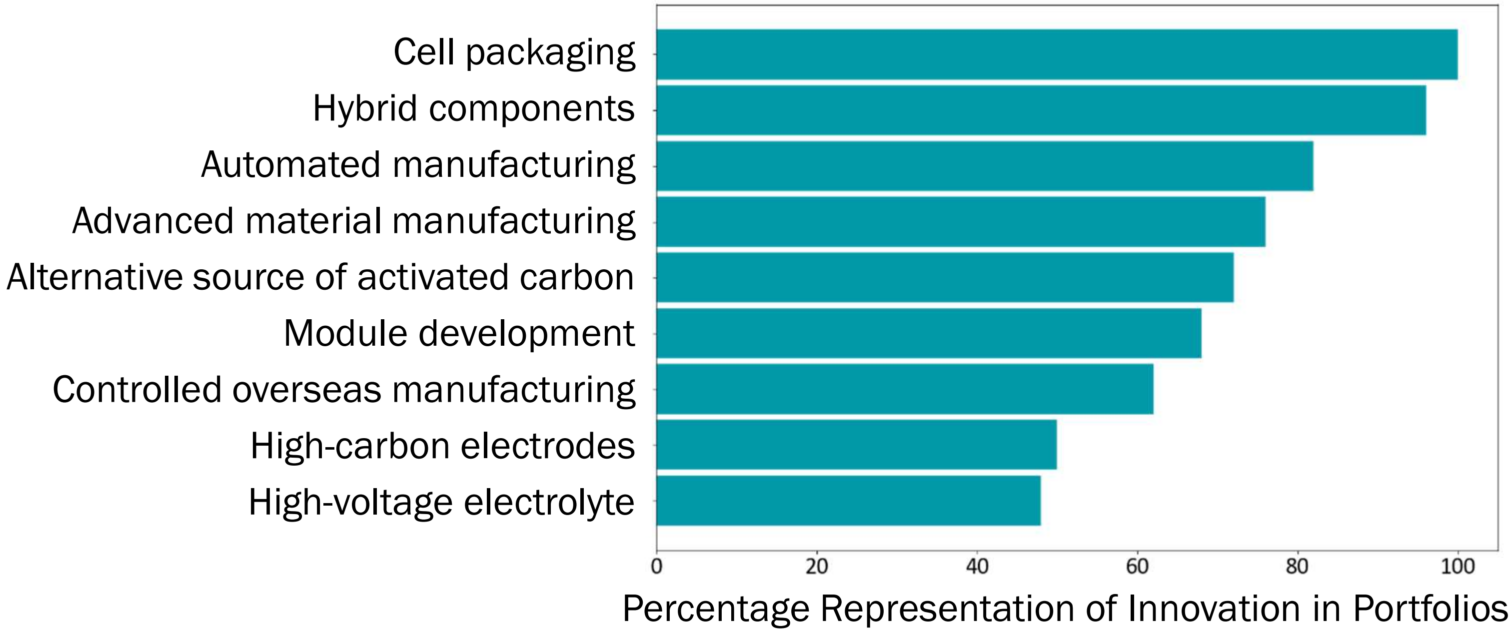


Cycles: ~1M
Energy density:
~8 Wh kg^{-1}

Cycles: ~200k
Energy density:
~20 Wh kg^{-1}

Cycles: ~100k
Energy density:
~150 Wh kg^{-1}

EDLC supercapacitors have several innovations key to LCOS reductions



Key takeaways:

(1) Activated carbon source diversification and manufacturing improvements

(2) Efficient packaging of cells and development of modules

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Technology Strategy Assessment: Bidirectional Hydrogen

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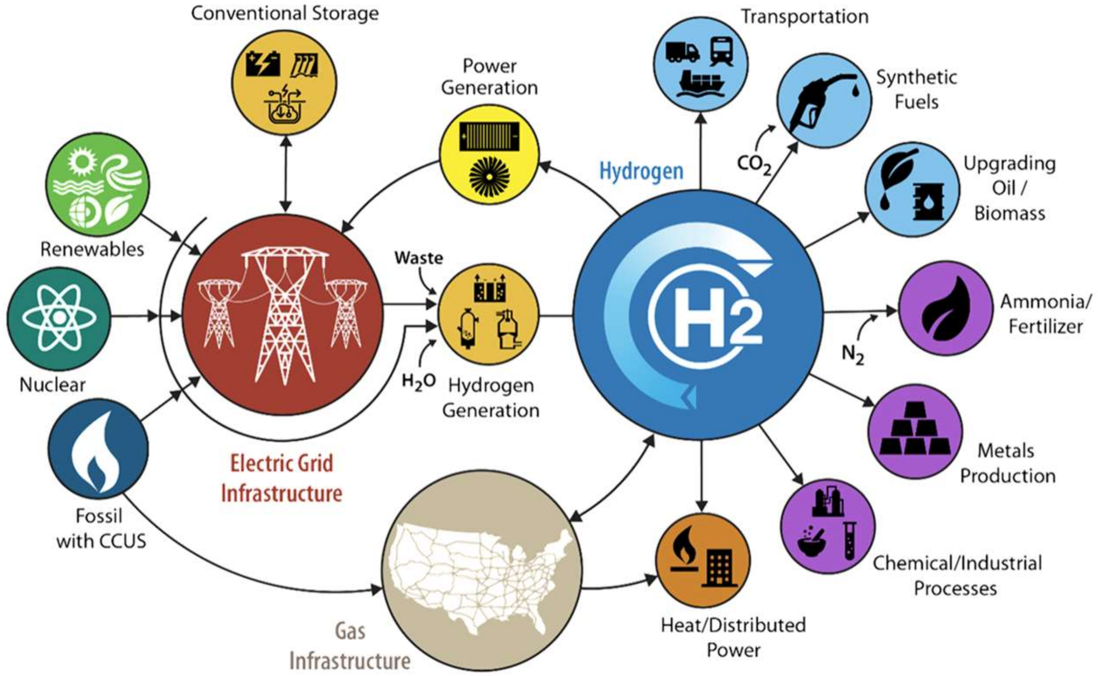
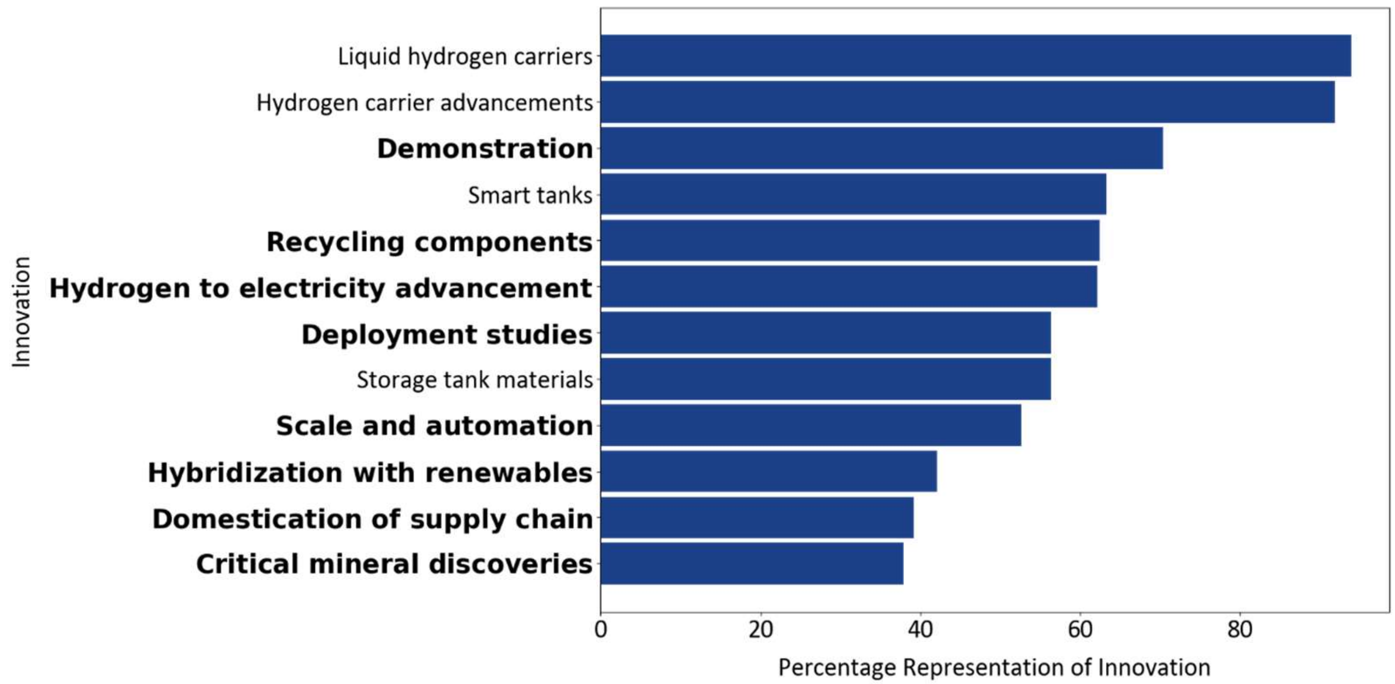
Bidirectional Hydrogen

Because bidirectional hydrogen can participate in multiple markets (electricity and hydrogen) it is less sensitive to the regularity of electricity price spreads. This makes it well suited for supporting the grid during extreme events.



R&D Themes

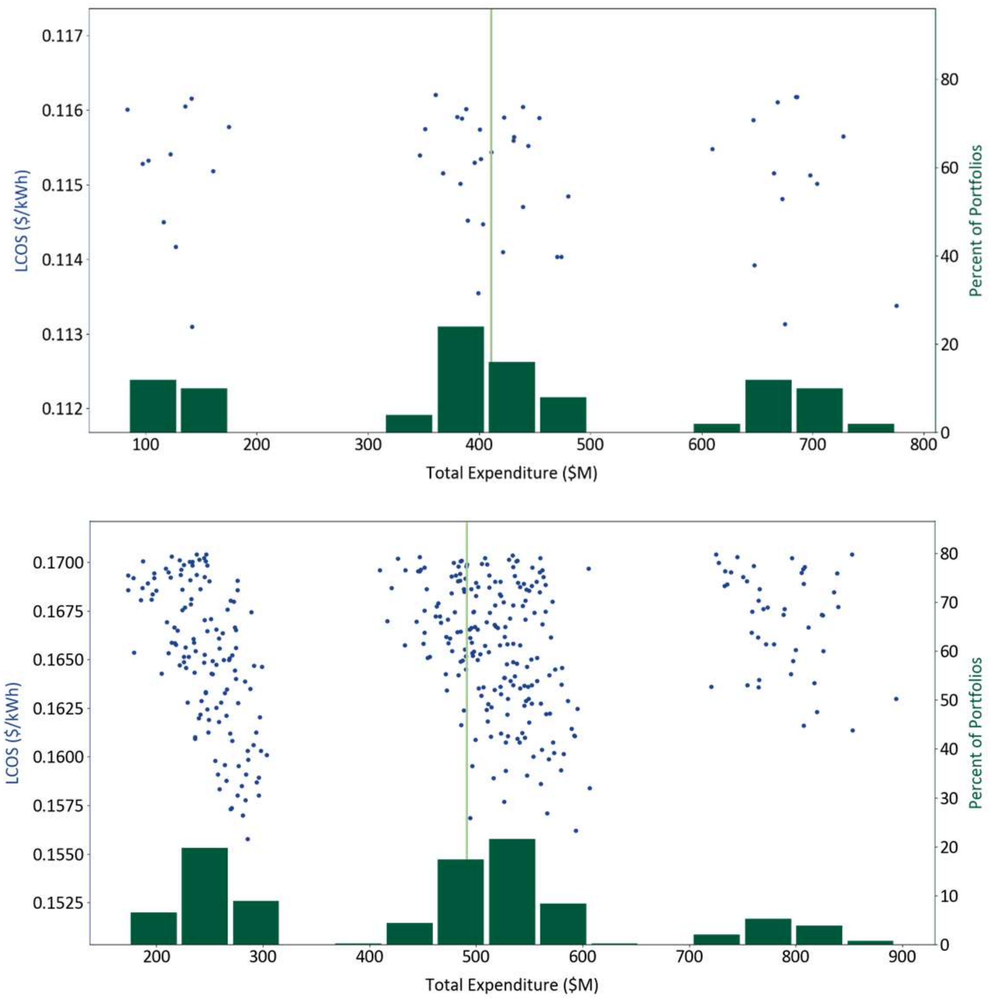
- Innovations that reduce the cost of storage in high pressure tanks had a large effect



Bolded innovations indicate applicability to both tank and salt cavern storage

R&D Themes

- Salt cavern storage (above) showed significantly lower LCOS for lower investment levels than tank storage (below).
- Round trip efficiency remains a major barrier for both
- High temperature electrolysis and reversible fuel cells may help



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SI 2030: Closeout

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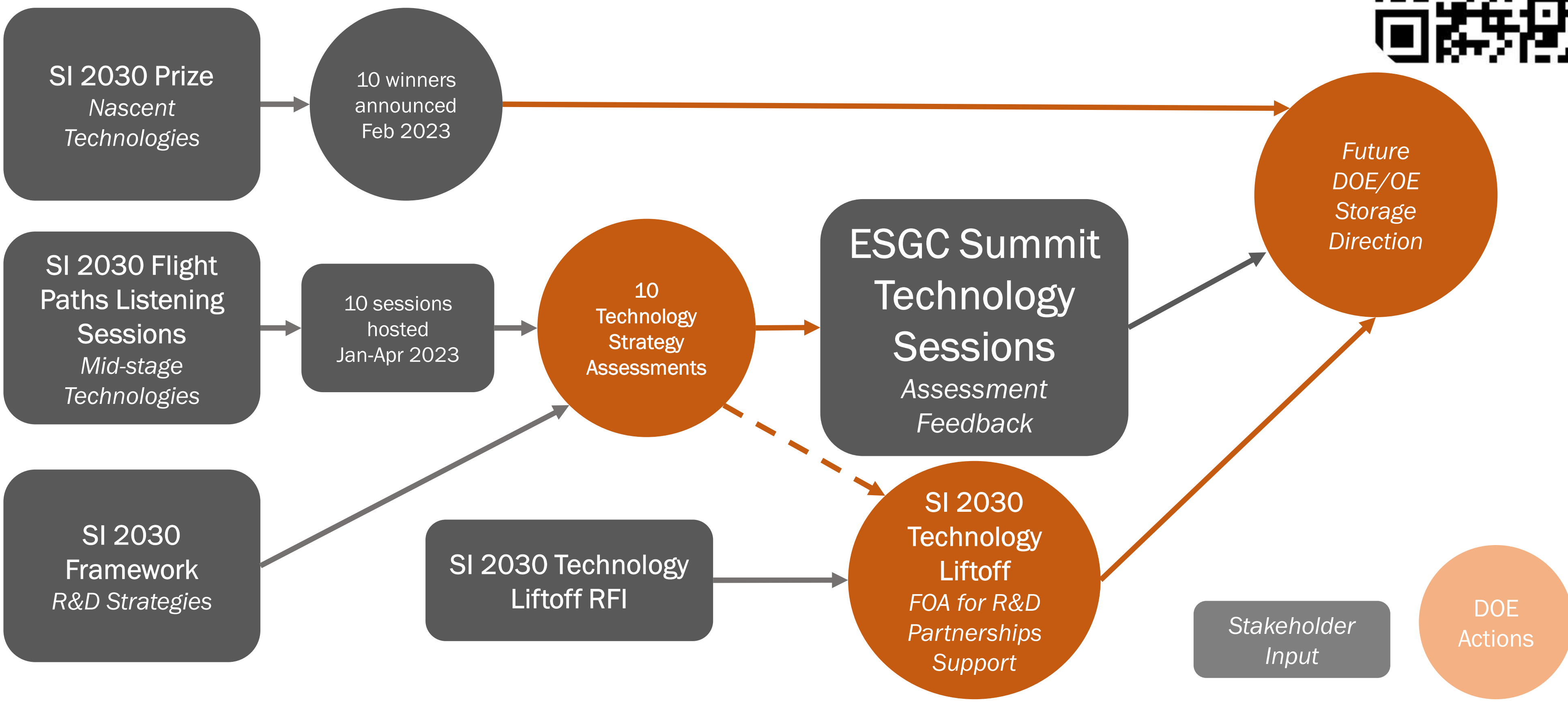
SI 2030 – Path Forward



Congratulations to the SI Prize Winners!

Storage Innovations Champions	Storage Innovations Finalists
Cryostone	Rondo Energy
RCAM Technologies	Thermal Battery Corporation
Gravity Power LLC	THEMES LLC
Electrified Thermal Solutions	NerG Solutions
KineticCore Solutions	Cache Energy

SI 2030: Technology Liftoff

- Letters of Intent due on **September 15, 2023**
- Informational and Q&A Webinar TBA
- Breakout rooms today will continue to inform SI strategy

RFI Released	RFI comments due	FOA Opens	Letters of Intent Due	Full Applications Due	Selections Made
March 8, 2023	April 3, 2023	July 25, 2023	September 15, 2023	December 4, 2024	Q1 2024

SI 2030 Acknowledgements

- 259 pages
- 32 authors representing 10 National Laboratories
- 37 technical reviewers
- 100+ individual & group conversations
- 100s of industry participants and stakeholders

THANK YOU!

We look forward to continuing the conversation!