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Storage™

Achieving the Promise of Low-Cost Long Duration Energy Storage

An Overview of 10 R&D Pathways from the Long Duration Storage Shot Technology Strategy Assessments

August 2024

Message from the Assistant Secretary for Electricity

Gene Rodrigues, Assistant Secretary, Office of Electricity

At the U.S. Department of Energy's (DOE's) Office of Electricity (OE), we pride ourselves in leading DOE's research, development, and demonstration programs to strengthen and modernize our nation's power grid. Our work helps our nation maintain a reliable, resilient, secure and affordable electricity delivery infrastructure. By working closely with industry and other stakeholders, we drive technological and operational advancements in grid systems and components, grid controls and communications, and grid-scale energy storage. These advancements ensure that every American home and business has reliable access to affordable energy, and that the U.S. sustains its global leadership in the clean energy transformation.

This report is one example of OE's pioneering R&D work to advance the next generation of energy storage technologies to prepare our nation's grid for future demands. OE partnered with energy storage industry members, national laboratories, and higher education institutions to analyze emergent energy storage technologies.

This report demonstrates what we can do with our industry partners to advance innovative long duration energy storage technologies that will shape our future—from batteries to hydrogen, supercapacitors, hydropower, and thermal energy. But it's not just about identifying the technologies that appear the most promising—it's also about evaluating their ability to revolutionize our energy landscape. That's why I'm excited that this report establishes stakeholder engagement and evaluation methods that measure the impact of innovations on levelized technology costs and the time to recoup investments. There has never been a time like this to be at the forefront of so much change in the energy industry, and I am proud that the Office of Electricity is leading the effort.

Sincerely,

Gene Rodrigues

Assistant Secretary for Electricity
Office of Electricity
U.S. Department of Energy

Executive Summary

Long Duration Energy Storage (LDES) provides flexibility and reliability in a future decarbonized power system. A variety of mature and nascent LDES technologies hold promise for grid-scale applications, but all face a significant barrier—cost. Recognizing the cost barrier to widespread LDES deployments, the United States Department of Energy (DOE) established the Long Duration Storage Shot[a] in 2021 to achieve 90% cost reduction[b] by 2030 for technologies that can provide 10+ hours duration of energy storage (the Storage Shot). In 2022, DOE launched the Storage Innovations (SI) 2030[c] initiative to develop specific and quantifiable research, development, and deployment pathways to achieve the Storage Shot. The initiative was part of DOE's Energy Storage Grand Challenge[d], a comprehensive, crosscutting program to accelerate the development, commercialization, and utilization of next-generation energy storage technologies and sustain American global leadership in energy storage.

This document utilizes the findings of a series of reports called the 2023 Long Duration Storage Shot Technology Strategy Assessments[e] to identify potential pathways to achieving the Storage Shot. Through combinations of innovations, or portfolios, the 2030 levelized cost of storage (LCOS)[f] targets for LDES are feasible or nearly feasible for multiple technologies. For a detailed analytical breakdown of innovation portfolios for each LDES technology, see the Technology Strategy Assessments[g].

The 10 LDES technologies described in this report and summarized in Table ES1 span four storage technology families:

- **Electrochemical energy storage**: flow batteries (FBs), lead-acid batteries (PbAs), lithium-ion batteries (LIBs), sodium (Na) batteries, supercapacitors, and zinc (Zn) batteries
- **Chemical energy storage:** hydrogen storage
- **Mechanical energy storage**: compressed air energy storage (CAES) and pumped storage hydropower (PSH)
- **Thermal energy storage (TES)**

Table ES1 also includes the top three potential innovations for each technology, which are explored further later in this document.

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[a] https://www.energy.gov/eere/long-duration-storage-shot

[b] Relative to a 2020 lithium-ion battery baseline.

[c] https://www.energy.gov/oe/storage-innovations-2030

[d] https://www.energy.gov/energy-storage-grand-challenge/energy-storage-grand-challenge

[e] https://www.energy.gov/oe/storage-innovations-2030

[f] The levelized cost of storage (LCOS) ($/kWh) metric compares the true cost of owning and operating various storage assets. LCOS is the average price a unit of energy output would need to be sold at to cover all project costs (e.g., taxes, financing, operations and maintenance, and the cost to charge the storage system). See DOE's 2022 Grid Energy Storage Technology Cost and Performance Assessment (https://www.energy.gov/sites/default/files/2022-09/2022 Grid Energy Storage Technology Cost and Performance Assessment.pdf).

[g] https://www.energy.gov/oe/storage-innovations-2030

Table ES1. Top 3 potential innovations to drive down the 2030 levelized cost of long duration energy storage technologies. Where indicated, innovations address specific storage technologies in each technology family.

Family & Technology		Description	Top 3 Potential Innovations
ELECTROCHEMICAL	**Flow Batteries (FBs)**	Pump negative and positive electrolytes through energized electrodes	• Novel active electrolytes • Manufacturing for scale • Accelerate the discovery of metrics/materials
	Lead-acid Batteries (PbAs)	Use a lead dioxide positive electrode and metallic lead negative electrode	• Re-design of standard current collectors • Advanced manufacturing • Demonstration projects
	Lithium-ion Batteries (LIBs)	Include lithium in the active materials in the positive electrode	• Rapid battery health assessment • Controls to improve cycle life • Impurities reduction technique
	Sodium-ion Batteries (NaIBs)	Include sodium in the active materials; this analysis also considers other sodium battery varieties	• Cathode-electrolyte interface • In-operations materials science research • Electrolyte development
	Electrochemical Double Layer Capacitor (EDLC) Supercapacitors	Accumulate electric charge on porous electrodes filled with an electrolyte; this analysis also considers other supercapacitors	• Cell packaging • Hybrid components • Automated manufacturing
	Zinc (Zn) Batteries	Include zinc in the active materials in the negative electrode	• Separator innovation • Pack/system-level design • Demonstration projects
CHEMICAL	**Hydrogen Storage**	Produces hydrogen through electrolysis in above ground tanks/below ground caverns	• Liquid hydrogen carriers (above) • Hydrogen carrier advancements (above) • Demonstration (above/below)
MECHANICAL	**Compressed Air Energy Storage (CAES)**	Stores electric energy in the form of potential energy through compressed air	• Demonstration projects • System modeling and design/operation • Mechanical compression/expansion
	Pumped Storage Hydropower (PSH)	Pumps water from a lower reservoir to an upper reservoir to store energy	• Hybrid PSH projects • Testing durability of new materials/structures • 3D printing technology at large scale
THERMAL	**Molten Salt Thermal Energy Storage (TES)**	Stores energy with heat as an input or output; this analysis also considers other TES varieties	• Single-tank storage • Heat-to-electricity conversion improvements • Large-scale demonstration

Innovation Reduces Long Duration Storage Costs

Figure ES1 shows the range of projected change in LCOS after implementing the top 10% of LCOS-reducing innovation portfolios for each LDES technology, relative to DOE's Long Duration Storage Shot target ($0.05/kWh LCOS or less).

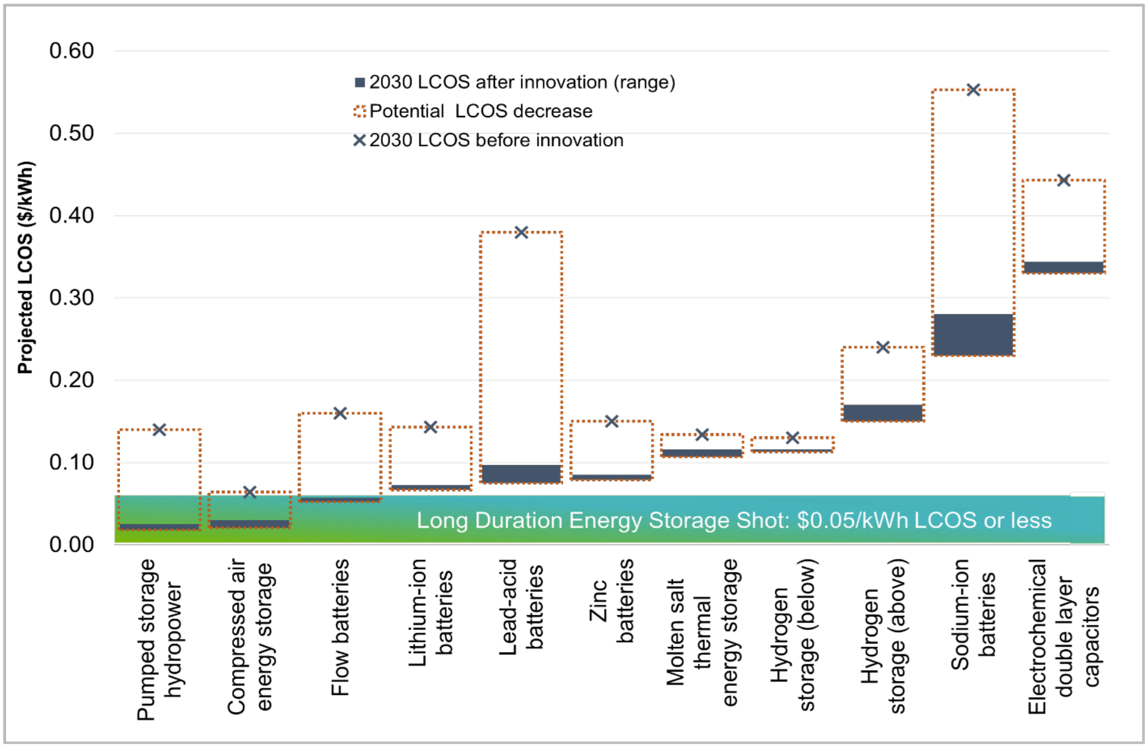

Figure ES1. For long duration energy storage, the range of impact on the 2030 LCOS after implementing the top 10% of LCOS-reducing innovations. Above and below ground hydrogen storage are shown separately. LCOS: levelized cost of storage.

The projected baseline 2030 LCOS of all technologies exceeds the Storage Shot target. The Technology Strategy Assessments'[h] findings identify innovation portfolios that enable pumped storage, compressed air, and flow batteries to achieve the Storage Shot, while the LCOS of lithium-ion, lead-acid, and zinc batteries approach the Storage Shot target at less than $0.10/kWh. Sodium-ion batteries and lead-acid batteries broadly hold the greatest potential for cost reductions (roughly -$0.31/kWh LCOS), followed by pumped storage hydropower, electrochemical double layer capacitors, and flow batteries (roughly -$0.11/kWh LCOS).

The range of projected LCOS after innovation is largest for sodium-ion, lead-acid batteries, and above ground hydrogen storage. The wide ranges may indicate that additional analysis in this area could help refine estimated reductions, given the absence of widely available industry data on costs.

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[h] https://www.energy.gov/oe/storage-innovations-2030

Innovation Implementation Cost & Duration Tradeoffs

The estimated cost and period of implementing innovations varies across energy storage technology and presents tradeoffs for lowering the projected LCOS. Figure ES2 compares the analysis's findings on the average duration and average cost of implementing the top 10% of innovation portfolios for each storage technology. The circle area and color reflect the average projected 2030 LCOS of each technology that may be achieved after innovations.

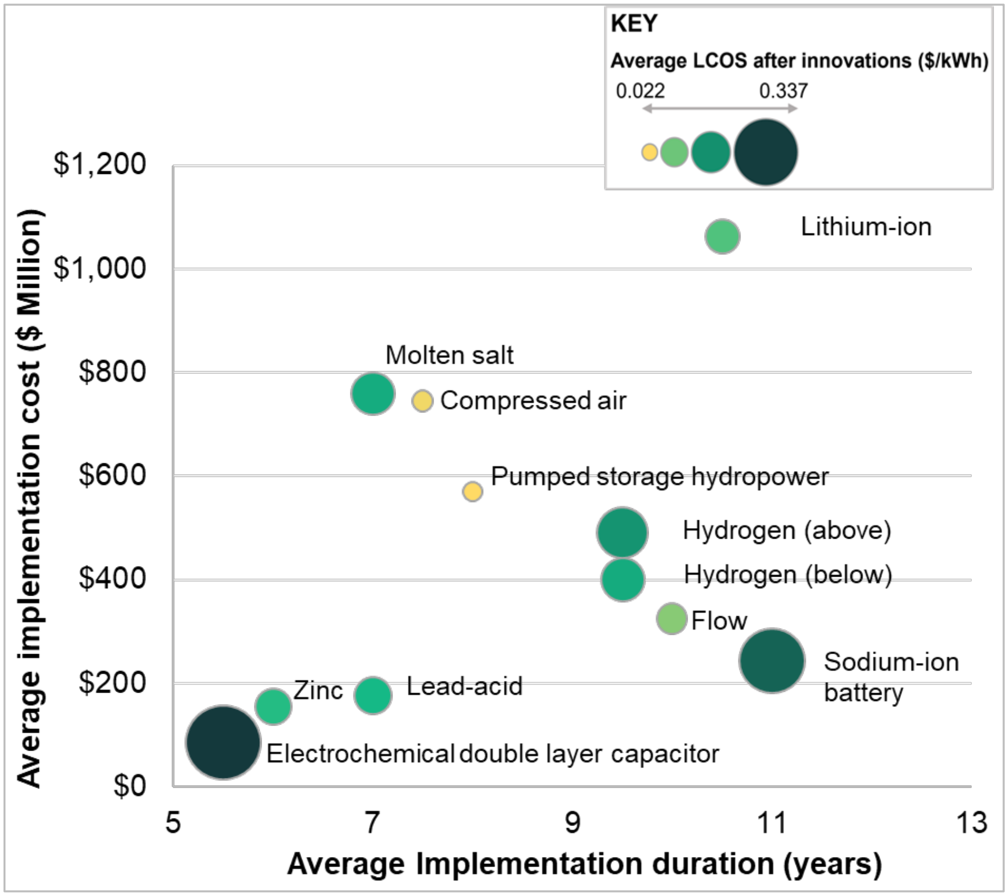

Figure ES2. The average duration and cost of implementing the top 10% of innovation portfolios that drive down the LCOS of long duration energy storage. The circle area and color correspond to the average projected LCOS after implementing the top 10% innovation portfolios for each technology. Above and below ground hydrogen storage are shown separately. LCOS: levelized cost of storage.

Relative to other technologies in the analysis, electrochemical double layer capacitors, zinc, and lead-acid batteries each have low innovation implementation durations (less than 7 years) and costs (less than $200 million). However, the average theoretical achievable LCOS of zinc and lead-acid batteries is considerably lower than it is for electrochemical double layer capacitors, which have the highest average LCOS after innovations.

Similarly, though the innovation cost for sodium-ion batteries is comparably low, the innovation implementation period is long and the projected average LCOS is the second highest across technologies. Conversely, the average innovation cost and duration are high for lithium-ion batteries, but the average LCOS range after innovation is low and close to the Storage Shot target.

Figure ES3 plots the time duration for implementing the top 10% innovation portfolios by the projected LCOS range, showing the cost-reduction opportunity space while accounting for uncertainty and average innovation implementation cost.

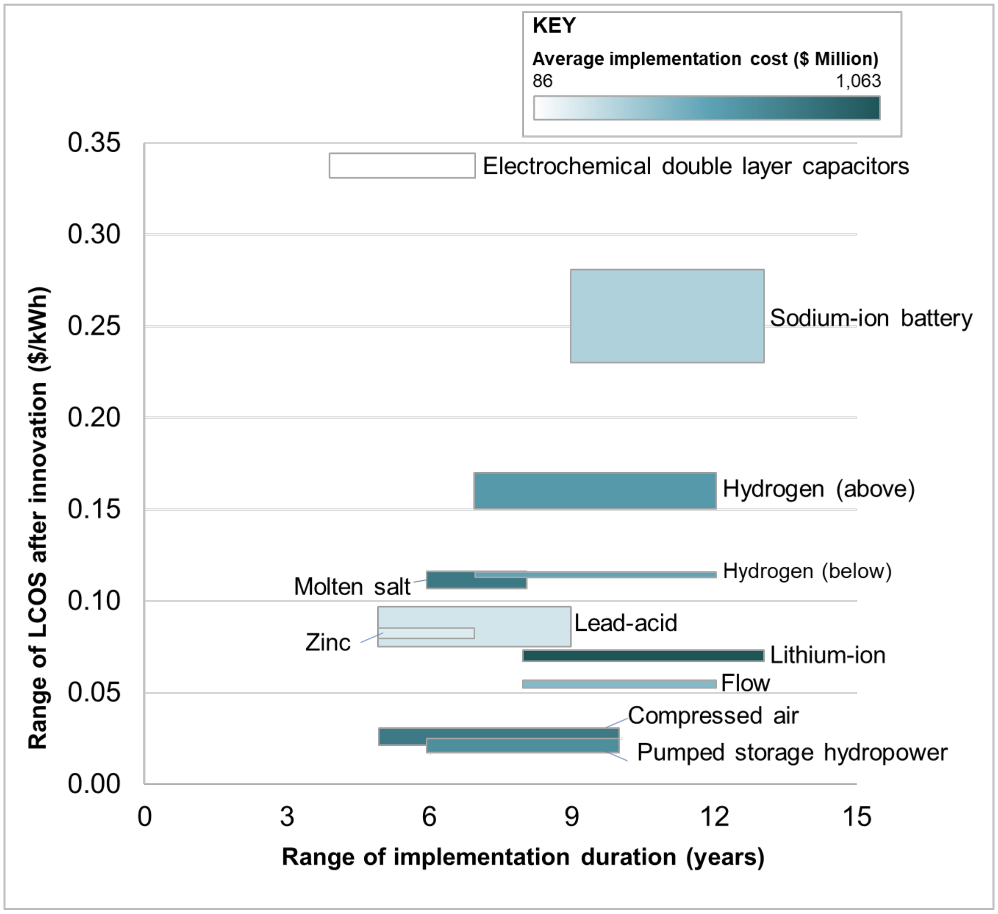

Figure ES3. For long duration energy storage, the range of time needed to implement the top 10% of LCOS-reducing innovations (years) compared to the range of projected LCOS after innovations ($/kWh). The block colors represent the average cost of implementing innovations ($ Million). Above and below ground hydrogen storage are shown separately. LCOS: levelized cost of storage.

Implementation durations vary across all technologies, with possible durations of 10 or more years for many technologies. Of the technologies with maximum durations of less than 10 years (electrochemical double layer capacitors, zinc, lead-acid batteries, and molten salt), all but molten salt thermal storage requires comparably low implementation costs.

Additional detailed findings are in Table ES2, including the percent change relative to the projected baseline 2030 LCOS after implementing the top 10% of innovations. Across technologies, on average, the top 10% of innovation portfolios can reduce LCOS by 12%–85% to $0.026/kWh–$0.255/kWh. The average cost of implementation is $86 million–$1,063 million with a duration of 5.5–11 years.

Table ES2. The projected impact of implementing the top 10% of innovation portfolios on the levelized cost of storage (LCOS) of long duration energy storage. All values are the average of ranges. Where indicated, innovations address specific storage technologies in each technology family.

Family & Technology		LCOS ($/kWh) after innovation	% LCOS change from 2030 baseline	Innovation portfolio cost ($M)	Implementation duration (years)
ELECTROCHEMICAL	**Flow Batteries (FBs)**	$0.055	-66%	325	10
	Lead-acid Batteries (PbAs)	$0.086	-77%	176	7
	Lithium-ion Batteries (LIBs)	$0.070	-51%	1,063	10.5
	Sodium-ion Batteries (NaIBs)	$0.255	-54%	244	11
	Electrochemical Double Layer Capacitor (EDLC) Supercapacitors	$0.337	-24%	86	5.5
	Zinc (Zn) Batteries	$0.082	-45%	155	6
CHEMICAL	**Hydrogen Storage** (above ground)	$0.160	-33%	491	9.5
	Hydrogen Storage (below ground)	$0.115	-12%	400	9.5
MECHANICAL	**Compressed Air Energy Storage (CAES)**	$0.026	-60%	745	7.5
	Pumped Storage Hydropower (PSH)	$0.022	-85%	570	8
THERMAL	**Molten Salt Thermal Energy Storage (TES)**	$0.112	-17%	759	7

Key Takeaways

Grid-scale energy storage is a critical element driving and supporting the evolution of the electricity system. Long-duration (10+ hours) energy storage technologies are needed to support a variety of clean energy and resilience applications. DOE formed SI 2030 to analyze pathways for the most promising technologies to meet future targets. The strategy developed as part of SI 2030 is described in a series of reports called the 2023 Long Duration Storage Shot Technology Strategy Assessments. The reports analyze the potential of long duration capable energy storage technologies to achieve future goals and benefit from widespread deployment on the Nation's electricity grid. They establish a systematic approach to engage with experts while quantifying the impact of innovation and will be revisited periodically to track progress.

The 2023 Long Duration Storage Shot Technology Strategy Assessments evaluated pertinent technologies using stakeholder engagement and modeling to determine the impact of innovation on the LCOS relative to a 2030 projected baseline. In addition to estimating investment needs and timescales, the analysis found that innovations can significantly drive down the LCOS and that several technologies can achieve, or approach DOE's Long Duration Storage Shot target. Furthermore, the innovations may advance storage options with diverse mineral supply chains and improve the accessibility of hydrological and geological storage technologies.

The results for the top 10% cost-reducing innovation portfolios varied across technologies. **On average[i], the top 10% of innovation portfolios can reduce LCOS by 12%–85% to $0.03/kWh–**$0.26/kWh across storage technologies. The average cost of implementing innovations ranges roughly from $100 million–$1 billion and would take 6–11 years.

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[i] The stated values (the LCOS after innovations and the percent change in LCOS from a 2030 baseline) are averages of ranges.

Table of Contents

Introduction

Report Background

Long Duration Energy Storage (LDES) is a key option to provide flexibility and reliability in a future decarbonized power system. A variety of mature and nascent LDES technologies hold promise for grid-scale applications, but all face a significant barrier—cost. This report quantifies specific R&D pathways for 10 LDES technologies to drive down LDES costs. The 10 LDES technologies span four energy storage technology families:

- **Electrochemical energy storage**: flow batteries (FBs), lead-acid batteries (PbAs), lithium- ion batteries (LIBs), sodium (Na) batteries, supercapacitors, and zinc (Zn) batteries
- **Chemical energy storage:** hydrogen storage
- **Mechanical energy storage**: compressed air energy storage (CAES) and pumped storage hydropower (PSH)
- **Thermal energy storage** (TES)

Recognizing the cost barrier to widespread LDES deployments, the U.S. Department of Energy (DOE) established the Long Duration Storage Shot[j] in 2021 to achieve 90% cost reduction[k] by 2030 for technologies that can provide 10+ hours or longer duration of energy storage [1]. In 2022, DOE launched the Storage Innovations (SI) 2030[l] initiative to develop specific and quantifiable research, development, and deployment (RD&D) pathways to achieve the Storage Shot [2]. The initiative was part of DOE's Energy Storage Grand Challenge[m], a comprehensive, crosscutting program to accelerate the development, commercialization, and utilization of next-generation energy storage technologies and sustain American global leadership in energy storage.

As part of SI 2030, DOE developed the 2023 Long Duration Storage Shot Technology Strategy Assessment[n] reports [3, 4, 5, 6, 7, 8, 9, 10, 11, 12]. The reports characterize potential pathways to achieving the Storage Shot through combinations of innovations, or portfolios, that reduce the 2030 levelized cost of storage (LCOS)[o] for LDES. The Technology Strategy Assessments evaluated 10 LDES technologies using stakeholder engagement and modeling to determine the impact of innovation on the LCOS relative to a 2030 projected baseline.

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[j] https://www.energy.gov/eere/long-duration-storage-shot

[k] Relative to a 2020 LIB baseline.

[l] https://www.energy.gov/oe/storage-innovations-2030

[m] https://www.energy.gov/energy-storage-grand-challenge/energy-storage-grand-challenge

[n] https://www.energy.gov/oe/storage-innovations-2030

[o] The levelized cost of storage (LCOS) ($/kWh) metric compares the true cost of owning and operating various storage assets. LCOS is the average price a unit of energy output would need to be sold at to cover all project costs (e.g., taxes, financing, operations and maintenance, and the cost to charge the storage system). See DOE's 2022 Grid Energy Storage Technology Cost and Performance Assessment (https://www.energy.gov/sites/default/files/2022-09/2022 Grid Energy Storage Technology Cost and Performance Assessment.pdf).

In addition to providing an overview of the findings of the Technology Strategy Assessments on potential pathways to achieving the Storage Shot, this document also summarizes two stakeholder engagement efforts: the Storage Innovations Flight Paths and the Storage Innovations Framework. The Flight Paths and the Framework are part of the larger SI 2030[p] effort and are fully documented in the Technology Strategy Assessments. This report also highlights the Champions and Finalists of the Storage Innovations Prize, which targeted highly- innovative, early-stage technologies.

The results presented in this report should not be taken as a statement of technology prioritization or de-prioritization.

Long Duration Energy Storage (LDES) Technologies

This report lays out a strategy to overcome financial hurdles for 10 LDES technologies, detailed in Table 1, in the U.S. by tapping innovations with the greatest potential to drive down LDES costs. These technologies span four storage technology families (electrochemical, chemical, mechanical, and thermal) and were selected based on engagement with the public through pitch sessions and structured stakeholder engagement. Table 1 also includes the top three potential innovations for each technology, which are explored further later in this document.

LDES technologies utilize a variety of storage mechanisms and vary in cost, range of suitable grid services, and the barriers to innovation and cost reduction that they face. Some of the technology areas, such as LIBs, represent a family of similar technologies with different battery performance characteristics. Energy storage performance characteristics are technology metrics that can be used to indicate a technology's ability to perform and provide a service.

Advancing LDES technologies in the U.S., especially non-traditional less mature varieties, can diversify energy storage material supply chains.

Commonly evaluated metrics include safety and thermal stability, how deeply a technology can be discharged, energy capacity measures, power capacity measures, the cycle life, and the duration that the storage technology can be discharged for. These features vary by technology but are also affected by other factors, including the battery format, size, configuration, operation, and the overall system design.

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[p] https://www.energy.gov/oe/storage-innovations-2030

Table 1. Top 3 potential innovations to drive down the 2030 levelized cost of long duration energy storage technologies. Where indicated, innovations address specific storage technologies in each technology family.

Family & Technology		Description	Top 3 Potential Innovations
ELECTROCHEMICAL	**Flow Batteries (FBs)**	Pump negative and positive electrolytes through energized electrodes	• Novel active electrolytes • Manufacturing for scale • Accelerate the discovery of metrics/materials
	Lead-acid Batteries (PbAs)	Use a lead dioxide positive electrode and metallic lead negative electrode	• Re-design of standard current collectors • Advanced manufacturing • Demonstration projects
	Lithium-ion Batteries (LIBs)	Include lithium in the active materials in the positive electrode	• Rapid battery health assessment • Controls to improve cycle life • Impurities reduction technique
	Sodium-ion Batteries (NaIBs)	Include sodium in the active materials; this analysis also considers other sodium battery varieties	• Cathode-electrolyte interface • In-operations materials science research • Electrolyte development
	Electrochemical Double Layer Capacitor (EDLC) Supercapacitors	Accumulate electric charge on porous electrodes filled with an electrolyte; this analysis also considers other supercapacitors	• Cell packaging • Hybrid components • Automated manufacturing
	Zinc (Zn) Batteries	Include zinc in the active materials in the negative electrode	• Separator innovation • Pack/system-level design • Demonstration projects
CHEMICAL	**Hydrogen Storage**	Produces hydrogen through electrolysis in above ground tanks/below ground caverns	• Liquid hydrogen carriers (above) • Hydrogen carrier advancements (above) • Demonstration (above/below)
MECHANICAL	**Compressed Air Energy Storage (CAES)**	Stores electric energy in the form of potential energy through compressed air	• Demonstration projects • System modeling and design/operation • Mechanical compression/expansion
	Pumped Storage Hydropower (PSH)	Pumps water from a lower reservoir to an upper reservoir to store energy	• Hybrid PSH projects • Testing durability of new materials/structures • 3D printing technology at large scale
THERMAL	**Molten Salt Thermal Energy Storage (TES)**	Stores energy with heat as an input or output; this analysis also considers other TES varieties	• Single-tank storage • Heat-to-electricity conversion improvements • Large-scale demonstration

Rechargeable battery technologies can also be categorized into classes or families based on the principal mechanism that governs their ability to store and release electric energy. Some technology types may be better suited for particular grid applications. Power applications typically require high power output for short periods of time, from a few seconds to a few minutes. Energy applications use storage for relatively large amounts of energy for longer periods of time, from minutes to hours.[q] There are a wide variety of storage categories. For example, technologies like LIBs and FBs are electrochemical batteries that rely on oxidation-reduction (redox) reactions.[r] Others, like PSH, rely on potential energy. The term TES refers to a group of energy storage technologies that capture and use heat, relying on thermodynamic principles.

Methods

Through SI 2030, DOE seeks to understand the full landscape of long duration-capable technologies and the specific innovations required to unlock the potential for long duration applications in a variety of these technologies. As of August 2023, SI 2030 has launched four components: the SI 2030 Framework, Flight Paths, Prize, and Technology Liftoff [2].

- **SI Framework:** This pillar designed an industry-focused R&D "Framework" to identify and measure the highest-impact R&D investments on the future of 10 energy storage technologies. The primary goals of the Framework were to stochastically model future outcomes of potential DOE investment portfolios on storage technology LCOS and to craft strategies around the highest-impact investments and technology suitability across different use cases.
- **SI Flight Paths:** This pillar complemented the SI Framework by providing a collaborative forum to explore technology R&D opportunities and potential pre-competitive R&D pathways. Flight Paths consisted of 10 industry Listening Sessions held January through April 2023, bringing together industry representatives to take part in collaborative discussions focused on specific technology areas.
- **SI Prize:** While the other two pillars targeted established or mid-stage technologies, the Prize invited the storage community to propose early-stage, emerging, and innovative energy storage ideas that may be disruptive to the industry in the future.
- **SI Technology Liftoff:** To expand upon the activities and outcomes of SI Flight Paths, while utilizing the insights gathered from the Prize and Framework, DOE launched the SI Technology Liftoff[s]. The SI Technology Liftoff is immediately leveraging the strategy developed through the Flight Paths listening session conversations and analytical Framework results. It aims to accelerate partnerships and enable pre-competitive R&D projects.

The 2023 Long Duration Storage Shot Technology Strategy Assessments [3, 4, 5, 6, 7, 8, 9, 10, 11, 12] are the product of the SI Framework and SI Flight Paths. Figure 1 below provides an overview of the SI 2030 components including stakeholder engagements and DOE actions.

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[q] See Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide (https://www.energy.gov/sites/prod/files/2016/10/f33/sandia_energy_storage_report_sand2010-0815_Feb_2010.pdf).

[r] Typically, when a battery discharges, electrically charged ions in the electrolyte near one node supply electrons (oxidation) while ions near the other electrode accept electrons (reduction). The process is reversed to charge the battery. See Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide (https://www.energy.gov/sites/prod/files/2016/10/f33/sandia_energy_storage_report_sand2010-0815_Feb_2010.pdf).

[s] https://www.energy.gov/oe/storage-innovations-2030-technology-liftoff

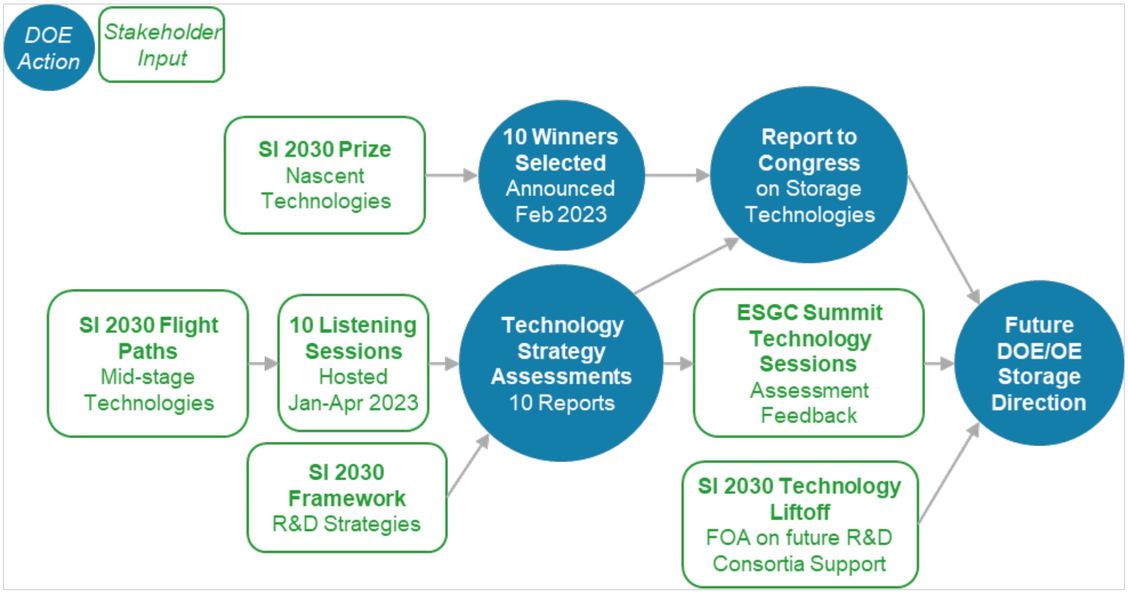

Figure 1. Diagram of the U.S. Department of Energy's (DOE) Storage Innovations (SI) 2030 process, detailing stakeholder input and DOE actions. R&D: research and development. FOA: funding opportunity announcement. ESGC: Energy Storage Grand Challenge. OE: Office of Electricity.

The Flight Paths listening sessions fostered discussion that contributed to the 2023 Technology Strategy Assessments. The analytical basis for much of the reports was derived from the SI Framework. Step 1 of the Framework, as shown in Figure 2, was to assess the RD&D trajectory status quo for a given technology and to project the performance and cost parameters out to 2030, given no marginal increase in industry investment over currently planned levels.

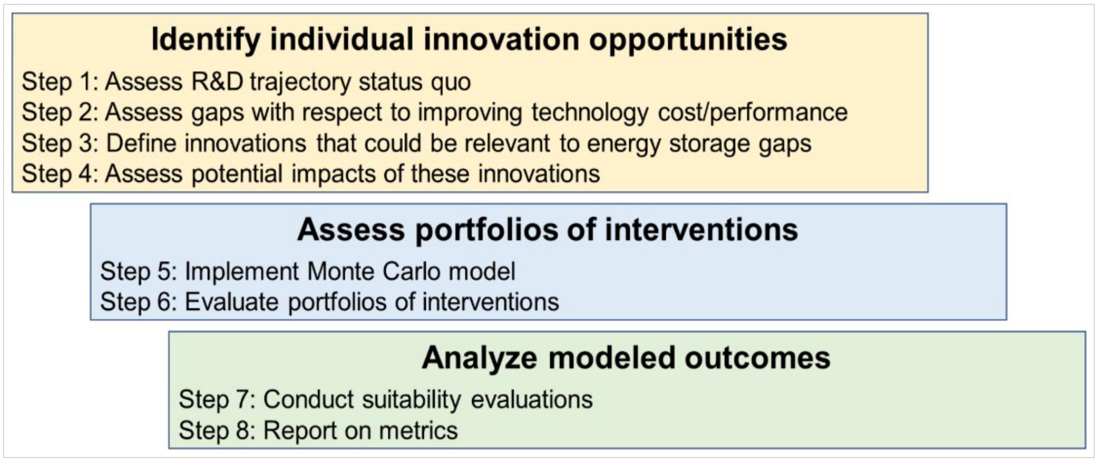

Figure 2. The 8-step Storage Innovations 2030 Framework Study.

The next steps established a taxonomy of innovations, along with definitions of each innovation, through a series of interviews with relevant subject matter experts (SMEs). Members of the research team reached out to hundreds of SMEs across the 10 chosen storage technologies to elicit views on innovations with potential to improve the cost and performance of the given technology.

Based on the SME input received, the Framework Team quantified the suitability, budget requirements, preferred R&D interventions, investment timelines, and cost and performance impacts of investment in each innovation. SMEs were asked their preferred method of R&D intervention most suitable for each innovation in each technology. The SMEs' preferences with respect to investment mechanisms for each innovation are presented in each individual technology report [3, 4, 5, 6, 7, 8, 9, 10, 11, 12].

In Step 4, SMEs defined investment requirements and the impact of each innovation defined in Step 2. For each innovation, SMEs quantified the investment requirements (funding levels and duration) and the expected impact on performance (e.g., round trip efficiency, energy density, and cycle life) and cost (e.g., storage block costs, and operations and maintenance costs) metrics. For some of the more established storage technologies, these investment requirement estimates build on existing investments.

The research team used the innovation metrics to model impacts employing an analytical technique called a Monte Carlo simulation. The model created a list of possible innovation portfolios and examined each portfolio separately. Portfolios were comprised of a unique set of innovations, each with a timeline, budget, and a list of effects on cost and performance metrics [13]. An innovation's effects on these parameters were specified by a probability distribution function, derived from survey responses. For each portfolio, the model randomly determined the effect of each innovation on the parameters using the corresponding probability distributions.

Next, the analysis determined which sets of interventions, or portfolios, were most critical for achieving high-impact scenarios. The model plotted the frequency distribution of LCOS outcomes and the innovations that appeared most frequently in the top 10% in terms of low LCOS outcomes.

The SI 2030 effort used the Long Duration Storage Shot LCOS target as a guiding metric. However, DOE's ongoing efforts advance storage technologies that support a range of service durations. As outlined in the March 2023 DOE report Pathways to Commercial Liftoff: Long Duration Energy Storage[t], market recognition of LDES's full value, through increased compensation or other means, will enable commercial viability and market "liftoff" for many technologies even before fully achieving the Storage Shot target.

See the Long Duration Storage Shot Technology Strategy Assessments Methodology[u] for a comprehensive explanation of the methods this analysis used [14].

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[t] https://liftoff.energy.gov/wp-content/uploads/2023/05/Pathways-to-Commercial-Liftoff-LDES-May-5_UPDATED.pdf

[u] https://www.energy.gov/sites/default/files/2023-07/Technology Strategy Assessment - Methodology.pdf

Technology Strategy Assessments

Electrochemical: Flow Batteries (FBs)

Potentially achieve

$0.06/kWh

LCOS

with

$330M

investments

over

10 YEARS

Values are rounded averages

Introduction

Redox flow batteries (RFBs) or flow batteries (FBs) are an innovative technology that offers a bidirectional energy storage system by using redox active energy carriers dissolved in liquid electrolytes. FBs work by pumping negative and positive electrolytes through energized electrodes in electrochemical reactors (stacks), allowing energy to be stored and released as needed.

FBs traditionally have unique characteristics, such as decoupled energy and power, scalability, and potential cost-effectiveness, due to their liquid nature. With the promise of cheaper, more reliable energy storage, FBs are poised to transform the way we power our homes and businesses and usher in a new era of sustainable energy.

Pathways to $0.05/kWh

The Long Duration Storage Shot Technology Strategy Assessment modeled the impact of portfolios of innovations on the projected 2030 LCOS of FBs. Based on a 100 MW FB system with 10 hours of storage in 2030, the projected baseline 2030 LCOS is $0.160/kWh.

Analysis findings indicate that in the top 10% of highest impact scenarios, the LCOS ranged from $0.052/kWh–$0.057/kWh with a mean portfolio cost of $325 million. This represents the value of the marginal investment over the currently planned levels required to achieve the corresponding LCOS improvements and approximately a 66% improvement in LCOS compared to the baseline. The timeline required to achieve these LCOS levels is estimated to be 8–12 years.

Innovations identified most frequently in the top 10% of the portfolios are presented in Figure 3. Seven innovations had 50% or greater share in the top 10% of FB portfolios with the greatest potential to reduce LCOS. These innovations hold significant promise for reducing the cost and improving the performance of FB systems:

1. Novel active electrolyte
2. Manufacturing for scalable FBs
3. Accelerate the discovery loop for battery metrics and materials
4. Secondary sourcing
5. System design and packing
6. Bipolar plates
7. Power performance

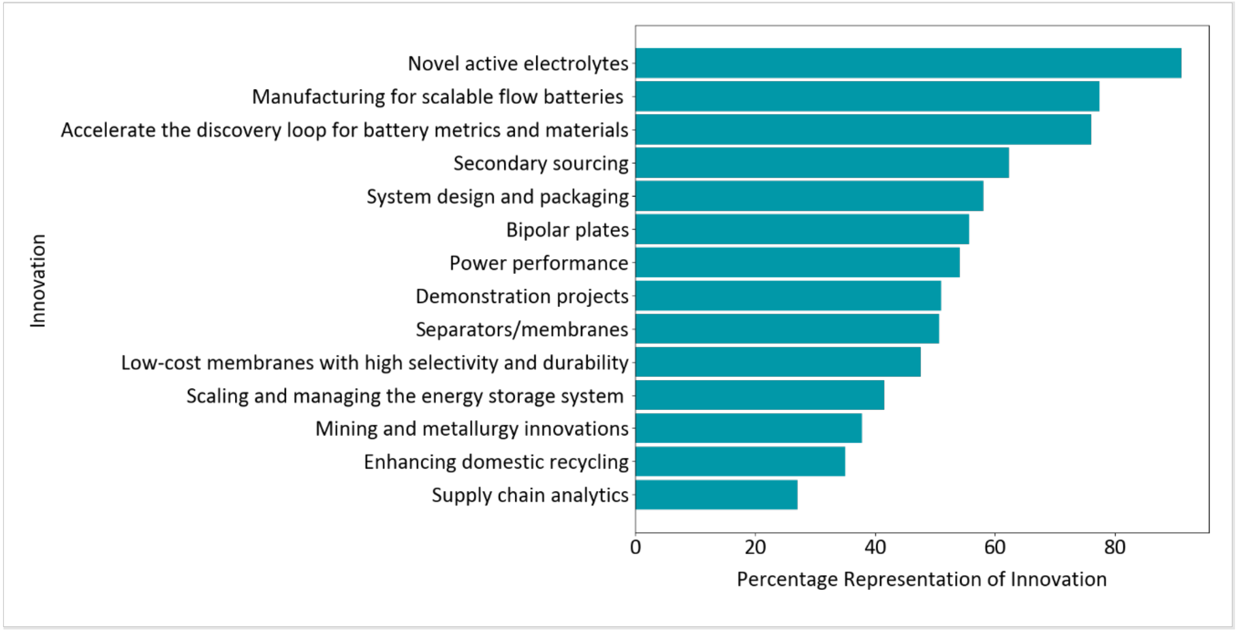

Figure 3. The share of innovations in top performing innovation portfolios for long duration flow batteries. Top performing portfolios are the top 10% of portfolios that reduce the projected 2030 levelized cost of storage.

Innovations such as novel active electrolytes and manufacturing for scalable FBs appear to have great potential to improve the cost of FB projects. Some innovations yield fairly solid impacts at relatively low investment levels, including accelerating the discovery loop for battery metrics and materials, enhancing domestic recycling, supply chain analytics, power performance, and system design and packaging. Investment in these innovations, along with those in separators/membranes, would yield meaningful reductions in LCOS at modest investment levels.

However, to achieve levels at or near the $0.05/kWh target, deep investment in advanced manufacturing for scalable FBs and novel active electrolytes that involve development and validation of advanced controls and management systems is required. See the full Technology Strategy Assessment[v] report for more detail on potential pathways to reduce the 2030 LCOS through innovation portfolios [5].

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[v] https://www.energy.gov/sites/default/files/2023-07/Technology Strategy Assessment - Flow Batteries.pdf

Electrochemical: Lead-acid Batteries (PbAs)

Potentially achieve

$0.09/kWh

LCOS

with

$180M

investments

over

7 YEARS

Values are rounded averages

Introduction

The lead-acid battery (PbA) was the first ever rechargeable battery. In the charged state, the positive electrode is lead dioxide (PbO_2) and the negative electrode is metallic lead (Pb); upon discharge in the sulfuric acid electrolyte, both electrodes convert to lead sulfate ($PbSO_4$). The storage of electricity occurs when the electrodes transition between these chemical states.

The energy density of a PbA battery is relatively low compared to LIBs [15]. However, its many advantages include excellent low temperature stability, low-cost and globally abundant raw materials, fundamental safety due to its aqueous electrolyte, and a 99% recycling rate [16]. Significant redesign may be required to meet LDES metrics including battery engineering to increase lifespan and optimize for energy instead of power.

Pathways to $0.05/kWh

The Long Duration Storage Shot Technology Strategy Assessment modeled the impact of portfolios of innovations on the projected 2030 LCOS of PbAs. Based on a 100 MW PbA system with 10 hours of storage in 2030, the projected baseline 2030 LCOS is $0.380/kWh.

Analysis findings indicate that in the top 10% of highest impact scenarios, the potential LCOS ranged from $0.075/kWh–$0.097/kWh with a mean potential portfolio cost of $176 million. This represents the potential value of the marginal investment over the currently planned levels required to achieve the corresponding LCOS improvements and approximately a 77% improvement in LCOS compared to the baseline. The timeline required to achieve these LCOS levels is estimated to be 5–9 years.

Innovations identified most frequently in the top 10% of the portfolios are presented in Figure 4. Five innovations had 50% or greater share in the top 10% of PbA portfolios with the greatest potential to reduce LCOS. These innovations hold significant promise for reducing the cost and improving the performance of PbA systems:

1. Re-design of standard current collectors
2. Advanced manufacturing of PbAs
3. Demonstration projects
4. Novel active material
5. Scaling and managing the energy storage system

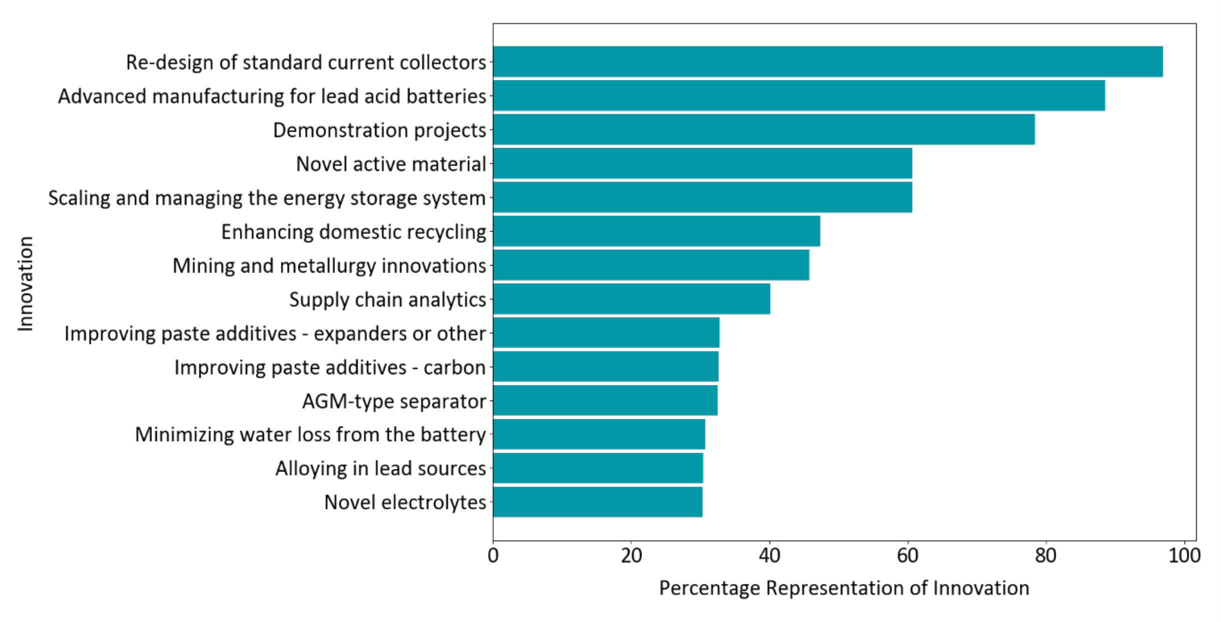

Figure 4. The share of innovations in top performing innovation portfolios for long duration lead-acid batteries. Top performing portfolios are the top 10% of portfolios that reduce the projected 2030 levelized cost of storage.

Cycling improvements are the most significant contributor to reduced LCOS of PbA batteries and several innovations demonstrate strength in this metric. While there are several basic research-focused innovations that appear to hold great promise for producing cost and performance improvements at modest investment levels (e.g., re-design of standard current collectors, novel active materials), these investments alone will not enable the deep reductions in LCOS targeted by the Long Duration Storage Shot. See the full Technology Strategy Assessment[w] report for more detail on potential pathways to reduce the 2030 LCOS through innovation portfolios [3].

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[w] https://www.energy.gov/sites/default/files/2023-07/Technology Strategy Assessment - Lead Batteries.pdf

Electrochemical: Lithium-ion Batteries (LIBs)

Potentially achieve
$0.07/kWh
LCOS
with
$1B
investments
over
11 YEARS
Values are rounded averages

Introduction
Lithium-ion batteries (LIBs) are a class of commercialized electrochemical batteries that include lithium in the active materials in the positive electrode of the battery. Common LIB varieties, also known as chemistries, include lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminum oxide (NCA), and lithium iron phosphate (LFP). As energy dense batteries, LIBs have driven much of the shift in electrification over the past two decades. Depending on how the battery system is designed, LIBs can provide energy and power for a variety of stationary storage services and small to large-scale deployments. In LIBs, power and energy are coupled, as increasing the energy capacity of a LIB system also means increasing the power capacity. Typical applications thus far can provide services for 10 hours or less. It is expected that significant growth will continue for LIB systems of up to 10 hours in the next several years, with the possibility of more than doubling the 2021 investment by the end of 2023.

As of 2022, U.S. deployments of batteries for grid-support applications totaled greater than 8.5 GW. In 2022 alone, more than 4 GW of batteries were deployed. Of battery storage technologies, LIBs represent the largest portion of new grid deployments at greater than 90% for 2020 and 2021 [17, 18].

Pathways to $0.05/kWh
The Long Duration Storage Shot Technology Strategy Assessment modeled the impact of portfolios of innovations on the projected 2030 LCOS of LIBs. Based on a 100 MW LIB system with 10 hours of storage in 2030, the projected baseline 2030 LCOS is $0.143/kWh.

The modeling analysis in the 2023 Technology Strategy Assessments found that in the top 10% of highest impact scenarios, the LCOS ranged from $0.067/kWh–$0.073/kWh with a mean portfolio cost of $1 billion. This represents the value of the marginal investment over the currently planned levels required to achieve the corresponding LCOS improvements and approximately a 51% improvement in LCOS compared to the baseline. The timeline required to achieve these LCOS levels is estimated to be 8–13 years.

Innovations identified most frequently in the top 10% of the portfolios are presented in Figure 5. Five innovations had 50% or greater share in the top 10% of LIB portfolios with the greatest potential to reduce LCOS. These innovations hold significant promise for reducing the cost and improving the performance of LIB systems:

1. Rapid battery health assessment
2. Controls to improve cycle life
3. Impurities reduction technique
4. Electrode and electrolyte innovations

5. Manufacturing process scale-up

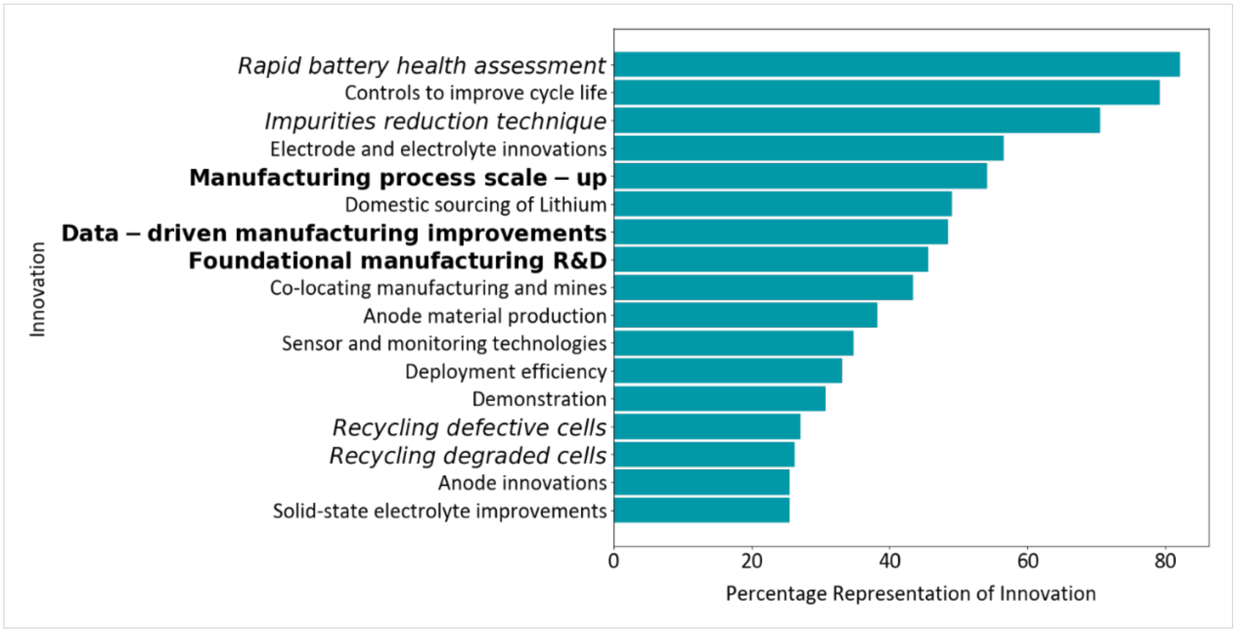

Figure 5. The share of innovations in top performing innovation portfolios for long duration lithium- ion batteries. Top performing portfolios are the top 10% of portfolios that reduce the projected 2030 levelized cost of storage. End-of-life innovations are italicized, and manufacturing innovations are bolded.

Notably, the top five include two end-of-life innovations and a manufacturing innovation. End-of-life refers to the point in time when an energy storage system reaches the end of its useful life for its original purpose. While some innovations are more impactful than others, no individual innovations dominate the LCOS impact or expenditure of the portfolio. Based on these findings, many of the opportunities for RD&D advancement suggest the ability to attain an LCOS below $0.10/kWh; however, achieving the target of $0.05/kWh appears difficult based on current analysis. Key RD&D topics can be roughly grouped into (1) activities associated with advanced controls, (2) advanced materials development and production, and (3) advanced processes for manufacturing. See the full Technology Strategy Assessment[x] report for more detail on potential pathways to reduce the 2030 LCOS through innovation portfolios [4].

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[x] https://www.energy.gov/sites/default/files/2023-07/Technology Strategy Assessment - Lithium-ion_0.pdf

Electrochemical: Sodium (Na) Batteries

Potentially achieve

$0.26/kWh

LCOS

with

$240M

investments

over

11 YEARS

Values are rounded averages

Introduction

Significant research and development of a variety of sodium (Na) batteries, which include sodium in the active materials, began more than 50 years ago [19]. As the sixth most abundant element in the Earth's crust and fourth most abundant in the ocean, Na is an inexpensive and accessible commodity. Sodium-sulfur (NaS) was the first molten NA battery and was followed by the sodium-metal halide battery (NaMH), also known as sodium-nickel chloride [20]. Though sodium-ion batteries (NaIBs) were the focus of the Framework Study, the Flight Path and Technical Assessment also discuss other varieties. NaIBs were initially developed at roughly the same time as LIBs in the 1980s; however, the limitations of charge/discharge rate, cyclability, energy density, and stable voltage profiles made them historically less competitive than their lithium-based counterparts [21].

Many NaIBs are structured and operated much like LIBs, and they are expected to adopt a significant market share by 2030 [22]. Presently, NaIBs are not commercially deployed at scale. Though Na batteries are rapidly growing technologies globally, Na battery manufacturing by U.S. companies is presently limited. No traditional transition metal oxide NaIBs are produced domestically.

Pathways to $0.05/kWh

The Long Duration Storage Shot Technology Strategy Assessment modeled the impact of portfolios of innovations on the projected 2030 LCOS of NaIBs. Based on a 100 MW NaIB system with 10 hours of storage in 2030, the projected baseline 2030 LCOS is $0.553/kWh. The research did not find industry-consistent projections of NaIB price points or performance metrics for 2030 and used projections from academic studies instead.

The modeling analysis in the 2023 Technology Strategy Assessments found that in the top 10% of highest impact scenarios, the LCOS ranged from $0.230/kWh–$0.280/kWh with a mean portfolio cost of $244 million. This represents the value of the marginal investment over the currently planned levels required to achieve the corresponding LCOS improvements and approximately a 54% improvement in LCOS compared to the baseline. The timeline required to achieve these LCOS levels is estimated to be 9–13 years.

Innovations identified most frequently in the top 10% of the portfolios are presented in Figure 6. Eight innovations had 50% or greater share in the top 10% of NaIB portfolios with the greatest potential to reduce LCOS. These innovations hold significant promise for reducing the cost and improving the performance of NaIB systems:

1. Cathode-electrolyte interface
2. In-operations materials science research
3. Electrolyte development
4. Volume/mass production for grid-scale deployment
5. Anodeless battery development

6. High-voltage cathode material development
7. Grid-scale Na-ion pilot testing
8. Controllers to improve cycle life

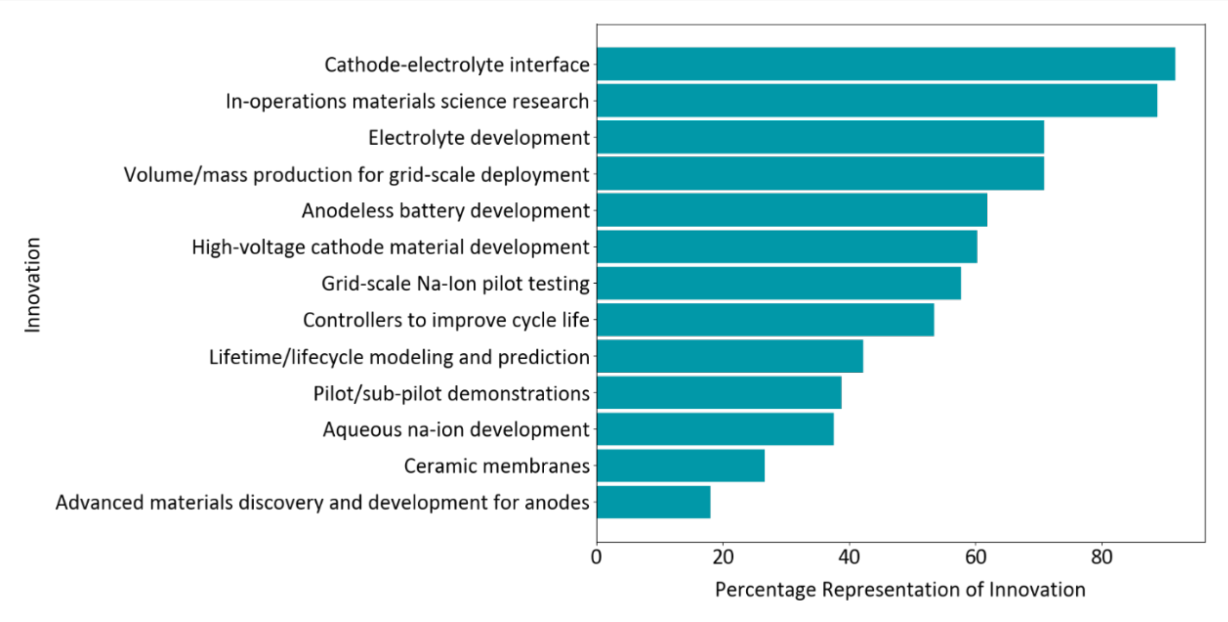

Figure 6. The share of innovations in top performing innovation portfolios for long duration sodium-ion batteries (NaIBs). Top performing portfolios are the top 10% of portfolios that reduce the projected 2030 levelized cost of storage.

The data reveal a strong emphasis on materials and chemistry research, prioritizing cathode and electrolyte research, as well as in-operations material science research. Anode development, ceramic membrane innovation, and aqueous chemistry were other, less significant materials-related innovations in this population. Ultimately, however, the more dominant emphasis on technology development over technology manufacture/deployment is consistent with the recognition that NaIBs are a relatively immature commercial technology currently. See the full Technology Strategy Assessment[y] report for more detail on potential pathways to reduce the 2030 LCOS through innovation portfolios [7].

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[y] https://www.energy.gov/sites/default/files/2023-07/Technology Strategy Assessment - Sodium Batteries.pdf

Electrochemical: Supercapacitors

Potentially achieve

$0.34/kWh

LCOS

with

$90M

investments

over

6 YEARS

Values are rounded averages

Introduction

Supercapacitors, or ultracapacitors, are electrochemical capacitors with high specific power compared with other electrochemical storage devices. Supercapacitors do not require a solid dielectric layer between the two electrodes. Instead, they store energy by accumulating electric charge on porous electrodes filled with an electrolyte solution and separated by an insulating porous membrane. Supercapacitors can be divided into three types based on the charge storing mechanism: electrochemical double-layer capacitors (EDLCs), pseudo capacitors, and hybrid electrochemical capacitors. EDLCs are the most mature 23].

Supercapacitors can be charged and discharged very quickly, offer excellent cycle life, long operational life, and operate over a broad temperature range. They are typically most attractive for shorter duration uses that require frequent small charges/discharges (e.g., ensuring power quality or providing frequency regulation).

The major drawbacks are low energy density and a high self-discharge rate. For example, a supercapacitor passively discharges from 100% to 50% in a month compared with only 5% for a LIB [24]. High capital cost and low energy density make the unit cost of energy stored ($/kWh) more expensive than alternatives technologies. Long duration energy storage traditionally favors technologies with low self-discharge that cost less per unit of energy stored.

However, supercapacitors are used in a broad range of applications, including providing electric grid services. Field demonstrations show that supercapacitors can provide black-start support to a hydropower-based distribution utility a temporary microgrid configuration [25]. They can also be deployed in combination with solar photovoltaic generation [26].

Pathways to $0.05/kWh

The Long Duration Storage Shot Technology Strategy Assessment modeled the impact of portfolios of innovations on the projected 2030 LCOS of EDLCs. Based on a 100 MW supercapacitor system with 10 hours of storage in 2030, the projected baseline 2030 LCOS is $0.443/kWh. The LCOS metric in this analysis enables comparison with other storage technologies for long duration services but does not reflect the value of grid services supercapacitors can provide.

The modeling analysis in the 2023 Technology Strategy Assessments found that in the top 10% of highest impact scenarios, the LCOS ranged from $0.330/kWh–$0.344/kWh with a mean portfolio cost of $86 million. This represents the value of the marginal investment over the currently planned levels required to achieve the corresponding LCOS improvements and approximately a 24% improvement in LCOS compared to the baseline. The timeline required to achieve these LCOS levels is estimated to be 4–7 years.

Innovations identified most frequently in the top 10% of the portfolios are presented in Figure 7. Seven innovations had 50% or greater share in the top 10% of EDLC portfolios with the greatest potential to reduce LCOS. These innovations hold significant promise for reducing the cost and improving the performance of EDLC systems:

1. Cell packaging
2. Hybrid components
3. Automated manufacturing
4. Advanced material manufacturing
5. Alternative source of activated carbon
6. Module development
7. Controlled overseas manufacturing

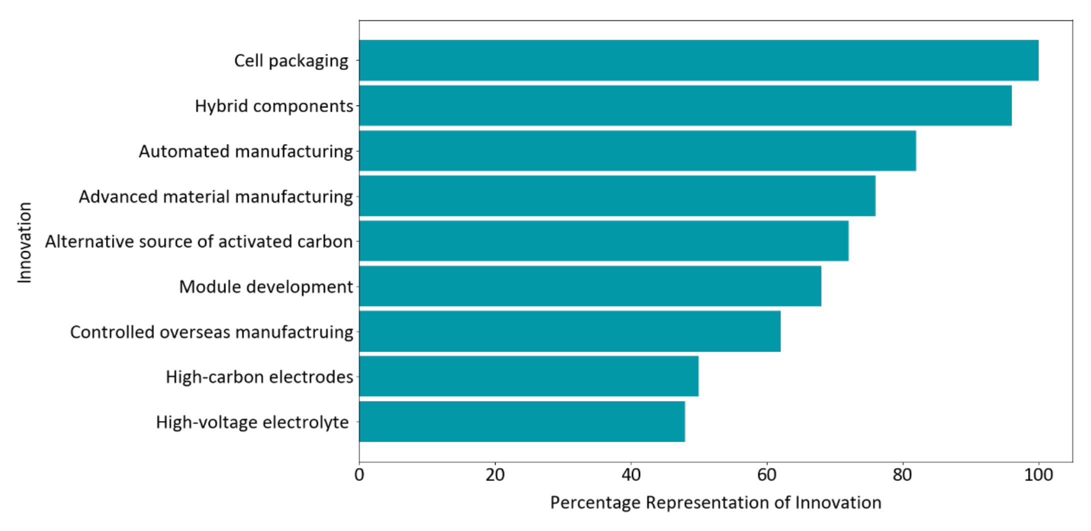

Figure 7. The share of innovations in top performing innovation portfolios for long duration electrochemical double-layer capacitors (EDLC) supercapacitors. Top performing portfolios are the top 10% of portfolios that reduce the projected 2030 levelized cost of storage.

Most innovations are refinements that produce incremental gains. The primary driver for reducing supercapacitor LCOS is the use condition in which a supercapacitor provides many charge/discharge cycles per day. The greater the number of cycles daily, the lower the theoretical LCOS could be. The analysis assumed 40 cycles per day for the EDLC system based on industry consultation, corresponding to an operational time of 30 minutes a day. Three of the top four innovations are related to manufacturing improvements, a key area to reducing LCOS. Most innovations improve the carbon material as it is the most important and expensive component. See the full Technology Strategy Assessment[z] report for more detail on potential pathways to reduce the 2030 LCOS through innovation portfolios [11].

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[z] https://www.energy.gov/sites/default/files/2023-07/Technology Strategy Assessment - Supercapacitors_0.pdf

Electrochemical: Zinc (Zn) Batteries

Potentially achieve
$0.08/kWh
LCOS
with
$160M
investments
over
6 YEARS
Values are rounded averages

Introduction

The low-cost, high-energy density, safety, and global availability of zinc (Zn) have made Zn-based batteries attractive targets for development for more than 220 years. The Zn-carbon battery, originally developed in the later 1800s, was manufactured as a popular primary battery until the 1980s [27]. Although there are several Zn-based batteries in active commercial development and in the early stages of deployment, market penetration today remains relatively immature, with significant opportunity for growth as the technical and economic landscapes for Zn-based battery storage evolve.

Emerging demonstrations and deployments of grid-scale $Zn\text{-}MnO_2$ batteries include backup power (assurance), grid stabilization, and renewable solar integration (particularly for microgrids) for both residential and commercial applications.

Pathways to $0.05/kWh

The Long Duration Storage Shot Technology Strategy Assessment modeled the impact of portfolios of innovations on the projected 2030 LCOS of Zn batteries. Based on a 100 MW Zn battery system with 10 hours of storage in 2030, the projected baseline 2030 LCOS is $0.150/kWh.

The modeling analysis in the 2023 Technology Strategy Assessments found that in the top 10% of highest impact scenarios, the LCOS ranged from $0.079/kWh–$0.085/kWh with a mean portfolio cost of $155 million. This represents the value of the marginal investment over the currently planned levels required to achieve the corresponding LCOS improvements and approximately a 45% improvement in LCOS compared to the baseline. The timeline required to achieve these LCOS levels is estimated to be 5–7 years.

Innovations identified most frequently in the top 10% of the portfolios are presented in Figure 12. Six innovations had 50% or greater share in the top 10% of Zn battery portfolios with the greatest potential to reduce LCOS. These innovations hold significant promise for reducing the cost and improving the performance of Zn battery systems:

1. Separator innovation
2. Pack/system-level design
3. Demonstration projects
4. Cathode materials optimization and new materials discovery
5. Developing a manufacturing ecosystem
6. Implementing of manufacturing best practices

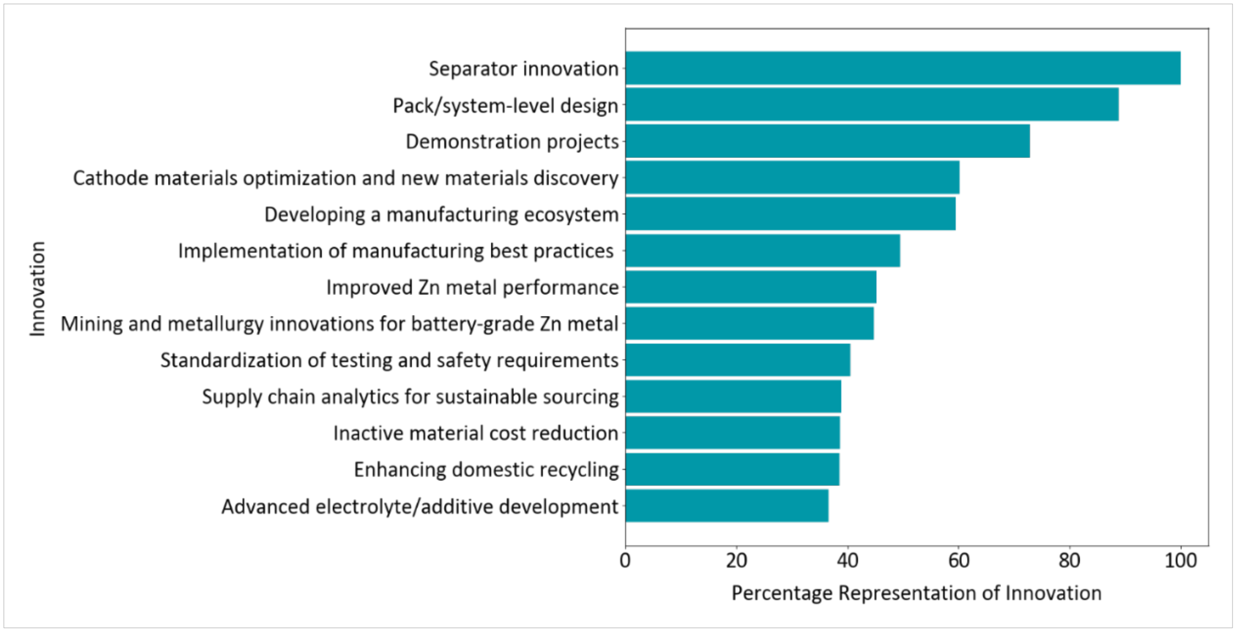

Figure 8. The share of innovations in top performing innovation portfolios for long duration zinc batteries. Top performing portfolios are the top 10% of portfolios that reduce the projected 2030 levelized cost of storage.

The outcomes broadly suggest that almost all interventions identified will result in impactful reductions to the LCOS. While there are some basic research-focused innovations that appear to hold great promise for reducing cost and improving performance at modest investment levels (e.g., cathode materials development and improved Zn metal performance), these investments alone will not reach the deep reductions in LCOS targeted by the Long Duration Storage Shot.

When discussing the "pre-competitive" innovations that could advance Zn-based batteries, a mix of both technical and non-technical opportunities were identified. The most desirable technical innovations included electrolytes, cathodes, and separators, which again correlate with the prioritized impact of the components that impact cycle life efficiency and lifetime, as mentioned above. See the full Technology Strategy Assessment[aa] report for more detail on potential pathways to reduce the 2030 LCOS through innovation portfolios [6].

[aa] https://www.energy.gov/sites/default/files/2023-07/Technology Strategy Assessment - Zinc Batteries_0.pdf

Chemical: Hydrogen Storage

ABOVE	BELOW
Potentially achieve **$0.16/kWh** LCOS with **$490M** investments over **10 YEARS**	Potentially achieve **$0.12/kWh** LCOS with **$400M** investments over **10 YEARS**

Values are rounded averages for above and below ground storage

Introduction

Hydrogen storage, also called bidirectional hydrogen storage, uses electrolysis to split water into hydrogen and oxygen with an electric current [28]. Stored hydrogen is converted back to electricity using a fuel cell or turbine.

More than 95% of hydrogen is produced for industrial processes [29]. To facilitate affordable decarbonization of industrial processes and advance the use of hydrogen to address other difficult-to- decarbonize sectors, DOE launched the Hydrogen Shot as part of the Energy Earthshots Initiative [30]. Its goal is to reduce the cost of clean hydrogen by 80% to $1/kg of clean hydrogen production within one decade. This is distinct from the Long Duration Storage Shot, which is the primary focus of this report; however, it is intrinsically linked [1].

Electrolysis technology can be classified into three main commercial electrolyzer technologies which rely on different electrolytes: liquid alkaline (LA), proton exchange membrane (PEM), and solid oxide.

LA electrolysis is the oldest, most mature, and least expensive technology, and uses a liquid potassium hydroxide solution as the electrolyte. 400 LA plants were in operation as early as 1902 [29]. Deployments of electrolyzers have accelerated in the past decade, with over 3.7 GW of PEM, alkaline, and solid oxide electrolyzer installations planned or under construction in the U.S. today [32]. PEM, or polymer electrolyte membrane, electrolysis uses an acid-impregnated polymer membrane as the electrolyte and typically offers 3-6 times more hydrogen production per unit cell area than LA electrolysis [30]. Solid oxide, or high- temperature, electrolysis utilizes a ceramic electrolyte and operates on steam rather than liquid water, enabling electrical efficiencies of more than 90%, which is up from 60% with PEM [31] [32]. Another key difference is how hydrogen is stored. Currently, the most cost-effective way to store large amounts of hydrogen gas is underground, such as in large, hollowed out salt caverns [33]. A more widely deployable option is above ground pressurized tanks, though they are about 10 times as expensive due to required materials and safety margins.

Pathways to $0.05/kWh

The Long Duration Storage Shot Technology Strategy Assessment modeled the impact of portfolios of innovations on the projected 2030 LCOS of hydrogen storage. Based on a 100 MW hydrogen system with 10 hours of storage in 2030, the projected baseline 2030 LCOS is $0.240/kWh for above ground tank storage and $0.130/kWh for below ground cavern storage [14].

Analysis findings indicate that in the top 10% of highest impact scenarios, the LCOS ranged from $0.150–$0.170/kWh with a mean portfolio cost of $491 million for above ground storage and $0.113–$0.116/kWh with a mean portfolio cost of $400 million for below ground storage.

This represents the value of the marginal investment over the currently planned levels required to achieve the corresponding LCOS improvements. The improved LCOS is approximately 33% and 12% less than the baseline for above and below ground hydrogen storage, respectively. The timeline required to achieve these LCOS levels for both varieties is estimated to be 7–12 years.

Innovations identified most frequently in the top 10% of innovation portfolios for above ground storage are presented in Figure 9. The top 20% of portfolios are shown in Figure 9 for salt cavern storage instead of the top 10% because there were fewer combinations of innovations. Nine innovations had 50% or greater share in the top 10% of hydrogen storage portfolios with the greatest potential to reduce LCOS. These innovations hold significant promise for reducing the cost and improving the performance of hydrogen systems:

1. Liquid hydrogen carriers (only above ground)
2. Hydrogen carrier advancements (only above ground)
3. Demonstration
4. Smart tanks (only above ground)
5. Recycling components
6. Hydrogen to electricity advancements
7. Deployment studies
8. Storage tank materials (only above ground)
9. Scale and automation

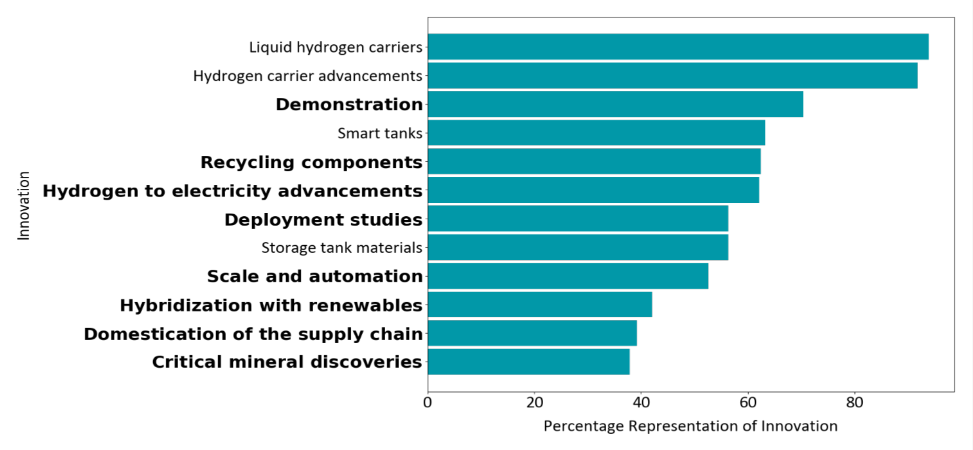

Figure 9. The share of innovations in top performing innovation portfolios for long duration hydrogen storage. Top performing portfolios are the top 20% of below ground storage and top 10% of above ground storage portfolios that reduce the projected levelized cost of storage. Bolded innovations apply to above and below ground storage; other innovations apply to only above ground storage.

See the full Technology Strategy Assessment[bb] report for more detail on potential pathways to reduce the 2030 LCOS through innovation portfolios [12].

[bb] https://www.energy.gov/sites/default/files/2023-07/Technology Strategy Assessment - Bidirectional Hydrogen Storage.pdf

Mechanical: Compressed Air Energy Storage (CAES)

Potentially achieve

$0.03/kWh

LCOS

with

$750M

investments

over

8 YEARS

Values are rounded averages

Introduction

Compressed Air Energy Storage (CAES) is one of the many energy storage options that can store electric energy in the form of potential energy (compressed air) and can be deployed near central power plants or distribution centers. In response to demand, the stored energy can be discharged by expanding the stored air with a turboexpander generator. An attractive feature of this technology is the relative simplicity of the process—a compressor is powered by available electricity to compress air (charging), which is then stored in a chamber until the energy is needed. During discharge, the compressed air is run through a turboexpander to generate electricity back to the grid.

The attributes of CAES that make it an attractive option include a wide range of energy storage capacities from a few megawatts to several gigawatts, an environmentally friendly process (especially when no fossil fuel is used for combustion), long life and durability, low self-discharge due to a loss of pressure and temperature, and the low cost of the energy stored.

Some of the challenges of this technology include high upfront capital costs, the need for heat during the expansion step, lower round-trip efficiency (RTE), siting and permitting challenges, difficulty in identifying and preparing natural caverns for storage, low depth of discharge, and longer response times. Though CAES may present opportunities for lower cost storage, it is constrained by specific geological requirements and natural features must align with existing grid infrastructure and demand. This further underscores the need to consider a wide technology portfolio to ensure viable storage options across a broad set of geological, scale, and temporal needs.

Pathways to $0.05/kWh

The Long Duration Storage Shot Technology Strategy Assessment modeled the impact of portfolios of innovations on the projected 2030 LCOS of CAES. The analysis used $0.064/kWh as the projected baseline 2030 LCOS for a 100 MW plant with 10 hours of energy storage. This estimate excludes some energy costs [9].

Analysis findings indicate that in the top 10% of highest impact scenarios, the LCOS ranged from $0.021/kWh–$0.030/kWh with a mean portfolio cost of $745 million. This represents the value of the marginal investment over the currently planned levels required to achieve the corresponding LCOS improvements and approximately an 60% improvement in LCOS compared to the baseline. The timeline required to achieve these LCOS levels is estimated to be 5–10 years.

Figure 10 below shows the percentage of top performing innovation portfolios that include specific innovations. Six innovations had 50% or greater share in the top 10% of CAES portfolios with the greatest potential to reduce LCOS. These innovations hold significant promise for reducing the cost and improving the performance of CAES systems:

1. Demonstration projects

2. System Modeling and Design/Operation Optimization
3. Mechanical Compression/Expansion
4. Advanced Manufacturing Techniques
5. Lower Temperature Turbines
6. Advanced Heat Exchanger Technologies

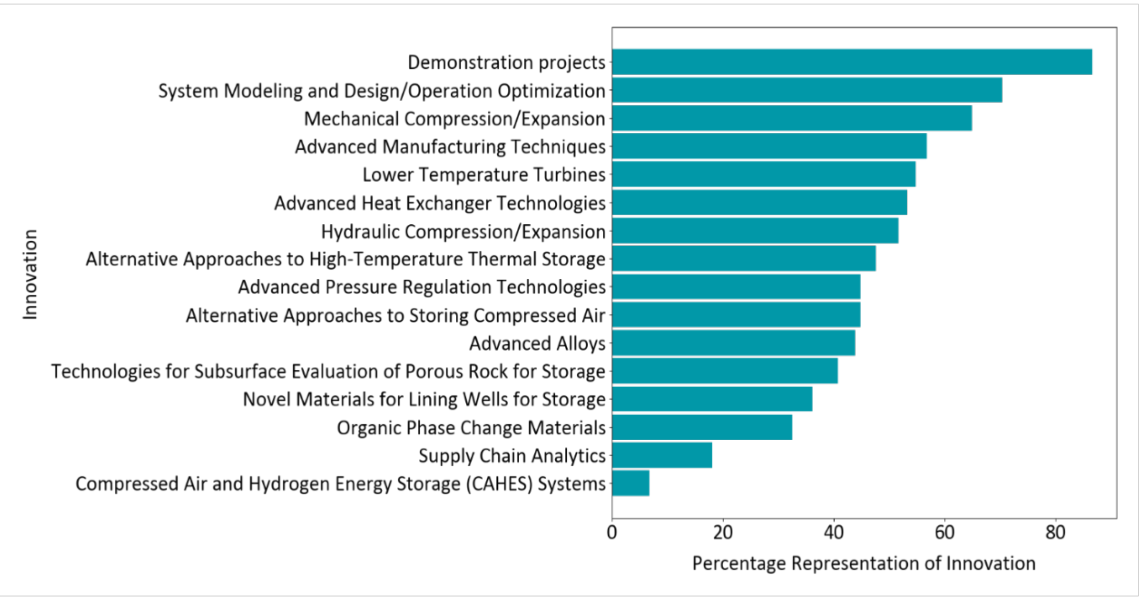

Figure 10. The share of innovations in top performing innovation portfolios for long duration compressed air energy storage. Top performing portfolios are the top 10% of portfolios that reduce the projected 2030 levelized cost of storage.

There is a small subset of portfolios that achieve deeply discounted LCOS levels without requiring investment in some of the higher cost innovations, such as demonstration projects and technologies for subsurface evaluation of porous rock for storage. The lower cost innovations have mid- to high-impact innovations with low investment requirements (e.g., system modeling and design/operation optimization, low temperature turbines). See the full Technology Strategy Assessment[cc] report for more detail on potential pathways to reduce the 2030 LCOS through innovation portfolios [9].

[cc] https://www.energy.gov/sites/default/files/2023-07/Technology_Strategy_Assessment_-_Compressed_Air_Energy_Storage_0.pdf

Mechanical: Pumped Storage Hydropower (PSH)

Potentially achieve

$0.02/kWh

LCOS

with

$570M

investments

over

8 YEARS

Values are rounded averages

Introduction

Pumped storage hydropower (PSH) is a proven energy storage technology. Its earliest U.S. operations date back to 1929. Since then, numerous projects have been developed in the United States, with a total of 43 plants and a total installed capacity of 21.9 GW currently in operation. In 2019, this capacity represented approximately 93% of U.S. utility-scale energy storage power capacity and approximately 99% of U.S. energy storage capability [34].

PSH functions as an energy storage technology through the pumping (charging) and generating (discharging) modes of operation. A PSH facility consists of an upper reservoir and a lower reservoir, which are connected by water conveyances (e.g., penstocks, tunnels). To generate electricity, water is released through the conveyances to a powerhouse in which pump-turbines, motor-generators, and control equipment are housed.

As water flows from the upper reservoir to the lower reservoir, it spins a turbine near the lower reservoir, which is connected to a generator that produces electricity. To store energy, water is pumped from the lower reservoir to the upper reservoir during low net electricity demand or when energy supply exceeds demand. Most PSH plants use reversible pumps/turbines; however, some designs use separate pumps and turbines.

PSH facilities can operate as open-loop or closed-loop systems. Open-loop systems are continuously connected to a naturally flowing body of water, whereas closed-loop systems are not. Closed-loop systems typically have fewer environmental impacts and a shorter timeline for licensing decisions. Open-loop systems are typically less expensive to implement but can face more environmental impact hurdles. Most proposed new PSH projects in the U.S. are closed-loop, typically using two manufactured reservoirs that are not connected to any natural bodies of water and are devoid of fish and other aquatic life.

Currently, 42 open-loop PSH projects and one 40 MW closed-loop PSH facility operate in the United States [35]. Applications for regulatory permits and licenses for PSH projects have increased considerably in recent years. The 2021 U.S. project development PSH pipeline included 79 closed-loop projects with a total capacity of 50.9 GW and 17 open-loop projects with a total capacity of 21.7 GW [36].

Though PSH may present opportunities for lower cost storage, it is constrained by specific geological requirements and natural features must align with existing grid infrastructure and demand. This further underscores the need to consider a wide technology portfolio to ensure viable storage options across a broad set of geological, scale, and temporal needs.

Pathways to $0.05/kWh

The Long Duration Storage Shot Technology Strategy Assessment modeled the impact of portfolios of innovations on the projected 2030 LCOS of PSH. Every PSH project is different, so capital costs are highly site-specific and depend upon many factors. This includes topology of the location, plant size and technology, and the civil works needed. The projected baseline 2030 LCOS of a 100 MW PSH plant with 10 hours of energy storage was estimated to be $0.140/kWh.

The modeling analysis in the 2023 Technology Strategy Assessments found that in the top 10% of highest impact scenarios, the LCOS ranged from $0.018/kWh–$0.025/kWh with a mean portfolio cost of $570 million. This represents the value of the marginal investment over the currently planned levels required to achieve the corresponding LCOS improvements and approximately an 85% improvement in LCOS compared to the baseline. The timeline required to achieve these LCOS levels is estimated to be 6–10 years.

The results of the analysis in Figure 11 indicate that five innovations had 50% or greater share in the top 10% of PSH portfolios with the greatest potential to reduce LCOS. These innovations hold significant promise for reducing the cost and improving the performance of PSH systems:

1. Hybrid PSH projects (deployment)
2. Testing durability of new materials and structures (advance material development)
3. 3D printing technology at large scale (manufacturing)
4. Innovations related to PSH head limits
5. Efficient underground geology characterization (technology components)

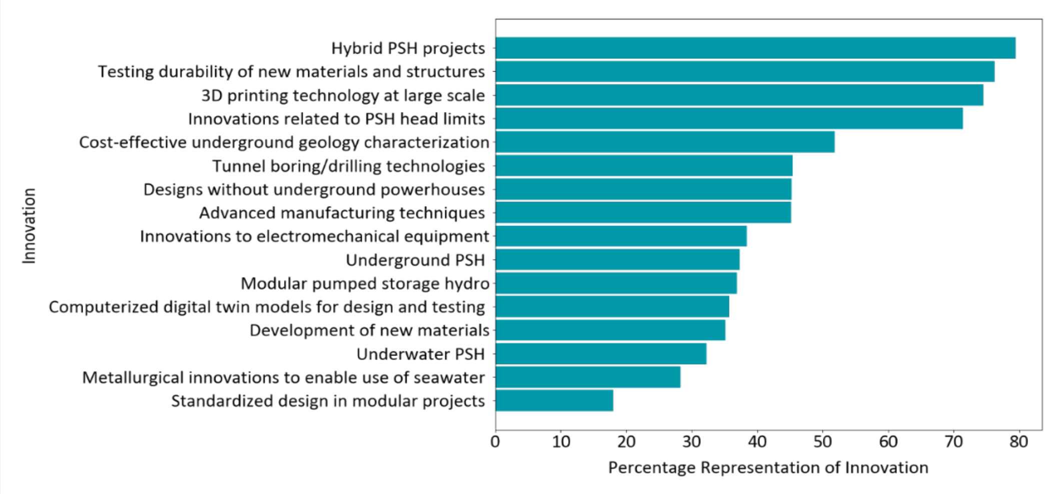

Figure 11. The share of innovations in top performing innovation portfolios for long duration pumped storage hydropower (PSH) energy storage. Top performing portfolios are the top 10% of portfolios that reduce the projected 2030 levelized cost of storage.

See the full [Technology Strategy Assessment][dd] report for more detail on potential pathways to reduce the 2030 LCOS through innovation portfolios [8].

[dd] https://www.energy.gov/sites/default/files/2023-07/Technology Strategy Assessment - Pumped Storage Hydropower_0.pdf

Thermal Energy Storage (TES)

Potentially achieve
$0.11/kWh
LCOS
with
$760M
investments
over
7 YEARS
Values are rounded averages

Introduction

Thermal energy storage (TES) systems provide many advantages for LDES uses, such as low costs, long operational lives, high energy density, synchronous power generation capability with inertia that inherently stabilizes the grid, and the ability to output both heat and electricity [37, 38, 13]. TES technologies can couple with most renewable energy systems, including wind, photovoltaic, and concentrated solar thermal energy, and can be used for heat-to-heat, heat-to-electricity, electricity-to-heat, and electricity-to-electricity (bidirectional electricity) applications [37, 39, 40].

The three types of TES that have heat as an input or output are grouped together for the purposes of this report. The Framework analysis was only applied to two-tank TES with molten salt storage media and steam turbines, though the full report discusses multiple TES varieties. Molten salt TES two-tank systems with a steam turbine were first considered for a pathway to $0.05/kWh$_\text{e}$ because of their existing use in commercial CSP and nuclear settings. Retrofitting retired thermal power plants can be a potential cost-effective option for TES with electricity output because they both use a similar thermal-to-electricity type of conversion [41]. Additionally, TES can directly serve heat demand for buildings and industrial processes, displacing fossil fuels to achieve broad decarbonization.

Pathways to $0.05/kWh

The Long Duration Storage Shot Technology Strategy Assessment modeled the impact of portfolios of innovations on the projected 2030 LCOS of TES. Based on a 100 MW two-tank molten salt TES system using a steam turbine system with 10 hours of storage in 2030, the projected baseline 2030 LCOS is $0.134/kWh.

The modeling analysis in the 2023 Technology Strategy Assessments found that in the top 10% of highest impact scenarios, the LCOS ranged from $0.107/kWh–$0.116/kWh with a mean portfolio cost of $759 million. This represents the value of the marginal investment over the currently planned levels required to achieve the corresponding LCOS improvements and approximately a 17% improvement in LCOS compared to the baseline. The timeline required to achieve these LCOS levels is estimated to be 6–8 years. Though this analysis targets a single variety of TES, there are many emerging TES technologies and innovations that may potentially achieve a low LCOS.

Innovations identified most frequently in the top 10% of the portfolios are presented in Figure 12. Six innovations had 50% or greater share in the top 10% of TES portfolios with the greatest potential to reduce LCOS.

These innovations hold significant promise for reducing the cost and improving the performance of TES systems:

1. Single-tank storage
2. Heat-to-electricity conversion improvements
3. Large-scale demonstrations
4. Mass production and automation
5. Component standardization
6. Small-scale demonstrations

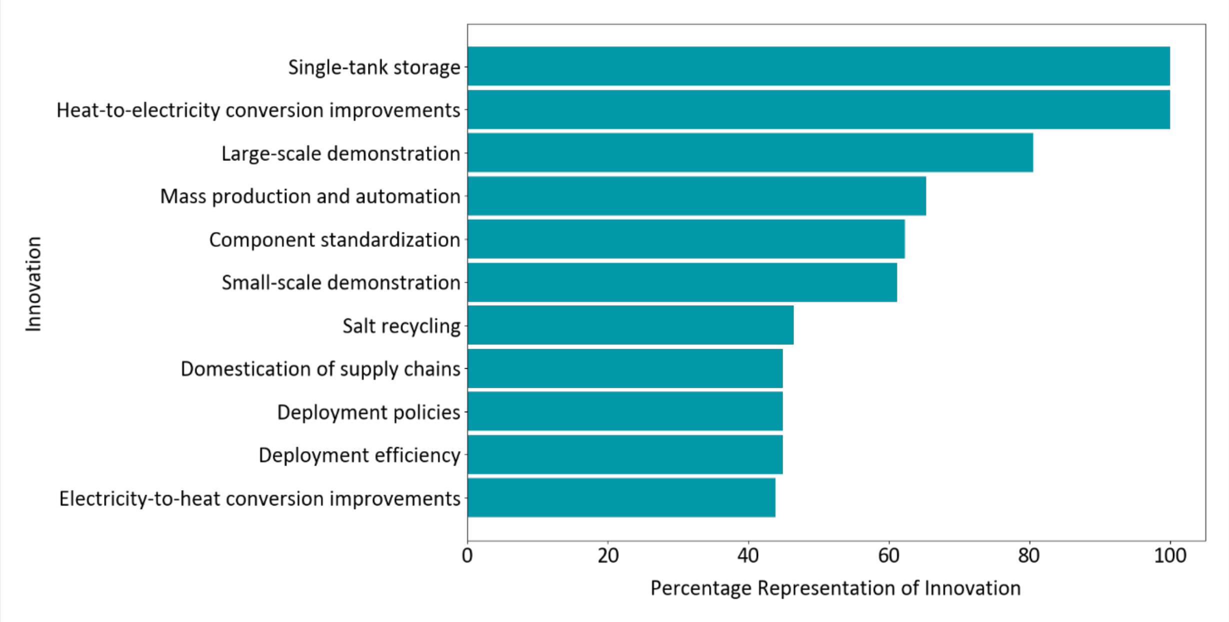

Figure 12. The share of innovations in top performing innovation portfolios for long duration molten salt thermal energy storage (TES). Top performing portfolios are the top 10% of portfolios that reduce the projected 2030 levelized cost of storage.

Round-trip efficiency and storage block cost improvements have the greatest impact on LCOS of molten salt TES; however, few innovations improve round-trip efficiency. See the full Technology Strategy Assessment[ee] report for more detail on potential pathways to reduce the 2030 LCOS through innovation portfolios [10].

[ee] https://www.energy.gov/sites/default/files/2023-07/Technology Strategy Assessment - Thermal Energy Storage_0.pdf

Cross-Cutting R&D Opportunities & Challenges

As applied to long duration energy storage (LDES), cross-cutting represents the R&D concepts that are present across multiple technologies (as well as the challenges and gaps associated with the different LDES technologies). The approach for establishing cross-cutting R&D opportunities for LDES was driven by a comparative analysis on findings on innovation impacts across all technologies and data collection efforts associated with the Storage Innovations 2030 Listening Sessions.

Comparative Analysis of Innovation Impacts

Innovation can Significantly Drive Down the LCOS

Figure 13 shows the range of projected change in LCOS after implementing the top 10% of LCOS-reducing innovation portfolios for each LDES technology relative to DOE's Long Duration Energy Storage Shot target ($0.05/kWh LCOS or less).

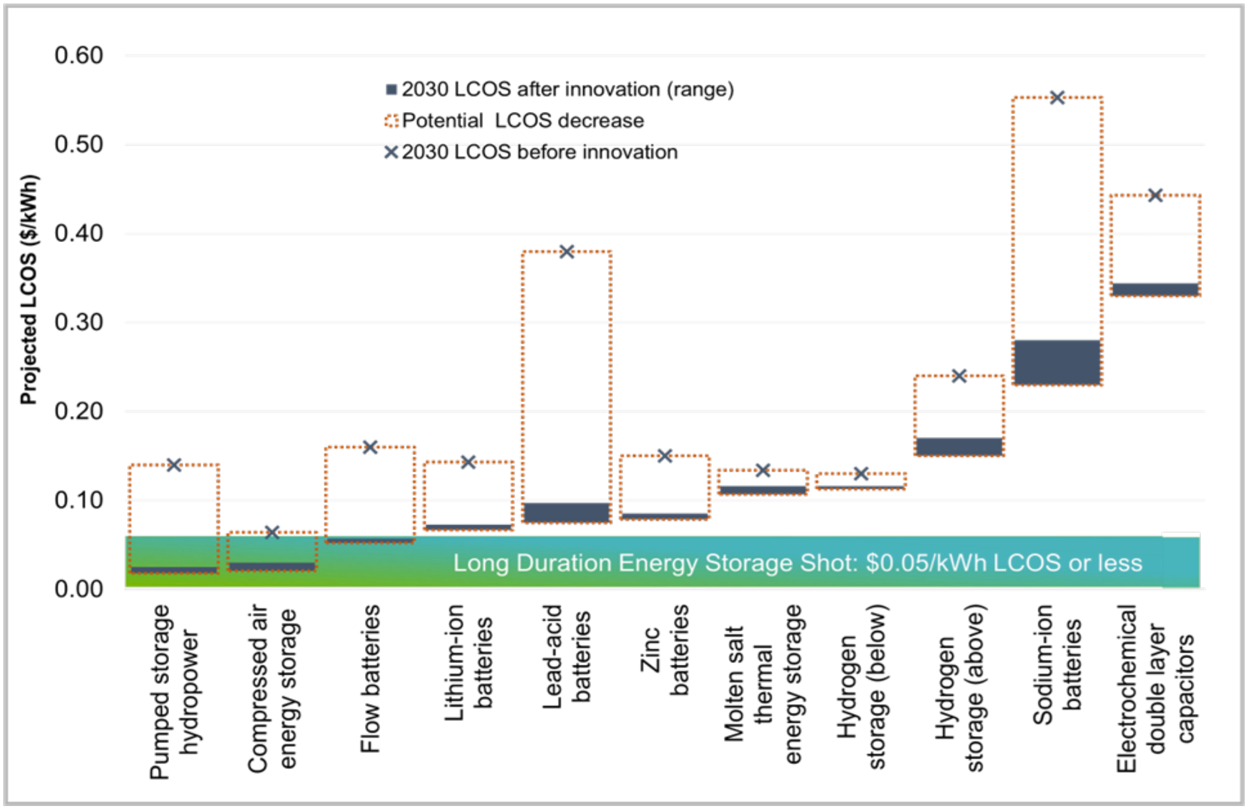

Figure 13. For long duration energy storage, the range of impact on the 2030 LCOS after implementing the top 10% of LCOS-reducing innovations. LCOS: levelized cost of storage.

The projected baseline 2030 LCOS of all technologies, apart from CAES, is approximately \$0.08–\$0.50/kWh greater than the Storage Shot target. The analysis's findings indicate that innovations may benefit PSH, CAES, and FBs in meeting the Storage Shot, while also driving the LCOS of LIBs, PbAs, and Zn batteries to less than \$0.10/kWh. Na batteries and PbAs broadly hold the greatest potential for LCOS reductions (roughly -\$0.31/kWh LCOS), followed by PSH, supercapacitors, and FBs (roughly -\$0.11/kWh LCOS). However, Na batteries drop from having the highest baseline 2030 LCOS before innovations to the second highest LCOS after innovations. The need for additional research in Na batteries is emphasized by the absence of widely available industry-consistent projections of the type of chemistry, price points, or performance metrics for 2030.

Innovation Cost and Duration Present Tradeoffs

The estimated cost and duration of implementing innovations varies across energy storage technology and presents tradeoffs for lowering the projected LCOS. Figure 14 compares findings on the average duration and average cost of implementing the top 10% of innovation portfolios for each storage technology. The circle area and color reflect the average projected LCOS that may be achieved after innovations.

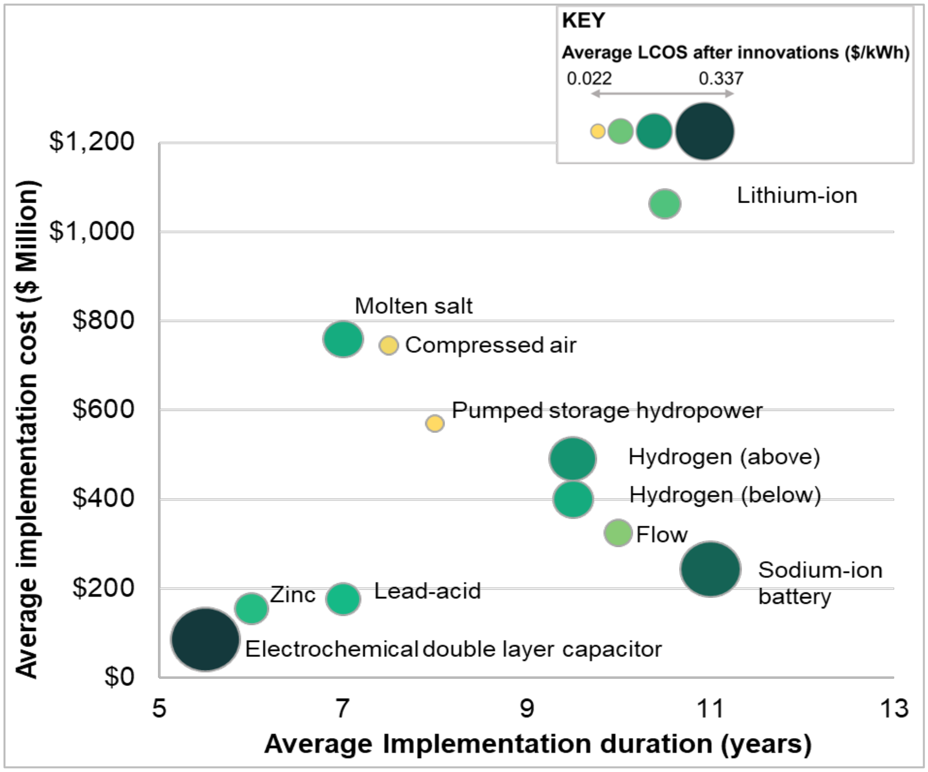

Figure 14. The average duration and cost of implementing the top 10% of innovation portfolios that drive down the LCOS of long duration energy storage. The circle area and color correspond to the average projected LCOS after implementing the top 10% innovation portfolios for each technology. LCOS: levelized cost of storage.

Relative to other technologies in the analysis, supercapacitors, Zn batteries, and PbA batteries have low innovation implementation durations (less than 7 years) and costs (less than \$200 million). However, the average theoretically achievable LCOS of Zn batteries and PbAs is considerably lower than it is for supercapacitors, which have the highest average LCOS for 10-

hour applications after innovations. Similarly, though the innovation cost for Na batteries is comparably low, the innovation implementation period is long and the projected average LCOS is the second highest across technologies. Conversely, the average innovation cost and duration are high for LIBs, but the average LCOS range after innovation is low and close to the Storage Shot target.

Figure 15 plots the time duration for implementing the top 10% innovation portfolios by the projected LCOS range, showing the LCOS opportunity space while accounting for uncertainty and average innovation implementation cost.

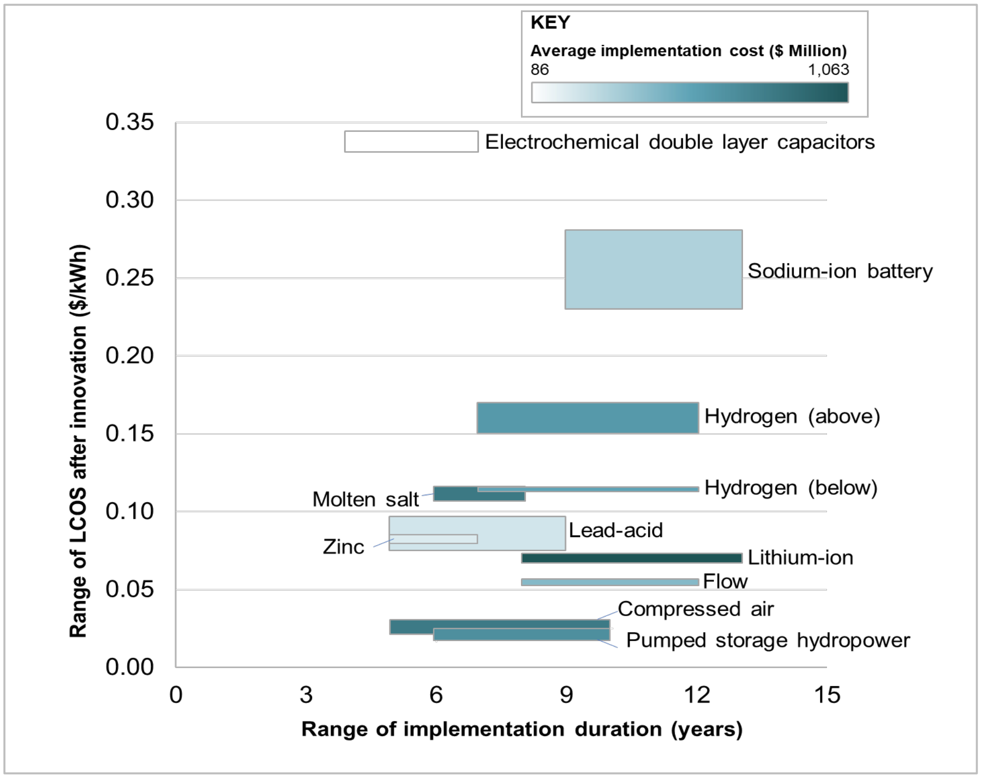

Figure 15. For long duration energy storage, the range of time needed to implement the top 10% of LCOS- reducing innovations (years) compared to the range of projected LCOS after innovations ($/kWh). The block colors represent the average cost of implementing innovations ($ Million). LCOS: levelized cost of storage.

Implementation durations vary across all technologies, with possible durations of 10 or more years for many technologies. Of the technologies with maximum durations of less than 10 years (supercapacitors, Zn batteries, PbAs, and TES), all but TES require comparably low implementation costs.

Shared R&D Challenges Identified in Listening Sessions

Commonly identified challenges across the technology listening sessions were documented and are summarized below. Information was also collected from a separate Storage Innovations 2030 Listening Session focused on cross-cutting topics.

Energy Storage Project Bankability

LDES projects require significant capital, as developing LDES involves constructing prototypes of varying scales while also proving manufacturing. Project bankability was discussed in the LIB, PbA, FB, Zn battery, NA battery, PSH, and CAES listening sessions. Traditionally, capital raised from investors and bank loans is used to finance energy storage RD&D projects. According to feedback from the SI 2030 Flight Path listening sessions, tax benefits can help but also come with challenges. These include that tax credits can (1) be difficult to assess; (2) change year to year, thereby creating uncertainty; (3) have complicated domestic content requirements; and (4) be insufficient in amount.

Confidence in LDES technologies and projects can be difficult without assurance over technology performance. Feedback suggested monetary assurance in the form of insurance could better stabilize the new technology and deployments. Yet, without a track record of a technology (e.g., 10–20 years of data and demonstration), technology risk may not be quantifiable or considered too high.

While tools for financial estimations of costs exist today, they may not be enough to support niche entries from new technologies. Analytical approaches or metrics associated with LCOS can be inconsistent, resulting in potentially challenging analysis for stakeholders. Feedback during the listening sessions suggested that new, consistent tools and methods are needed to support both project costs analysis and early risk assessment. Tools that leverage the latest LCOS approaches, consider regulatory processes risks, and examine technologies from a bottom-up approach could potentially encourage confidence. Predictive end-of-life and preventative maintenance systems are needed to provide assurance and guarantee the system is operational for the period of performance. Long duration systems are anticipated to require additional maintenance due to the length of operational run time.

Technology Validation for Industry Acceptance

The electric grid industry or electric utilities have a core mission of providing customers access to continuous and reliable electrical power at the lowest cost. Hence, by nature, the industry is extremely conservative in technology selection and deployment. Proof of principle demonstrations are a critical means for vetting any planned integration technologies. This is true for the different prototyping stages and for the various commercial and industrial and utility-owned projects. For demonstrations to be of value, the technology must be functional and operated in multiple use cases. This may require the adoption of new control modes, communication protocols, and integration strategies.

Technology validation for industry acceptance was discussed in the FB, Zn battery, CAES, and TES listening sessions. While demonstration projects can be deployed directly into field locations, stakeholder feedback suggests that representing all available use cases for a technology at a single site is unlikely. This creates the need for either multiple site demonstration projects and/or the utilization of flexible testbeds for use case evaluations. These test-beds should run near real-life use case examples and be open to third party independent organizations. Only in this way, can the necessary, robust proof-of-principles use cases and demonstrations provide value. Testing also should consider methods establishing longer-life through accelerated aging techniques. Furthermore, demonstration data on the proof of principles and technology should be available and widely shared with stakeholders.

Utility Interconnection Queue and Permitting

The interconnection of new generation assets, loads, or storage within the electric grid must first be evaluated by planning engineers. Developers looking to deploy must hire or utilize consultants at their own risk to perform initial screening studies to find reasonable sites for the energy storage technology. System impact studies are performed to establish electrical interconnection effects of a deployment, including understanding the potential limits associated with heavily saturated utilization corridors and capacity expansion. For managing the requests for these studies, a queue system typically employs a 'first-come, first-served' basis.

The volume of interested developer projects injected into the queue are expected to create continuing backlogs of several years.

Utility interconnection queue and permitting was discussed in the LIB, PbA, FB, PSH, and CAES listening sessions. Participants suggested that queue backlogs create uncertainty in deployment deadlines, require significant investment to support the analysis, and lead to project delays that consume valuable company resources. Systematic transparent approaches are needed to reduce this uncertainty.

Though technical resources to support utility interconnection projects and speed up the system impact studies could beneficial, multiple ownership models offer further complications.

Traditionally, the generation mix producing electricity delivered to customers has been utility owned. As new business models have evolved, ownership and control paradigms have shifted to creating a new flux of deployed products. While providing new opportunities for potential cost savings, many utilities may also observe these installations as new challenges for integration. New cooperative agreement between stakeholders may be required before completing an interconnection agreement. This can further delay projects and commissioning of systems. Use case evaluations of ownership models need to be established and standardized to guide future collaborations.

Energy Storage Integration Technologies

For energy storage technologies to be connected to the electric grid, integration technologies are often required. These integration technologies may include power electronic systems, conversion, electric motors, and protection and isolation systems. Due to varying sizes and functionality requirements of the different storage technologies, integration systems must be uniquely designed to fit that purpose. As a result, new storage technologies often face an additional hurdle of establishing partnerships or in-house development approaches for these integration technologies. Integrating technologies was discussed in the FB, Zn battery, Na battery, and PSH listening sessions.

Integration systems must also support the necessary control and communication functions to provide the intended use case functionality. This systems developments exercise can take years of integration beyond the base energy storage technology. Integration systems typically are not developed in the U.S. and can also add significant costs to the overall storage system. Continued R&D is necessary to establish more broadly applicable solutions.

Manufacturing Supply Chain

Supply chain challenges are a significant hurdle to energy storage technology manufacturing. Volume and durability are key issues and variations in battery cells and/or other components can lead to early failures and system wide challenges. The lack of openness in the supply chain industry has significant impact on quality and cost of the product.

Manufacturing supply chain opportunities were discussed in the PbA, FB, Na batteries, and supercapacitor listening sessions. New energy storage technologies customarily face difficulties in gaining traction with the manufacturing industry. New materials, electrolytes, membranes, and other components must be ramped quickly to production to achieve critical mass and to reduce overall system costs targets. This must also occur at the various stages of prototyping from small, medium, and large systems. In many cases, the volume of small prototypes is not sufficient to warrant interest from the suppliers. Furthermore, modifying existing manufacturing automation requires a large volume purchase, particularly within the U.S. Evaluation and analysis of storage supply chains could support suppliers with clear pathways for large volume production.

Stakeholder Education, Collaborative Initiatives, and Workforce

Today, expertise in energy storage technology areas can be difficult to find, in both collaborative agreements between companies and in direct hires. Stakeholder education, collaborative initiatives, and workforce topics were discussed in the PbA, Zn battery, Na battery, CAES, and supercapacitor listening sessions. Hiring pools may seek international talent if the U.S. does not have core curriculum that supports the necessary skills need by industry.

According to listening session participants, education systems do not provide the full spectrum of information needed. Community colleges do not have the necessary curriculum and cannot create the appropriate courses until enough enrollment is existent. In many cases, education in the core technology development is left to the hiring company, expending valuable resources.

While finding talent is not yet a critical barrier, moving the industry forward will require new means to identify and grow talent. National capability repositories for energy storage could provide a means to interconnect resources and expertise. Universities, community colleges, and trade associations could collaborate with DOE and industry through public-private partnerships to design core curriculum, foster education programs, and promote workforce development.[ff] Public-private working groups could be established to share ideas and establish the necessary taxonomy for the industry.

Standards

Standardization is a key element to reducing development and deployment costs and was discussed in the PbA, FB, and Zn battery listening sessions. Nascent storage technologies may lack standard interfaces. Since integration of many different communication and grid interfacing technologies is often custom and requires significant interactions between many component manufacturers, this can add years to the development stage.

Standardization considering modular energy storage technologies, as has been applied in Europe, could create an ecosystem of services and competition among service providers. In this way, these modular energy storage systems can be shared between manufacturer to meet long duration project needs.

[ff] An example of in the electric vehicle industry is the partnership between the University of Alabama and Mercedes Benz International. See [Mercedes Benz International – Alabama Transportation Institute (ua.edu) (https://ati.ua.edu/tag/mercedes-benz-international/).](https://ati.ua.edu/tag/mercedes-benz-international/)

Storage Innovations Champions

Cryostone

HOUSTON, TX — Cryostone's first-of-its-kind adiabatic cryogenic energy storage improves upon current air-based energy storage technologies with a significantly lower system footprint and higher round-trip efficiency (RTE). This technology enables fast charging and slow discharging for diurnal storage applications with a low-cost, mineral-independent, and durable system. The novel design uses conventional compression and expansion alongside a proprietary direct-contact TES system to double the efficiency of today's CAES (1,000 MWh at 30% RTE) at a fraction of the size (1 MWh at >60% RTE). In addition, this design enables fast charging and slow discharging for diurnal storage applications.

Electrified Thermal Solutions

MEDFORD, MA — Electrified Thermal Solutions created the Joule Hive™ thermal battery that uses novel electrically conductive firebricks to store renewable electricity as zero-carbon heat. The stacked-brick storage system is an all-in-one electric heater, thermal store and heat exchanger that can supply hot gas (such as air) to any industrial processes including boilers, furnaces, and turbines. When delivering heat to a turbine, the Joule Hive™ can reproduce electricity at 1 MW–200 MW at a fraction of the cost of LIBs and extend the duration of energy storage as needed. Additionally, the versatile design can plug into existing processes to fully decarbonize hard-to-abate industrial sectors including cement, steel, and chemicals production.

Gravity Power LLC

SANTA BARBARA, CA — The Gravity Power Plant developed by Gravity Power LLC builds on the success of PSH to create an improved system with a reduced footprint and increased round-trip efficiency. The Gravity Power Plant replaces hydropower water reservoirs with a deep vertical shaft excavated with conventional equipment. Using a standard hydropower turbine, the system pumps water down a penstock and into the storage shaft to lift a large steel-walled piston. As needed, this piston forces water back through the turbine to generate power. Although system performance will depend on the plant size, Gravity Power estimates that this design can store 200 MWh–6,400 MWh and output 50 MW–1,600 MW of power, supplying a pathway to grid decarbonization. Gravity Power delivers all the advantages of PSH (low levelized cost, high round trip efficiency, and grid stability) plus a tiny footprint, minimal environmental impact, and ease of siting.

KineticCore Solutions

LOVELAND, CO — KineticCore Solutions has developed a patented all-composite flywheel design that supports long-duration energy storage as a cost-effective alternative to LIBs. This chemical-free Kinetic Battery system boasts a 25+ year operational life and unlimited daily charges with a lightweight and small, modular footprint that enables easy deployment and flexible scale-up. KineticCore's evolutionary jump in flywheel structural design introduces an ellipsoid, 3D curved composite structure allowing 240% higher speeds with 10x lower mass than traditional cylindrical flywheel systems manufactured with the same materials. This results in flywheel storage with improved efficiencies and significantly decreased system costs. Additionally, the KineticCore carbon flywheel design poses no fire or explosive dangers compared to its chemical battery counterparts and is fully recyclable to support decarbonization across the system lifecycle.

RCAM Technologies

LOS ANGELES, CA — RCAM Technologies' marine-pumped hydroelectric (MPH) energy storage is a disruptive long-duration technology that integrates with offshore renewable energy plan to supply more reliable power for coastal communities. This design uses the same proven operating principle as conventional pumped hydro, using a hydroelectric turbine to channel seawater in and out of concrete spheres on the sea floor to charge, store, and discharge energy. RCAM has reduced manufacturing costs for these low-cost, corrosion-resistant spheres with automated 3D concrete printing. The energy storage capacity of an MPH system averages around 20 MWh depending on the location, size, and pump-turbine unit, but can be interconnected as a modular pod to extend the storage capacity.

Storage Innovations Finalists

Cache Energy

CHAMPAIGN, IL — Cache Energy has invented a novel solid material fuel that can provide thermochemical energy storage based on the reversible chemical reactions of calcium oxide and hydroxide. This non-toxic, non-explosive material can be safely stored and transported at room temperature to meet energy needs nationwide just like coal but in a cleaner fashion. The Cache Energy system can store these solid fuel pellets without special containment, moving the material back and forth through a reactor. Using existing infrastructure of fossil fuel plants and domestically abundant material, Cache Energy can provide a low-cost and scalable energy solution that can be scaled to provide hundreds of hours of energy storage and supply.

NerG

KNOXVILLE, TN — NerG Solutions builds on the success of the team's prior work with the Oak Ridge National Laboratory Ground-Level Integrated Diverse Energy Storage (GLIDES) pumped- storage hydropower system. The proposed technology aims to leverage the energy density of chemical reactions within pumped-storage hydropower. The result is a closed-loop, hybrid electro-mechanic-chemical storage system that stores energy in the chemical bonds of metal hydride materials and releases the energy in the form of a hydraulic water head captured by hydraulic turbomachinery. This innovative system boasts an energy density of 20 kWh/m3 (~20x higher than GLIDES) and could potentially costs less than $20/kWh. Using abandoned materials, NerG designed a system with no expected environmental, supply chain, or recycling concerns.

Rondo Energy

ALAMEDA, CA — The Rondo Heat Battery charges with intermittent wind and solar electricity to deliver high-temperature, continuous heat, steam, or electric power to industrial facilities at over 98% total efficiency. The battery design uses electric heating elements to convert electricity to thermal radiation, warming blast furnace bricks at temperatures up to 1,500°C. These conventional materials have been used for years and, as part of Rondo Energy's novel system, enable an efficient, low-cost, and proven energy storage system. The automated, patented controls within the Rondo Heat Battery control airflow to ensure that heat is delivered at exactly the desired temperature as air or steam to supply reliable, zero-emission energy for industrial processes. Industrial emissions today constitute over 25% of the country's carbon emissions. Rondo Heat Batteries can reduce industrial emissions by 80%+. A single Rondo Heat Battery eliminates ~45,000 tons/year of CO2—the equivalent to the CO2 savings of 8,500+ electric vehicles.

THEMES

HOUSTON, TX — Thermal Mechanical Energy Storage (THEMES) LLC repurposes idle gas wells for thermal and mechanical energy storage systems, initially innovating on traditional CAES methods. Our unique technique eliminates the need for natural gas on the surface, providing a carbon free CAES system, while utilizing the saline aquifer zone via idle wells for storage. This not only manages the surplus of idle wells near underserved communities, but also significantly reduces CAES storage costs. THEMES aims to promptly establish 6 GWh (100+MW, 12 hours) of power generation nationwide by 2030 by leveraging Oil & Gas offtake customers. Post scale-up and optimization, THEMES projects storage costs could be as low as $1/kWh at 100 MW scale and result in an LCOS of $0.05/kWh by 2030.

Thermal Battery Corporation

CAMBRIDGE, MA — Thermal Battery Corporation combines three key technological breakthroughs in a novel design for a long-duration-capable TES system. This design starts by taking electricity from any source and converting it to high-temperature heat, where it is stored at 2,000°C in inexpensive graphite blocks. When energy is needed, this heat is transferred by mechanically pumping liquid tin through carbon pipes to a power block. Here, high-efficiency thermophotovoltaic cells convert light emitted from the white-hot infrastructure back to electricity. Thermal Battery Corporation has eliminated material interactions that typically cause corrosion by using carbon components throughout the system. The resulting thermal battery system offers a low-cost energy storage solution (less than $20/kWh LCOS) and 50% round-trip efficiency.

Storage Innovations 2030 Technology Liftoff: Funding Opportunity Announcement

On July 25, 2023, DOE’s Office of Electricity launched the $15 million Storage Innovations 2030: Technology Liftoff (SI Liftoff) funding opportunity announcement (FOA)[gg] to enable long duration energy storage technologies through durable research partnerships [44]. SI Liftoff aims to leverage the Flight Paths listening sessions and analytical Framework results, both described in the 2023 Long Duration Storage Shot Technology Strategy Assessments[hh] released on July 19, 2023, to accelerate partnerships and enable pre-competitive R&D projects that have the potential to benefit entire technology industries.

This FOA enables collaborative partnerships of two or more entities with a focus on one or several energy storage technologies. The selected technology or technologies must have a pathway to cost-effective, grid-scale, LDES. Each partnership is led by a central organization or a single member who will act as the primary recipient, and at least one other participating entity who will receive funds by applying with the primary recipient as a project partner (more than two entities is encouraged).

The partnership developed in response to this announcement are collaborating with two primary objectives: partnership development and pre-competitive R&D.

[gg] https://netl.doe.gov/grid-resilience/FOA3020

[hh] https://www.energy.gov/oe/storage-innovations-2030

Entities organize by coordinating with each other, engaging in meetings and discussions, and setting up durable channels of communication to effectively collaborate through this award period and afterwards. Entities are encouraged to think creatively to develop lasting partnerships. Such activities should propel an entire technology industry forward, and the outputs of this work should provide value to all participating members of the partnership.

Conclusions

Grid-scale energy storage is a critical element driving and supporting the electric system evolution. LDES technologies will enable a variety of clean energy and resilience applications. DOE formed SI 2030 to enable the most promising technologies to meet future targets. The strategy developed as part of SI 2030 is described in a report series called the Long Duration Storage Shot Technology Strategy Assessments. The reports analyze the potential of long duration capable energy storage technologies to achieve future goals and benefit from widespread deployment on the Nation's electricity grid. They establish a systematic approach to engage with experts while quantifying the impact of innovation and will be updated biannually.

DOE engaged with the energy storage community through targeted listening sessions during the Storage Innovations Flight Paths[ii] in July 2023. The sessions discussed a range of energy storage technologies and identified pre-competitive RD&D innovation pathways to achieve DOE's Long Duration Storage Shot target—reduce the LCOS to \$0.05/kWh by 2030 for technologies that can provide 10+ hours of storage.

The Long Duration Storage Shot Technology Strategy Assessments published in 2023 also includes results from the Storage Innovations Framework[jj], which evaluated 10 LDES technologies using stakeholder engagement and modeling to determine the impact of innovation on the LCOS relative to a 2030 projected baseline. The analysis simulated portfolios of innovations for individual LDES, employing an uncertainty analysis on the dollar value of innovations, the degree of interaction between implemented innovations, and time duration required for implementation. The research team identified innovations, their cost benefits, and other simulation inputs from SMEs, published literature, white papers, and grey literature. The results of this analysis showcase the most impactful combinations of innovations that drive down the LCOS of 10 LDES technology areas spanning four energy storage families: FBs, LIBs, PbAs, hydrogen storage, NaIBs, EDLCs, Zn batteries, PSH, CAES, and molten salt TES.

The analysis found that innovations can significantly drive down the LCOS and that many LDES technologies have the potential to achieve or approach DOE's Long Duration Storage Shot target. On average, the top 10% of innovation portfolios can reduce LCOS by 12%–85% to \$0.03/kWh–\$0.26/kWh across LDES technologies. The average cost of implementing innovations ranges roughly from \$100 million–\$1 billion and would take 6–11 years. To jump start industry progress on these pathways, DOE launched the \$15 million Storage Innovations 2030: Technology Liftoff (SI Liftoff) funding opportunity announcement (FOA) in July 2023[kk]. For the full suite of innovations and full reports on the results for each LDES technology area, see the Technology Strategy Assessments[ll].

[ii] https://www.energy.gov/oe/storage-innovations-2030-stakeholder-engagement-process

[jj] https://www.energy.gov/oe/storage-innovations-2030-stakeholder-engagement-process

[kk] https://netl.doe.gov/grid-resilience/FOA3020

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