



LDES NATIONAL CONSORTIUM

LDES Consortium Landscape Assessment

The National Consortium for the
Advancement of Long Duration Energy
Storage (LDES) Technologies

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and Energy Innovation

Office of Clean Energy Demonstrations



U.S. DEPARTMENT
of **ENERGY** | Office of Technology
Commercialization

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A. EXECUTIVE SUMMARY

This report reflects perspectives gathered through the work of the National Consortium for the Advancement of LDES Technologies (“the Consortium”) during the time period of January 2024 through September 2026. The Consortium operated as a Department of Energy (DOE)-funded, national laboratory facilitated, and industry-driven initiative. The primary purpose of the Consortium was to create a centralized forum enabling stakeholders across the LDES ecosystem in the U.S. to convene and identify barriers; determine potential synergies; and collaboratively develop and implement strategies necessary to achieve LDES technology commercialization within the next decade.

LDES technologies—defined by the DOE as energy storage systems capable of delivering electricity for 10 or more hours in duration—includes a wide scope of diverse technology families such as electrochemical, mechanical, thermal, and chemical energy storage. The Consortium followed an “all-inclusive” approach toward LDES, meaning that any technology that either currently or potentially had the capability to deliver 10 hours+ of duration was considered within scope of the initiative.

Many challenges facing LDES technologies were identified and vetted by the Consortium, and this report summarizes this analysis along with discussions of remedial approaches toward addressing identified challenges. The report also provides a current status report of LDES commercialization activity that is underway in the U.S.

It is clear from this report that LDES technologies have made significant advancements over the last three years. As electricity demand grows, the supply mix changes, and electric companies continue modernizing the grid, proven and tested LDES technologies will be critical to making the system more dynamic, flexible, and efficient. Commercializing LDES technologies can improve reliability and resilience, reduce supply costs during high-price periods, and optimize infrastructure investment by making better use of the existing electric system.

As of October 1, 2026, the Edison Electric Institute (EEI) has been selected by Sandia National Laboratories to lead the Consortium going forward into a new phase of industry leadership. EEI is uniquely suited to lead this effort. EEI’s member companies serve nearly 250 million Americans across the country and will be at the forefront of deploying new electric technologies.

As a member-based organization, EEI has deep experience bringing together stakeholders to address complex challenges and deliver outcomes that benefit customers and the nation. EEI will continue to convene LDES stakeholders, including industry leaders, technical experts, national laboratories, government partners, investors, regulators, and technology developers to identify barriers, develop solutions, and accelerate commercialization and deployment.

B. INTRODUCTION

The National Consortium for the Advancement of LDES Technologies (“the Consortium”) was launched in January 2024 as a three-year¹ national laboratory initiative intended to drive forward a wide range of commercialization pathways for diverse and emerging long-duration energy storage (LDES) technologies. Funding originated from the Infrastructure Investment and Jobs Act (IIJA) Technology Commercialization Fund (TCF) and was disbursed through the U.S. Department of Energy Office of Technology Commercialization (DOE OTC) and the DOE Office of Critical Minerals and Energy Innovation, Office of Clean Energy Demonstrations (CMEI-OCED). This federal funding enabled a coalition of six national laboratories² to create the Consortium and oversee a centralized, unbiased forum through which industry stakeholders across the LDES ecosystem convened to identify barriers, determine potential synergies, and collaboratively develop recommended strategies necessary to achieve the commercialization of a diverse range of LDES technologies within the next decade.

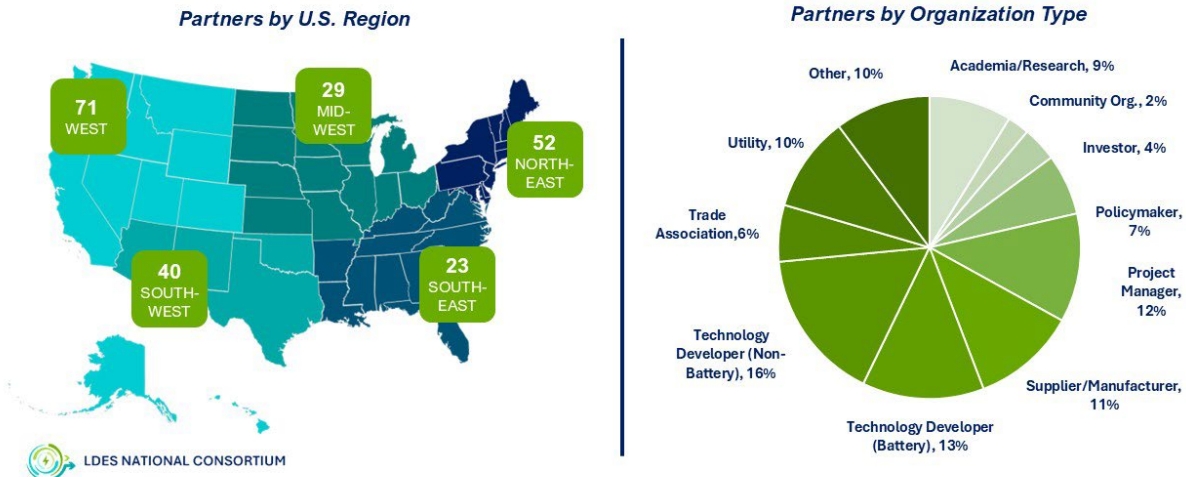
While funded through the DOE OTC and CMEI-OCED and facilitated by national laboratories, critical to the Consortium has been the participation of industry representatives (i.e., “Teaming Partners”). Over the course of the project, over 200 Teaming Partner organizations engaged with the Consortium representing the full scope of the LDES ecosystem, including technology developers, financial investors, utilities, regulators, academics and other community stakeholders.

¹ The tenure of the Consortium was from January 1, 2024, to December 31, 2026.

² Sandia National Laboratories (Sandia) serving as the Lead Lab with five lab partners: Argonne National Laboratory (ANL), Idaho National Laboratory (INL), National Laboratory of the Rockies (NLR), Oak Ridge National Laboratory (ORNL), and Pacific Northwest National Laboratory (PNNL).

Current Teaming Partner Demographics

215 U.S. TEAMING PARTNERS



1

The Consortium has provided a number of unprecedented value streams to LDES stakeholders, including but not limited to:

- ❖ assembling key energy stakeholders from across state government agencies, utilities, academia, industry, and customer representatives (including community-based organizations and representatives) to identify data availability, data gaps, system structure, and modeling objectives;
- ❖ assisting market planners with how to prioritize LDES commercialization pathways;
- ❖ building, with stakeholder input, a decision support model in a system dynamics modeling setting that allows users to experiment with different future LDES configurations and to develop preferred scenarios;
- ❖ providing technical input at state energy offices and public utility commissions on how to incorporate emerging LDES technologies into their policies and regulations;
- ❖ articulating multiple preferred strategies for LDES that can be advocated to wholesale market planning entities;
- ❖ instructing on how to expedite approvals of LDES projects with minimal environmental impacts; and
- ❖ informing markets on measures that improve LDES customer project viability.

The Consortium benefitted tremendously from the direct participation of industry representatives who served as part of Consortium’s Leadership Team in one-year, elected assignments. The Consortium extends its gratitude to the following industry representatives who served on the Leadership Team:

2024	2025	2026
• Todd Q. Adams, Visibility Marketing Inc. • Gaurav Argade, Cummins, Inc. • Elias Greenbaum, GTA, Inc. • Kimberly Johnston, NextGen Energy Partners • Mike Perry, Largo Clean Energy • Indresh Rampell, Holtec Government Services • Rachel Wilson, Form Energy	• Fouad Dagher, National Grid • Huiyi Jackson, Edison Electric Institute • Ralph Masiello, Quanta Technology (Danovo) • Bret Raymis, PWRJoule • Navneet Trivedi, Vrinda, Inc. • Seyi Febode, RWE Clean Energy • Joseph Ferrarri, Mainspring Energy	• Konstantinos Chiotinis, DTE Energy • Chuancheng Duan, University of Utah • John Langhus, Photon Vault, Inc. • Tasha A McCarter, RWE Clean Energy • Hugh McDermott, Qnetic Corp. • Darryl Mendivil, Sytis • Walt Vernon, Mazzetti

Along with federal funding and sponsorship provided by the DOE OTC and CMEI-OCED, the Consortium also benefitted from tangential guidance offered by the Department of Energy—Office of Electricity (DOE OE) Energy Storage Division, which drives the DOE’s efforts to rapidly deploy technologies commercially and expedite grid-scale energy storage in meeting future grid demands. The Consortium acknowledged that LDES is a subset of broader energy storage initiatives, and thus ensuring consistency with DOE OE perspectives was a critical guidepost of the Consortium’s mission.

The Consortium’s activities were driven primarily through 13 break-out groups referred to as “Tiger Teams.” The Tiger Teams served as the work engines of the Consortium, with each of the teams meeting monthly to provide the forums for in-depth discussions of topics germane to specific LDES focus areas. These focus areas that defined the scope of the 13 Tiger Teams were as follows:

- 1) Customer Adoption
- 2) Demonstrations and Deployments
- 3) Economics and Valuation
- 4) Electricity Market Design and Participation
- 5) Grid Infrastructure

- 6) Investor Confidence and Financing
- 7) Policy and Regulations
- 8) Reliability and Resilience
- 9) Safety and Grid Security
- 10) Supply Chain and Manufacturing Efficiencies
- 11) Technology Development, Evaluation, and Testing
- 12) Use Case Development
- 13) Utility Resource Planning

This Landscape Assessment summarizes perspectives gathered across the Consortium during the time period of January 2024 through September 2026.

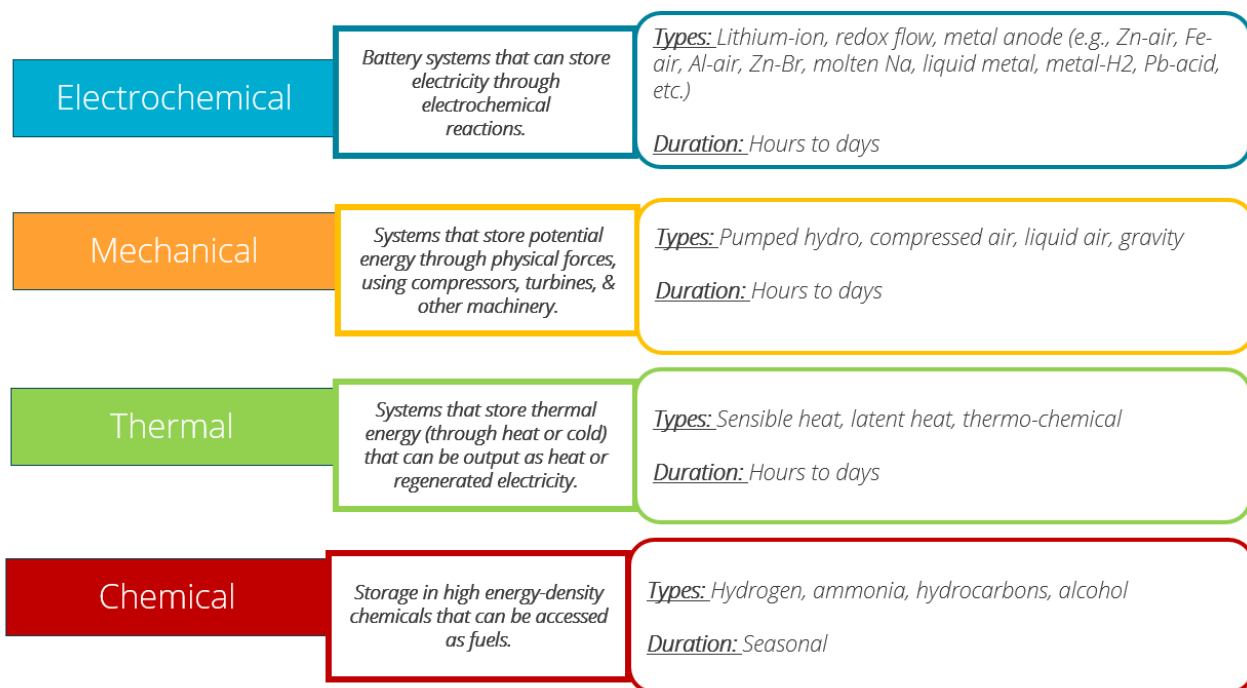
C. ASSESSMENT OF LDES COMMERCIALIZATION

C1. Technology & Market Assessments

From its inception, two guiding principles underlined the approach undertaken by the LDES Consortium: 1) LDES is viewed as a subset of broader energy storage principles and considerations; and 2) an “all-inclusive approach” toward LDES technologies was embraced, meaning that, consistent with the DOE’s definition of LDES as being any energy storage technology capable of providing at least 10 hours of duration, all forms of energy storage technologies with a current or anticipated capability to provide this level of duration were considered to be within scope of the Consortium’s work.

Taken together these two guiding principles significantly influenced the work of independent but integrated Tiger Teams as the Consortium embraced the fundamental concept that next Generation Large Scale Energy Storage (i.e., LDES) is not a singular concept but in fact refers to a diverse technology class with a range of potential system types.

LDES technology types typically are classified under four technology categories or “families”: electrochemical, mechanical, chemical, and thermal energy storage technologies. Within these categories are literally hundreds of technologies in varying levels of development and deployment, from early-stage research and development to a comparatively mature level of market readiness (i.e., commercialization).



Increasingly, LDES technology distinctions based on durations have emerged to designate:

- ❖ “Diurnal (or intra-day)” referring to 10 hours up to 20 hours, which may be primarily used to reconcile daily cycles of generation surpluses and deficits with services such as peak-shifting;
- ❖ “Seasonal,” referring to those technologies with ability to provide 20 hours + duration, particularly in the 100 hour + range.

Pumped hydro-storage remains the most dominant LDES technology type as it continues to account for approximately 95% of the world’s grid storage and 88% of installed utility-scale storage in the United States. Despite this industry dominance, there is a recognition across the industry that the opportunities to build new pumped hydro-storage facilities are limited due to the lack of appropriate water sources and other geographical constraints, and thus emerging LDES technologies have become increasingly desirable for long-term industry needs.

Novel (i.e., emerging) LDES technologies are competing not only for those market opportunities that exist in the vacuum that cannot be served by pumped hydro storage but also against lithium-ion because it is perceived as a mature technology that benefits from existing manufacturing scale, is bankable and comparatively inexpensive. Even with operating limitations (i.e., lithium-ion batteries typically provide duration capability in the range of 2-4 hours) and known fire risks, lithium-ion continues to make up the majority of the 2030 energy storage

project pipeline³. This is largely due to the fact that lithium-ion benefits from massive cross-industry scaling driven by the electric vehicle (EV) sector, which gives lithium-ion an overwhelming cost advantage that alternative startups (such as flow or iron-air batteries) struggle to match.

As the Consortium concludes its federally funded period of operation in the fall of 2026, energy storage as a broad category of which LDES is a subset continues on a strong growth trajectory. Of the 1,643 operational energy storage projects worldwide, 49% are located in the U.S., with another 131 projects under construction. The United States installed 9.7 GWh of battery energy storage in the first quarter of 2026, up 32% year over year. California, Texas and Arizona continue to top the charts: California (60 GWh), Texas (29.2 GWh) and Arizona (20.2 GWh) of utility-scale energy storage capacity installed⁴.

Battery energy storage continues to dominate new energy storage deployments in the U.S. As of July 2026, there are 1022 utility-scale battery storage projects in the US, with an operating capacity of 49,181 MW. In 2025, there were 187 battery storage projects built in the US. Battery energy storage system installations are projected to reach 200 GW/655 GWh of cumulative installed energy storage capacity by 2031, driven mainly by the utility sector, which will make up 85% of installations between 2026 and 2031. The forecast for energy storage remains bullish: 613 GWh of energy storage deployment on U.S. soil by 2030⁵.

Providing this baseline of energy storage is important because LDES—those technologies with the capability to provide 10 hours + in duration—will continue to benefit from the advances that energy storage in general is making. Indeed, as a subset of energy storage, LDES has also seen an acceleration in deployment. LDES has attracted interest by the Consortium participants from utilities, suppliers, and state policy makers as a solution to the continued pursuit of alternatives to lithium-ion batteries. Both Front-of-Meter (FTM) and Behind-the-Meter (BTM) deployments provide great application potential for LDES technologies to meet market needs.

Between 2023 and 2026, annual LDES deployments surged, with LDES installations (capacities ≥8 hours) hitting more than 15 GWh in 2025 alone (a recognized record year of deployment activity). The total U.S. installed capacity specifically for long-duration energy storage (8 hours +) sits at around 15 GWh to 17 GWh of total operational energy capacity, with pumped-storage hydropower providing the bulk of multi-day gigawatt-scale duration. Investments in the LDES

³ Special Report: Lithium's Critical Role in Battery Energy Storage Systems (BESS). June 16, 2026. Sprott. <https://sprott.com/insights/lithium-s-critical-role-in-battery-energy-storage-systems-bess/>

⁴ Data sources: Wood Mackenzie. "U.S. energy storage market Q1 2026 sets records across sectors." June 23, 2026. <https://www.woodmac.com/press-releases/u.s.-energy-storage-market-sets-q1-2026-records-across-sectors>

⁵ Data sources: Cleanview project tracker. <https://cleanview.co/power-projects/operating/battery-storage-projects/us>

space are notable (Hydrostor, EOS Energy, and Form Energy have raised more than \$1 billion in financing since 2021⁶), which indicates strong interest among financing engines.

The year 2024 marked a breakthrough moment for long-duration energy storage technologies. With growth exceeding 800% compared with 2023, the sector appeared to be entering a promising medium-term phase for solutions such as compressed air energy storage and redox flow batteries.⁷

In 2025, however, the outlook began to shift. Although the sector continued to expand, its growth rate slowed dramatically and investment momentum weakened. That trend emerges clearly in the new Long Duration Energy Storage Trends report released by Wood Mackenzie.⁸ The report outlines a series of mounting challenges for the LDES sector, validated by the Consortium's independent findings. Specifically, three major factors are discouraging investors from backing long-duration energy storage projects:

- ❖ **High interest rates**, which penalize projects with long payback periods
- ❖ **Competition for capital** from AI data centers and grid infrastructure investments
- ❖ **Falling lithium prices** combined with longer-duration lithium batteries, reducing the economic advantage of alternative storage technologies

As a result, even though global LDES capacity surpassed 15 GWh in 2025, the growth rate dropped by 93.9% and overall financing declined by 30%.⁹ These challenges underscore the fact that the perspectives outlined in this Landscape Assessment address complex issues within the energy industry that will require ongoing, comprehensive remedial actions from a range of industry participants in order to continually rejuvenate commercialization momentum for LDES technologies.

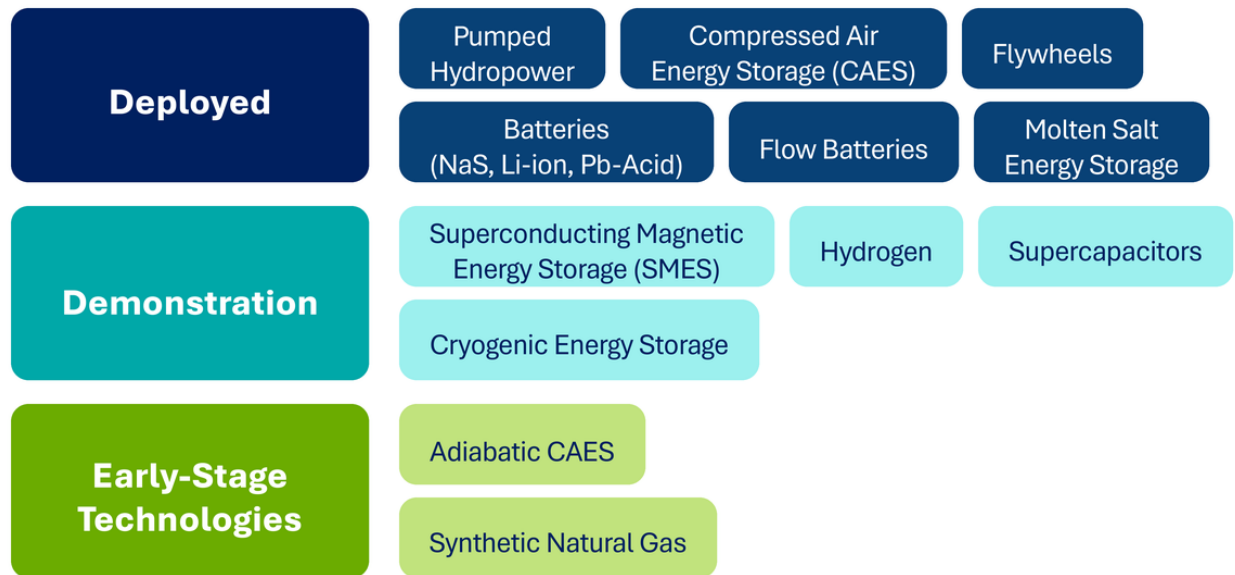
Nevertheless, with acknowledgement of these market factors, of late 2026 a number of LDES technologies can be considered technically proven. A strong case can be made that: 1) the LDES sector has moved past the pilot stage and 2) LDES is moving from a set of niche technologies to a strategic priority in energy resource planning and deployment.

⁶ Data sources: 1) Cleanview project tracker. <https://cleanview.co/power-projects/operating/battery-storage-projects/us>. 2) Wood Mackenzie. "U.S. energy storage market Q1 2026 sets records across sectors." June 23, 2026. <https://www.woodmac.com/press-releases/u.s.-energy-storage-market-sets-q1-2026-records-across-sectors>

⁷ "Long-Duration Energy Storage: When Does It Actually Win?" Net Zero Insights. June 2, 2026. <https://netzeroinsights.com/resources/long-duration-energy-storage-when-does-it-actually-win/>

⁸ "Long-duration energy storage installations surge 49% in 2025 but sector faces critical financing crunch." Wood Mackenzie news release. March 9, 2026. <https://www.woodmac.com/press-releases/lides-2025-outlook/>

⁹ Ibid.



As noted, LDES continues to represent a wide range of technologies, and the diversity of technologies will very likely remain a key attribute within the LDES sector. Different technologies serving different customers in different geographies with different use case applications will continue to be the blueprint for LDES deployment in the near term, and this should be viewed as a positive for the sector as it provides ample opportunities for the full scope of LDES technologies.

A key metric used to determine the viability of specific technology types is the designation of “technology readiness level,” a 9-point scale used to measure how mature a technology is, ranging from basic research (TRL 1) to a fully working system used in the real world (TRL 9). The system was created by NASA in the 1970s and is now used globally by many groups. Applied to LDES technologies, TRL can be used by investors and project developers to evaluate the readiness level of the specific technology type, along with other factors (such as geographical requirements) in the technology selection process. As defined by the DOE, the nine levels of technology readiness are defined as follows:

The Nine Levels of Technology Readiness¹⁰

- ❖ **TRL 1:** Basic ideas and science rules are seen and written down.
- ❖ **TRL 2:** A practical use or basic concept for the technology is thought up.
- ❖ **TRL 3:** Lab tests and studies prove that the idea works in theory (proof of concept).

¹⁰ EERE R 540.112 02: Technology Readiness Levels (TRL). U.S. Department of Energy (DOE) Energy Efficiency & Renewable Energy (EERE). <https://www.energy.gov/documents/technology-readiness-levels-trl>

- ❖ **TRL 4:** Parts of the system are tested together in a clean lab setting.
- ❖ **TRL 5:** The lab tests are made more realistic by testing parts in a setting that looks like real use.
- ❖ **TRL 6:** A working model or prototype is tested in a real or close-to-real environment.
- ❖ **TRL 7:** A full prototype is tested right where it is meant to be used.
- ❖ **TRL 8:** The final product is finished and fully tested to make sure it works.
- ❖ **TRL 9:** The technology is completely proven and working in everyday or real operations.

The Consortium reviewed a variety of source data (e.g., technology documents, evaluations by laboratory experts, input from Teaming Partners and supplementary public information) to assign estimate TRL levels for specific LDES technologies. As of late 2026, the TRL designations of the major LDES technology types are as follows¹¹:

Table 1.
LDES TECHNOLOGIES TRLs

Technology Type	Detailed Technology	TRL
Electrochemical	Lithium-ion	9
Electrochemical	Sodium-ion	6
Electrochemical	Lead-acid	9
Electrochemical	Zinc-Anode	3
Electrochemical	Iron-Flow	8
Electrochemical	Vanadium-Flow	9
Electrochemical	Organic-Solid Flow	7
Thermal	Molten Salt TES	7
Thermal	Solid Media TES - Pumped TES	7
Thermal	Solid Media TES - TPV	6

¹¹ Data compiled in the LDES Technology Evaluation Matrix developed by the Consortium. Ides-tool.sandia.gov

Technology Type	Detailed Technology	TRL
Thermal	Thermochemical	5
Mechanical	Pumped Storage Hydropower (PSH)	9
Mechanical	Advanced Compressed Air Energy Storage (Caverns)	8
Mechanical	Compressed Gas Energy Storage	7
Mechanical	Liquid Air	7
Mechanical	Gravitational Storage (Blocks)	5
Mechanical	Gravitational Storage (Railcars)	7
Chemical	Hydrogen	6

A primary deliverable from the Consortium is the release of [Long Duration Energy Storage Evaluation & Tracking Tool](#), an interactive application designed to support dynamic visualization and assessment of long-duration energy storage metrics and projects. The tool leverages data from industry reports, academic literature, and expert insights to help users filter, compare, and down-select storage options based on high-priority metrics. By providing a centralized and accessible view of key technology and project information, the tool is intended to enhance decision-making and deepen understanding of the evolving long-duration energy storage landscape. The tool can be accessed here: <https://ldes-tool.sandia.gov>,

C2. Deployment & Project Trends

Along with TRL designations, the overall state of LDES commercialization can be evaluated through the consideration of existing project examples pulled from industry sources. Since the inception of the Consortium in January 2024, a number of LDES projects have launched across a variety of geographies and technology types, which again underscores the diversity of the technologies that fall within the scope of LDES. The following information compiled by Modo Energy¹² and published in 2026 provides a comprehensive snapshot of leading LDES technology types, approximate capital raised within that technology, capacity (operational or under construction), key players, and average TRL.

¹² “Billions raised, early stages on delivery: can alternative LDES close the gap?” Timothée Lauvergne. Modo Energy. February 2026. <https://modoenergy.com/research/en/ldes-alternative-long-duration-gb-germany-caiso-ercot-vanadium-iron-air-zinc-caes-laes-thermal>

Table 2.
Snapshot of LDES Commercialization
(Modo Energy)

Technology	Description	Type	Capital Raised	MWh (operational or under construction)	Key developers	Average TRL
CO ₂ batteries	Electricity compresses and expands CO ₂ in a closed-loop system.	Mechanical	\$100M	200	Energy Dome	9
Flow batteries (VRFB)	Energy stored in liquid electrolytes circulated through electrochemical stacks.	Electrochemical	\$1,500M	400	Invinity, CellCube, Sumitomo	9
Adiabatic Compressed Air	Electricity compresses air for later expansion through a turbine.	Mechanical	\$600M	<50	Hydrostor, Storelectric	7
Liquid Air	Electricity liquefies air, later re-gasified to generate power.	Mechanical	\$600M	300	Highview	8
Zinc hybrid	Electricity plates and dissolves zinc in an aqueous electrolyte.	Electrochemical	\$1,000M	N/A	Eos Energy	8
Gravity-based	Electricity lifts heavy masses and recovers energy on descent.	Mechanical	\$400M	<100	Energy Vault, Gravitricity, Gravity Power	6
Iron-air (metal-air)	Electricity reversibly rusts iron to store energy over multiple days.	Electrochemical	\$1200M	<10	Form Energy	6
Thermal (latent / sensible)	Electricity stored as high-temperature heat in solids or molten materials, reconverted via turbine	Thermal	\$400M	<150	Antora, Rondo Energy	6
High density hydro	Dense fluids or water are pumped between engineered reservoirs.	Mechanical	\$15M	<10	RheEnergise	6



Technology	Description	Type	Capital Raised	MWh (operational or under construction)	Key developers	Average TRL
Hydrogen	Electricity produces hydrogen via electrolysis for later power generation or direct use.	Chemical	\$100,000M	<50	Mitsubishi Power, Siemens Energy, Plug Power, ACES Delta	5/6

While not intended to be an exhaustive list, the following project examples (organized by technology type) also illustrate the continuing process of large LDES projects that are taking place across the U.S.

❖ **Batteries**

- **[Iron-Air]:** Google & Xcel Energy Iron-Air Battery (Pine Island, MN); Capacity: 300 MW / 30,000 MWh (30 GWh) Duration: 100 hours. Announced in 2026, this landmark facility developed by Form Energy utilizes "reversible rusting" technology (oxidizing and de-oxidizing iron particles) to provide multi-day, continuous power for Xcel Energy and Google's data centers.¹³
- **[CO₂]: 1)** Columbia Energy Center (Pacific, WI) Capacity: 20 MW / 200 MWh. Duration: 10 hours. Details: Approved by Wisconsin regulators and developed by Energy Dome alongside Alliant Energy, this pilot project stores energy by compressing and liquefying carbon dioxide in a closed thermodynamic loop.¹⁴ **2)** Energy Dome CO₂ Battery project (St Johns, Arizona): 19 MW power output with a 10-hour duration, providing 190 MWh of storage capacity. Expected to come online in 2029.¹⁵
- **[Iron-Sodium]** Inlyte Energy Utility Demonstration (Alabama): In partnership with Southern Company, this iron-sodium battery deployment at an energy storage

¹³ "Xcel Energy to power new Google data center in Minnesota." Xcel Energy news release. February 24, 2026. <https://newsroom.xcelenergy.com/news/xcel-energy-to-power-new-google-data-center-in-minnesota>

¹⁴ "Pioneering energy storage project advances in Wisconsin." Alliant Energy news release. July 18, 2025. <https://www.alliantenergy.com/news/news-center/2025/07/071825-columbialongdurationenergystorageapproved>

¹⁵ "Energy Dome and SRP to Add Long-Duration Energy Storage Project to the Grid, Expand Google Collaboration." Energy Dome news release. June 15, 2026. <https://energydome.com/energy-dome-and-srp-to-add-long-duration-energy-storage-project-to-the-grid-expand-google-collaboration/>

test site in Wilsonville, Alabama, is designed to provide 4 to 24+ hours of discharge capacity for multiday, resilient grid services.¹⁶

- **[Iron-flow]:** Project New Horizon Iron-Flow Battery (Florence, AZ) Capacity: 5 MW / 50 MWh. Duration: 10 hours. Details: Developed by Salt River Project (SRP) and ESS Tech, this project uses iron-flow technology (which relies on iron, salt, and water) to evaluate non-lithium solutions for LDES grid stabilization.¹⁷
- **[Zinc-based]:** Abound Energy's Community Project (Queens, New York) Zinc-air flow battery system. Duration: Up to 15 hours. This 100kW/1.5MWh BTM demonstration project is backed by the New York State Energy Research and Development Authority (NYSERDA) and couples the zinc-air storage with an on-site Combined Heat and Power (CHP) system. The project remains in a pre-operational/demonstration planning phase as Abound Energy (formerly Zinc8 Energy Solutions) continues corporate restructuring, technology platform expansion, and financing milestones.¹⁸
- **[Organic acid solid flow]:** The "Desert Blume" project between Salt River Project and CMBlu in Florence, Arizona utilizing CMBlu's Energy Organic SolidFlow™ organic acid/flow batteries, 5 MW / 50 MWh (10-hour duration). SRP and CMBlu expect the pilot to be operational in December 2027.¹⁹
- ❖ **A-CAES:** The Hydrostor Willow Rock Energy Storage Center in Kern County, CA. The 500 MW/4,000 MWh project received its final California Energy Commission (CEC) approval in late 2025 and is on track to break ground this year. Duration capability is estimated at 8 hours+.²⁰
- ❖ **Flywheels:** Qnetic project at Metro Air Park in Sacramento, CA, where it will begin low-volume manufacturing of its Q500 solid-state mechanical flywheel battery. The basic

¹⁶ "Iron-sodium grid batteries just took a big step toward US rollout." Electrek. December 11, 2025. <https://electrek.co/2025/12/11/iron-sodium-grid-batteries-just-took-a-big-step-toward-us-rollout/>

¹⁷ "SRP and ESS Announce New 50 MWh Long Duration Energy Storage Pilot Project." ESS news release. October 9, 2025. <https://essinc.com/srp-and-ess-announce-new-50-mwh-long-duration-energy-storage-pilot-project/>

¹⁸ "ZINC-AIR BATTERY AND PV TO POWER APARTMENT COMPLEX." Abound Energy news release. January 26, 2022. <https://www.abound.energy/zinc-air-battery-and-pv-to-power-apartment-complex/>

¹⁹ "Salt River Project and CMBlu Energy Announce Launch of Innovative Long-Duration Energy Storage Project." SRP news release. August 31, 2023. <https://media.srpnet.com/salt-river-project-and-cmblu-energy-announce-launch-of-innovative-long-duration-energy-storage-project/>

²⁰ "Hydrostor's Willow Rock Energy Storage Center Obtains Final Approval for Power Plant License." Hydrostor news release. December 19, 2025. <https://hydrostor.ca/hydrostors-willow-rock-energy-storage-center-obtains-final-approval-for-power-plant-license/>

spec of Q500 is 500 kWh, 125 kW, four hours discharge at max power, and up to 12 hours discharge at lower power.²¹

- ❖ **Pumped hydro storage:** The Rye Development ‘Goldendale’ project (Washington state). Designed to generate 1.2 GW of electricity with the ability to store energy for up to 12 hours. Granted a 40-year license by FERC; will commence construction in 2027 with completion date in 2032. Expected to have an operational life of 80 years.²²
- ❖ **Other noteworthy projects & partnerships:**
 - ***Tumbleweed Energy Storage*** facility in Kern County, California. The project is the first eight-hour battery energy storage system serving Northern California, the project was brought online ahead of California Public Utilities Commission’s (CPUC) requirements.²³
 - ***Form Energy’s data center project in Minnesota.*** The project includes iron-air batteries that could provide multiple days of electricity for Crusoe, a company that builds data centers for AI firms. Form also revealed plans to install a multiday battery for a Google data center in Minnesota. It’s expected to be the world’s biggest battery by energy capacity.²⁴
 - ***The XL Batteries / Prometheus partnership.*** Multi-year agreement to deploy on-site long-duration energy storage systems based on organic flow batteries at data centers. In the first phase of the partnership, XL Batteries will deliver and commission a 333 kilowatt (kW) demonstration-scale standalone Organic Flow Battery at Prometheus’ facility in 2027. After that, Prometheus intends to purchase one 12.5 megawatt (MW) / 125 megawatt-hour (MWh) commercial-scale system in 2028 and an additional 12.5 MW / 125 MWh system in 2029.²⁵

²¹ “US startup begins manufacturing grid-scale flywheel ESS.” ESS News. March 30, 2026.

<https://www.ess-news.com/2026/03/30/us-startup-begins-manufacturing-grid-scale-flywheel-ess/>

²² “US FERC approves a 1.2 GW pumped-storage hydropower project in Washington.” Enerdata. January 27, 2026. <https://www.enerdata.net/publications/daily-energy-news/us-ferc-approves-cips-12-gw-pumped-storage-project-washington.html>

²³ “CPUC Celebrates First Long-Duration Energy Storage Project Developed Under Integrated Resource Planning Process.” The California Public Utilities Commission. June 25, 2026.

<https://www.cpuc.ca.gov/news-and-updates/all-news/cpuc-celebrates-first-long-duration-energy-storage-project-developed-under-irp-process>

²⁴ “Form Energy & Crusoe Announce Agreement for 12 Gigawatt-Hours of Iron-Air Batteries for AI Data Centers.” Form Energy news release. March 24, 2026. <https://formenergy.com/form-energy-crusoe-announce-agreement-for-12-gigawatt-hours-of-iron-air-batteries-for-ai-data-centers/>

²⁵ “Prometheus Hyperscale and XL Batteries Partner to Deploy Long-Duration Energy Storage Systems at U.S. Data Centers.” XL Batteries news release. May 14, 2026.

<https://www.prometheushyperscale.com/news/xl-batteries-partnership>

<https://www.xlbatteries.com/news/2025/05/14/prometheus-hyperscale-and-xl-batteries-partner>



- **Meta & Noon Energy.** Meta signed with Noon Energy for 1 GW / 100 GWh of multi-day storage. Google invested in Energy Dome's CO₂-based LDES. 8-hour applications are emerging across the US specifically for data center capacity.²⁶
- **Energy Dome & Salt River Project.** Partnership announced to add a 19 MW, 10-hour CO₂ battery system to the grid in Arizona. The pilot is a part of Google and SRP's effort to advance new non-lithium-ion long duration energy storage technologies.²⁷

C3. State Regulatory Activities

Along with the LDES project and partnership examples summarized above, state regulatory activity focused on LDES deployment that has taken place in the last three years also provides a positive indicator regarding the progress being made in LDES commercialization. The primary examples of LDES-focused, state-level regulatory activity in the 2024-2026 during which the Consortium has operated are as follows:

- ❖ **CALIFORNIA:** Within its broader energy storage policy focused on targeted and centralized procurement, the California Public Utilities Commission (CPUC) is targeting 2 GW of LDES, with 1 GW specifically for multi-day storage and another 1 GW for storage with at least a 12-hour discharge period. The California Department of Water Resources (DWR) will act as the central procurement body for LDES.²⁸
- ❖ **NEW YORK:** The state's roadmap includes a target of 20% of 8+ hour resources in bulk storage procurements, aiming for 1200 MW of LDES by 2030.²⁹
- ❖ **MASSACHUSETTS:** Within the state's broader ES procurement target (legislative mandate that utilities solicit proposals to secure up to 5 GW by 7/1/30), the target includes specific capacities for mid-duration (4-10 hours), long-duration (10-24 hours), and multi-day (24+ hours) storage.³⁰

²⁶ "Noon Energy and Meta Announce Plans for Up to 1 GW of 100+ Hour Energy Storage for Data Centers." Noon Energy news release. April 21, 2026.

<https://www.noon.energy/post/noonenergyandmetapartnership>

²⁷ "Energy Dome and SRP to Add Long-Duration Energy Storage Project to the Grid, Expand Google Collaboration." Salt River Project news release. June 15, 2026. <https://media.srpnet.com/energy-dome-and-srp-to-add-long-duration-energy-storage--project-to-the-grid-expand-google-collaboration/>

²⁸ "CPUC Advances Clean Energy with Centralized Procurement Strategy." California Public Utilities Commission. August 24, 2024. <https://www.cpuc.ca.gov/news-and-updates/all-news/cpuc-advances-clean-energy-with-centralized-procurement-strategy>

²⁹ "PSC Approves NYSEDA's Bulk Energy Storage Program Implementation Plan." Hodgson Russ News & Insights. March 27, 2025. <https://www.hodgsonruss.com/newsroom/publications/psc-approves-nyserdas-bulk-energy-storage-program-implementation-plan>

³⁰ "2024 Clean Energy Act Promotes Energy Storage Deployment Across Massachusetts." JD Supra News & Insights. November 21, 2024. <https://www.jdsupra.com/legalnews/2024-clean-energy-act-promotes-energy-1960739/>



- ❖ **MAINE:** Currently exploring the potential for LDES and how to expand upon existing ES target of 300 MW of installed capacity by end of 2030.³¹
- ❖ **MICHIGAN:** The Michigan Public Service Commission (MPSC) was mandated by Public Act 235 of 2023 to conduct a formal study on LDES and multi-day storage systems, which resulted in the Statewide Energy Storage Target initiatives.³²
- ❖ **VIRGINIA:** Virginia enacted landmark energy storage legislation (Senate Bill 448 and House Bill 895) mandating 4.5 GW of LDES by 2045. It requires a minimum 10-hour generation capacity and is part of a broader 20.78 GW energy storage expansion for the state's major utilities.³³

C4. Reality Checks

While the examples of projects, partnerships and regulatory policy directives provide data points indicating a strong trajectory for LDES commercialization, there are market realities that must be acknowledged as they continue to provide challenges for LDES technology adoption and deployment. The challenge that most LDES technologies continue to face is the dominance of lithium-ion batteries. Shorter-duration lithium-ion batteries have monopolized the 4-to-8-hour storage market due to optimized supply chains and rapidly falling material costs. Put another way, lithium-ion does the work of LDES because lithium-ion is bankable and gets deployed where LDES technologies would actually provide more functionality. While LDES technologies could offer more value if they could achieve scale with costs and risks coming down, as of this writing that is not the case for the majority of LDES technologies under development. Thus, lithium-ion is still perceived to be cheaper, less risky, and therefore more bankable when compared to LDES alternatives. This is a market reality that cannot be denied, particularly for those LDES technologies that are still in early or pre-commercial stages, with unproven manufacturing processes and limited production precedent.

Unlike lithium-ion batteries, which have benefited from decades of consumer electronics manufacturing, most LDES chemistries lack adjacent industries from which to borrow tooling, talent, or process knowledge. This does not always attract capital investment needed to achieve cost-competitiveness through scale, as technologies have not reached sufficient maturity,

³¹ “Long-Duration Energy Storage: A review of technology options, key considerations, costs, and scenarios for the use of long-duration energy storage in Maine pursuant to Public Law 2023, Chapter 374: An Act Relating to Energy Storage and the State’s Energy Goals.” Maine Governor’s Energy Office. February 2024. https://www.maine.gov/energy/sites/maine.gov.energy/files/inline-files/LDES%20Report_Final_0.pdf

³² “Study of Long Duration and Multi Day Energy Storage.” Michigan Public Service Commission. February 27, 2025. <https://www.michigan.gov/mpsc/-/media/Project/Websites/mpsc/workgroups/2023-Energy-Legislation/Study-of-LDES-and-MDES.pdf?rev=19cb096812f8414393b0d65d6030da14&hash=C2F5E6FAFD75C4FA2488B00897C0BAD7>

³³ “Virginia Enacts Landmark Energy Storage Expansion Bills.” Williams Mullen Legal News. May 26, 2026. <https://www.williamsmullen.com/insights/news/legal-news/virginia-enacts-landmark-energy-storage-expansion-bills>

creating a difficult timing tension between urgency and readiness. The onus will remain on LDES technology developers to distinguish their own unique value propositions to investors and end-use customers, including duration capabilities, supply chain considerations, and safety benefits.

In addition, the cost of emerging storage technologies and uncertainties about ownership benefits are ongoing challenges that emerging LDES technologies will continue to face for the remainder of this decade. Without definitive technology paths the cost of LDES is unclear and the ownership impacts, including benefits and cost, are also unclear. Investigation and understanding of the cost of storage and overall benefits is a challenge for customer adoption of LDES. Support to overcome cost barriers could include policy for grid resilience, capacity adequacy, shifting electricity production supply, and unpredictable weather events.

Moreover, uncertainties about technology maturity that reduce customer acceptance levels will also impede LDES technology development for the near term. An increase of demonstrations and deployment to show technology maturity is imperative; however, sources of funding support on technology demonstrations are unclear and still a challenge because of the risk and hesitance to invest in “first of a kind” (FOAK) technologies. Federal, state, and venture participants of FOAK are needed to aid in technology development and deployment.

Market projection on the “when, what, how, and where” different LDES technologies will be adopted remain very subjective and without a consistent verification methodology. While the general industry consensus is that the LDES market is going to be large and could constitute trillions of dollars of investment, the exact timing and types of LDES technologies that will achieve commercial success remain very difficult to predict.

However, while emerging LDES technologies are likely better suited for multiday, multiweek and seasonal storage applications, as of mid-2026 robust development of these emerging technologies remains sluggish due to insufficient demand and minimal pricing mechanisms at both the wholesale and retail levels, creating perpetual market uncertainties about whether the revenue model exists to make LDES financeable at scale.

A barometer of commercialization achievement that has been established by the DOE is that LDES needs roughly \$50 to \$75 per kilowatt-year in capacity market revenue, according to industry analyses, to support a bankable project finance case.³⁴ Given that many LDES technologies demonstrate strong TRL profiles and thus can be considered “proven,” the Consortium consistently sought to answer the question of what is the fundamental conundrum that continues to thwart broad LDES adoption, and one leading conclusion is that most US markets simply don’t provide the compensation mechanisms that result in the needed revenue level of \$50 to \$75 per kilowatt range for LDES technologies. This is largely due to three persistent truths that exist across US markets:

³⁴ “Pathways to Commercial Liftoff: Long Duration Energy Storage.” U.S. Department of Energy. March 2023.

- ❖ **Lack of Pricing Mechanisms:** US electricity markets and capacity mechanisms compensate utilities for short-term power delivery, not the ability to continuously serve a load for multiple days.
- ❖ **Financing Hurdles:** High interest rates and a tightening of venture capital funding have severely restricted the capital required for unproven, utility-scale LDES technologies.
- ❖ **Regulatory Roadblocks:** Regional transmission organizations (RTOs) and independent system operators (ISOs) continue to lack regulatory frameworks or standardized capacity accreditations for LDES, making procurement difficult.

C5. The Path Forward

As the Consortium concludes its federally funded period and transfers ownership to a private entity for continued operation, there are several emerging dynamics that have emerged in the 2025/2026 timeframe that bode well for continued LDES commercialization. The most significant emerging dynamic is the rapid growth of data centers in multiple locations across the US. While it is true that LDES technologies may also face competition for capital from AI data centers, as previously mentioned, there is perhaps a greater opportunity to form partnerships with those data centers that choose to “bring their own generation” and require energy storage systems at their facilities. With their associated surging electricity demand and skyrocketing costs (data centers consumption could double or triple by 2028. It already sits at 176 TWh per year. 4.4% of total US electricity), it is conceivable that data centers alone could become the primary market opportunity for LDES technologies.

Moreover, the sheer speed at which new data centers are being deployed is creating concentrated demand for power in specific locations, putting pressure on local grids and, in some cases, contributing to higher electricity prices. As a result, access to LDES technologies is increasingly becoming a competitive factor rather than simply an energy consideration. The rapid proliferation of data centers that require 24/7 power resources that can be deployed quickly and closer to load sources (i.e., oftentimes not interconnecting to distributions or transmission grids) create new opportunities for LDES technologies to develop customized use case applications.

LDES technologies will certainly continue to mature and, through utility-scale deployments, the Consortium remains confident that the economics of LDES will continue to mature, although economic opportunities will be largely influenced and impacted by market mechanisms developed within the electricity wholesale markets.

The Consortium’s fundamental goal was to identify barriers to LDES commercialization and approaches to address these barriers. The identified approaches are discussed in detail in the subsequent sections of this Landscape Assessment. Working in tandem with these approaches to address market barriers, the Consortium believes there are systemic factors within the energy industry that will continue to create the need for LDES technologies, and which will likely continue to drive LDES forward through the end of this decade and beyond. The factors include:

- ❖ Grid congestion
- ❖ Aging infrastructure
- ❖ Unique weather trends that will make resilience a priority.
- ❖ Grid infrastructure investment is accelerating.
- ❖ Procurement teams are prioritizing supply chain diversity
- ❖ Safety as a decision-making criterion.
- ❖ Replacement of peaker plants.

While it is certainly true that cost dominates most storage investment decisions, these non-cost factors will likely create market niches for LDES technologies, particularly when compared as an alternative to lithium-ion batteries. These factors could increasingly create previously unforeseen opportunities for LDES technologies in scenarios such as fire-sensitive environments and isolated grids.

D. THE CONSORTIUM'S APPROACH

Assessments made by the Consortium across the 13 Tiger Teams validated the premise that U.S. electricity market reform is needed to accelerate customer adoption of LDES. The Consortium concluded that through the continued identification of challenges (i.e., deployment barriers) facing LDES in both wholesale and retail electricity markets, remedial action across these two sectors arguably offers the most feasible pathways for LDES commercialization through the remainder of this decade. It is the Consortium's conclusion that market development through regulatory reform can bridge the gap between the theoretical need for LDES solutions within different markets and the technical reality of integrating new technologies into an existing or modified market construct.

A clear conclusion from Consortium discussions was that technology innovation alone will not accelerate LDES deployment. Changes in policy, regulation, and market design are necessary to support adoption at scale. A successful strategy for LDES involves more than subsidies or procurement targets. It requires a broader modernization of how the grid values flexibility, resilience, and long-term efficiency.

In assessing existing and future markets for LDES technologies, the Consortium concentrated primarily on wholesale and retail electricity markets and the reforms across both sectors that will be needed to create pathways for the development of emerging LDES technologies. This concentration included acknowledgements that: 1) markets, with few notable exceptions, are inherently correlated with regulatory and policy frameworks; and 2) a valid hypothesis is that LDES deployment at commercial scale, at least for the foreseeable future, will require policy support due to the fact that in most cases LDES technologies are not considered profitable on a

level playing field with short-duration storage. Because costs for LDES are high and the demand remains low, policy support may in fact be the only driver of large-scale LDES deployment through this decade.

The Consortium observed this trend particularly across regulated utility integrated resource plans (IRPs), in which capacity expansion models typically select four-hour lithium-ion on the basis of cost, while LDES remains a policy-driven add-on due to regulatory requirements. While utilities may see a role for eight-hour and multiday systems over time, especially as winter peaks grow and thermal retirements accelerate, in the near-term there is a perception that LDES is still too expensive without expanded policy support.

At the wholesale level, these policy frameworks are regulated by the Federal Energy Regulatory Commission (FERC) and implemented and managed by unique independent system operators (ISOs) and regional transmission organizations (RTOs). At the retail level, these frameworks are developed primarily by state regulatory commissions with what appears to be an increasing role for state energy offices, state legislatures and state executives (e.g., governors).

In assessing these markets, the Consortium sought to identify a future state comprising a strong energy marketplace for LDES technologies and conducted a gap analysis focused on the barriers that exist that are preventing strong markets from developing. The Consortium considered the following factors as being indicators of a strong LDES marketplace:

- ❖ **Robust policy frameworks** (i.e., the existence of more than one policy lever within an ISO/RTO or individual state).
- ❖ **Large-scale projects** (i.e., the development of massive battery storage projects, which significantly contribute to overall capacity in a specific region).
- ❖ **Decreasing costs** (i.e., falling costs of batteries and other energy storage technologies that make deployment more economically viable).
- ❖ **Grid reliability** (i.e., evidence that LDES technologies are actively contributing to maintain grid stability).

One key step is to give LDES projects more predictable long-term revenue. This can be achieved through capacity contracts, cap and floor arrangements, or seasonal reliability products. Market operators also have a major role to play in this regard. As ISOs develop sub-annual capacity markets and refine capacity accreditation methods, policymakers can encourage the creation of products that reward multi day flexibility and resilience. The goal is not to transform wholesale markets overnight, but to gradually introduce structures that reflect real system needs.

Finally, the regulatory environment must explicitly acknowledge the potential for LDES to operate as transmission infrastructure. Requiring evaluation of storage in regional transmission plans, clarifying how cost recovery works, and enabling hybrid models that combine

transmission functions with wholesale market participation could all help reduce utility risk and support innovation.

E. ADDRESSING IDENTIFIED CHALLENGES FOR LDES

At its starting point when it commenced operations in January 2024, the Consortium adopted the previously published report from the DOE entitled “Pathways to Commercial Liftoff: Long Duration Energy Storage.”³⁵ The Lift-off report established an end-goal that the U.S. will need 225-460 GW of LDES capacity by 2060, representing a \$330 billion capital investment. Further, achieving the goal of commercial liftoff will require significant technology, cost, regulation, and supply chain improvements, along with addressing a set of identified challenges that create barriers for LDES commercialization.

Eleven (11) distinct challenges that provided the basis for the subsequent work of the Consortium’s Tiger Teams. The 11 identified challenges were:

1. Cost of an LDES system needs to come down by 2030.
2. LDES technologies must achieve 7-15% improvement in roundtrip efficiency to compete with Li-ion storage and hydrogen.
3. The specific needs related to LDES workforce training (i.e., skills and training) are presently not well defined.
4. A comprehensive assessment of necessary supply chain improvements specific to LDES technologies does not presently exist.
5. A uniform approach toward developing resource adequacy compensation for LDES technologies does not exist, in either regulated markets (PUC evaluation) or competitive markets (ISO/RTO).
6. There is presently a lack of resources regarding how to evaluate grid upgrades or expansions that will be necessary to accommodate both new variable renewable generation sites and LDES systems.
7. LDES is not included in most utility grid firming plans.
8. Presently, there is no publicly available evaluation of LDES technologies against primary competitive factors.

³⁵ U.S. Department of Energy. (2023). *Pathways to Commercial Liftoff: Long Duration Energy Storage*. U.S. Department of Energy.

9. LDES use cases require market changes.
10. ISO and RTO markets will need to develop support mechanisms.
11. State-level policymaking specific to LDES has been very limited.

The following subsections cover the Consortium’s perspectives on these challenges as of September 2026, including both progress that has been made during the Consortium’s tenure and remaining remedial approaches that the industry will need to address further. To aid in the evaluation of the current state of LDES commercialization as measured against these identified challenges, the Consortium offers a “status grade” with two icons reflecting:



= Significant improvement addressing the challenge has been achieved during the tenure of the Consortium.



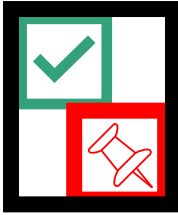
=The challenge remains a significant barrier to LDES commercialization and additional action is needed from various industry participants.



=While some improvements have been made to address the challenge, significant action is still needed from various industry participants to address the challenge.

E1. Cost of an LDES system needs to come down by 2030.

Status:



=While some improvements have been made to address the challenge, significant action is still needed from various industry participants to address the challenge.

Based on data from a variety of sources, it is the Consortium's conclusion that the costs for LDES systems have decreased since 2023, driven by manufacturing scale-ups, supply chain industrialization (fueled by the EV market), and technology innovations.

Data points that substantiate this conclusion are:

- ❖ **Cost Competitiveness:** The least expensive LDES technologies—such as thermal energy storage and CAES—have achieved capital expenditures (capex) of about \$232/kWh and \$293/kWh respectively. For comparison, lithium-ion 4-hour systems averaged \$304 in 2023, making these LDES alternatives highly competitive for multi-hour storage.³⁶
- ❖ **Turnkey Storage Drops:** Overall turnkey energy storage costs have fallen by roughly 30% to 117/kWh.³⁷
- ❖ **Future Projections:** Cost benchmarks indicate that many LDES solutions are expected to drop in cost by another 37% by 2030.³⁸

While these cost trends are promising, continued work on cost reductions will be needed across the full set of LDES technologies to maintain a trajectory of cost-competitiveness with lithium-ion through the end of this decade. LDES costs need to come down further to better compete with technologies that provide similar grid services (e.g., Li-ion batteries, gas turbines). Declining LDES costs that are maintained for a multi-year period will widen the possible economic opportunities for various technologies, assuring investors that LDES can achieve viability, market share and generate profit/revenue.

³⁶ "Lithium-Ion's Grip on Storage Faces Wave of Novel Technologies." Bloomberg NEF. June 4, 2024. <https://about.bnef.com/insights/clean-energy/lithium-ions-grip-on-storage-faces-wave-of-novel-technologies/>

³⁷ "Battery storage system prices continue to fall sharply, BNEF and Ember reports find." Energy Storage News. December 15, 2025. <https://www.energy-storage.news/battery-storage-system-prices-continue-to-fall-sharply-bnef-and-ember-reports-find/>

³⁸ "Long duration energy storage costs expected to decline by 2030, new LDES Council–EPRI study finds." Long Duration Energy Storage Council. <https://ldescouncil.com/ldes-epri-cost-benchmarking-study/>

As a unique exercise within the Consortium, analysis was conducted regarding the primary cost contributors to LDES technologies and, accordingly, opportunities for cost-reduction pathways. This information is provided in the following table.

Table 3.
Factors impacting cost of various LDES technologies

Technology Class	Technology / Concept	Primary Cost Contributors	Cost-Reduction Pathways	Notes / Implications
Mechanical	Hybrid Liquid Air Energy Storage (HLAES): LACC / HPLAPS	Charging: cryogenic refrigeration; sensitive to storage utilization rate (SUR). Discharge: turbomachinery + heat exchangers; ORC is novel. Storage: above/below-ground tanks (LNG-like).	Increase SUR (higher specific power output per kg liquid air via higher firing temperature, steam injection). Competitive procurement across cryogenic-cycle suppliers. Business models (e.g., tolling for liquid air) to reduce owner CAPEX. Simplify architecture (e.g., remove ORC).	ORC bottoming-cycle efficiency improvements help. HPLAPS increases power output → lower \$/kW. Removing ORC reduces cost/risk but lowers efficiency.
Chemical	Offshore hybrid LDES: subsea electrolysis H ₂ production + storage + delivery (H ₂ /NH ₃); coastal grid balancing	OPEX: electricity (often 50–70% of cost). CAPEX: electrolyzer stacks + manufacturing; hydrogen compression/handling; subsea transport/storage.	Co-location (generation–electrolyzer–storage–offtaker) to reduce infrastructure and losses. Low-cost stack materials (commodity polymers/metals). High-volume manufacturing (thermoplastic injection molding, digital wire winding). Avoid mechanical compression using hydrostatic pressure + cold seawater cooling. Composite/fiberglass pipelines for subsea H ₂ .	Composite subsea pipelines can reduce installed cost vs steel and lower maintenance (corrosion/embrittlement). Subsea siting improves resilience (weather/EMP/lightning) and safety (oxygen separation, distance from population). Long-life alkaline Ni electrodes reduce replacement OPEX (20–30 yrs claimed). Permitting may be simpler than O&G offshore, but still requires confirmation case-by-case.

Technology Class	Technology / Concept	Primary Cost Contributors	Cost-Reduction Pathways	Notes / Implications
Thermal	Liquid Salt Combined Cycle (LSCC)	Storage medium: salt dominates CAPEX (~\$2,000/metric ton delivered + melt). Secondary: tanks, charging heaters. Discharge: mature GTCC-like equipment.	Hybrid integration with gas turbine exhaust to reduce required salt mass (lower SUR). Tank cost control via moderate operating temperature (e.g., 427°C). Higher voltage electric heaters (e.g., direct 13 kV bus) to reduce cabling/transformers. Scale-up, manufacturing volume, and higher discharge capacity factor to reduce \$/kW and fixed O&M.	Higher salt temperature (e.g., solar salt ~565°C) may reduce salt mass but can raise tank cost (stainless) and complexity. Low-freezing-point salts (e.g., Hitec®, Yara) reduce freeze risk and protect residual value. Oil storage is cheaper but increases SUR and fire risk (historical issues at SEGS-II). Solid media and direct steam concepts are earlier-stage. DOE support for domestic tank design/fabrication could reduce risk/cost.
Electrochemical	Organic redox flow battery	Energy capacity: electrolyte (dominant at >6–8 h). Power capacity: stacks (membranes/electrodes). BOP: pumps/tanks/controls (often comparable to stacks).	Replace vanadium with organic active materials (major electrolyte cost reduction). Use lower-cost hydrocarbon membranes (enabled by organics). Reduce electrode material via faster kinetics. Use milder pH electrolytes to enable steel tanks and reuse existing tank infrastructure.	Two largest stack cost elements are typically membranes + electrodes (often ~75% of stack cost). Compatibility of pumps/tanks with electrolyte remains a design driver. Repurposing tanks can significantly reduce installation/civil costs.

Technology Class	Technology / Concept	Primary Cost Contributors	Cost-Reduction Pathways	Notes / Implications
Mechanical	Conventional pumped storage hydropower (PSH)	Permitting/licensing (FERC) time/cost uncertainty. Civil works (dams/reservoirs). Siting + transmission. Habitat/cultural mitigation.	Improve siting strategy (lower-cost geology/topography ; proximity to load vs transmission trade). Early stakeholder/community collaboration. Develop/communicate co-benefits (water supply, recreation) to improve acceptance and economics.	Regulatory unpredictability is often a first-order cost/schedule driver. Co-benefits can offset costs and reduce opposition if incorporated early.
Mechanical	Small-scale PSH / PSH at existing dams & reservoirs	Disproportionate licensing/permitting burden for low-impact systems. High cost of new reservoirs/tanks. Habitat/cultural impacts if greenfield.	Regulatory pathway tailored to micro/low-impact PSH (potential exemptions/streamlining). Use existing reservoirs/tanks/infrastructure; paired reservoir additions near existing sites. Site near population centers when feasible to reduce transmission and improve resilience.	Reservoir construction can dominate total cost in fully man-made systems (often cited as >90%). Using existing assets can dramatically reduce CAPEX (example: large municipal reservoir projects are very costly). Urban open reservoirs may provide greenspace/habitat co-benefits, depending on design.
Chemical	Clean fuels as LDES (H ₂ , NH ₃ , etc.) + compatible generation	Power block CAPEX: limited set of mature generators compatible with clean fuels. Storage CAPEX: fuel storage (liquid easier than bulk H ₂). Fuel price: delivered \$/MMBtu learning curve.	Scale-driven EPC/CAPEX reductions for clean-fuel-capable generators. Leverage established bulk liquid fuel storage experience (esp. ammonia). Policy/planning recognition of clean fuels as LDES to unlock funding and planning inclusion.	Clean fuels are key for multiday/seasonal storage; likely complements “traditional” 8–20 h LDES. Bulk H ₂ storage remains complex (caverns/pipelines).

Technology Class	Technology / Concept	Primary Cost Contributors	Cost-Reduction Pathways	Notes / Implications
Thermal	Moving particle thermal energy storage (MPTES) + sCO ₂ RCBC	Power cycle CAPEX/risk: sCO ₂ recompression Brayton cycle components (turbomachinery, HX, cooling). Primary HX: particle-to-working-fluid heat exchanger. Heaters/electronics: replacement risk; high-speed power electronics. OPEX: operational complexity.	Reduce RCBC cost via state-point optimization, component design, and supply chain maturation. Improve particle HX designs and fabrication methods. Develop lower-CAPEX heater designs and controls to extend element life. Scale high-speed/high-power electronics supply chains. Increase automation to reduce staffing.	RCBC is less mature than Rankine, driving cost and perceived risk. Primary HX is immature and currently expensive; fabrication readiness is critical.
Electrical	Fired ceramic semiconductor battery (saline-based)	Materials: low-cost commodity ceramics; some refined conductors (e.g., copper). Factory CAPEX: tile fabrication + test/assembly automation. Kiln OPEX/CAPEX: fuel/electric firing; potential solar-thermal integration. Power electronics: inverters/transformers.	High-throughput ceramic manufacturing to reduce \$/kWh. Improve automation for test/assembly and logistics. Optimize kiln energy source (efficient roller kilns; electrification/solar-thermal as viable). Scale supply chains for inverters/transformers.	Claims include very low leveled cost targets contingent on performance/lifetime and manufacturing yield. Economics are highly sensitive to practical energy density, reliability, and factory commissioning risk.
Mechanical	PSH (micro): regulatory items	FERC filings and required studies; licensing timelines create economic uncertainty.	Exemptions/streamlined pathways for PSH below a size threshold; early stakeholder alignment to avoid re-licensing delays.	Licensing/re-licensing can be order \$10M and multi-year (project-dependent). Clarify study requirements early to reduce downside risk.
Thermal	Deep hot rock / dry geothermal (DHDRG)	Deep well drilling (dominant).	Improved drilling methods; alternative well diameters/designs.	Drilling learning curves and tool reliability are central to cost reduction.

Technology Class	Technology / Concept	Primary Cost Contributors	Cost-Reduction Pathways	Notes / Implications
Thermal	Pumped thermal energy storage (PTES)	Storage reservoirs are the largest cost component; then EPC, turbomachinery, heat exchangers.	Larger unit designs can reduce balance-of-plant per MW; focus innovation on reservoir design/cost.	For large units, reservoir design tends to dominate total installed cost.

The Consortium determined that approaches toward achieving cost decreases for LDES technologies are closely correlated to perceptions of investors. Put another way, an increase in investments into emerging LDES technologies will enable a considerable scale up of these technologies, which will in turn help to drive costs down. Many similar energy technology sectors (e.g., Li-ion batteries) have had to go (and still are going) through this process to achieve access to consistent, low-risk, low-cost project finance. Different LDES companies and technologies have had success gaining private sector investment and project finance, but the sector overall has not reached widespread investor confidence or widespread support from low-risk, low-cost institutional financiers.

While increasing overall investor and financier understanding of LDES requires a harmonization around language and standardization to reduce complexity, different investors and financiers provide different products, benefits, and services and are looking for different things in return. When LDES technologies, particularly those that are still in an R&D phase, seek financial investment support, knowing the audience (i.e., type of investor or financier) is critical.

The impediments identified by the Consortium pertaining to LDES investment and finance were: (1) LDES capital costs need to decline and (2) state policy needs improvement. Each of these tied closely with two subsequent challenges identified: (3) first-of-a-kind (FOAK) funding and financing and (4) investor community confidence needed to increase.

The issue of FOAK funding and financing was seen as critical barrier to LDES cost declines, and the reason for this is that LDES cost declines are expected with increasing deployment, and the most challenging from a financial perspective is funding the FOAK deployment. Subsequently, clearer signals from state policy makers that LDES will be valued and compensated through some market mechanism will increase an investor's confidence in investing today while the market and technologies are relatively nascent,

As TRL improves, financing costs also decrease (i.e., cheaper capital, lower interest loans) meaning overall project costs decline. While much of the burden for LDES cost declines falls on LDES developers, government incentives (states and federal) could develop policies that would help to reduce LDES costs further.

Overwhelmingly, the Consortium found the most important driver of LDES cost declines and increased investor confidence identified was deployments, namely the FOAK deployment.

Achieving a successful FOAK leads to rapid growth and large increase in access to capital, which will in turn be a key driver for reduced technology costs.

As of this writing, Levelized Cost of Storage (LCOS) remains the primary metric used to evaluate the economics of LDES technologies. LCOS calculates the total lifetime costs of a system divided by the total energy discharged, typically expressed in dollars per megawatt-hour (\$/MWh) or cents per kilowatt-hour (cents/kWh). It is the Consortium's conclusion that revisions to how LCOS is determined is a key starting point for comprehensive efforts targeting reduced costs for LDES technologies.

Forecasts of LCOS for most LDES technologies range from 15-40 cents/kilowatt-hour (kWh) in 2030.³⁹ While LCOS estimates could reach as low as 10 cents/kWh for pumped storage hydro (PSH) and compressed air energy storage (CAES) by 2030, these costs are far higher than the 5 cents/kWh targeted by DOE's Long Duration Storage Shot. Based on the findings of the LDES Liftoff Study, further cost reductions will be needed to achieve commercial liftoff.

A key challenge with LCOS calculations that the Consortium observed, and which has been validated by other industry analysis, is that LCOS is best suited for comparing energy-focused (kWh) use cases with frequent cycling. For power-focused applications (capacity, backup), infrequent cycling can yield misleadingly high values. Relying primarily or solely on LCOS to evaluate the economics of LDES technology may therefore result in an incomplete cost determination. Another challenge with LCOS also reflects theoretical performance under assumed utilization; real project economics depend on market dynamics, revenue stacking, and site-specific factors. This analysis benchmarks the "natural domain" of each technology, not project-level investment decisions.

There are several DOE offices and industry groups that have developed alternative definitions of LCOS or pathways to reductions in LDES costs. These groups offer competing approaches for defining LCOS (ARPA-E DAYS⁴⁰, Lazard⁴¹, Energy Storage Grand Challenge Cost and Performance Study⁴², and Storage Innovations 2030⁴³), each with their own set of parameters and assumptions used for forecasting reductions in cost and defining pathways to pursue in achieving cost reductions.⁴⁴

³⁹ ESGC Storage Cost and Performance Database. Available at <https://www.pnnl.gov/ESGC-cost-performance>.

⁴⁰ "Why Long-Duration Energy Storage Matters." ARPA-E. Department of Energy. <https://arpa-e.energy.gov/news-and-events/news-and-insights/why-long-duration-energy-storage-matters>

⁴¹ Lazard's Levelized Cost of Storage Analysis—Version 4.0. Lazard. November 2018. <https://www.lazard.com/media/sckbar5m/lazards-levelized-cost-of-storage-version-40-vfinal.pdf>

⁴² "2022 Grid Energy Storage Technology Cost and Performance Assessment." Department of Energy. <https://www.energy.gov/cmei/2022-grid-energy-storage-technology-cost-and-performance-assessment>

⁴³ "Achieving the Promise of Low-Cost Long Duration Energy Storage." Department of Energy. August 2024. https://www.energy.gov/sites/default/files/2024-08/Achieving%20the%20Promise%20of%20Low-Cost%20Long%20Duration%20Energy%20Storage_FINAL_08052024.pdf

⁴⁴ Hill Balliet, W., Balducci, P., Durvasulu, V., & Mosier, T. (2025). Determining the profitability of energy storage over its life cycle using levelized cost of storage. *Energy Economics*, 142.

One key finding from the Consortium is that presently there is no coordination between these competing organizations and no principles guiding the definition of LCOS or evaluation of cost reduction pathways. There is a need for a coordinated and consolidated single LCOS definition and more consistent and comprehensive assessments of high-value R&D pathways.

In the area of economics, valuation and financing, the Consortium pursued four related assessment tracks: 1) evaluating existing and potential pathways for measuring and monetizing LDES services; 2) examining cost reduction pathways and value streams from societal and operational perspectives; 3) identifying risk to technology development that stems from economic uncertainty; and 4), and defining key policy gaps that will lead to refining traditional frameworks for financing, setting policy standards, and capturing value to ensure market readiness for the full range of LDES technologies.

For further industry action to reduce LDES costs, the Consortium has the following suggested approaches:

- ❖ *Define a unified approach to calculating levelized cost of storage (LCOS), ensuring it encompasses the entire system lifecycle.* There is a need for a unified LCOS definition and set of equations. Because different groups will have varying perspectives when defining LCOS, working groups that can address these competing perspectives and considerations should be consulted in order to facilitate broad-based acceptance of the final LCOS definition. Decommissioning costs should be estimated and included, as they vary across technologies and are frequently omitted from LCOS calculations. Once a final LCOS approach is defined, we recommend building and carrying out a rollout plan that could include Webinars, presentations at conferences, and user work sessions.
- ❖ *Continue investment in Storage Innovations (SI) 2030 and the enhanced targeting of high-value R&D investment for Federal and non-Federal resources.* DOE has historically supported 30+ storage technologies across several offices (e.g., Fuel Cell Technologies Office, Water Power Technologies Office, Office of Electricity Storage Division), often without pre-determined targets in mind or coordination between offices. LDES requires comprehensive planning for R&D investment that targets high-value R&D innovations to meet pre-defined goals with interoffice collaboration. SI 2030 and its underlying principles and results could help improve the performance of DOE R&D investments by defining high-value innovation targets, informing the development of the funding opportunity process, and improving cross-office coordination.
- ❖ *Drive cost reductions by segment through targeted investment and share lessons learned through publicly available databases and reports.* DOE published Storage Innovations (SI) 2030 in 2023. SI 2030 presented a framework for identifying high value R&D targets for 10 LDES technologies. This and other similar efforts can chart the path for industry to support fundamental breakthroughs for core LDES technologies. Support could target:
 - Material science breakthroughs,

- Development of improved manufacturing for LDES components, which could include modular designs to reduce costs and improve flexibility for project scalability and potential for applications,
- Efforts to reduce cost and improve reliability of LDES balance of system by advancing common component use,
- System integration efforts to lower costs and provide higher reliability and improved performance through improved and standardized interfaces when possible, and
- Efforts to reduce engineering, procurement, and construction costs by leveraging wider industry lessons learned in construction, commissioning, and interconnection efforts.
- Documentation of FOAK to nth-of-a-kind (NOAK) cost trajectories, so utilities and regulators can distinguish between inherent technology costs and costs related to early deployment when evaluating LDES investments.

E2. LDES technologies must achieve 7-15% improvement in roundtrip efficiency to compete with Li-ion storage and hydrogen.

Status:



=While some improvements have been made to address the challenge, significant action is still needed from various industry participants to address the challenge.

As a metric of performance, round-trip efficiency (RTE) measures how much energy a storage system returns compared to the energy used to charge it. Specifically, RTE measures the percentage of electricity retrieved from a storage system compared to the energy put in.

By DOE's estimates, average LDES RTEs theoretically range from 40% to 90% today but must improve by 7%–15% by 2030 for the sector to achieve sustained investment. Pumped hydro, for context, typically has a 70%–80% round trip efficiency. The 7-15% improvement in RTE is an industry target for 2030 rather than a universally achieved milestone. The Consortium acknowledges that RTE improvements across the spectrum of LDES technologies remains an ongoing goal.

For LDES, RTE is vital because low efficiency compounds over deep cycles, directly increasing operational costs and reducing project profits; can support strategic system sizing by requiring fewer generation assets to absorb storage losses; and improves market viability through improved comparisons with other system alternatives. RTE for LDES technologies has seen

incremental, project-specific gains rather than sweeping systemic jumps since 2024. Technical assessments indicate that while individual developers continue optimizing thermal and mechanical setups, overall industry efficiency targets still require a 7% to 15% boost to fully rival short-duration lithium-ion benchmarks.

The Consortium has observed that specific LDES technology types have achieved RTE improvements during the last three years, as validated by external resources:

- ❖ **Compressed Air & Mechanical:** Optimized adiabatic compressed air (A-CAES) designs and large-scale mechanical setups have pushed practical efficiencies closer to the 70% range through better thermal management, up from lower baseline prototypes.⁴⁵
- ❖ **Thermal & Fluidized Systems:** Advanced thermal configurations (such as fluidized sand beds) report low daily thermal dissipation losses (under 2%), maintaining high discharge capacity over extended multi-day periods.⁴⁶
- ❖ **Electrochemical & Flow:** Flow and iron-air chemistries hold steady in practical operational windows (typically 50% to 80% depending on scale), with institutional focus remaining heavily tied to system availability and cost-per-kWh reductions rather than RTE alone.⁴⁷

As of this writing, the Consortium acknowledges the following RTE performance data for LDES technologies⁴⁸:

Table 4.
RTE Ranges for LDES Technologies

Technology Type	Detailed Technology	RTE (Low)	RTE (High)
Electrochemical	Lithium-ion	85	92
Electrochemical	Sodium-ion	80	92
Electrochemical	Lead-acid	79	85
Electrochemical	Zinc-Anode	69	73
Electrochemical	Iron-Flow	71	72

⁴⁵ “Compressed Air Energy Storage (CAES): A Comprehensive 2025 Overview.” Urban A&O. January 31, 2025. <https://urbanao.com/compressed-air-energy-storage-caes-a-comprehensive-2025-overview/>

⁴⁶ “Innovation trends on high-temperature thermal energy storage to defossilize energy systems.” Journal of Energy Storage. December 2024. <https://www.sciencedirect.com/science/article/pii/S2352152X24038477>

⁴⁷ “Flow Batteries (Vanadium vs. Iron): LCOS Analysis for 10+ Hour Storage.” Energy Solutions Intelligence. December 2025. <https://energy-solutions.co/articles/sub/flow-batteries-vanadium-vs-iron>

⁴⁸ Data compiled in the LDES Technology Evaluation Matrix developed by the Consortium. <https://lidesconsortium.sandia.gov/lides-competitive-factor-matrix/>

Technology Type	Detailed Technology	RTE (Low)	RTE (High)
Electrochemical	Vanadium-Flow	60	75
Electrochemical	Organic-Solid Flow	70	80
Thermal	Molten Salt TES	45	60
Thermal	Solid Media TES - Pumped TES	51	65
Thermal	Solid Media TES - TPV	25	40
Thermal	Thermochemical	50	55
Mechanical	Pumped Storage Hydropower (PSH)	79	80
Mechanical	Advanced Compressed Air Energy Storage (Caverns)	60	70
Mechanical	Compressed Gas Energy Storage	74	75
Mechanical	Liquid Air	45	70
Mechanical	Gravitational Storage (Blocks)	82	83
Mechanical	Gravitational Storage (Railcars)	89	90
Chemical	Hydrogen	30	31

Charting new territory in RTE evaluations, the Consortium prepared information that can assist LDES technology evaluations by recognizing the factors that can influence RTE for specific technologies, sometimes in a negative way.

Table 5.
Factors impacting RTE for various LDES technologies

Technology	RTE Factor	Potential Improvements	Assumptions / Notes
Redox Flow Batteries (RFBs)	Cell voltage efficiency	Improved cell materials and designs	Reduce overpotentials (kinetic, ohmic, mass-transport)
	Coulombic efficiency	Improved membranes; improved cell/stack/system designs	Reduce crossover, shunt currents, and side reactions
	Parasitic (BOP) losses	Lower pressure drop; improved pumps and BOP design	System/BOP redesign to reduce pump power and auxiliary loads

Technology	RTE Factor	Potential Improvements	Assumptions / Notes
	Power conversion (DC–DC, DC–AC)	Higher-efficiency power conversion system (PCS)	New or improved PCS; depends on operating range and sizing
Lithium-ion	Electronic/ionic conductivity	Higher-conductivity materials; improved interfaces/contacts; higher-conductivity electrolyte	May introduce cost/manufacturability tradeoffs
	Thermal management	Lower-energy heat removal; higher operating temperature (within limits); higher effective thermal mass	Must maintain safety/lifetime constraints
	Coulombic efficiency	Reduce parasitic reactions; minimize SEI growth; reduce degradation mechanisms	Assumes improved materials and lower contaminants that catalyze parasitics
	Internal resistance & wiring	Reduce resistive losses (cells, busbars, interconnects)	Often involves cost/pack-design tradeoffs
	Charge/discharge rates	Reduce resistive heating at high C-rates	Assumes improved materials and thermal control to limit heat generation
	Standby losses	Lower self-discharge; improved degradation characteristics	Depends on chemistry and BMS strategy
Flow Batteries (general)	Electronic/ionic conductivity	Higher-conductivity materials; improved contacts; higher-conductivity electrolytes	Achievable, with potential cost tradeoffs
	Thermal management	Lower-energy heat removal; higher operating temperatures; higher thermal mass	Must maintain electrolyte stability and component compatibility
	Coulombic efficiency	Reduce parasitic reactions and degradation	Assumes improved materials and reduced contaminant-driven parasitics
	Charge/discharge rates	Reduce resistive losses	Assumes improved heat management at higher rates
	Internal resistance & wiring	Improved conductivity; reduced resistive losses	Achievable with design/cost tradeoffs
	Standby losses	Lower self-discharge; improved long-term stability	Chemistry- and design-dependent
Electrochemical ESS (cross-cutting)	Battery chemistry	Select chemistries with higher intrinsic efficiency	Chemistry sets fundamental voltage losses and side reactions

Technology	RTE Factor	Potential Improvements	Assumptions / Notes
	Side reactions & internal resistance	Reduce irreversible reactions (heat generation) and internal resistance	Materials, design, and operating window dependent
	Charge/discharge efficiency	Improve energy-transfer efficiency during charge and discharge	Minimize losses in cells, BOP, and controls
	Service life	Improve durability to maintain RTE over time	Aging increases resistance and parasitics
	State of charge (SOC)	Operate within SOC ranges that maximize efficiency	Avoid extreme SOC regions that increase losses
Large-format aqueous supercapacitors	Electronic/ionic conductivity	Higher-conductivity materials; improved contacts; higher-conductivity electrolyte	Generally achievable
	Thermal management	Lower-energy heat removal; higher operating temperatures; higher thermal mass	Generally achievable within device limits
	Coulombic efficiency	Reduce parasitic reactions; expand stable voltage window	Assumes improved materials and reduced contaminants; improved voltage stability window
	Internal resistance & wiring	Reduce resistive losses	Achievable with design/cost tradeoffs
	Charge/discharge rates	Reduce resistive losses at high power	Achievable with design/cost tradeoffs
Compressed hydrogen storage	Compression efficiency	OEM improvements in compressor technology	Generally achievable; depends on pressure ratio and duty cycle
	Storage pressure	Optimize compression staging and final pressure	Trade between tank volume, compression energy, and process needs
	Thermal energy management	Recover and reuse heat of compression / vessel fill	Use recovered heat on expansion or elsewhere in system
	Energy conversion device	Improved fuel cell performance or combustion efficiency	Dependent on end-use device selection and operating conditions
UPSH in salt domes (Underground PSH)	Wellbore size / fluid flow losses	Change from dual 24" tubing to single 36" wellbore	Estimated +5% RTE; may also reduce drilling costs; requires rigs capable of larger wellbores
Thermal energy storage (TES)	Thermal-to-electric conversion	Improved power cycles (combined cycle, sCO ₂ Brayton); improved thermal PV	Achievable with ongoing R&D and commercialization progress

Technology	RTE Factor	Potential Improvements	Assumptions / Notes
	Storage heat loss (hold period)	Improved insulation design / reduced thermal leakage	Strongly design- and temperature-dependent
	Electric-to-thermal conversion	High-temperature heat pumps; Joule heating; Induction heating	Depends on achievable temperature lift and COP; Material dependency
	Storage media handling	Improved high-temperature solids handling (e.g., skip-hoists)	Applies to circulating/particle/solid media concepts
	Primary heat exchanger	Higher heat-transfer coefficients; improved HX design; New material and manufacturing methods	Materials/fouling/pressure-drop; manufacturing constraints apply
	Parasitic power	Reduce pressure drop (gas HTF systems); natural circulation where feasible	Natural circulation may reduce pump power but adds design constraints

While RTE for some LDES technologies are improving, a broader and perhaps ultimately more significant observation made by the Consortium is that, while RTE and LCOS frequently cited as a determining performance metric, they are insufficient as a standalone basis for comparison across diverse LDES solutions. The Consortium identified the need to establish a broader, mapped metric set that spans functional performance, cost, environment/health/safety, manufacturability and supply chain constraints, operability/maintainability, deployability (siting, permitting, integration), and lifecycle attributes (longevity, degradation, duty cycle fit). Without a standardized metric framework (and consistent definitions/measurement methods), comparisons remain subjective and technology claims are difficult to evaluate.

Indeed, the Consortium observed that discussions in the broader community often overweight RTE and LCOS, even though overnight CAPEX and project finance realities can dominate decision-making – especially for first-of-a-kind deployments. Many end users optimize across multiple criteria (cost, safety, reliability, degradation, lifetime, operability, and bankability), and the “best” technology depends on the application and risk posture.

Specifically, the Consortium has observed an industry need to deploy an LDES evaluation tool that reflects end-user priorities. To address over-reliance on one-size-fits-all metrics (e.g., RTE, LCOS), the Consortium initiated development of an LDES evaluation tool that enables users to compare technologies using the metrics and quantitative or qualitative values of key metrics they value, rather than relying on externally imposed rankings. This supports more transparent trade-space exploration across CAPEX, lifetime, degradation, operability, safety, geographical constraints, and other criteria.

E3. The specific needs related to LDES workforce training (i.e., skills and training) are presently not well defined **& E4.** A comprehensive assessment of necessary supply chain improvements specific to LDES technologies does not presently exist.

The Consortium consistently recognized that supply chain and workforce development challenges are inter-related, and thus these two identified challenges are discussed in tandem.

Status:



=While some improvements have been made to address the challenge, significant action is still needed from various industry participants to address the challenge.

With regard to workforce training, LDES is facing a number of challenges. Consistent with some parts of the energy industry, an aging workforce is nearing retirement. This is found particularly with established LDES technologies like pumped storage hydro; as with the rest of the hydro industry, members of the workforce are retiring faster than the rate at which new workers are entering. The largest gap seems to exist in mid-career professionals as young workers are starting to successfully be brought into early-career jobs.

Something that affects the LDES industry in general and its workforce specifically is a lack of knowledge of its importance. It does not have the high profile of variable energy resources technologies, and is under-recognized as a critical element of the energy transition. People entering the workforce – even the energy workforce – are not as aware of career opportunities in energy storage and are therefore less likely to pursue the field.

The Consortium suspects, but does not have citable evidence, that there is a mismatch between worker location and workforce needs. This is found in the energy industry in technologies such as hydro and nuclear: people with the appropriate skills may not want to move to the locations where the skills are needed.

Many relevant skills in energy storage may be highly transferrable, so those trained in LDES jobs may leave the industry to move to competing industries that may offer better pay, opportunities, or locations. That is, if an individual can work on stationary batteries he or she can likely work on EV batteries as well, and the unregulated EV industry may offer higher wages in more exciting places than the regulated electric power industry.

On the other hand, there is a lack of standardization and badging of transferrable workforce skills. Some energy storage providers train their workers on their own proprietary systems, which makes them less mobile and competitive in the marketplace. Companies can effectively

create a “captive” workforce, and may wish to do so since the company is investing in worker training.

Trade schools and (especially) higher education shift their curricula slowly and tend to do so towards field where they know their graduates will have jobs. Because long-duration energy storage encompasses a broad array of technologies, and because there are not yet “clear winners” among the technologies, some training programs are reluctant to commit to LDES curricula that they fear will not be valuable to their students soon after graduation.

In addition, the Consortium remained very much aware that LDES technology development can be directly impacted by a number of supply chain factors. LDES technologies depend on a range of critical materials for which the U.S. is heavily or entirely import-dependent, with limited domestic production capacity. As deployment scales, demand for these materials will grow substantially, and current domestic supply chains are not positioned to keep pace.

Moreover, the Consortium acknowledged that LDES supply chains that originate outside the US may be compromised through intentional malicious action, fraud, or negligence of foreign actors. Reliance on overseas supply for critical LDES material and components may introduce safety risks due to variable quality standards, counterfeit parts, limited traceability, as well as reduced oversight of manufacturing practices.

The Consortium has observed that the LDES sector is entering a period of meaningful structural transition, with supply chain and manufacturing dynamics expected to shift considerably over the next decade across two key dimensions:

- ❖ *Technology Diversification*— The industry is moving toward a broader technology mix – chemical, electrochemical, thermal, and mechanical storage – and supply chain risk expands with it. Select countries of concern have consolidated control over strategic minerals, components, and manufacturing equipment across the full energy storage value chain, not just raw materials. Supply vulnerabilities may therefore emerge at multiple tiers, not just at the raw material level, and Western supply chain strategies will need to account for this depth of dependence. Compounding this, many emerging LDES technologies require entirely new manufacturing ecosystems with few adjacent industries to draw from, demanding disciplined, stage-gated capital deployment tied to technical maturity.
- ❖ *Regionalization of Supply Chains* — Geopolitical pressures and pandemic-era disruptions are driving a shift from hyper-globalized to regionally oriented supply chains. Realizing this shift requires modernizing domestic permitting and mining frameworks, while carefully calibrating policy responses to counter overseas state-subsidized competition without creating new vulnerabilities.

However, with this realization, the Consortium served an important purpose of evaluating current-state challenges associated with supply chain considerations specific to LDES technologies, including key considerations in the areas of extraction and processing; components manufacturing; storage system assembly and end-of-life management.

Related to this analysis specific to supply chain challenges, the Consortium assessed known and new barriers to workforce availability for LDES technologies. These barriers included competition for the same workers across industries, geographic mismatch between available labor pool and LDES-related jobs, lack of knowledge amongst potential trainees of opportunities in LDES, and several issues involved in connecting with members of historically underserved communities that could be potential sources for recruiting suitable workforce members.

Key observations that the Consortium reached include the following:

- ❖ LDES manufacturing readiness is as critical as technology readiness. A technology at TRL 7 that cannot be manufactured repeatably and cost-competitively is not deployment-ready.
- ❖ The US faces a two-layer supply chain vulnerability, including both raw materials (vanadium, nickel, zinc, graphite, rare earth elements, predominantly imported) and specialized manufacturing capabilities not yet widely available domestically.
- ❖ The workforce gap is structural. The talent pipeline is fragmented, and there is no clearly articulated national vision to coordinate training investment.
- ❖ Federal investment and industry-lab partnerships are the highest-leverage interventions.

The Consortium recognizes that several federal policy instruments are already actively shaping the domestic LDES manufacturing and critical materials landscape. The Infrastructure Investment and Jobs Act (IIJA), the Inflation Reduction Act (IRA), and the CHIPS and Science Act collectively provide billions in grants, loans, tax credits, and production incentives aimed at onshoring critical mineral processing, battery manufacturing, and supply chains. The IRA's Advanced Manufacturing Production Credit (45X) and Clean Vehicle Credit (30D) create direct financial incentives for domestic production of battery components and materials. The Defense Production Act (Title III) has been invoked to fund domestic graphite, vanadium, and nickel projects. The DOE's CMEI office plays a central role in translating federal policy intent into actionable supply chain and workforce outcomes for LDES and broader energy technologies.

In a unique exercise, the Consortium evaluated LDES supply chain and manufacturing efficiency from four angles: 1) material supply; 2) technology risk; 3) supply safety, and 4) workforce needs. Key findings across these four angles are provided for industry consideration.

1. *Material supply* — LDES technologies depend on a range of critical materials for which the U.S. is heavily or entirely import-dependent, with limited domestic production capacity. As deployment scales, demand for these materials will grow substantially, and current domestic supply chains are not positioned to keep pace.

The team assessed materials' supply risks for a range of LDES technologies, for which team members provided information. This assessment estimates the quantity of materials required to deploy 1 GWh of LDES capacity in 2024, and projects material demand through 2030, with a target of 12 GW of installed LDES capacity⁴⁹. Technologies evaluated include Zinc Ion, Compressed H₂, Liquid H₂, Ammonia/LOHC, Proton Exchange Membrane (PEM), Liquid Alkaline Electrolysis (LAE), and Vanadium Flow Battery (VFB). Material demand was estimated from industry-provided intensity data (per GWh) and scaled to 2030 projections. Domestic supply was projected using historical production data and compound annual growth rates (CAGR, 2015–2023). Each scenario assumes single-technology deployment to isolate material risks per technology, and identify which technologies are most resource-intensive or vulnerable to material shortages without the confounding effects of mixed deployment.

Findings indicate that the U.S. critical material supply chain for LDES is uneven and vulnerable. The most material-intensive technologies — Zinc Ion, PEM, VFB, and LAE — face potential shortages in key inputs. Core vulnerabilities include:

- ❖ Zinc & Manganese — High import dependence; key domestic mine nearing closure
 - ❖ Graphite — Near-total reliance on imports
 - ❖ Vanadium — Minimal domestic mining; primary production from a single producer
 - ❖ Platinum Group Metals — Geographically concentrated; limited domestic output
2. *Technology risk* — Many LDES technologies are still in early or pre-commercial stages, with unproven manufacturing processes and limited production precedent. Unlike lithium-ion batteries, which benefited from decades of consumer electronics manufacturing, most LDES chemistries lack adjacent industries from which to borrow tooling, talent, or process knowledge. This does not always attract capital investment needed to achieve cost-competitiveness through scale, as technologies have not reached sufficient maturity, creating a difficult timing tension between urgency and readiness.

The Consortium developed a risk framework to assess potential barriers to scale. This risk assessment provides a structured framework to identify, prioritize, and mitigate supply chain vulnerabilities threatening the commercialization of LDES technologies. Risks are evaluated across two dimensions — likelihood (High/Medium/Low) and impact (High/Medium/Low) and grouped into four categories: Material Supply (Scarcity or

⁴⁹ U.S. Department of Energy. (2023). *Pathways to Commercial Liftoff: Long Duration Energy Storage*. U.S. Department of Energy.

unavailability of key materials due to geopolitical issues or high demand), Manufacturing Capacity (Domestic production to meet scale or demand), Policy & Regulation (Tariffs, trade restrictions, or budget changes) and Workforce Development (Skilled labor shortages hindering manufacturing and deployment).

Findings suggest highest-priority risks are policy shifts and trade/market conditions — both highly likely and highly impactful, with potential to significantly disrupt costs and material supply. Medium-high risks are workforce gaps and funding shortfalls, which constitute threats to compound domestic manufacturing limitations and slow innovation.

3. *Supply safety* — Global LDES supply chains are exposed to risks beyond simple scarcity, including counterfeit components, variable quality standards, limited traceability, and deliberate interference by foreign actors. China in particular holds dominant positions not just in raw material production, but across processing, component manufacturing, and equipment supply, meaning vulnerabilities can emerge at multiple tiers of the supply chain simultaneously. Addressing this requires not only diversification of sourcing, but active engagement with U.S. government agencies.

The Consortium assessed available resources reporting/providing guidance regarding potential foreign supply threats. Reliance on overseas suppliers for critical LDES materials and components introduces significant safety and security risks. Foreign supply chains may be compromised through malicious action, fraud, or negligence, manifesting in three key vulnerabilities:

- *Quality Control* — Inconsistent overseas manufacturing standards can compromise material purity and component reliability, leading to performance or safety failures;
- *Counterfeiting* — Globalized supply chains increase the risk of counterfeit or tampered components entering the U.S., threatening battery safety and longevity; and
- *Traceability* — Limited visibility into overseas operations hinders compliance tracking and standard enforcement.

Securing the LDES supply chain is as critical as the technology itself. By leveraging available government, NGO, and industry resources, the LDES community can accelerate deployment while protecting safety and national security.

4. *Workforce needs* — Deploying LDES at scale requires a specialized workforce spanning engineering, advanced manufacturing, grid integration, installation, and maintenance, among other skills. Many LDES technologies represent a significant departure from conventional power systems, meaning workers may require substantial re-skilling.

Without deliberate investment in workforce development through partnerships between industry, labor organizations, community colleges, trade schools, and universities, labor shortages risk constraining deployment even where technology and materials are available.

The LDES sector is entering a period of meaningful structural transition, with supply chain and manufacturing dynamics expected to shift considerably over the next decade across three key dimensions:

- ❖ **Technology diversification**— The industry is moving toward a broader technology mix – chemical, electrochemical, thermal, and mechanical storage – and supply chain risk expands with it. Select countries of concern have consolidated control over strategic minerals, components, and manufacturing equipment across the full energy storage value chain, not just raw materials. Supply vulnerabilities may therefore emerge at multiple tiers, not just at the raw material level, and Western supply chain strategies will need to account for this depth of dependence. Compounding this, many emerging LDES technologies require entirely new manufacturing ecosystems with few adjacent industries to draw from, demanding disciplined, stage-gated capital deployment tied to technical maturity.
- ❖ **Regionalization of Supply Chains** — Geopolitical pressures and pandemic-era disruptions are driving a shift from hyper-globalized to regionally oriented supply chains. Realizing this shift requires modernizing domestic permitting and mining frameworks, while carefully calibrating policy responses to counter overseas state-subsidized competition without creating new vulnerabilities.
- ❖ **Automation as enabler for emerging technologies** — Advances in robotics, AI, digital twins, and process control offer a competitive opening for LDES. Unlike existing Li-ion facilities with entrenched processes, new facilities can integrate automation from day one - potentially achieving cost competitiveness faster than historical precedents suggest, once technologies reach capital-attracting maturity.
- ❖ **Workforce Development as a Structural Requirement** — The transition to new LDES technologies cannot rely on talent pipelines built for Li-ion or adjacent industries. Building the necessary workforce - spanning manufacturing, engineering, installation, and maintenance - will require deliberate investment in education and training programs, industry-academic partnerships, and long lead-time planning to ensure skilled labor availability keeps pace with deployment targets.

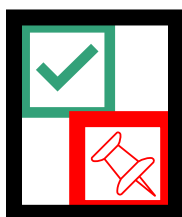
Taken together, these trends describe a supply chain landscape that will be more technologically diverse, more regionally structured, and more automation-intensive, with specific workforce skills — but also considerably more complex to navigate. Success will require coordinated action across industry, government, and the investment community to build new ecosystems, secure critical inputs, and establish the policy frameworks needed to compete on a field that is not yet level.

Remedial approaches that the Consortium believes are critical to address the supply chain and workforce development challenges that have identified include:

- ❖ Leverage available government, NGO, and industry resources, to help accelerate deployment while protecting safety and national security. A collaborative approach across these entities is essential to building a resilient and secure LDES ecosystem.
- ❖ Work toward diversified material sources across multiple suppliers and geographies. It is also important to scale domestic refining and processing capacity for critical materials, foster recycling ecosystems to supplement primary supply, and sustain development of emerging domestic projects.
- ❖ Expand domestic manufacturing capacity through economic incentives and workforce development partnerships, with utilities and education institutions.
- ❖ Advocate for stable, innovation-friendly policies and regulations that support the long-term growth of LDES technologies.
- ❖ Develop supply chain characterization/documentation for different LDES technologies, to identify potential points of vulnerability for primary, secondary and tertiary suppliers where applicable. This might encourage greater participation as it would not require single organizations to reveal any unique vulnerabilities and rather provide a more general look at the sector.

E5. A uniform approach toward developing resource adequacy compensation for LDES technologies does not exist competitive markets (ISO/RTO).

Status:



=While some improvements have been made to address the challenge, significant action is still needed from various industry participants to address the challenge.

It remains the case that there is no uniform approach toward developing resource adequacy compensation for LDES technologies does not exist, in either regulated markets (PUC evaluation) or competitive markets (ISO/RTO). However, it is the Consortium's observation that several markets are actively evolving their frameworks to provide RA compensation for LDES. In

addition, the Consortium has facilitated extensive dialogues among industry stakeholders to further identify remedial approaches toward addressing this challenge, which reflects progress that has been made.

To be clear, at present no organized wholesale electricity markets fully or explicitly compensate LDES technologies to simply exist and be available to serve the grid (i.e., to provide for multi-day resource adequacy). Existing capacity and resource adequacy frameworks predominantly favor short-duration storage (typically 4 hours or less). This is largely due to the fact that wholesale capacity constructs rely upon Effective Load Carrying Capability (ELCC) accreditation rules that are typically structured around peak hours matching 2-to-4-hour battery profiles rather than multi-day deficits that could be served by LDES technologies. As a result, the opportunity for LDES technologies to be compensated for RA does not universally exist due to the lack of the lack specific multi-day or deep reserve products that appropriately value the continuous energy-shifting capabilities (or monetize the prolonged reliability and resilience attributes) that are inherent to LDES.

Wholesale market regulators are well aware of this deficit and the Consortium recognized that efforts to develop market mechanisms to fully reflect the unique values of LDES to provide RA are taking place within specific markets. Examples of market reform approaches that have been observed include and categorized as follows:

- ❖ **Shifting toward “multi-hour” frameworks:** While traditional RA models have largely been constructed around a single monthly or annual gross peak hour structure, market reforms to address the unique capabilities provided by LDES technologies are being pursued via a transition to frameworks that examine net peak risks across all 24 hours of a day. Examples of this are the California ISO’s implementation of its Slice-of-Day (SOD) RA framework, wherein instead of assessing capacity based on a single peak hour, Load-Serving Entities (LSEs) must prove they have enough capacity to cover 24 discrete hourly “slices” on the worst day of each month.⁵⁰ The anticipated result of this framework is that LDES technologies can be appropriately recognized and compensated for charging and discharging sufficiency over continuous blocks of time, allowing them to monetize their multi-hour capacity across multiple slices. In practice, this appears to be resulting in LSEs contracting with storage resources to guarantee capacity availability over specific periods, providing developers with steady, de-risked income.
- ❖ **Transitioning to seasonal and sub-annual markets.** Market reforms intended to recognize the unique RA needs associated with extended multi-day weather events (as opposed to just weather incidents that last for hours) are also developing that provide more suitable market constructs for LDES technologies. ISO-New England is advancing its Capacity Auction Reforms (CAR) initiative. This will switch the market from an annual capacity construct to a sub-annual (seasonal) market structure, scheduled to launch by

⁵⁰ “Storage Reforms in California’s Resource Adequacy Proceeding.” California Energy Storage Alliance. February 4, 2026. <https://storagealliance.org/news/cesa-advances-storage-focused-reforms-in-californias-resource-adequacy-proceeding>

June 2028.⁵¹ The anticipated impact is that, under seasonal tracking, LDES technologies would be more appropriately compensated for winter scarcity and multi-day fuel-security shortfalls, serving as a direct mechanism to replace retiring fossil-fuel peaker plants.

- ❖ ***Establishing duration-based valuation mechanisms.*** It is likely that market operators will continue to shift from flat-rate capacity counting in RA compensation mechanisms toward a duration-based valuation construct such as Effective Load Carrying Capability (ELCC) that offers a more accurate measurement of a resource's actual contribution to, for example, preventing blackouts. This transition is being observed in PJM, MISO, and NYISO.⁵² This shift acknowledges the unique value propositions of LDES technologies when compared to shorter-duration energy storage technologies. By comparison, the *marginal* reliability value of shorter-duration energy storage assets (e.g., lithium-ion batteries) typically declines during prolonged grid stress events, whereas LDES technologies can maintain a much higher marginal ELCC rating due to the inherent ability to remain operational through multi-hour and multi-day reliability events.

While these examples of market reform are promising, they do not suggest a universal or even consistent approach toward developing market constructs to account for LDES resource adequacy compensation. The evolution of market reform at the wholesale level remains a patchwork effort with individual ISOs and RTOs developing their own unique approaches. The Consortium devoted extensive resources toward evaluating approaches toward developing a more universal approach that could be adopted, and the analysis consistently landed on the need for more effective modeling tools to account for the unique ways in which LDES technologies contribute to RA requirements.

For example, one distinction identified by the Consortium was that, while shorter-duration energy storage may be more typically dispatched during periods of peak demand, LDES can be operated more similarly to a baseload resource for prolonged periods of time. As a result, in addition to peak shaving, LDES resources can potentially defer investments in new firm generation capacity. This system value is traditionally captured through capacity markets and other resource adequacy mechanisms. However, current capacity market structures do not always fully recognize the ability of LDES to provide sustained energy generation over prolonged periods.

A consensus across the Consortium was that the determination of optimal resource mixes necessary for reliability will require modelling and coordination between modelers, resource adequacy market participants, resource owners and developers. These models will need to

⁵¹ "Capacity Auction Reforms Key Project." ISO-New England. <https://www.iso-ne.com/committees/key-projects/capacity-auction-reforms-key-project>

⁵² "Energy Storage Market Design Reforms: A Roadmap to Unlock the Potential of Energy Storage" Brattle Group. April 3, 2025. https://cleanpower.org/wp-content/uploads/gateway/2025/04/Storage-Market-Reform-Roadmap-Analysis_FINAL.pdf

capture storage resource operational parameters to ensure reliable outcomes. These are additional complexities that are not included in most resource adequacy constructs today.

Accordingly, the Consortium developed a set of suggested approaches that can be considered in the effort to create a more consistent, universal approach toward wholesale market RA compensation for LDES technologies:

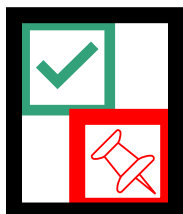
- ❖ Develop a suite of resource adequacy constructs based on duration that can serve a variety of use cases and support grid reliability. ISOs/RTOs should consider developing a portfolio of resource adequacy products with longer durations (e.g., 10 , 24, 100 hours) to address a variety of use cases and grid needs. Doing so would provide a clear market signal to technology and project developers that will enable them to sign offtake agreements with utilities and finance projects of varying durations. Deploying energy storage resources with a range of durations (possibly up to seasonal timescales) will enhance grid reliability in the face of weather-driven cycles and improve its ability to integrate variable energy resources (VERs).
- ❖ Move away from compensation paradigms that introduce revenue uncertainty. Mechanisms like ELCC introduce uncertainty in future revenue streams for resources, as does the often volatile nature of the forward capacity markets. Revenue uncertainty increases risk, which in turn increases financing costs. These costs can prevent resources from being developed and increase overall costs for future grid operations. These increased costs are passed on to ratepayers.
- ❖ Ensure open access by defining eligibility requirements on the basis of performance rather than technology attributes.
- ❖ Ensure that resource adequacy accreditation increases with increasing storage duration and reflects marginal reliability value.
- ❖ Offer multi-day firm energy products with performance incentives tied to EUE reduction
- ❖ Consider market mechanisms to de-risk investments, such as cap-and-floor or indexed contract-for-differences.
- ❖ Formalize the value of storage as a transmission asset in market design and planning procedures.
- ❖ Eliminate double charging and harmonize hybrid settlement procedures.
- ❖ Develop enhanced capacity accreditation methods to capture the value of LDES in market-driven resource adequacy frameworks, specifically ensure that capacity accreditation is duration-aware.
- ❖ Establish standardized approaches to considering extreme weather conditions in resource adequacy assessments.

- ❖ Develop and implement new market mechanisms that enable resources to split their bids to reflect individual attributes beyond energy (e.g., load following, synchronous inertia, short-circuit current, grid resilience).
- ❖ Investigate and analyze options for a multi-day forward energy or capacity product to support resilience to unforeseen extreme events and quantify the potential market impacts. For example, a week-ahead capacity market with bids structure in units of MW-day.
- ❖ Develop and implement methods to capture LDES value without extending energy market horizons, for example through resource adequacy mechanisms or new non-traditional market structures specific to LDES.
- ❖ Investigate de-risking mechanisms, such as a cap-and-floor or indexed long-term contracts, to provide additional incentives for LDES resources whose value is not fully captured in merchant markets.
- ❖ Improve tariff clarity and dual-use rules to avoid double charging and clarify hybrid and transmission-related treatment.

E6. There is presently a lack of resources regarding how to evaluate grid upgrades or expansions that will be necessary to accommodate both new LDES systems & **E7.** LDES is not included in most utility grid firming plans.

The Consortium observed that the challenge of LDES not being included in most utility grid firming plans is closely related to a lack of resources regarding how to evaluate grid upgrades or expansion, and thus these two identified challenges are discussed in tandem.

Status:



=While some improvements have been made to address the challenge, significant action is still needed from various industry participants to address the challenge.

The Consortium acknowledges that, at the start of its operation in January 2024, it was generally the case that LDES was not routinely required as the firming/grid reliability needs for current conditions can typically be achieved with shorter duration energy storage. The default to select shorter duration energy storage alternatives over LDES technologies was largely due to the

long-standing condition in which utilities are bound by an obligation to ratepayers and accordingly may be averse to pursue emerging or novel technologies that may put ratepayers at risk. Without consideration of scenarios that may demonstrate the value of LDES or the means to quantify all grid firming and reliability services, utilities will not plan for the deployment of these technologies.

Since January 2024, the Consortium has witnessed a paradigm shift, as evidenced by a number of examples that can be cited, to suggest that a shift is taking place to more routinely consider LDES technologies in utility grid firming plans, integrated resources plans (IRPs), distribution system upgrades, etc. This shift is occurring both due to regulatory mandates requiring such a consideration and more voluntary, proactive determinations by utility planners that recognize both the long-term value that LDES technologies offer and the necessity of including the resources across grid operations.

While still not a standard practice, more forward-thinking utilities are now actively including LDES in long-term planning. The Consortium identified the following examples to illustrate this shift toward including LDES technologies in utility grid firming plans:

- **Xcel Energy:** Serving Minnesota, Colorado, and New Mexico, Xcel is including LDES in its resource plans. Partnering with storage developer Form Energy, Xcel integrated multi-day pilot projects and massive gigawatt-hour scale iron-air storage systems into its resource planning for retiring coal plant sites in Minnesota and Colorado.⁵³
- **PacifiCorp:** In its comprehensive PacifiCorp Integrated Resource Plan, the utility incorporated multi-day iron-air battery storage into its preferred long-term portfolio, scheduling hundreds of megawatts of 100-hour LDES scaling up toward multi-gigawatt integration by 2045.⁵⁴
- **Georgia Power:** The largest subsidiary of Southern Company has partnered with Form Energy to test and deploy a 100-hour iron-air battery to assist with grid firming. The plan is to deploy a 15 MW /1500 MWh iron-air battery system in Georgia, as part of the utility's plan to integrate additional cost-effective resources into its system while maintaining grid reliability and resiliency.⁵⁵

⁵³“ Form Energy Partners with Xcel Energy on Two Multi-day Energy Storage Projects.” Form Energy news release. January 26, 2023. <https://formenergy.com/form-energy-partners-with-xcel-energy-on-two-multi-day-energy-storage-projects/>

⁵⁴2025 Integrated Resource Plan. PacifiCorp. <https://www.pacificorp.com/energy/integrated-resource-plan.html>

⁵⁵“ Form Energy, Georgia Power Continue Forward With 15 Megawatt Iron-Air Battery System Agreement.” Form Energy news release. June 12, 2023. <https://formenergy.com/form-energy-georgia-power-continue-forward-with-15-megawatt-iron-air-battery-system-agreement/>

- **Puget Sound Energy:** Partnered on memorandum-of-understanding frameworks to evaluate and integrate 10-MW/100-hour multi-day pilot deployments directly into resource adequacy assessments for the Pacific Northwest footprint.⁵⁶

These examples from diverse regions across the US suggest what the Consortium believes is a trend of utilities incorporating LDES technologies into their long-range resource plans that will continue to gain momentum through this decade and beyond. Another related indicator that the Consortium identified in its analysis is the shift from localized modeling to holistic, 20-year grid planning.

In late 2024, FERC issued Order No. 1920, mandating that regional transmission providers adopt 20-year long-term planning scenarios, replacing short-sighted, piecemeal local planning with mandatory, forward-looking regional planning spanning at least 20 years. This holistic shift accounts for shifting power demands, large-scale renewable generation, and extreme weather events. Driven by FERC Order No. 1920, it is the Consortium's observation that planners will now increasingly evaluate transmission expansions and LDES as complementary, system-wide assets rather than isolated point-to-point solutions.

LDES will be a necessary component of a modern, reliable grid. However, there is currently an unlevel playing field for evaluating the benefits of LDES relative to traditional generators and other shorter-duration storage systems. Current toolsets fail to capture: the full 8,760 hours in a 1-year simulation, value at all levels of the grid (e.g., bulk energy, ancillary services, distribution, transmission), sub-hourly flexibility, the value of reliability services, and the value of LDES' contribution to grid resilience through an assessment of low frequency high impacts. Models, frameworks, and data sets are required to more fully value the services provided by LDES technologies.

While these examples indicate what could become a standard practice of including LDES technologies in utility grid forming plans in coming years, the Consortium has identified a set of approaches to address this challenge that it offers to the industry for consideration. These approaches include:

- ❖ **Perform needed research to identify and close key modeling gaps for LDES technologies, and develop tools and datasets for closing these gaps.** Research organizations should reach out to stakeholders (e.g., developers, market operators, regulators, utilities) to formulate a list of key gaps and modeling needs and efforts should be made to develop models, frameworks, and data sets required to more fully value the services provided by LDES technologies. Enhanced datasets could include those relating to future weather patterns and the associated impact on resource production and load. Third party (i.e., national labs and other research organizations) validation of performance to inform cost and performance inputs to the model/planning process

⁵⁶ "Puget Sound Energy partners with Form Energy to evaluate multi day energy storage solutions." Puget Sound news release. January 5, 2024. <https://www.pse.com/en/press-release/details/Puget-Sound-Energy-partners-with-Form-Energy-to-evaluate-multi-day-energy-storage-solutions>

would also be valuable. The focus should not be on the development of a comprehensive model but rather filling key gaps to support the advancement of existing commercial tools, including those related to capacity expansion, transmission expansion, production cost, resource adequacy, and other more comprehensive tools used in the integrated resource planning process.

- ❖ **Grid firming plans should include scenarios of greater penetration of VERs that produce protracted energy deficit and surplus periods.** Higher levels of VER penetration and long duration events such as extreme weather that leads to long-term spikes in energy demand that coincides with reduced energy production increases the need for LDES. The fact that grid firming plans neglect LDES could be a result of not planning for these realistic, though lower-probability, scenarios. If grid firming plans were required to include scenarios that include higher penetration of VERs, evolving weather patterns, and protracted energy deficit and surplus periods, LDES would be a logical means of planning for addressing those needs.
- ❖ **Utilities and regulators should be provided with tools or other means of measuring the value of grid firming and the resilience and reliability provided by LDES.** Utilities and regulators will require additional models, tools, and data to consider the grid firming impacts of LDES deployment, such as foregone outages, facilitating regional economic growth, and other social, environmental, and economic factors. While there is a burgeoning literature on these topics and much can be learned from spending time reviewing the academic contributions to our understanding of these benefits, there is a lack of consensus among experts and such knowledge may not be particularly accessible to utilities and regulators.
- ❖ **Grid Investment Planning. Capture the full array of grid investments that address energy deficits directly tied to reliability and resilience performance metrics in resource planning and other grid planning processes by applying all-inclusive solutions and a sound cost framework.** Comprehensive grid investment planning is needed as a national energy security priority to solve energy deficits arising from VER adoption, electrification demand, and other factors at localized regions tailored to extreme events and typical weather conditions. The Consortium recommends the formation of a “Grid Energy Deficit Working Group” comprised of DOE, FERC, NARUC, Utilities, RTOs/ ISOs to: a) perform gap analysis of grid investment planning to identify risks and constraints; b) expand reliability and resilience analysis to include high renewable penetration rates and electrification across sectors under varied weather scenarios and for all time scales; c) establish mechanisms and accountability metrics for resource planning outcomes; d) adopt a comprehensive approach taking into consideration the full array of grid investments to be deployed in resource planning and other major planning processes across generation, T&D, and retail in regulated and competitive markets; adopt an all-inclusive cost methodology encompassing localized costs of outages and other non-economic factors.



- ❖ **Prudency Standards. Enhance prudency standards set by public utility commissions (PUCs) by applying all-inclusive solutions and a cost framework.**
Today's prudency standards are outdated and must be enhanced to unlock the full array of prudent grid performance investments tied to a set of metrics that solve energy deficits.
- ❖ **Dynamic Modeling. Perform real-time grid threshold modeling in regulated and competitive markets to signal the deployment of mechanisms to address energy deficits.** To solve energy deficits from accelerated renewable adoption and rapid electrification demand across varied weather conditions, dynamic grid modeling is needed urgently. Formation of working groups are recommended to: a) expand today's grid modeling to plan for energy deficits at all time scales incorporating demand, production, weather variations and other externalities; b) embed the capability to model a full array of diversified mechanisms tied to metrics in regulated and competitive markets for a localized energy deficit strategic approach; c) embed price and other major risks in modeling (i.e., natural gas prices, including volatility driven by electrification and the associated impact of gas pricing during winter peaks); d) linkage of dynamic modeling to grid investments, energy deficit mechanisms, and metrics to drive improved grid resilience and reliability outcomes; and e) establish standardized energy deficit policies with a set of protocols to deploy efficient and stackable mechanisms based on indicators and deviations as signals for deployment.
- ❖ **Planners and modelers should introduce the following metrics when reporting on historical or simulated future grid performance: EUE, and the 95th percentile of EUE (EUE95) for reliability; 95th percentile of SAIDI for resilience.** Historically, reliability planning has relied on LOLE and LOLP, which do not indicate the severity of potential loss-of-load events. Metrics like EUE and LOLH provide more information about the severity and magnitude of bulk grid reliability needs. Common reliability metrics (e.g. LOLE, LOLP, LOLH, EUE, SAIDI, SAIFI, and CAIDI) are average metrics, reporting on the average performance of the system; they do not provide clear insight into performance during infrequent high-impact events, like the expected magnitude of a 1-in-20-year loss of load event. The most concerning reliability challenges happen infrequently, and average metrics will not provide information about the duration, frequency, and severity of the most important challenges. Information on the 90th, 95th or 99th percentile of key reliability metrics can identify what resources the grid will need to address the most challenging issues. EUE and SAIDI provide information on the severity of reliability events; the 95th percentiles thereof provide information on the severity of infrequent, yet consequential reliability events.

The suggested approaches also point to important opportunities in cybersecurity, physical security, and system planning. As LDES becomes more interconnected with grid operations, distributed resources, and digital communications, security must be addressed as a core design and integration issue rather than as a secondary consideration. Risk-based guidance for different LDES use cases, improved data-risk management, more consistent interconnection security expectations, and better tools for evaluating grid upgrades and lifecycle impacts would

all help support wider adoption. Taken together, these opportunities suggest that progress in LDES safety and grid security will depend on a more integrated approach that links standards, training, planning, and operational protection into a coherent foundation for commercialization.

E8. Presently, there is no publicly available evaluation of LDES technologies against primary competitive factors.

Status:



= Significant improvement addressing the challenge has been achieved during the tenure of the Consortium.

Providing a product for the industry to address this challenge is one of the most significant accomplishments of the Consortium. When the Consortium commenced in January 2024, there was indeed no publicly available tool that enabled the evaluation of diverse LDES technologies against a set of primary competitive factors. In response, the Consortium developed a release for public use a Web-based tool⁵⁷ that can be used by industry stakeholders to evaluate and track LDES technologies, which greatly enhances the selection process when determining which specific technology option is best suited for unique geographical, performance, and use case considerations. This tool builds on that foundation by also providing an interactive platform for visualizing LDES metrics and tracking projects.

This particular challenge comprised many levels of complexity. Fundamental to the challenge is the fact that the Consortium, upon commencing operations in January 2024, quickly discovered there was no unified, consistently maintained list of “what counts” as LDES technology that existed in the public domain. Across the LDES ecosystem, multiple organizations track technologies using different definitions, boundaries, and category schemes.

The Consortium repeatedly encountered inconsistent nomenclature (e.g., what duration thresholds qualify, how hybrid systems are categorized, and where emerging concepts fit). This fragmentation makes it difficult for end users, funders, and evaluators to communicate clearly, compare like-for-like options, or identify gaps. A living, homogenized taxonomy and tracking tool is needed – one that defines clear categories, supports consistent sub-classifications, and is updated to include emerging technologies.

The Consortium also discovered that there was no clear, consensus-based set of key LDES metrics suitable for apples-to-apples comparison across diverse LDES technologies. While RTE

⁵⁷ LDES Technology Evaluation Matrix developed by the Consortium. ides-tool.sandia.gov

and LCOS are frequently cited, they are insufficient as a standalone basis for comparison across diverse LDES solutions. The Consortium identified the need to establish a broader, mapped metric set that spans functional performance, cost, environment/health/safety, manufacturability and supply chain constraints, operability/maintainability, deployability (siting, permitting, integration), and lifecycle attributes (longevity, degradation, duty cycle fit). Without a standardized metric framework (and consistent definitions/measurement methods), comparisons remain subjective and technology claims are difficult to evaluate.

Moreover, it was the Consortium’s observation that an over-reliance on RTE and LCOS has been pervasive across the industry; overnight CAPEX and multi-metric tradeoffs are underweighted. The group observed that discussions in the broader community often overweight RTE and LCOS, even though overnight CAPEX and project finance realities can dominate decision-making – especially for first-of-a-kind deployments. Many end users optimize across multiple criteria (cost, safety, reliability, degradation, lifetime, operability, and bankability), and the “best” technology depends on the application and risk posture. Consequently, the Consortium identified a critical need for tools that allow users to compare technologies based on user-selected weighting of criteria, rather than a single “universal” ranking determined by others.

The Consortium created a unified LDES technology inventory and taxonomy entitled the “LDES Technology Evaluation Tool. The tool includes a consolidated list of LDES technologies (over 60 unique technologies) to create a shared baseline for what is considered relevant for LDES and how technologies are categorized. No requirement of “storage hours” was implemented due to ambiguity of long duration requirements for various applications and ability of most energy storage technologies to achieve “long duration” status with increased deployment of units. The technologies included in the LDES Technology Evaluation Tool are listed in the following table:

Table 6.
Energy Storage Technology List

Electrochemical	Lithium-ion Batteries	Lithium-ion Nickel Manganese Cobalt Oxide (NMC)
		Lithium-ion Nickel Cobalt Aluminum Oxide (NCA)
		Lithium-ion Iron Phosphate (LFP)
		Lithium-ion Cobalt Oxide (LCO)
		Lithium Manganese Oxide (LMO)
		Lithium Titanium Oxide (LTO)
		Lithium Sulphur (S)
	Lithium-metal Batteries	Liquid state metal
		Solid state metal
	Calcium-ion Batteries	Calcium-ion Batteries
	Sodium Batteries	Sodium-ion (Na-ion)
		Sodium Sulphur
	Lead Batteries	Lead-acid Batteries (PbA)
		Bi-polar lead batteries
		Non-aqueous lead batteries
		Crystal modified lead batteries
	Zinc Batteries	Zinc-air (Zn-air)
		Zinc-bromine
		Zinc-ion (Zn-MnO ₂)
		Zinc-manganese dioxide (Zn-MnO ₂)
	Hybrid Flow Battery	Iron-Iron redox flow battery
		Zinc-bromine redox flow battery
		Zinc-Iron flow battery
	Redox Flow Battery (RFB)	Vanadium redox flow battery
		Organic redox flow battery
		Metal complex flow battery
		Polysulfide bromine flow battery
		Aqueous electrolyte
		Uranium redox flow battery
		Hydrogen Bromide
	Iron Batteries	Iron air batteries (Fe-air)
	Dry Cell Batteries	Zinc-carbon batteries
		Carbon-oxygen
		Alkaline
		Nickel cadmium
		Nickel-metal hydride
		Nickel Hydrogen
	Magnesium Batteries	Magnesium Batteries
	Aluminum Batteries	Aluminum Batteries
Thermal	Sensible Heat Storage	Two-Tank Molten Salt
		Thermocline Packed Bed
		Fluidized bed (FBTES)
		Static Bed
		Moving particle thermal energy storage (MPTES)
		Reservoir thermal energy storage (RTES)
		Borehole thermal energy storage (BTES)
		Aquifer thermal energy storage (ATES)
		Fractured thermal energy storage (FTES)
		Cavern thermal energy storage (CTES)
		Deep Hot Dry Rock Geothermal (DHDRG)
		Pit thermal energy storage
	Latent heat	Water/ICE storage
		Metal alloy
		Phase change materials (PCMs)
	Thermochemical	Metal oxide
		Carbonates
		Sulfur cycle
Mechanical	Pumped Storage Hydropower (PSH)	Conventional

Electrochemical	Lithium-ion Batteries	Lithium-ion Nickel Manganese Cobalt Oxide (NMC)
		Lithium-ion Nickel Cobalt Aluminum Oxide (NCA)
		Lithium-ion Iron Phosphate (LFP)
		Lithium-ion Cobalt Oxide (LCO)
		Lithium Manganese Oxide (LMO)
		Lithium Titanium Oxide (LTO)
		Lithium Sulphur (S)
	Lithium-metal Batteries	Liquid state metal
		Solid state metal
	Calcium-ion Batteries	Calcium-ion Batteries
	Sodium Batteries	Sodium-ion (Na-ion)
		Sodium Sulphur
	Lead Batteries	Lead-acid Batteries (PbA)
		Bi-polar lead batteries
		Non-aqueous lead batteries
		Crystal modified lead batteries
	Zinc Batteries	Zinc-air (Zn-air)
		Zinc-bromine
		Zinc-ion (Zn-MnO ₂)
		Zinc-manganese dioxide (Zn-MnO ₂)
	Hybrid Flow Battery	Iron-Iron redox flow battery
		Zinc-bromine redox flow battery
		Zinc-Iron flow battery
	Redox Flow Battery (RFB)	Vanadium redox flow battery
		Organic redox flow battery
		Metal complex flow battery
		Polysulfide bromine flow battery
		Aqueous electrolyte
		Uranium redox flow battery
	Iron Batteries	Hydrogen Bromide
		Iron air batteries (Fe-air)
	Dry Cell Batteries	Zinc-carbon batteries
		Carbon-oxygen
		Alkaline
		Nickel cadmium
		Nickel-metal hydride
		Nickel Hydrogen
	Magnesium Batteries	Magnesium Batteries
	Aluminum Batteries	Aluminum Batteries
	Pumped Storage Hydropower (PSH)	Mines
	Pumped Storage Hydropower (PSH)	Salt Caverns
	Pumped Storage Hydropower (PSH)	Low Impact PSH
	Pumped Storage Hydropower (PSH)	Small Scale PSH
	Compressed Air Energy Storage (CAES)	Diabatic
	Compressed Air Energy Storage (CAES)	Adiabatic
	Compressed Air Energy Storage (CAES)	Hybrid
	Compressed Air Energy Storage (CAES)	Isothermal
	Compressed Gas Energy Storage	Above Ground Compressed Gas Energy Storage
	Flywheels	Flywheels
	Liquid Air	Liquid Air
	Geomechanical	Geomechanical
	Gravitational Storage	Rail Cars
	Gravitational Storage	Blocks
Chemical		Above ground
		Underground
	Hydrogen	Subsea
	Ammonia	Anhydrous Ammonia (NH ₃)
	Organic Hydrides	Methyl Cyclohexane - Toluene cycle
	Inorganic Hydrides	Sodium borohydride (NaBH ₄)
	Biomass	Green Hydrocarbons

Electrochemical	Lithium-ion Batteries	Lithium-ion Nickel Manganese Cobalt Oxide (NMC)
		Lithium-ion Nickel Cobalt Aluminum Oxide (NCA)
		Lithium-ion Iron Phosphate (LFP)
		Lithium-ion Cobalt Oxide (LCO)
		Lithium Manganese Oxide (LMO)
		Lithium Titanium Oxide (LTO)
		Lithium Sulphur (S)
	Lithium-metal Batteries	Liquid state metal
		Solid state metal
	Calcium-ion Batteries	Calcium-ion Batteries
	Sodium Batteries	Sodium-ion (Na-ion)
		Sodium Sulphur
	Lead Batteries	Lead-acid Batteries (PbA)
		Bi-polar lead batteries
		Non-aqueous lead batteries
		Crystal modified lead batteries
	Zinc Batteries	Zinc-air (Zn-air)
		Zinc-bromine
		Zinc-ion (Zn-MnO ₂)
		Zinc-manganese dioxide (Zn-MnO ₂)
	Hybrid Flow Battery	Iron-Iron redox flow battery
		Zinc-bromine redox flow battery
		Zinc-Iron flow battery
	Redox Flow Battery (RFB)	Vanadium redox flow battery
		Organic redox flow battery
		Metal complex flow battery
		Polysulfide bromine flow battery
		Aqueous electrolyte
		Uranium redox flow battery
	Iron Batteries	Hydrogen Bromide
		Iron air batteries (Fe-air)
	Dry Cell Batteries	Zinc-carbon batteries
		Carbon-oxygen
		Alkaline
		Nickel cadmium
		Nickel-metal hydride
		Nickel Hydrogen
	Magnesium Batteries	Magnesium Batteries
	Aluminum Batteries	Aluminum Batteries
Electrical	Capacitors	Supercapacitors
	Capacitors	Electro-chemical Capacitors
	Capacitors	Aqueous
	Superconducting Magnetic Energy Storage	Superconducting Magnetic Energy Storage

The LDES evaluation tool enables users to compare technologies using the metrics and quantitative or qualitative values of key metrics they value, rather than relying on externally imposed rankings. This supports more transparent trade-space exploration across CAPEX, lifetime, degradation, operability, safety, geographical constraints, and other criteria. The metrics incorporated into the tool include:

- ❖ **Technology definition.** Identifies the LDES technologies for evaluation and inclusion in the tool.

- ❖ **Taxonomy consolidation.** Groups technology-specific risks into overarching common risks, filtered by potential impact on commercial liftoff, and creates a systematic way to compare all LDES technologies side-by-side.
- ❖ **Subcategory definition.** Defines precise, technology-agnostic subcategory definitions to ensure proxy indicators emerge naturally and consistently across technologies.
- ❖ **Proxy indicator mapping.** Defines measurable proxy indicators for each technology-agnostic risk subcategory and map the relevant indicator for each technology while maintaining the same underlying risk dimension.
- ❖ **Quantitative evaluation and aggregation.** Standardizes collected data into risk scores reflecting uncertainty for consistency and generate a comprehensive risk heatmap by technology with user-adjusted weighting.

The tool provides an established a standardized list of key LDES metrics spanning cost, performance, deployability, and safety, as outlined in Table 7. The list is intended to support more consistent, apples-to-apples comparisons across technology classes. Not all metrics identified are applicable to every technology, however the list generally spans most technologies and identifies metrics that should be considered if possible.

Table 7.
Competitive Factors and Definitions

Functional Performance	
Energy Rating (MWh)	Rated usable energy capacity of the system (deliverable energy under specified conditions).
Power Rating (MW)	Rated charge and/or discharge power capacity of the system. Specify separate charge and discharge ratings if they differ, and the conditions under which ratings apply.
Minimum feasible energy rating (MWh)	Smallest feasible energy rating achievable based on current technology and practical system integration constraints.
Minimum feasible power rating (MW)	Smallest feasible power rating achievable based on current technology and practical system integration constraints.
Maximum feasible energy rating (MWh)	Largest feasible energy rating achievable based on current technology and practical system integration constraints.
Maximum feasible power rating (MW)	Largest feasible power rating achievable based on current technology and practical system integration constraints.
Nominal discharge duration (h)	Time the system can discharge at the designed power rating; calculated as energy capacity divided by discharge power rating (MWh/MW)(MWh/MW) under stated conditions.
Round trip efficiency	Ratio of energy discharged from the system (from a defined starting state of charge) to the energy received to return the system to the same starting state of charge, under specified operating conditions.
Self Discharge Rate (%/hr)	Rate at which the storage device loses stored energy while in a hold/idle state, expressed as percent of stored energy per hour under specified conditions.
Operational Life (Yrs)	Maximum designed years of operation prior to removal from service, based on specified duty cycle and operating conditions.
Inertia Constant (s)	Kinetic energy stored in the LDES system at rated speed divided by rated apparent power.
Degradation Rate (% Energy Capacity Change/Cycle)	Rate at which the energy capacity of the ESS changes per cycle, expressed as percent change in energy capacity per cycle under defined cycling conditions.
Ramp rate (%rated power/s)	The speed at which the system can increase or decrease input/output power, expressed as percent of rated power per second under specified conditions.

Functional Performance	
Response time from off state (s)	Time required for a system to output (or input) energy at full rated power from a shutdown/off state, including start-up and synchronization as applicable.
Response time from active state (s)	Time required for a system to output (or input) energy at full rated power from an idle/standby operating condition (define the assumed idle level, e.g., 10% of rated power).
Power Capacity De-Rating Factor (%)	De-rate factor applied to charge and/or discharge power based on operating conditions (e.g., state of charge, temperature, altitude, grid conditions). Example: de-rating of peak charging power at 80% state of charge.
Expected Downtime (frequency & hr)	Disruption to service due to scheduled maintenance and expected forced outages; provide expected event frequency and duration (hours per event and/or hours per year).
Operating temperature range (C)	Temperatures over which the system can operate at stated efficiencies and ratings without requiring auxiliary support, under defined environmental conditions.
Operating Voltage range (V)	Voltage range over which the system can operate at stated efficiencies and ratings without requiring auxiliary support, at the specified point of interconnection.
Operating Current range(I)	Current range over which the system can operate at stated efficiencies and ratings without requiring auxiliary support, under specified conditions.
Operating Power Quality Requirement	Power quality requirements needed for the system to operate at stated efficiencies and ratings (e.g., frequency range, voltage unbalance, harmonics/THD, flicker, ride-through requirements).
Auxiliary Energy Consumption (kWh/yr)	Annual consumption of electricity for auxiliary loads (e.g., lighting, controls, pumps/fans/heaters) beyond energy use reflected in the round-trip efficiency calculation.
Intended Use Case(s)	Use cases of the system intended by the manufacturer (grid and non-grid), including applicable operating modes and services (e.g., simultaneous charge/discharge capability, ancillary services, black start, droop, frequency response, reactive power/VAR support, energy arbitrage, thermal delivery to industrial processes).
Infrastructure	
Footprint (m ² /MWh)	Amount of land required to deploy 1 unit energy capacity of the ESS.
Energy Density (acre/MWh)	Land area required per unit of rated usable energy capacity of the system, expressed as acres per MWh (include all required on-site footprint such as equipment, access, spacing/setbacks, and balance-of-plant, under stated design assumptions).
Power Density (acre/MW)	Land area required per unit of rated charge/discharge power capacity of the system, expressed as acres per MW (include all required on-site footprint such as equipment, access, spacing/setbacks, and balance-of-plant, under stated design assumptions).
Geological Feature Requirement	Does the technology rely on/require a geological feature? (Yes/No)
Environment and Safety	
Lower Flammability Limit (g/m ³)	Minimum airborne concentration (mass per unit volume) at which the substance is flammable, at a specified temperature and pressure.
Toxicity (mg/kWh)	Toxicity of the active (or most toxic/active) material in the energy storage system, normalized per kWh of energy capacity (specify exposure pathway/metric basis if available).
Radioactivity (Curie)	The activity (frequency of radioactive decay) emitted by a given quantity of material, expressed in curies (decays per unit time).
Population Proximity Restrictions (e.g. meters from structure)	Restriction(s) on allowable siting proximity to people, occupied structures, or population centers (e.g., minimum setback distance or exclusion radius) required by design, code, or policy.
Environmental Impact	Degree to which the system is negatively intrusive in the natural environment where it is situated (e.g., water consumption, land use/footprint, habitat disruption, soil erosion, noise/visual impacts, and routine releases/waste streams).
Catastrophic Event Safety Considerations	Safety, cleanup, and total impact mitigation considerations for low-probability/high-consequence events (community, environmental, and asset impacts), including emergency response and remediation requirements.
System Security (Highly vulnerable - Nearly Invulnerable)	The vulnerabilities of a system to damage, disruption, or attack by human or natural causes, - especially where it may result in loss of function or create a safety risk (e.g., cyberattack, physical attack, extreme weather, arson, theft), considering equipment, software, enclosure/housing, monitoring, and staffing.
Lifecycle GHG Emissions (CO ₂ e/kWh over lifetime)	Life-cycle CO ₂ e emissions per kWh of energy capacity over the system lifetime, including material sourcing, processing/manufacturing, distribution/installation, operation/maintenance, and end-of-life.
Historical Fire Events (>5 = high, 1-5 = medium, 0 = low)	Number of documented fire events associated with the LDES technology attributable to the LDES system itself; categorized as >5 (high), 1-5 (medium), 0 (low).

Functional Performance Manufacturing and Supply Chain	
Supply Chain Security (Highly vulnerable - Nearly Invulnerable)	The vulnerabilities of a system supply chain, including storage and power components, to disruption via material shortage, pandemic, natural disaster, global catastrophe, war, etc.
Ease of Use/Complexity	
Controls/communication Interoperability	Storage system adheres to interoperability standards and has demonstrated correct interaction with utility control systems and the storage internal control systems (EMS to BMS)
Technology Readiness Level (#)	Level of technology maturity on a 1–9 scale (from basic principles observed to system proven in operational environment).
Adoption Readiness Level (#)	Level of readiness for market adoption and deployment, capturing non-technical barriers (e.g., permitting, safety certification, insurability/bankability, supply chain availability, O&M capability, and customer acceptance) on a defined ordinal scale (1-9).
Manufacturing Readiness Level (#)	Level of maturity of the manufacturing capability for the technology (process maturity, quality controls, yield, supply chain, tooling, and capacity to produce at scale) on a defined readiness scale (1-9).
Largest Deployed System	Largest real-world demonstration/deployment of this technology
Delivered Cost	
Storage Block Cost (\$/kWh)	Cost of the energy component of the ESS on a unit energy basis
Storage Balance of System Cost (\$/kWh)	Additional equipment costs for supporting the storage block
Storage System Cost (\$/kWh)	<i>Sum of Storage Block Cost and Storage Balance of System Cost</i>
Power Equipment Cost (\$/kW)	Power conversion system equipment for both charging and discharging
Controls & Communication Cost (\$/kW)	Control equipment required to control the system.
System Integration Cost (\$/kWh)	Cost associated with integrating system components into a cohesive system and integrating the system into the deployment site
Energy Storage System Cost (\$/kWh)	Sum of Storage System Cost, Power Equipment cost, Controls & Communication Cost, and System Integration cost
Engineering, Procurement, & Construction Cost (\$/kWh)	Single occurrence engineering and construction costs. Includes siting, installation and commissioning.
Project Development Cost (\$/kWh)	Permitting, PPA, interconnection agreement, site control, and financing costs
Grid Integration Cost (\$/kW)	Cost for connecting to the grid including hardware
Fixed O&M Cost (\$/kW-year)	Costs necessary to keep the storage system operational throughout its life that do not fluctuate based on energy throughput.
Variable O&M Cost (\$/kWh)	Costs necessary to keep the storage system operational throughout its life that fluctuate based on energy throughput
Warranty Cost (\$/kWh-year)	Fees to maintain equipment warranties
Insurance Cost (\$/kWh)	Insurance fees to cover risks
Operating Costs (\$/kWh)	Sum of Fixed O&M, Variable O&M, Warranty, and Insurance Costs
Disconnection Cost (\$/kWh)	Costs associated with the disconnection from the grid
Disassembly/Removal Cost (\$/kWh)	Costs associated with removing the equipment from the site
Site Remediation Cost (\$/kWh)	Costs associated with remediating the project site
Recycling/Disposal Cost (\$/kWh)	Costs associated with recycling materials of the ESS

Functional Performance	
Decommissioning Costs (\$/kWh)	Sum of Disconnection, Disassembly, Site Remediation, and Recycling Costs
Total Installed Costs (\$/kWh)	Sum of Energy Storage System Cost, Operating Costs, Decommissioning Costs, EPC Costs, Project Development Costs, and Grid Integration Costs
LCOS _N ^T (\$/kWh)	The average \$/kWh value that energy discharged from a T hr storage system must be sold at to recover total project revenue requirements over a N year analysis period
	Methodology: https://www.pnnl.gov/sites/default/files/media/file/ESGC%20Cost%20Performance%20Report%202022%20PN-NL-33283.pdf

While the Consortium believes this tool significantly advances the industry’s ability to evaluate LDES technologies against a consistent set of primary competitive factors, thus directly addressing the identified challenge. However, the Consortium also recognizes that as LDES technologies continue to develop, mature, and evolve, the evaluation tool that has been developed is but a first step within a comprehensive set of remedial actions that the Consortium believes should be pursued further to continually support the industry’s ability to effectively evaluate LDES technologies and address persistent challenges that may continue to thwart effective evaluation of LDES technologies. These challenges are described below and followed by suggested remedial actions that the Consortium believes should still be pursued by further industry action.

First, the Consortium recognizes that contracting barriers for LDES projects persist, driven by what may be referred to as a “demonstration gap.” Technology developers reported recurring contractual challenges stemming from limited large-scale operating references. Utilities and other end users want proven performance, warranties, and operational history before committing to a project; developers need that first utility-scale deployment to generate the data and track record required to secure future deals and financing. This circular dependency slows market entry, lengthens sales cycles, increases transaction costs, and can prevent otherwise promising technologies from reaching commercial scale.

Second, LDES solutions remain too expensive and often non-bankable without favorable market structures. The Consortium repeatedly returned to affordability and bankability as central barriers for LDES projects. Many current LDES projects struggle to pencil without reliance on arbitrage revenue or other stacked-value mechanisms that may be uncertain or market-dependent. High capital cost, uncertainty in lifetime performance, and limited field validation elevate perceived risk and increase the cost of capital. The group identified the need for continued cost reduction, performance improvements, and stronger evidence packages (validated data, standardized testing) to enable financing on terms that support wider deployment.

A third challenge is that limited availability of field data inhibits learning, validation, and adoption. Operational data from LDES projects is often not public due to confidentiality, competitive concerns, and contractual restrictions. Even when federal initiatives (e.g., Rapid Operational Validation Initiative (ROVI)) are intended to improve data sharing, program disruptions and project cancellations reduced the amount of data ultimately captured and disseminated. The

lack of accessible, high-quality field data constrains model validation, slows identification of failure modes, and weakens the evidence base needed for bankability assessments, standards development, and technology improvement.

A fourth challenge is that standards and end-user requirements are underdeveloped, enabling non-standardized data to substitute for verification. The team identified a gap in widely used, fit-for-purpose standards and performance test codes tailored to LDES technologies and use cases. End-user requirements are often unclear or inconsistent, and developers may present performance claims using non-comparable assumptions or test conditions. This environment increases buyer risk and can lead to misaligned expectations. Neutral, third-party testing and standardized evaluation protocols, which are aligned with end-user requirements, were seen as critical to de-risk deployments and improve trust, comparability, and procurement confidence.

A fifth challenge is low visibility of test facilities and pathways for independent validation. Developers and stakeholders reported limited awareness of where LDES testing can be performed, what capabilities exist (power level, duration, grid-integration infrastructure, safety testing, environmental testing), and how to access those facilities. This lack of visibility can force expensive one-off infrastructure builds, delay development schedules, and reduce opportunities for third-party assessment that would strengthen bankability and contracting. The Consortium emphasized the need to map facilities/hubs and clarify access mechanisms so developers can leverage existing infrastructure for both R&D and credible independent validation.

Suggested remedial actions to address these ongoing challenges pertaining to effective LDES technology evaluation that the Consortium believes will be needed are summarized as follows:

- ❖ **Expand federal demonstration funding to break the “demonstration gap” contracting barrier.** The Consortium has emphasized that targeted federal support for first-of-a-kind and early commercial demonstrations is critical to generate operating history while reducing risk exposure for utilities, owners/operators, and ratepayers. Well-structured demonstration programs can accelerate bankability by producing credible data, establishing warranty expectations, and enabling repeatable contracting models.
- ❖ **Create actionable cost and performance driver maps by technology class.** The Consortium compiled lists of key factors that drive cost (please see Table 3) and round-trip efficiency/performance (Table 5) across LDES technologies and identified improvement levers for each factor. These driver maps are intended to guide R&D priorities, focus scale-up investments, and help developers communicate credible improvement pathways to investors and customers.
- ❖ **Increase participation in federal data initiatives and build sustainable data-sharing infrastructure.** The Consortium recommended stronger industry participation in federal data efforts (e.g., ROVI) to improve the quantity and quality of shared field data. The team also identified a role for national laboratories to collect, process, and distribute data in ways that protect sensitive information, such as through approaches inclusive of anonymization, IP redaction, and structured “scrubbing” of proprietary details. A more

durable national-lab-enabled data management and dissemination network is needed to support learning without relying on broad NDAs that are costly and time intensive.

- ❖ **Increase standards awareness and extend performance test codes to address longevity and degradation.** The Consortium highlighted the need for broader dissemination and education around ASME PTC 53 as an existing performance test code for LDES performance characterization at a point in time. The team also encouraged additional standards/code development to better capture longevity, degradation, and performance changes over time, and recommended deeper engagement from standards bodies (e.g. IEEE) to strengthen the LDES performance standards ecosystem.
- ❖ **Improve visibility and access to LDES testing and demonstration facilities.** To address limited awareness of where and how technologies can be tested and independently validated, the Consortium created a list of LDES-capable and/or related testing facilities across the country and recommended sharing it broadly. Increasing facility visibility (capabilities, access pathways, costs, and points of contact) helps developers leverage existing infrastructure for R&D and third-party assessment, which can support with establishing bankability and accelerating deployments.

E9. LDES use cases require market changes & E10. ISO and RTO markets will need to develop support mechanisms.

The Consortium observed that the challenge of LDES use cases requiring market changes will largely need to be addressed through support mechanisms developed by the ISOs and RTOs, and thus these two challenges are discussed in tandem.

Status:



=The challenge remains a significant barrier to LDES commercialization and additional action is needed from various industry participants.

The Consortium posits that the areas of necessary market changes and the need for the development of support mechanisms by ISO and RTO markets⁵⁸, which these two challenges address, arguably comprise the most significant, persistent barrier to LDES commercialization that stands before the industry. In other words, this is the area in which the greatest, and

⁵⁸ The U.S. based ISOs and RTOs that were considered within scope of the Consortium's analysis are: CAISO: California Independent System Operator; ERCOT: Electric Reliability Council of Texas; ISO-NE: ISO New England; MISO: Midcontinent Independent System Operator; NYISO: New York Independent System Operator; PJM: PJM Interconnection; and SPP: Southwest Power Pool.

perhaps the most important, work still needs to be done to further the cause of LDES commercialization.

Wholesale markets are an enabler for energy storage, due to arbitrage and ancillary services, and are necessary for storage projects to generate revenue, ensuring investment viability. In addition, wholesale markets help to facilitate grid stability by providing the means by which energy storage resources can offer fast-acting capacity during high-demand peaks. The issue is that the wholesale markets, although they've been directed by FERC to allow energy storage resources to participate in wholesale markets (via Order 841 issued in 2018), the wholesale markets are still not set up to provide compensation for storage resources beyond short-duration lithium-ion batteries.

The result is that the regulatory frameworks and market rules for these wholesale markets, operated by RTOs/ISOs and regulated by FERC, fail to create clear revenue streams for all these services simultaneously or adequately compensate storage for the value it adds to grid stability and resilience. This regulatory inertia creates market uncertainty, making investment decisions riskier for potential developers and financiers.

Market rules are slowly evolving to accommodate LDES, but full integration remains a work in progress. While it is true that support mechanisms for energy storage have been implemented by ISOs and RTOs, those exist vary dramatically between markets, having in common only that they tend to be focused on short-duration battery storage.

While the Consortium has identified issues and developed useful perspectives on these challenges that were compiled directly from active participants in these markets—which most certainly serve to advance the discussion—the onus will remain on other external parties such as FERC and individual ISOs and RTOs, to further address these persistent challenges. While past frameworks like FERC Order 841⁵⁹ and Order 2222⁶⁰ helped integrate short-term batteries and distributed resources, they are generally not optimized for multi-day or multi-week LDES.

Indeed, the challenges that fall into the scope of (wholesale) market reform and support mechanisms within the ISOs and RTOs are so pervasive that the Consortium could envision a future, comprehensive order issued by FERC. Order 841, issued by FERC in 2018, was a landmark regulation designed to remove barriers allowing electric storage resources to fully participate in wholesale capacity, energy, and ancillary services markets. It is conceivable that an additional order, or amendment to Order 841, may be necessary to further address the unique aspects of LDES.

⁵⁹ Order 841: Electric Storage Participation in Markets Operated by Regional Transmission Organizations and Independent System Operators. Federal Energy Regulatory Commission. February 15, 2018. <https://www.ferc.gov/media/order-no-841>

⁶⁰ FERC Order No. 2222 Explainer: Facilitating Participation in Electricity Markets by Distributed Energy Resources. Federal Energy Regulatory Commission. <https://www.ferc.gov/ferc-order-no-2222-explainer-facilitating-participation-electricity-markets-distributed-energy>

At the most fundamental level, it is the Consortium's position that wholesale markets must shift from simple energy arbitrage (buying low, selling high) toward capacity accreditation that measures a resource's ability to reliably serve electrical loads over extended, multi-day periods. These changes will have to come directly from the RTOs / ISOs and FERC.

To summarize the work accomplished to date, the Consortium first assessed current practices in United States wholesale electricity markets, primarily in the context of the current market participation practices of mature LDES technologies, e.g., pumped storage hydropower. This included a review of current market rules and structures that are relevant to LDES participation, along with a parallel review of studies and reports that have previously analyzed these rules and structures. The Consortium also conducted a subsequent review of wholesale electricity market practices in the U.S. to specifically identify critical challenges and opportunities related to overcoming investment barriers to LDES. This was accompanied by a parallel review of market and policy mechanisms across six additional countries and regions, which then motivated development of a set of best practices that should be considered as market reforms are designed and implemented in the U.S.

Along with examining the existing state of wholesale markets, the Consortium conducted a forward-looking assessment of how different changes in market design and structure may affect the ability of organized markets to capture the value of LDES in both short-term operations and long-term planning processes, with a specific focus on establishing core market needs, challenges, and opportunities. The objective of these reviews was to identify a set of opportunities and challenges for LDES technologies related to their participation in both wholesale markets. In particular, the team has assessed how changes to the following market design elements may impact the ability of markets to capture the value that LDES resources provide to the electricity system and compensate them commensurately:

- ❖ Wholesale market participation models for LDES.
- ❖ Wholesale market rules, e.g., market product definitions and market-clearing intervals.
- ❖ Market structure, e.g., roles and responsibilities and risk allocation.
- ❖ Aggregation models for distributed, behind-the-meter, resources.
- ❖ Retail rate structures and the availability of real-time or time-of-use pricing for resources that do not participate in wholesale markets.

These two reviews were accompanied by a forward-looking assessment of how different changes in market design and structure may affect the ability of organized markets to capture the value of LDES in both short-term operations and long-term planning processes, with a specific focus on establishing core market needs, challenges, and opportunities.

One clear conclusion drawn from the analysis was that wholesale electricity markets in the U.S. were primarily designed to support reliable and economically efficient operations in system

dominated by traditional generation resources, such as large thermal plants, or hydropower facilities. It is true that market rules and structures have evolved over time to accommodate evolving generation portfolios and associated system requirements, most notably driven by rapid deployment of intermittent resources and subsequent deployment of energy storage resources with 1-4 hours duration.

However, due to the fact that LDES / MDS resources provide a variety of benefits to the grid and customers, market signals may not be in place to incentivize their deployment, even though there is overall value to customers. Additionally, organized markets can be inflexible in certain ways that stymie the deployment of beneficial LDES / MDS resources. Prospects for comparable future growth in LDES deployments are now prompting similar reviews and revisions to ensure that these technologies are properly compensated for the full suite of grid services they are able to provide.

Several key challenges facing commercial scale LDES technologies were highlighted, including 1) the need to design and implement accurate capacity accreditation methodologies, 2) the importance interconnection positioning and challenges related to interconnection delays, and 3) the value of working with an ISO or RTO to model emerging technology in cluster studies. These challenges present very real and pressing market barriers that inhibit LDES deployment and overcoming them will enable a host of new opportunities for further LDES market engagement.

The Consortium established that continuing to develop efficient electricity market designs and market participation models is crucial for LDES resources. This is particularly the case as electricity markets were initially designed to support large, inflexible resources, involatile system loads, and little to no consumer participation. It takes years to properly redesign markets and implement changes efficiently, which is work must start today to ensure that markets of the future are compatible with evolving resources mixes and resources needs.

Further, energy storage technologies have the ability to provide a number of valuable grid services that support reliable and affordable operation of the electric grid. Much of this system value generated from these services is recognized and compensated through current wholesale electricity market structures. However, LDES resources also have several unique attributes that make it more challenging to capture their value and provide commensurate compensation through traditional market structures. This is particularly relevant for value streams related to moving energy across days, months, or seasons, which greatly exceeds the daily or hourly operational horizons in current electricity markets.

In an effort to highlight these gaps, the Consortium reviewed existing literature and identified a set of important grid services that LDES resources can provide, with a particular focus on the novel capabilities of LDES relative to other technologies. The reviewed services include:

- ❖ **Reliability and resilience during extreme weather events:** Energy storage resources, both LDES and shorter duration, are able to provide valuable reliability services during periods of extreme weather and generator outages. Such events

have been observed to increase in frequency and duration over the past decade⁶¹. However, currently organized electricity markets do not provide direct compensation for energy storage or other resources based on their ability to support system resilience; such compensation instead manifests through standard capacity remuneration mechanisms and wholesale electricity prices during such extreme periods. As a result, storage valuation is focused on the benefits of mitigating shorter-term outages and the ability of LDES to provide longer-term reliability and hence resilience may be undervalued.

- ❖ **Seasonal load shifting:** The ability of energy storage to help balance sub-hourly, hourly, and daily load volatility introduced by variable / intermittent resources and shifting load profiles (e.g., due to transport electrification and large data center loads) is increasingly recognized. In addition to these shorter-term balancing services, LDES can also help to align periods of surplus supply with periods of high demand by moving energy over multi-day periods, months or even seasons. These system benefits are harder to capture in current electricity markets, which are typically operated on a daily basis.
- ❖ **Resource adequacy:** While shorter-duration energy storage, which may be more typically dispatched during periods of peak demand, LDES can be operated more similarly to a baseload resource for prolonged periods of time. As a result, in addition to peak shaving, LDES resources can potentially defer investments in new firm generation capacity. This system value is traditionally captured through capacity markets and other resource adequacy mechanisms. However, current capacity market still do not have the established mechanisms to distinguish LDES technologies from shorter duration energy storage technologies.

The Consortium sought to clearly identify, firstly, how LDES resources provide value to electricity systems and, secondly, how LDES resources generate revenues through participation in wholesale electricity markets. A subsequent comparison of these two categorizations was then conducted to establish areas of misalignment between system value and market incentives and identify potential enhancements to remedy them. The following table summarizes the findings of this review.

⁶¹ According to the National Oceanic and Atmospheric Administration, the number of weather events that have exceeded one billion dollars in CPI-adjusted losses in the U.S. has steadily increased from an average of 3.3 per year in the 1980s, to 5.7 per year in the 1990s, 6.7 per year in the 2000s, 13.1 in the 2010s, and 23.0 per year from 2020-2024. <https://www.ncei.noaa.gov/access/billions/state-summary/US>.

Table 8.
LDES Value Stream Alignments

	LDES provides system value by...	LDES generates revenue by...	Alignment between value and revenue requires...	Market enhancements are needed to...
Energy arbitrage	Moving energy through time from periods where there is high supply/low demand to periods when there is low/supply/high demand.	Participating in energy markets, consuming energy to charge when prices are low and generating energy when prices are high.	Efficient spot prices for energy with sufficiently high spatiotemporal resolution.	Develop organized forward energy markets over extended horizons, extend optimization look-ahead horizons to better reflect LDES charging cycles. Adopt pricing signals that adequately reward extended discharge cycles. Allow revenue stacking without disadvantaging LDES.
Capacity and resource adequacy	Being available to provide energy during periods of system stress or supply shortages.	Participating in capacity markets or other capacity remuneration mechanisms.	Well defined resource adequacy objectives and definitions. Capacity accreditation methods that reflect the true ability of each resource to support resource adequacy objectives.	Improve capacity accreditation, develop new market mechanisms that support resource adequacy in systems that are energy limited rather than capacity limited.
Operating reserves	Reserving capacity to provide energy when called upon within a defined response time over operational timescales.	Participating in markets for regulation, spinning reserve, non-spinning reserve, supplemental reserve etc.	System reserve requirements that reflect system needs and reflect the marginal system value of reducing LOLP.	Improve resolution and representation of operating reserve demand curves, improve the spatial resolution of reserve requirements and demand curves.

	LDES provides system value by...	LDES generates revenue by...	Alignment between value and revenue requires...	Market enhancements are needed to...
Flexibility (e.g., load following and ramping)	Providing reserve capacity that can be used to ramp (up or down) quickly during real-time security constrained economic dispatch (SCED) to support operational reliability and reduced renewable curtailments.	Participating in markets for flexible ramping, where they exist.	Efficient spot prices for energy with sufficiently high spatiotemporal resolution, or alternatively a clearly defined flexible ramping requirement and associated product.	Provide compensation for flexibility either through a standalone flexibility product or through enhancements to energy and operating reserve market clearing.
Voltage support	Injecting or absorbing reactive power to maintain acceptable system voltage levels.	Entering bilateral contracts to provide this service.	Appropriate recognition of the value of this service in bilateral contracts	
Black start	Providing energy to support system restoration following a black out event.	Entering bilateral contracts to provide this service.	Appropriate recognition of the value of this service in bilateral contracts	
Inertial response	Provide rotational inertia or synthetic inertia to help maintain acceptable system frequency.	Entering bilateral contracts to provide this service.	Appropriate recognition of the value of this service in bilateral contracts	

	LDES provides system value by...	LDES generates revenue by...	Alignment between value and revenue requires...	Market enhancements are needed to...
Resilience and energy security	Supporting power system reliability during extreme weather events, periods of extreme operating conditions, or periods of disruptions to fuel supply.		Formal recognition of the need for and value of these services that is additive to other existing market products	Develop a resilience-based framework/metrics that better reflect reliability contributions during extreme operating periods in resource adequacy compensation mechanisms. Market product for ~week ahead forward energy/capacity that is intended to mitigate disruptions from unforeseen extreme events.
Transmission deferral and congestion relief	Consistently generating energy during periods of transmission congestion so as to reduce the need for transmission investments and reduce cost to consumers.		Formal recognition of the ability of energy storage to provide transmission services	Integrate LDES into transmission planning as non-wires alternative by integrating resource planning and transmission planning.

Recommended actions to have organized markets better facilitate beneficial deployment of LDES / MDS include:

- ❖ **Ensuring that each organized market has posted a capacity accreditation** for 8-, 12-, 24-, and 100-hour battery systems, to allow transparency into the assigned value of these resources.
- ❖ **Tailoring market products to extract the value of LDES / MDS resources** for customers. Examples could include market products that manage “carried state of charge” for the battery fleet when energy shortfall concerns exist, multi-day capacity

products, or accommodating state policy-driven desires for non-emitting capacity resources.

- ❖ **Updating capacity remuneration methods** to better account for the ability of LDES to provide firm generation over multi-day periods.
- ❖ **Implementing duration-aware capacity accreditation** and performance-based payments to align market incentives with LDES value.
- ❖ **Introducing new forward energy products** to offer LDES a financial mechanism to quantify the future value of energy, efficiently manage their state-of-charge, and hedge long-term energy price risk.
- ❖ **Extending market clearing timeframes** to enable LDES resources to optimize the operational strategies and maximize system value over complete charge/discharge cycles.
- ❖ **Establishing new market mechanisms for reliability services** to support resilience under extreme operating conditions, create ratepayer savings by enabling reliable and efficient grid operations, and provide commensurate compensation for LDES resources that provide these services.

Overall, wholesale markets should be tailored to incentivize an overall resource portfolio that is optimized for customers. Regional studies can be enlightening on the benefits of LDES / MDS to overall utility portfolios, and may signal the need for market reform to incentivize such resources. Market products should be designed with reference to a view of optimized overall resource portfolios, and adjusted if beneficial resources are not being deployed.

The Consortium observed that ERCOT represents a unique opportunity to observe the impact and interaction between variable resources and storage in a wholesale energy market. From 2017 to 2023, ERCOT's annual share of generation from intermittent resources increased from approximately 18% to 31%⁶²; in parallel, the average annual real-time energy market price increased from \$28.25/MWh to \$65.13/MWh. This increase led to greater arbitrage values energy storage which increased from \$107 per megawatt hour in 2017 to \$256 per MWh in 2023.⁶³

By the end of 2025, total energy storage capacity in ERCOT reached 13.9 GW and 22.9 GWh, roughly on par with storage deployments in California and far greater than any other state. Over this same period, the arbitrage value of energy storage dropped to \$85/MWh, reducing the market signal that drove storage investments over the previous several years. Energy storage relies on wholesale price volatility. If reduced price volatility is a clear market objective, additional market signals may be necessary to align storage investment signals with system

⁶² "2017 State of the Grid." ERCOT.

https://www.ercot.com/files/docs/2018/04/10/ERCOT_2017_State_of_the_Grid_Report.pdf

⁶³ "2023 State of the Market Report for the ERCOT Electricity Markets." Potomac Economics. Independent Market Monitor for ERCOT. May 2024. https://www.potomaceconomics.com/wp-content/uploads/2024/05/2023-State-of-the-Market-Report_Final.pdf

objectives. For example, a network interconnection charge may be established and allocated to generation resources that introduce price volatility.

Another significant challenge with the wholesale markets is that interconnection queue backlogs and processes are delaying implementation of new LDES resources and creating project uncertainty. Like other generation resources, LDES projects face long delays and significant uncertainty in interconnection queues managed by ISOs/RTOs and utilities, hindering project development timelines and increasing costs. The backlog of projects seeking interconnection is substantial and growing. The Consortium established the following activities that could be undertaken to help overcome these challenges.

- ❖ Implement general interconnection queue reforms to reduce processing timelines and establish processes to streamline approvals for high-priority resources.
- ❖ Develop a detailed public hosting capacity analysis of both injections and withdrawals to increase transparency of transmission planning data (upgrades and forecasts).
- ❖ Improve coordination across generation and transmission planning to ensure the value of LDES as both a transmission asset and as a storage asset is adequately captured.
- ❖ Clarifying that energy storage interconnection queue positions can be used for LDES / MDS resources, even if originally contemplated as short-duration. As long as capacity values remain the same, there is no reason why modifying duration should result in “material modifications” that trigger re-studies or loss of queue position.

Over the next 5-10 years, it is the Consortium’s belief that the LDES industry must continue to explore ways to ensure market design aligns with new technologies to support reliable and affordable electricity system operation. Specifically, efforts are still needed to enhance or develop models and tools to help prioritize LDES investments as technologies become increasingly commercialized and cost-effective. Additional coordination between transmission and distribution system planning will also be required in order to account for the distribution-level behavior of LDES resources that may or may not be reflected in wholesale markets. Emerging priorities include mitigating challenges and exploring opportunities related to supporting data centers, industrial electrification and other new and evolving use cases. Finally, U.S. electricity markets should continue to review market mechanisms that have been successfully implemented in other countries, such as the cap-and-floor approach that has sought to de-risk storage investments in the United Kingdom.

E11. State-level policy-making specific to LDES has been very limited.

Status:



=The challenge remains a significant barrier to LDES commercialization and additional action is needed from various industry participants.

The Consortium considers state-level policymaking specific to LDES to be arguably the most positive barometer that has transpired in the last three years. Particularly given the complex challenges that exist at the wholesale level, as discussed in the previous section, coupled with the painstaking process of addressing these challenges, state-level activity to drive forward LDES commercialization appears far more achievable in the near-term.

Key examples of state-level LDES policymaking that have taken place within the last several years include:

- ❖ **California**—An LDES specific procurement carve-out. The California Public Utilities Commission (CPUC) established a specific procurement carve-out and target for LDES totaling 2 GW as part of a centralized procurement authorization under Assembly Bill 1373. Within the 2GW total LDES capacity, 1 GW of resources with a discharge duration of at least 12 hours and 1 GW of multi-day storage must be included, commissioned and deployed between 2031 and 2037.⁶⁴
- ❖ **New York**—The state's roadmap includes a target of 20% of 8+ hour resources in bulk storage procurements, aiming for 1200 MW of LDES by 2030. New York's energy storage roadmap includes a mandate for the New York State Energy Research and Development Authority (NYSERDA) to target 20% long-duration (8+ hour) resources in its bulk storage procurements. This is part of the broader framework approved by the Public Service Commission to reach 6 gigawatts of storage by 2030, working toward broader LDES and clean-firm capacity milestones heading into the mid-2030s and 2050.⁶⁵

⁶⁴ "CPUC Advances Clean Energy with Centralized Procurement Strategy." California Public Utilities Commission. August 26, 2024. <https://www.cpuc.ca.gov/news-and-updates/all-news/cpuc-advances-clean-energy-with-centralized-procurement-strategy>

⁶⁵ "New York PSC adopts energy storage road map detailing path to 6 GW by 2030." Dive Brief. Utility Dive. June 25, 2024. <https://www.utilitydive.com/news/new-york-psc-energy-storage-roadmap/719814/>

- ❖ **Massachusetts**—An LDES specific procurement carve-out, with the target includes specific capacities based on duration. In 2024, legislation (SB 2967 was enacted directing every utility to jointly and competitively solicit proposals for energy storage systems, entering into cost-effective long-term contracts for up to 5 GW of energy storage, of which 3.5 GW must be mid-duration energy storage (4-10 hours), 750 MW being long-duration storage (10-24 hours), and 750 MW of multi-day storage (24 hours). In aggregate, distribution companies must enter into long-term contracts for up to 5 GW of storage by July 31, 2030, a new procurement target for the state.⁶⁶
- ❖ **Virginia**— A whopping mandate of 4.5 GW of LDES by 2045. Legislation in the state (HB895, during the 2026 Regular Session) raises and extends the state’s existing energy storage targets to 16 GW by 2045. The bill sets requirements for the state’s two major utilities (Dominion Energy and Appalachian Power) to construct, acquire, or procure energy storage. This is the largest storage target of any state in the country. The legislation sets the state’s first long-duration energy storage target, at 4.5 GW by 2045, defining LDES as “10 hours or more of generation capacity operating at full nameplate capacity.” It also specifies that half of the LDES target should be met by 10-24 hour storage capacity and the other half by 24+ hour storage capacity.⁶⁷

While the number of states actively promoting LDES may still be relatively small, those states that are taking steps are definitely driving momentum. This is being done primarily through:

- ❖ Setting procurement targets (e.g., CA, MA, NY, and VA as described above)
- ❖ Providing direct financial incentives like grants and funding for projects (again, CA, MA, NY)
 - ✓ California: The Self-Generation Incentive Program (SGIP) offers rebates, performance-based payments, and additional funds for projects in high-fire-threat districts and for low-income customers.
 - ✓ New York: The Market Acceleration Bridge Incentive Program provides upfront incentives that vary by location.
 - ✓ Massachusetts: The ConnectedSolutions program provides performance-based payments to reduce the cost of battery installation.

⁶⁶ Massachusetts Energy Storage Target. DSIRE. NC Clean Energy Technology Center. March 19, 2026. <https://programs.dsireusa.org/system/program/detail/22113/energy-storage-target>

⁶⁷ “Virginia Targets a Long-Duration Energy Future.” Center for Climate and Energy Solutions. April 15, 2026. <https://www.c2es.org/2026/04/virginia-targets-a-long-duration-energy-storage-future/>

- ❖ Creating enabling policies such as rate reform and streamlined permitting
 - ✓ California: Has a "one-stop" permitting process through a single state agency and limited the time for state environmental impact studies to 270 days.
 - ✓ Michigan: Passed a law in 2023 to streamline permitting for energy projects.
 - ✓ Minnesota: Has implemented reforms aimed at accelerating its energy goals.
- ❖ Legislatively mandated studies (e.g., Michigan)
- ❖ Demonstration projects (California, New York, Minnesota, and Virginia)

With these examples, the Consortium posits that LDES is certainly on the radar of state policymakers, but there is a long way to go toward making LDES planning a common practice. With that said, LDES is a subset of broader energy storage policymaking (i.e., policies that pertain to energy storage without regard to duration specifications), and LDES has likely benefitted from broader energy storage policies, and will likely continue to do so. Moreover, evaluating state-level policymaking specific to LDES should occur against the backdrop of broader energy storage deployment trends.

As of September 2026, 13 states have adopted an energy storage procurement policy⁶⁸. Procurement policy at the state level can include mandates, targets, and goals, defined as follows.⁶⁹

- ❖ A Mandate is a goal with legal liability for non-attainment
- ❖ A Target is a defined goal with measures for follow-through
- ❖ A Goal is a number without defined accountability.

While procurement policies may be the most common approach taken by those states with developed energy storage policy frameworks, there are other enabling levers that have been pursued as well, including:

- ❖ State subsidies or incentives
- ❖ Requiring the inclusion of energy storage in regulated utility integrated resource plans
- ❖ State sponsored pilot or demonstration projects
- ❖ Interconnection queue reform
- ❖ Distribution system planning / modeling

⁶⁸ "Table of State Energy Storage Targets and Progress." Clean Energy States Alliance. <https://www.cesa.org/projects/energy-storage-policy-for-states/table-of-state-targets/>

⁶⁹ Ibid.

Assessing energy storage deployment, with and without regard duration capability, California, Arizona, and Texas are leading overall BESS and LDES capacity. In early 2026, In February, Texas passed California to become the country’s leader in battery storage capacity (14,984 MW in Texas and 14,365 MW in California) based on an analysis of U.S. Energy Information Administration data.⁷⁰ Arizona ranks third with 4,983 MW of installed capacity.⁷¹

Of course, distinctions between MW and MWh are important to note. Megawatts capacity, measures the maximum power output at any given moment, while megawatt hours reflect the amount of electricity a system can discharge before it needs to be recharged. While California no longer leads in megawatts, it still leads in megawatt-hours. That’s because the average utility-scale system in California runs for about three hours, which is about twice as long as the average in Texas. A complete list of utility-scale battery energy storage by state, again compiled from EIA data, appears in the following table:

Table 9.
Utility-scale Battery Energy Storage By State
(as of February 2026)

State	MW	MWh
Texas	14,984	22,795
California	14,365	48,375
Arizona	4,983	18,513
Nevada	1,704	4,766
Florida	1,182	3,048
New Mexico	1,126	4,643
Indiana	587	1,322
Oregon	523	2,054
Hawaii	517	1,625
Massachusetts	487	1,094
Colorado	470	1,615

⁷⁰ “Which State Leads in Battery Energy Storage? It Depends on How You Measure.” Inside Climate News. April 2, 2026. <https://insideclimatenews.org/news/02042026/inside-clean-energy-us-battery-storage/>

⁷¹ Ibid.

State	MW	MWh
Idaho	459	1,832
Oklahoma	432	1,513
North Carolina	293	450
Wisconsin	284	1,153
New York	251	699
Maine	239	436
Utah	201	801
Mississippi	152	602
Georgia	146	424
Alaska	132	189
Michigan	120	458
New Jersey	110	111
Iowa	110	126
Illinois	100	66

As the above data bears out, while California, Texas and Arizona have relatively high penetrations of short duration storage on their systems that have been developed within the last few years, storage penetrations on any duration are generally low elsewhere in the U.S. Not inclusive of legacy pumped hydroelectric generating systems, there has been almost no uptake in new LDES resources within the last few years. There continues to be little actual operating experience to draw on for LDES resources.

Arizona and California are both closer to developing LDES resources than many other states in the country. California continues to represent the leading example of a state that has driven energy storage development through policy (not only the procurement mandate but incentives). This includes specific modeling from the California Public Utilities Commission that shows that the state needs significant LDES in the very near-term. Specifically, their work concludes that

over 11 GW of LDES is needed by 2031, and more than 18 GW is needed by 2036.⁷² Other examples of California’s policy-driven approach toward energy storage deployment include:

- ❖ Procurement policies: 1,825 MW procured by 2020 and installed by 2024. Carve-out of 500 MW for BTM. Additional 2 GW (1 GW of 12-hr storage and 1 GW multi-day) of LDES to be deployed between 2031 and 2037.
- ❖ Subsidies and incentives offered.
- ❖ State-sanctioned procurements through the California Energy Commission

In California, the combination of storage, intermittent resource deployment and natural gas resource retirement has impacted wholesale electricity market outcomes. This includes upward pressure on prices during overnight hours, which have historically been some of the lowest priced hours of the day. The state of California has not observed significant moderation of prices during peak hours, and most days typically have several peak hours with significantly elevated prices. This creates a value proposition for shorter duration storage resources, but current electricity prices are not indicative of sufficient revenue to support LDES resources.

Arizona has some energy storage policies in place (e.g., utilities under Arizona Corporation Commission (ACC) regulation are required to include energy storage in their resource planning, with significant targets proposed (e.g., 3,000 MW by 2030). However, it would not be accurate to say that policy has been the main driver of energy storage deployment in Arizona. Rather, the utilities in the state, along with municipalities, have been initiating their own energy storage efforts outside of regulatory directives. For example:

- ❖ **Arizona Public Service:** Plans to add nearly 1,800 MW of integrated storage by the end of 2025/early 2026 through agreements with facilities like its 1,200 MWh Papago Storage project.⁷³
- ❖ **Salt River Project:** Aiming for 1,100 MW of total battery storage by 2025 and has committed to adding 1,500 MW of new batteries and 1,000 MW of pumped hydro by 2035.⁷⁴
- ❖ **Tucson Electric Power:** Adding nearly 400 MW of battery capacity by 2026.⁷⁵

⁷² Ibid.

⁷³ “Recurrent Energy to deliver 1,800 MWh of energy storage to Arizona Public Service by 2026.” Recurrent Energy news release. October 31, 2024. <https://recurrentenergy.com/recurrent-energy-to-deliver-1800-mwh-of-energy-storage-and-150-mwac-of-solar-capacity-to-arizona-public-service-by-2026/>

⁷⁴ “SRP and Google Launch Collaboration to Advance Long Duration Energy Storage Innovation, Grid Resilience in Arizona.” SRP news release. September 8, 2025. <https://media.srpnet.com/srp-and-google-launch-collaboration-to-advance-long-duration-energy-storage-innovation-grid-resilience-in-arizona/>

⁷⁵ “TEP Celebrates Energy Storage Expansion with Tucson Mayor Regina Romero, Local Leaders.” TEP news release. August 2026. <https://www.tep.com/news/tep-celebrates-energy-storage-expansion-with-local-leaders/>

These examples suggest that Arizona's major utilities are aggressively integrating storage to manage "peak" periods and store abundant midday energy for nighttime use. In addition, Arizona cities such as Phoenix, Peoria, and Surprise enacted local laws for battery storage safety and permitting.

There are other observations that can be drawn from this list of states where energy storage capacity has been developed. For instance, the list includes both vertically integrated and restructured states, suggesting that energy storage is being pursued as a resource strategy regardless of whether deregulation of generation has taken place in the state. In addition, these states demonstrate a mix of states in which policy has clearly driven energy storage deployment (e.g., California) and those states in which market dynamics have been more of a catalyst than policy drivers (e.g., Texas). This illustrates what is a long-standing difference among state regulators (i.e., public utility commissions), wherein some are very prescriptive toward market design with explicit regulations, while others are more reactive and simply provide guidance rather than directives.

Thus, this data underscores an ongoing question of whether policymaking at the state level is absolutely necessary to drive commercialization forward (i.e., is there a correlation between ES policymaking and ES deployment?) There are no clear answers to this question as examples can be cited on both sides of the debate. Increasingly, the economics of energy storage alone appear to be driving its inclusion in utility resource planning, even in the absence of explicit regulatory mandates.

One example, which the Consortium heard about directly, is Southern Company's efforts to increasingly incorporate energy storage into the long-term resource plans of its utility subsidiaries (e.g., Georgia Power) in the Southeastern U.S. Southern Company has been very candid that its "all of the above" approach toward resource planning absolutely includes energy storage because it is economically strategic. This is a decision that has been made in the virtually non-existent regulatory mandates in the states in which Southern Company operates.

However, the Consortium also heard directly from LDES technology providers that they welcome state-level policies, including procurement policies because they send the strong message to the marketplace that the state is not only open to but welcomes energy storage deployment. In that sense, with regard to energy storage and LDES policy frameworks, there is a "build it and they will come" sensibility that continues to play out with regard to policies driving ES development. While policy mechanisms may not be absolutely essential, they certainly can be viewed as beneficial to jumpstarting, expanding, and diversifying the deployment of LDES in individual states.

Moreover, the Consortium has maintained a position that state policymaking and regulatory directives can continue to be a very effective driver of LDES deployment for the foreseeable future. Accordingly, the Consortium focused a significant amount of its efforts on assisting state regulators on how to develop an LDES "roadmap." Very few states have taken a long-term planning approach to developing their energy storage market, and even when there is evidence of a "roadmap," it's likely to be more of a loose collection of actions and barriers to remove

While it may sound elementary, there are fundamental questions that state regulators should be asking: For example, how does LDES fit into the state's broader energy goals? If there's fit, how much is needed, what duration is needed, when is it needed, where is it needed, etc. Once policymakers have a firm grasp on the need and on the barriers to deployment, more targeted policymaking can happen.

These questions should be considered in the context of market segments, as the point of interconnection tends to determine jurisdiction and what policies may be applicable to an energy storage asset. The Consortium suggests the following market segments should be considered:

- ❖ Front-of-the-Meter, Transmission level (FTM-T)
- ❖ Front-of-the-Meter, Distribution level (FTM-D)
- ❖ Behind-the-Meter (BTM)

In a series of in-depth discussions with Teaming Partners representing a broad set of LDES stakeholders, the Consortium consistently heard that a number of suggested approaches, undertaken by states, would greatly improve opportunities for LDES commercialization:

- ❖ Requiring utility IRPs to include at least LDES of 8-hour duration as a supply resource in FTM-T and FTM-D market segments.
- ❖ Requiring utilities to report on additional reliability metrics in their IRP planning processes alongside existing metrics (e.g., reliability metrics that capture event severity (like EUE or LOLH) as the basis for establishing reliability targets.
- ❖ Requiring utilities to include LDES in any high electrification / high load growth scenarios.
- ❖ Requiring utilities to improve their assumptions about LDES chronology and host a technical workshop or RFI ahead of IRP to understand full stack of energy benefits LDES can provide.
- ❖ Increasing the use of approved modeling companies and tools that will enable a collective understanding of (accurate) LDES costs and benefits.
- ❖ Mandating the inclusion of LDES into utility distribution plans (approximately 20 states already have some form of regulatory requirements regarding utility distribution plans).
- ❖ In those states where energy storage procurement targets already exist, additional carve-out for LDES should be adopted based on specified duration levels that have been verified by modeling exercises.
- ❖ Align state policies with wholesale market policies, particularly regarding compensation mechanisms for LDES, including capacity accreditation for durations beyond 4 hours and reliability attributes (e.g., voltage support, synchronous inertia).

- ❖ Improve grid planning models that are capable of dispatching across multi-day horizons to properly value LDES.
- ❖ State governments should provide financial incentives (e.g., tax credits, grants, loan guarantees) for FOAK deployments of LDES technologies and/or manufacturing facilities. Different financial incentives could be prioritized by diverse state priorities.

F. LOOKING FORWARD

The federally funded start-up phase of the Consortium ends on September 30, 2026, with an official transfer to its new private industry owner the Edison Electric Institute (EEI), the association that represents all U.S. investor-owned electric companies. EEI members are responsible for providing electricity to nearly 250 Americans, operate in 49 of the 50 U.S. states⁷⁶ and D.C., and are projected to make more than \$1.1 trillion in grid investments during the next five years.

From its inception, the fundamental goal of the Consortium was to assemble a centralized forum in which industry stakeholders could convene to identify pathways for LDES commercialization. In its next phase of operation, utility scale deployment will likely continue to be the primary driving engine for commercialization of the full range of LDES technologies, many of which remain in early stages of development toward technology maturity. As has been the case up to this time, going forward the groundswell of LDES development in the U.S. will be conducted against the backdrop of utility operations.

The data clearly validates this projection. Utility-scale battery storage capacity in the United States increased significantly during the last three years, with an annual average growth rate of 70%.⁷⁷ As of July 2026, there are 1022 utility-scale battery storage projects in the US, according to Cleanview's project tracker.⁷⁸ Their total operating capacity is 49,181 MW. By comparison, in 2025 there were 187 battery storage projects built in the US to electrochemical LDES technologies, battery energy storage system installations are projected to reach 200 GW/655

⁷⁶ No investor-owned utilities operate in Nebraska. Nebraska is the only state in the United States where 100% of the electric utility services are publicly owned, operated as non-profits, or run as consumer-owned cooperatives.

⁷⁷ "Battery storage capacity averaged 70% growth over the last three years." Energy Information Administration. August 7, 2026.

<https://www.eia.gov/todayinenergy/detail.php?id=67925#:~:text=During%20the%20first%20six%20months,Preliminary%20Monthly%20Electric%20Generator%20Inventory.>

⁷⁸ "U.S. utility-scale battery storage capacity reaches 52 GW in mid-2026, averaging 70% annual growth over three years." Energies Media. August 16, 2026. <https://energiesmedia.com/us-battery-storage-capacity-2026-energy/#:~:text=U.S.%20battery%20storage%20surpasses%2052,of%20operational%20battery%20storage%20capacity.>

GWh of cumulative installed energy storage capacity by 2031, driven mainly by the utility sector, which will make up 85% of installations between 2026 and 2031.

Given that utilities generally fall under the regulatory oversight of state utility commissions, the opportunity to continue to drive LDES through regulatory directives ensures a strong platform for continued commercialization going forward. Indeed, in three specific ways, regulatory mechanisms at the state level that drive utility-scale deployment of LDES is likely to remain the primary engine for commercialization through this decade and into the next decade. Those mechanisms are: procurement targets, the requirement to include energy storage in utility IRPs, and demonstration programs, as described here:

- As discussed in this Landscape Assessment, 13 states⁷⁹ currently require utilities to acquire a specified quantity of energy storage by a defined deadline. Four of those 13 states (California, New York, Massachusetts and Virginia) have explicit carve-out requirements that are specific to LDES. This number is likely to increase as the necessity of utilizing LDES technologies to achieve system resilience becomes an undisputed reality across regulatory jurisdictions. Thus, procurement targets specific to LDES may be the single most important driver toward commercialization that can be established in the near term.
- In addition, 21 states require that utility resource plans include energy storage.⁸⁰ Many of these states are vertically integrated, meaning that regulated utilities in those states will have clear pathways to own energy storage assets. (Ownership in restructured states may be uncertain if energy storage is defined as a generation asset). Given that utilities in a near majority of states are required to consider energy storage in their long-term resource planning, it is a safe assumption that LDES technologies will be increasingly among the menu of options that will be given consideration.
- Moreover, also falling into the domain of state regulatory authority and directly impacting utility-scale deployment is the concept of LDES demonstration projects (i.e., those instances in which a state authorizes or requires, and in some cases funds, energy storage for the purpose of exploring operational data. Given that some LDES technologies remain in early-stage research and development, state-mandated demonstration projects are likely to remain an additional mechanism through utility-scale deployment of LDES continues to drive broad commercialization.

These three mechanisms underscore the fundamental correlation between regulatory drivers and utility-scale deployment of LDES, which the Consortium believes will remain the most effective approach toward achieving the fundamental goal of LDES commercialization through this decade and into the 2030s. The challenges and suggested remedies that have been

⁷⁹ California, Connecticut, Illinois, Maine, Maryland, Massachusetts, Michigan, Nevada, New Jersey, New York, Oregon, Rhode Island, and Virginia.

⁸⁰ Arizona, California, Colorado, Connecticut, Florida, Hawaii, Indiana, Kentucky, Maine, Maryland, Massachusetts, Michigan, Minnesota, Missouri, New Mexico, North Carolina, Oregon, Utah, Virginia, Washington, and Illinois.

outlined in this Landscape Assessment should be viewed as the platform from which EEI can continue to act from its unique vantage point of representing investor-owned utilities. It is the hope of the Consortium that EEI will continue its collaborations with groups such as the American Public Power Association (APPA) and the National Rural Electric Cooperative Association (NRECA) to ensure that public power / municipalities and electric cooperatives, respectively, are included in a broad approach toward utility-scale deployment of LDES that will be undertaken.

In closing, the LDES National Consortium now begins its new phase of ownership and leadership under EEI. The national laboratories as funded by the DOE, in conjunction with the efforts of Teaming Partners, has set the foundation for continued focus on the challenges facing the full range of LDES technologies. With this foundation and the new leadership from EEI, pathways for LDES commercialization will continue to develop and remain achievable to increasingly support the U.S. energy industry.

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