ESTAP

Energy Storage Technology Advancement Partnership

The Road Forward for Medium- and Long-Duration Energy Storage

September 9, 2026

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

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- Facilitate public/private partnerships to support joint federal/state energy storage demonstration project deployment
- Support state energy storage efforts with technical, policy and program assistance
- Disseminate information to stakeholders through webinars, reports, case studies and conference presentations

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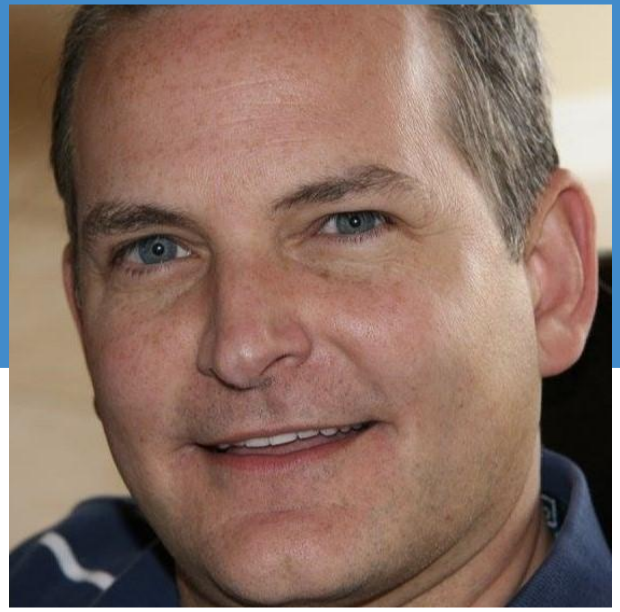

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CESA/ESTAP WEBINAR: MDES/LDES

"LDES COMMERCIALIZATION—WHERE THINGS STAND TODAY"

Will McNamara
Principal Investigator
LDES National Consortium

SEPTEMBER 9, 2026

What I will be covering in this session.

- The state of LDES commercialization today.
- The 30,000 foot view.
- The numbers on LDES specifically.
- LDES Consortium approach to industry challenges.
- Reality checks.

First—what is LDES (and MDES)?

- *Definitions may vary, but generally speaking:*

  - ✓ *LDES*: **10 hours to several days, weeks, or seasons**, required for multi-day weather lulls and seasonal shifts.

  - ✓ *MDES*: Typically **8 to 24 hours**, used for daily load-shifting.

- Within these two categories, there are literally hundreds of emerging energy storage technologies claiming to provide extended duration capability.

The 30,000 foot view. LDES within the context of ES.

- Energy storage, of which LDES is of course 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 installed.
- Other states are driving LDES policy forward.

Data Sources: Wood Mackenzie

The 30,000 foot view. LDES within the context of ES.

- ➢ Battery energy storage continues to lead the pack.

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- ➢ As of July 2026, there are 1022 utility-scale battery storage projects in the US, according to Cleanview's project tracker. Their total operating capacity is 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 2030 (Cleanview).

LDES—those technologies with the capability to provide 10 hours + in duration—will continue to benefit from the advances that ES in general is making.

The numbers on LDES specifically.

- LDES has also seen an acceleration in deployment.

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- Between 2023 and 2026, annual LDES deployments surged, with LDES installations (capacities ≥8 hours) hitting more than 15 GWh in 2025 alone (record year).

- 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.

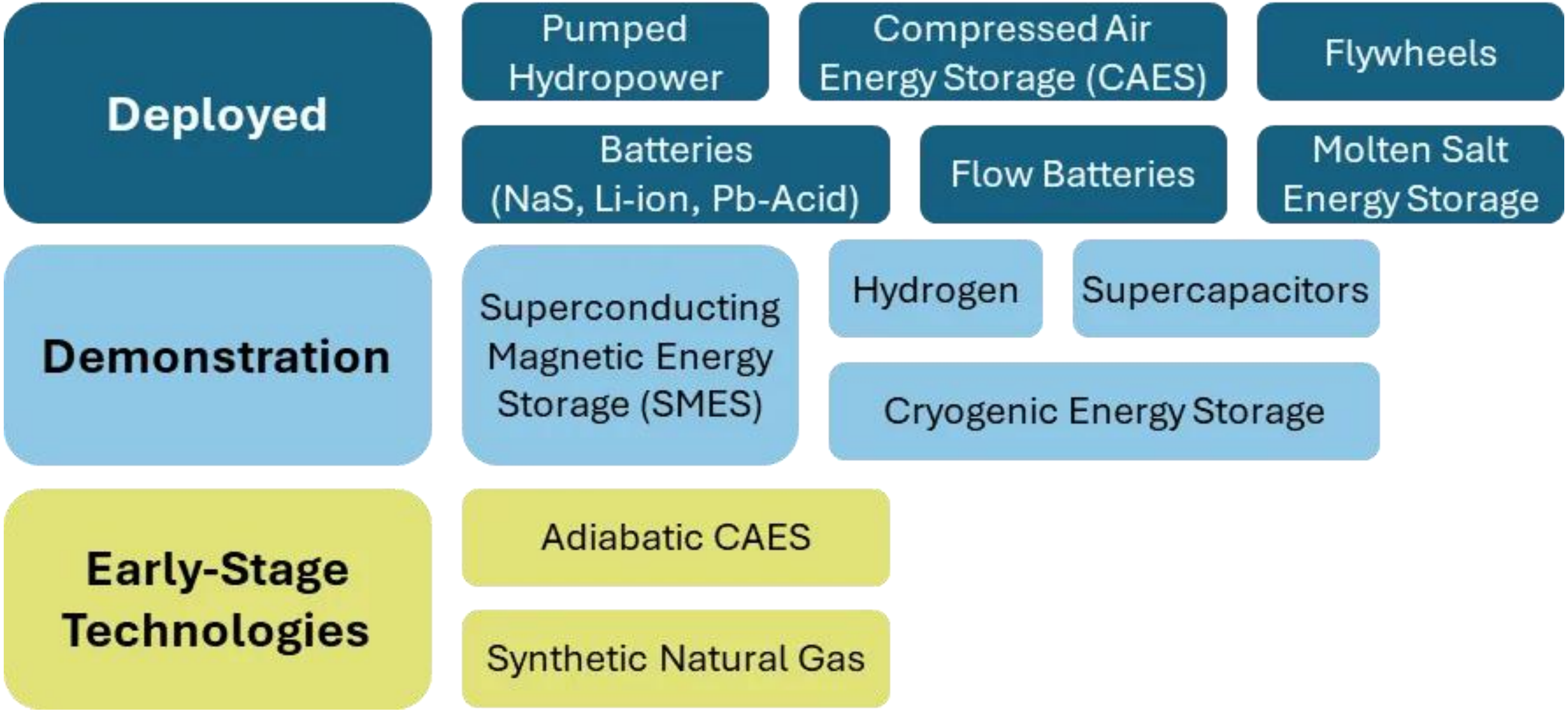
- Investments are notable: Hydrostor, EOS Energy, and Form Energy have raised more than $1 billion in financing since 2021.

LDES NATIONAL CONSORTIUM

Data Sources: Wood Mackenzie

The good news.

- As of today, (some) LDES is technically proven. That's no longer the argument.



Key projects & trends.

- **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 commerce construction in 2027 with completion date in 2032. Expected to have an operational life of 80 years.

- **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 estimated at 8 hours+.

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

- **Molten Salt:** Crescent Dunes Energy Project (Tonopah, NV): This 110 MW plant features a massive molten salt thermal energy storage system that can provide full power for 10 hours (delivering approximately 1.1 GWh of total storage).

Key projects & trends (2)

- **Batteries**

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- **[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.

- **[CO2]** 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.

- **[NaS]** Inlyte Energy Utility Demonstration (Alabama): In partnership with Southern Company, this iron-sodium battery deployment at an energy storage test site in Wilsonville, Alabama, is designed to provide 4 to 24+ hours of discharge capacity for multiday, resilient grid services.

Key projects & trends (3)

- **Batteries**

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- **[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.

- **[Zinc-based]:** Zinc8 Energy Solutions 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) and solar system.

- **[Lithium-ion]:** We are seeing lithium-ion BESS making claims of 8-hour LDES energy shifting. A prominent example is the Tumbleweed project located near Rosamond in Kern County, California. Key details: 69 MW capacity, 552 MWh (discharging continuously for 8 hours) Developer: REV (a subsidiary of LS Power).

What do these examples tell us?

- 4 hours is the floor, not the ceiling.
- The LDES sector arguably has moved past the pilot stage.
- The case can be made that LDES is moving from niche technology to strategic priority.
- LDES continues to represent a wide range of technologies.
- The diversity of technologies remains a key attribute within the LDES sector.
- There is no clear “winner” in the LDES sector. Different technologies serving different customers in different geographies with different use case applications will continue to be blueprint.

Technology Type	Detailed Technology	TRL
Electrochemical	Lithium-ion	9
Electrochemical	Sodium-ion	6
Electrochemical	Lead-acid	9
Electrochemical	Zinc-Anode	2.5
Electrochemical	Iron-Flow	7.5
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
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	7.4
Mechanical	Gravitational Storage (Blocks)	5.44
Mechanical	Gravitational Storage (Railcars)	7
Chemical	Hydrogen	6

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
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

Back where we started from…way back in 2023.

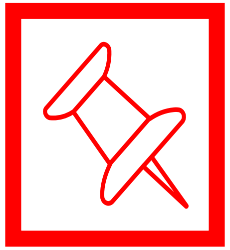
- Cost of an LDES system needs to come down by 2030.
- LDES technologies must achieve 7-15% improvement in roundtrip efficiency to compete with Li-ion storage and hydrogen.
- The specific needs related to LDES workforce training (i.e., skills and training) are presently not well defined.
- A uniform approach toward developing resource adequacy compensation for LDES technologies does not exist, in either regulated markets (PUC evaluation) or competitive markets (ISO/RTO).
- A comprehensive assessment of necessary supply chain improvements specific to LDES technologies does not presently exist.
- 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.
- Presently, there is no publicly available evaluation of LDES technologies against primary competitive factors.
- LDES is not included in most utility grid firming plans.
- LDES use cases require market changes.
- ISO and RTO markets will need to develop support mechanisms.
- State-level policymaking specific to LDES has been very limited.

Yellow highlights indicate challenges I will discuss today.

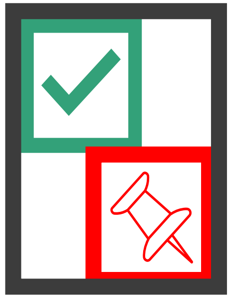
Source: Pathways to Commercial Liftoff: Long Duration Energy Storage, DOE

A scoring system.

= 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.

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

- 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.

- Specific cost trends and benchmarks include:

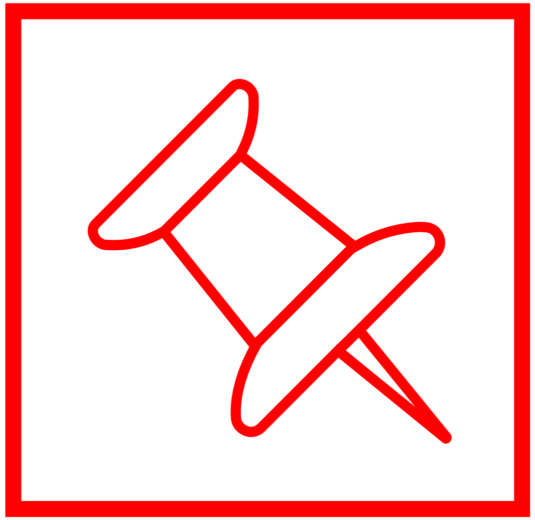
    - ***Cost Competitiveness:*** The least expensive LDES technologies—such as thermal energy storage and CAES—have achieved capital expenditures (capex) of about \$232/kWh and \$293/kWh respectively. For comparison, lithium-ion 4-hour systems averaged \$304 in 2023, making these LDES alternatives highly competitive for multi-hour storage. (Bloomberg NEF)

    - ***Turnkey Storage Drops:*** Overall turnkey energy storage costs have fallen by roughly 30% to 117/kWh. (Bloomberg NEF).

    - ***Future Projections:*** Cost benchmarks indicate that many LDES solutions are expected to drop in cost by another 37% by 2030 (EPRI).

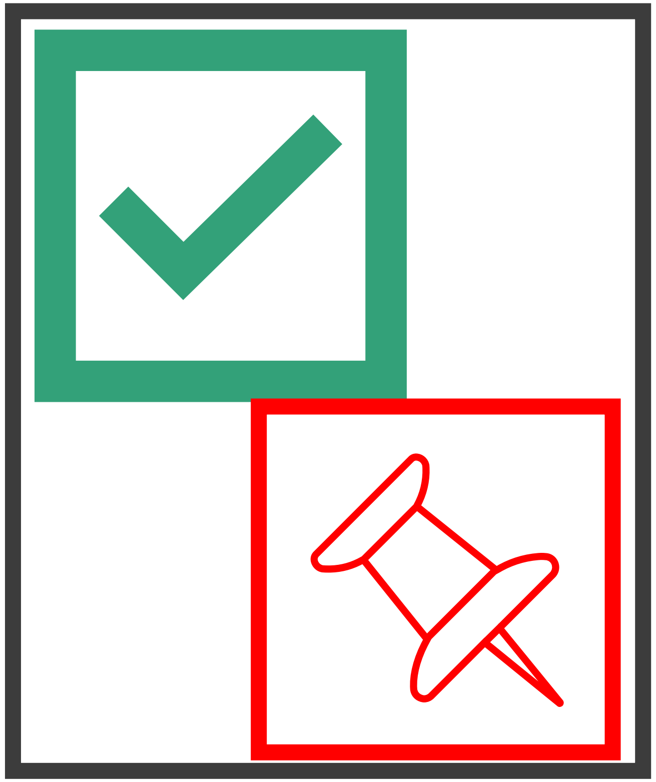
LDES technologies must achieve 7-15% improvement in roundtrip efficiency to compete with Li-ion storage and hydrogen.

- The 7-15% improvement in RTE is an industry target for 2030 rather than a universally achieved milestone.
- Lithium-ion maintains the highest performance benchmark with an RTE of 85–95%.
- Flow and metal-air batteries currently operate at 70–80% RTE.



The specific needs related to LDES workforce training (i.e., skills and training) are presently not well defined.

- We've identified needs in the areas of LDES workforce training….there is much work that still needs to be done in this area:
  - ✓ High-voltage technology integration
  - ✓ High-voltage system maintenance
  - ✓ Safety
  - ✓ Cyber-security
  - ✓ Lifecycle & Asset Management



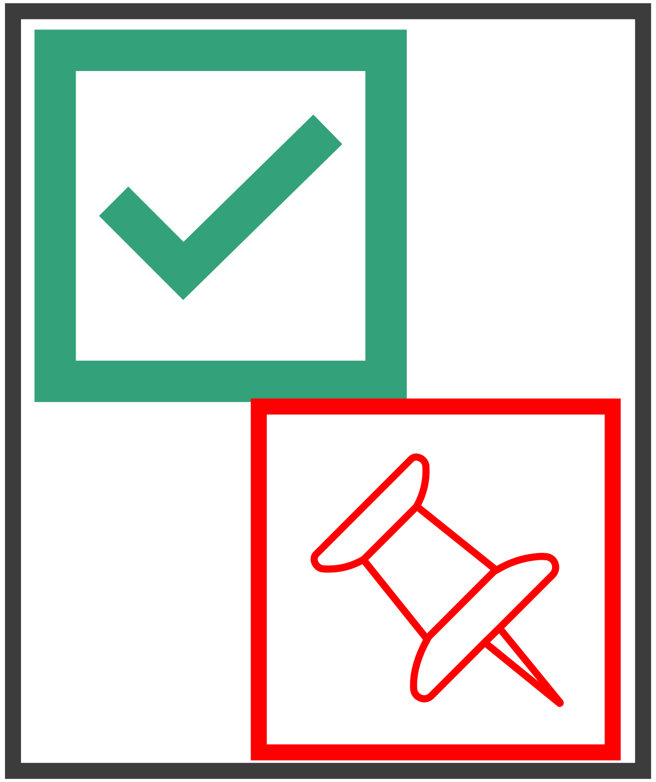
A uniform approach toward developing resource adequacy compensation for LDES technologies does not exist, in either regulated markets (PUC evaluation) or competitive markets (ISO/RTO).

➢ While a uniform approach does not yet exist across all regions, several markets are actively evolving their frameworks to provide RA compensation for LDES.

❖ **California ISO (CAISO):** LSEs contract with storage resources to guarantee capacity availability over specific periods, providing developers with steady, de-risked income. The CPUC continues to refine how this state-level RA framework models and accredits LDES across multiple days.

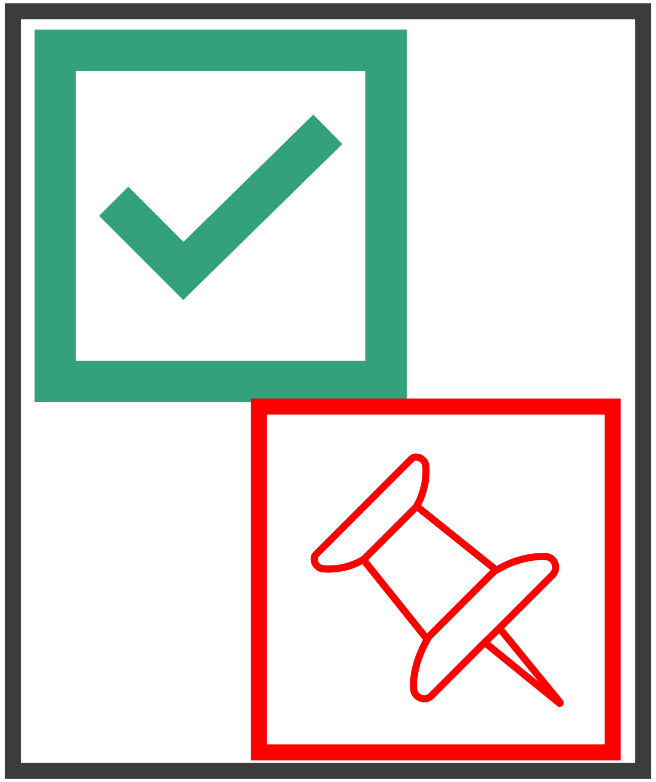
❖ **PJM Interconnection:** This regional market requires a storage asset to have at least 8 hours of duration to be fully compensated in its capacity market.

❖ Other regions and states generally lack consistent policy or market constructs for LDES resource adequacy.



A comprehensive assessment of necessary supply chain improvements specific to LDES technologies does not presently exist.

- Progress has been made; still a lot of work ahead.
- We've identified key considerations in the areas of extraction and processing; components manufacturing; storage system assembly and end-of-life management
- In late 2025, the LDES Council published the Accelerating LDES Bankability report, creating a framework to evaluate technology-specific risks, engineering reviews, and insurance products for first-of-a-kind (FOAK) deployments.



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.

- Significant progress has been made. There's been a promising 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.
- Driven by FERC Order No. 1920 planners now evaluate transmission expansions and LDES as complementary, system-wide assets rather than isolated point-to-point solutions.

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

- This has been one of the key deliverables from the Consortium.
- We have released a web-based tool for evaluating and tracking long-duration energy storage technologies.
- This tool builds on that foundation by providing an interactive platform for visualizing LDES metrics and tracking projects.

Access the tool here:
https://ldes-tool.sandia.gov

LDES is not included in most utility grid firming plans.

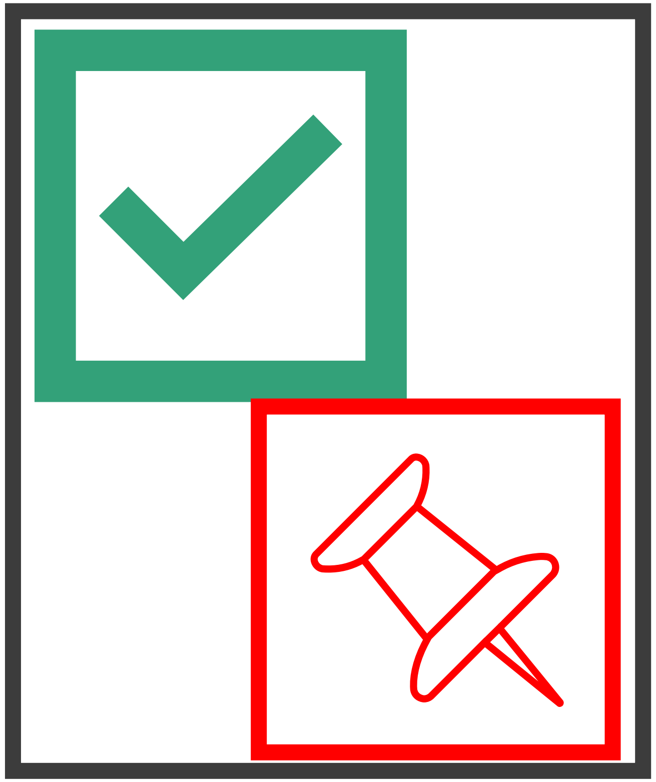
- While still not a standard practice, more forward-thinking utilities are now actively including LDES in long-term planning.

- Two examples:

  - **Xcel Energy:** Serving Minnesota, Colorado, and New Mexico, Xcel includes LDES in its resource plans. The utility is testing Form Energy’s 100-hour iron-air batteries and Ambri’s liquid metal batteries.

  - **Georgia Power:** Partnered with Form Energy to test and deploy a 100-hour iron-air battery to assist with grid firming.

- Making this a common practice may require regulatory mandates.



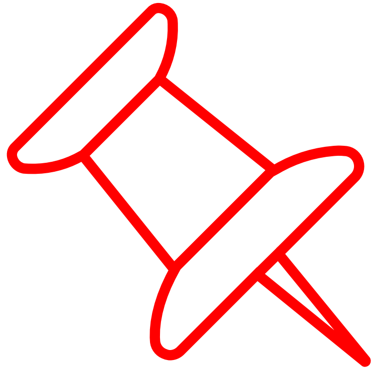
LDES use cases require market changes.

- Market rules are **slowly** evolving to accommodate LDES though full integration remains a work in progress.

- While past frameworks like FERC Order 841 and Order 2222 helped integrate short-term batteries and distributed resources, they are generally not optimized for multi-day or multi-week LDES.

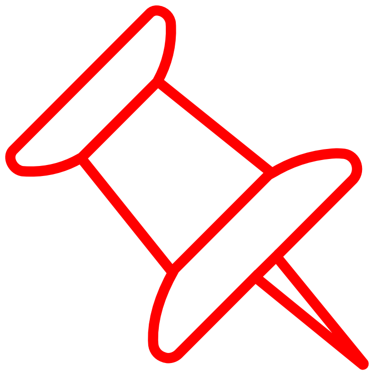
- Wholesale markets must shift from simple energy arbitrage (buying low, selling high) toward capacity accreditation that measures a resource's ability to reliably serve electrical loads over extended, multi-day periods.

- These changes will have to come from the RTOs / ISOs and FERC.



ISO and RTO markets will need to develop support mechanisms.

- The area where the greatest, and perhaps the most important, work still needs to be done.
- The Consortium has certainly identified the issues. Now the onus will be on FERC and the individual RTOs/ISOs to enact LDES specific support mechanisms.
- Something similar to Order 841, but specific to LDES?

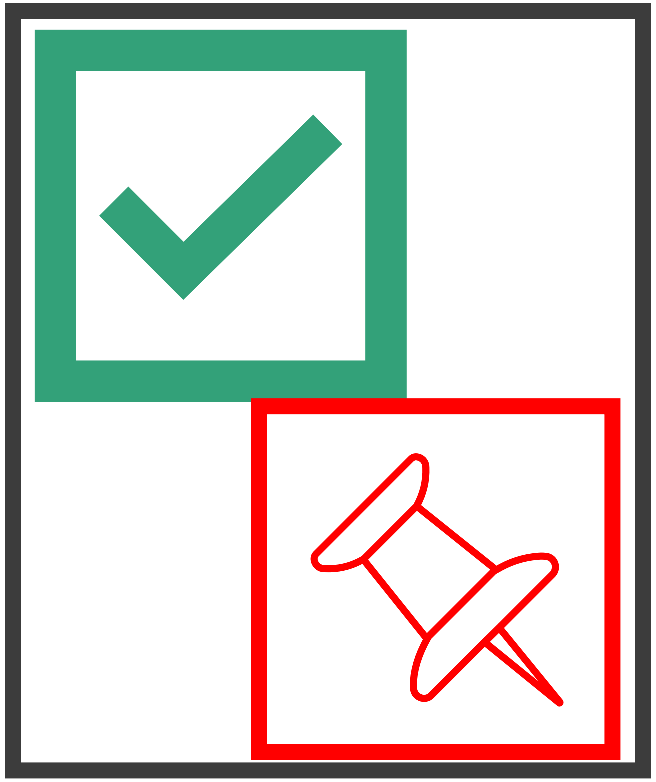


Wholesale market actions that would encourage LDES

1. **Ensure Market Access and Transparency:**
   a. Accredit LDES and multi-day systems to properly reflect value
   b. Interconnection flexibility around duration of storage systems
   c. Interconnection pathways for needed resources
2. **Improve Modeling and Assessments of Multi-Day Storage Values:**
   a. Ensure modeling is able to capture operations of LDES / multi-day energy storage
   b. Consider multi-day risks to resource adequacy
   c. Ensure energy and capacity adequacy
3. **Tailor Market Design:**
   a. Longer-term pricing signals to enable development of new resources
   b. Tailored market products that extract value for customers
   c. Integrate market services with state policy

State-level policymaking specific to LDES has been very limited.

- Perhaps the area where we have witnessed the greatest progress.
  - ✓ **CA-** LDES specific procurement carve-out.
  - ✓ **NY**—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.
  - ✓ **MA**—LDES specific procurement carve-out, with the target includes specific capacities for mid-duration (4-10 hours), long-duration (10-24 hours), and multi-day (24+ hours) storage.
  - ✓ **VA**—Whopping mandate of 4.5 GW of LDES by 2045.



We can confidently say 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.

The factors that will continue to drive LDES forward.

- Surging electricity demand + 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).*
- Grid congestion
- Aging infrastructure *(70% of US power generation is approaching retirement by 2035).*
- 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
- Technologies will continue to mature
- The economics of LDES will continue to improve, as market mechanisms mature.

Reality check.

- The argument is whether the revenue model exists to make it financeable at scale.

- LDES needs roughly $50 to $75 per kilowatt-year in capacity market revenue, according to industry analyses, to support a bankable project finance case.

- The challenge we continue to face is that lithium-ion does the work of LDES because lithium-ion is bankable.

- Four-hour storage gets deployed where 10-hour + storage would actually provide more functionality.

- If the technologies are proven, what is the conundrum?

- Most US markets don’t get us to the level of $50 to $75 per kilowatt range.

Reality check (2).

- **Lithium-Ion Dominance:** Shorter-duration lithium-ion batteries have monopolized the 4-to-8-hour storage market due to optimized supply chains and rapidly falling material costs.
- **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:** RTOs and ISOs continue to lack regulatory frameworks or standardized capacity accreditations for LDES, making procurement difficult.

Accentuating the positive

- The race to build data centers for artificial intelligence companies is offering a new niche for long-duration batteries.

- Next-Generation Tech Deployments: Alternatives to standard lithium-ion, such as iron-air batteries, flow batteries, and gravity-based storage, are rapidly seeing utility-scale commercialization.

- LDES offers a solution to California’s fossil-fuel peaker plant reliance.

Acknowledgements

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THANK YOU!

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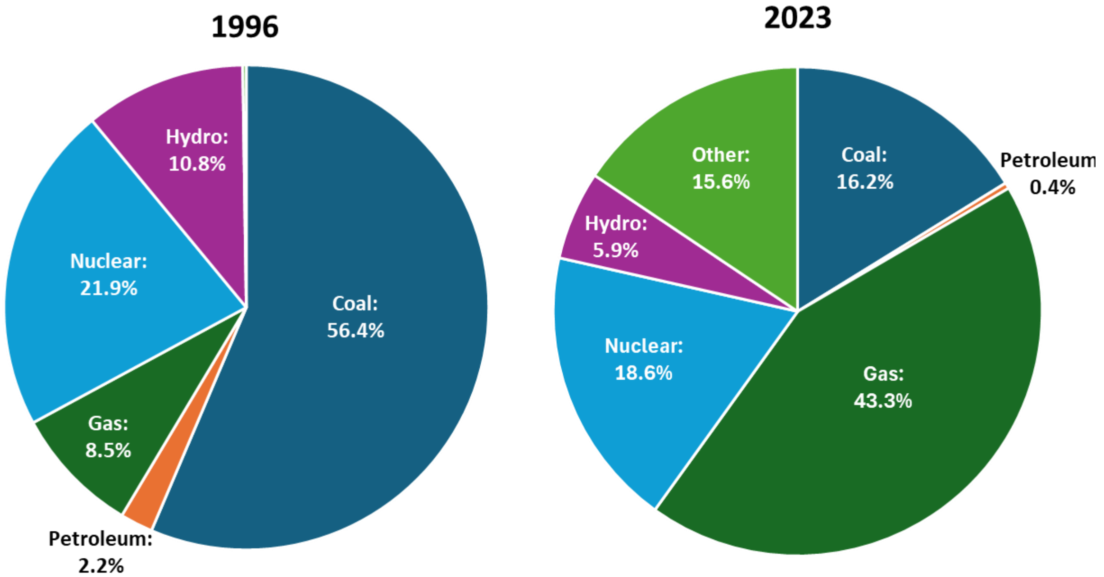
Long-Duration Energy Storage for Thermal Integration

Problem: New, long-duration energy storage (LDES) technologies can help integrate thermal generation sources, but those connections and benefits aren't well documented

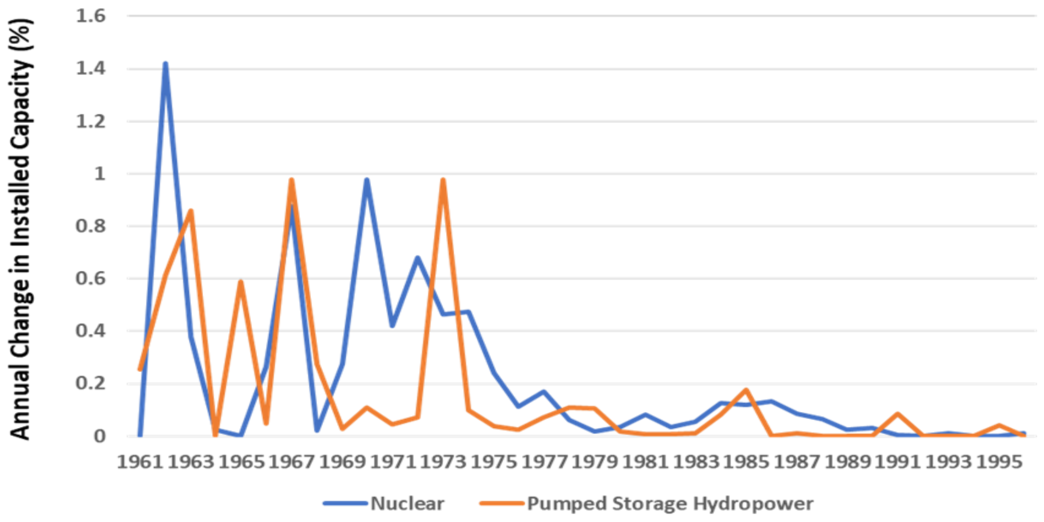
Approach: Describe and quantify how LDES can help optimize the operations and economics of natural gas, advanced nuclear, and advanced geothermal generation

PSH and Nuclear: The Start of a Beautiful Friendship

- Pumped storage hydropower (PSH) played a critical role in buffering nuclear power from daily load swings
- New construction of both technologies paused after 1996



U.S. Electric Fuel Mix, 1996 and 2023



Annual growth rates for nuclear and PSH in the U.S., 1961-1996

- The generation resource mix has changed significantly since 1996
- The growth of new types of thermal generation, coupled with the rise of new LDES technologies, offers the potential for new pairings

Storage with Combined Cycle Natural Gas

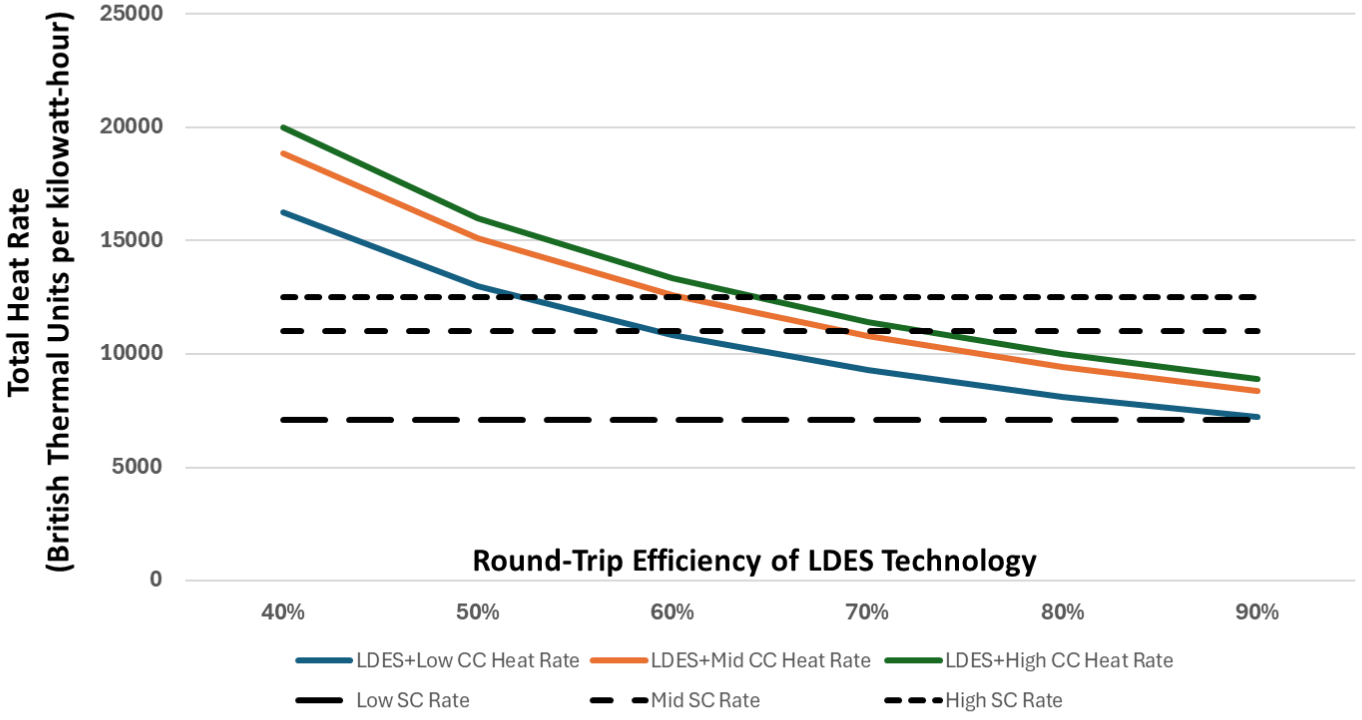
Literature review: when combined with lithium-ion, combined cycle natural gas achieves:

- Fewer starts and stops
- Less ramping
- Increased run time at optimal level

All of which translates into less money spent on fuel and maintenance

LDES technologies can provide all these benefits for combined cycle natural gas while also using the stored energy to displace the need for higher-cost generation from single-cycle natural gas peakers.

The figure at right shows that under many conditions, combined cycle generation paired with LDES has a lower (more efficient) overall heat rate than a simple cycle peaker



Heat rate efficiency frontier for combined cycle (CC) + LDES technologies versus simple cycle (SC) peakers

LDES Council – Decarbonising the Global Energy Sector

Any long duration technology storing energy in various forms – chemical, thermal, mechanical, or electrochemical – and able to dispatch energy or heat for **8+ hours** to days, weeks, or seasons.

www.ldescouncil.com

The LDES Council forges **powerful partnerships** with stakeholders, amplifying awareness of the **critical need for LDES** to ensure flexibility, resilience, reliability, security, and affordability across all industrial sectors.

Vision for 2040

8 TW Deployed

Total potential LDES capacity including power (3 TW) and heat (5 TW)

$4 Trillion Invested

Total capex required to deploy LDES by 2040, in USD

$540B Annual Savings

Realized across the entire energy system, in USD

LDES LONG DURATION ENERGY STORAGE COUNCIL

LDES Council Global Membership

Membership Details

LDES Long Duration Energy Storage Council

ANCHOR MEMBERS

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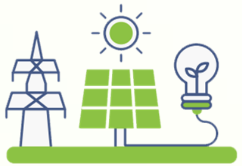
LDES = A diverse suite of solutions that are "fit for purpose"

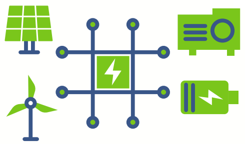
LDES can do things li-ion cannot:

- Shift clean energy across hours, days, and seasons
- Extend grid services that traditional resources provide
- Provide 24x7 heat for chemical, food and beverage manufacturing, and heavy industrial needs
- Meet off-grid and microgrid electrical needs during peak demand
- Keep the energy system supplied during long gaps in generation
- Remove excess generation avoiding curtailment costs

POWER-TO-POWER



Grid Scale
(Energy/
Transmission Alternative)

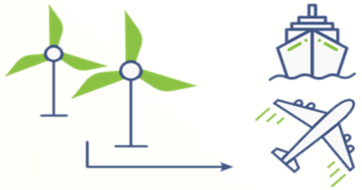


Microgrids Distribution Systems

Off-grid

POWER-TO-HEAT

POWER-TO-X



Thermal / TES	Electrochemical	Mechanical	Chemical
Stores heat or cold in materials like **molten salt, sand, bricks or rocks**, and releases it later as heat, cooling, or electricity.	Stores energy in batteries using chemistries such as **flow, metal-air, zinc, sodium or lithium**, and discharges it later as electricity.	Stores energy using systems like **pumped hydro, gravity, flywheels, compressed air (CAES) or liquid air (LAES)**, and releases it later as mechanical power or electricity.	Stores energy in **chemical fuels such as hydrogen or ammonia**, which can be held long-term and used later for power, heat, or industrial processes.

The Challenge & Scope

- LDES is a critical component of future energy systems.
- LDES is not being deployed at the scale required to meet global and national decarbonisation, energy security and affordability goals.
- The LDES Council estimates that ~2 GW will be required by 2030 and up to 8 TW by 2040, implying a 50x scale-up from today's pace.
- A significant barrier is a lack of **Bankability**.

To understand the core issues around bankability, the LDES Council, in collaboration with Teneo, conducted two workshops in 2025, (London and NYC during Climate Weeks), with investors and technology providers to identify best practices for addressing bankability challenges. The white paper was released in Dec 2025.

What’s holding LDES back?

€ LDES represents a **$4 trillion investment** opportunity by 2040, with the potential to deliver up to **$540 billion** in annual system cost **savings.** €

Yet large-scale deployment is still slowed by a few critical gaps:

- Policy frameworks don’t yet fully value what LDES delivers
- System planning hasn’t caught up with long duration needs
- Investment lacks stable, long-term signals

How can states help LDES deploy at scale?

1. **Recognizing LDES as a distinct category (10+, multi day)**
2. **Strengthening Capital & Market Certainty**
   Clearer market signals, durable funding pathways informed by OCED lessons learned, and endorsements or guarantees that de-risk private capital
3. **Accelerating Manufacturing & American-made Technology Growth**
   Expanding domestic manufacturing capacity, supporting emerging technologies, recognizing the changing nature of LDES resources, and marketing American-made technologies in DOE forums
4. **Advancing State & Local Policy Support**
   Supporting state-level planning, providing guidance on federal moratoriums and the energy landscape for states, cities, and counties, and incorporating safety standards
5. **Providing an LDES carveout in state-level policy & procurements**
   Helps make the financial case for LDES more economically feasible while leveling the playing field.

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