

The Case for Long-Duration Energy Storage (LDES)

Douglas Bryan
Julia Millot

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Acronyms and Abbreviations

CA: California	ME: Maine
CAES: compressed air energy storage	MN: Minnesota
CAISO: California Independent System Operator	MW: megawatt
CO ₂ : carbon dioxide	MWh: megawatt-hour
DOE: Department of Energy (United States)	NERC: North American Electric Reliability Corporation
ERCOT: Electric Reliability Council of Texas	PHES: pumped hydroelectric storage
FERC: Federal Energy Regulatory Commission	PJM: Pennsylvania-New Jersey-Maryland
gCO ₂ /kWh: grams of CO ₂ per kilowatt-hour	TW: terawatt
GW: gigawatt	TWh: terawatt-hour
GWh: gigawatt-hour	UK: United Kingdom
ITC: Investment Tax Credit	US: United States
kW: kilowatt	UT: Utah
kWh: kilowatt-hour	WI: Wisconsin
LAES: liquid air energy storage	
LDES: long-duration energy storage	

Executive Summary

Wind and solar are the cheapest sources of new electricity in most markets. The global energy transition now hinges on solving a harder problem: storage. Storage is what enables firm power delivery, even in calm or cloudy weather. Four-hour, lithium-ion batteries dominate today's storage market. However, they cannot bridge multi-day renewable energy gaps, replace gas peaker plants that run for 12–16 hours at a stretch, or provide seasonal balancing in northern locations. Long-duration energy storage (LDES) systems are designed to close that gap, and can discharge for eight hours or longer (up to days or weeks). In this paper, Relae offers an assessment of where LDES technologies are currently being adopted in the market, and what it would take for them to reach full-scale deployment across most or all suitable use cases.

There are four types of LDES technologies: mechanical (e.g., pumped hydro, compressed air, liquid air), chemical (hydrogen and derivatives), electrochemical (flow batteries), and thermal (molten salt and similar technologies). Each type is suited to different durations, geographies, and use cases. The right choice follows from the application, not from whichever chemistry attracts the most funding in a given year.

The LDES market is small but accelerating. LDES represents just 6% of annual global energy storage installations today, heavily concentrated in China, but deployments grew 49% in 2025 and the project pipeline shows real signs of maturing. Two technologies (iron-air flow batteries and compressed air) have crossed from demonstration into commercial scale, state utility commissions are approving LDES into the rate base, corporate offtakers are signing long-term contracts, and more than US\$2.5 billion in public capital is unlocking private investment behind flagship projects.

LDES technologies have the potential to bring value over a range of use cases. Industrial process heat currently offers the strongest economics, already beating natural gas boilers on cost in well-sited projects. Multi-day reliability for uptime-sensitive buyers like data centers, diesel displacement at off-grid sites, and renewable curtailment capture are also viable now. However, broad grid-scale deployment to displace natural gas peaker plants at the multi-day and seasonal level remains constrained by cost, market design, and a limited operating track record that makes the technology hard to underwrite.

Key Takeaways

- **LDES fills a gap that lithium-ion batteries cannot close.** As renewable energy adoption increases, grids need average storage duration to grow from today's roughly 2.5 hours to approximately 20 hours. This shift requires fundamentally different technology, not incremental battery scaling.
- **The LDES market is small but inflecting.** LDES represents only 6% of annual storage installations, but deployments have grown 49% in 2025; two technologies (iron-air flow batteries and compressed air) have reached commercial scale; and over US\$2.5 billion in public capital is catalyzing private investment.
- **Scaling LDES to gigawatt levels depends on four conditions converging.** Capital costs need to fall toward US\$20 per kilowatt-hour (kWh) or lower, markets must compensate storage for duration rather than capacity alone, LDES will need to maintain competitiveness against a falling lithium-ion cost curve, and decarbonization policy must remove unabated natural gas from the option set at an appropriate pace.

Introduction

The global energy system is at an inflection point. Wind and solar generation have become the cheapest sources of new electricity in most markets, and deployments are accelerating at a pace that would have seemed implausible a decade ago. Solar and wind alone now make up roughly a third of global installed generating capacity, up from a fraction of that ten years ago. Load growth is moving in tandem. The latest assessment from the North American Electric Reliability Corporation (NERC)³ projects summer peak demand in the United States (US) will grow 224 gigawatts (GW), or 24%,⁴ over the next ten years. This growth is expected to be driven largely by data centers, but two-thirds of the new generation capacity utilities have planned is in solar and batteries rather than firm, dispatchable resources like natural gas. In the national interconnection queue, the imbalance is even starker with 993 GW of solar and wind awaiting connection compared to just 253 GW of natural gas.⁵

The world is currently grappling with how to deliver clean, firm power when sunshine and wind are inaccessible. Short-duration, lithium-ion batteries have become the default storage solution, and have provided important grid benefits in some locations like Texas.⁶ However, they fall short in several critical ways: they cannot bridge multi-day gaps in renewable generation, cannot replace natural gas peaker plants capable of dispatching continuously for 12–16 hours, and cannot provide the seasonal balancing that grids in northern latitudes require. LDES is designed to fill those gaps.

LDES systems are capable of discharging electricity for eight hours or longer, sometimes for days or even weeks at a time. Unlike the four-hour, lithium-ion systems that have come to dominate utility procurement, LDES technologies are designed to discharge continuously and support load through extended periods. LDES technologies are also designed to maintain a charged state for weeks or longer without significant energy loss to leakage, allowing them to

³ North American Electric Reliability Corporation. 2026. Long Term Reliability Assessment. [accessed 2026 Sept 8]. https://www.nerc.com/globalassets/our-work/assessments/nerc_ltra_2025.pdf

⁴ Walton R. 2026 Jan 30. NERC forecasts peak demand to rise 24% on new data center loads | Utility Dive; [accessed 2026 Sept 8]. <https://www.utilitydive.com/news/nerc-10-year-peak-demand-forecast-jumps-24-on-new-data-center-loads/810955/>

⁵ Rand J, et al. 2026. Queued Up: 2026 Edition, Characteristics of Power Plants Seeking Transmission Interconnection As of the End of 2025 | Energy Markets & Planning, Berkeley Lab; [accessed 2026 Sept 8]. <https://emp.lbl.gov/publications/queued-2026-edition-characteristics>

⁶ Zeitlin M. 2026 Aug 26. The Texas Grid Has Had a Boring Summer Thanks to Batteries | Heatmap News; [accessed 2026 Sept 8]. <https://heatmap.news/energy/texas-grid-reliability-batteries>

shift stored renewable energy on a seasonal basis. These features make them uniquely valuable to grid reliability, renewable energy integration, and the economics of a net-zero power system.

Relae conducted an independent assessment of where LDES technologies stand today, what the market for LDES systems looks like, and what it will take for LDES to reach the scale the energy transition requires. We identified four conditions that will need to converge to allow LDES to scale to gigawatt levels: falling capital costs, markets that compensate storage for duration rather than capacity alone, sustained competitiveness with lithium-ion storage costs, and decarbonization policy that removes unabated natural gas from the option set at the needed pace.

Lithium-Ion Is Not Ideal For Long-Duration Storage

Lithium-ion batteries dominate the four-hour storage segment, but they are a poor fit for longer durations. In a lithium-ion cell, power capacity (i.e., how fast a battery charges or discharges) and energy capacity (i.e., how much it holds) are bundled into the same hardware, like a hose permanently welded to its bucket.⁷ If you add more cells for more energy duration, stretching a system from four hours to eight, you are forced to add flow capacity too, whether it's needed or not, and cost follows. LDES technologies, like flow batteries and pumped hydro, sidestep this issue because their hose (e.g., pumps, turbines) and bucket (e.g., electrolyte tanks, reservoirs) are separate pieces of equipment. Extending duration just means adding more cheap buckets, without adding expensive, unused hoses.

The cost curve for lithium-ion batteries is driven primarily by electric vehicle manufacturing at global scale, while LDES technologies will be shaped entirely by demand for grid applications and clean-firm investment decisions in the power industry. Beyond cost, lithium-ion systems degrade with deep cycling and face thermal management challenges at the very large scales required for multi-day storage, a challenge LDES systems solve for.

Why This Matters Now

The gap between electricity demand with fast growing, large loads and the intermittent supply of solar and wind energy has grown harder to manage as storage capacity designed for four-hour dispatch loses runway. Globally, average storage duration needs to grow from roughly 2.5 hours today to approximately 20 hours⁸ if grids are to

⁷ Power is the rate of energy transfer (measured in watts), while energy is the total capacity to do work (measured in watt-hours).

⁸ Martucci B. 2026 Mar 10. Long-duration energy storage deployments rose 49% in 2025: WoodMac | Utility Dive. [accessed 2026 Sept 8]. <https://www.utilitydive.com/news/long-duration-energy-storage-deployments-rose-49-in-2025-woodmac/814336/>

maintain reliability while continuing to add renewables at the pace current climate commitments require. This represents an advancement of the storage stack that cannot be achieved with marginal adjustments.

The policy environment is also moving to catch up with this physical reality. The Inflation Reduction Act's standalone energy storage Investment Tax Credit (ITC) will still be available through at least 2032 under the One Big Beautiful Bill Act.⁹ State-level mandates in California,¹⁰ New York, and elsewhere¹¹ are specifically targeting long-duration procurement, and the Federal Energy Regulatory Commission (FERC) is advancing market reforms¹² that would better compensate storage for the services it provides. These tailwinds translate into a rare alignment of regulatory support, improving technology costs, and growing grid needs.

The market opportunity is substantial. LDES deployments rose 49% in 2025, yet the technology still represents only 6% of annual global energy storage installations, which dramatically understates its eventual role. The LDES Council estimates that the world needs 8 terawatts (TW) of long-duration storage by 2040,¹³ a 50-fold increase from today's 0.22 TW global pipeline, and US\$4 trillion in investment, underscoring how much more urgent the buildout has become as renewable deployment has accelerated.

Overview Of LDES Technologies

LDES encompasses a diverse range of technologies unified by a single functional requirement: the ability to store large quantities of energy and discharge it for periods of eight hours or more. Unlike short-duration, lithium-ion

⁹ Abramowitz L, Sausen DA, Olaya L. 2025 July 22. From IRA to OBBBA: A New Era for Clean Energy Tax Credits | Advisories. Arnold & Porter; [accessed 2026 Sept 8].

<https://www.arnoldporter.com/en/perspectives/advisories/2025/07/from-ira-to-obbbba-a-new-era-for-clean-energy-tax-credits>

¹⁰ Martucci B. 2024 Aug 27. California targets up to 2 GW of long-duration storage as part of 10.6 GW clean energy procurement | Utility Dive. [accessed 2026 Sept 8].

<https://www.utilitydive.com/news/california-long-duration-energy-storage-procurement-clean-energy-geothermal-offshore-wind/725396/>

¹¹ Lazaroff AMA, Curran ME. 2026. State Energy Storage Policy Trends for 2026. [accessed 2026 Sept 8].

<https://www.morganlewis.com/pubs/2026/03/state-energy-storage-policy-trends-for-2026>

¹² Kissinger A, Ramadevanahalli A. 2026. Federal Regulatory Outlook for Electric Storage, QFs, and Inverter-Based Resources. [accessed 2026 Sept 8]. <https://www.morganlewis.com/pubs/2026/03/federal-regulatory-outlook-for-electric-storage-qfs-and-inverter-based-resources>

¹³ Long Duration Energy Storage Council. 2024. Annual Report. [accessed 2026 Sept 8].

<https://ldescouncil.com/wp-content/uploads/2025/05/2024LDESAnnualReport-1.pdf>

batteries, which are optimized for rapid, high-power response over a few hours, LDES systems are designed for energy capacity and duration. The cost of additional duration in an LDES system is often far lower than the equivalent lithium-ion expansion, because extending discharge time only requires adding storage medium (e.g., water reservoirs, electrolyte tanks, gas caverns) rather than expensive electrochemical cells.

The LDES landscape spans four broad technology families—mechanical, chemical, electrochemical, and thermal—each with distinct operating principles, maturity levels, cost drivers, and deployment constraints. No single technology is optimal for every application. The right choice depends on geography, discharge duration, grid services required, and local regulatory and market structures. **Table 1** provides a comparison of major LDES technology pathways by key performance and deployment parameters.

Table 1. Comparison of major long-duration energy storage (LDES) technology pathways by key performance and deployment parameters

Technology	Duration	Roundtrip Efficiency	Maturity	Geographic Constraints	Examples of Current Manufacturers
Pumped hydro	8–100+ hours	70–85%	Commercial	High (elevation + water)	GE Vernova, Andritz
Compressed air (CAES)	8–24 hours	42–60%	Early commercial	Moderate (suitable geology)	Hydrostor, Energy Dome
Liquid air (LAES)	8–24 hours	20–50%	Early commercial	None	Highview Power
Hydrogen	Days	25–45%	Early commercial	Low	Mitsubishi Power/Magnum Development (ACES Delta), Plug Power
Vanadium redox flow	4–24 hours	65–80%	Commercial	None	Rongke Power, Invinity, CellCube
Iron-air battery	100+ hours	30–45%	Early commercial	None	Form Energy
Thermal	6–24 hours	40–65%	Commercial (concentrated solar power)	Low	Rondo Energy, Antora Energy

Source: Relae

Mechanical LDES

Mechanical LDES systems store energy in the form of physical potential (e.g., gravitational, pneumatic, or thermal) and release it by converting that potential back into electricity. These approaches leverage mature engineering

principles and, in the case of pumped hydro, have provided the vast majority of grid-scale energy storage for decades. Pumped hydro accounts for over 90%¹⁴ of global electricity storage capacity today. That dominance is a function of being cost competitive with newer technologies at durations beyond three hours. The 50–100-year asset life for pumped hydro also amortizes capital costs over a far longer horizon than batteries or emerging LDES chemistries. Mechanical LDES systems typically offer very long asset lives and low operating costs once built. Their capital costs are generally site-specific, construction timelines can be long, and geographic constraints vary by sub-technology.

Pumped Hydro

Pumped hydroelectric storage (PHES) is by far the most deployed form of LDES in the world, with more than 200 GW installed globally.¹⁵ The technology is conceptually simple: surplus electricity pumps water from a lower reservoir to an upper reservoir, storing energy as gravitational potential, and when power is needed, water is released downhill through turbines to generate electricity (**figure 1**). Round-trip efficiencies of 70–85% and asset lives of 50–100 years make PHES one of the most cost-effective, long-duration options over its lifetime. Discharge durations of 8–100 hours¹⁶ or more are achievable depending on reservoir size. The primary constraint is geographic since suitable sites require an adequate elevation differential and access to water. Permitting timelines can also stretch to a decade or more.¹⁷ These barriers limit greenfield PHES expansion in many developed markets, though upgrades to existing facilities and new closed-loop designs that minimize environmental impact are extending the viable project pipeline.

¹⁴ Xu R et al. 2026. Environmental and geographic constraints shape global pumped hydroelectric storage for long-duration energy storage. *Energy Environ Sci.* 19(12):3804–3822. <https://doi.org/10.1039/d6ee01331g>

¹⁵ International Hydropower Association. 2026 June 24. World Hydropower Outlook launches The year of the ‘water battery’ - global pumped storage capacity surpasses 200 GW. [accessed 2026 Sept 8]. <https://www.hydropower.org/news/year-of-the-water-battery-global-pumped-storage-capacity-surpasses-200-gw>

¹⁶ International Energy Agency Technology Collaboration Programme on Energy Storage (IEA-ES TCP). 2024. Technology fact sheet: pumped hydroelectric energy storage. [accessed 2026 Sep 9]. https://iea-es.org/wp-content/uploads/public/FactSheet_Mechanical_Pumped_Hydroelectric.pdf

¹⁷ Oakes T. 2022 May 16. Navigating the Pumped-Storage Development Life Cycle. 2022. National Hydropower Association; [accessed 2026 Sept 8]. <https://hydro.org/powerhouse/article/navigating-the-pumped-storage-development-life-cycle/>

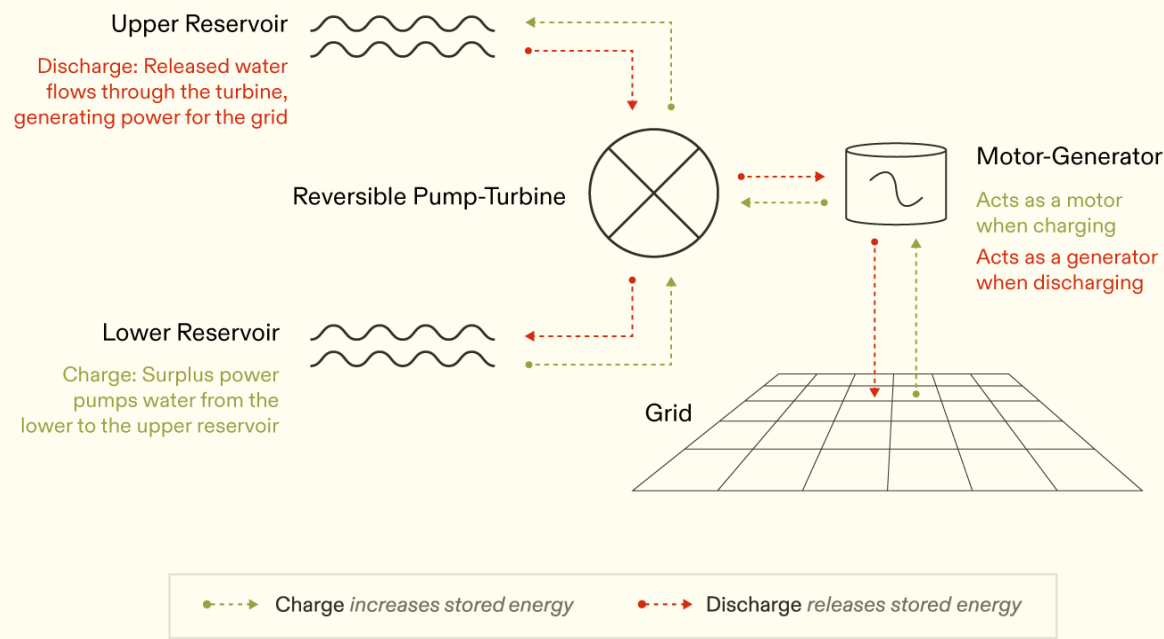


Figure 1. Pumped hydro, an example of mechanical long-duration energy storage using gravitational potential energy. Source: Relae.

Compressed Air

Compressed air energy storage (CAES) uses surplus electricity to compress air into underground geological formations (e.g, depleted natural gas reservoirs, salt caverns, or hard rock cavities) and then releases it through expanders or turbines when power is needed (**figure 2**). Conventional CAES plants burn natural gas to reheat the air before expansion, limiting their clean energy credentials; newer adiabatic designs capture and store the heat of compression for reuse, achieving round-trip efficiencies of up to 70% without combustion.¹⁸ CAES is well suited to multi-hour to multi-day discharge durations and can be sited near existing grid infrastructure where suitable geology exists. A CO₂-based variant of this approach, commercialized by Energy Dome, stores the working fluid above ground in a steel gasholder rather than injecting it into a geological cavern, trading CAES's siting constraint for a modular,

¹⁸ Kahana L. 2025 Nov 19. Adiabatic compressed air storage is viable for 10–100 h applications: research. ESSNews; [accessed 2026 Sept 8]. <https://www.ess-news.com/2025/11/19/adiabatic-compressed-air-storage-is-viable-for-10-100-h-applications-research/>

site-independent design. That flexibility attracted Google to strike a global strategic partnership and investment with Energy Dome in July 2025 to deploy the technology toward its 24/7 carbon-free energy target.¹⁹

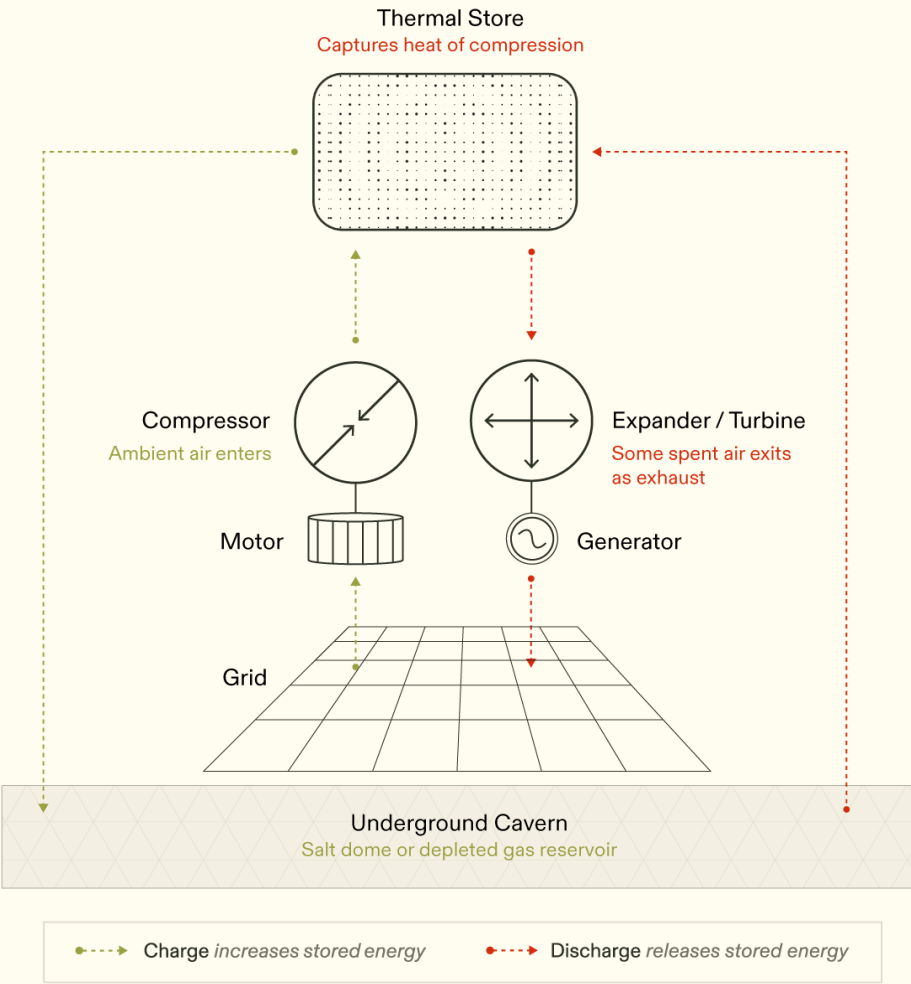


Figure 2. Compressed air energy storage, an example of mechanical long-duration energy storage using compressed-air potential energy. Source: Relae.

¹⁹ Lukiyanova L. 2025 Jun 25. Energy Dome inks a strategic commercial agreement with Google. Energy Dome; [updated 2025 Jul 25; accessed 2026 Oct 1]. <https://energydome.com/energy-dome-inks-a-strategic-commercial-agreement-with-google/>

Liquid Air (Cryogenic)

Liquid air energy storage (LAES), sometimes called cryogenic energy storage, works by using electricity to cool ambient air to cryogenic temperatures (approximately -196°C), converting it to a liquid that can be stored in insulated tanks at atmospheric pressure. When power is needed, the liquid air is warmed and re-expanded to drive a turbine. LAES systems can be sited anywhere industrial storage tanks can be installed and can leverage the existing cryogenic supply chain. Round-trip efficiencies in standalone configurations exist in the 20–50% range,²⁰ though waste heat integration with nearby industrial processes can improve performance substantially.

Chemical LDES

Chemical LDES systems convert surplus renewable electricity into energy-dense molecules, most commonly hydrogen or hydrogen derivatives like ammonia, that can be stored and later reconverted to electricity or heat on demand. The defining advantage of this approach is duration: chemical storage can hold energy for days, weeks, or months, making it the only viable pathway for seasonal storage balancing at grid scale. The primary challenge is round-trip efficiency. Each conversion step—electricity to hydrogen, hydrogen to a carrier molecule if needed, and back to electricity via fuel cell or combustion—involves significant energy losses, yielding overall round-trip efficiencies that currently lag behind mechanical and electrochemical LDES alternatives. Cost-competitive reconversion infrastructure is still maturing, particularly outside of industrial hydrogen markets.

Electrochemical LDES

Electrochemical LDES systems store energy in chemical form but convert it directly to and from electricity through electrochemical reactions, without the intermediate combustion or thermodynamic steps that characterize chemical storage pathways. Electrochemical systems generally offer faster response times than mechanical alternatives and do not face geographic constraints, but their economics and performance characteristics vary considerably by chemistry and application.

²⁰ She X et al. 2025. Liquid air energy storage – A critical review. *Renewable and Sustainable Energy Reviews*. 208:114986. <https://doi.org/10.1016/j.rser.2024.114986>

Flow Batteries

Flow batteries store energy in liquid electrolytes held in external tanks, with the electrochemical reaction occurring at a membrane where the electrolytes are pumped into contact (**figure 3**). The defining advantage of flow batteries for long-duration applications is that power and energy capacity can be scaled independently. Increasing duration simply requires adding electrolyte tank volume without replacing the electrochemical stack. This decoupling makes flow batteries particularly cost-competitive at longer discharge durations compared with conventional batteries. Vanadium redox flow batteries are the most commercially mature chemistry, with demonstrated projects in the range of hundreds of megawatts (MW) of power and gigawatt-hours (GWh) of energy. Emerging chemistries like iron-based, zinc-bromine, and organic-electrolyte systems are expanding the competitive field.

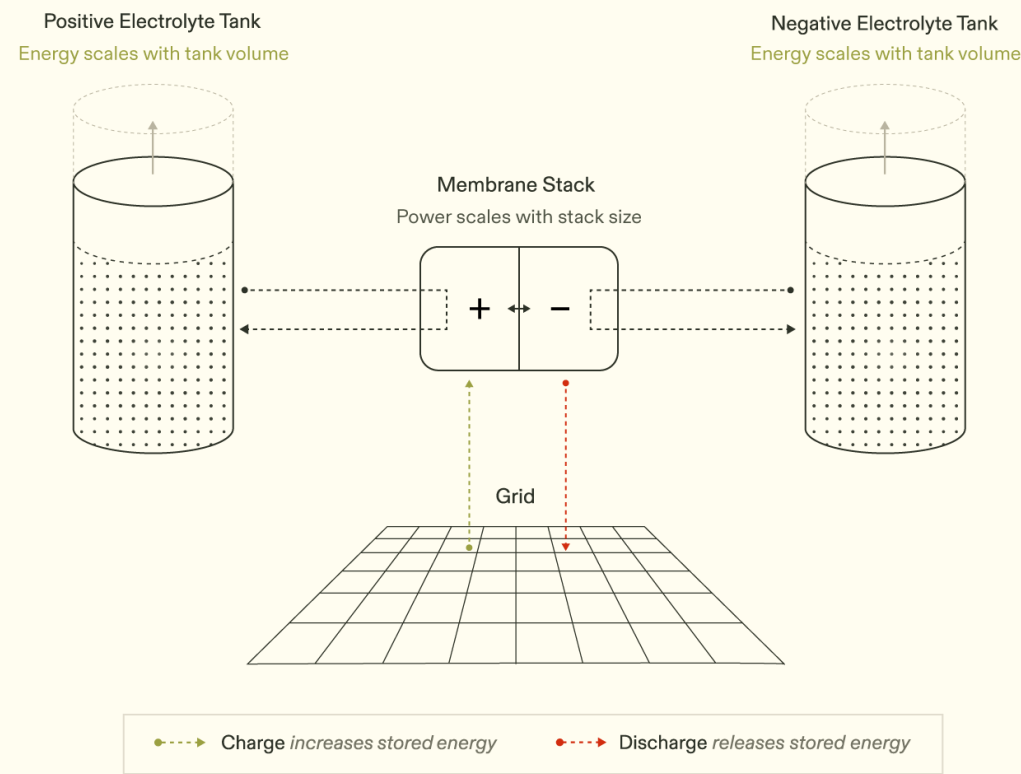


Figure 3. Flow batteries, an example of electrochemical long-duration energy storage using energy stored in liquid electrolyte. Source: Relae.

Thermal LDES

Thermal LDES systems generally store energy as heat in materials such as molten salts, rocks, ceramite, graphite, or phase-change media, and release it to generate electricity when needed (**figure 4**). Molten salt thermal storage has been deployed commercially for decades in concentrated solar power plants, where mirrors focus sunlight to heat a salt mixture that can store energy for 6–16 hours. Thermal LDES systems are notable for their very low material costs and lack of geographic constraints. They are particularly well-suited to co-location with industrial facilities that have large heat loads. As the technology matures, thermal LDES is expected to compete effectively in the 6–24-hour segment, particularly in markets where heat integration is available.

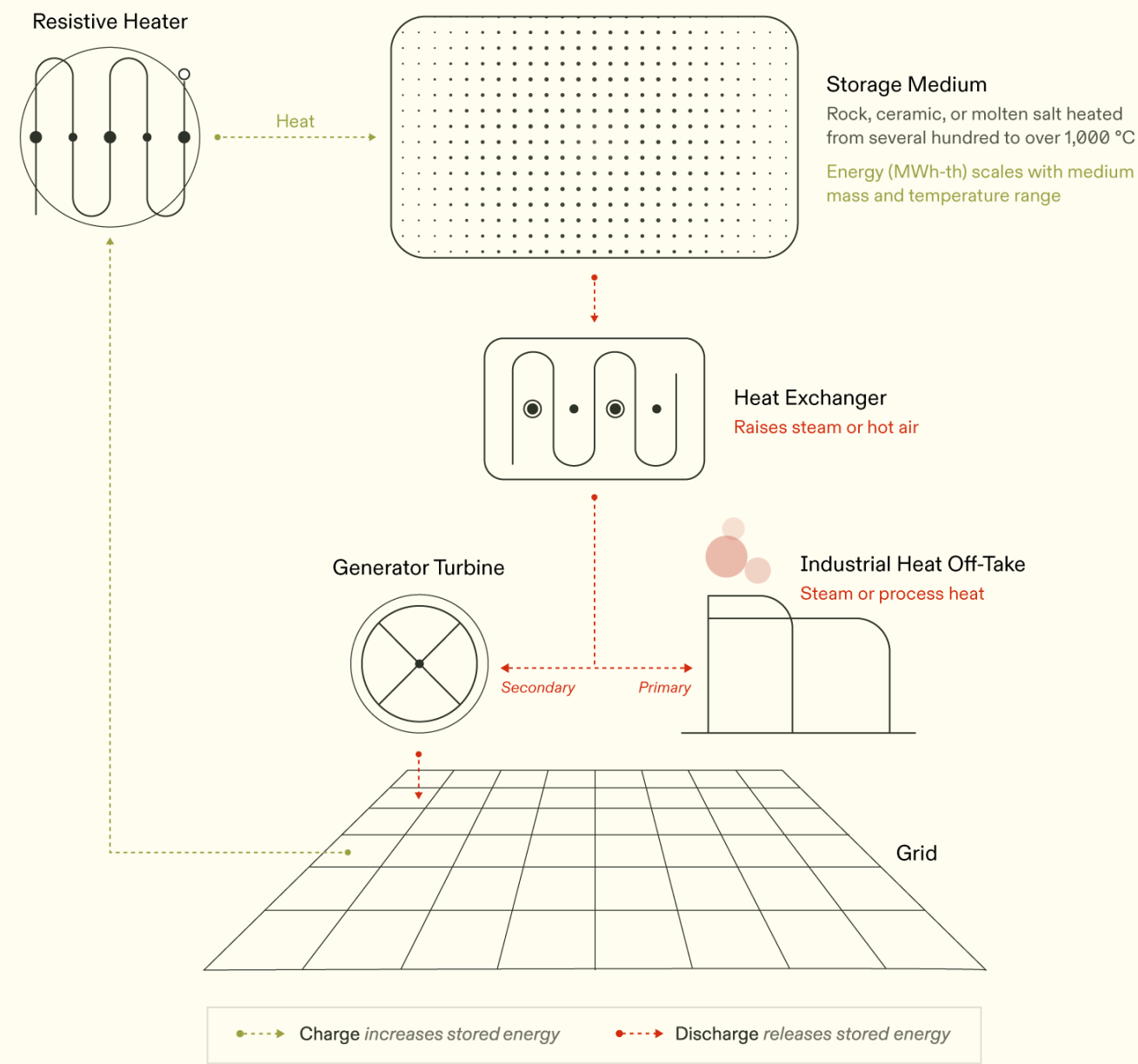


Figure 4. Thermal long-duration energy storage using sensible-heat storage in rock, ceramic, or molten salt. Note: MWh-th = megawatts hours to thermies. Source: Relae.

State Of The Market

As of 2026, LDES has made a number of commercial breakthroughs but is structurally small, both against the power system it serves and against the short-duration storage that still dominates the sector. Global electricity generation is roughly 31,000 terawatt-hours (TWh),²¹ of which renewables now supply about 34% (10,730 TWh) and natural gas roughly 20%. Meanwhile, total global energy storage capacity stood at roughly 630 GWh by the end of 2025, just a fraction of a percent of the global generation base. LDES remains a small and recent slice of that stock, heavily concentrated in China, which holds 93% of cumulative LDES deployment. While Global LDES additions grew 49% in 2025 to exceed 15 GWh, that was still only about 6% of all new types of storage capacity installed worldwide that year.

The Shape Of The Installed Base

The technologies actually being installed today are not the ones that dominate the discourse. Of LDES capacity added globally in 2025, CAES accounted for 45%, thermal LDES systems 33%, and vanadium redox flow batteries 21%. All three draw on supply chains already operating at industrial scale. Iron-air batteries hold the largest commercial commitments but are not yet a meaningful share of operating capacity, because most of those projects are still moving from contract to construction.

China's dominance of the installed base reflects state-led deployment rather than merchant economics. Much of the deployment is driven by vanadium redox flow battery and CAES projects, in part due to China's control over 70% of global vanadium mining capacity.²² Notable projects include Rongke Power's 175 MW/700 MWh vanadium redox flow

²¹ International Energy Agency. 2026. Electricity supply – Global Energy Review 2026 – Analysis. [accessed 2026 Sept 8]. <https://www.iea.org/reports/global-energy-review-2026/electricity-supply>

²² Bou E. 2026 Jun 24. Long-Duration Storage Is Still Anyone's Race. Forbes; [accessed 2026 Sept 8]. <https://www.forbes.com/sites/elenabou/2026/06/24/long-duration-storage-is-still-anyones-race/>

battery at Wushi, Xinjiang²³ in December 2024 and a 300 MW/1,800 MWh CAES project under construction at Feicheng in Shandong.²⁴

In the US, installation has been more modest, but it is growing. Operational utility-scale battery storage reached 43.6 GW at the end of 2025 and approximately 52 GW by mid-2026.²⁵ The first quarter of 2026 set a record at 3.3 GW/8.4 GWh installed, 54% above the previous first quarter record. However, almost none of this is in LDES systems. Even in the most storage-saturated US market, the California Independent System Operator (CAISO) grid, the average duration of the installed fleet was 3.8 hours²⁶ at the end of 2025 and new 2025 builds averaged 3.5 hours. In the Electric Reliability Council of Texas (ERCOT) grid, the fleet average is 1.65 hours, and only 112 MW of capacity with duration of longer than 2.5 hours was commissioned in the entire year.²⁷

What The Project Pipeline Is Telling Us

While installed capacity is modest, the pipeline for LDES is growing with more and more projects going from announcement to approval (**table 2**). These projects illuminate five things about where LDES is finding a market:

- **Two technology families, iron-air batteries and CAES, have crossed from demonstration into commercial scale by different routes.** Iron-air batteries lead on announced energy capacity: Form Energy's 300 MW/30 GWh project, supporting a Google data center on Xcel Energy's Minnesota system, is the largest LDES project ever announced, with an 85 MW/8.5 GWh project in Lincoln, Maine just behind it. CAES leads on delivery, accounting for 45% of installed LDES capacity worldwide in 2025. Hydrostor's 500 MW/4 GWh Willow Rock project received full power plant licensing in December 2025, the largest of its kind outside China.

²³ Energy-Storage.News. 2024 Dec 10. Rongke Power completes grid-forming 175MW/700MWh vanadium flow battery in China, world's largest. [accessed 2026 Sep 9].

<https://www.energy-storage.news/rongke-power-completes-grid-forming-175mw-700mwh-vanadium-flow-battery-in-china-worlds-largest/>

²⁴ PV Magazine. 2024 May 16. World's largest compressed air energy storage project comes online in China. [accessed 2026 Sep 9].

<https://www.pv-magazine.com/2024/05/16/worlds-largest-compressed-air-energy-storage-project-comes-online-in-china/>

²⁵ United States Energy Information Administration (EIA). 2026. Today in Energy. [accessed 2026 Sept 8]. <https://www.eia.gov/todayinenergy/>

²⁶ Modo Energy. 2026. CAISO battery storage in 2026: 8 things to watch. 2026 [accessed 2026 Sep 9].

<https://modoenergy.com/research/en/caiso-battery-storage-2026-things-to-watch>

²⁷ Modo Energy. 2026.ERCOT Annual Buildout Report: Battery capacity reaches 14 GW entering 2026. [accessed 2026 Sept 8].

<https://modoenergy.com/research/en/ercot-battery-buildout-2025-annual-report>

- **The buyer base has broadened from grant funding to regulated utilities and corporate offtakers.** Three state commissions have now approved LDES into the rate base: Minnesota for Xcel's 10 MW/1 GWh Sherco system at roughly US\$0.30 per residential customer per month, Wisconsin for Alliant's Energy Dome plant, and Georgia for a 15 MW/1.5 GWh Form Energy agreement. Load-serving entities under procurement mandates are writing long-term contracts, as Central Coast Community Energy did with its 25-year agreement for 200 MW of the Willow Rock project. Google has now committed twice, to Form Energy and to Energy Dome, structuring the Minnesota deal through a tariff modeled on NV Energy's Clean Transition Tariff.
- **Projects are converging on durations at two extremes.** One cluster sits at 6–10 hours and includes Highview's 50 MW/300 MWh liquid air plant at Carrington, Alliant's 8-hour system, Willow Rock at 8 hours, and Ottana at 10 hours. The other cluster sits at 100 hours, where Form Energy's entire portfolio is aimed, matching the multi-day renewable energy gaps that shorter storage cannot cover.
- **Public credit is unlocking private capital, and the pipeline is converting.** More than US\$2.5 billion of public commitment now sits behind these projects: a US\$1.76 billion US Department of Energy conditional loan guarantee for the Willow Rock project, US\$504.4 million for ACES Delta in Utah, a US\$147 million US Department of Energy grant for Lincoln, €60 million from the European Investment Bank for Ottana, and £300 million from the United Kingdom Infrastructure Bank for Carrington. This public support is doing what it is designed to do. Form Energy's Cambridge system is operating, Sherco and Columbia County are approved, Carrington is under construction, Willow Rock is licensed, and all 40 of ACES Delta's electrolyzers are installed and running at full load.
- **Private capital is scaling to match the commercial pull.** Form Energy closed a US\$750 million Series G in August 2026, led by T. Rowe Price, taking its total equity raised past US\$2 billion. Antora Energy closed a US\$550 million Series C the same summer, bringing its cumulative raise to US\$770 million since 2017. Both are now funding factories, not just research and development. By contrast, Noon Energy raised just US\$31 million to date even as it landed a 1 GW/100 GWh supply agreement with Meta in April, a sign that commercial pull is outrunning capital formation for some technologies faster than others.

Table 2. Notable long-duration energy storage (LDES) projects in the development and deployment pipeline

Project	Developer	Location	Size	Funding/Project Status
Minnesota (Xcel System)	Form Energy	Becker, Minnesota (US)	300 MW/30 GWh	Largest LDES project ever announced; supports a Google data center via a tariff modeled on NV Energy's Clean Transition Tariff
Lincoln	Form Energy	Lincoln, Maine (US)	85 MW/8.5 GWh	US\$147 million US Department of Energy grant
Willow Rock	Hydrostor	Rosamond, California (US)	500 MW/4 GWh	Full power-plant license December 2025; largest CAES outside China; US\$1.76 billion US Department of Energy conditional loan guarantee; 200 MW/25-yr offtake with Central Coast Community Energy
Sherco	Xcel Energy/Form Energy	Becker, Minnesota (US)	10 MW/1 GWh	Approved into Minnesota rate base (~US\$0.30/residential customer/month)
Columbia County	Alliant Energy	Columbia County, Wisconsin (US)	20 MW/200 MWh	Approved into Wisconsin rate base; first US utility-scale carbon dioxide battery
Georgia Power	Form Energy	Georgia (US)	15 MW/1.5 GWh	Utility agreement approved
Carrington	Highview Power	Carrington (UK)	50 MW/300 MWh	Under construction; £300M UK Infrastructure Bank
Ottana	Energy Dome	Ottana (Italy)	1.5 MW	€60 million European Investment Bank; offtake agreement with Engie
Cambridge	Form Energy/Great River Energy	Cambridge, Minnesota (US)	1.5 MW/100-hr	Operating; Form Energy's first commercial pilot
ACES Delta	Mitsubishi Power Americas/Magnum Development	Delta, Utah (US)	220 MW	US\$504.4 million US Department of Energy conditional loan guarantee; all 40 electrolyzers installed, running at full load

Notes: GWh = gigawatt-hour, MW = megawatt, MWh = megawatt-hour, UK = United Kingdom, US = United States. Source: Relae

Where LDES Works Best

In many ways LDES has its work cut out competing with lithium-ion systems. LDES is superior where the deciding factor is duration and reliability rather than cost per kWh, which favors shorter-duration energy storage.

LDES works particularly well when grid reliability is at risk from facing multi-day supply gaps on systems with high shares of solar and wind. Short-duration batteries stop being economical in these scenarios, since they're built to cycle frequently, not sit charged and ready through a week of low wind or overcast skies. LDES also provides multi-day energy security for uptime-focused buyers, such as data center operators and hyperscalers, who increasingly value these assets as precautionary measures.

The strongest economics today, however, are in industrial process heat. Thermal energy storage is already beating natural gas boilers on cost for medium-pressure steam applications, with internal rates of return reaching 28%²⁸ in well-sited projects. Medium-pressure steam (e.g., chemicals, food and beverage), district heating, high-pressure steam in alumina refining, and off-grid cogeneration are commercially viable now (provided the site has access to abundant, low-cost, renewable generation to charge against).

Beyond these applications, LDES also fits well in diesel displacement for remote and off-grid sites, where the bar is beating diesel rather than lithium-ion systems. LDES also fits well in curtailment capture and transmission deferral, where storing renewable output that would otherwise be wasted offsets the cost of new grid infrastructure.

Ultimately, LDES does not necessarily need to out compete short-duration storage on cost since it is designed to solve a duration and reliability problem that short-duration batteries structurally cannot solve.

How To Deploy LDES

Deployment starts with matching technology to the specific gap being filled. A project sized for multi-day grid reliability needs a fundamentally different asset than one solving for industrial process heat or data center backup. The technology selection should follow from the use case, and not be dictated by whichever chemistry is best funded that year. Geography can often determine the best technology for a particular site: pumped hydro and compressed

²⁸ McKinsey. 2022. Net-zero heat: Long-duration energy storage to accelerate energy system decarbonization. [accessed 2026 Sept 8]. <https://www.mckinsey.com/capabilities/sustainability/our-insights/net-zero-heat-long-duration-energy-storage-to-accelerate-energy-system-decarbonization>

air need a cavern or reservoir; thermal storage needs co-location with an industrial heat load. Finding such natural fits is the best way to develop a technically sound asset that is likely to succeed commercially.

The harder problem is revenue, because most markets still do not price what LDES sells. Ancillary markets are built to reward fast response, not sustained duration. The US Department of Energy estimates roughly US\$50–75 per kW-year of additional resource adequacy compensation is needed by 2030 before duration gets properly valued.²⁹ Further, capacity markets typically have derating factors for 2-, 4-, and 8-hour storage systems but do not necessarily reflect the value that LDES systems provide in sustaining output during extended shortage hours.

Until market design catches up, bankable projects are being built on layered, contracted revenue, such as long-term bilateral offtake agreements, paired renewable power purchase agreements that bundle energy and capacity, and hedge agreements that put a floor under merchant cash flow in more liquid markets like Texas. Portfolio financing (i.e., bundling several projects so no single asset's performance sinks the debt) is becoming the preferred way to spread the remaining risk across lenders.

The last mile is underwriting the technology itself, which is where the sector's limited track record shows. Because no utility-scale LDES fleet has run long enough to prove 20-year degradation assumptions, lenders now require independent engineering review, performance guarantees, and operation and maintenance agreements with built-in augmentation provisions that shift long-term performance risk onto the vendor rather than the project owner. Policy support in the form of investment and production tax credits, US Department of Energy loan guarantees, and demonstration funding can bridge projects through this credibility gap today, but none of this closes until manufacturing capacity catches up too. Given that annual manufacturing capacity needs to reach 3 GW per year by 2030, supply-chain constraints are just as much of a bottleneck to deployment as financing and siting considerations.

²⁹ US Department of Energy. 2024 Oct. Long duration energy storage (LDES) fact sheet. Pathway to Commercial Liftoff. [accessed 2026 Oct 1]. <https://yardsale.energy/wp-content/uploads/2025/05/DOE-Liftoff-LDES-Fact-Sheet.pdf>

What LDES Needs To Scale

Four conditions will determine whether LDES is able to scale: 1) capital cost per unit of stored energy, 2) how markets pay for duration, 3) competitiveness with lithium-ion, and 4) the speed and trajectory of decarbonization. We discuss each of these in turn in the sections below.

Cost Is The Binding Constraint

In a decarbonized energy system, LDES competes with two alternatives: transmission and clean, firm power generation. Additional transmission increases access to variable renewable energy resources, by connecting the resource location with the demand center. To take an extreme and hypothetical example, a world fully connected by limitless transmission lines with no congestion constraints could feasibly run entirely on wind and solar without the need for alternative forms of energy. Of course, the transmission network does have congestion constraints, which is why proximity to load is important. Clean, firm power generation, like nuclear reactors and enhanced geothermal systems, offer a like-for-like replacement with fossil fuel, base-load power, and can be co-located with load centers. This is what LDES is up against, which is why cost is the most important factor.

The modeling literature is consistent about the cost LDES has to reach.³⁰ Energy capacity costs need to fall to US\$20 per kWh or below for long-duration storage to cut system electricity costs by 10% or more. Displacing nuclear generation requires costs below US\$10 per kWh. Displacing all firm, low-carbon generation, including natural gas with carbon capture and geothermal, requires roughly costs of US\$1 per kWh. The threshold also tightens with duration, with costs required to be below US\$100 per kWh at 10 hours, below US\$10 per kWh at 100 hours, and close to US\$1 per kWh for seasonal storage.

The modeling literature also presents two findings that matter for technology selection. First, energy capacity cost and discharge efficiency dominate the economics, while power capacity cost and charging efficiency are secondary. This is why low round-trip efficiency is an acceptable trade-off for securing a multi-day duration asset. Because it cycles rarely, efficiency losses apply to a small share of throughput while capital cost is paid regardless. This is the

³⁰ Sepulveda NA et al. 2021. The design space for long-duration energy storage in decarbonized power systems. Nat Energy. 6(5):506–516. <https://doi.org/10.1038/s41560-021-00796-8>

basis of the iron-air battery proposition at 40–50% efficiency. Second, the reliability standard set by regulators moves the cost target more than any technology improvement. Requiring a renewables-plus-storage system to meet 100% of demand implies a storage cost near US\$20 per kWh. Accepting a 5% annual shortfall raises the allowable cost to roughly US\$150 per kWh.

LDES therefore has a residual addressable market, set by what transmission cannot move and what clean, firm power generation cannot cover. Interconnection reform and the cost trajectory of advanced nuclear and geothermal shape the size of the LDES opportunity as much as LDES costs do.

A Market That Pays For Duration

A long-duration asset provides its value in the hours when nothing else can run. Those hours are rare, and that rarity cuts both ways. It is the source of the asset's value, because no other resource covers those hours. It is also why the asset is hard to finance, because a lender is asked to underwrite revenue that may arrive only a few times over the life of the debt.

Compounding this, wholesale markets were built around dispatchable thermal generation, which is bound by capacity rather than stored energy: a natural gas plant runs as long as fuel keeps arriving, so the market only needs to know how many MW it can deliver in each interval. Payment follows that logic, based on energy provided interval-by-interval and peak available capacity. A resource that is providing value across only a handful of extreme days fits neither category. Most of the value it creates goes to consumers and other generators as avoided outages and lower prices, while the revenue reaching the owner is small and uncertain. Bridging the social value LDES provides with the private value it receives is key for getting the technology built.

The ERCOT and PJM grids sit at opposite ends of US wholesale market design, and represent the range of valuation approaches. ERCOT permits offers up to US\$5,000 per MWh, more than twice the cap in FERC-jurisdictional markets, but has no mechanism that pays more for eight hours of duration than for two. Revenue is volatile and cannot be underwritten. PJM does the opposite. It publishes³¹ accreditation values years in advance and credits storage at 59% of nameplate at four hours and 78% at 10 hours, which gives a developer something a lender will recognize. The US

³¹ PJM. 2026. Preliminary ELCC Class Ratings for period Delivery Year 2026/27 – Delivery Year 2034/35. [accessed 2026 Sep 8]. <https://www.pjm.com/-/media/DotCom/planning/res-adeq/elcc/preliminary-elcc-class-ratings-for-period-2026-2027-through-2034-2035.aspx>

Department of Energy estimates that roughly US\$50–75 per kW-year of resource adequacy compensation is needed by 2030 to finance these assets at scale.³²

Markets are unlikely to correct this on their own, because the risk cannot be laid off. Recent work³³ on contracting for long-duration storage finds that incomplete risk markets substantially suppress investment, and that the available remedies trade against each other: centrally administered contracts restore investment to the level a risk-neutral investor would choose but require transfers from consumers, while bilateral contracts avoid those transfers and provide weaker incentives. No structure delivers the investment without a cost somewhere.

In the meantime, buyers are contracting directly. California is centrally procuring 2 GW of long-duration storage under AB 1373,³⁴ explicitly excluding lithium-ion batteries and pumped hydro, and Virginia requires 3,480 MW of storage of 10 hours or longer by 2045.³⁵

Competitiveness Within Lithium-Ion

Lithium-ion continues to set the benchmark. Its cost curve is driven by electric vehicles and consumer electronics, industries with demand that dwarfs grid storage. Up to a certain duration, a lithium-ion system can be built to do whatever an LDES system does. Beyond that duration it stops being economical: extending a lithium-ion system to 100 hours would cost roughly US\$24,000 per kW of energy capacity alone.

The line currently sits somewhere between 12 and 24 hours, and it is moving upward. Stationary storage battery pack costs fell 45% in 2025 to US\$70 per kWh,³⁶ the cheapest segment of the lithium-ion market. A US four-hour

³² United States Department of Energy. 2023. Pathways to Commercial Liftoff. [accessed 2026 Sep 8].

<https://yardsale.energy/wp-content/uploads/2025/05/DOE-Liftoff-Introduction.pdf>

³³ Brown PR, Botterud A. 2021. The Value of Inter-Regional Coordination and Transmission in Decarbonizing the US Electricity System. *Joule*. 5(1):115–134. <https://doi.org/10.1016/j.joule.2020.11.013>

³⁴ California Public Utilities Commission. 2024. AB 1373 Centralized Procurement of Specified Long Lead-time Resources. [accessed 2026 Sept 8]. <https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/electric-power-procurement/long-term-procurement-planning/ab-1373-centralized-procurement-of-specified-long-lead-time-resources>

³⁵ Commonwealth of Virginia. 2026. HB895 - 2026 Regular Session | LIS. [accessed 2026 Sept 8]. <https://lis.virginia.gov/bill-details/20261/HB895>

³⁶ BloombergNEF. 2025. Lithium-Ion Battery Pack Prices Fall to \$108 Per Kilowatt-Hour, Despite Rising Metal Prices.[accessed 2026 Sept 8]. <https://about.bnef.com/insights/clean-transport/lithium-ion-battery-pack-prices-fall-to-108-per-kilowatt-hour-despite-rising-metal-prices-bloombergnef/>

system costs around US\$334 per kWh, split between US\$372 per kW of power capacity and US\$241 per kWh of energy capacity. Because power conversion cost is fixed per kW, cost per kWh falls as duration lengthens and approaches the cell cost as a floor. At eight hours it is already close to that floor. California tested this directly with a 1 GW procurement³⁷ designed to elicit non-lithium, long-duration storage. It drew 51 bidders and more than 9 GW of proposals across flow, hydrogen, gravity, pumped hydro, and thermal technologies, and awarded contracts to eight-hour lithium-ion.

Below the line, LDES has to compete on attributes other than energy cost. Vanadium redox flow batteries, for example, offer 20,000–30,000 cycles and 25–30 year lifespans with no capacity decline and no depth-of-discharge penalty, compared to a 15-year system life and periodic augmentation for lithium-ion. They are also non-flammable. Their supply chains are better placed to meet the domestic content thresholds the One Big Beautiful Bill Act applies to storage,³⁸ which rise from 55% in 2026 to 75% by 2030.

The same competition decides the data center opportunity. Large loads now face curtailment obligations in both PJM³⁹ and Texas,⁴⁰ but can meet them with on-site capacity including storage. Separately, AI training loads swing tens of MW within milliseconds, which has already caused multi-GW load transfers off the PJM system following transmission faults.⁴¹ Both applications need instantaneous dispatch and high power relative to energy capacity, which is what multi-day technologies give up to reach low cost per kWh. A 100-hour system is a C/100 device by

³⁷ Bonner A. 2026 Jun 23. REV Renewables and LS Power commission California's first 8-hour duration lithium-ion BESS. Energy-Storage.News; [accessed 2026 Sept 8].

<https://www.energy-storage.news/rev-renewables-and-ls-power-commission-californias-first-8-hour-duration-lithium-ion-bess/>

³⁸ United States Internal Revenue Service. Treasury, IRS provide guidance for certain energy tax credits regarding material assistance provided by prohibited foreign entities under the One, Big, Beautiful Bill. [accessed 2026 Sept 8].

<https://www.irs.gov/newsroom/treasury-irs-provide-guidance-for-certain-energy-tax-credits-regarding-material-assistance-provided-by-prohibited-foreign-entities-under-the-one-big-beautiful-bill>

³⁹ PJM. 2026. Reliability Backstop Procurement To Address Resource Adequacy Concerns Stemming From Large Loads. [accessed 2026 Sep 8]. <https://www.pjm.com/pjmfiles/directory/etariff/FercDockets/9806/20260731-er26-3380-000.pdf>

⁴⁰ Texas State Legislature. Texas SB6 | 2025-2026 | 89th Legislature. LegiScan; [accessed 2026 Sept 8]. <https://legiscan.com/TX/text/SB6/id/3248460>

⁴¹ Carbon Direct. 2026 May 7. Inside NERC's Level 3 Alert on data center loads. [accessed 2026 Sept 8]. <https://www.carbon-direct.com/insights/nerc-level-3-alert-data-center-loads>. Note: As of September 21, 2026, Carbon Direct is now Relae.

construction,⁴² and Form Energy assigns⁴³ fast frequency response and 15-minute ancillary markets to two- and four-hour batteries rather than to iron-air batteries. Flow batteries have a credible claim on this duty, with Invinity publishing a 110 millisecond response time verified by third-party testing.⁴⁴ For the rest of the field, the stronger claim is capacity accreditation rather than ride-through: a 10-hour resource covers more of a large load's demand per MW installed than a four-hour resource does.

The Speed And Trajectory Of Decarbonization

The three conditions discussed above must be supported by a policy environment that encourages decarbonization, and cannot compensate for a system that keeps burning unabated gas. Mechanically, a natural gas peaker plant is close to an ideal long-duration asset. It holds weeks of stored energy in the pipeline that feeds it, costs little to build relative to its output, and is paid for the hours it runs. Storage cannot beat that on cost alone. LDES becomes necessary only when emissions limits remove unabated natural gas from the option set, which is why this wave of innovation is recent rather than decades old. The physics behind iron-air batteries, compressed air caverns, and molten salt have been understood for a long time. What has changed is that a growing number of systems are committed to reducing unabated, fossil-fueled power generation. The pace at which those commitments tighten sets the size of the market more directly than any engineering improvement.

Modeling identifies where the threshold sits. Firm, low-carbon resources, and by extension LDES, begin lowering system costs below roughly 50 grams of CO₂ per kilowatt-hour (gCO₂/kWh).⁴⁵ Above that level, gas does the job more cheaply. In fully decarbonized scenarios, firm resources reduce electricity costs by 10–62%. The value of both rises sharply in the final increment. Reaching 100% decarbonization costs an additional US\$93 per MWh in a system planned state-by-state, compared to US\$33 per MWh in one with coordinated interregional transmission. Deep

⁴² A C/100 device refers to a battery discharged or charged at a rate where the current is 1/100th of its nominal capacity, providing or accepting power over 100 hours.

⁴³ Kann S. 2023. What do you do with a 100-hour battery? Latitude Media; [accessed 2026 Sept 8].

<https://www.latitudemedia.com/news/catalyst-what-do-you-do-with-a-100-hour-battery/>

⁴⁴ Invinity Energy Systems. 2021. Flow Battery Response Time and the Business Case for Ancillary Services. Invinity; [accessed 2026 Sept 8].

<https://invinity.com/flow-battery-response-time/>

⁴⁵ Sepulveda NA, Jenkins JD, Sisternes FJ de, Lester RK. 2018. The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation. *Joule*. 2(11):2403–2420. <https://doi.org/10.1016/j.joule.2018.08.006>

decarbonization is the regime under which transmission, firm generation, and long-duration storage all become necessary at once, which is also why they compete with one another.

Relae's own capacity expansion modeling confirms this pattern at the regional level. Across PJM, ERCOT, and CAISO, LDES deployment under a high-growth load forecast is highly sensitive to the depth of decarbonization and to the cost of competing clean, firm resources. In a low-decarbonization future, deployment is negligible in all three markets at the LDES costs modeled, regardless of the cost of clean, firm resources. **Table 3** focuses on the high-decarbonization case where deployment ranges from near zero when clean, firm power is available at lower costs to well over 100 GW in PJM when costs are higher.

Table 3. Long-duration energy storage (LDES) deployment under high-decarbonization and high-load forecast, in gigawatts (GW)

	PJM	ERCOT	CAISO
Higher-Cost Clean Firm	31.0–176.6	23.6–54.5	11.3–13.6
Lower-Cost Clean Firm	0.0–10.8	4.5–11.9	0.0–9.0

Note: Ranges represent LDES deployment outcomes under reference 2040 technology costs (lower bound) and ambitious technology cost declines (upper bound). The high-decarbonization target is 10 grams of carbon dioxide equivalent per kilowatt hour (gCO₂e/kWh) and 100% carbon free energy requirement for data center loads. Lower-cost clean firm = moderate scenario costs from the National Renewable Energy Laboratory's 2025 Annual Technology Baseline (ATB) for clean, firm technologies (e.g., geothermal, small modular reactors, natural gas fired generation with carbon capture and storage, and hydrogen combustion turbines); higher-cost clean firm = 1.5 times those costs. A low-decarbonization case (i.e., no grid emissions rate requirement) is omitted because it produced negligible LDES deployment in all three markets. Source: Relae.

In a high-decarbonization future, the relative cost of clean, firm resources can change the size of the LDES market by as much as 16-fold. If other forms of clean, firm power stay expensive, LDES deployment could reach 31–177 GW in PJM, 24–55 GW in ERCOT, and 11–14 GW in CAISO. If the costs of clean, firm alternatives fall, those same high-decarbonization scenarios yield 0–11 GW, 5–12 GW, and 0–9 GW, respectively: a reduction of roughly 80–95% at the top of the range in PJM and ERCOT, and about a third in CAISO. The depth of decarbonization determines whether LDES has a significant role to play; the cost of clean, firm alternatives determines how large that role is.

Policy is the mechanism that turns targets into demand. The US Department of Energy puts the requirement at 225–460 GW of LDES for a net-zero economy by 2050,⁴⁶ compared to roughly 60 GW of LDES under business as usual. Closing that gap depends on demand appearing before costs have fallen, and the volume needed to start the process is smaller than it appears. Modeling of corporate 24/7 clean power procurement suggests 1–2 GW of committed load is enough to begin the cost learning curve, worth a 16–44% reduction in iron-air battery costs depending on participation.⁴⁷ A small group of large buyers could feasibly make this kind of procurement commitment, sending a strong demand signal and getting the process started. Private action, along with public policy, will need to work together to meet decarbonization goals and support LDES deployment.

⁴⁶ United States Department of Energy. 2024. Long duration energy storage: pathways to commercial liftoff. [accessed 2026 Sep 9]. <https://liftoff.energy.gov/long-duration-energy-storage/>

⁴⁷ The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation: Joule. [accessed 2026 Sept 8]. [https://www.cell.com/joule/fulltext/S2542-4351\(18\)30386-6](https://www.cell.com/joule/fulltext/S2542-4351(18)30386-6)

Acknowledgements

Authors and Contributors

Douglas Bryan, Senior Manager of Power and Energy Systems

Julia Millot, Senior Power Decarbonization Manager

Adrianna Sutton, Director of Science Writing and Editing

Shirin Mavandad, Senior Research Associate

Kelli Cribb, Design Lead

Nicki Stuckert, PhD, Director of Industrial Technology Diligence

Colin McCormick, PhD, Chief Innovation Officer

Derya Eryilmaz, PhD, Vice President of Power

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