U.S. DEPARTMENT OF ENERGY

Pathways to Commercial Liftoff: Long Duration Energy Storage

March | 2023

Comments

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Authors

Authors of the Long Duration Energy Storage Pathway to Commercial Liftoff:

Office of Technology Transitions: Katheryn (Kate) Scott, Stephen Hendrickson

Office of Policy: Nicole Ryan

Office of Clean Energy Demonstrations: Andrew Dawson, Kenneth Kort, Jill Capotosto

Office of Electricity: Benjamin Shrager, Vinod Siberry

Office of Energy Efficiency and Renewable Energy: Paul Spitsen

Argonne National Laboratory: Susan Babinec, Patrick Balducci, Zhi Zhou

Cross-cutting Department of Energy leadership for the Pathways to Commercial Liftoff effort:

Office of Clean Energy Demonstrations: David Crane, Kelly Cummins, Melissa Klembara

Office of Technology Transitions: Vanessa Chan, Lucia Tian

Loan Programs Office: Jigar Shah, Jonah Wagner

Acknowledgements

The authors would like to acknowledge analytical support from Argonne National Laboratory and McKinsey & Company; as well as valuable guidance and input provided during the preparation of this Pathway to Commercial Liftoff from:

Office of Clean Energy Demonstrations: Catherine Clark, Caroline Grey, Jason Munster, Brian O'Donnchadha

Office of Technology Transitions: Marcos Gonzales Harsha, Hannah Murdoch, James Fritz, Anna Siefken, Erik Hadland

Loan Programs Office: Julie Kozeracki, Ramsey Fahs, Kevin Johnson, Carolyn Davidson, Leslie Rich, Christopher Creed

Office of Policy: Carla Frisch, Steve Capanna, Elke Hodson, Colin Cunliff, Ravahn Samati, Jay Vaingankar, Piper O'Keefe

Office of Energy Efficiency and Renewable Energy: Alejandro Moreno, Courtney Grosvenor, Sam Baldwin, Diana Bauer, Changwon Suh, Samuel Bockenhauer, Matthew Bauer, Sunita Satyapal, Heather Croteau, Lauren Boyd, Jeffrey Bowman, Sean Porse, Tien Duong

Office of Electricity: Gene Rodrigues, Eric Hsieh

Office of the Secretary: Kate Gordon

Office of Economic Impact and Diversity: Shalanda Baker

Office of Energy Jobs: Betony Jones, Christy Veeder

Office of International Affairs: Julie Cerqueira, Matt Manning

Office of the General Counsel: Avi Zevin, Brian Lally, Ami Grace-Tardy

Office of Manufacturing and Energy Supply Chains: David Howell, Jacob Ward, Mallory Clites

Office of Science: Asmeret Asefaw Berhe, Craig Henderson, John Vetrano

Argonne National Laboratory: Aymeric Rousseau, Thomas H. Fanning

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LDES: Executive Summary

These Pathways to Commercial Liftoff reports aim to establish a common fact base and ongoing dialogue with the private sector around the path to commercial liftoff for critical clean energy technologies. Their goal is to catalyze more rapid and coordinated action across the full technology value chain.

Introduction to LDES

To answer emerging environmental and social challenges as well as meet the Biden administration's targets for 2050 Net Zero emissions and 100% carbon-pollution free electricity by 2035, the power sector will need to rapidly scale and transition. Currently, the power sector is responsible for one third of domestic emissions. Successfully decarbonizing requires a transition away from uncontrolled fossil-fuels-based generation assets towards carbon-free power sources such as renewables (e.g., wind, solar) and nuclear. The power sector will need to simultaneously transition to new power sources and scale rapidly to meet new electrified downstream uses. As variable renewables cannot be turned on and off to meet peak demand in the same manner as fossil-fuels-based generation assets, the grid will need a new way of providing flexibility and reliability.

New options, like Long Duration Energy Storage (LDES), will be key to provide this flexibility and reliability in a future decarbonized power system. LDES includes a set of diverse technologies that share the goal of storing energy for long periods of time for future dispatch. The form of energy that is stored and released, as well as the duration of dispatch is highly variable across technologies.

This report focuses on the application of LDES systems for electricity purposes (e.g., energy is stored and then dispatched in the form of electricity at a later time). To evaluate the commercial feasibility of LDES within the U.S., this effort consulted a wide range of existing research[1] and modeled a U.S.-power-sector decarbonization pathway with varied decarbonization and technical scenarios to assess LDES's role in the power sector and factors influencing LDES deployment pathways for electricity needs. The integrated modeling scenarios serve three purposes:

1. **Estimating a business-as-usual trajectory:** The business as usual (BAU) scenario represents the current trajectory and includes the impacts of the 2022 Inflation Reduction Act (IRA) but without additional commercialization interventions.
2. **Forecasting least-cost pathways to meet decarbonization goals:** Net-zero decarbonization scenarios forecast what it would take to reach net-zero by 2050 under different constraints on variable renewables and on transmission capacity. We forecast scenarios both with and without achieving interim clean power by 2035.
3. **Exploring technology potential:** Technology-specific sensitivities represent conditions for the uptake of different types of LDES under different operating parameters and competing technology conditions (e.g., net-zero without LDES).

Based on this analysis, **the U.S. grid may need 225-460 GW of LDES capacity for power market application for a net zero economy by 2050, representing $330B in cumulative capital**. While this requires significant levels of investment, **analysis shows that by 2050 net-zero pathways that deploy LDES result in $10-20B[i] in annualized savings in operating costs and avoided capital expenditures** compared to pathways that do not (by 2050). The focus of this commercialization effort is to understand the challenges, solutions, and potential long-run benefits of LDES achieving technology "liftoff" by 2030. **"Liftoff" is defined as the point where the LDES industry became a largely self-sustaining market** that does not depend on significant levels of public capital and instead attracts private capital with a wide range of risk. "Liftoff" is characterized by significant improvement in technology and operating parameters, market recognition of LDES's full value, and realization of industrial-scale manufacturing and deployment capacity. These improvements are needed for LDES to compete with alternative technologies.

1 Including research from the Department of Energy and the National Laboratories, as well as cross-technology reports including the White House Pathways to Net Zero, Princeton Net Zero America, NREL Clean Electricity, and the Long Duration Energy Storage (LDES) Council

Technology Landscape

This report defines LDES market segments by duration of dispatch in a power context—the most standard way of defining LDES across the industry to discussing different storage types. Many existing classifications group storage technologies into two categories (diurnal and seasonal), but this report uses four storage classifications (short, inter-day LDES, multi-day / week LDES, and seasonal) as many new technologies are focused on the LDES categories. **This report focuses on those two intermediate duration market segments—inter-day and multi-day / week LDES**.

- Inter-day LDES is defined as shifting power by 10–36 hours and includes almost all mechanical storage technologies and some electrochemical technologies (e.g., flow batteries). These technologies primarily serve a diurnal market need by shifting excess power produced at one point in a day to another point within the same or next day.
- Multi-day / week LDES is defined as shifting power by 36–160+ hours and includes many thermal and electrochemical technologies. It fills a market and end-use customer need where there may be an extended shortfall of power (e.g., multiple days of low wind and solar or resiliency applications) several times per year; Multi-day / week LDES can also reduce the required curtailment / interconnection over-build to support variable renewables.

NOTE: Two other market segments of storage are not directly covered in this report, short duration and seasonal balancing. Short duration is defined as shifting power by less than 10 hours, often through Li-ion storage (primarily in the 0–4-hour range, while other storage such as pumped storage hydropower competes for 4-10 hours). Seasonal balancing is defined as moving energy for an extended time period, mostly over several months (e.g., summer to winter) and is a need likely to be filled by a fuel-based technology (e.g., hydrogen or natural gas with carbon capture). Both short duration and seasonal storage are accounted for as competitive technologies to prove and disprove in various business cases for inter-day LDES and multi-day / week LDES.

Value Proposition and Requirements for “Liftoff”

LDES has the potential to play a significant role in the decarbonization by the U.S. power system-from bulk power to resiliency and behind-the-meter applications. By following the path outlined in this report, LDES technologies could be the least-cost option to provide stability and flexibility to the grid as a variable renewables expand. In addition, LDES could be the best solution to improve local and regional resiliency with increasing frequency of extreme-weather events while also reducing the cost and risks around grid expansion. LDES represents an attractive future asset class to investors given the expected scale of capital investment required and the diversity in end-use application and business models. The end-use applications are broad enough to enable the potential for more than one type of LDES technology to be part of a net-zero solution. The technologies are often modular and flexible, which reduces investment risk over long-time horizons. While LDES technologies provide the high-potential way to decarbonize a range of use cases, there are other technologies competing for the same use cases (e.g. Li-ion for inter-day uses, natural gas paired with carbon management technologies for multi-day uses). Pathways that deploy LDES are $10-20B cheaper[i] than those that do not based on system savings in operating costs (reduced renewable curtailment and fuel spend) as well as reduced capital investment for dispatchable firm generation.

To realize its full potential and play a leading role in a net-zero grid, LDES must achieve a technology “liftoff”. As mentioned above, “liftoff” is the state where private capital can take over due to development in three areas: significant improvements in technology cost and operating parameters, market recognition of LDES’s full value- through increased compensation or other means- and industrial-scale manufacturing and deployment capacity (Figure 1)

Achieving liftoff[1] by 2030-2035 requires improvements in technology, cost declines, regulatory support, and supply chain development

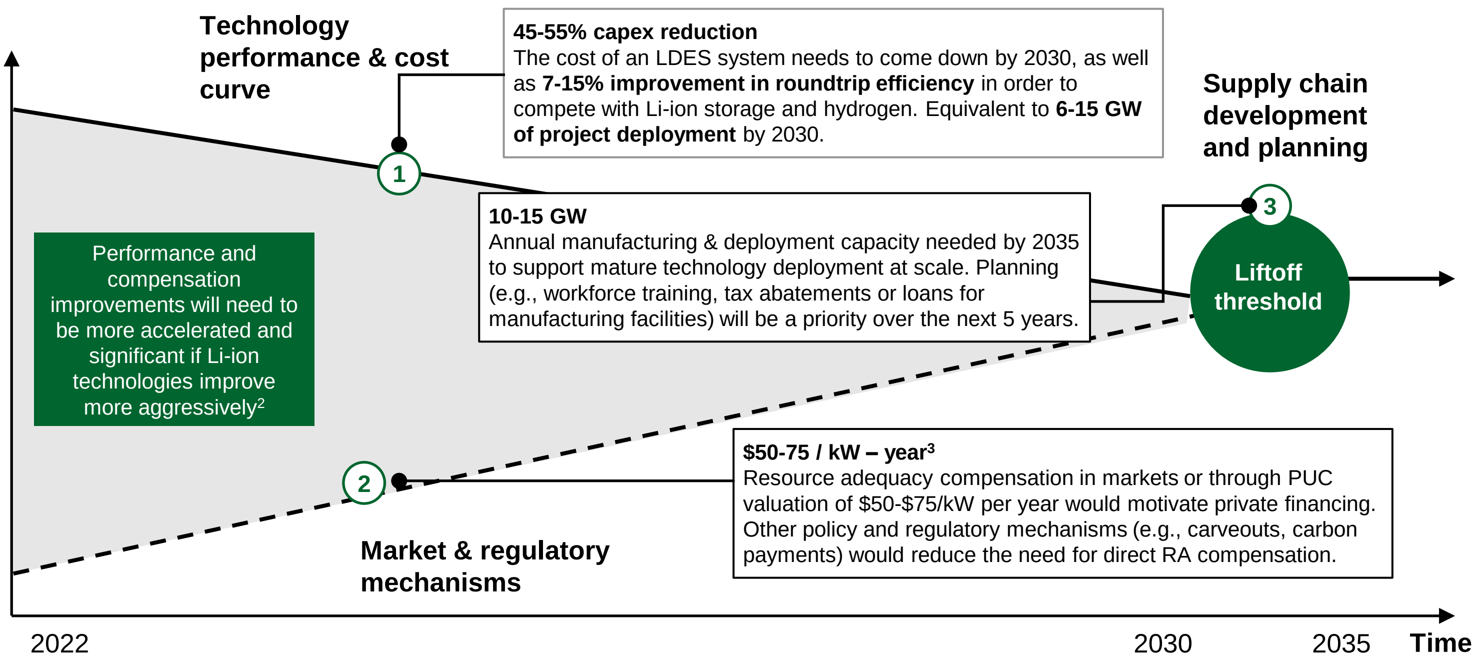


Figure 1: Liftoff by 2030-2035 requires improvements in technology, cost declines, regulatory support, and supply chain development. Notes: PUC stands for Public Utilities Commission, RA for Resource Adequecy. [1]Liftoff is defined as the point where the LDES industry becomes a largely self-sustaining market; [2]Need for multi-day / week LDES technologies remains in both Li-ion scenarios, and aggressive Li-ion will reduce the need for supply chain build out. [3]$/kW – year varies by geography.

LDES's share in the long-term net-zero economy depends on meeting significant milestones in the near-term, which would require concentrated and coordinated efforts across the LDES ecosystem from LDES companies, regulators, investors, and organizations. These critical milestones are described below:

Technology performance and cost curves must improve to attract sustained investment. Early public and private investment support in commercial-scale project demonstration and deployment are necessary to generate the economies of scale and manufacturing improvements that will drive further improvement in LDES cost and performance beyond what is possible in-lab. These technology cost curves must come down by 45–55% by 2028-2030 relative to costs reported by leading technologies today, and both the performance and the working lifetime of LDES technologies must improve.[2,3] By 2030, inter-day LDES technologies must reduce costs from $1,100–1,400 per kW to $650 per kW and improve round trip efficiency (RTE) from the 69% seen in best-in-class technologies in 2022 to ~75%. Likewise, multi-day technologies must improve from $1,900–2,500 per kW and 45% RTE today to $1,100 per kW and 55–60% RTE by 2030. Demonstration and deployment projects—primarily deployed by utilities, developers, Independent Power Producers with the support of outside funding—are essential for achieving technology performance and cost-curve improvements and making LDES a competitive option in a net-zero pathway (Section 4a.i). Where these improvements are likely to come from in the next decade varies by technology; there are some technologies where conventional research and development could drive a substantial portion of the cost declines needed. However, most technologies will likely reduce costs by developing large, standardized installations and unlocking manufacturing efficiencies. These learnings will depend on scaled demonstration and commercialization projects.

2 Technology improvement and compensation goals outlined in this report are in-line with existing DOE Energy Storage Grand Challenge (ESGC) goals of $0.05/kWh for long-duration stationary applications.
3 Newer companies may need to reduce costs as much as 75% relative to their 2021 reported costs.

Compensation for the range of economic and reliability benefits would need to be realized. State, regional, and national interventions could ensure that LDES is valued for the benefits it provides to energy markets and infrastructure utilization (e.g., dynamic capacity markets, differentiated capacity products, and a recognition of storage for its dual role in generation and transmission systems). There are many reliability and transmission benefits that LDES systems can provide that markets do not yet fully compensate. Predictable compensation for LDES resource adequacy benefits—(roughly equivalent to an additional ~$50–75 per kW per year by 2030[i] when considering other potential energy market payments)—would be one of the direct ways to support a business case for investment.[4] This compensation could come directly from market participation or could be indirectly valued in its selection as part of an integrated resource planning process outside competitive energy markets. The regulatory and market change also requires identification of the differentiated need for longer duration, firm, dispatchable power in addition to the monetary compensation (e.g., expanding from 4–6-hour firm capacity products to longer duration such as 12 hour and 24-hour firm based on market need).

In order for that value and need to be realized, many jurisdictions would require changes to modeling methodology for integrated resource planning (e.g., regulated utilities receive approval to deploy LDES as a part of a lowest-cost system), resource adequacy studies and their associated methodology for evaluating the firm and variable resources, and transmission planning. New, more transparent market products and more open procurement processes are also likely needed. Market and regulatory mechanisms would need to evolve if LDES economics are to be supported; priority interventions are needed to increase market certainty and improve risk-adjusted returns (Section 4a ii).

Power markets (e.g., Independent System Operators [ISOs] / Regional Transmission Organizations [RTOs]) would need to adjust compensation and planning methodologies to value different types of reliability resources in their resource adequacy studies (e.g., hourly energy attribute certificates, nodal and locational pricing).

Regulators (e.g., public utility commissions [PUCs]) would need to adapt system modeling to account for integrated and longer-term net-zero needs (e.g., resource planning, resource adequacy studies, and transmission planning looking out beyond the typical 15-year horizon). They could also need a common, standardized recognition of storage as a generation, transmission, and distribution asset.

Supply chain formation must quickly follow the above two milestones to support at least 3 GW of annual LDES manufacturing and deployment capacity per year by 2030 (compared to <1 GW in 2022) and up to 10–15 GW by 2035[i]. The timing of the supply chain expansion is linked to renewables penetration. As renewable generation reaches an inflection point in some parts of the U.S., the broader market need to provide grid integration and flexibility services increases, rapidly expanding the potential market for LDES. The supply chain will need to handle this anticipated growth of LDES in the 2030s—10-20x the amount of LDES deployment in the 2020s.[i] Planning for this expansion requires workforce training (or re-skilling) programs and local support for manufacturing facilities. This scale-up could require 1.5–2.1M “direct” job-years in fields such as engineering and construction over the 30-year development cycle and would potentially have significant overlap with the renewable workforce, which could accelerate supply chain scaling. In addition, LDES supply chain will need to access financing options to build these facilities at the GW scale.

For this ramp to occur, technology players with government entities and financiers must form a preemptive supply chain for leading technologies at the giga-watt scale—tracked in project demonstration and deployment phases described above. Bringing down supply chain formation related costs requires repeat deployments of the same technologies suggesting the potential need to identify leading technologies early |to enable scaled manufacturing. For leading technologies, supply chain risks and interventions will need to be identified for raw materials, sub-components, manufacturing and assembly, and workforce development (Section 4a iii).

4 This is based on a 15-20% unlevered IRR; For more details on modeling please go to Appendix 4.

Workforce will be the most significant risk to deployment, as most forms of LDES are highly engineering and construction intensive—this workforce timing will align with the required workforce development needed for meeting renewables, nuclear, carbon capture utilization and storage (CCUS), hydrogen, and other clean technology buildout needs to reach net-zero by 2050. Active planning to preclude these gaps—such as expansion of on-the-job training and registered apprenticeship programs, project hybridization and modular project deployment—will be necessary for the annual construction jobs needed to support LDES at this scale of project demand.[i]

Conclusion

LDES could play a critical role in the United States' decarbonized energy system. LDES technologies are an option to complement the expansion of variable renewables and improve local and regional resiliency while decreasing the costs and risks of grid expansions. To achieve this vision of the future, many interventions are needed and must reflect the regional variations in existing market support, physical resources, and infrastructure. Despite these variances, a relatively small set of priority actions for each stakeholder group is needed to support the project deployment, revenue mechanisms, and supply chain scale-up of LDES.

In addition to continued R&D funding for LDES technologies, the federal government can potentially help in three ways: **(1) offering targeted financial support (grants/loans) for individual projects**—ranging from lab-based research for novel technologies to demonstration projects for projects ready to achieve commercial scale; **(2) providing educational sessions, modeling tools and valuation frameworks** for regulators and ISOs and commercial customers to evaluate their behind-the-meter and grid-scale applications; and **(3) developing transparency on technology cost and performance** for investors, regulators and policymakers to quickly adapt their portfolios. The first has begun at the DOE across both the Energy Storage Grand Challenge, Long Duration Storage Shot and Office of Clean Energy Demonstrations. The final two pieces will be supported heavily by the National Laboratories, where research on technology vetting and certification for deployment readiness—in addition to publicly available tools and market compensation standards—may create a "source of truth" for all other players in the ecosystem.

Chapter 1: Introduction & Objectives

Section 1.a: Objectives

This U.S. Department of Energy (DOE) Pathway to Commercial Liftoff report aims to inform business decision-makers on which types of projects, customers, and policy / regulatory conditions will favor a rapid scale-up of Long Duration Energy Storage (LDES) technologies. It relies on both analysis and stakeholder input to summarize the current state and inform potential actions.

This Pathway to Commercial Liftoff report complements DOE's Energy Storage Grand Challenge (ESGC) which aims to accelerate the development, commercialization, and utilization of next-generation energy storage technologies and sustain American global leadership in energy storage. This report informs ESGC future strategy, especially the ESGC Roadmap for addressing technology development, commercialization, manufacturing, valuation, and workforce challenges to position the United States for global leadership in the energy storage technologies of the future.[5]

Section 1.b: Approach and Methodology

To evaluate the commercial feasibility of LDES within the U.S. and identify what it would take to commercialize it, this effort:

- Leveraged existing research from the Department of Energy, White House, and the National Laboratories to develop a repository of existing and public resources on storage, including the technology landscape, end-use sectors and demand projections, techno-economic considerations, and the current state of the industry (outlined in Chapter 2);
- Modeled U.S.-power-sector decarbonization pathways with varying decarbonization and technical scenarios to assess LDES's role in the power sector and factors influencing LDES deployment pathways for electricity needs;
- Identified core challenges to market commercialization and potential solutions, which were tested and iterated through stakeholder engagement and financial modeling (outlined in Chapters 3 and 4); and
- Analyzed the business case for specific LDES projects to assess core market dynamics, determine the feasibility of early commercial deployment, and test sensitivities to these analyses (outlined in Chapter 4).

To model a U.S.-power-sector decarbonization pathway, we ran a range of integrated scenarios through a capacity expansion model for the entire U.S. power grid. This model used differing system parameters and input assumptions to forecast the expansion of each technology in the system, based on least-cost optimization to meet system demand. This process enabled us to identify the potential role of LDES. As part of this effort, we consulted a range of existing cross-technology reports: *The Long-Term Strategy of the United States: Pathways to Net-Zero, Greenhouse Gas Emissions by 2050*, Princeton Net Zero America, NREL Clean Electricity, and the Long Duration Energy Storage (LDES) Council; the latter report being the only one to include future projections for novel LDES technologies. In comparison to the LDES Council modeling output, this report's scenario modeling allowed for net-zero emissions, which allows natural gas generation that is offset by carbon capture or removal, to remain on the system in a decarbonized pathway. As a result, the upper range of the LDES Council report (i.e., 600 GW of LDES in the U.S. by 2050) is slightly higher that what is captured in this report.

5 View the ESGC roadmap at https://energy.gov/energy-storage-grand-challenge/downloads/energy-storagegrand-challenge-roadmap.

Section 1.b: Approach and Methodology (continued)

The integrated modeling scenarios run in this report serve three purposes:

1. **Estimating a business-as-usual trajectory:** The business as usual (BAU) scenario represents the current trajectory and includes the impacts of the 2022 Inflation Reduction Act (IRA) but without additional commercialization interventions.
2. **Forecasting least-cost pathways to meet decarbonization goals:** Net-zero decarbonization scenarios forecast what it would take to reach a net-zero economy by 2050 under different constraints on variable renewables and on transmission capacity. We forecast scenarios both with and without achieving interim clean power by 2035.
3. **Exploring technology potential:** Technology-specific sensitivities represent conditions for the uptake of different types of LDES under different operating parameters and competing technology conditions (e.g., net-zero without LDES).

Section 1.c: Source of Insight

As part of this work, we interviewed and gathered insights from various stakeholders, primarily with a focus on the U.S. LDES market. These interviews included conversations with technology original equipment manufacturers (OEMs), market-makers (e.g., ISOs), PUCs, and customers (e.g., utilities), potential future project developers, and investors.

Additionally, we gathered insights from a wide range of industry forums, including clean energy, grid, storage, and LDES-focused conferences; publications from research institutions and consortia (e.g., the National Energy Laboratory system, research universities); and public announcements from industry members.

Section 1.d: Scope/Definition

This effort focuses on the commercialization pathways for LDES in the power sector and considers the ranges of technologies and business models that could be deployed across that value chain.

This effort is technology and business-model agnostic. It is not meant to be a comprehensive evaluation of all potential technologies and business models that could be deployed. From analyses and stakeholder engagement, this report identifies and evaluates the dynamics that are most likely to hinder or support acceleration of LDES commercialization based on a current understanding of the technology and forecasts of the sector. The report discusses the vast array of different technologies (100+ players) that may ultimately develop to meet the needs of a net-zero grid.

Section 1.e: Technology Role

Our analysis shows that LDES has a significant role to play in decarbonized systems and particularly in scenarios which allow for unconstrained renewable build out. The capacity growth, as measured in GW, of LDES has the potential to be larger than any power technology other than renewable generation in the net-zero scenarios modeled in this report. LDES' ability to deliver several critical services drives its potential:

- **Clean dispatchable energy capacity in highly decarbonized power systems**: LDES can partially replace the fossil-fuels-based generation assets that currently provide flexibility and reliability by providing dispatchable capacity for longer time periods to balance the grid.
- **Energy shifting of bulk power from clean generation during one time period to another:** this capability can also include firming of variable renewables assets (e.g., wind, solar) to match individual customer load shapes (e.g., 24/7 power production purchase agreements [PPAs]), standalone power market participation, or inclusion as a part of a utility's generation portfolio.
- **Reliability and resiliency for localized grid needs,** providing both decarbonization and grid flexibility requirements.
- **Transmission and distribution (T&D) deferral at congested areas of the grid**, especially when T&D upgrades cannot be made in a timely or cost-efficient manner.
- **Behind-the-meter load management,** specifically for large loads with multiple extended peaks and / or periods of intense upswing in demand (e.g., peak delivery season for a retailer).

LDES competes with more established technologies for some of these services (e.g., Li-ion, hydrogen). However end-use applications that require storing energy over one day and up to one week are particularly underserved or currently less economical when using Li-ion or hydrogen. These technologies also have competing end-uses outside the power sector which may be prioritized over power-sector applications (e.g., hydrogen is expected to be used in ammonia production to decarbonize shipping, transportation, and some industrial and agriculture end-uses; Li-ion batteries are needed for electric vehicles [EVs]). Therefore, LDES technologies provide a portfolio hedge for achieving all aspects of the net-zero transition.

However, few mature forms of LDES exist today, and more than 100 active players offer LDES technologies—ranging from lab stage to early commercialization. This report accounts for this complexity in two ways. First, the report groups storage technologies by similar operating characteristics to indicate what grid needs could be most effectively filled (while not picking winners). Second, the report identifies the common challenges and solutions that are the highest priority for commercialization across all LDES technologies. This grouping results in a framework that can track the development and maturity of these technologies over time in relation to their readiness to be a part of net-zero pathways.

Chapter 2: Current State – LDES Technologies and Markets

Section 2.a: Value Proposition

Key takeaways

- Cost-effective LDES technologies are an option to enable high renewable pathways, lower the cost of grid expansions, improve grid resilience, reduce the need for new natural gas buildout, and diversifying domestic energy storage supply chains.
- Integrated modelling shows a net-zero U.S. power grid could include ~60-460 GW of LDES by 2050 in business-as-usual and net-zero by 2050 scenarios, respectively.
- The capital investment required is very large (~$330B), and the applications are diverse resulting in the potential for multiple technologies to scale.

LDES systems provide three primary, market-related benefits:

1. **LDES technologies support and complement the expansion of variable renewables** by giving the grid greater reliability and flexibility. While variable renewables are among the cheapest forms of generation, their intermittency means that the grid needs a dispatchable source of energy to balance supply and demand and to meet peak consumption levels. In addition, connecting new variable renewable generation sites to the grid may require grid upgrades or expansions. Grid upgrades are very capital intensive, have long lead times, and are often delayed due to permitting requirements. As a result, the rapid expansion of the grid needed to support variable renewables is one of the key challenges to achieving both interim and long-term net-zero pathway goals. LDES can reduce the cost of grid expansions by providing optionality and planning flexibility. This type of planning flexibility will become more valuable with the electrification of transportation and building loads that could be harder to predict compared to conventional load growth.

2. **LDES can enhance grid resiliency and reduce the need for new natural gas capacity.** Most reliability and grid resiliency services are provided by hydro and fossil resources today. In the future, natural gas peakers—with or without carbon capture storage (CCS)—could continue to provide these services, but LDES technologies could have higher utilization and adaptability to changing grid needs. Utilities considering the deployment of natural gas to meet peak load while decarbonizing could deploy LDES instead to decarbonize without the risk of a system becoming a stranded asset. Figure 2 shows that multi-day / week LDES technologies (i.e., durations 36–160 hours) may supplant 200+ GW of new natural gas (i.e., peaking) capacity in net-zero by 2050 scenarios[i]. All modeled scenarios with LDES reduce the natural gas capacity needed to serve the expanding electric power system.[ii]

3. **LDES can diversify the domestic energy storage supply chain.** A diversified set of storage technologies reduces the risk of net-zero goals being contingent upon lithium-ion manufacturing buildout. Developing a range of LDES technologies will potentially require various new supply chain elements; however, many LDES technologies have little to no reliance on hard to source raw materials (e.g., mechanical technologies). In addition, developing viable storage technologies for the grid increases the potential availability of lithium-ion for EVs.

Total Installed Capacity in 2050, GW

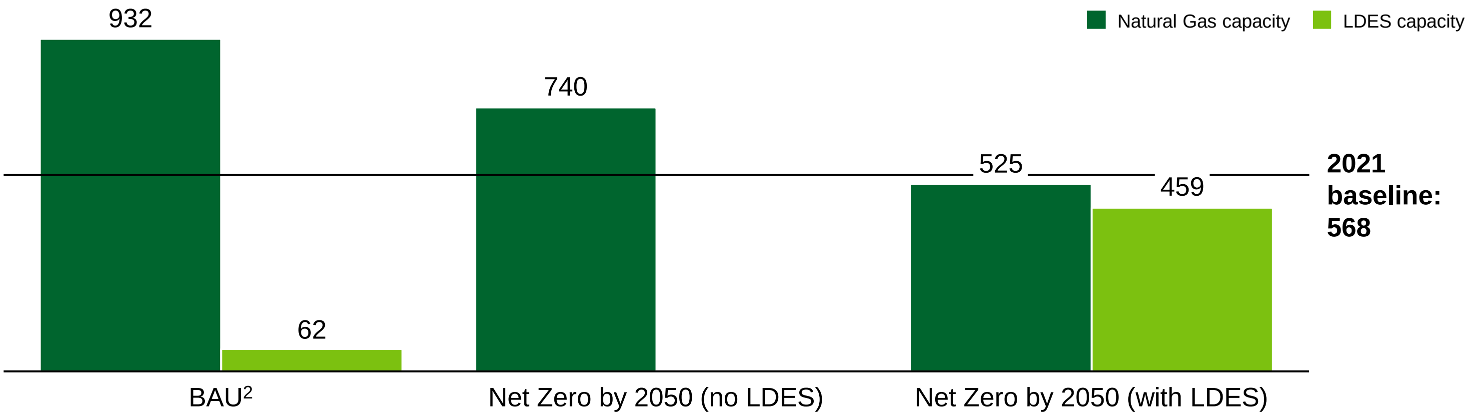


Figure 2: Under a "Net-Zero by 2050" scenario, multi-day / week LDES may supplant as much as 200+ GW of new natural gas (i.e., peaking) capacity in net-zero scenarios, dependent upon the level of gas retirements. Most Natural Gas capacity in the Net Zero scenarios is due to existing natural gas, which remains on the system. In no-LDES scenarios, net new systems are built.[i] [1]Includes both Diurnal and Seasonal LDES but does not include Li-ion; [2]BAU stands for Business as Usual.

Due to these market benefits, integrated modeling shows that deployed storage capacity is expected to increase rapidly across both the Business As Usual (BAU) and Net Zero by 2050 pathways (Figure 3), especially between 2030 and 2040, when grids begin to reach high renewables penetrations.

National Storage Capacity, GW

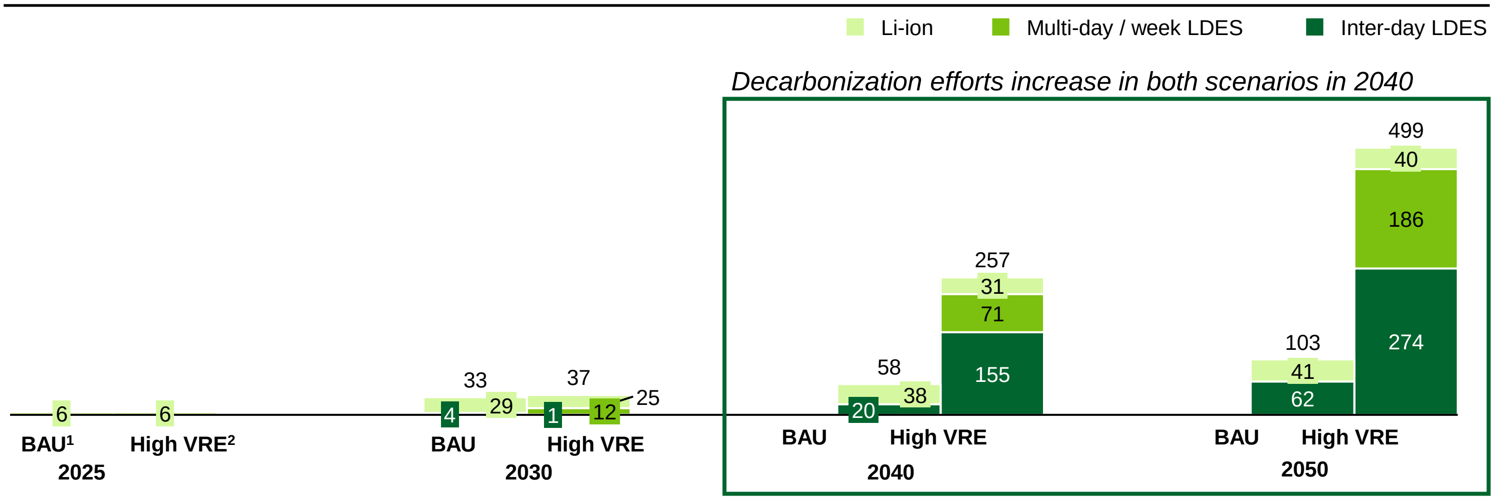


Figure 3: Between 60-460 GW of LDES may be deployed by 2050 to meet decarbonization targets under the BAU and Net-Zero by 2050 with High variable renewables penetration scenarios.[i] [1]BAU stands for Business as Usual; [2]Net-zero by 2050 with high renewable penetration.

There is a very large range of how much LDES could be deployed by 2050. In a BAU scenario, only 60MW of multi-day is deployed; however, across net-zero scenarios, between 225 to 460 GW of LDES may be deployed.[i] This level of deployment is consistent with The U.S. Long-Term Strategy, which finds substantial growth in energy storage, including LDES, to meet U.S. climate targets.[iii] This range of deployment indicates that–despite long-term market fundamentals–localized policies and market supports will be important to ensure that some companies and technologies scale and create a viable and sustainable market.

LDES represents an attractive opportunity for investors for three reasons:

- **The capital deployment opportunity for LDES in the U.S. could total ~$330B by 2050[i].** Achieving liftoff with a "Net-Zero by 2050" pathway could require up to 460 GW of LDES capacity, split across multiple durations of dispatch and operating parameter requirements. The varied applications are broad enough to enable the potential for more than one type of LDES technology to scale.

- **LDES can tap into a diverse set of revenue streams**, including but not limited to energy and capacity payments, ancillary services, time-of-use arbitrage, and demand management, etc. As new market products and business models emerge, LDES technologies already installed for early- market applications (e.g., Power Purchase Agreement (PPA) shaping, behind-the-meter energy management) could adapt and adjust their operating model to preserve or enhance their value proposition.[6,iv]

- **Many LDES systems are both modular and scalable, reducing investment risk.** Compared to deploying other forms of clean, firm capacity, such as nuclear, or other forms of firming capacity (e.g., carbon capture, hydrogen), LDES systems are often more modular and scalable. These attributes result in lower capital cost per deployment, allowing a larger number of investors to enter the market—spurring earlier technology learning and competition.

Section 2.b: Technology Landscape

Key takeaways

- Long-duration Energy Storage (LDES) can be defined by duration of dispatch. DOE includes all durations of 10 hours or more as LDES. This report focuses on inter-day LDES (i.e., power shifted by 10–36 hours) and multi-day / week LDES (i.e., power shifted by 36–160 hours).

- Short duration storage (i.e., <10 hours) includes Li-ion technologies, which dominates the short duration market segment; seasonal shifting (i.e., more than 160 hours for summer-to-winter) is considered part of the hydrogen use cases and is covered in a separate pathway report.[7]

- A wide range of technology types (>10) are vying to be dominant in the Inter-day and Multi-day LDES market segments; the technologies can be sorted into three types—mechanical (e.g., pumped storage hydropower), thermal (e.g., sensible heat), and electrochemical (e.g., flow batteries).

- Three main groups of stakeholders are assessed across the ecosystem—technology original equipment manufacturers (OEMs), project developers, and market makers (e.g., power market operators, customers).

6 Shaped PPAs help remove some or all of the price volatility associated with PPAs by giving the buyer a fixed generation shape over a predetermined period of time.
7 Li-ion systems can technically be used to service durations of >10 hours, but at a much higher marginal cost per additional hour.

LDES systems can be conceptualized based on the form of energy they store and release:

- **Electricity (commonly referred to as "power")—the focus of this report—is defined as energy stored for the purpose of becoming electricity at a later point in time.**

- Direct Thermal—not the focus of this report—is defined as thermal or electricity storage for end-uses that requires direct heating or cooling and is most relevant in discrete-industrial or district-heating use cases.

- Fuel—the focus of a separate pathways report—is defined as the chemicals, primarily hydrogen, stored for the purpose of generating usable energy such as electricity or heat at a future time with minimal time-dependent energy loss. The market services provided by fuel based LDES (e.g., hydrogen) could overlap significantly with seasonal shifting (~160+ hour) LDES systems.

This report defines storage in the context of duration of dispatch in a power context (Figure 4)—the most standard definition used across the industry for discussing different storage types.

LDES technologies can be used for inter-day and multi-day use cases at a variety of scales

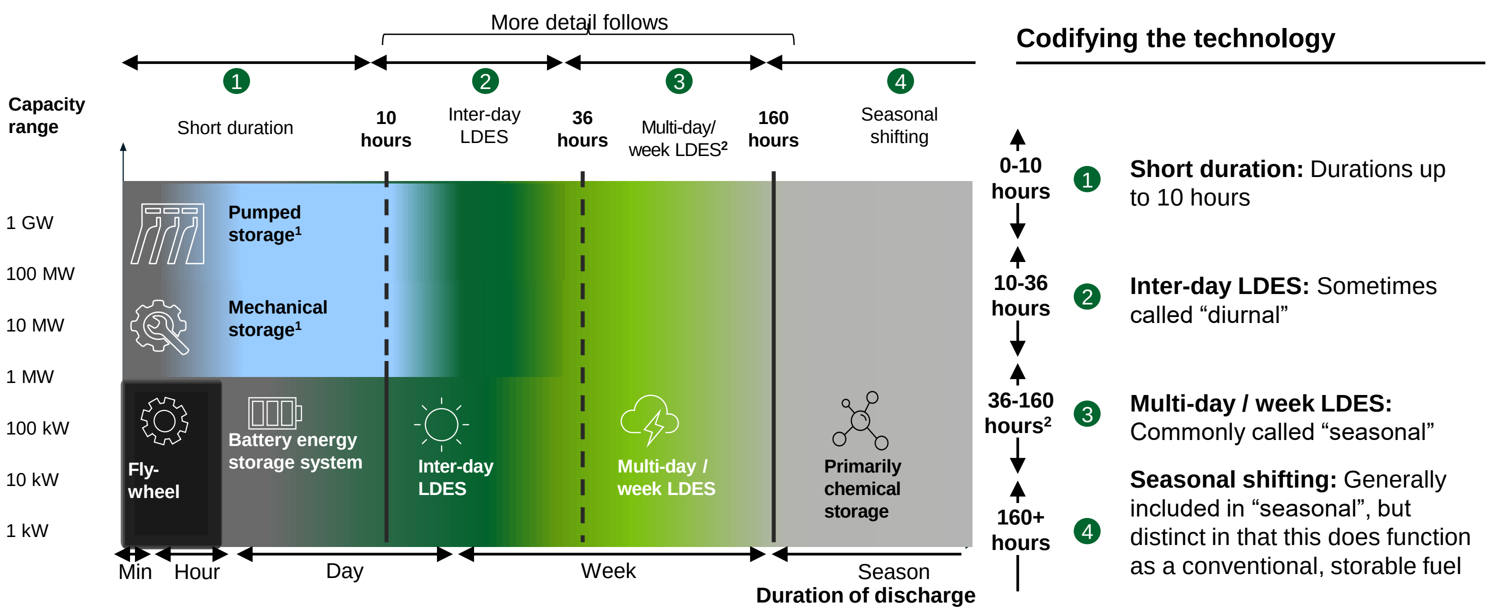


Figure 4: LDES technologies can be used for inter-day and multi-day use cases at a variety of scales. Technologies and market use cases may span across duration categories (e.g., technology's duration may encompass both multi-day LDES and seasonal shifting). [1]Pumped storage hydropower and mechanical storage can operate effectively as both short-duration and inter-day LDES systems; [2]LDES systems with 36+ hours of duration are considered multi-day / week LDES as they can discharge to cover 2+ full days of peak demand (e.g., 8am to 8pm).

This report focuses on two duration categories—inter-day LDES and multi-day / week LDES (i.e., dark green and light green portions of Figure 4). Note that Pumped storage hydropower and mechanical storage can also be used for short durations.

- Inter-day LDES is defined as shifting power by 10–36 hours and includes almost all mechanical storage technologies and some electrochemical technologies (e.g., flow batteries). This market segment fills a diurnal (e.g., day-to-night) need by shifting excess power produced at one point in a day to another point within the same day or the next day.

- Multi-day / week LDES is defined as shifting power by 36–160 hours and includes many thermal and electrochemical technologies. This market segment can be used for energy shifting like inter-day LDES, but also used during an extended shortfall of power (e.g., multiple days of low wind and solar, resiliency applications) several times per year. Multi-day / week LDES can also reduce the required curtailment / interconnection over-build to support variable renewables.

- **NOTE:** Other segments of the energy storage market are not directly covered in this report: short duration and seasonal balancing. Short duration is defined as shifting power by less than 10 hours, primarily through Li-ion storage. Seasonal balancing is defined as moving energy over an extended time period, mostly over several months (e.g., summer to winter) and is a need likely to be filled by hydrogen or fossil fuels with carbon capture. Both short duration and seasonal shifting are accounted for as competitive technologies to prove and disprove in various business cases for inter-day and multi-day / week LDES.

Twelve primary types of LDES technologies that were evaluated for this report (Figure 5). These technology types are organized based on their duration (Inter-day LDES vs. Multi-day / week LDES) and their energy storage form (Mechanical, Thermal, or Electrochemical). As previously mentioned, Li-ion is not examined as part of this analysis, hence its exclusion from the Electrochemical section. Hydrogen as Multi-day LDES is discussed later in the chapter.

NON-EXHAUSTIVE – HYDROGEN AND HYBRID LONG DURATION STORAGE EXCLUDE

△ Faces geologic constraints[4] | Not enough public datapoints to obtain a reliable value | Less Desirable – More Desirable

Inter-day | Can function as both | Multi-day/week

Duration	Energy storage form	Technology	Nominal duration, hrs	LCOS[5], $/MWh	Min. deployment size, MW	Average RTE, %	TRL
Inter-day	Mechanical	Traditional pumped hydro (PSH) △	0–15	70–170	200 – 400	70–80	9
		Novel pumped hydro (PSH)	0–15	70–170	10–100	50–80	5-8
		Gravity-based △	0–15	90–120	20–1,000	70–90	6-8
		Compressed air (CAES) △	6–24	80–150	200–500	40–70	7-9
		Liquid air (LAES) [1]	10–25	175–300	50–100	40–70	6-9
		Liquid CO2 [1]	4–24	50–60	10–500	70–80	4-6
Multi-day / week	Thermal	Sensible heat (e.g., molten salts, rock material, concrete) [2]	10-200[2]	300	10–500	55–90	6-9
		Latent heat (e.g., aluminum alloy)	25–100	300	10–100	20–50	3-5
		Thermochemical heat (e.g., zeolites, silica gel)	XX	XX	XX	XX	XX
	Electrochemical	Aqueous electrolyte flow batteries	25–100	100-140	10–100	50–80	4-9
		Metal anode batteries	50–200	100	10–100	40–70	4-9
		Hybrid flow battery, with liquid electrolyte and metal anode (some are Inter-day) [2,3]	8–50[2]	XX	>100	55–75	4-9

Figure 5: LDES technologies can be grouped based on physical characteristics and are in varying stages of development[v,vi,vii]
[1]Codified based on primary technology type; [2]Can function as inter-day LDES, but organized based on longest duration potential; [3]Some flow batteries under development will not work for multi-day, but it is categorized given the technology's maximum duration; [4]Demand potential is limited by the requirement for specific geological formations; [5]Current LCOS as reported by technology.

LDES technology can also be divided into three groups based on physical characteristics: mechanical, thermal, and electrochemical. As of late 2022, these technologies exhibit a range of maturities based on technology readiness to be deployed beyond the lab.

- Mechanical technologies are generally the most mature, and some are already at the commercial-demonstration stage. Mechanical technologies typically require a relatively large minimum size for a demonstration project (i.e., ~50–100 MW costing ~$100M+).
- Thermal technologies used in power applications are moving into commercial demonstrations and also require large demonstration projects.
- Electro-chemical technologies are largely "in lab" or in the pilot phase (i.e., <10 MW) and can be deployed and tested in smaller, discrete projects and in conjunction with many technologies. This flexibility means that electro-chemical technologies are moving into several first-of-a-kind (FOAK) commercial demonstrations that may lead to more rapid iteration and innovation versus other technologies. In addition, a higher number of small-scale deployments may accelerate learnings in this technology type. For example, ten projects at 10 MW may produce more learning than one project of 100 MW in another technology type.

A more detailed assessment of the current strengths for each LDES Technology is included in Appendix 6. Note that there is significant ongoing development across LDES technologies, and this assessment is based on the current landscape of publicly available information.

Pumped storage hydropower (PSH) is a mature and viable option, but has limitations

There is 22GW of existing PSH operating in the US today, and new needs for LDES have renewed interest in this technology. There is approximately 20 GW of PSH in development in the US[v.a.]; these projects demonstrate how LDES can create value in the context of a large-scale power market.[iv]

The scale-up potential of traditional PSH (i.e., using two bodies of water at different elevations) is limited by market compensation for LDES services and the need for a long-term planning process to get a project approved and built; a typical planning-to-deployment cycle spans 8–10 years. Novel PSH technologies are working to reduce these challenges by reducing the costs and expanding the geographic topology in which they can be developed.

PSH projects could be accelerated if assistance was provided in several areas: permitting, pooled IRPs (e.g., multiple utilities), regional ISO planning, and special carveouts within state / regional markets or utility integrated resource plans (IRPs).

Figure 5 summarizes technologies focused on the long duration energy storage market. However, technologies developed for other applications are considering electrical power generation applications. Both Hydrogen and Geothermal technologies are discussed for LDES applications in addition to other applications.

- **Hydrogen** is the primary technology expected to provide seasonal shifting for applications in need of 160+ hours duration in addition other end-uses (e.g., industrials). However, configurations like Hydrogen fuel cells with salt cavern storage (H2+Salt) have been evaluated as a technology to provide Multi-day LDES of approximately 48 to 120 hours.[viii] Hydrogen projects for Multi-day LDES would have large minimum deployment sizes (1GW+) and require specific geological features (i.e., salt caverns). While LCOS today for H2+Salt has been estimated by one study to be between $200-400/MWh, future costs are projected to be competitive with technologies listed above[ix]. Locations with Hydrogen Hubs would likely see improved economics. If Hydrogen meets projected costs, it could compete with other Multi-day LDES technologies and Natural Gas CT-CCS for peaking capacity. Hydrogen is particularly attractive where utilization rates are expected to be low. However, energy storage is only one end-use of Hydrogen; for more information on drivers for the Hydrogen industry and power sector applications, please see the Hydrogen Pathway to Commercial Liftoff report.

- **Reservoir Thermal Energy Storage (RTES)** – a geothermal energy technology - is an approach that can store excess thermal energy in permeable reservoirs such as aquifers and depleted oil reservoirs. This energy can be dispatched for large-scale district / community direct use (i.e., heating and cooling), industrial heating and processing, or electrical power generation applications. Geothermal storage for low-temperature (< 50°C) building and district heating applications has been successfully implemented in the United States and western Europe for decades. There are currently no commercial-scale reservoir thermal storage projects, although demonstration projects being evaluated in the U.S.[ix]

In addition to competition within the LDES category, LDES technologies must compete with alternative grid firming and flexibility sources (e.g., base-load coal, gas, and nuclear plants; flexible coal and gas peaking plants; a growing base of Li-ion batteries). Inter-day LDES will need to reach cost and operating parameters such that – when paired with the cost of building variable renewables – they are financially and operationally competitive with high-efficiency gas plants (e.g., Combined Cycle Gas Turbines [CCGTs]). In addition, LDES technologies will need to add enough value during extended periods of power shortfalls to justify the upfront cost differential with Li-ion. In pathways with high penetrations of variable renewables, multi-day / week LDES compete with the cost and operating parameters of new peaking capacity (e.g., CTs) while providing additional value throughout the course of the year (e.g., regular cycling for a smaller portion of total discharge depth).[8]

Section 2.c: Use Cases

Key takeaways

- Six use cases were developed based on existing business models and existing work from DOE’s Energy Storage Grand Challenge (ESGC) to show near-term applications and economics of LDES deployment throughout the United States.
- Certain use cases (e.g., behind-the-meter load management services, firming for PPAs) may be more primed for deployment between now and 2025, as they do not require broad market compensation or regulatory change to be deployed economically.
- Other use cases (e.g., bulk energy shifting, utility integrated resource planning) have larger potential (i.e., 100 MW+) for deployment but will take longer (i.e., 3–5 years) to plan, approve and deploy.

8 Discharge depth is capacity that is discharged from the storage system relative to the storage system’s total nominal capacity. It is measured as a percent of this total nominal capacity.

Six use cases (Figure 6) represent possible applications for LDES in the power market context – it is also possible for LDES to fill multiple of these use cases at the same time (e.g., value stacking).

Six project templates lay out potential business models to guide market scale-up through 2030 (Appendix 1). These templates were based on existing project proposals for energy storage and work done by DOE’s Energy Storage Grand Challenge (ESGC) and are discussed in detail in the next chapter on challenges (financial and non-financial) and potential solutions to unlock these business models.

Likely timing of commercialization	Use case	Application	Key stakeholders (not exhaustive)	Direct Competition with Lithiumion[1] (Low / Medium / High)
2023	**Load management services**	Large energy consumers (e.g., distribution centers, industrials) could use LDES to manage seasonal or week to weekend demand changes (e.g., freight charging purposes during peak season)	• Large peaking power consumers • Energy services players	High
	Firming for PPAs	Renewable PPAs can use LDES to ensure that businesses can procure 24/7 (and additional) renewable electricity	• Leading ESG customers	High
	Microgrid resiliency	LDES can ensure reliable power in isolated areas or the grid has shown to be unreliable / insufficient for a specific set of needs	• Local power authorities • Microgrid developers or integrators	High
	Utility resource planning	Utilities or CCAs can include LDES as an energy resource in integrated long-term energy planning to meet VRE balancing needs	• Vertically integrated & T&D utilities	High
	Transmission and Distribution Deferral	LDES can offset the need for new transmission and distribution capacity by installing storage in constrained areas to avoid costly, long-term asset upgrades	• Utilities • T&D developers • Equity infra investors	Medium
2030+	**Energy market participation**	LDES can play a role in shifting electricity from times of high supply to times of high demand, meet demand during system peak, and provide power system stability (e.g., inertia, frequency regulation)	• RES / T&D developers • Asset owners (IPPs) • Debt investors	Low

Figure 6: The LDES use cases require a varying degree of market change to become competitive.[v,x,xx] [1]Economic (e.g., IRR for customer) and strategic (e.g., resiliency needs, ESG goals) competitiveness for LDES compared to Li-ion batteries; e.g., high means an area where LDES would potentially outperform a Li-ion battery and eventually be able to solve a need that Li-ion cannot.

Section 2.d: Competitive Landscape

Key takeaways

- Li-ion batteries may compete with LDES technologies for the Inter-day LDES market. If Li-ion cost reductions highly exceed expectations approximately 85% of Inter-day LDES market will compete with Li-ion batteries.
- Multi-day LDES systems (36 to 160 hours) play a consistent role in both Li-ion cost reduction scenarios.
- LDES technologies will compete for applications based on a set of criteria whose importance varies depending on the final use case. Key criteria for LDES systems include nominal duration, ramp rate, response time, levelized cost of storage (LCOS), minimum deployment size, and footprint.

If Li-ion batteries become very cost-competitive, LDES technologies will compete directly with Li-ion batteries at lower-duration (approx. 10 hours); approximately 85% of the inter-day LDES market being served with Li-ion batteries if Li-ion costs aggressively reduce[i]. LDES technologies will need to have higher risk-adjusted returns than Li-ion to gain market share in this segment of the storage market. As a result, the amount of LDES technologies built and connected to the grid is highly sensitive to its price relative to Li-ion batteries and the design of compensation in energy markets.[xi] Figure 7 details the relationships between the amount and type of deployed LDES technologies and the cost improvements of Li-ion batteries.

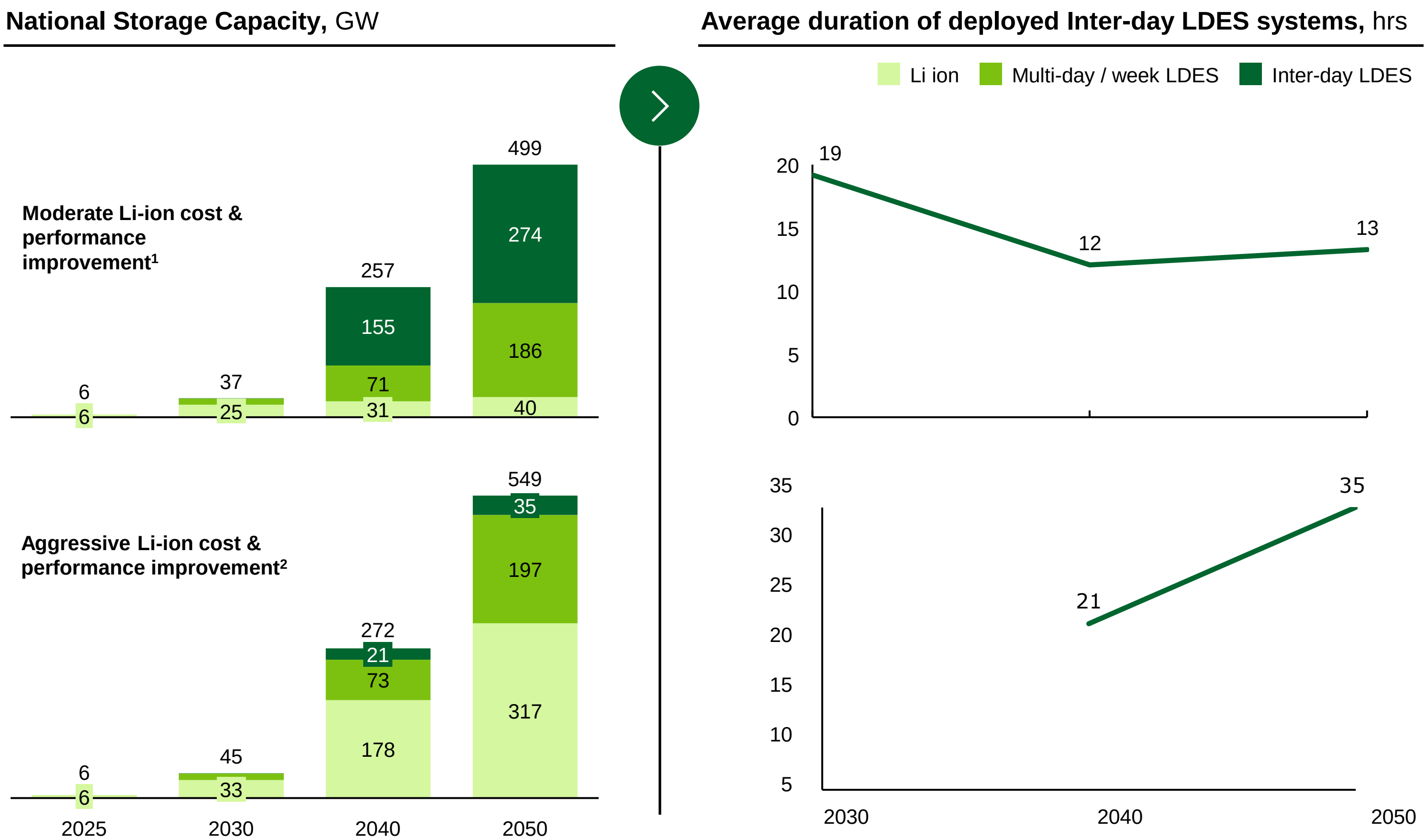


Figure 7: Deployments of inter-day LDES technologies depend on whether they can outcompete Li-ion's cost and performance.[xii] Average duration of Inter-day LDES systems is lowered if Li-ion costs are in-line with predictions since more ~10-hour LDES systems will come online. However, if Li-ion costs reduce aggressively, Li-ion will be built instead of 10-hour LDES systems, and economic LDES systems will be longer duration (20+hour). No duration is shown for 2030 in the aggressive Li-ion scenario due to limited projected Inter-day LDES deployment. [1]Assumes Li-ion batteries improve costs and performance at a moderate rate based on current Li-ion cost curves (54% cost improvements through 2030 and 65% total improvements through 2050 relative to 2021 prices); [2]Assumes capex costs associated with energy component (i.e., battery cell) are 50% lower than in moderate scenario.

The degree to which Inter-day LDES technologies can compete varies widely with up to 274GW in a moderate Li-ion case and only 35GW in an aggressive Li-ion case (discussed below). Given the uncertainties surrounding the cost trajectories of Li-ion and LDES technologies and compensation mechanisms, two Li-ion deployment scenarios were considered:

Scenario 1: Moderate Li-ion cost & performance improvement

In this scenario, Li-ion batteries improve costs and performance at a moderate rate (i.e., 54% cost improvement through 2030 and 65% total improvement through 2050 relative to 2021 prices), and LDES technologies continue to compete directly with Li-ion for inter-day use cases. As a result, ~274 GW of inter-day LDES are deployed by 2050, compared to just 40 GW of Li-ion.[i] The average duration of these inter-day LDES systems remains relatively low (i.e., ~13 hours), reflecting the technology's ability to outcompete Li-ion for some short duration use cases. In addition, multi-day / week LDES is deployed at a lower rate than Inter-day LDES (i.e., 186 GW vs. 274 GW). To be competitive in the inter-day market, LDES technologies must consistently achieve moderately-high RTE roundtrip efficiency (i.e., 60%+, although 75–80% is an ideal range) and long system life (i.e., at least 20–25 years).[xiii, i]

Scenario 2: Aggressive Li-ion cost & performance improvement

In this scenario, Li-ion batteries experience aggressive cost and performance improvements resulting in 50% lower CAPEX costs associated with the energy component (e.g., battery cell) than the in Scenario 1. These improvements enable Li-ion technologies to outcompete LDES technologies for many inter-day applications. As a result, 35 GW of inter-day LDES is deployed compared to ~317 GW of Li-Ion.[i] The average duration of the deployed inter-day LDES is ~35 hours, reflecting the fact that Li-ion is a more cost-effective solution for shorter durations. Multi-day / week LDES solutions remain the most effective option for longer durations, with expected deployment of ~197 GW. This deployment level is higher than in Scenario 1 and is a result of inter-day LDES not unlocking learnings at the same rate due to reduced deployment.[i]

These projections demonstrate that LDES solutions that are capable of discharging for durations of 30+ hours are needed in all scenarios, even when other technologies experience cost and technology performance improvements at a faster rate than LDES. To reach deployment targets, these longer-duration technologies must achieve a sufficient technology readiness level (TRL) and technology performance and cost maturity by 2035, even with limited economic use cases before that time period. Public stakeholders (e.g., ISOs, state regulators) may need to provide "make a market" support mechanisms (e.g., targeted tenders or procurement carveouts for LDES of 30–50 hours, risk-reduction mechanisms) to scale certain technologies that will be needed in 2040 and beyond.

Scenario 2B: Aggressive Li-ion cost reductions with supply chain constraints. The rapid expansion of electric vehicles (EVs) may make the aggressive cost curves and deployment of Li-ion in the power sector more likely. However, potential supply chain constraints created by this expansion could limit Li-ion's competition with inter-day LDES. If supply chain constraints continue to create scaling challenges, Li-ion may not realize full cost reductions, and production may be targeted toward auto industry customers rather than the energy sector.

In addition to competition with Li-ion and other firming options, there is competition within the LDES market for what technologies to deploy. There are six primary competitive factors that will influence which technologies are deployed:

- **Nominal duration**—Measure of how long the storage system can discharge at its maximum power rating (e.g., a 20 MW LDES systems with a 30-hour duration can provide 20 MW of energy for 30 hours)
- **Ramp rate**—The speed at which a storage system can increase or decrease output (e.g., 5% per minute systems can increase or decrease discharge at a rate of 5% per minute)
- **Response time**—The time it takes for a system to provide energy at its full rated power (e.g., a system with a 5-minute response time can increase power from zero to full power after five minutes)
- **Levelized cost of storage (LCOS)**—Cost of the LDES system measured in $ per MWh. Derived by accounting for all costs incurred and the total energy discharged throughout the storage system's lifetime, not accounting for charging costs as they are related to grid prices rather than techno-economics
- **Minimum deployment size**—Smallest capacity deployment that is technically feasible
- **Footprint**—Amount of land needed to deploy the system

Figure 8 analyzes the primary LDES use cases against these six competitive factors.

The key performance criteria varies across LDES use cases

Critical Criteria / Secondary Criteria

Use case	High VRE demand potential[1], GW	Aggressive Li-ion demand potential[2], GW	Nominal duration, hrs	Ramp rate, %/min	Response time	LCOS, $/MWh	Min. deployment size, MW	Footprint, sq. m
Load management services	28 28[3]	30 30[4]	Critical	Secondary	Secondary		Critical	Critical
Firming for PPAs	10 10[3]	1 1[4]	Critical			Critical		
Microgrid resiliency	24 24[3]	26 26[4]	Critical	Critical	Critical			Secondary
Utility resource planning	157 85 242	17 77 94	Critical	Secondary				
Transmission and distribution deferral	Highly dependent on state regulatory decisions – will be most applicable for multi-day / week LDES		Secondary			Secondary	Critical	Critical
Energy market participation	117 101 217	18 119 137	Critical	Secondary		Critical		

Figure 8: The key performance criteria varies across LDES use cases. VRE stands for Variable Renewables. [1]Net-zero by 2050 with high renewables penetration; [2]Based on net-zero 2050 scenario with a significant drop in Li-ion capex according to NREL 'optimistic' projections; [3]Based on the LDES Council Report use case opportunity sizing and adjusted to meet expected ISO demand; [4]Adjusted following the same ratio between these use cases, energy market participation and utility resource planning to account for Li-ion improvements.

The most important criteria for each use case varies significantly:

- **Load management services**—Behind-the-meter siting will require LDES with a small footprint as well as future modularity to maintain its benefit even with changing needs. Modularity is important for shifting to different uses over time. A longer duration will help LDES outcompete Li-ion, while a fast ramp rate and response time can ensure effective power delivery.

- **Firming for 24-7 PPAs**—The decision for load firming solutions will be highly cost-based, and thus LDES with a low LCOS will be necessary. As customer targets are set to require higher time-matching granularity within 24-7 PPAs, short duration technologies will lose the LCOS advantage in being able to meet customer demand through all hours of the year (e.g., multiple systems would need to be stacked for extended periods of low resources / high demand).

- **Microgrid resiliency**— For local grids, LDES can be used to provide energy in times of a resiliency event. The most critical success factor is an extended duration with a quick response time to quickly begin providing energy to the grid. A competitive ramp rate will help LDES respond to changes in demand quickly without other intervention methods. For space-constrained urban areas or small islands, a small footprint will also be important.

- **Utility resource planning**—While similar to energy market participation, within utility resource planning, there are different portfolios of existing assets which are considered on a total system cost versus marginal cost basis. Thus, the existing utility assets can shift the timing and type of asset needed to solve for flexibility, reliability, and resilience. This combined assessment of cost and “fit” with existing investment generally puts less emphasis on the cost of the system compared to energy market participation. Like many other applications, this use case will directly compete with Li-ion. Utility and regulatory recognition of need for longer duration, firm, dispatchable power will improve the competitive position of LDES in this use case. Depending on existing assets, ramp rate may also be a decision criterion.

- **Transmission and distribution deferral**—The ability to site an LDES technology in the location it is needed is most critical to obtaining the highest deferral value. To achieve this, the deployed LDES will need to have a small footprint and modularity to be able to meet changing needs over time. While less direct, a longer nominal duration, fast ramp rate, and fast response time will help LDES stay competitive with Li-ion.

- **Energy market participation**—Energy market applications for LDES are expected to be very cost sensitive. To best suit this use case, LDES must have a lower LCOS to outcompete Li-ion in the near term. When markets signal a need for longer nominal duration products to serve resource adequacy and reliability needs, a large potential market for LDES emerges. Performance on other characteristics such as ramping could be important in some markets depending on resources available that can also fill that need, e.g., hydro or natural gas.

Section 2.e: Techno-economics

Key takeaways

- LDES technologies must reduce costs by 45–55% by 2030[9]—relative to 2021 costs from leading technologies—and prove efficiency and performance in the field to be seen as competitive, scalable assets.
- Over the next 5–10 years, LDES's cost, efficiency and risks are expected to improve with continued R&D, economies of scale of deployment, and manufacturing / supply chain improvements resulting from modularized, industrial-scale facilities and workforces.

Many technologies are still in lab-stage and will only benefit from continued research & development (R&D) funding. Technology costs across the landscape are highly varied, with commercial-ready players achieving:

1. Inter-day LDES: $1,100–1,400 per kW of power capacity capex; $20–30 per kWh of energy capex; 62% RTE; 25-year lifetime[10,i,iv]

2. Multi-day / week LDES: $1,900–2,500 per kW of power capacity capex; $10–15 per kWh of energy capex; 45% RTE; 27-year lifetime [i,iv]

Three factors could drive down costs by 60% by 2040: 20-35% from R&D, 20-35% from economies of scale, and 10-20% from manufacturing and supply chain improvements.

R&D can lead to decreased technology and manufacturing cost through design optimization and improved manufacturing performance. Specifically, manufacturing R&D can address manufacturing tool development, improvements in manufacturing processes, and precision control and optimization across production lines. Continued R&D funding for mature technologies (e.g., advanced flow battery chemistries) is vital, as R&D advances could contribute 20-35% of the total performance and cost curve improvements. Improving cost efficiency via R&D is especially important for electrochemical and thermal technologies, as many are still in the lab.

Economies of scale will be achieved through improved project management, the scale-up of logistics, and learnings gained through iterative deployment. Unlocking economies of scale depends on demonstration and deployment funding and engagement from ecosystem players (e.g., project developers; engineering, procurement, and construction [EPC]). If successful, economies of scale could contribute 20–35% of the total technology performance and cost curve improvement potential. Economies of scale are likely to be particularly relevant for thermal and mechanical technologies, as these systems resemble large construction projects and will benefit from more efficient project management and logistics scale-up.

Manufacturing and supply chain improvements will also drive down costs, as more consistent and predictable project pipelines will yield manufacturing efficiency improvements (e.g., leaner production processes, cost-efficient sourcing, automated assembly). Successful manufacturing and supply chain improvements could contribute 10–20% of the total technology performance and cost curve improvement potential. These improvements will benefit technologies that can be modularized during manufacturing (e.g., electro-chemical flow batteries), but these processes could be susceptible to commoditization and/or offshoring.

When considering these different sources of techno-economic improvement, several technology characteristics of LDES will impact its ability to capture its market potential and total levelized-cost-of-storage. In particular, improving CAPEX, RTE, and lifetime (or cycle life) will make LDES technologies more competitive. CAPEX is likely to decrease as learnings are captured via successive deployments, whereas gains in RTE and lifetime will require additional R&D breakthroughs.

9 Technology improvement and compensation goals outlined in this report are in-line with existing DOE Energy Storage Grand Challenge (ESGC) goals of $0.05/kWh for long-duration stationary applications.
10 Reported and studied cost and operating parameters range widely. Conventional compressed-air energy storage can have cost ranges of $960–1,740 / kW of power capacity capex; $32–250 / kWh per kWh of energy capex; 40–80% RTE; and 20,000+ cycles over its lifetime.

Chapter 3: Pathways to Commercial Scale

Section 3.a: Implied Capital Formation

Key takeaways

- LDES will need to attract at least ~$9–12B of investment before 2030 (Figure 9). This funding will be especially critical to LDES's ability to compete with Li-ion batteries in the short-term and to reduce the risk profile for larger-scale investors in the long term.
- To scale-up to its potential in a net-zero context, LDES will need to attract ~$230–335B of investment capital from 2023–2050 to support the deployment and build out of the upstream supply chain.
- LDES technologies are currently attracting government and venture capital (VC) funding, with increasing interest from utilities, and these will continue to be the main sources of funding in the short term. Technology solutions are still maturing—except pumped storage hydropower—and considered too early stage for other capital providers (e.g., Private Equity (PE), infrastructure funds, banks).
- Near-term project-level commitments and investments are needed to enable technology players to achieve rapid learnings and reach commercial scale, especially from early-stage capital providers including: the government; utilities; venture capital; and capital providers interested in tax equity and Inflation Reduction Act (IRA) tax credits.

Forecasted investment needs

Industry players are projected to need at least ~$9–12B of investment before 2030 to support R&D, commercial deployments, and supply chain scale-up (Figure 9).[i]

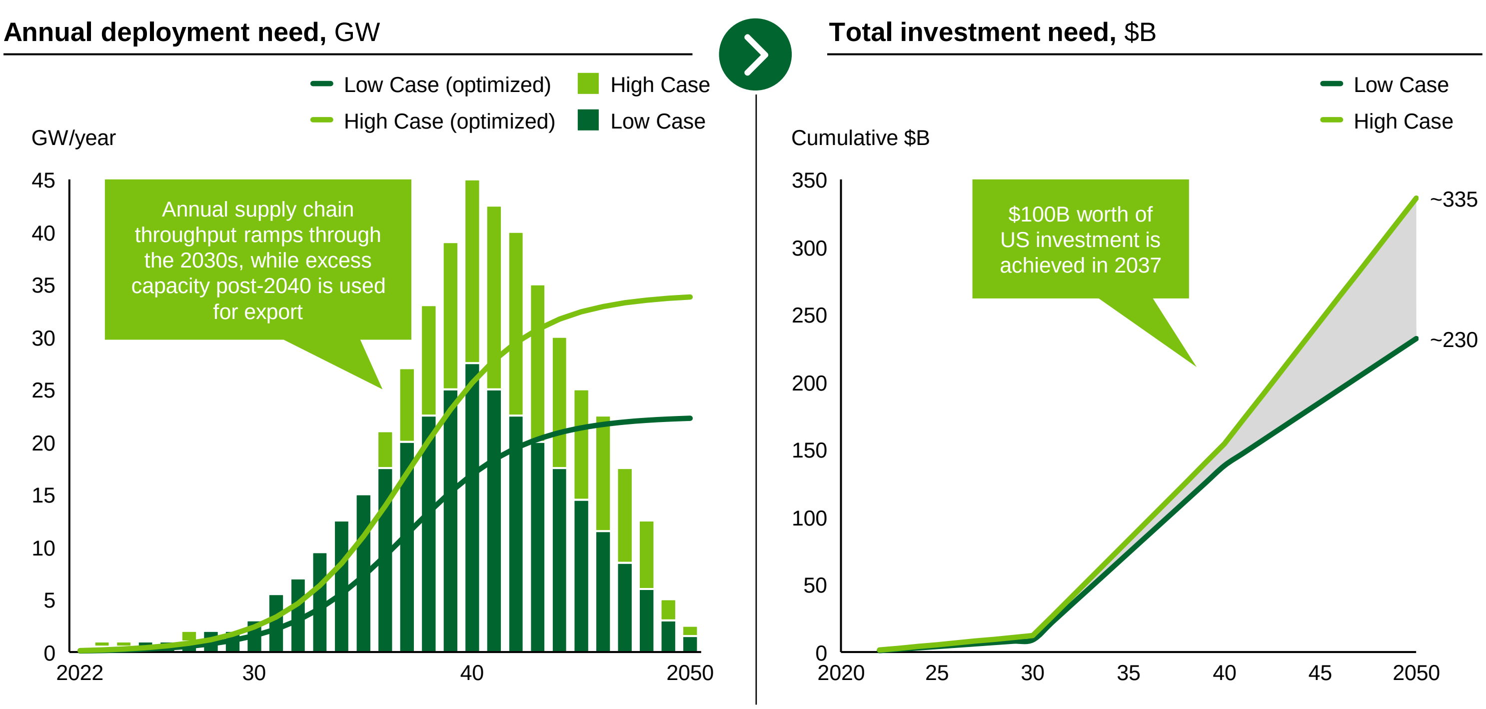


Figure 9: Meeting the most ambitious decarbonization targets could require a cumulative investment of ~$232–336B from 2021–2050

To meet Net Zero by 2050 goals, a cumulative investment of ~$230–335B could be needed from 2023–2050 and another ~$160 to 250B of cumulative capital relative to the business as usual (BAU) scenario.[i] Unlocking capital on this scale would require LDES technologies to be proved and scaled to the point where relatively risk-averse capital providers (e.g., infrastructure funds, banks, corporations & utilities, insurers, institutional investors) feel comfortable injecting both equity and debt into LDES companies and assets.

Many LDES technologies are still in the pre-commercial demonstration stage. As a result, LDES investments are currently viewed by most capital providers as being outside their risk appetite. As of 2022, funding for LDES players has come primarily from venture capital in the form of equity investments to support technology players' R&D. Some private equity firms (e.g., growth equity players) are also starting to make equity investments in technology players. There is small but growing liquidity for commercial demonstration projects, and industry stakeholders (e.g., utilities) have begun to announce project-level commitments.

In addition to technology maturity, capital providers are uncertain on the role that LDES will ultimately play in the transition, the demand for LDES being enough to support the development of a robust industry and supply chain, and the ability of LDES technologies to compete with Li-ion. However, some capital providers think that grid operators and regulators will require and reward longer term energy storage and that LDES solutions will be a critical component of the grid beyond 2030. Others are not yet convinced that these new technologies in R&D and piloting will be ultimately deployed at scale.

More project-level commitments and investments are needed to enable technology players to achieve rapid learnings and reach commercial scale. Four sources of capital are likely to play an outsized role at this early juncture: the government; utilities; venture capital; and capital providers interested in tax equity and Inflation Reduction Act (IRA) tax credits. Securing investment will be critical to ensuring LDES's ability to compete with Li-ion batteries in the short-term and to reduce the risk profile for larger-scale investors in the long term.

It is worth noting that project finance requires a high level of repetition and deep benchmarking of engineering and performance data. Banks will only consider financing those solutions already deployed at scale multiple times. Those technologies able to reach scale maturity first will attract more follow-on investment and continue to improve, creating even more distance with the other options and driving them out of the market, unless there are new technology breakthroughs with dramatic performance improvements.

Section 3.b: Broader Implications of LDES Scale-up

Key takeaways

- If LDES can gain traction in the market before 2030, it has the potential to generate up to 2.1 million direct job-years in fields such as engineering and construction and create up to $530 billion in cumulative economic benefit over the next 25 years.
- Thoughtful planning could enable transitions of specialized labor currently scaling variable renewables and electric vehicle manufacturing and potentially take advantage of the transition from the oil and gas industries.
- The specific workforce risks, skills, and training associated with LDES vary according to the technology.

If LDES can gain traction in the market before 2030, supply chain infrastructure must scale significantly to meet the large deployment needed in this decade. Moreover, multiples of this investment will be needed in the following decade as LDES continues to scale. Supply chains should mature throughout this timeline and grow to resemble current supply chains in utility-scale variable renewables, battery storage development, and pumped storage hydropower projects.

The majority of LDES projects likely require a short period of labor-intensive construction involving engineering, procurement, and construction firms (EPCs). As a result, many LDES technologies have the potential to provide upfront economic impacts, including jobs. This holds especially true for mechanical technologies (e.g., gravity-based apparatus) and thermal technologies (e.g., sensible heat apparatus using molten salts).

Between now and 2050, this buildout of LDES could generate: 1.5–2.1M “direct” job-years in fields such as engineering and construction; between 900k and 1.4M in “indirect” job-years in fields such as industrial-scale manufacturing, and raw materials supply chain; and 1.7–1.9M in “induced” job-years at restaurants, car dealerships, barbers, and other service jobs that benefit from the increased economic activity.[i] In the long run, this build-out would amount to a cumulative $510–530B impact on GDP through 2050.[i]

“First mover” benefits could occur as these construction jobs are created. For example, states that more quickly establish a “hub” for LDES activity may attract disproportionately large shares of manufacturing jobs, the best EPC talent, and other positive economic development externalities (e.g., development of innovation ecosystems around pilot technologies, creation of testing sites, revitalization of distressed communities).

According to the 2022 U.S. Energy and Employment Report, there were 81,000 jobs in energy storage in the U.S. in 2021[xiv]. Over 95% of these jobs were in electrochemical and pumped storage hydropower, and approximately half of those jobs were in fields other than construction. As the U.S. further develops the supply chain for LDES, the share of non-construction (indirect) jobs could increase substantially. As with the creation of all new energy technologies, it will be important to ensure that LDES jobs are high-quality jobs that will attract and retain the skilled workforce required to scale with safe and reliable LDES systems. High-quality jobs provide above-average wages and benefits, strong health and safety standards, investments in worker education and training, and an affirmative commitment to employee’s free and fair chance to be represented by a union. The Pathway to Commercial Liftoff Societal Considerations and Impacts Overview provides an in-depth discussion of the significance of these quality jobs characteristics and how they can be achieved.

The specific risks and hazards associated with LDES vary according to the technology, i.e., mechanical energy storage, thermal energy storage, and electrochemical energy storage. The workforce needs, in terms of skills and training required, correspond to these deployment considerations. In addition, engaging workers in the design of health and safety plans is important across technologies.

Mechanical energy storage, such as pumped storage hydropower, involves work that is comparable to work in the construction and mining sectors. As this technology relies on the mechanical storage and release of energy, there are risks for on-site workers. It is important to ensure that the amount of stored energy does not exceed each system’s capacity. Additionally, the potential risks of natural disasters (such as earthquakes or cave-ins) must be carefully mitigated to prevent changes in topography from releasing the stored energy and injuring workers and surrounding communities.

Thermal energy storage involves work with a variety of materials and temperatures used to harness and release energy stored as heat. The processes associated with charging, storing, and discharging energy requires workers trained in the risks associated with the method they are helping to deploy. Storage systems that aren’t properly managed or maintained are dangerous for onsite workers, as the heat stored by these systems can injure or kill a worker. Since many of the materials used in thermal energy storage come with combustion risks, workers should be trained to recognize and prevent the causes of fires as well as how to extinguish fires[xv]. Workers should be provided with appropriate protective gear and training on how to interact with the specific storage system properly. Precautions must also be taken to prevent the system from being overloaded, which requires accounting for both the dynamic supply of the heated material and the dynamic demand for electricity generated from it.

Electrochemical energy storage is the technology that employs the largest number of workers within the energy storage sector. Of the different types of electrochemical energy storage, the risks and hazards associated with lithium-ion battery chemistry (such as potential for thermal runaway and toxic exposure) are well known. Like with different thermal storage technologies, companies should hire workers who are trained on the specific chemistry, risks, and handling of a battery technology and its component parts (e.g., flow vs. lead-acid). Industry consensus on training guidelines or standards for battery manufacturing and other supply chain jobs will support the growth of a qualified workforce for this industry. For battery installation, it will be important to hire licensed electricians to properly install and connect battery energy storage systems.

Energy and Environmental Justice (EEJ)

Key takeaways

- LDES deployment can provide much-needed benefits (e.g., reliability, resilience, clean energy access, affordability, and pollution reduction) to overburdened, underserved communities.
- Depending on the technology deployed, LDES projects must address EEJ concerns including siting decisions and mining impacts; there are many ways for projects to maximize benefits and minimize harms covered below and in the Pathway to Commercial Liftoff Societal Considerations and Impacts Overview.
- More information on the potential benefits and negatives of each LDES technology area can be found in Appendix 8.

Investors and developers play a critical role in determining whether the deployment of LDES projects supports an equitable energy transition or compounds existing injustices. The Pathway to Commercial Liftoff Societal Considerations and Impacts Overview covers key considerations and actions for equitable and just projects and provides online resources. This section highlights EEJ considerations specific to LDES (see Appendix 8 for a table on EEJ concerns by technology).

LDES deployment can provide much-needed benefits (e.g., reliability, resilience, clean energy access, affordability, and pollution reduction) to overburdened, underserved communities. Often rural, low-income, or communities of color, these groups are at the highest risk of experiencing outages, while being least equipped to withstand them; face greater energy burden, energy poverty, and high demand charges;[xvi] have the least access to clean energy; and are disproportionately burdened by fossil fuel power plants.[xvii,xviii] Despite this need, these communities have had relatively little access to LDES; as with most technologies, early adopters have been well-resourced communities and companies.[xvi] This contributes to a long-standing gap between well-resourced and under-resourced communities in energy access, burden, and poverty; pollution exposure; and grid reliability.[xix] If sited and scaled intentionally, LDES can close this gap and support community health and wealth by maintaining non-emitting grids, mitigating fuel price spikes and supply chain shortages, and improving grid reliability and resiliency.[xvi]

To support public health and safety, LDES siting decisions must consider impacts on land, air, and water.[xx] While some systems may repurpose existing infrastructure (e.g., retired mines or quarries),[xxi] others (e.g., compressed air energy systems) may require new excavation and construction, generating greenhouse gases, heat, and drilling waste. These impacts may continue during operations, which may also pose risks of seismicity or storage cavity failure.[xxii] While low, these risks are important as low-income communities and communities of color disproportionately faces risks of energy infrastructure failure.[xxiii] Another critical siting concern, especially for tribes, is maintaining the cultural, aesthetic, and ecological significance of land and water.[xxiv] Energy infrastructure, especially dams, have inundated or limited access to many tribal ancestral landscapes and other sites of cultural, medical, or historical significance.[xxv]

LDES technologies also have embodied environmental and human health impacts. Mining for materials requires clearing and excavating land and storing mine tailings, which can poison water supplies, while mining dust pollutes air and causes respiratory and other health impacts for miners and communities.[xxvi] Growing global demand has led to the extraction of lower quality ore, producing more toxic waste. Increased mining activity combined with climate-induced extreme weather has caused more frequent and severe failings of tailings dams, causing deadly flooding.[xxvii] To limit harms, mine operators can regularly monitor and inspect waste facilities, including dams; obtain ongoing consent from surrounding communities; and employ strong safety procedures, including evacuation drills.[xxvii] The toxicity of constituent metals and materials creates additional environmental and health impact during LDES (e.g., battery) construction and end-of-life disposal.[xx] Deriving scarce minerals from other sources (e.g., through recycling or extracting from unconventional supplies) could limit the need for new mines.[xxvii]

Beyond being a moral imperative, EEJ is critical to project success—LDES projects may experience delays or cancelation because of community- or organization-led lawsuits or protests.[xxiv,xxiii] Projects can mitigate EEJ risks—risks both *to* the project and caused *by* the project—by being aware of potential impacts, taking steps to maximize benefits and minimize harms, and engaging in early, frequent, transparent, and two-way dialogue with impacted groups.

There are many ways for projects to maximize benefits and minimize harms in line with EEJ goals and principles. The Pathway to Commercial Liftoff Societal Considerations and Impacts Overview covers actions related to (1) the distribution of impacts (i.e., who experiences benefits vs burdens) and (2) procedure (i.e., giving power to impacted individuals/groups to make decisions about things
that affect their lives).

One way to promote EEJ and ensure community buy-in is by developing business and ownership models that advance community wealth. This includes co-ownership agreements for storage assets by communities and utilities, subsidizing loans to low-income households to participate in community energy storage systems (CES), and proactively promoting distributed energy resources.[xxviii] Utility regulatory decisions impact equity in critical ways by shaping access to electricity, rates and rate design, access to energy efficiency programs and clean energy technologies, and infrastructure distribution, which in turn has implications for people’s health, property, and environment.[xxix] CES is designed with a community ownership and governance approach to generate socio-economic benefits, including renewable energy penetration, emissions reductions, decreased energy costs, and revenue generation potential.[xxviii]

Chapter 4: Challenges to Commercialization and Potential Solutions

Introduction

LDES technologies are now entering a critical period of accelerating commercialization to achieve technology liftoff. "Liftoff" is defined as the point where the LDES industry becomes a largely self-sustaining market that does not depend on significant levels of public capital and instead attracts private capital with a wide range of risk. Liftoff is characterized by significant improvement in technology and operating parameters, market recognition of the value of LDES's services, and industrial-scale manufacturing and deployment capacity. These improvements are needed to attract sufficient private capital to meet LDES deployment targets. After "liftoff", the market will have reached a level of maturity that can support broad financing and be less reliant on government funding. This chapter discusses the challenges and potential solutions that are needed to reach this liftoff threshold.

Section 4.a: Overview of Challenges and Considerations Along the Value Chain

Key takeaways

For LDES to be deployed at a rate that supports meeting net-zero commitments by 2050, three conditions must be met concurrently through 2030 (Figure 10):

- **Technology performance and cost reductions**: The cost of an LDES system must come down by 45–55% and realize a 7–15% improvement in roundtrip efficiency.[11]
- **Predictable compensation for resource adequacy benefits provided by LDES**, roughly equivalent to ~\$50–75 per kW per year by 2030, to support a business case for investment.[12]
- **Build-up of LDES-specific supply chains**, as 10–15 GW of manufacturing and deployment capacity is needed at scale by 2035 and at least 3 GW by 2030.[i]

Three conditions must be met by 2030-2035 for LDES technologies to fulfill their potential role in the 2050 net-zero pathways (Figure 10):

1) **Technology performance and cost curves** must improve so the economics of LDES technologies are comparable to technologies fulfilling the same need (e.g., Li-ion, hydrogen, conventional generation). Based on the reported 2021 costs from leading technologies, the costs of LDES systems must come down by 45–55% and roundtrip efficiency (RTE) must improve 7–15%.[i,12] Newer companies may need to reduce costs as much as 75% relative to their 2021 reported costs.

2) **Market and regulatory mechanisms** must evolve to support the reliability, flexibility, and stability services that LDES systems provide. The current mechanisms were designed for systems largely served by conventional energy generation (e.g., coal, natural gas) with very little grid-scale variable renewables or storage. Thus, the dispatch flexibility provided by grid-scale storage—especially flexibility that allows dispatch days or weeks after electricity is generated—is not fully valued by markets or regulatory systems. Predictable compensation for LDES resource adequacy benefits, roughly equivalent to ~\$50–75 per kW per year by 2030 would be one of the direct ways to support a business case for investment.[i]

11 This cost reduction is based on goal-seeking cost curves for leading companies and is based on 2021 numbers. Newer companies may need to reduce costs as much as 75% relative to their 2021 reported costs. Additionally, technology improvement and compensation goals outlined in this report are in-line with existing DOE Energy Storage Grand Challenge (ESGC) goals of \$0.05/kWh for long-duration stationary applications.
12 This production figure is based on a 15–20% unlevered IRR; for more details on modeling, see Appendix 4.

This compensation could come directly from market participation or could be indirectly valued as part of an integrated resource-planning process outside competitive energy markets. Unlocking this value in many jurisdictions will require changes to modeling methodologies for integrated resource planning, resource adequacy studies, and transmission planning. Market and regulatory dynamics must also evolve to recognize the need for longer duration, firm, dispatchable power. This could be done by providing market products that support the benefits from these longer duration technologies (e.g., expanding from 4-6 hour firm capacity products to longer duration such as 12 hour and 24 hour firm based on market need). It is expected that these system changes will take time, and development of these mechanisms must visibly start by 2025.[xxx]

3) **Supply chain formation**—especially for components that will be needed across technologies (e.g., engineering and construction workforce)—must be planned in advance of the anticipated, rapid scale-up to meet market needs in 2030**.** The provision of an adequate amount of cost-effective raw materials, subcomponents, manufacturing, and assembly—plus a workforce that can put it all together—will be necessary to sustain LDES deployment in the long run. The supply chain will need to handle the anticipated growth of LDES in the 2030s—10-20x the amount of LDES deployment in the 2020s.[i]

Achieving liftoff[2] by 2030-2035 requires improvements in technology, cost declines, regulatory support, and supply chain development

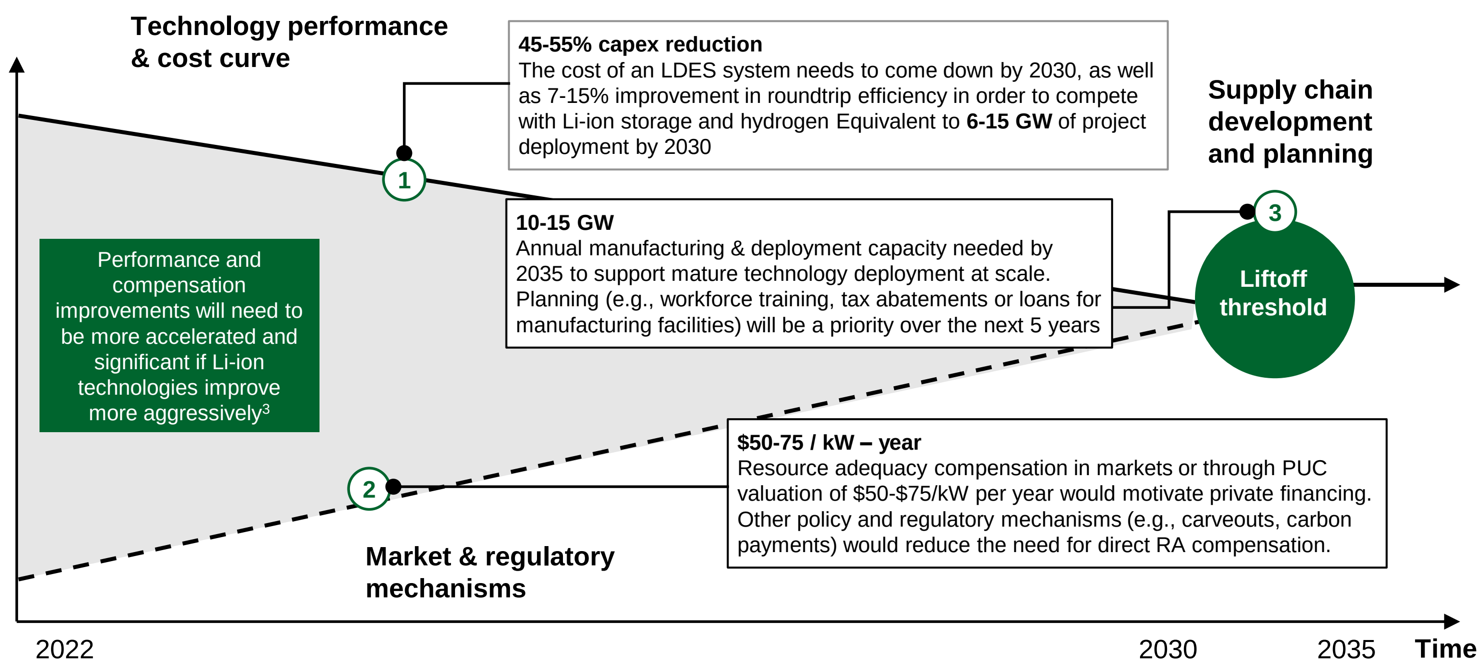


Figure 10: Liftoff by 2030-2035 requires improvements in technology, cost declines, regulatory support, and supply chain development. [1]$/kW – year varies by geography; [2]Liftoff is defined as the point where the LDES industry becomes a largely self-sustaining market; [3]Need for multi-day / week LDES technologies remains in both Li-ion scenarios, and aggressive Li-ion will reduce the need for supply chain build out.

These three conditions are interrelated; the timing and success of each will affect the others[13]. For instance, if technology cost curves come down more rapidly than expected, it could reduce the need for electricity market reforms. Or, if there are more market reforms that value LDES attributes (e.g., capacity payments), there would be less need for accelerated price reductions. The timing of these breakthroughs should inform when and how to begin supply chain planning.

Section 4.a.i: Overcoming Near-term Challenges to Improve Technology Performance and Cost Curves

Key takeaways

To get to a largely self-sustaining market (i.e., "liftoff"), LDES technologies must go through three phases of commercialization: Demonstrations, Scaling and Selection, and Deployment. These projects must happen in-field, and the market will identify optimal technology cost and operating parameters.

- **The Demonstrations phase** (2023–2025) supports many smaller demonstrations to create a visible set of case studies across the market landscape.
- **The Scaling and Selection phase** (2025–2028) proves out which technologies benefit the most from scaling and creates visibility for technology players standing up supply chains for utility-scale deployment (e.g., 100MW+ per year).
- **The Deployment phase** (2028–2030+) features large demonstration projects that affirm the viability of LDES technologies and shows the limited need for outside support (e.g., standalone, bankable use cases).

A rigorous, standardized process for in-field demonstration projects is needed for LDES to be most helpful to net-zero ambitions and commercially viable for private investors in the long term.

Currently, demonstration projects are run through many different channels, and each demonstration is evaluated on a case-by-case basis. Creating a more centralized evaluation and data-tracking system would improve efficiency and possibly accelerate learning across LDES systems, especially for deployments of similar technologies. This tracking system would need standard feasibility metrics, cost and performance certification and tracking, and deployment lighthouses to serve as public examples of technology readiness. In addition, establishing standardized architectures for the design and deployment of LDES technologies would increase interoperability and possibly accelerate deployment.[14]

To get to the technology performance and cost curves consistent with commercial liftoff conditions by 2028-2030, the market of LDES technologies must go through three phases of commercialization: Demonstrations, Scaling and Selection, and Deployment (Figure 11).[15]

These phases of commercialization aim to ensure that LDES technology is perceived as increasingly reliable, bankable, and in possession of a secure supply chain; while decreasing risk and the need for government support.

13 The interconnected nature of these conditions was assessed as part of the modeling effort used in this report. For more details, see Appendix 4.
14 The MESA architecture has helped utilities that are deploying battery storage.
15 Each phase is characterized by larger projects, fewer non-financial risks / uncertainties, and larger total market size than the previous phase.

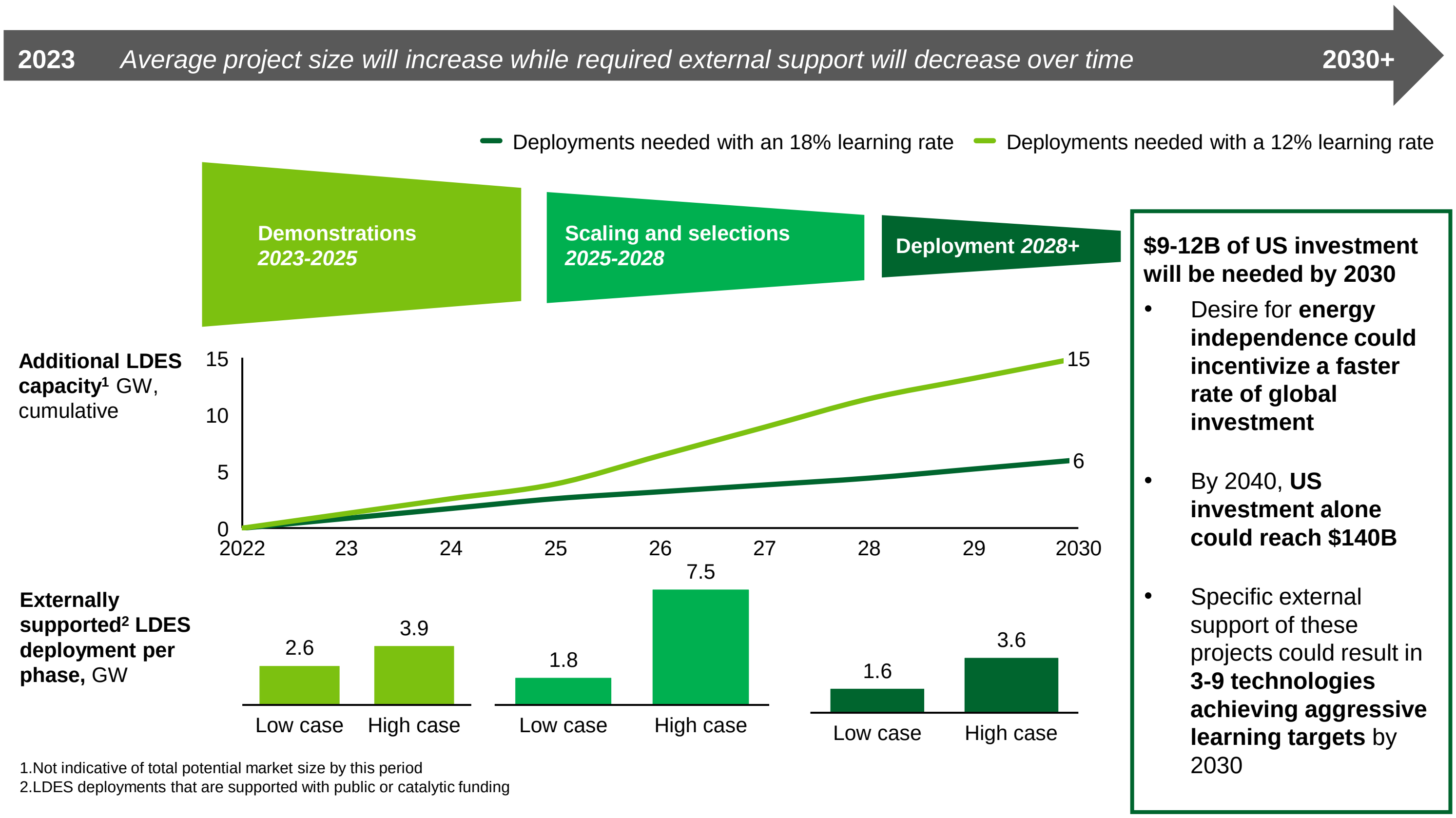


Figure 11: The learning curve and project size increases as use cases advance from the Demonstrations phase to the Deployment phase. [1] Not indicative of total potential market size by this period; [2]LDES deployments that are supported by public funding (e.g., governments, philanthropic organizations, other grant-making bodies).

All business cases in this section are illustrative and based on publicly available information and work done by DOE's Energy Storage Grand Challenge (ESGC). The options proposed are not exhaustive.

The following use cases are presented in order of near-term to longer-term applicability. However, project use cases should materialize across Demonstration, Scaling and Selection, and Deployment phases. This report focuses on deployments in the United States, demonstrations and deployments abroad are not factored into the projected learning curves. However, there may be opportunities to accelerate learnings and lower the number of supported projects if there is significant activity abroad with shared data and learnings.

The Demonstrations Phase, 2023–2025

The first phase of commercialization is the Demonstrations phase and is focused on cost and performance improvements. The primary objective of this phase is to support ~15–30% improvements among many players (e.g., 50–100). This effort may require up to $25M in some form of concessionary finance per project to ensure projects offer attractive internal rate of return (IRR) and are deployed.[i]

Certain technologies are already beyond the initial demonstration phase (i.e., may be ready for larger-scale projects) but will need additional support to de-risk project development capital for first-of-a-kind (FOAK) projects.

The Demonstrations Phase, 2023–2025

To accelerate the formation of private capital, players that clear the initial screens (e.g., lab data, existing feasibility studies) can be given funding for in-field pilots, demonstrations, and commercial-scale projects. At the start of the Demonstrations phase (i.e., 2023), a project and its business model must be acknowledged and supported by a group of stakeholders; have a plan for market formation; provide a projected cost curve; and demonstrate a path to a stable supply chain. At the end of the Demonstrations phase (i.e., 2025), a project must prove its technical feasibility, demonstrate its progress on the cost curve, and provide an updated assessment of its supply chain. Target project size during this stage should be from 10–20 MW and can span many technologies[16]. Clear targets for all technologies can help players understand the scope of their challenge as they attempt to meet the stage gates for the second phase: Scaling and Selection.

Three example projects for the Demonstration phase are included in Appendix 1: Load Management Services for an EV fleet, Firming for future PPAs, and Transmission and distribution (T&D) deferral. These illustrative business cases would require smaller amounts of external funding allowing for a greater number of projects during the Demonstrations phase. Appendix 1 includes detail on potential business models, stakeholders, system parameters, expected costs, and target returns.

The Scaling and Selection Phase, 2026–2028

The second phase of commercialization is Scaling and Selection. The primary aim of this phase is to accelerate technology learning (i.e., reach a 15% cost reduction) for promising technologies. Funding support for these projects will shift from primarily concessionary finance to favorable financing (e.g., low-interest loans, guarantees, first-loss equity).

In this phase, players that clear the stage gates could be given funding for discrete, grid-scale projects of a medium-large size (i.e., 50+ MW). These projects, ~50–100 in total, will remain spread among several technologies, and each will be able to point to prior successful demonstrations as justification for funding. At the start of the Scaling and Selection phase (i.e., 2026), a project must prove its cost trajectory (e.g., 25% cost improvement), its operating parameters (e.g., meets or beats performance on RTE, limited operations overspend), and its readiness to deploy in a short timeframe (e.g., cost, capability, supply chain readiness). At the end of the Scaling and Selection phase (i.e., 2028), a project must prove its progress along its cost curve, demonstrate its ability to reduce or eliminate risk for investors, provide an updated assessment of its supply chain, and deliver an updated assessment of stakeholder support.

Many growth-equity funds, banks, and institutional investors look for companies with proven business models in order to confidently evaluate potential cashflows. Demonstrating the technology's efficacy at grid-scale would help prove which business models have the most potential to evolve into standalone, bankable businesses.

Two example projects for the Scaling and Selection phase are included in Appendix 1: Microgrid and resiliency on an island and Utility resource planning. These illustrative business cases would require a larger amount of funding per project but allow for greater learnings on economies of scale than project sizes in the Demonstration phase. Appendix 1 includes detail on potential business models, stakeholders, system parameters, expected costs, and target returns.

The Deployment Phase, 2028 and Beyond

The third phase of commercialization is the full-scale deployment phase. This phase is characterized by much larger "lighthouse" projects (e.g., projects with publicly available performance data and a referenceable cost-benefit analysis), derived from a smaller subset of the most promising technologies.

Funding for these projects will shift from public-supported financing (e.g., low-interest loans, guarantees) toward market-rate financing. Funding in this stage will require less upfront government outlay, although long-run loan support or guarantees may still be required where the private sector is wary of the size of the project. Capital providers such as banks and infrastructure funds have indicated that they would like LDES players to demonstrate that they can create strong, predictable cash-flows and the ability to reduce costs at scale.

16 For some select technologies that are hard to subscale (e.g., gravity-based, CAES, sensible heat), larger-scale projects (e.g., 50–100 MW) may be needed in this phase sooner than would be needed for more modular technologies (e.g., flow batteries).

In this phase, players that clear the stage gates can be given funding for grid-scale projects (e.g., 50+ MW). Several projects, 10–60 in total, could be spread among several technologies, and each of these projects should be able to point to many prior successful demonstrations to support funding. At the start of the Deployment phase (i.e., 2029), a project must prove its cost trajectory, demonstrate its operating parameters, and support its readiness to deploy in a short timeframe. At the start of the Deployment phase (i.e., 2030+), a project must prove its ability to be invested in by the private sector. Projects that meet minimum parameters will move into the market to be investable opportunities for private sector players.

Primary aims of this phase are to test and understand the ability of costs to scale with size and to identify the relative needs associated with industrializing manufacturing for certain key technologies. Other technologies that are still emerging from lab may still be supported by earlier demonstrations, however, only if they have significant promise to improve upon industry-wide cost and operating parameters.

One example project for the Deployment phase is included in Appendix 1: Energy market participation. Appendix 1 includes detail on potential business models, stakeholders, system parameters, expected costs, and target returns.

Section 4.a.ii: Lack of Market Mechanisms

Key takeaways

- Geographies—as characterized by state policy, power market dynamics, and grid conditions—in the U.S. have differing levels of readiness for LDES deployment due to various grid conditions, policies, and market constructs.
- Interventions across five categories—long-term market signals, revenue mechanisms, analytics, direct support, and stakeholder support—can be enacted to improve LDES deployment. The full list can be found in Appendix 5.
- Interventions can be assigned to stakeholders by locality and prioritized by impact

In 2023, no electricity market supports standalone LDES economics, although each electricity market—and even each locality within electricity markets—has unique characteristics that can improve or reduce the attractiveness of LDES (Figure 12).

Two factors can be used to evaluate market LDES readiness: Grid conditions and policy and market constructs.

Grid conditions measure both the desirability and relative feasibility of LDES in a particular state, as well as the overall generation mix. Factors include the percent penetration of variable renewables, the transmission and distribution investment gap, grid resilience as measured by SAIDI/SAIFI scores, and the ease of interconnection.

Policy and market constructs measure the favorability of local policies and revenue constructs for deploying LDES with favorable risk-adjusted return expectations in the state. Factors include Renewable Portfolio Standards (RPSs), capacity payments, and storage carve-outs.

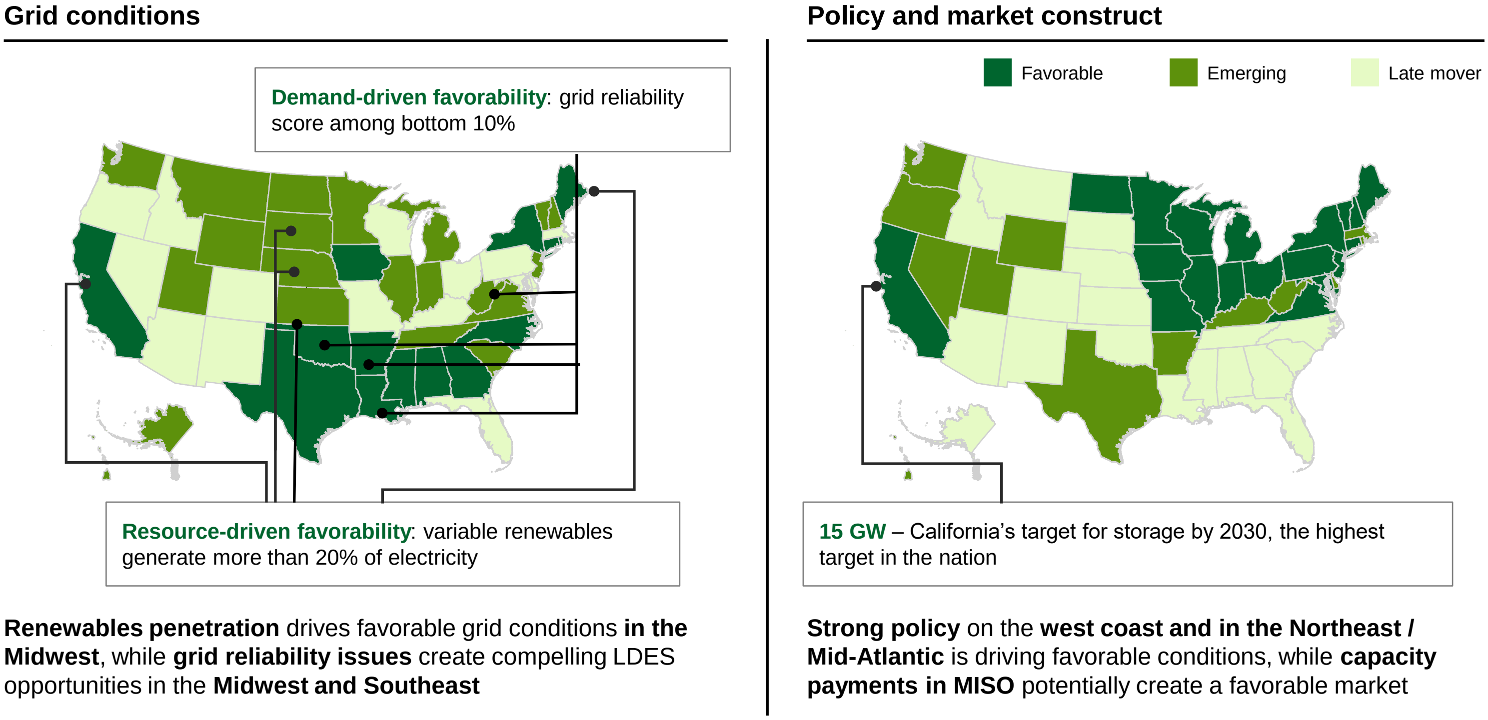


Figure 12: LDES deployment readiness varies among the states, with California, Texas, New York, Maine, Iowa, and Connecticut being high potential in the near-term.

Interventions in five categories can be enacted to improve LDES deployment. See Appendix 5 for the full list. Key interventions are highlighted below by category.

Long-term market signals address stakeholder uncertainty and are particularly valuable for investors. Some examples of these signals are tax credits, carbon pricing, GHG reduction targets, and transmission expansion to support variable renewables or address bottlenecks in densely populated areas.

Revenue mechanisms also improve investors' risk-adjusted return on LDES. Revenue mechanisms include the introduction of capacity markets or other market products that support the deployment of longer duration firm dispatchable power, long-term bilateral contracts, and 24/7 virtual PPAs for corporate emissions targets.

Analytics help increase transparency and reduce uncertainty among stakeholders to enable long-term planning. By making high-quality models more accessible, modeling insights can be used to improve analytics for all stakeholders. Ideally, all stakeholders can analyze LDES alongside other decarbonization technologies with a similar set of modeling tools and parameters, equip themselves with the same fact base, apply insights across geographies, and access high-grade professional models.

Direct technology support and enabling measures boost the market for LDES. These measures include direct grants and incentives (e.g., PTCs, storage ITCs) and loan guarantees.

Stakeholder support ensures the long-term viability of LDES. Stakeholder support can be boosted by increasing the number of people and the amount of capital devoted to variable renewables or storage in a given state. Stakeholders are capable of interventions across three archetypes that can impact project economics (Figure 13). Example measures of stakeholder support include jobs related to variable renewables or energy storage and workers in fossil fuels or related industries who could be retrained to work on energy storage.

The interventions can be assessed across three metrics and prioritized. First, the interventions can be evaluated on how much they enhance the viability of LDES projects. The financial models used in this report rated interventions on how they would improve the risk-return profile of an LDES project, relative to external funding.

Second, the interventions can be assessed on how attractive they make the LDES market in the long term. The models used in this report rated interventions on how much they increased the overall market size and accelerated the scale-up trajectory of LDES.

Third, the interventions can be assessed on ease of implementation. The models used in this report rated interventions on the level of complexity required for implementation (e.g., single player implementations, broad consensus, and market change requirements).

Stakeholder group capable of intervention

XX = Preliminary priority interventions

Archetype	DOE/ Fed. govt.	Market level (i.e., ISO)	State govt.	State regulator	Other[3]	Intervention impacting economics
Initial Interventions	■	■		■		**Grid planning**
	■	■		■	■	**Integrative modeling[1]**
		■			■	Renewable energy procurement targets[2]
	■	■	■	■	■	Build stakeholder support
Expanded Interventions	■		■	■	■	**Risk reduction mechanisms[3]**
		■	■	■		**Develop a dynamic capacity requirement**
	■		■			Renewable energy and storage subsidies
			■	■		Storage capacity targets
		■	■			"Fast-track" permitting and interconnection
Advanced Interventions		■		■		**Expanded capacity markets**
		■		■		**Transparency of T&D deferral data**
			■	■		**LDES procurement targets**
				■	■	Targeted tenders

Figure 13: Each group of stakeholders can intervene to boost LDES economics as the technology matures.[xxxi] [1]Integrative modeling can make tradeoffs among technologies; [2]Renewable energy targets can support other monetization (e.g., through hourly energy attribute certificates); [3]Loan guarantees, loan-loss guarantees, inflation protection, insurance, return guarantees / securitizing decarbonization tech investment.

Section 4.a.iii: Need for Industrialization

Key takeaways

- Currently, the LDES supply chain is nascent, <1 GW of LDES was deployed as of 2022, excluding pumped storage hydropower.
- For LDES to be a viable piece of the net-zero equation, annual manufacturing and deployment capacity must approach 10–15 GW/year by 2035 and 30 GW/year by 2040.
- In the immediate term, possible interventions—addressing raw materials and manufacturing issues—could help unblock the creation of an LDES supply chain; in the medium-term, finding an LDES workforce will be a priority.

Because building a reliable, robust, domestic end-to-end supply chain can take 10–15 years, planning must begin before technology demand reaches an inflection point between 2030 and 2035.

Manufacturing capacity and project deployment capacity must approach 10–15 GW/year by 2035 and 30 GW/year by 2040[i]—from less than 1 GW/year at-scale in 2022—to meet LDES's potential as an advanced decarbonization technology in 2040 and beyond.

To get a sense of which interventions might be most useful, LDES technologies and Li-ion for comparison were assessed across four potential vulnerabilities in the supply chain: raw materials; sub-components; manufacturing and assembly; and the workforce needed to design, build, and operate projects (Figures 14 and 15).

Inter-day LDES supply chain vulnerabilities from 2030

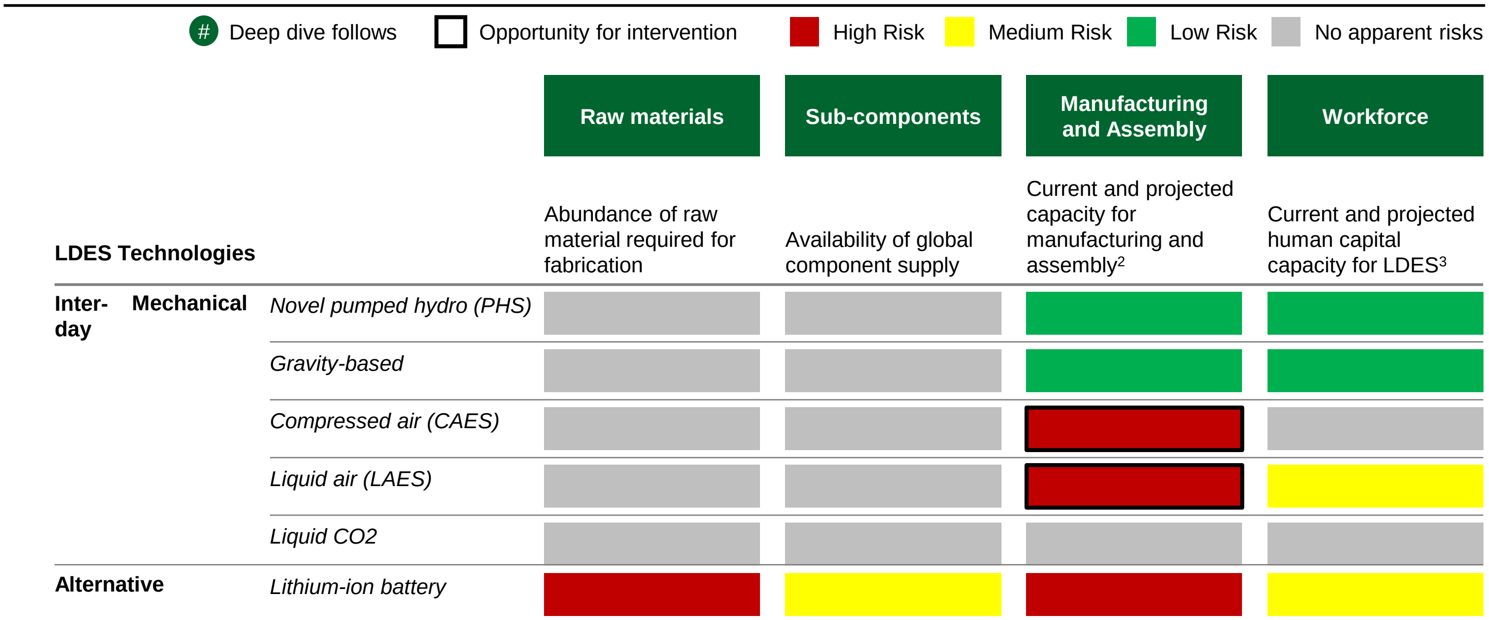


Figure 14: Inter-day LDES systems have fewer supply chain vulnerabilities compared to Li-ion alternatives.[xxxii] [1]Excludes geographies with potential access issues as assessed by DOE. U.S. and global supply chains were assessed separately but combined on this page; [3]For example, available supply of components, operational manufacturing capacity; [5]Highly-skilled and specialized talent for design and technical components and systems, highly skilled (likely unionized) talent for construction and operations

Multi-day / week LDES supply chain vulnerabilities from 2030

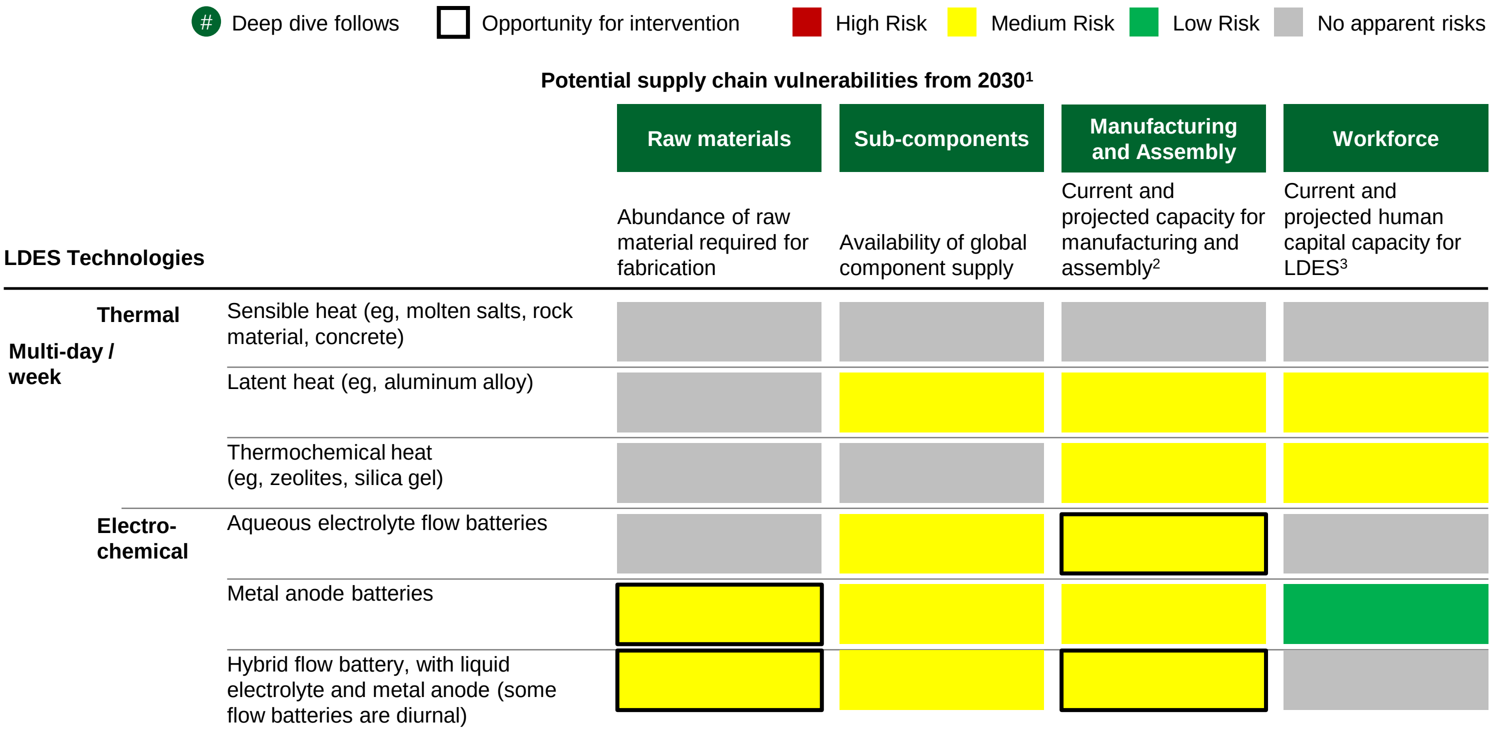


Figure 15: Multi-day / week LDES systems have moderate potential supply chain risks, but there are opportunities to mitigate these risks.[xxxi, 1]Excludes geographies with potential access issues as assessed by DOE. U.S. and global supply chains were assessed separately but combined on this page; [3]For example, available supply of components, operational manufacturing capacity; [5]Highly-skilled and specialized talent for design and technical components and systems, highly skilled (likely unionized) talent for construction and operations.

For inter-day LDES technologies, which involves mostly mechanical storage (e.g., pumped storage hydropower, compressed air, gravity-based), the highest risks are in the manufacturing and assembly of compressed air (CAES) and liquid air (LAES) storage apparatus and in finding the skilled workforce at sufficient scale. Raw materials and sub-components are not rare for these technologies. However, the skilled trade workforces (e.g., construction, manufacturing) for each of the technologies may be a constraint, particularly if the wages and benefits are not competitive relative to other opportunities. Also, without interventions, the U.S. is at risk of not having adequate facilities and know-how to build the more technical inter-day LDES apparatus (e.g., CAES and LAES).

For multi-day / week LDES, which involve mostly thermal and electrochemical storage (e.g., sensible heat, latent heat, metal anode batteries, flow batteries), the highest risks are in having a sufficient and skilled workforce, particularly if the wages and benefits are not competitive relative to other opportunities, procuring raw materials, and manufacturing and assembling for metal anode and flow batteries. Finding sufficient amounts of raw nickel and vanadium from secure mines may be an especially acute vulnerability. Additionally, the workforces for thermal and electrochemical storage are likely to be as constrained in the same way as the workforces for mechanical storage. National training guidelines and standards for on-the-job training could relieve some of these constraints.

For Li-ion storage, acute risks exist in the procurement of raw lithium and in the manufacturing and assembly of the batteries.

Possible interventions (non-exhaustive) to address the most acute supply chain vulnerabilities (i.e., in raw materials and in manufacturing and assembly) include:[17]

1. **Demonstrations and pilots**: Demonstrations and pilots to accelerate learning in manufacturing and assembly in advance of large-scale private investment.

2. **Targeted tenders:** Contingent on successful demonstrations and pilots, offer contracts to promising players in the LDES ecosystem to boost private-sector capacity to supply LDES in the near and medium term.

3. **Subsidized private sector capacity:** Tax breaks or other subsidies extended to the private sector to boost domestic capacity to supply LDES in the near- and medium-term.[18]

4. **Clear demand signals:** Long-run (e.g., 5 years) project pipelines for leading technology players in the giga-watt scale.[19] For example, contracts can have line-of-sight to ramp-up over time (e.g., 25 MW in year 1, 50 MW in years 2–5, 100 MW in year 6+).

5. **Ecosystem convening (e.g., LDES hubs) and partnership formation:** Gatherings of disparate players to facilitate knowledge transfer and recognize top players could accelerate solutions to bottlenecks in manufacturing and assembly, including building industry consensus on skills needs and training standards.[18]

6. **National reserve or stockpile:** Advanced purchases of rare metals and/or other raw materials (e.g., vanadium, nickel) would allow the manufacturing, shipment, and installation of LDES to continue even in the case of supply chain or geopolitical disruption.[18]

7. Capacity building for LDES workforces: On-the-job training and registered apprenticeship programs to inform / train workforces on the manufacturing, assembly, and deployment of LDES could accelerate the stable and sustainable deployment of projects.[18]

17 Many interventions will be most effective when action is taken across the U.S. Government.
18 DOE efforts could combine with those of other agencies (e.g., DOD) that are already engaged in stockpiling key metals, subsidizing private sector capacity, convening ecosystems, building capacity, etc.
19 These topline demand signals should also be segmented into part-specific demand signals and then broadcast widely so that sub-tier suppliers also have clarity on what to expect.

Section 4.b: Potential Key Accelerating Actions

Key takeaways

- For LDES technologies to be a competitive option for flexibility, stability, and resilience needs, stakeholder action is needed across the public and private sector.
- In addition to continued R&D funding for maturing LDES technologies, the federal government could accelerate LDES commercialization through (1) targeted support for LDES projects, (2) educational sessions, modelling tools, and valuation frameworks for other stakeholders, and (3) transparency of LDES project data (costs / operating metrics).
- Action across Independent System Operator (ISO) and state regulators and policy makers on market standards and policies that value the reliability and flexibility services that LDES technologies provide would support accelerated LDES commercialization.
- Additional early action across LDES stakeholders would further support LDES scale-up.

LDES could play a critical role in decarbonizing the U.S. energy system. LDES technologies are an option to enable renewable generation, reduce pressure on transmission and siting, and increase system utilization and reliability. To achieve this vision of the future, interventions are needed, which may vary regionally based on current and potential market outcomes and physical resources and infrastructure. However, there is a set of priority actions for each stakeholder group to support the project deployment, revenue mechanisms, and supply chain scale-up of LDES.

In addition to continued R&D funding for LDES technology maturation, the federal government can potentially help commercialization in the near-term in three ways: (1) offering targeted financial support for individual projects; (2) providing educational sessions, modeling tools, and valuation frameworks for regulators and ISOs and commercial customers to evaluate their behind-the-meter and grid-scale applications; and (3) developing transparency on LDES technology cost and performance for investors, regulators and policymakers to quickly adapt their portfolios.

Independent System Operators (ISOs) and Regional Transmission Operators (RTOs) have a leading role in market product formation and transmission planning. States control direct-storage portfolio requirements, and public utility commissions oversee utility investment decisions and long-term planning. However, in each of these areas, targeted federal support and incentives can change the economic case. Coordination and education can allow early movers to gain a larger share of federal dollars. There are multiple kinds of federal support structures that can be used (e.g., cap and floor offtake, production credit, cost-share grants, risk reduction PPA adders).[20] These options suggest an important indirect role for the federal government in guiding investment and highlighting available policy levers. These efforts are aligned to the DOE's current goals and efforts in the Energy Storage Grand Challenge and Long Duration Storage Shot.

ISOs will determine how grids can maintain their flexibility and their reliability as they service higher amounts of variable renewables. New capacity market design, interconnection queue reform, and consideration of storage assets both as generation and load in transmission planning would each have a significant impact on valuation of new technologies like LDES. For example, ISOs could adjust their resource adequacy study methodologies and/or create new or adjusted compensation mechanisms that account for clean, firm capacity (e.g., potentially duration dependent). In addition, ISOs could value LDES as a transmission asset and compare LDES against other transmission options.

State Renewable Portfolio Standards (RPS) could drive additional LDES deployment. Within each of those targets could be near-term carveouts for the deployment of storage, including LDES-specific carveouts. In addition, state governments could consider tax breaks or other incentives to attract early deployment or manufacturing hubs.

State Public Utility Commissions (PUCs), through a standardized methodology on longer-term, integrated modeling, could better value the system benefits of LDES. In some states, this effort will require codifying LDES technologies as assets that can be deployed as generation, transmission, and distribution—in addition to clarifying which types of players can own LDES systems.

20 For a longer list of potential market mechanisms, see Appendix 5.

PUCs could update their integrated resource planning and resource adequacy methodologies (e.g., lengthen duration of IRP assessments) and allow utilities to rate base LDES investments or even mandate its inclusion in future IRP submissions. Finally, PUCs could approve early, non-economic investments within rate-base (e.g., grid-scale pilots) to accelerate market transformation and reduce longer-term customer costs.[21]

Other stakeholders can also consider early action:

Variable renewable developers can consider piloting LDES add-ons at larger sites that are close to their Commercial Operations Dates (CODs). These add-ons would help developers better understand LDES's system integration and operations implications.

Energy customers, especially those that have ambitious ESG targets and relatively low electricity spend as a percentage of their operating costs, can demand higher-percentage load-following PPAs (e.g., 24-7 time matching) and consider deploying LDES of their own in applicable on-site, behind-the-meter use cases.

Storage associations and broader industry stakeholder groups can advocate for more stringent standards on ESG accounting for Scope 2 emissions, moving from aggregate accounting (i.e., not time or geographically matched) to load-following accounting.

Early investors (e.g., tax equity players, VCs) could publicize their successful use of LDES revenue mechanisms (e.g., capacity payments), pioneer new business models and financial products, help to build out the LDES supply chain—including a nascent ecosystem to service the LDES technologies, and publicize how they address key technical, project, and market risks.

Follow-on investors (e.g., private equity, utilities) could help scale the LDES supply chain for promising technologies and produce evidence that points later-stage investors toward the most successful markets and the most successful business models.

Later-stage investors (e.g., pension funds, banks) could begin early investigation of promising LDES technologies and business models to allow for shorter lead-times once LDES projects are mature enough for late-stage capital.

Operators of government backed first-of-a-kind (FOAK) projects could increase data transparency around specific projects (e.g., uptime rate, cashflows). This transparency could inform other capital providers so that they could better assess technical, project, and market risks.

Chapter 5: Metrics and Milestones

Section 5a: Explaining the KPIs

Three types of key performance indicators (KPIs) can be tracked to understand the progress that LDES technologies are making toward the successful market scale-up by 2030:

- **Leading indicators** are indicative of the relative readiness of technologies and markets for at-scale adoption (e.g., early signs that LDES is "on-track" to play a role in a net-zero grid).
- **Lagging indicators** are representative of successful scaling and adoption of LDES, in addition to readiness for 2030 and beyond deployment of the technology (e.g., supply readiness).
- **Outcomes** show the relative impact of LDES on broader targets (e.g., job creation, emissions reduction).

These topline demand signals should also be segmented into part-specific demand signals, and then broadcast widely so that sub-tier suppliers also have clarity on what to expect.

21 These topline demand signals should also be segmented into part-specific demand signals, and then broadcast widely so that sub-tier suppliers also have clarity on what to expect.

These indicators could be tracked and reported periodically through a dashboard; they may evolve over time as other metrics are identified and prioritized

Section 5b: Priority KPIs

Several priority KPIs are indicative of successfully progress toward a net-zero pathway. Other metrics—outlined in the next section—may also be important for impacting storage deployment. The following KPIs lay out the targets for technology deployment readiness.

Leading indicators show the ability of LDES technologies and players to create the pathway needed by 2026 to meet 2050 net-zero goals:

Each given technology has been deployed or can be contracted for:

- Inter-day LDES technologies
  - Capex target: $1,000 per kW; AND
  - Roundtrip efficiency target: 70%

- Multi-day / week LDES technologies
  - Capex target: $1,700 per kW; AND
  - Roundtrip efficiency target: 50%

Number of utilities including LDES in their Integrated Resource Plans (IRPs), as well as MW capacity and MWh included in plans

Number of states mandating LDES procurement

Reliable capacity or resource adequacy payments on top of normal arbitrage opportunities (tracked by number of hubs / zones meeting this threshold) target: $75 per kW -per year at an ISO-level

- In power markets, consistent, reliable capacity or resource adequacy payments may also be necessary. Whether through special provisions (e.g., clean capacity adder, duration-dependent capacity adder) or natural market mechanisms, capacity payments must increase to value the services provided by LDES. In addition to adequate compensation levels, market products that support the differentiated need for longer duration, firm, dispatchable power must emerge (e.g., expanding from 4-6 hour firm capacity products to longer duration such as 12 hour and 24 hour firm based on market need)

Lagging indicators will be most important for setting interim and 2030 targets that show successful deployment execution. These KPIs also allow for retrospectives that inform future technology commercialization efforts:

Total deployed LDES capacity target: 6–15 GW (~75% of capacity deployed should be in the inter-day technology category)

Private capital mobilized across the value chain target: $9–12B

Domestic manufacturing capacity target: 3 GW/year (although 2035 and beyond goals may need to be much higher in a net-zero world, assuming LDES technologies continue to improve in technology performance and cost)

For a longer list of KPIs to be tracked, see Appendix 7.

Appendices

Appendix 1 – Illustrative LDES Project Templates

Demonstration Phase (2023-2025):

1. Load management services
2. Firming for future PPAs
3. Transmission and distribution (T&D) deferral

Scaling Phase (2026-2028):

1. Microgrid resilience – Island example
2. Utility resource planning

Deployment Phase (2028-2030):

1. Energy Market Participation

Example project 1: Load management services—EV fleet use case

Value generation:	Peak-shaving opportunities for fleets with multiple contiguous shifts
Decision makers:	Customer (e.g., corporations, DOD, city governments)
Approximate upfront costs:	$15–20M
LDES system:	10 MW, 12-hour duration
Target annual return:	16–18%[22]

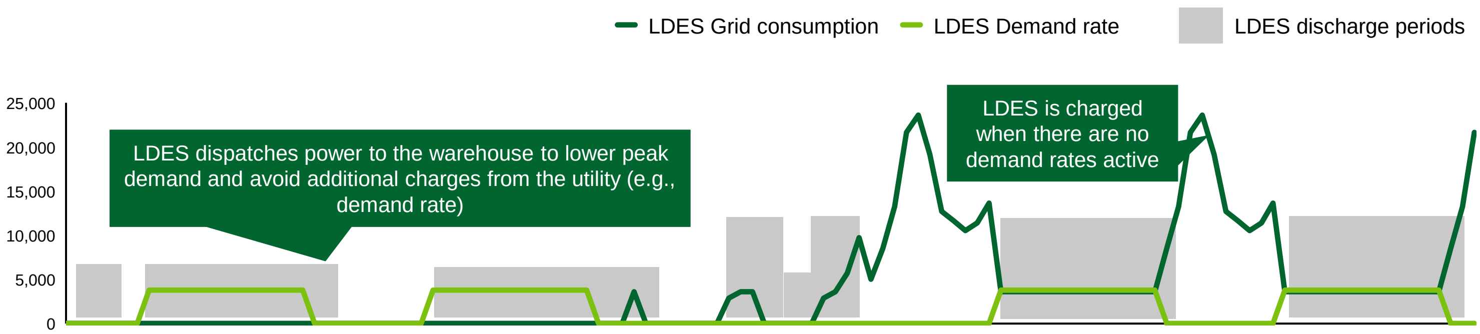
- **Description:** Organizations can consider deploying behind-the-meter LDES in tandem with procuring large electric-vehicle (EV) fleets with high seasonal usage (e.g., Amazon and USPS during December) or DOD facilities that may face high demand charges due to multiple extended charging peaks. This use case is especially relevant if vehicle charging is driven by extrinsic schedules (e.g., deliveries, shifts / patrols, truck rolls for routine maintenance inspections) that are critical functions or services. In cases where hundreds of vehicles must be charged over multiple peaks across the day, LDES can provide a more cost-effective solution than deploying multiple Li-ion systems to cycle throughout the day (Figure 16). The use case is based on near-term customer demand and does not require system-wide changes in energy markets or regulation.[xxxiii]

- **Implications for capital formation:** The largest electricity buyers have both the authority and incentives to dedicate capital to build LDES and mitigate the risk of business / operational interruptions from outages. However, corporate buyers have indicated that they would need to understand the economics and logistics of building and operating LDES systems before they could receive approval from their internal investment offices. DOD facilities may need additional authority to issue targeted tenders for LDES.

- **Key risks to consider**: Decision makers presently lack knowledge and confidence about the value of LDES systems as compared to Li-ion technologies. The DOE's latest research, integrated planning and data assessment tools, and convening ability could be used to educate industry on LDES. Additionally, a 3–5% premium (e.g., through grants or performance-based subsidies) could address the additional technology risk assumed by these first movers.

22.The comparable return for the competing Li-ion alternative is 10–12%. Offering a higher potential return than Li-ion—a well-known, mature technology—is often necessary in order to compensate investors for the risk inherent in a lesser-known, less-mature technology.

LDES dispatch for a warehouse with a large EV fleet, KW.



LDES dispatch for a warehouse with a large EV fleet, KW.

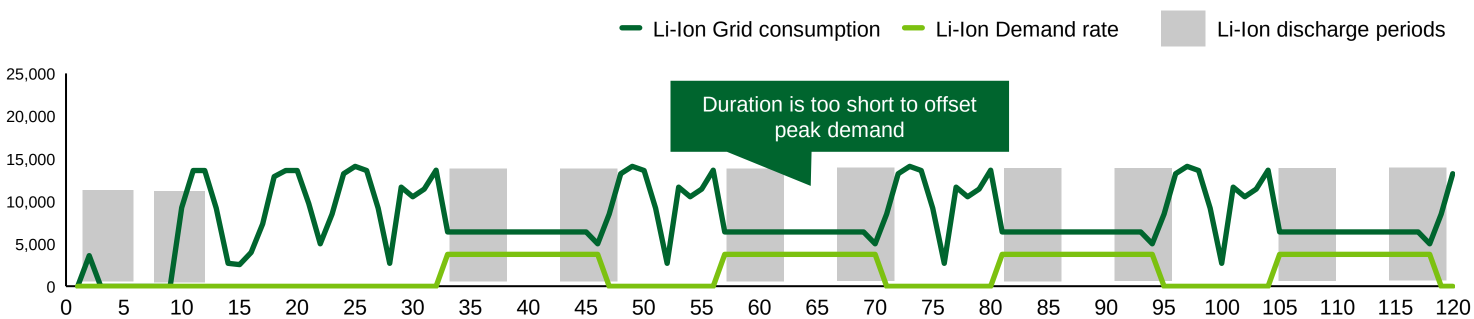
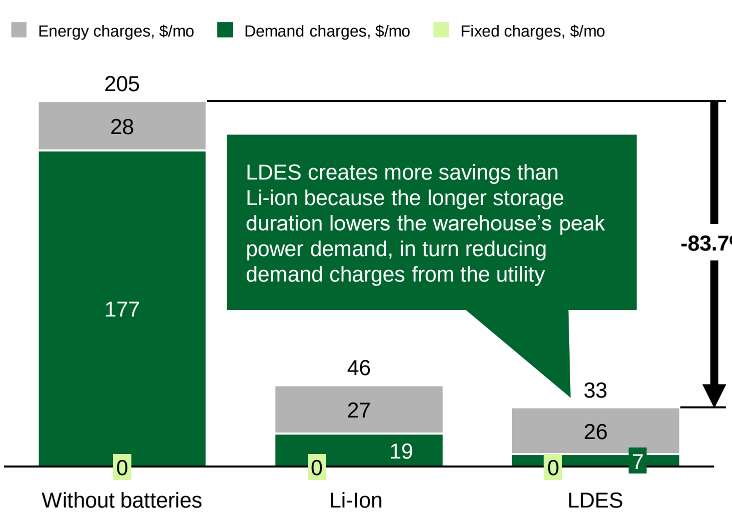


Figure 16: LDES's long duration of dispatch offers higher coverage of peak load, in addition to the ability to cover multiple peaks per day without repeated cycling—which could otherwise degrade Li-ion.[i,xxxiv]

Analysis shows that LDES creates more savings than Li-ion on a monthly basis. These savings offset the higher capital costs over the long-term (Figure 17).

Warehouse average monthly electricity bill, $ thousands



10 MW LDES vs Li-Ion capital cost (2025), $M

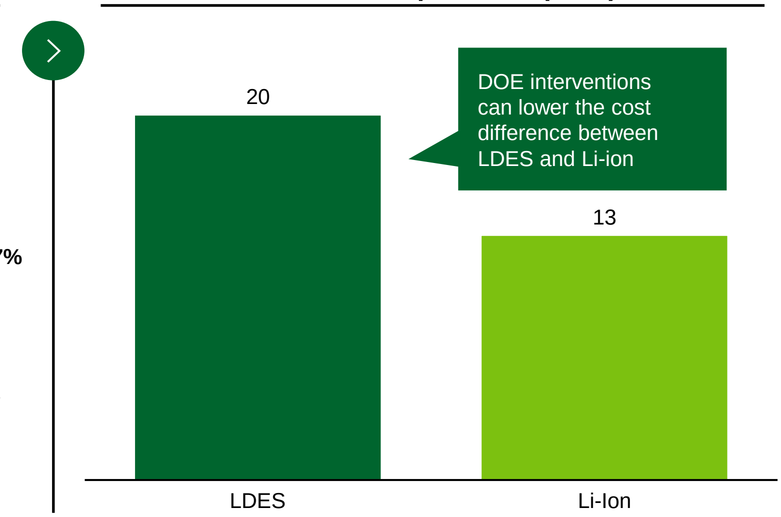


Figure 17: LDES offers better comparative savings over a much longer potential cycle life.[i,xxxi,xxxv]

Example project 2: Firming for future PPAs

Value generation:	Time and geography matched firming beyond Li-ion to meet ESG commitments through an expanded standard of performance
Decision makers:	ISOs, renewable energy developers, and offtakers (e.g., corporations)
Approximate upfront costs:	$6–8M
LDES system:	20 MW, 10-hour duration
Target annual return:	N/A

- **Description**: Expansion beyond Li-ion firming of renewable projects to LDES (e.g., 20 MW, 10 hours) with the goal of deploying lower-cost shaped variable renewables to meet near-term Scope 2 emissions targets of corporate / government PPA buyers, which could be more aggressive than state-level targets (e.g., 2030 net-zero goals, expanded definitions of meeting “additionality” hurdles for renewable purchases).[23] Companies can use LDES to expand their Environmental, Social, and Governance (ESG) commitments by applying an expanded standard of performance (e.g., percentage of time matching) to match their energy needs with local supply at the same time they use that energy. This framing of 24-7 energy commitments significantly expands the likelihood that the corporate commitments will be additional and not lean on scarce flexibility resources at the grid level. However, this framing would also require right-sizing a hybrid renewables site (e.g., wind, solar, and storage) for LDES to accurately and responsively charge and discharge to meet customer load. Owners of existing variable renewables sites could use LDES to expand their variable renewables positions or improve reductions in grid emissions using the same interconnection and transmission investment to co-site LDES.[xxxvi]

- **Implications for capital formation**: By demonstrating the lower cost for LDES compared to Li-ion battery storage for customers looking to highly time-matched renewable energy targets, LDES could become a more attractive risk-adjusted return prospect for investors with a higher risk tolerance (Figure 18).

- **Key risks to consider**: IPPs and developers have limited experience in sizing or operating LDES facilities as part of a shaped PPA. Some communities may express concerns on the expansion of existing variable renewables for out-of-state benefits**.** To account for these concerns, for example, the DOE could provide a grant—100% of the differential in LDES and Li-ion capital costs—to encourage the deployment of an LDES system at higher levels of PPA firming (e.g., 98%) while funding front-end engineering design (FEED) for LDES integration in partnership with research institutions for codification. Also, the PUCs could provide utility mandates to ensure a significant percentage of the renewable energy benefits (e.g., jobs, taxes) are provided to residents.

23 “Additionality” hurdles could include decisions to match total hours of clean energy production to customer load around-the-clock and within a defined region where the load is located

LCOE by PPA firming percentage, $/MWh[1]

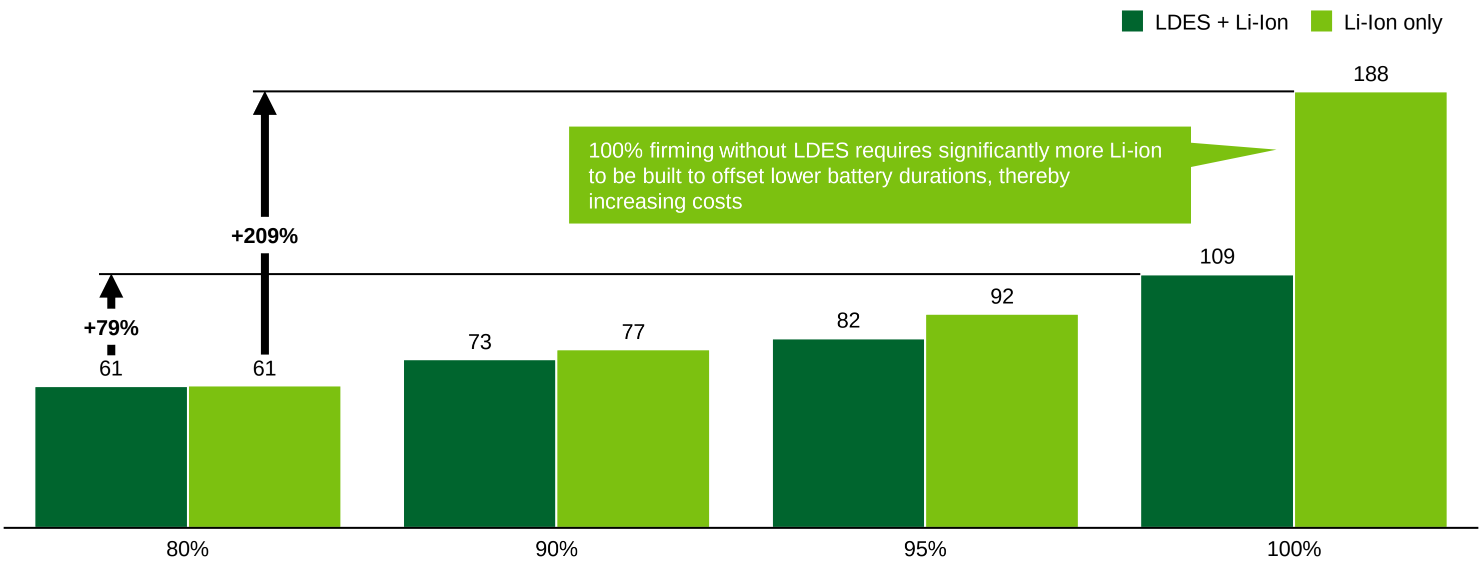


Figure 18: LDES provides a distinctive advantage over Li-ion when considering the LCOE of high time-matched PPAs (80% or more).[i] [1]Assumes 20-year PPA contract.

Example project 3: Transmission and distribution (T&D) deferral

Value generation:	Deploy LDES to manage load constraints and defer large T&D upgrades
Decision makers:	Utility, Public Utility Commission (PUC)
Approximate upfront costs:	$55–60M
LDES system:	20 MW, 80-hour duration[24]
Target annual return:	~9-12%[25]

- **Description**: A utility experiencing transmission or distribution constraints due to changing / growing load at a specific substation may consider deploying LDES to create value versus committing to a large investment in upgrades. The savings from the T&D deferral (Figures 19 and 20) would allow this project to be justified and approved by the boards of utilities or by PUCs. T&D deferral may be more desirable in regions with ample variable renewable capacity and where building transmission and distribution is especially technically complex (e.g., in localities with extreme weather), geographically challenging (e.g., on archipelagos), exceptionally expensive (e.g., in densely populated areas), or politically difficult (e.g., in regions with strong private landowners). This option may be especially pertinent in congested transmission zones (e.g., the Northeast) that will experience transformational load patterns due to EV and heat pump adoption, as well as an influx of generation from offshore wind interconnections. LDES can be used to provide substation-level flexibility, especially where siting new infrastructure cannot be achieved in a timely manner. T&D deferrals could be significant drivers of LDES deployment in the medium term. In many ISOs, rulemaking may need to be changed to have a standard set of allowances for rate-based storage assets to participate in power markets.

24 Duration sized for a 3-day event
25 Latest returns on equity (ROEs) for Federal Energy Regulatory Commission (FERC) Transmission assets range from 9–12%; this range is dependent on geography and specific use-case application.

- **Implications for capital formation:** Utilities may be inclined to provide a significant portion of the capital needed to build LDES projects contingent upon PUC approval, which will consider both cost and technology maturity / track record. Utility buy-in would demonstrate to other types of private capital that there are long-term demand signals for LDES. Risk-averse types of capital providers (e.g., infrastructure funds) have indicated that they need to see these long-term demand signals before they invest.

- **Key risks to consider**: Developers may have difficulty permitting and siting due to competition with other land-use needs and hard-to-get data on distribution and local system constraints. Some ISOs or PUCs also may not consider LDES as a T&D resource. State governments or PUCs could develop/distribute a data platform that provides the information needed to better target LDES-appropriate locations on the electric grid where needs are greatest. A common fact-set around LDES codification and consideration could be syndicated with ISOs and PUCs.

Key assumptions

LDES
Capacity: 20 MW
Duration: 80 hrs
Storage: 1,600 MWh
Energy Capital Cost: $8.8/kWh
Power Cost: $1,812/kW
ITC: 30%

Transmission upgrade
Constraint: 20 MW
Upgrade costs ($/KVA): ~$22,000
Discount rate: 11%
Inflation rate: 2%
Deferral period: 8 years

Analysis assumes that LDES is considered a transmission investment

Illustrative transmission investment scenarios, $M

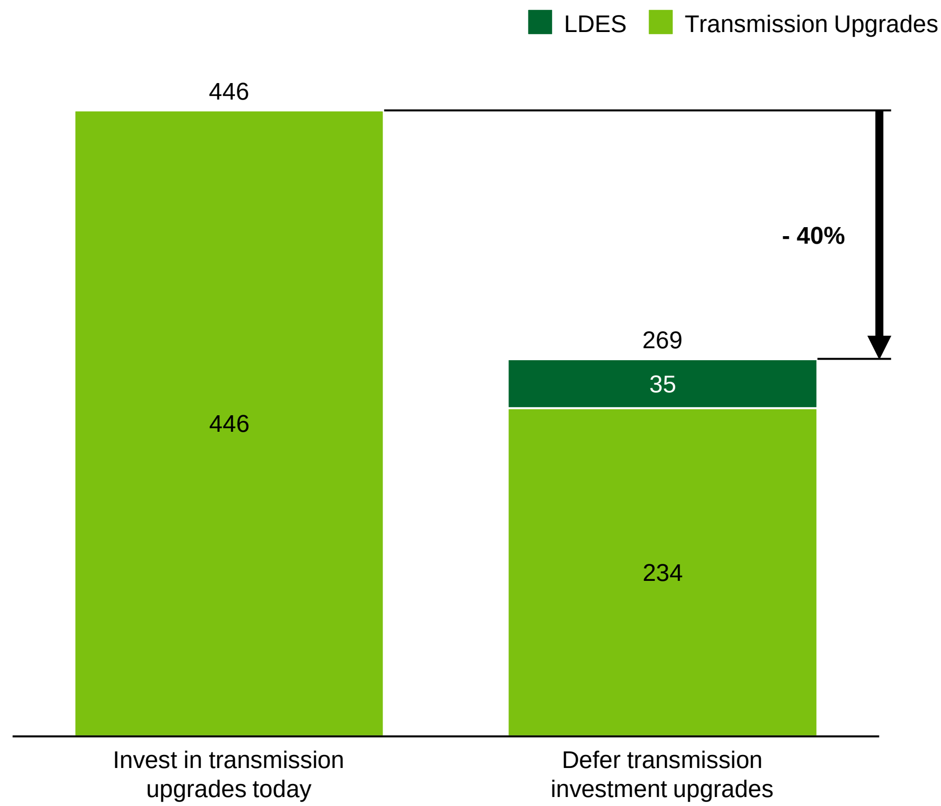


Figure 19: A deferral period of 8 years could lead to 40% lower costs, on an NPV basis, for the same transmission need.[i, xxxvii]

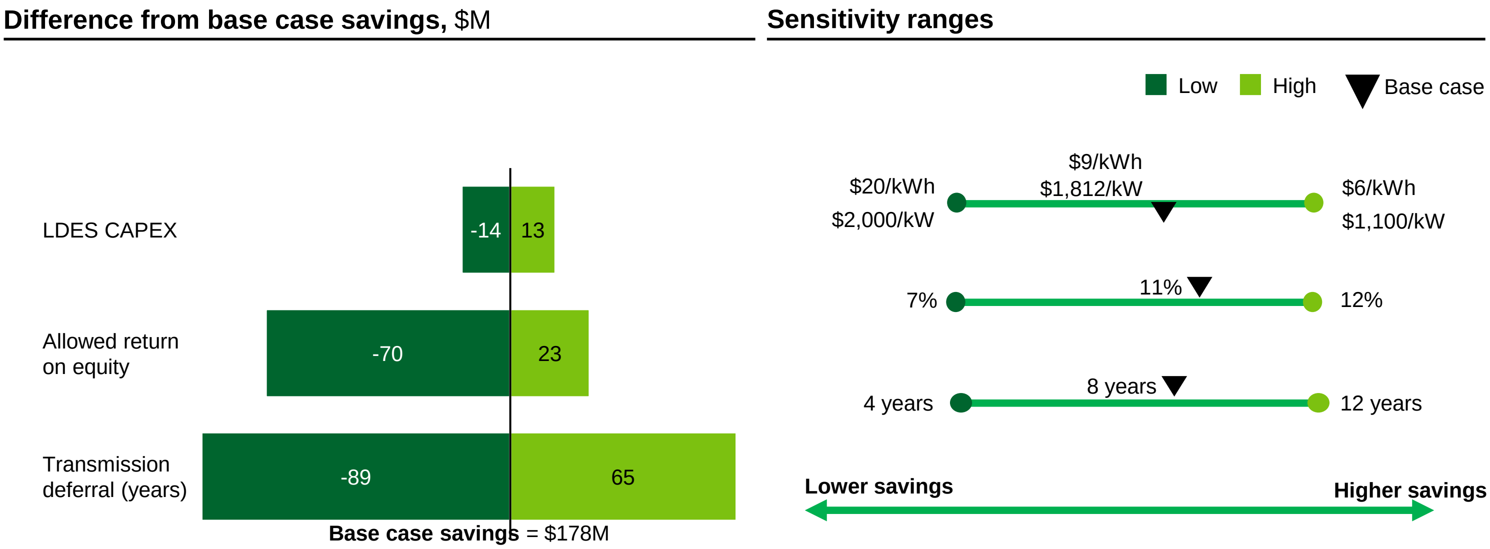


Figure 20: Even in conservative deferral sensitivities, LDES can provide an attractive financial value proposition for T&D deferral [i]

Example project 4: Microgrid and resiliency— Island example

Value generation:	Increase grid resiliency by supplementing baseload generation while decarbonizing
Decision makers:	Grid operator, government
Approximate upfront costs:	$110–120M
LDES system:	40 MW, 150-hour duration
Target annual return:	~9-12%[26]

- **Description**: A local grid with high decarbonization targets and reliability issues (e.g., Puerto Rico) may consider LDES as an attractive portion of their generation transition. In isolated areas, where importing and exporting electricity is not an option, LDES (40 MW, 150 hours as a demonstration) can be used to supplement baseload generation and obviate the import of fossil fuels (Figure 21). This use case is especially pertinent where solar resources are readily available and access to other forms of fuel (e.g., natural gas, coal, oil) can be costly or at risk.

- **Implications for capital formation:** Capital providers have indicated a need to understand the serviceability (e.g., maintenance and upkeep requirements) of LDES technologies to accurately predict the cashflows of those technologies. Demonstrating that a technology can perform at scale in isolated areas would help private capital understand risks related to serviceability.

- **Key risks to consider**: Long and uncertain interconnection queues, lack of available land, or lack of stakeholder support could all delay LDES adoption. PUCs can streamline interconnection by allowing a co-location model, allowing developers to use already interconnected assets. Grid operators, PUCs and state governments could also develop / distribute a data platform that provides the information needed to better target LDES-appropriate locations (e.g., most congested or most likely to be congested nodes). State governments and stakeholder groups could build stakeholder support for LDES through reports and ecosystem convening.

26 Latest Returns on Equity (ROEs) for Federal Energy Regulatory Commission (FERC) Transmission assets range from 9–12%; Range is dependent on geography and specific use-case application

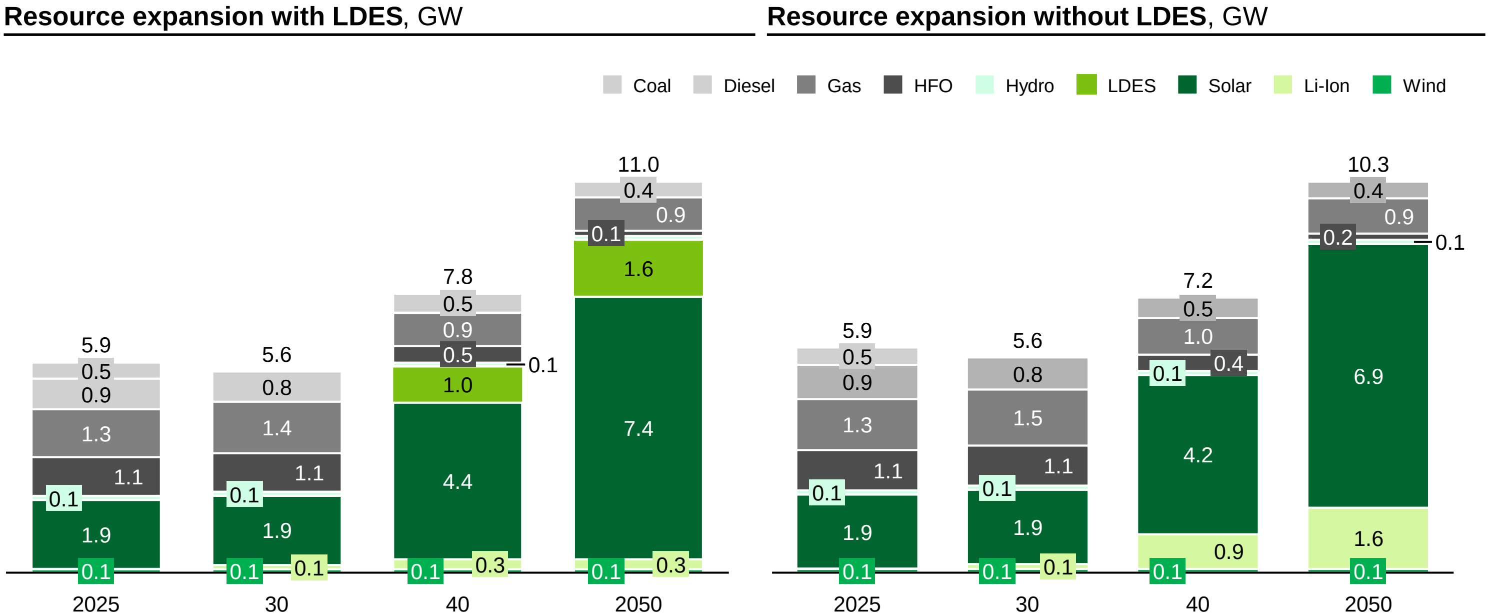


Figure 21: The modeled generation transition in the “net-zero by 2050” scenario for Puerto Rico identifies a potential need for 1.6 GW of LDES as a part of a “least-cost” pathway.[i]

Analysis shows that LDES technologies deliver superior savings than other options (e.g., Natural gas & Li-ion) over time (Figure 22).

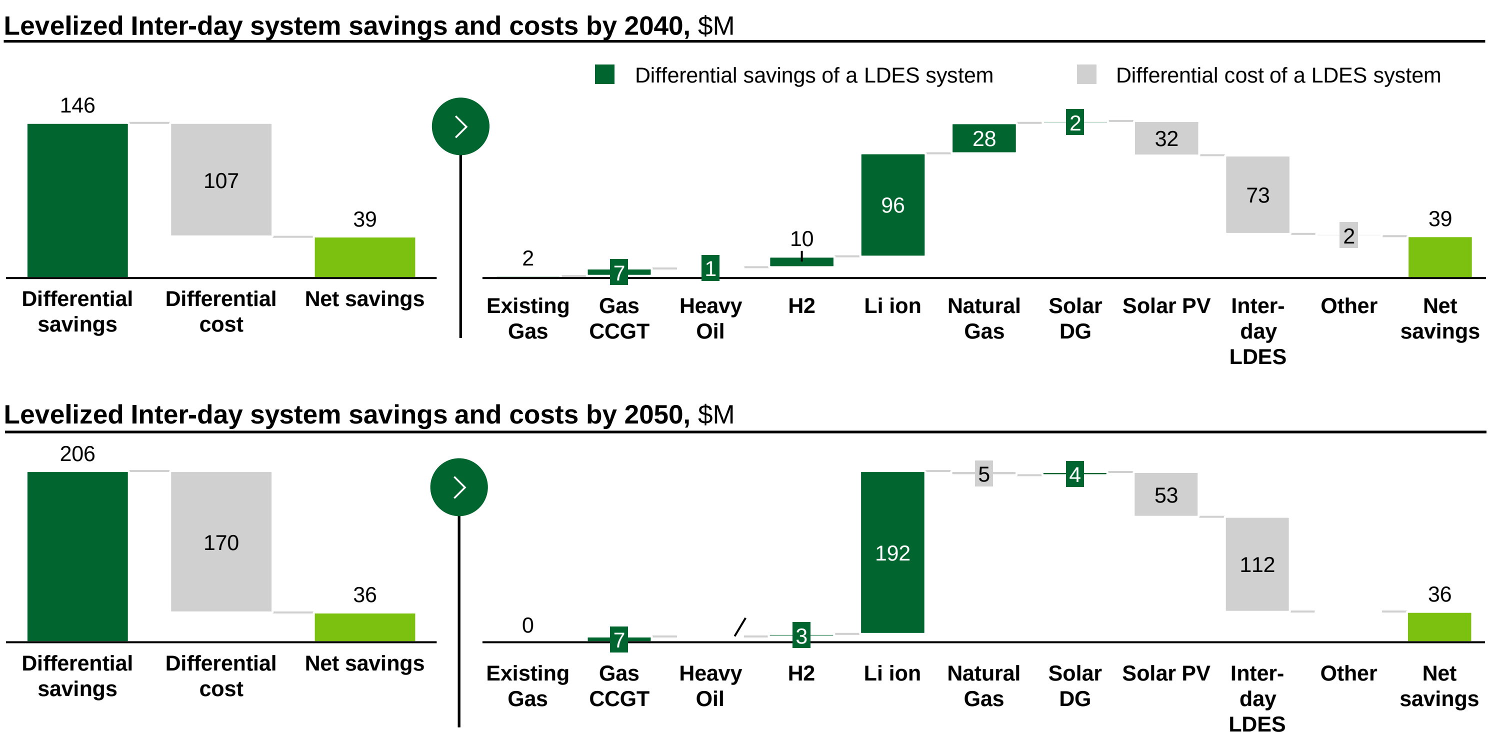


Figure 22: On a total-systems cost basis, LDES technologies could potentially offer 10–16% savings on total capex build out over the 2030–2050 period for Puerto Rico.[i]

Example project 5: Utility resource planning

Value generation:	Leverage LDES to balance and manage a high-renewables grid
Decision makers:	Utility and PUC
Approximate upfront costs:	~200M for each project; ~800M over the four projects by 2030
LDES system:	150 MW, 65-hour duration
Target annual return:	~9-12%[27]

- **Description**: A vertically integrated utility that is pursuing aggressive variable renewables deployment by 2030—especially relevant with a large portfolio of offshore wind—considers LDES investment in its least-cost planning as a portion of its generation mix to balance the system. The scale of the opportunity would be regionally dependent based on the existing availability of other grid flexibility resources (e.g., this scenario would be especially attractive in PJM-South, where up to 700 MW could be deployed economically within the decade). LDES of 150 MW and 65 hours provides the lowest-cost pathway to meet the state's integrated resource plans and decarbonization goals while providing a comparable rate-base opportunity for utilities / investors (Figure 23).

- **Implications for capital formation**: At-scale capital providers want to see that permitting delays will not add significant cost burdens. Uncertainty about potential delays adds volatility to projects' cash flow profiles. Demonstrating that utilities and ISOs can work together to expedite approvals with a standardized permitting process can increase investor confidence. Large contracts with developers can also have a debt equivalency impact on the utility balance sheet.

- **Key risks to consider**: Adoption could be delayed due to a lack of standardized permitting and low support for LDES from PUCs and ISOs (e.g., recent IRPs have stated that Li-ion would be the dominant form of energy storage for the planning horizon). These risks could be mitigated by highlighting the differentiated role of LDES via expanded horizons for IRP planning and economy-wide capacity expansion modeling approaches. Expanded considerations regarding climate resiliency and portfolio strategy could also enhance LDES's position. In addition, state governments could create targets so that utilities aim to procure a minimum amount of storage (or, specifically LDES). Local, state, and federal government entities could also provide additional funding for LDES projects.

27 Latest Returns on Equity (ROEs) for Federal Energy Regulatory Commission (FERC) Transmission assets range from 9-12%; Range is dependent on geography and specific use-case application

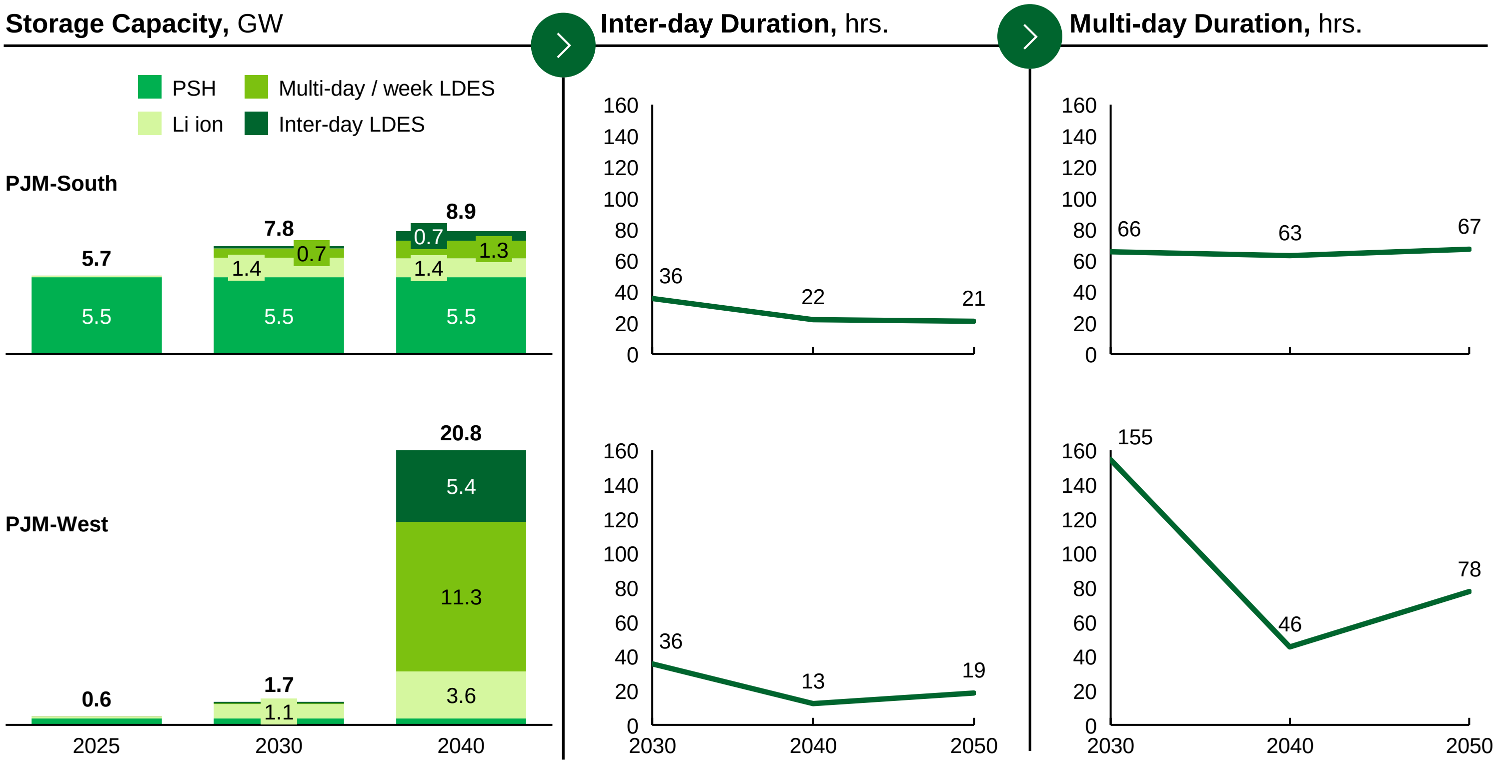


Figure 23: Large scale LDES buildout could be a least-cost-option for generation transition for vertically integrated utilities in PJM.[i]

Example project 6: Energy market participation

Value generation:	Capture energy arbitrage opportunities to monetize LDES's grid firming capabilities
Decision makers:	Renewable energy developers and asset investors (e.g., private equity, infrastructure firm)
Approximate upfront costs:	$170-190M
LDES system:	100 MW, 12-hour duration
Target annual return:	12-15%

- **Description**: A developer or IPP deploys LDES technologies in CAISO to capture energy arbitrage and monetize the grid firming capabilities of an LDES storage system through the Resource Adequacy market, as penetration of variable renewables continues (Figure 24). These assets would function as critical reliability assets in the event of Public Safety Power Shutoffs and could be procured partially through Community Choice Aggregator solicitation. The LDES system of 100 MW and 12 hours would provide the opportunity to adequately meet the state's resource and clean energy goals through the provision of services across multiple streams (e.g., grid firming).

- **Implications for capital formation:** Capital providers have expressed interest in LDES business models that can arbitrage the power markets. Proving the economic viability of such opportunities would help capital providers understand the cash flow profiles of such projects.

- **Description**: A developer or IPP deploys LDES technologies in CAISO to capture energy arbitrage and monetize the grid firming capabilities of an LDES storage system through the Resource Adequacy market, as penetration of variable renewables continues (Figure 24). These assets would function as critical reliability assets in the event of Public Safety Power Shutoffs and could be procured partially through Community Choice Aggregator solicitation. The LDES system of 100 MW and 12 hours would provide the opportunity to adequately meet the state's resource and clean energy goals through the provision of services across multiple streams (e.g., grid firming).

- **Implications for capital formation:** Capital providers have expressed interest in LDES business models that can arbitrage the power markets. Proving the economic viability of such opportunities would help capital providers understand the cash flow profiles of such projects.

- **Key risks to consider**: Transmission interconnection and permitting and land constraints could delay projects (e.g., some interconnection queues are creating delays of more than 4 years.). ISOs and some PUCs can streamline interconnection by allowing a co-location model, allowing developers to take advantage of interconnected assets. The federal government can offer public lands to developers for projects at reduced rates or provide government funding (e.g., low-interest loans, grants).
- **Approximate financial intervention to make bankable**: $65–85M (35–45% of capex)

Indicative cumulative arbitrage potential in CAISO, $M/MW

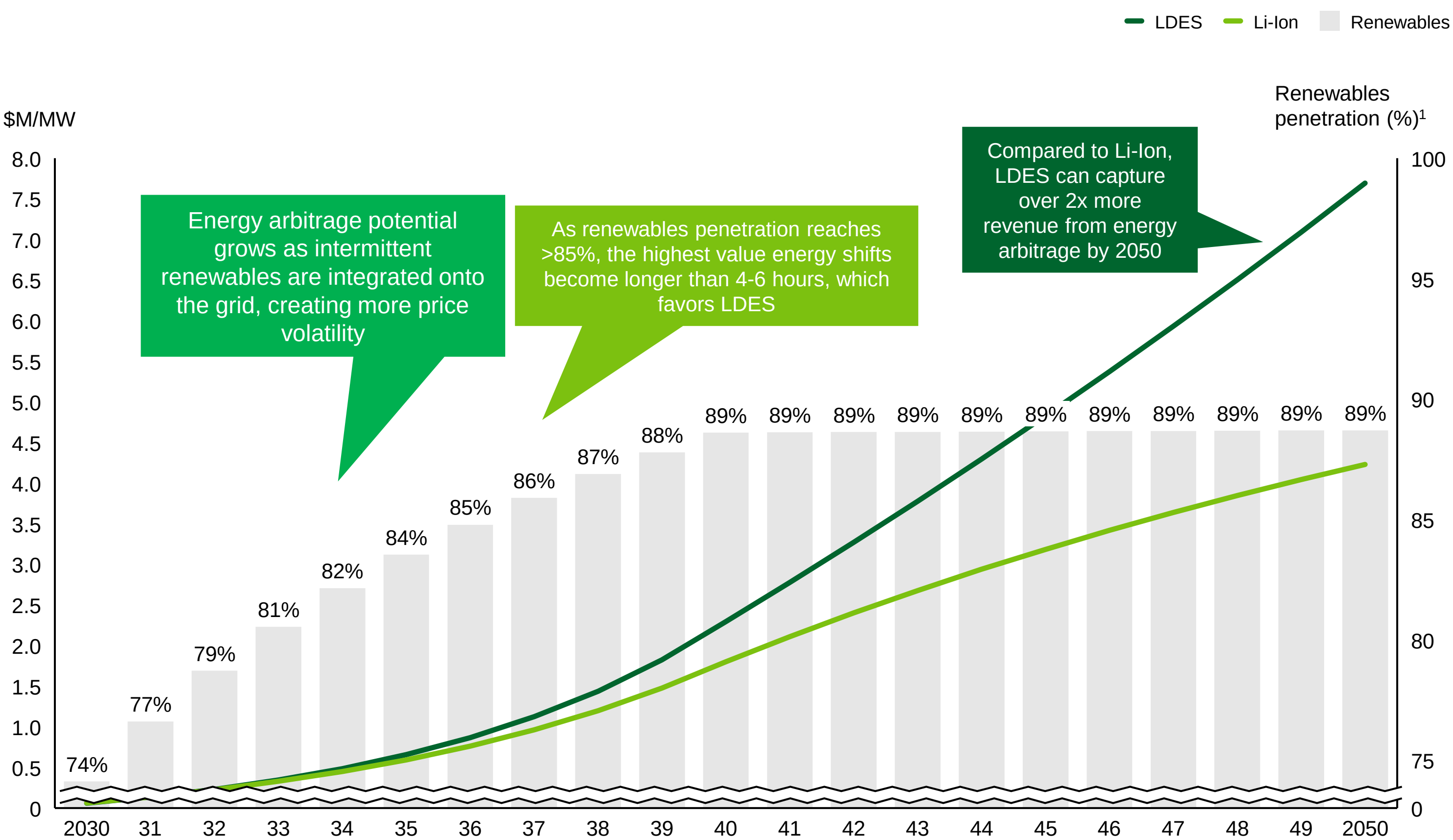


Figure 24: The arbitrage opportunity for LDES increases steadily as variable renewables penetration grows.[i] [1]Percent of total CAISO energy generation from renewables (Net-zero 2050 High renewables scenario).

Appendix 2 – Project Templates Modeling Methodology

Example project 1 — Load-management services, EV-fleet use case

Representative stakeholder

- A large organization with emission-reduction targets that uses a significant amount of grid-based electricity and faces peak-demand charges from their local utility

LDES use case

- LDES could be used to lower peak-demand charges by lowering the organization's peak-electricity consumption from the grid

Objective of analysis

- To show where such a stakeholder might face peak-demand charges and answer the questions: how often might this happen and how much would LDES help save compared with the next-best alternative?

Expected output

- An estimate of LDES's savings for this stakeholder in this scenario

Methodology

- Modeled the hourly electricity demand and hourly electricity costs for an illustrative delivery warehouse with a large EV fleet (e.g., 200 delivery vans, 10 linehaul trucks) and high seasonal-power demand
  - Calculated a large delivery company's hourly electricity demand data from data on the charging patterns of heavy-duty-fleets
  - Extended "peak-electricity demand periods" throughout the winter months to reflect increased trucking for this stakeholder during the holiday season
  - Calculated the cost of charging the EV fleet based on electricity rates from Con-Edison (New York)
- Entered the hourly electricity demand and hourly electricity costs into a distributed-energy resource-optimization model to determine how storage could be deployed to lower the warehouse's electricity bill
  - Configured the model to optimize for electricity cost savings by dispatching the battery when electricity prices are the highest
  - Compared Li-ion and LDES scenarios in the distributed-energy resource-model to assess the savings potential of the two technologies

Key inputs

- Amount of grid electricity use
- Stakeholder's timing and use of electricity
- Electricity pricing schedule for the local utility
  - Characteristics of LDES battery (cost, duration, battery life)
  - Characteristics of next-best alternative (Li-ion battery in this case—cost, duration, battery life)
  - Distributed-energy resource-optimization model

Specific assumptions and outputs

- **EV charging patterns**
  - 10 linehaul trucks with a charging profile from 5 a.m. – 3:15 p.m.
  - 100 delivery vans with a charging profile from 1 p.m. – 11:15 p.m.
  - 100 delivery vans with a charging profile from 7 p.m. – 5:15 a.m.

- **Battery characteristics**
  - **Capacity:** 10 MW
  - **Duration:** 12 hours (LDES); 4 hours (Li-ion)
  - **Operating life:** 27 years (LDES); 10 years (Li-ion)
  - **Round trip efficiency (RTE):** 69% (LDES); 85% (Li-ion)
  - **Capital cost:**
    - **LDES:** $20M (energy capital cost: $23 / kWh; power and balance of system cost: $1,075 / kW)
    - **Li-ion:** $13M (energy capital cost: $235 / kWh; power and balance of system cost: $175 / kW)

- **ITC, depreciation, and tax rate**
  - **ITC:** 30%; assumed that 100% of capex is eligible
  - **Depreciation schedule:** 5-year MACRS
  - **Depreciable basis reduction:** 50% of the ITC amount
  - **Tax rate:** 21%

- **Revenue / savings**
  - **Demand charges:** Assumed primary savings is from reduced demand charges from the battery lowering the peak demand
    - **LDES:** $2M per year
    - **Li-ion:** $1.9M per year
  - **Energy charges:** Lower energy charges by using the battery to shift power demand from high-price periods to low-price periods
    - **LDES:** $17,000 per year
    - **Li-ion:** $6,500 per year

- **Operating expenditures:**
  - **Operations and maintenance:** $19 / kW per year (LDES) and $6 / kW per year, escalating at 2% p.a.

- **Financing**
  - **Debt:** Sizes contribution based on a debt service coverage ratio of 1.8x with an interest rate of 4% for 10 years for LDES and 8 years for Li-ion
  - **Project owner:** Contributes remaining capital and retains ownership through the life of the asset. Owner assumed to have a large enough tax liability to be able to effectively monetize the ITC without a tax equity investor.

- **Illustrative model outputs:**
  - **Monthly electricity bills across scenarios:**

Load management illustration

Electricity bills without batteries

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Energy charges, $/mo	$24,225	$21,780	$24,113	$23,335	$24,113	$23,335	$24,113	$24,113	$23,335	$24,113	$23,335	$72,228	$332,138
Demand charges, $/mo	$106,591	$106,591	$106,591	$106,591	$106,591	$264,847	$264,847	$264,847	$264,847	$106,591	$106,591	$319,774	$2,125,299
Fixed charges, $/mo	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$80
Total monthly bill, $/mo	$130,822	$128,377	$130,711	$129,933	$130,711	$288,188	$288,966	$288,966	$288,188	$130,711	$129,933	$392,008	$2,457,516

Electricity bills with LDES

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Energy charges, $/mo	$22,626	$20,298	$22,631	$22,626	$22,631	$21,853	$22,631	$22,631	$21,853	$22,631	$21,853	$70,746	$315,010
Demand charges, $/mo	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$84,574	$84,574
Fixed charges, $/mo	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$80
Total monthly bill, $/mo	$22,632	$20,304	$22,638	$22,632	$22,638	$21,860	$22,638	$22,638	$21,860	$22,638	$21,860	$155,326	$399,664

Electricity bills with Lithium Ion

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Energy charges, $/mo	$23,576	$21,248	$23,582	$22,804	$23,582	$22,804	$23,582	$23,582	$22,804	$23,582	$22,804	$71,697	$325,648
Demand charges, $/mo	$4,440	$4,440	$4,440	$4,440	$4,440	$10,371	$10,371	$10,371	$10,371	$4,440	$4,440	$150,023	$222,585
Fixed charges, $/mo	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$80
Total monthly bill, $/mo	$28,023	$25,695	$28,029	$27,251	$28,029	$33,181	$33,959	$33,959	$33,181	$28,029	$27,251	$221,726	$548,312

Figure 25: Load management with LDES creates the highest level of monthly electricity cost savings.

Example project 2 — Firming for future PPAs

Representative stakeholder

- Companies with energy-intensive businesses that are looking to procure ~24/7 clean energy via a PPA to meet near-term net-zero goals

LDES use case

- The PPA purchased by the customer would be based on a renewable asset that is paired with LDES to provide around-the-clock renewable energy

Objective of analysis

- To compare the cost of a 24/7 clean PPA that uses LDES versus one that uses Li-ion

Expected output

- To size the intervention needed to bridge the cost gap between a 24/7 PPA using Li-ion versus one that uses LDES

Methodology

- Assumed that a data center was interested in signing a renewable PPA that could match their electricity demand at all hours
- Assumed that the PPA would feature a battery paired with a renewable asset to provide 24/7 clean energy matching
- Deployed a PPA-firming model, which calculates the levelized-cost-of-energy under electricity-demand and energy-resource parameters to determine the costs of this PPA
- Compared the levelized cost of energy for LDES vs. Li-ion to assess the relative cost of each technology when it is used as part of a firmed PPA offering

Key inputs

- Hourly, electricity demand profile of a data center
- Characteristics of the LDES and Li-ion batteries (e.g., costs, duration)
- Local solar and wind prices
- PPA firming model

Specific assumptions and outputs

- **Asset characteristics**
  - **Capacity:** 60 MW
  - **Duration:** 10 hours (LDES); 4 hours (Li-ion)
  - **Operating life:** 27 years (LDES); 15 years (Li-ion)
  - **Round trip efficiency (RTE):** 69% (LDES); 85% (Li-ion)
  - **Capital cost:**
    - **LDES:** $78M (energy capital cost: $23 / kWh; power and balance of system cost: $1,075 / kW)
    - **Li-ion:** $54M (energy capital cost: $157 / kWh; power and balance of system cost: $264 / kW)

Illustrative output for a firmed PPA with LDES

PPA firming illustration

	100% firmed	95% firmed	90% firmed	80% firmed
LCOE [USD/MWh]	**109**	**82**	**73**	**61**
Storage stack				
LDES24_150 charge nominal power [MW]	0	0	0	0
LDES8_24 charge nominal power [MW]	60	31	19	4
LiIonBattery charge nominal power [MW]	4	10	6	1
Storage capacity				
LDES24_150 storage energy capacity [MWh]	0	0	0	0
LDES8_24 storage energy capacity [MWh]	4275	1377	764	168
LiIonBattery storage energy capacity [MWh]	23	52	27	3
Generation				
GridBuying annual energy generation [MWh]	-	19,113	38,226	76,452
GridSelling annual energy generation [MWh]	(133,642)	(87,928)	(90,898)	(87,840)
Hydro annual energy generation [MWh]	-	-	-	-
PV annual energy generation [MWh]	183,516	165,348	150,213	120,309
WindOffshore annual energy generation [MWh]	-	-	-	-
WindOnshore annual energy generation [MWh]	419,812	341,908	325,639	284,540
Capacity				
GridBuying nominal power [MW]	0	44	44	44
GridSelling nominal power [MW]	160	150	131	91
Hydro nominal power [MW]	0	0	0	0
PV nominal power [MW]	90	81	73	59
WindOffshore nominal power [MW]	0	0	0	0
WindOnshore nominal power [MW]	123	100	95	83

Figure 26: 100% PPA firming with LDES can be achieved at an LCOE of $109 / MWh.

Example project 3 — Transmission and distribution (T&D) deferral

Representative stakeholder

- A utility that needs to upgrade infrastructure—due to a transmission constraint—while maintaining customer affordability and meeting a growing load in its service territory

LDES use case

- LDES could be used to address a transmission constraint and defer costly transmission upgrades—such as a substation expansion—by providing power to meet periods of peak demand

Objective of analysis

- To compare the cost of investing in a transmission upgrade today versus using LDES to defer that transmission upgrade by a certain period of time

Expected output

- An illustration of potential savings from using LDES to defer transmission upgrades

Methodology

- Modeled two scenarios and compared the illustrative savings from using LDES to defer a transmission upgrade:
  - Scenario 1: A 20 MW transmission and substation constraint is upgraded in year 1
  - Scenario 2: A 20 MW LDES system is deployed in year 1 to defer the transmission upgrade by 8 years
- Assumed that LDES is allowed to earn a transmission rate-of-return given that LDES is being used to address a transmission constraint
- Assumed that the deferred transmission increases at the inflation rate each year
- Discounted any future costs to year 1 to compare the present value of the transmission deferral savings

Key inputs

- Size of the transmission constraint
- The cost to upgrade that transmission constraint (e.g., substation upgrades, transmission line extensions)
- Characteristics of LDES battery (e.g., cost, duration, battery life)
- Allowable rate-of-return for transmission assets
- Length of deferral

Specific assumptions and outputs

- **LDES characteristics**
  - **Capacity:** 20 MW
  - **Duration:** 80 hours
  - **Operating life:** 29 years
  - **Round trip efficiency (RTE):** 55%
  - **Capital cost:** $58M (energy capital cost: $9 / kWh; power and balance of system cost: $1,812/kW)
  - **ITC:** 30%
  - **Rate of return:** 10.6%
  - **Length of transmission-upgrade deferral enabled by LDES:** 8 year

- **Transmission and substation upgrade**
  - **Line size:** 115 kV
  - **Upgrade cost ($ / kW):** $22,319

- **Illustrative model outputs**

Option 1: Invest in LDES today to defer transmission upgrade	
LDES	
LDES cost today (pre-ITC)	51
LDES cost today (w/ ITC)	**35**
Transmission	
Transmission upgrade cost in 8 years ($M)	523
Tranmission upgrade cost discounted	**234**
Total cost	**269**

Option 2: Invest in transmission upgrade today	
LDES	
LDES cost today (pre-ITC)	-
LDES cost today (w/ ITC)	-
Transmission	
Transmission upgrade cost today	446
Total cost	**446**
Cost difference	**177**

  - **Sensitivity analysis across scenarios:**

Savings sensitivity analysis				Absolute Savings			Difference from base case	
Sensitivities	Base	Low	High	Base	Low	High	Low	High
Energy capital cost ($ / kWh)	8	20	6	177	156	187	(21)	10
Power + BOP capital cost $ / kW)	1812	2000	1100					
Rate of return	11%	7%	12%	177	107	200	(70)	23
Deferral period (years)	8	4	12	177	88	242	(89)	65

Figure 27: T&D deferral saves $177M in the modeled base case.

Example project 4 — Microgrid and resiliency— Island example

Representative stakeholder

- A utility on an isolated, remote, or unreliable grid (e.g., Puerto Rico) with high energy charges and a high-variable-renewables penetration

LDES use case

- To replace baseload technologies—such as natural gas—and increase grid reliability as more variable renewables are integrated onto the grid

Objective of analysis

- To demonstrate that LDES can be used to provide reliability and system cost-savings by lowering fuel costs or the need for additional generation capacity

Expected output

- A comparison of system costs under LDES and Li-ion under a net-zero by 2050 scenario

Methodology

- Deployed a capacity expansion model to project the resource buildout required to achieve net-zero by 2050 in a self-contained island (i.e., no off-island transmission)
  - As with the following templates in CAISO and ERCOT, the model was configured to optimize for net-zero by 2050 at the lowest cost
- Assessed multiple capacity-expansion scenarios to compare how system costs change with LDES (e.g., net-zero with no LDES, net-zero with LDES)
- Referenced 2040 and 2050 as comparison years as those years show an acceleration in decarbonization investments and an improvement in LDES economics
- Compared the system costs under net-zero with LDES and net-zero without LDES

Key inputs

- Characteristics of the LDES and Li-ion batteries (e.g., cost, duration, battery life)
- Characteristics of the variable renewable generation profile in the system
- Characteristics of local power system (e.g., existing generation, power imports / exports)
- Characteristics of other storage and generation technologies (e.g., cost, efficiency)
- Capacity expansion model

Specific assumptions and outputs

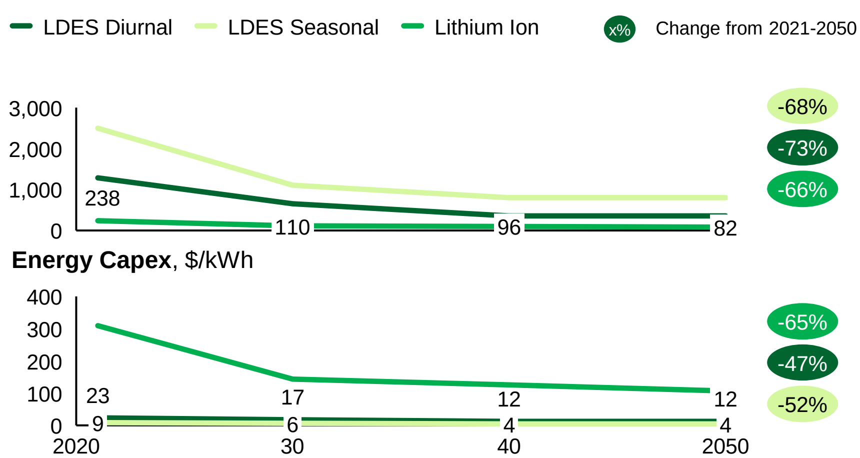
- **LDES diurnal**
  - **RTE:** 79%
  - **Weighted average cost of capital:** 6%
  - **Lifetime:** 27 years
  - **Fixed opex (% of capex)**: 2.5%

- **LDES seasonal**
  - **RTE:** 58%
  - **Weighted average cost of capital:** 6%
  - **Lifetime:** 29 years
  - **Fixed opex (% of capex)**: 0.2%

- **Lithium Ion**
  - **RTE:** 85%
  - **Weighted average cost of capital:** 4.3%
  - **Lifetime:** 15 years
  - **Fixed opex (% of capex)**: 5.7%

- **Storage cost declines overtime:**

GSD, $/kW



Power Capex, $/kW

	LDES Diurnal	LDES Seasonal	Lithium Ion
RTE	79%	58%	85%
WACC	6%	6%	4.3%
Lifetime	27	29	15
Fixed OPEX (% of CAPEX)	2.5%	0.2%	5.7%

Source: LDES Council Report, NREL ATB 2022

Figure 28: Storage costs decline between 50–70% by 2050

Example project 5 — Utility resource planning

Representative stakeholder

- A utility with growing renewable-energy generation. In this case, the analysis compared the impact of integrating offshore wind versus onshore wind

LDES use case

- To smooth offshore or onshore wind loads and provide resilience as more variable renewables are integrated onto the grid

Objective of analysis

- To demonstrate the LDES can be used to support renewable integration onto the grid

Expected output

- An illustration of when LDES is built, how much is built, and the average duration of the system across those time periods

Methodology

- Deployed capacity expansion model for PJM to project the resource buildout required to achieve net-zero by 2050
  - Included incentives from the Inflation Reduction Act and parsed PJM into 20 different transmission zones to get a localized view of LDES deployment
- Compared the zones with and without offshore wind to assess how LDES is built and operated under different scenarios

Key inputs

- Characteristics of the LDES and Li-ion batteries (e.g., cost, duration, battery life)
- Characteristics of the local power system (e.g., existing generation, local transmission zones)
- Characteristics of other technologies (e.g., cost, efficiency)

Capacity expansion model

Specific assumptions and outputs

- **Onshore wind**
  - **Capacity factor:** 42%
  - **Weighted average cost of capital:** 5%
  - **Lifetime:** 30 years

- **Offshore wind**
  - **Capacity factor:** 49%
  - **Weighted average cost of capital:** 5.9%
  - **Lifetime:** 30 years

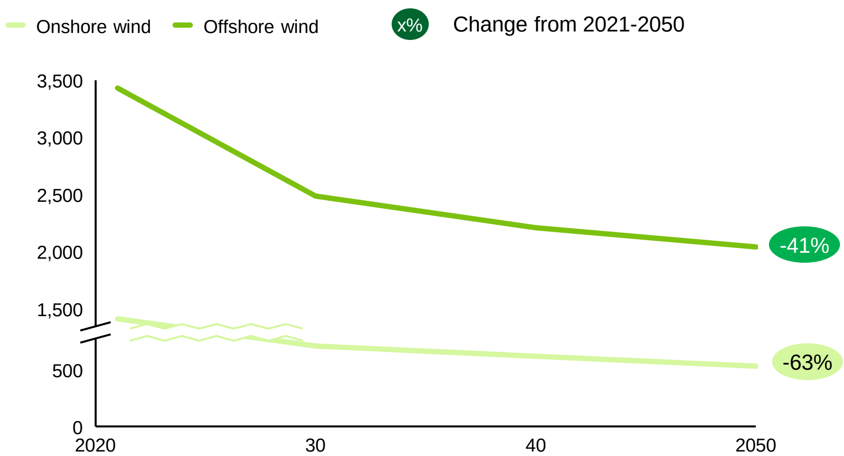
- **Inter-day LDES**
  - **RTE:** 79%
  - **Weighted average cost of capital:** 6%
  - **Lifetime:** 27 years
  - **Fixed opex (% of capex)**: 2.5%

- **Multi-day LDES**
  - **RTE:** 58%
  - **Weighted average cost of capital:** 6%
  - **Lifetime:** 29 years
  - **Fixed opex (% of capex)**: 0.2%

- **Lithium Ion**
  - **RTE:** 85%
  - **Weighted average cost of capital:** 4.3%
  - **Lifetime:** 15 years
  - **Fixed opex (% of capex)**: 5.7%

- **Wind cost decline assumptions:**

GSD, $/kW



	Solar PV	Onshore wind	Offshore wind[2]
CF	28%	42%	49%
WACC	4.3%	5.0%	5.9%
Lifetime	30	30	30

Source: NREL ATB 2022

Figure 29: Onshore and offshore wind costs decline 40–60% by 2050.

Example project 6 — Energy market participation

Representative stakeholder

- A developer or independent power producer that is looking to understand the economics and use cases for LDES in a deregulated market

LDES use case

- To capture value from multiple revenue streams (e.g., energy arbitrage, capacity markets, ancillary services)

Objective of analysis

- To demonstrate how LDES technologies' economics may compare against Li-ion under CAISO market design and to paint a picture of "what you would need to believe" for LDES to be attractive to developers / IPPs

Expected output

- An illustration of LDES vs. Li-ion returns and sensitivities to key parameters (e.g., capacity prices, arbitrage potential, capital costs)

Methodology

- Deployed a capacity expansion model to project the required buildout of energy resources to achieve net-zero by 2050
  - The capacity expansion model incorporated incentives from the Inflation Reduction Act and co-optimized deployment across the four technologies to reach net-zero at the lowest cost
- Calculated hourly power prices based on the energy-resource deployment from the capacity-expansion model
- Entered these hourly prices into a battery-dispatch model to determine potential income from charging the battery during hours with low prices and discharging the battery during hours with high prices (i.e., energy arbitrage)
- Constructed a financial model to assess project-level economics based on the energy-arbitrage values and capacity prices
- Conducted a sensitivity analysis with the financial model to assess project performance under multiple scenarios (e.g., increased price volatility, faster / slower cost declines, different debt or equity structures)

Key inputs

- Project location
- Characteristics of the LDES and Li-ion batteries (e.g., cost, duration, battery life)
- Capacity expansion model to forecast power prices at the hourly level
- Battery dispatch model to determine when the battery charged / discharged to maximize energy-arbitrage revenue based on the forecasted power prices
- Capacity prices, if applicable
- Financial model to determine project economics, along with indicative capital contributions from different investors (e.g., debt, tax equity)

Specific assumptions and outputs

- **Asset characteristics**
  - **Capacity:** 100 MW
  - **Duration:** 12 hours (LDES); 4 hours (Li-ion)
  - **Operating life:** 27 years (LDES); 15 years (Li-ion)
  - **Round trip efficiency (RTE):** 74% (LDES); 85% (Li-ion)
  - **Capital cost:**
    - **LDES:** $182M (energy capital cost: $23 / kWh; power and balance of system cost: $1,075 / kW)
    - **Li-ion:** $105M (energy capital cost: $157 / kWh; power and balance of system cost: $264 / kW)

- **ITC, depreciation, and tax rate**
  - **ITC:** 30%; assumed that 100% of capex is eligible
  - **Depreciation schedule:** 5-year MACRS
  - **Depreciable basis reduction:** 50% of the ITC amount
  - **Tax rate:** 21%

- **Revenue**
  - **Energy shifting / arbitrage:**
    - **LDES:** $6,242 / MW in 2030 and increasing to $58,664 / MW by 2050
    - **Li-ion:** $6,336 / MW in 2030 and increasing to $18,623 / MW by 2050
  - **Capacity payment:** $75 / kW per year

- **Operating expenditures:**
  - **Operations and maintenance:** $11 / kW per year (LDES) and $7 / kW per year, escalating at 2% p.a.

- **Financing**
  - **Investors:** Tax equity, debt (e.g., back-leveraged loan), project owner
  - **Structure:** With the passage of IRA, assumed to follow the same structure of solar ITC transaction
  - **Tax equity:** Targets an 8.5% yield by year 6 with a yield flip structure (allocated 99% of tax benefits / liabilities and 15% of the project cash pre-flip before dropping to 5% across tax benefits / liabilities and cash post-flip)
  - **Debt:** Sizes contribution based on a debt-service coverage ratio of 1.7x with an interest rate of 3% for 15 years for LDES and 7 years for Li-ion
  - **Project owner:** Contributes remaining capital and retains ownership throughout the life of the asset

- **Illustrative LDES model outputs**
  - **Revenue, operating expenditures, and depreciation:**

Operating Period	0	1	2	3	4	5	6	7	8	9	10
Revenue											
Energy arbitrage	-	0.6	0.8	0.9	1.1	1.4	1.7	2.1	2.6	3.1	3.8
Capacity payment	-	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
DOE revenue mechanism support	-	-	-	-	-	-	-	-	-	-	-
Total revenue	-	**8.12**	**8.26**	**8.44**	**8.64**	**8.90**	**9.21**	**9.60**	**10.07**	**10.64**	**11.35**
Operating Expenditures											
O&M	-	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.3	1.3	1.3
Lease Expense	-	-	-	-	-	-	-	-	-	-	-
Property Taxes	-	-	-	-	-	-	-	-	-	-	-
Total Operating Expenditures	-	**1.1**	**1.1**	**1.1**	**1.2**	**1.2**	**1.2**	**1.2**	**1.3**	**1.3**	**1.3**
EBITDA		7.02	7.14	7.29	7.48	7.71	8.00	8.36	8.81	9.36	10.03
Less: MACRS Depreciation		(31.01)	(49.61)	(29.77)	(17.86)	(17.86)	(8.93)	-	-	-	-
EBIT		(23.98)	(42.47)	(22.48)	(10.38)	(10.15)	(0.93)	8.36	8.81	9.36	10.03
Plus: Depreciation		31.01	49.61	29.77	17.86	17.86	8.93	-	-	-	-
Asset Cash Flow		**7.02**	**7.14**	**7.29**	**7.48**	**7.71**	**8.00**	**8.36**	**8.81**	**9.36**	**10.03**
Project tax benefits / (liabilities)											
Tax Credit	-	54.72	-	-	-	-	-	-	-	-	-
Tax Benefit / Liabilities	-	5.04	8.92	4.72	2.18	2.13	0.20	(1.76)	(1.85)	(1.96)	(2.11)
Total Benefit / (Liability)	-	**59.76**	**8.92**	**4.72**	**2.18**	**2.13**	**0.20**	**(1.76)**	**(1.85)**	**(1.96)**	**(2.11)**

Figure 30: LDES revenue in this use case is dependent on energy arbitrage and capacity payments.

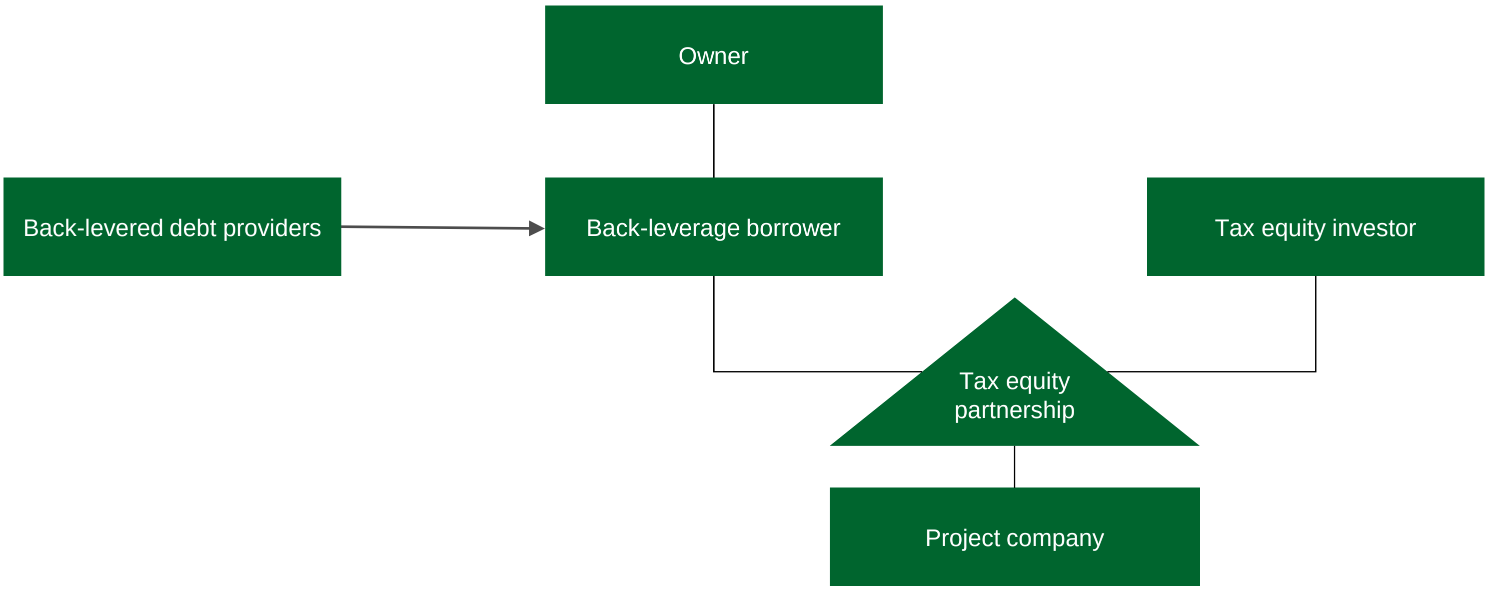
– **Investor contributions and allocations:**

Operating Period	0	1	2	3	4	5	6	7	8	9	10
Tax Equity capital contribution	**80.09**						**Flip Year**				
Capital Contribution		($80.09)									
Tax Benefits / (Liabilities)											
ITC	-	54.17	-	-	-	-	-	-	-	-	-
Operating tax benefit / (liability)	-	4.99	8.83	4.67	2.16	2.11	0.19	(0.09)	(0.09)	(0.10)	(0.11)
Cash Allocation	-	1.05	1.07	1.09	1.12	1.16	1.20	0.42	0.44	0.47	0.50
Total Inflow / (Outflow)	$0.00	($19.88)	$9.90	$5.77	$3.28	$3.27	$1.39	$0.33	$0.35	$0.37	$0.40
Running Tax Equity XIRR			*-50%*	*-16%*	*-3%*	*6%*	*8%*	*9%*	*10%*	*10%*	*10%*
Debt capital contribution	**53.59**										
Cash Flow Available for Debt Sizing											
Remaining Cash Flow after TE		5.97	6.07	6.20	6.36	6.55	6.80	7.94	8.36	8.89	9.53
Net cash flow available for debt service		3.51	3.57	3.65	3.74	3.86	4.00	4.67	4.92	5.23	5.61
Debt Sculpting											
Beginning Balance		53.59	51.66	49.61	47.42	45.07	42.53	39.76	36.23	32.34	28.02
Interest		1.58	1.52	1.46	1.39	1.31	1.23	1.14	1.03	0.91	0.77
Amortization		1.93	2.05	2.19	2.35	2.54	2.77	3.53	3.89	4.32	4.84
Ending Balance		51.66	49.61	47.42	45.07	42.53	39.76	36.23	32.34	28.02	23.18
Owner capital contribution	**$48.72**										
Owner returns											
Upfront Capital Contribution	($48.72)										
Cash	-	7.02	7.14	7.29	7.48	7.71	8.00	8.36	8.81	9.36	10.03
Less: Tax Equity Cash Allocation	-	(1.05)	(1.07)	(1.09)	(1.12)	(1.16)	(1.20)	(0.42)	(0.44)	(0.47)	(0.50)
Less: Debt Service	-	(3.51)	(3.57)	(3.65)	(3.74)	(3.86)	(4.00)	(4.67)	(4.92)	(5.23)	(5.61)
Tax Benefits / (Liabilities)	-	-	-	-	-	-	-	-	(0.41)	(1.68)	(1.84)
Total Inflow / (Outflow)	**($48.72)**	**$2.46**	**$2.50**	**$2.55**	**$2.62**	**$2.70**	**$2.80**	**$3.27**	**$3.04**	**$1.98**	**$2.08**
Project IRR	**7.3%**										

Figure 31: Multiple investors can monetize LDES technologies.

– **Assumed financing structure:**

Assumed financing structure commonly seen in other renewable energy transactions



Source: Latham & Watkins LLP

Figure 32: Standalone storage ITC may allow projects to use the same funding structure as other variable renewables technologies.

Appendix 3 – External Sources of Insight

Overall framing (Used in all chapters)

- LDES Council Flagship and Net-zero Power Report — Explanation of technology types and high-level opportunity assessment
- Why Long Duration Storage Matters — Explanation of LDES use cases
- Storage Futures Study — Series of seven reports scanning storage deployment and opportunities

Modeling assumptions and methodology (Chapters 3 and 4)

- DOE Energy Storage Valuation — Valuation modeling methodology and value streams
- 2020 Grid Energy Storage Technology Cost and Performance Assessment — Cost and performance benchmarking for some LDES technologies
- Pumped Storage Hydropower Valuation Guidebook — Inputs for valuation methodologies for LDES technologies
- Cost Projections for Utility-Scale Battery Storage — Primary resource for Li-ion prices
- Energy Storage Financing: Project and Portfolio Valuation — Overview of storage valuation and revenue streams
- IRENA Energy Storage Valuation Framework — Additional input on storage valuation (Li-ion focused)

Challenges and opportunities (Chapter 4)

- The Journey to Net-Zero: An Action Plan to Unlock a Net-Zero Power System — High-level view of challenges and interventions
- A Path Towards Full Grid Decarbonization with 24/7 Clean Power Purchase Agreements — Information for 24/7 PPA opportunity use case
- Energy Storage as an Equity Asset — Discussion of qualitative challenges to storage deployment and potential positive environmental / socioeconomic impacts of storage
- Decarbonizing Virginia's Economy: Pathways to 2050 — Example of a state-level decarbonization pathway that mentions LDES but requires additional input for action
- Heavy-Duty Truck Electrification and the Impacts of Depot Charging on Electricity Distribution Systems — Information on load-shape implications for Load Management Services use case

Appendix 4 – Power Modeling Assumptions

To determine the likely future role of LDES in the power sector, we ran a range of integrated scenarios through a capacity-expansion model for the entire U.S. power grid. This model used differing system parameters and input assumptions to forecast the expansion of each technology in the system, based on least-cost optimization to meet system demand. We also consulted a range of existing cross-technology reports: the White House Pathways to Net Zero Greenhouse Gas Emission by 2050, Princeton Net Zero America, NREL Clean Electricity, and the Long Duration Energy Storage (LDES) Council. Only the latter model included future projections for novel LDES technologies. In comparison to the LDES Council modeling output, this report's scenario modeling allowed for net-zero emissions, which allows natural gas generation that is offset by carbon capture or removal to remain on the system in a decarbonized pathway. As a result, the upper range of the LDES Council report (600 GW of LDES in the U.S. by 2050) is slightly higher that what is captured in this report.

The integrated modeling scenarios ran in this report serve three purposes:

1. **Estimating business-as-usual trajectory:** The business as usual (BAU) scenario represents the current trajectory, including the impacts of the 2022 Inflation Reduction Act (IRA) but without additional commercialization interventions.

2. **Forecasting least-cost pathways to meet decarbonization goals:** Net-zero decarbonization scenarios forecast what it would take to reach net-zero by 2050 under different constraints on variable renewables and on transmission capacity. We forecast scenarios both with and without achieving interim clean power by 2035.

3. **Exploring technology potential:** Technology-specific sensitivities represent conditions for the uptake of different types of LDES given different operating parameters and competing technology conditions.

   Determining the role that LDES can play in the U.S. power grid depends on emissions trajectory (e.g., net-zero economy-wide emissions by 2050, a net-zero power grid by 2035 per policy targets), the constraints (e.g., it is only possible to build a certain amount of new infrastructure per year), and the tradeoffs (e.g., hydrogen or carbon capture, utilization, and storage instead of LDES). The role of LDES through 2050 was modeled in five over-arching scenarios:

4. **Business-as-usual (BAU) (i.e., current policy)**

   Description: This scenario includes the 2022 Inflation Reduction Act (IRA) and incorporates its many impactful provisions (e.g., the standalone storage investment tax credit [ITC]). This scenario also assumes that technology performance and cost curve improvements are hindered by current market challenges (e.g., limited compensation, technology uncertainty).

   Hypothesis tested: This scenario deepens an understanding of current-state trajectories for LDES with moderate cost improvement to 2050.

5. Net-zero 2050 with constrained renewable energy

Description: This scenario includes the 2022 IRA and assumes the LDES industry successfully scales along strong learning curves—in line with a net-zero-by-2050 economy. This scenario also includes a 1.1 TW variable-renewables cap comparable to what has been applied in other scenario models (e.g., Princeton, NREL).

Hypothesis tested: This scenario highlights an optimal decarbonization pathway under realistic assumptions and deepens understanding of the required build-out for LDES under an optimal decarbonization pathway.

To model each of the five scenarios, we used an energy-infrastructure capacity-expansion model that covers both fuel and electricity demand and the interaction between them. This model minimizes cost, subject to the constraints of each scenario. Planning margin is modeled on an hourly basis, comprised of: the derating for output (thermal plant outages, actual RES production, storage/hydro/transmission performance) and buffer for load (weather, mis-forecasting of load). As a result, reserve margin of 10%+ (across regions) is maintained across the entire year.

As inputs, the models use six types of parameters: level of electrification; CO2 and renewable portfolio standard (RPS) constraints; state and local policy requirements; technology performance; exogeneous fuel demand; and cost trajectories. Based on these inputs, the model provides a "least-cost system decarbonization," including capacity and generation mix, sources of flexibility, and initial cost (i.e., investment required).

For LDES, the model calculates the capacity and optimal duration within time series for 2025, 2030, 2040, and 2050 for two groupings of technologies used in the power grid: inter-day LDES (i.e., 10-36 hour duration) and multi-day / week LDES (i.e., 36-160 hour duration).

Appendix 5 – Long-list of Market Mechanisms

Long-term market signals to address stakeholder uncertainty; these signals are particularly valuable for investors.

1. Carbon pricing
2. Greenhouse gas (GHG) reduction targets
3. Transmission expansion to support variable renewables or address bottlenecks in densely populated areas
4. Increased use of low-carbon fuels
5. Aspirational targets for installed storage capacity
6. Aspirational targets for LDES
7. Variable renewables procurement targets or subsidies
8. EV subsidies
9. Other demand-side subsidies

Revenue mechanisms to improve investors' risk-adjusted return on LDES.

10. Introduction of capacity markets
11. Market products that support longer duration firm dispatchable power
12. Long-term bilateral contracts
13. 24/7 virtual PPAs for corporate ESG commitments
14. Regulated asset-base approvals for system or transmission deferrals
15. Hourly energy attribute certificates
16. Nodal and locational pricing
17. Cap and floor mechanisms

Analytics to increase transparency and reduce uncertainty among stakeholders to enable long-term planning.

18. Modeling tools and parameters to analyze LDES alongside other decarbonization technologies
19. Transparent, integrative modeling capabilities that look out beyond a traditional integrated resource planning period (15 years is typical, but a 20-30 year view may allow stakeholders to value LDES more adequately)
20. Standardized modeling and analytics, (e.g., using the same base model) could allow users to understand relative benefits to each geography

Direct technology support and enabling measures to boost the market for LDES.

21. Direct grants and incentives (e.g., PTCs, storage ITCs)
22. Loan guarantees
23. Targeted tenders
24. Loan-loss reserves
25. Inflation protection
26. Yet-to-deploy financial support mechanisms (e.g., insurance, return guarantees, securitization, and enhanced support for permitting and siting)

27. Creation of storage-specific market rules
28. Building capacity for regulatory agencies to readily understand and evaluate LDES
29. Development of an ecosystem with government, investors, technology developers, customers, and other intermediaries to aid with business model and partnership formation

Stakeholder support to ensures the long-term viability of LDES; stakeholder support is boosted by increasing the number of people and the amount of capital devoted to variable renewables or storage in a given state. Examples include:

30. Jobs related to variable renewables or energy storage
31. Workers in fossil fuels or related industries who could be retrained to work on energy storage
32. Invested capital in variable renewables or energy storage
33. A local company headquarters for an organization that operates in variable renewables or the energy storage industry

Appendix 6 – LDES Technology Types

While there is also significant ongoing development for all LDES technologies, the current landscape shows the 11 novel LDES technology types have different strengths.[vii,xxxviii]

Mechanical storage

Mechanical forms of storage are relatively mature, but performance still varies.

- **Novel pumped storage hydropower**—A form of storage that expands on traditional pumped-hydro storage to provide more modular applications. It has a low range of LCOS and a smaller footprint than its traditional counterpart, while maintaining a fast response time and ramp rate. It will mostly be used for inter-day LDES applications.

- **Gravity-based**—Storage within the potential energy of large masses, it has a response time that is almost competitive with batteries, an extremely high RTE, and a low range of LCOS. It is highly modular and will mostly be used for inter-day LDES applications.

- **Compressed air (CAES)**—Storage that utilizes energy derived from the pressure of compressed air; the technology has a low range of LCOS and is extremely modular. It has a footprint that is significantly smaller than other mechanical forms of energy storage, and its duration approaches the multi-day / week threshold. CAES systems use underground geological storage systems, so they can be very cheap to deploy, but require the right geological formations.

- **Liquid air (LAES)**—Similar to CAES technologies, LAES derives energy from compressed air, but compresses it further—to the point of liquid. LAES technologies maintain a low range of LCOS, are even more modular than CAES, and can have an even smaller footprint. LAES systems rely on above-ground storage systems, so upfront CAPEX tends to be more expensive than CAES. Its duration is mostly inter-day but approaches the multi-day / week threshold.

- **Liquid CO2**—The most nascent of the mechanical storage technologies, liquid CO2 systems are similar to LAES technologies, but they use pure streams of liquid CO2. Liquid CO2 systems are expected to have competitive LCOS ranges and response times. In addition, liquid CO2 systems are expected to be modular and capable of providing multi-day / week duration.

Thermal storage

Thermal storage technologies are more nascent than other types but are highly scalable and attractive for multi-day / week LDES uses. Thermal-storage technologies may also be able to provide significant co-benefits if waste heat can be leveraged for applications beyond electricity dispatch.

- **Sensible heat**—Sensible-heat technologies are the most developed of the thermal LDES systems and should be able to be deployed with a very small footprint relative to mechanical technologies. Sensible heat systems are also expected to provide very long nominal durations. For example, Molten Salt Thermal Energy Storage has predominantly been deployed coupled to concentrating solar power plants. Current power plants hold between 6 and 17 hours of dispatchable energy at scales beyond 1 GWh. Multiple systems could be placed in parallel to expand to multi-day storage.

- **Latent heat**—Latent-heat technology stores energy within aluminum alloys. This type of system is more modular than other thermal technologies but requires a slightly larger footprint.

- **Thermochemical heat**—The most nascent of all LDES technologies, there are several different approaches including both chemical reactions and sorption processes being researched with a wide range of potential performance characteristics.

Electrochemical storage

Electrochemical-storage technologies for LDES are in early-stages of development, but expect to provide significant benefits for both inter-day LDES and multi-day / week LDES use cases.

- **Aqueous-electrolyte flow batteries**—Flow batteries that use chemical cathodes and anodes separated by electrolytes to store energy. They are expected to have near-instantaneous response times. Flow batteries have very modular designs that can be deployed with a small footprint. Flow batteries are expected to have a wide range of durations, spanning across both inter-day and multi-day / week use cases.

- **Metal-anode batteries**—Metal anode batteries are very similar to Li-ion batteries. They also have highly modular designs and near-instantaneous response times. They can be deployed within a small footprint for both inter-day and multi-day / week use cases.

- **Hybrid flow batteries**—These batteries have metal anodes and liquid electrolytes. Like other electrochemical technologies, they can be deployed with a small footprint and have a near-instantaneous response time. Their expected duration spans across inter-day and multi-day / week use cases.

Appendix 7 – Long-list of KPIs

Leading Indicators	Lagging Indicators	Outcomes
For each demonstration technology: • Capex ($/kW, $ / kWh • Roundtrip efficiency • Ramp time • Operational costs	Total deployed LDES capacity (GW)	CO2e reduction from LDES deployment
Number of players claiming these technology characteristics	Private capital mobilized across the value chain ($B, by source)	GDP impact from LDES (annual $M)
Capacity or similar payments (e.g., tracking value of payments; rule adjustments that value clean, firm capacity or longer durations)	Domestic Manufacturing and deployment capacity (GW)	Jobs impact from LDES (direct, indirect)
Number of states with storage carveouts or mandates (within RPS or PUC procurement)	Supply chain vulnerabilities (periodic assessment)	
Total capacity of storage carveouts or mandates (GW)	Number of LDES projects and total capacity in the pipeline for beyond 2030	
Number of utilities including LDES in their integrated Resource Plans (RP's)	Achieved lifetime/cycle life of demonstration projects	
Number of states mandating LDES procurement	Achieved operational costs of demonstration projects	

Appendix 8 – Energy and Environmental Justice Concerns by LDES Technology

LDES Technology	Potential Benefits	Potential Negative Impacts
Cross-cutting	• Energy resiliency • Energy reliability • Fossil energy replacement/reduction • Pollution reduction • Energy cost reduction, increased renewable energy mix due to reduction of curtailments in times of excess generation	• Widening energy resiliency, reliability, cost gap • Air, water, and soil pollution from mining • Health impacts from pollution • Safety impacts from infrastructure failure
Mechanical (e.g., PHS, CAES, LAES, flywheels)	• Existing infrastructure repurposing (e.g.,mine shafts)	• Land use change, loss of (access to) culturally significant sites • Noise pollution • Air, water, and soil pollution from operation • Safety impacts from cavity failure
Thermal (e.g., high-temp sensible heat, phase change, thermo-photovoltaic)	• Decarbonizing heat for industrial and other applications • Existing infrastructure repurposing	• Land use change, loss of (access to) culturally significant sites • Air, water, and soil pollution from disposal/decommission • Heat pollution from operation
Electrochemical (e.g., NA-ion, lead acid, redox flow, reversible fuel cells)		• Air, water, and soil pollution from disposal/decommissioning
Lithium-based* (e.g., lithium-ion batteries, BESS) *included for comparison	• Number of LDES projects and total capacity in the pipeline for beyond 2030	• Significant air,water,and soil pollution from mining battery materials • Air, water, and soil pollution from disposal/ decommissioning • Increased fire risk, especially in remote areas

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