TECHNOLOGY WORKING GROUP

POLICY RECOMMENDATIONS TO UNLOCK THE VALUE OF LONG-DURATION ENERGY STORAGE

C2ES CENTER FOR CLIMATE AND ENERGY SOLUTIONS

Center for Climate and Energy Solutions
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Meeting our long-term climate goals will require the large-scale deployment of a multitude of new, innovative technologies and low- and zero-carbon fuels across every sector of the economy. First-of-a-kind technologies will need to rapidly reach commercial scale without sacrificing safety, social equity, or sustainability. This can only be achieved through systemwide collaboration between corporate incumbents, financiers, innovators, communities, and policymakers. To help meet this challenge, C2ES has created four distinct technology working groups focused on the technologies of long duration energy storage, engineered carbon removal, sustainable aviation fuel, and clean hydrogen. This brief presents findings and recommendations from the long-duration energy storage working group.

OVERVIEW

Long-duration energy storage (LDES) will play an increasingly important role in decarbonizing the power sector as more variable renewable energy is added to the electric power grid. LDES is defined by the U.S. Department of Energy (DOE) as any system that can store energy for 10 or more hours. It is a diverse technology class with a range of potential system forms, including electrochemical, mechanical, chemical, and thermal energy storage. While shorter-duration lithium-ion batteries (typically 0 to 4 hours) will continue to address storage needs in the near-term, LDES will be essential to enabling the long-term decarbonization of the power system. The DOE estimates that the U.S. grid may need 225 to 460 gigawatts of LDES capacity for a net-zero economy by 2050.[1] This estimate assumes total deployment of 4 to 13 gigawatts of LDES by 2035.[2] Reaching this near-term milestone necessitates federal- and state-level policy support of LDES deployment and integration. While some progress has been made, more work is needed to fully unlock the value of LDES. To meet this challenge, the Center for Climate and Energy Solutions (C2ES) has established a technology working group that convenes power sector stakeholders to discuss and identify policy solutions that can help address the current barriers to LDES deployment while simultaneously unlocking its key value drivers. This brief offers five policy recommendations following the working group's inaugural year.

INTRODUCTION

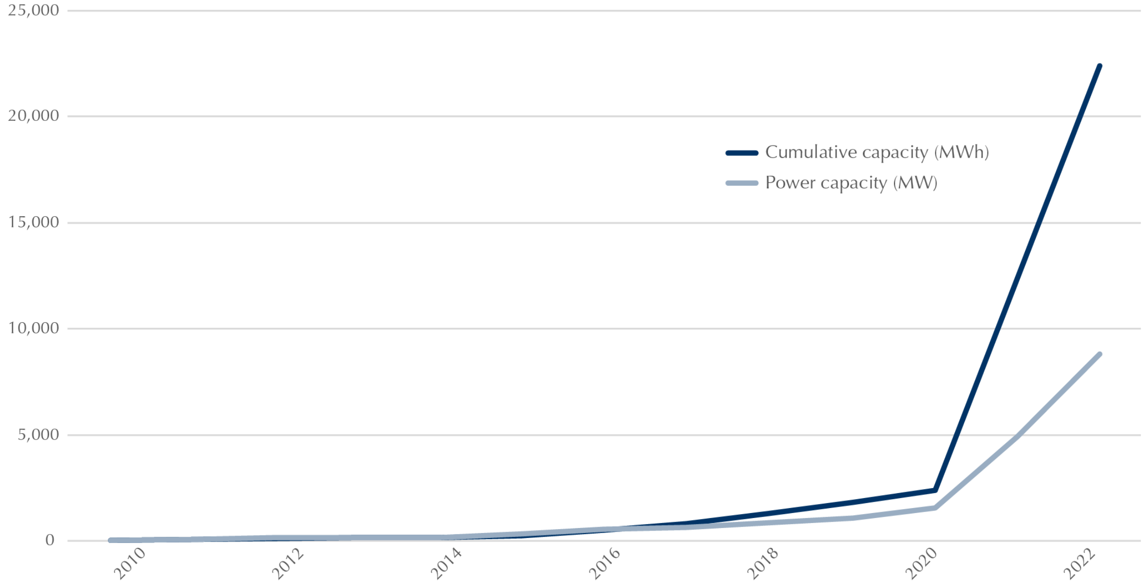
The United States has reached a critical tipping point: renewable energy sources are cost-competitive with fossil fuels. Utility-scale variable renewable energy generated over 14 percent of all U.S. electricity in 2023, and in certain states this was significantly higher.[3] For example, in May 2023, California derived nearly 49 percent of its electricity from non-hydroelectric renewables.[4] Nearly one terawatt of new solar and wind capacity is expected to be added to the U.S. power grid between 2024 and 2035, spurring demand for storage solutions that can help enable widespread deployment and grid integration of these renewables.[5] At the same time, the United States is entering a period of growing electricity demand, with current estimates projecting 15 to 20 percent growth in the next decade. This growth is due to a combination of a surge in electricity demand from new data centers and reshoring of manufacturing, as well as increasing electrification of the transportation, building, and industrial sectors—a result of economywide decarbonization.[6] This growing electricity demand has led to a renewed focus on the need to immediately invest in clean bulk power generation and storage.

THE GROWING IMPORTANCE OF ENERGY STORAGE

Variable renewables, evolving demand patterns, and the impacts of a changing climate on grid resiliency and reliability are helping to catalyze the energy storage market. U.S. battery storage capacity has grown exponentially year-over-year since 2020 (see Figure 1). Between 2020 and 2021, cumulative storage capacity grew by over 10,000 megawatt-hours (MWh), representing a 422 percent growth from the prior year. This translated to an addition of over 3,300 MW in power capacity to the U.S. power system, a 216 percent increase from 2020. This aggressive growth continued into 2022, with cumulative capacity growing another 80 percent and power capacity growing by 79 percent from the prior year.[7] By the end of 2023, there were 16 gigawatts (GW) of planned and currently operational utility-scale battery capacity in the United States, with the U.S. Energy Information Administration (EIA) projecting that total battery capacity could reach 30 GW by the end of 2024.[8]

However, the batteries added to the grid between 2020 and 2022 are predominantly short-duration in nature,

FIGURE 1: Large-scale battery storage net cumulative capacity (2010–22)



Battery storage grew exponentially starting in 2020. Much of this recent increase was due to the co-location or connection of battery energy systems to solar projects. A subset of states are driving this demand, most notably California and Texas, which are looking to shore up their rapidly expanding solar and wind capacity.

Source: U.S. Energy Information Administration, U.S. Energy Information Administration, "2023 Early Release Battery Storage Figures", July 2023, https://www.eia.gov/analysis/studies/electricity/batterystorage. See also U.S. Energy Information Administration, "U.S, battery capacity expected to nearly double in 2024", January 9, 2024, https://www.eia.gov/todayinenergy/detail.php?id=61202.

and will likely be insufficient to address extended periods of grid stress. In 2020, the average battery added had an approximate duration of 1.2 hours. In 2021, the duration was 3 hours, and in 2022 it was 2.5 hours.[9] While these short-duration additions will generate value via short-term ancillary services and energy arbitrage (i.e., charging up the storage system during periods of high renewable output and discharging power when renewable output is low and prices are comparably higher), a major gap for longer-duration storage remains.[10]

As of 2024, lithium-ion batteries—which usually have between zero and four hours of duration—account for over 90 percent of global installed energy storage capacity.[11] These batteries will continue to play an essential role in decarbonization efforts (specifically through electric vehicles), but they are unlikely to become economic in the power sector at longer durations.[12] Lithium-ion batteries are also highly dependent on international supply chains, with China leading the manufacturing of lithium-ion batteries, including the processing of raw materials.[13] Alternatives to lithium-ion batteries, such as LDES technologies, can increase storage duration at marginal costs and rely less on critical minerals and international supply chains.[14]

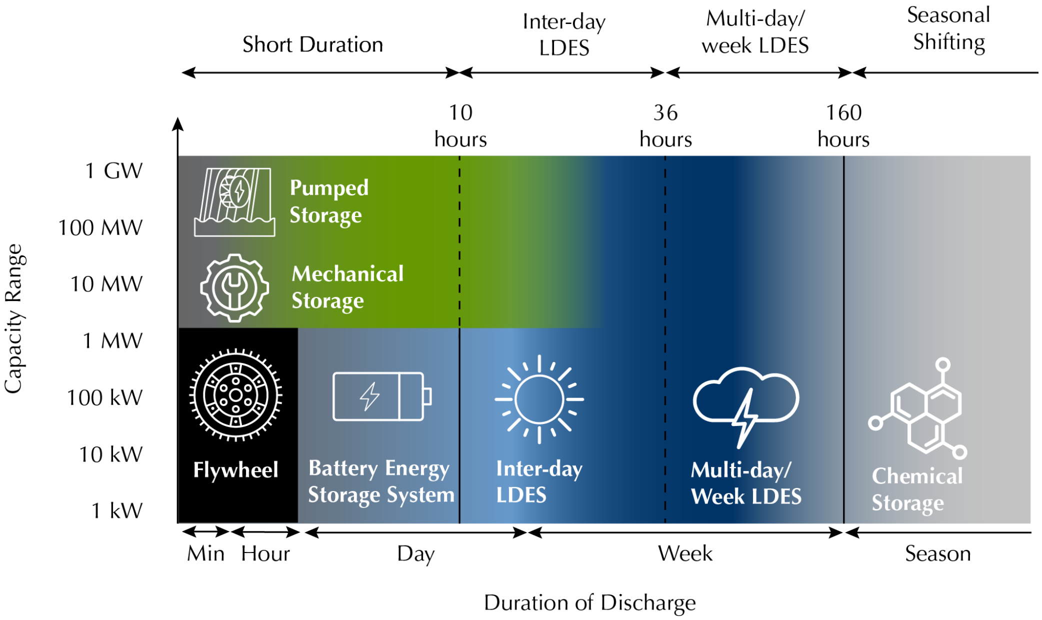
LONG DURATION ENERGY STORAGE OVERVIEW

LDES solutions are varied. The U.S. Department of Energy considers any energy stored for 10 hours or greater to be "long duration."[15] Within the categorization of long-duration storage, there are two main categories of storage durations:

- **"Inter-day"** storage provides 10 to 36 hours of energy, which can shift excess power produced at one point in the day to another point in the same day or the next day. For example, excess solar generated during the day can be stored to provide power at night.
- **"Multi-day"** storage provides 36 to 160 hours of energy, which can both shift energy produced at one point in the day to later in the week and serve as backup power in the event of an extended outage. For example, power generated during good weather can be stored to provide power through a winter storm, when solar or gas generation may be down for multiple days.[16]

LDES is a diverse technology class with a range of potential system forms, including mechanical, electrochemical, thermal, and chemical energy storage (see Figure 2). Some examples of these system forms are provided below; however, this list is non-exhaustive since

FIGURE 2: Scalability of use cases of a variety of LDES technologies



Source: U.S. Department of Energy, "The pathway to: Long Duration Energy Storage Commercial Liftoff," March 2023, https://liftoff.energy.gov/long-duration-energy-storage.

new technologies continue to be developed. Please note that other frameworks or stakeholders may categorize durations differently, but the ranges below provide a starting reference point.

- **Mechanical storage** technologies use kinetic or gravitational forces to store and discharge energy. Examples of mechanical storage technologies include pumped hydroelectric power, compressed air, gravity-based storage, liquid air, and liquid carbon dioxide. Mechanical storage typically provides **inter-day** storage and can discharge up to 15 to 25 hours. Many of these technologies can also be used for short-duration storage (less than 10 hours).
- **Electrochemical storage** technologies use chemical processes to store and discharge energy. Examples of electrochemical storage technologies include aqueous electrolyte flow and metal anode flow batteries. Electrochemical storage is classified as **inter-day or multi-day** and can discharge anywhere from 8 to 200 hours.
- **Thermal storage** technologies use high heat to store energy that can later be used either as heat or to generate electricity. Examples of thermal storage include "sensible heat" like molten salt, rock material, and concrete; "latent heat" like aluminum alloy; and "thermochemical heat" like silica gel. Thermal storage can be used for **inter-day or multi-day** storage and can discharge 10 to 200 hours.[17]
- **Chemical storage** technologies convert electricity into energy-carrying chemicals such as hydrogen, which can be stored and/or transported as fuel and used to produce electricity at a later time or in a different location. Chemical storage is sometimes considered "**seasonal storage**" as it can shift energy produced in one season to use in another.

These LDES technologies are at varying technology readiness levels with a range of potential cost reductions and deployment timelines. However, in order to achieve a net-zero economy by 2050, the DOE estimates that the U.S. grid may need 225 to 460 gigawatts of LDES capacity.[18] This assumes total deployment of 4 to 13 gigawatts of LDES by 2035.[19] At the same time, the current scale of commercial LDES projects remains small, typically in the tens of megawatts.[20]

The nascent nature of many LDES technologies emphasizes the need to support a portfolio of potential and diverse LDES technologies in the near term. Indeed, an August 2024 report from the DOE found that no clear technology winners emerge when comparing tradeoffs between the cost, duration, and impact of various LDES innovations.[21] Further emphasizing the need to support a broad portfolio of LDES technologies, they will play a critical role in helping enable widespread deployment of renewables, enhancing grid resilience, reducing use of natural gas peaker plants, and diversifying the domestic energy storage supply chain.

While policies that support LDES deployment have been put in place at the federal level and in a handful of states, they are not sufficient to drive LDES deployment at the speed and scale necessary to reach our decarbonization goals. The Infrastructure Investment and Jobs Act (IIJA) has provided the DOE's Office of Clean Energy Demonstrations (OCED) up to $505 million for an "LDES Portfolio" to help advance LDES systems toward widespread commercial deployment. The portfolio includes the LDES Pilot Program, the LDES Demonstrations Program, and a joint program between OCED and the U.S. Department of Defense to demonstrate LDES technologies on government facilities.[22] Other federal offices engaged in LDES include the DOE's Grid Deployment Office as well as the DOE's Loan Programs Office (LPO), which in August 2024 announced a conditional commitment for up to $72.8 million in partial loan guarantees to finance the development of a solar-plus LDES microgrid on Tribal lands.[23]

In addition to federal funding and policies, states and the private sector are seriously considering LDES as a climate solution. Sub-nationally, a small subset of states— including but not limited to California, New York, and Massachusetts—have begun to explore LDES technologies through both pilot and demonstration projects, as well as through research studies.[24] Some industry actors are also beginning to consider how clean transition tariffs (CTTs) and accelerating clean energy (ACE) tariffs—mechanisms that allow large companies seeking 24/7 clean energy to pay a higher rate to utilities to help finance the costs of developing and procuring clean, firm energy technologies—can help spur private sector investment in LDES and other clean energy resources.[25] While federal policies and several recent state-level procurement announcements include support for LDES, more actions will be needed to accelerate the widespread and coordinated deployment and commercialization of LDES technologies.

Currently, the full economic and environmental benefits of LDES are still not captured in most grid planning activities. Most integrated resource plan modeling does not fully capture the value and need for LDES. There are few, if any, LDES carveouts or policies in electricity portfolio standards or state climate action plans, nor are there requirements to consider LDES in most utility integrated resource plans (IRPs). Additionally, because LDES represents a set of comparably new emerging technologies, many decision-makers remain unfamiliar with how to deploy it. These gaps, combined with first-of-a-kind (FOAK) upfront costs, make it difficult for utilities and public utility commissions (PUCs) to make an economic case for LDES.

These challenges are further exacerbated by the fact that power markets and balancing authorities have not identified and established ways to compensate LDES resources for the distinct benefits that they provide, preventing utilities from fully monetizing their LDES deployments. A joint report from the LDES Council and McKinsey & Company identified three key market failures which are hindering the deployment of LDES:

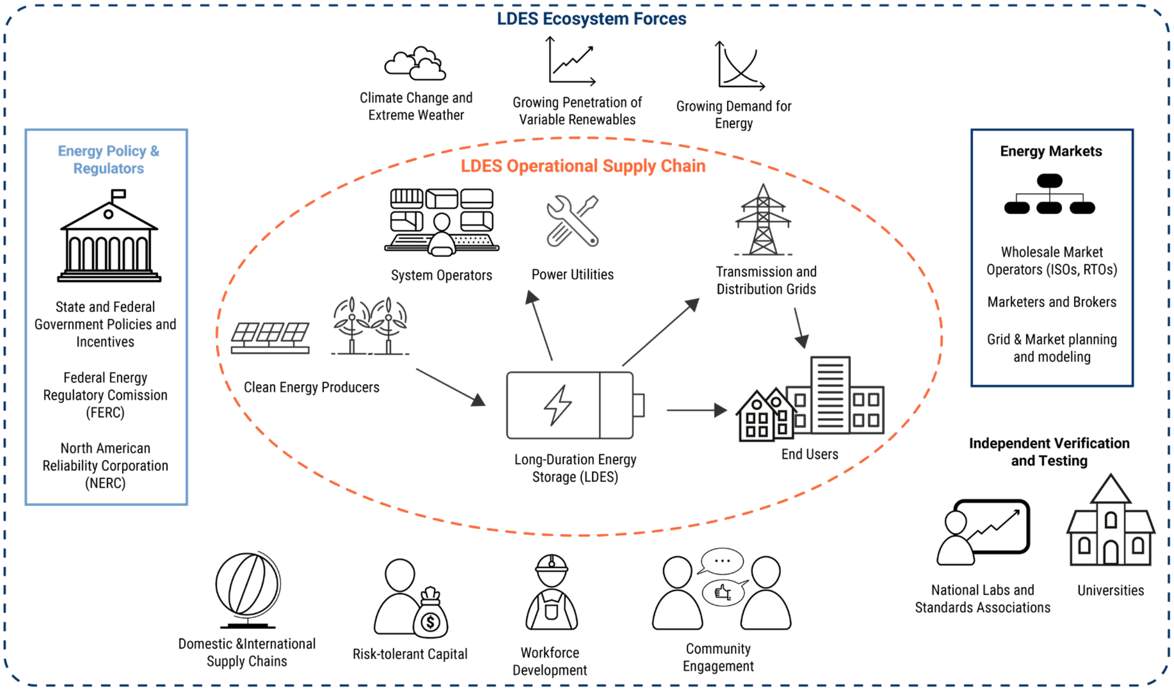
1. Power markets are generally short term (i.e., day-ahead and intraday markets), and are not designed to enable long-term agreements that could help derisk capital-intensive FOAK projects.
2. Multi-day and multi-week market signals are comparably weaker than intraday signals, leading to a devaluation of low-cycling storage options like LDES which do not need to frequently recharge.
3. Carbon-reduction compensation programs are either nonexistent or insufficient, meaning that LDES asset owners are not able to be compensated for the carbon dioxide emissions reductions that an LDES asset may enable.[26]

Without reforms to the generally short term-focused design of energy systems, the specific use cases where LDES has a competitive and operational advantage to shorter duration storage may not become fully evident.

ABOUT THE LDES TECHNOLOGY WORKING GROUP

The LDES working group convenes leading companies across the power sector ecosystem, including utilities, inter-day and multi-day LDES providers, Independent System Operators/Regional Transmission Organizations (ISOs/RTOs), and other power sector stakeholders (see Figure 3). During the first year of the working group, we focused specifically on mechanical and electrochemical LDES with a duration of dispatch greater than 10 hours.

FIGURE 3: The LDES Ecosystem



Our discussions with working group members revealed that some of the most significant obstacles to scaling LDES included:

1. lagging market and planning processes that do not capture the full value of LDES
2. the high cost of LDES
3. lack of a duration component in procurement mandates and subsidies
4. lack of sufficient LDES technology demonstrations and pilot projects.

Through member presentations and interactive discussions, the working group examined the obstacles impacting LDES deployment as well as the potential value drivers of LDES technologies. Informed by working group discussions, as well as members of C2ES's Business Environmental Leadership Council (BELC), C2ES produced a shortlist of high-impact federal and sub-national (i.e., largely state-focused) policy recommendations.

ON INNOVATION

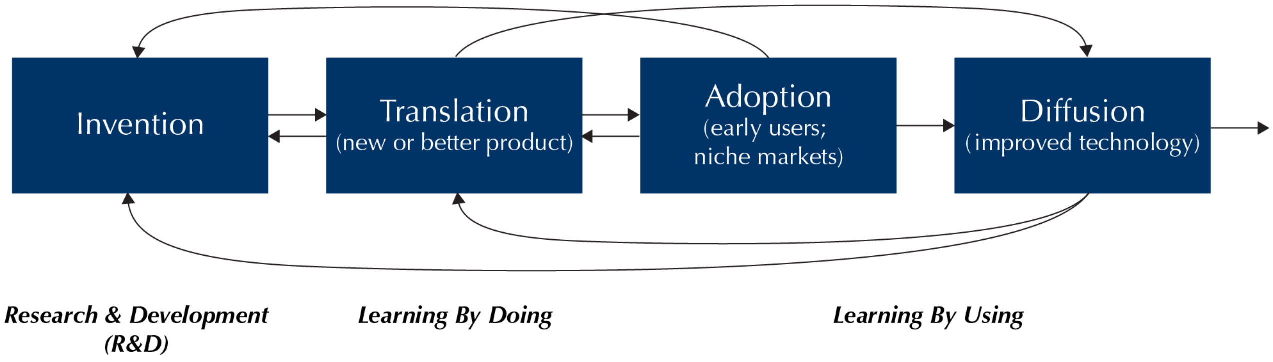
Today, policymakers play a fundamental role in shaping the priorities and incentive structures of the electric power industry by devising and administering a range of market and regulatory constructs. These constructs, along with policies targeted more narrowly at LDES, will shape both the speed and direction of LDES technological innovation. By integrating a variety of technologies into grids that face diverse supply and demand conditions, technology and project developers will learn which LDES attributes and configurations create the best value propositions. They can then focus on innovations that lower costs and boost revenue to enhance that value. Policies that enable such experimentation in practice require navigating complex dynamics: balancing supply- and demand-side incentives that will grow the LDES market, navigating existing market paradigms while identifying potential future states, providing opportunities for rigorous testing of diverse technologies in a range of real-

FIGURE 4: Project Stages of a New Innovation

As an innovation is developed and evolves, it moves through different stages before achieving commercial deployment and widespread diffusion. Throughout these stages, different feedback loops of the innovation process are triggered, helping enable continuous improvement.

Process graphic adapted from: David Ye, "From FOAK to NOAK", *CTVC by Sightline Climate* (blog), April 19, 2024, https://www.ctvc.co/from-foak-to-noak/?ref=ctvc-by-sightline-climate-newsletter.

FIGURE 5: The Innovation Process



The innovation process is made up of four interrelated stages: invention, translation, adoption, and diffusion. From ITIF: "Programs and policies across these stages shape a complicated innovation ecosystem that includes a diverse network of institutions. Few technologies move from research to market in a linear fashion. Most are aided by feedback from later stages to earlier ones, so that downstream learning is incorporated into design and development."

Source: Jetta L Wong and David Hart, "Mind the Gap: A Design for a New Energy Technology Commercialization Foundation" ITIF, May 2020, https://d1bcsfjk95uj19.cloudfront.net/sites/default/files/2020-mind-gap-energy-technology.pdf.

world settings, and encouraging new entrants while also allowing down-selection among relatively mature system forms. During the first year of our LDES working group, we explored these dynamics in detail.

C2ES will continue to build on this work, integrating learnings from other technology working groups (i.e., clean hydrogen, sustainable aviation fuels, and engineered carbon removal), and helping to align each technology ecosystem around a vision for innovation that can effectively and responsibly speed the commercial deployment of this critical set of technologies.

OVERVIEW OF POLICY RECOMMENDATIONS

C2ES has produced the following policy recommendations based on discussions over the course of the first year of the LDES working group (see Table 1). The LDES working group has focused on the "integration of innovation" into both the markets and metrics that govern the power sector. We considered the need to appropriately value LDES across a suite of applications in the energy, capacity, and ancillary services markets. Doing so necessitates a transformation of the accompanying modeling and planning tools used by market operators. We also focused on the need to enable the unique regional exploration of LDES in a variety of use cases and applications.

Given the distinct roles and influence of the federal government and state and regional decision-makers in the U.S. power system, our recommendations speak to a wide range of decision-makers, including federally regulated entities such as ISOs/RTOs; federal agencies like the Federal Energy Regulatory Commission (FERC); the White House and Congress; state PUCs; state legislatures; and electric utilities.

All recommendations are intended to remove a barrier to deployment, unlock a value driver, and/or accelerate private sector demand for LDES technologies. While this brief is framed around how to enable LDES deployment, implementing these recommendations should also be beneficial for the broader clean energy market. Our recommendations help address growing reliability and resiliency needs, add more nuance into outdated energy modeling and planning techniques, and enable power market decision-makers (e.g., ISOs/RTOs and other balancing authorities) to better capture and value the full suite of technologies available.

TABLE 1: Summary of policy priorities

CATEGORIES	POLICY PRIORITY	LEAD
Modeling Approaches *Market Certainty*	1. ISOs/RTOs and electric utilities should shift to a resource adequacy (RA) evaluation framework that focuses on year-round adequacy ("energy adequacy") instead of peak-load targeted needs ("capacity adequacy"). Doing so necessitates adopting more comprehensive and nuanced RA modeling and accreditation approaches to better evaluate the evolving needs of a decarbonizing power system and the potential role for LDES in a changing climate.	🅢
Market Certainty	2. ISOs/RTOs should support and expand ongoing reforms to increase system flexibility through increased megawatt (MW) and megawatt hour (MWh) requirements for existing operating reserves in the short-term. ISOs/RTOs should also introduce new ancillary services and energy market reforms in the medium-term to address increasing uncertainty from variable renewable output, extreme weather, and other drivers.	🅢
Market Certainty *State-level action*	3. State legislators and regulators should set clear and distinct procurement targets for LDES deployment.	🅢
Coordination *State-level action*	4. The Department of Energy and the LDES National Consortium should collaborate with state government entities to review, assess, and fill gaps in the national suite of LDES pilot and demonstration projects.	🅐 🅢
Market Certainty	5. The administration and Congress should examine options and work toward enacting an economywide market-based carbon pricing program that could contribute to the achievement of net-zero emissions by 2050.	🅛 🅐

The column labelled "leads" indicates whether the policy falls under federal legislative 🅛, federal administrative 🅐, or state 🅢 purview.

1. RESOURCE ADEQUACY REFORMS

SUMMARY

ISOs/RTOs and electric utilities should shift to a resource adequacy (RA) evaluation framework that focuses on year-round adequacy ("energy adequacy") instead of peak-load targeted needs ("capacity adequacy"). Doing so necessitates adopting more comprehensive and nuanced RA modeling and accreditation approaches to better evaluate the evolving needs of a decarbonizing power system and the potential role for LDES in a changing climate. Resource adequacy measures whether a power system has enough capacity and reserves to balance supply and demand—even under challenging conditions of low supply or exceptionally high demand (see Table 2).[27] Today's power systems are characterized by greater variability in both supply (due to weather-dependent and inverter-based resource generation like wind and solar) and demand (due to flexible loads and distributed generation resources). Additionally, climate change is increasing grid stress events (i.e., the intensity, frequency, and duration of extreme weather events and/or periods of under generation), which diminish grid resiliency and lead to extended power outages.[28] These changing conditions reveal a need to change RA frameworks.

TABLE 2: Key Resource Adequacy Terms Used in This Brief*

TERM (ACRONYM)	TYPE OF METRIC	DEFINITION
Resource Adequacy (RA)	N/A	Resource adequacy measures whether a power system has enough capacity and reserves to balance supply and demand—even under challenging conditions of low available supply or exceptionally high demand.
Loss of Load Expectation (LOLE)	Metrics that measure the resource adequacy of a system over a period of time.	A resource adequacy metric that measures the expected number of events in which load is unserved. Does not distinguish or measure the severity, duration, size, frequency, or timing of shortfall events.
Expected Unserved Energy (EUE)		A resource adequacy metric that measures the average amount of consumer demand that is greater than supply (i.e., is unserved) in terms of energy. Measures both the duration and magnitude of load shed events.
Loss of Load Hours (LOLH)		A resource adequacy metric that estimates the number of hours during a given period (typically a year) where system demand will exceed generating capacity. In conjunction with EUE, LOLH can account for magnitude, depth, and duration of events.
Effective Load Carrying Capability (ELCC)	Capacity Accreditation: Metrics that value the individual contributions of different resources to meet resource adequacy needs	An accreditation approach that uses a comprehensive reliability model to measure the impact on system reliability of an incremental addition or removal of a given resource from the supply mix.
Supply Tightness		An accreditation approach that assesses expected resource contribution during hours when insufficient supply exists over the course of a year.
Marginal Reliability Impact (MRI)		An accreditation approach that uses various methods (sometimes simpler, non-ELCC approaches) to estimate the marginal impact that a change in the capacity of an individual resource will have on system reliability.

*As noted in the Summary portion of this recommendation, this list of metrics is non-exhaustive, and other metrics continue to be developed and evaluated.

In addition, the attributes and capabilities of storage and LDES technologies are unique and warrant consideration of new modeling tools that can effectively capture their value to grid reliability. For example, most available modeling tools used in energy system planning (e.g., capacity expansion models) use "representative" days, hours, or weeks to reflect operations. These representative periods are intended to reflect typical operations by pulling together sample data from different periods of the year. However, a key drawback of this method is that the models usually do not use sequential hours, days, or weeks for the sample data. While this approach may work for low penetrations of short-duration energy storage, it cannot capture the capabilities of longer-duration storage resources. Because modeling non-sequential representative periods does not fully capture the ability to shift energy between long periods of time—meaning it cannot capture multi-day or seasonal shifting—it cannot provide an accurate picture on reliability for LDES.[29]

Thus, as LDES plays an increasingly prominent role in decarbonized regions, utilizing a menu of RA evaluation frameworks and accreditation approaches will become more important. The menu of options should: (1) model LDES with linked representative periods; (2) consider availability of other resources; and (3) allow for temporal resolution instead of (or in addition to) spatial resolution for capturing the operational realities of LDES.

As renewable and energy storage resources are brought online, there is a need to shift away from peak-load capacity adequacy RA planning frameworks and toward year-round energy adequacy RA frameworks. The specific characteristics and system dynamics of LDES technologies will necessitate new modeling approaches and metrics that will likely need to be evaluated and developed to accurately determine how LDES can contribute to RA. However, as a starting point, ISOs/RTOs and electric utilities should prioritize metrics like expected unserved energy (EUE), loss of load hours (LOLH), and other relevant metrics as they develop. They should also pair this with a shift away from capacity adequacy planning frameworks primarily based on loss of load expectation (LOLE). Doing so should better capture hourly, seasonal, and annual adequacy needs, and help grid operators identify where LDES can be used to address gaps. Moreover, given the fact that utility integrated resource plans (IRPs) currently inform RA planning, it could be useful for grid operators to ensure alignment between these two planning processes, particularly with respect to the reliability metrics, input assumptions, and modeling approaches used. Indeed, RA planning of the future may look so similar to IRP planning that ISOs and RTOs may be able to obviate the need for RA programs.

Alongside RA reforms, capacity accreditation—a measure of the individual contributions different resources make to meeting resource adequacy needs—will also require a newer methods as a more diverse suite of energy and storage technologies becomes available. If the energy system evolves to measure resource contributions more on a temporal basis, then current RA accreditation methodologies may no longer be adequate or necessary. The question of what this future paradigm will look like is a source of active discussion and research for the LDES working group and the power sector writ large. In the interim, grid operators will need to adjust their current accreditation methods to better reflect and compensate for the reliability contributions of LDES and all other resource types. This may look like using new accreditation approaches altogether, or thoughtfully pairing existing methods—for example, effective load carrying capability (ELCC), marginal reliability impact (MRI) derating, or supply tightness—with novel approaches that are actively being researched and developed. Long-term reforms of RA programs and near-term changes to accreditation approaches will help increase the accuracy of LDES contributions to reliability by better expressing system reliability needs and by better valuing LDES with respect to resource adequacy.

RATIONALE

As more renewable electricity is added to the grid, RA needs change in several ways. This includes shifting of peak demand to winter seasons in many regions, variations in generation availability due to this seasonal shifting, and demand forecasts that differ significantly from historical trends.[30] Moreover, increased penetration of solar and wind, paired with increasing load due to electrification (particularly from heating loads in winter) are shifting the seasonality of RA risk. For example, long-duration winter weather events can knock out entire swaths of generation assets (particularly when they have not been winterized) and backup generators for hours or days at a time.[31] As a result, RA risk is increasing during winter peaks, shoulder seasons (the time between energy-intensive winter and summer peak seasons), and non-peak hours when renewable output is low.[32]

While LDES can be used to address RA risk during all seasons, its value is particularly evident during winter events (see Box 1). Four-hour storage solutions like lithium-ion batteries are not well-suited to managing extended winter events, particularly if they cannot be recharged during an extended power outage or shortage.

Because LDES can store and dispatch energy for up to days at a time, it ensures resource adequacy and grid reliability when other energy sources are unavailable. LDES' flexibility means that it can also be used as backup power for a multitude of use cases. However, power markets currently do not adequately capture and quantify this value; as a result, utilities are unable to justify investments in LDES. Reforming the current method of modeling RA would allow markets to appropriately value the benefits of LDES to the grid.

In addition, limiting language in a utility's energy storage target or a state legislature's definition of energy storage can further complicate efforts to properly value LDES. In the case of regulated utilities, a requirement to focus on least-cost investment has made it challenging to make the case to PUCs for an innovative demonstration project. Potential solutions to these challenges are explored in greater detail in our subsequent recommendations.

Currently, most of the power sector measures RA using loss of load expectation (LOLE). This RA metric measures the expected number of events in which load is unserved but does not distinguish or measure the severity of events. LOLE does not consider the duration, size, frequency, or timing of shortfalls and does not sufficiently capture tail risks associated with high-impact, low-probability events. Larger and longer duration outages have greater impacts than smaller or shorter duration events, and their effects increase non-linearly. [33]

By contrast, EUE measures the average amount of consumer demand that is greater than supply (i.e., is unserved) in terms of energy. EUE better contextualizes the nature of reliability events and additionally accounts for when systems are energy (as opposed to capacity) limited. One drawback of EUE is that it does require more sophisticated statistical modelling approaches. LOLH is an estimate of the number of hours during a given period (typically a year) where system demand will exceed generating capacity. It is a simple metric that is easier to calculate/model and accounts for duration of events. In conjunction with EUE, LOLH can account for magnitude, depth, and duration of events.[34]

An example of the efficacy of these metrics can be seen in Figure 2. The PJM RTO assembled a heatmap that leveraged the EUE metric to look at where there may be energy shortfalls over the course of 24 hours in a year (see Figure 6).[35] In the summer, there was a shorter, single-peaking period of risk in the late afternoon and into early evening. By contrast, in winter there were two longer shortfall risk periods—before sunrise and after sunset. The ability to quantify these seasonal and hour-by-hour risk periods will be increasingly important for systems that have greater amounts of energy-limited storage or non-dispatchable renewable resources. It can

BOX 1: The Impact of Winter Weather in Warmer Regions

A 2023 report from the National Renewable Energy Laboratory (NREL) found that certain warmer regions in the United States, notably Texas and parts of the Southeast, have shifted to net winter peak demand in recent years.[*] Since these regions have not historically needed to manage high RA risk during winter months, they can be unprepared when extreme winter weather events do occur. This was the case in February 2021 in Texas, when a severe winter storm led to historically low temperatures, snow, and ice. During the days-long event, system operators resorted to rolling blackouts to prevent the collapse of the power grid when power demand exceeded supply.[†] Texas suffered at least 146 deaths due to hypothermia and an estimated cost of $195 billion attributed to blackouts.[‡] Following this incident, ERCOT proceeded to add over 569 MW of mostly short-duration battery storage capacity to the Texas grid by the end of 2021, more than 5 times what they added in 2020.[§]

** Paul Denholm, Wesley Cole, and Nate Blair, Moving Beyond 4-Hour Li-Ion Batteries: Challenges and Opportunities for Long(er)-Duration Energy Storage, NREL/TP-6A40-85878 (Golden, CO: National Renewable Energy Laboratory, 2023), https://www.nrel.gov/docs/fy23osti/85878.pdf.*

† Cheng-Chun Lee, Mikel Maron, and Ali Mostafavi, "Community-scale big data reveals disparate impacts of the Texas winter storm of 2021 and its managed power outage," Humanities and Social Sciences Communications 9 (September 2022), https://doi.org/10.1057/s41599-022-01353-8.

‡ Texas Department of Health and Human Services, "February 2021 Winter Storm-Related Deaths – Texas," December 31, 2021, https://www.dshs.texas.gov/sites/default/files/news/updates/SMOC_FebWinterStorm_MortalitySurvReport_12-30-21.pdf; Mitchell Ferman, "Winter storm could cost Texas more money than any disaster in state history," The Texas Tribune, February 25, 2021, https://www.texastribune.org/2021/02/25/texas-winter-storm-cost-budget/.

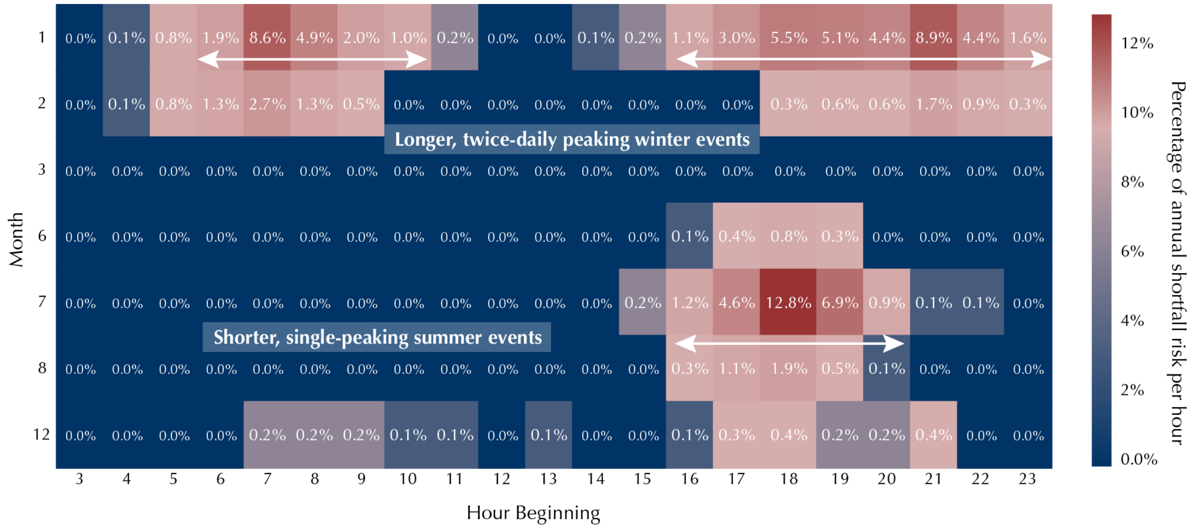
§ U.S. Energy Information Administration, 2023 Early Release of Battery Energy Storage Report Figures (Washington, DC: U.S. Energy Information Administration, 2023), https://www.eia.gov/analysis/studies/electricity/batterystorage.

also help strengthen the case for LDES by demonstrating when the power grid may need storage resources that can run for longer than the typical 0–4 hours provided by shorter-duration storage.

Capacity accreditation—a measure of the individual contributions different resources make to meeting resource adequacy needs—will also require newer methods as a more diverse suite of energy and storage technologies becomes available. Currently, power sector decision-makers are considering several methods, including ELCC, methods based on supply tightness, and simple methods to approximate MRI. ELCC uses a comprehensive model that measures the impact to system reliability based on an incremental addition or removal of a given resource from the supply mix.[36] Supply tightness approaches assess expected resource contribution during hours when insufficient supply exists over the course of a year. An MRI framework uses various methods (sometimes simpler, non-ELCC approaches) to estimate the marginal impact that a change in the capacity of an individual resource will have on system reliability.[37] All three accreditation methods seek to better measure the relative contributions that different resource types can have on emerging hourly, seasonal, and annual reliability needs, especially in conjunction with improved modeling of extreme weather.

While the RA metrics and capacity accreditation methods described in this recommendation can serve as a helpful steppingstone, it is likely a fully decarbonized energy system will need an entirely new set of metrics and methods for ensuring RA. Recent research from the LDES National Consortium indicates that on their own reliability metrics like ELCC, EUE, and LOLH may be inadequate at defining LDES' contributions to resource adequacy.[38] Further, these metrics and associated RA schemes will not provide least cost system compensation for these contributions as systems decarbonize. This is because these metrics seek to define the effectiveness of providing energy when the grid needs it most, which is inadequate for developing a compensation strategy—and financially incentivizing least cost resources—for decarbonizing systems. A comprehensive resource adequacy framework must include a temporal modeling of hourly demand, alongside resource capabilities that could potentially serve that demand. The LDES National Consortium is actively researching new metrics and mechanisms which could serve as a complement or alternative to these existing approaches.

FIGURE 6: PJM Base Case Expected Unserved Energy (EUE) Heatmap



Month	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0.0%	0.1%	0.8%	1.9%	8.6%	4.9%	2.0%	1.0%	0.2%	0.0%	0.0%	0.1%	0.2%	1.1%	3.0%	5.5%	5.1%	4.4%	8.9%	4.4%	1.6%
2	0.0%	0.1%	0.8%	1.3%	2.7%	1.3%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	0.6%	0.6%	1.7%	0.9%	0.3%
3	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
6	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.4%	0.8%	0.3%	0.0%	0.0%	0.0%	0.0%
7	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	1.2%	4.6%	12.8%	6.9%	0.9%	0.1%	0.1%	0.0%
8	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	1.1%	1.9%	0.5%	0.1%	0.0%	0.0%	0.0%
12	0.0%	0.0%	0.0%	0.0%	0.2%	0.2%	0.2%	0.1%	0.1%	0.0%	0.1%	0.0%	0.0%	0.1%	0.3%	0.4%	0.2%	0.2%	0.4%	0.0%	0.0%

This heat map was assembled by PJM as part of their 2023 capacity market reform proposal. It assesses resource adequacy risk on an hour-by-hour basis across a full calendar year. The month of January includes two longer duration periods where RA risk is high. This is in contrast to the month of July, where RA risk is limited to a single, shorter duration period.

Source: Capacity Market Reform: PJM Proposal," PJM, accessed August 12, 2024, https://www.pjm.com/-/media/committees-groups/cifp-ra/2023/20230727/20230727-item-02a---cifp---pjm-proposal-update---july-27.ashx

INNOVATION LENS

RA modeling and accreditation reform will create demand-pull for deployment of LDES technologies across a range of ISOs/RTOs and vertically integrated geographies. Pairing this reform with a broader shift away from traditional cost-of-service regulation and toward alternatives (e.g., performance-based regulation), would give project developers and owners substantial flexibility to experiment with new technologies. These actors will be able to invest in whichever technological configuration they expect will achieve performance targets, which may include environmental and efficiency metrics in addition to emissions goals, while still providing economic returns. The decisions load-serving entities and end-users make will ultimately determine whether their expectations are realized as LDES systems operate under evolving grid conditions. This feedback process will allow investors in follow-on LDES projects to learn which technologies perform well and drive innovation toward these performance outcomes. A diverse set of technologies may continue to flourish over time, as each fits a particular set of grid conditions best, or the field may converge on a single technological paradigm across all geographies that can move rapidly down a learning curve, as was the case for lithium-ion batteries.

IMPLEMENTATION

Resource adequacy reforms can be implemented through multiple pathways; who makes these reforms varies depending on the market and region in the United States. In the case of markets overseen by ISOs/RTOs, RA reforms would be mostly directed by either the ISO/RTO or FERC. An exception to this rule is ERCOT, which still undergoes stakeholder processes for reforms, but is regulated only by the Public Utilities Commission of Texas and not FERC. In California, RA reforms are under the purview of the California Public Utilities Commission, rather than the California ISO.

There are two primary avenues, formally defined through the Federal Power Act Sections 205 and 206, through which ISOs/RTOs can submit amendments to their market rules (additionally referred to as market tariffs) under FERC's jurisdiction. In the case of Section 205, an ISO/RTO submits a "205 filing" to FERC to request reforms and/or changes to their market rules. This submission is driven either by a stakeholder process by a coalition of market participants within the ISO/RTO or led by the ISO/RTO itself. After a Section 205 filing is submitted to FERC, the commissioners will assess the proposed revisions and either accept the proposal, deny the proposal, or request additional revisions to the proposal, which then go back through a revision process with stakeholders at the ISO/RTO. The Section 205 process is the most frequently utilized and successful process for reforms. By contrast, the Section 206 process involves a party going directly to FERC to file a complaint alleging that a document (or any part thereof) that is currently in vigor under FERC's jurisdiction is unjust, unreasonable, unduly discriminatory, or preferential. Under Section 205, ISOs/RTOs and utilities have the legal burden of demonstrating that the proposed reforms are "just and reasonable." However, in a Section 206 filing, the complaining party (i.e., the ISO/RTO) must show that the document currently on file is "unjust and unreasonable," which is a significantly higher legal standard than under a Section 205 filing.[39]

These resource adequacy reforms will also be important in utilities outside of ISOs/RTOs, particularly those located in states with ambitious decarbonization goals (i.e., expected high penetration of variable renewable generation). These utilities also use reliability metrics in their IRPs and other resource planning processes, as well as reliability models to calculate the capacity value of resources. For these utilities, changes to reliability metrics and resource adequacy valuation fall under the purview of public utility commissions through a utility-led reform process. In these cases, stakeholder engagement would be focused around commenting on utility resource planning and public utility commission proceedings.

Recently, experts from industry and the federal government have renewed calls to reform RA accreditation and metrics for planning.[40] For example, the North American Reliability Corporation (NERC) hosted a workshop on the need to update reliability and planning criteria for a decarbonizing grid. Additionally, the Electric Power Resource Institute (EPRI) is researching potential solutions for reform.[41] The newly formed LDES National Consortium, a DOE-funded effort facilitated by six national laboratories and driven by industry stakeholders, is also doing work on the role of resource adequacy reform in catalyzing LDES deployment.[42] Coordinating efforts across these different stakeholders—utilities, ISOs/RTOs, industry experts, federal government actors, researchers, and others—can help coalesce the power sector around a clear set of priorities for resource adequacy reforms.

2. OPERATIONAL FLEXIBILITY VALUATION AND REFORMS

SUMMARY

ISOs/RTOs should support and expand ongoing reforms to increase system flexibility through increased megawatt and megawatt hour requirements for existing operating reserves in the short term. ISOs/RTOs should also introduce new ancillary services and energy market reforms in the medium term to address increasing uncertainty from variable renewable output, extreme weather, and other drivers. These are examples of incremental reforms that can be done within the existing market paradigm to help unlock the value-stream for LDES technologies, which are well-suited to providing the services needed to manage increasing supply/demand imbalances due to their fast response times and long-duration charge/discharge capabilities. Expansion of existing operating reserves in terms of both capacity adequacy (increasing the total amount of MWs) and energy adequacy (increasing the total amount of MWhs), combined with the development of new operational flexibility products can serve as a helpful steppingstone on the path to larger reforms.

Additionally, ISOs/RTOs should revise market mechanisms so that LDES technologies can participate in multiple markets (e.g., capacity, ancillary, energy markets) within an ISO/RTO or provide multiple services simultaneously within a state. LDES is likely to make its most important contributions through RA and capacity markets, and it should be appropriately compensated for those services (see “Resource Adequacy Reforms”). However, the more markets or services LDES can participate in or provide without compromising its ability to fulfill RA obligations, the more valuable it will become and the more rapidly it will be deployed.

A prerequisite to the success of these operational flexibility and market reforms is the more effective coordination of planning practices between individual states and regional entities such as ISOs/RTOs. The impact of these reforms will be limited without first establishing consistency between the ISO/RTO market rules and what is happening in the states within that region.

RATIONALE

Operational flexibility refers to the ability of a power system to respond to changes in electricity demand and generation.[43] The nature of electricity and the grid imposes rigorous requirements on power systems: supply and demand must be instantaneously balanced, and the grid’s frequency must remain stable within narrow parameters. If these and other requirements are not met, customers will experience service interruptions, equipment damage, and worse (e.g., cascading blackouts). Yet system operators, such as ISOs/RTOs and utilities, do not control all the factors that can impact their ability to meet these requirements. If a supply resource goes offline, the system operator must be able to backfill it rapidly. If demand spikes unexpectedly, the system operator must mobilize supply to address the gap. If the system’s frequency deviates because of a supply/demand imbalance, the system operator must be able to compensate accordingly. This is why operational flexibility is such an important aspect of a well-functioning power system.

The need for additional operational flexibility is driven by greater amounts of weather-dependent (and inverter-based) wind and solar supply, and less predictable demand due to weather-dependent generation resources being interconnected at the distribution level. To date, most power systems have a supply mix that has consisted nearly entirely of dispatchable resources—generation sources that can be turned on, off, or adjusted to meet demand. As a result, these power systems have required flexibility so they can balance varying demand and account for uncertainty related to unexpected losses of system elements (e.g., a large 1,000 MW generating unit tripping offline). As power systems decarbonize and add more generation with variable and uncertain (i.e., non-dispatchable) output, the need for fast-responding/flexible resources will increase beyond what is currently procured by system operators.

In the short term, system operators should focus on incrementally addressing evolving flexibility needs by expanding the procured capacity for existing tools (e.g., increase operating reserves), which would allow them to prioritize both capacity adequacy and energy adequacy. The expanded operating reserves can account for both the total amount and the duration of energy available during grid stress events. In the medium term, new operating reserves products aimed at addressing both varying renewable supply and varying demand will need to be designed. Examples of these could be ramping products designed to manage sudden changes in demand or generation of renewables. Examples include reserving flexible resources for evening ramp requirements or short-term uncertainty products designed to reserve resources to be “on call” for estimated day-ahead uncertainty from load and weather forecast errors.

LDES systems have a range of potential value drivers in the power sector. As discussed in the first recommendation, LDES can be particularly effective in addressing resource adequacy needs. Like shorter-duration storage solutions, there will also be opportunities for LDES technologies to generate value through energy arbitrage and by providing ancillary services. Ancillary services of particular relevance for LDES technologies include black start capabilities (i.e., enabling the grid to recover from a shutdown), operating reserves (i.e., readily available resources for when demand unexpectedly exceeds supply), and active/reactive power services (i.e., helping maintain grid stability and balancing through frequency response, inertial service, and other service types).[44] Beyond these energy services, there are also opportunities for LDES technologies to aid in the optimization and deferral of transmission build outs.[45]

Without reforms to the generally short-term focused design of energy systems, the specific use cases where LDES has a competitive and operational advantage to shorter duration storage may not become fully evident. Power systems should expand ongoing reforms to increase system flexibility on the basis of both capacity adequacy (MW increase) and energy adequacy (MWh increase). This approach would maximize the value of LDES and accelerate their build-out.

INNOVATION LENS

The expansion of existing operating reserves and reform of ancillary services and energy markets would create demand-pull for deployment of LDES technologies across a variety of grid types. Project developers will select the technological configurations that optimize their ability to meet RA needs and broader performance metrics adopted by regulators. For instance, technologies that can respond most quickly may be more highly valued in ancillary services markets than in capacity markets. The realization of value from LDES systems will depend on the combination of market outcomes and performance-based regulatory incentives that emerge as each grid operates over the long run. These market and regulatory signals will, in turn, drive follow-on investments that accelerate innovation in specific LDES technologies. Because a wider variety of conditions is likely to be experienced across regional grids, the net impact of implementing this recommendation, in addition to other regulatory reforms, may be maintaining technological diversity for a longer period of time compared to implementing only RA reform.

IMPLEMENTATION

As is the case with the first recommendation, the process of market reform varies depending on the market and region. In the case of deregulated markets (ISOs/RTOs), market reforms would be directed by either the ISOs/RTOs and stakeholders through a Section 205 process or before FERC directly with a Section 206 process (see “Resource Adequacy Reforms” for a more in-depth description of each of these processes). An exception to this rule is ERCOT, which still undergoes stakeholder processes for reforms but is regulated only by the Public Utilities Commission of Texas and not FERC. Another exception is in California, where RA reforms are under the purview of the California Public Utilities Commission, rather than the California Independent System Operator.

The process to be followed in states with traditional utility regulation would also follow the same utility-led approach to reforms as in our first recommendation. In the case of reforms to increase operating flexibility, priority activities for stakeholder engagement would involve attending and commenting on public utility commission proceedings.

3. SETTING CLEAR AND DISTINCT STATE LDES PROCUREMENT TARGETS

SUMMARY

State legislators and regulators should set clear and distinct procurement targets for LDES deployment. State LDES procurement targets should encourage utilities, developers, and other power system stakeholders to consider a range of durations (e.g., inter-day and multi-day) and LDES forms (e.g., electrochemical, mechanical, chemical, and thermal), so they can choose the LDES technology that will work best for their specific regions and needs. State LDES procurement targets should also align with the DOE's definition of LDES, which is 10 hours or longer. These targets will accelerate deployment of LDES technologies so that they are widely available when needed. This will be one of the most effective ways to accelerate utility uptake of LDES and level the playing field with other shorter- duration storage technologies.

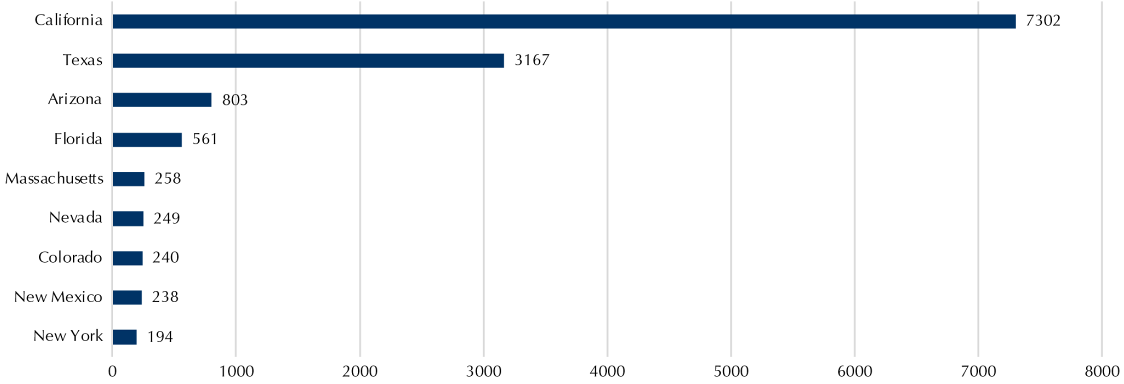
We recommend that PUCs or other state agencies consider several design structures for LDES procurement programs to help share costs with utilities, enable price discovery, and manage costs to both taxpayers and ratepayers. These structures include a price floor with procurement programs, reverse auctions, and clean transition tariffs (CTTs) or accelerating clean energy (ACE) tariffs.

RATIONALE

Recent growth in installed battery capacity has been driven almost entirely by shorter-duration storage solutions. This is because energy markets are not set up to reward longer-duration, lower-cycling storage technologies. The unique set of technical, market, and policy risks associated with LDES technologies makes it challenging for first-of-a-kind projects to secure the long-term market agreements they need to help reduce these risks. In addition to these market failures, most state storage incentives and targets are geared toward four-hour storage solutions like lithium-ion batteries, which have historically been the only storage option available. By setting a distinct LDES procurement target, states can help correct for these market and policy inefficiencies and provide LDES technologies with the long-term market certainty needed to catalyze public and private sector investment.

Short-duration lithium-ion battery uptake was largely accelerated by the rapid scaling of the electric vehicle market. An analogous market-demand dynamic for LDES may look more like a long-duration extreme winter weather event. State LDES-specific procurement targets, like general storage targets, can help ensure states are prepared ahead of these events and have a demonstrated track record of success. For example, in 2013, the California Public Utilities Commission adopted a 1,325-MW

FIGURE 7: Top 10 U.S. states with the most installed battery capacity (Megawatts)



Data shown above is up through November 2023. California and Texas continued to lead in utility-scale battery installations through 2024.

Source: U.S. Energy Information Administration, U.S, battery capacity expected to nearly double in 2024. January 9, 2024, https://www.eia.gov/todayinenergy/detail.php?id=61202 procurement mandate for electricity storage by 2020. The state now has more installed battery capacity storage than any other state in the United States.[46]

As of October 2024, eleven states have established energy storage procurement mandates, targets, or goals, but only California and New York include clear and distinct targets for LDES.[47] The policy design used by these two states can serve as a useful guide for how other states could approach an LDES procurement target or mandate. To illustrate, California Assembly Bill 1373 requires the California Public Utilities Commission (CPUC) to identify a diverse and balanced portfolio of resources that will ensure a reliable electricity supply while providing optimal integration of renewable energy in a cost-effective manner. The legislation also directs the CPUC to determine if there is a need to procure additional eligible energy resources.[48] In response, in August 2024, the CPUC established a centralized procurement strategy to boost the state's clean energy resources. Under the framework, the California Department of Water Resources (DWR), through the Statewide Energy Office, will spearhead the procurement of long lead-time clean energy resources, including LDES. The CPUC intends to request that DWR procure up to 10.6 GW of nameplate capacity, the maximum output under ideal conditions, from emerging technologies, including up to 2 GW of LDES—1 GW for multi-day storage and 1 GW for LDES with at least a 12-hour discharge period. By centralizing the procurement of these resources through a single state agency, California can simplify the process of acquiring advanced energy resources. This approach may reduce future costs for ratepayers and speed up the development of clean energy technologies.[49]

In New York, similar efforts were spurred by the Climate Leadership and Community Protection Act (CLCP), which requires 70 percent of New York's electricity generation to come from renewables by 2030 and 100 percent by 2040.[50] In June 2024, the New York Public Service Commission issued an order establishing an updated energy storage goal and deployment policy of 6 GW of energy storage deployment by 2030 and 1.5 GW of energy storage by 2025. The order also directs the New York State Energy Research and Development Authority (NYSERDA) to conduct a minimum of three bulk energy storage procurements (considered 5 GW or larger), to be held no less than annually, to procure 3 GW of bulk energy storage. In each bulk procurement, the New York Public Service Commission directs NYSERDA to include a target of 20 percent longer-duration 8-hour energy storage resources. NYSERDA has identified a need for 4 GW of LDES by 2035 and 6.8 GW by 2050, supported through the 20 percent longer duration target within bulk procurements.[51] Like California's program, this initiative aims to streamline and de-risk the purchase of nascent technologies that are needed to meet climate goals but are not yet cost-competitive.

Government procurement mandates are influential levers for scaling nascent clean energy technologies. Since the 1990s, federal policies directing purchasing of energy-efficient products helped make them more affordable while also strengthening public awareness of the value of energy efficiency through the EPA's Energy Star program.[52] This was also the case with state renewable portfolio standards (RPS), where carve-outs within the standards for solar photovoltaics helped the technology surpass wind as the most widely deployed electricity generation technology.[53] State LDES procurement targets would mirror this proven approach by supporting the development of the nascent LDES market and sharing performance-related information that can offer developers valuable insights into system integration and operating challenges. This will also direct attention to other barriers impeding LDES deployment, setting the stage for further policy and market reform.

INNOVATION LENS

Clear and distinct state procurement targets for LDES would stimulate demand and accelerate deployment of LDES technologies. Compared to entirely market-driven decision-making structures, state procurement targets provide greater upfront certainty to LDES technology and project developers, reducing risks and making it less costly to secure project financing. To spur innovation in multiple segments, state policymakers may choose to concentrate demand on specific LDES technologies or storage system forms. For example, California's segmentation of its procurement target by duration (i.e., multi-day and 12-hour categories) will likely allow more opportunities for multi-day systems to be developed than a purely market-driven structure would. This firm and concentrated demand would help technology providers and developers within this segment learn and scale more rapidly than they would otherwise. Similar segmentation could enable new technology forms to flourish.

IMPLEMENTATION

In most cases, enactment of state LDES procurement targets would require enabling legislation and is under the purview of state legislators. As seen in California and New York, existing orders or legislation (either for storage `targets or broader decarbonization laws) can provide sufficient authorization for the utilities or another state agency to carry out an LDES procurement target. States that already have energy storage targets and/or procurement mandates should incorporate LDES-specific carveouts. If a state already has a storage procurement target, they could dedicate a proportion of that target to LDES. They could identify what their LDES target should be by using a combination of their estimates of new load growth and relevant applications of LDES as a guide for the capacity (MW) target that would be appropriate.

There are several design characteristics that states must consider for LDES procurement targets, which will likely vary by region. Thoughtful analysis will be required to determine the appropriate procurement amount. For example, by late 2022, California load-serving entities had committed to build only about 510 MW of LDES resources through 2035.[54] However, a December 2023 analysis sponsored by the California Energy Commission revealed the need for more LDES capacity in the state and led to the state mandating a 2 GW procurement strategy announced in August 2024.[55] Procurement amounts will likely be determined based on a myriad of factors, including but not limited to, the state's ambition on decarbonization and/or energy storage, penetration of renewable energy, electricity demand, energy modeling capabilities, funding availability, and projected impacts on ratepayers and taxpayers.

There are several design structures for government procurement programs that allow for price discovery and mitigate costs on ratepayers. For example, New York's bulk energy procurement program adopts an index storage credit (ISC) mechanism, similar to the state's Index Renewable Energy Credit mechanism.[56] Storage developers will bid on the price they believe provides adequate revenue for the energy storage project, also known as a strike price. The strike price is then compared to a reference price, which will be calculated based on expected revenue from New York Independent System Operator's (NYISO's) Energy and Capacity Markets. The ISC will be equal to the strike price minus the reference price. If the strike price exceeds the reference prices, then NYSERDA will pay out the difference to the developer. If the strike price is lower than the reference prices, the project would owe NYSERDA a payment.[57] This structure could help mitigate the cost on taxpayers for a state-funded LDES procurement program.

Another government procurement approach is a reverse auction, where sellers (i.e., storage developers) will compete for a buyer's (i.e., the state government) bid. States may elect to design a diversified procurement portfolio with distinct verticals for a range of durations (e.g., inter-day and multi-day) and LDES forms (e.g., electrochemical, mechanical, chemical, and thermal energy storage) to enable maximum flexibility for utilities, developers, and other power system stakeholders. Distinct reverse auctions for a diversity of ranges and forms could ensure that these LDES approaches compete with their peers—rather than different duration and application types—for least-cost innovation. Through this approach, utilities subject to LDES procurement targets could explore a range of opportunities in detail and make the case for the best long-term options.

To avoid increasing costs on ratepayers, state governments and utilities subject to these mandates or targets can share the costs of procuring LDES. State cost-sharing could be offered in the form of grants, low-cost debt financing, tax breaks, or other funding mechanisms such as regulated clean energy revenue riders.[58] PUCs could also approve mechanisms—for example, accelerating clean energy (ACE) tariffs and/or clean transition tariffs (CTTs)—that allow large companies seeking 24/7 clean energy can pay a higher rate to utilities to help finance the costs of developing and procuring clean firm energy technologies like LDES.[59] PUCs could also engage with large energy customers, such as data centers, who are prime candidates for CTTs and could utilize LDES as a clean backup power option. Both NV Energy and Duke Energy have proposed ACE and CTT financing concepts for tech companies with advanced climate or 24/7 clean energy commitments that are willing to bankroll early deployments of nascent technologies like LDES.[60] Through these innovative financing options, state procurement programs can mitigate passing high costs on to individual ratepayers.

4. NATIONAL COORDINATION AND ACCELERATION OF LDES DEMONSTRATION PROJECTS

SUMMARY

The Department of Energy and the LDES National Consortium should collaborate with state government entities to review, assess, and fill gaps in the national suite of LDES pilot and demonstration projects. A coordinated national initiative can help produce the key insights and best practices necessary to enable effective demonstration, grid integration, and market compensation of LDES technologies. Doing so should also strengthen private and public sector confidence in the role that LDES technologies can play in addressing the needs of a decarbonizing energy system. Recent federal and state LDES investments and initiatives provide a solid foundation to build up this effort.

The effort should encompass diverse LDES technologies that range in duration (e.g., inter-day and multi-day), form (e.g., electrochemical, mechanical, chemical, and thermal energy storage) and use cases. Demonstration projects should also account for regional and market differences across the United States. Financial assistance may be offered by federal and state agencies directly to project developers through grants, low-cost debt financing or guarantees, investment tax breaks, or other funding mechanisms such as regulated clean energy revenue riders.[61] Operating revenue could also be bolstered and assured through public procurement and innovative financing mechanisms, like clean transition tariffs. Project developers that receive benefits from these public policies should be required to disclose and validate data that utility resource planners and project developers can use to enable follow-on investments.

RATIONALE

While the timing and ultimate level of demand for LDES technologies will vary across regional grids, it is likely to be significant nationwide. California, New York, and Massachusetts have each sponsored pilot studies and/or projects to assess LDES capabilities and system needs. Each study has determined LDES can be a cost-effective solution for the respective state's energy transition pathway.[62] These regional demands will aggregate to the hundreds of gigawatts that the DOE Liftoff report estimates may be necessary nationwide. Without LDES resources, grid reliability and resiliency may degrade, and the nation may fail to meet its decarbonization goals.

Many LDES technologies have reached a stage where they are ready to be deployed. Across the board, LDES technologies have reached the phase where larger scale experimentation and piloting will be necessary to drive down costs. In August 2024, DOE released a report reviewing the 10 most promising LDES technology pathways and the top three potential innovations that could help drive down the levelized cost of LDES technologies.[63] The report found that demonstration projects are a top innovation for 50 percent of the technologies assessed, including lead-acid batteries, zinc batteries, compressed air energy storage, hydrogen storage, and molten salt thermal energy storage. Several other demonstration-scale innovations were also identified, including manufacturing for scale, in-operations science research, and 3D printing technology at large scale.

However, the path to demonstration and widespread deployment remains daunting for capital-intensive first-of-a-kind technologies, like LDES. Many promising technologies stall at this stage, falling into the "demonstration valley of death."[64] The main reason for this valley is reluctance from private investors to fund FOAK projects due to their high costs and uncertain revenue. An added challenge for LDES is that demonstration projects often need to be approved by PUCs, a typically risk-averse decision-maker that is focused on keeping costs low for ratepayers, as well as ensuring grid resiliency and reliability.

Grid-integrated LDES demonstration projects will be a necessary step to enabling the long-term efficacy and competitiveness of LDES. Any FOAK endeavor is likely to be more costly and risky than its successors. Indeed, a crucial purpose of any demonstration project is to facilitate learning-by-doing. The knowledge and information generated by FOAK projects allows follow-on projects of the same type to avoid mistakes, eliminate unneeded costs, gain economies of scale, and optimize revenue. Federal and state support plays a role here: helping to absorb a sufficient share of the upfront cost and risk, so private co-investors will "crowd in" behind them and PUC concerns can be alleviated.[65]

Both the federal government and several states have begun to take on this challenge. Through the IIJA, Congress authorized DOE to create an LDES demonstration program. Subsequently, OCED has announced 15 awards totaling $379 million to launch the program.[66] These projects typically receive an additional 50 percent or more non-federal cost-share. Other offices at DOE and units of the U.S. Department of Defense (DOD) are also funding LDES projects that may advance the industry's learning objectives, such as the Army's installation of an LDES flow battery in Fort Carson, Colorado.[67] At the state level, the California Energy Commission (CEC) supported 11 field demonstrations in 2020 and recently awarded three more.[68] In New York, NYSERDA has invested in six LDES projects.[69] State regulators have also given approval to some utilities, such as Xcel Energy, Dominion Energy, and the Salt River Project, to undertake such projects.[70] LDES projects can also benefit when both the federal and state governments collaborate to support demonstration projects. For instance, Massachusetts led the New England states' "Power Up" initiative, which won $147 million from DOE's Grid Deployment Office to build the world's largest battery system as part of a larger regional effort to expand and manage access to variable renewable resources.[71]

In total, 30–40 LDES projects are slated to receive federal and/or state support, with more support on the way: DOE is expected to invest an additional $100 million, CEC has allocated $190 million, and NYSERDA, $5 million.[72] Additionally, DOE's Loan Programs Office has a growing balance sheet that could be tapped to support even more LDES projects. The DOD is likely to continue to invest in LDES projects that strengthen the reliability and resilience of grids supplying its installations.[73] However, to fully achieve liftoff, the national portfolio of LDES projects needs to significantly grow. DOE's Pathways to Commercial Liftoff report on LDES estimates that a diverse set of 100 or more mid-scale projects (10–20 MW) would take the industry through the demonstration phase, and another 50–100 large-scale projects (50 MW or more) would take it to scale.[74] The report also highlights the need to share information and accelerate learning to maximize the value of each project.

LDES demonstration projects will also need to prove their value in a range of market and regulatory settings, including by making the economic case for LDES to state regulators and PUCs. A coordinated initiative on demonstration projects will also help clarify the different revenue-generation opportunities for LDES technologies. Some may earn the bulk of their revenue in capacity markets, others in energy and ancillary markets, and others in new markets yet to be finalized (see our first and second recommendations). A comprehensive review of the full array of LDES projects nationwide would provide insights into the trajectory of the industry's development and highlight gaps that should be filled by future projects. As discussed in our third recommendation, accelerating clean energy tariffs and clean transition tariffs could also play a role in helping reduce costs passed on to individual ratepayers.[75]

With the first tranche of LDES projects advancing toward and through construction, the time is ripe for the federal government, the states, and other power system stakeholders to work together to ensure that these projects, taken as a whole, meet key shared objectives. While the national suite of LDES demonstration projects will benefit from diversity across duration, storage system form, market, use case, and other attributes, the market will also benefit greatly from standardization of disclosure and validation of key project data. Accessible, comparable, validated cost and performance data (e.g., response time, round trip efficiency, degradation rate) from LDES projects will enable resource planners and project developers to model them. These models should allow a highly accurate assessment of how new LDES resources will perform in specific locations and grid configurations, including in locations that currently have no LDES projects planned and where stakeholders are unfamiliar with their potential contributions. Mandatory disclosures should not impinge on proprietary LDES technology. Validation processes should protect this intellectual property while still ensuring that operators and investors learn what they need to make informed decisions. This approach will allow utilities, developers, investors, and regulators to gain the most confidence toward commercial follow-on projects.

INNOVATION LENS

This recommendation will enable broader demonstration of LDES technologies, which will be critical to enabling long-term demand-side deployment of the technology at commercial scale. Public financial assistance to FOAK projects, however it is provided, helps these projects overcome barriers that usually inhibit private investment, such as high capital costs, upfront technological risks, and early stage revenue uncertainty. The developers and operators of these projects will have opportunities to learn-by-doing, gaining insights that lower costs and improve performance of similar future projects. Requiring projects to be grid-integrated and revenue-generating ensures that the knowledge generated is applicable in a real-world market or regulatory setting. If multiple projects using similar technologies are included in the demonstration portfolio, the suppliers of these technologies may begin to build out supply chains and deepen customer and investor confidence. Conditioning public financial assistance for demonstration projects on information disclosure and validation would also strengthen the deployment phase of innovation by broadening the learning across the industry and among regulators. In the long run, this learning process should enable LDES developers to gain access to conventional, lower-cost project financing. Collaboration between federal and state LDES demonstration programs will be important, enhancing the efficiency and efficacy of knowledge sharing, while reducing duplication.

IMPLEMENTATION

The collaborative review and assessment process should be led by an impartial organization with high technical credibility and strong convening power, such as EPRI or the LDES National Consortium. The LDES National Consortium (in collaboration with the Office of Clean Energy Demonstrations and the Office of Technology Transitions) may be the most natural fit, and such an initiative could dovetail nicely into the expected deliverables that the consortium currently plans to produce over the next few years.[76] Given the plan to transfer the ownership of the LDES National Consortium to private industry partners in three years, it will be important that this new entity maintains a commitment to sharing data with key energy decision-makers. The organization should seek out and gather input into the planning process from a wide range of federal, state, and other participants—both those that have already committed to supporting project investments and those that have not done so—in a transparent and inclusive process. The same body that leads the assessment and review should also aim to articulate the core elements of a standardized disclosure and validation process for project data. The DOE may be best positioned to lead in implementing such a process for the projects that it funds. Other funders, including other federal and state agencies, should be asked to adopt the OCED disclosure and validation template to the extent allowed by applicable laws and regulations.

The national collaboration effort should inform legislative and agency decision making, but the specific mode of support will be determined by each potential funding agency or authority. States may choose to offer direct financial cost-sharing, aid in accelerated project permitting, or create enabling legislative or regulatory actions. For example, Colorado's Promote Innovative and Clean Energy Technologies Act empowers investor-owned utilities within the state to apply to the PUC to recover costs of "innovative, zero-emission technologies for energy generation and storage" through an alternative recovery mechanism (i.e., the clean energy plan revenue rider).[77] In many cases, jurisdictions may benefit from working together to develop and support projects, as exemplified by New England's "Power Up" initiative.

5. FEDERAL ECONOMYWIDE CARBON PRICING

SUMMARY

The administration and Congress should examine options and work toward enacting an economywide market-based carbon pricing program that could contribute to the achievement of net-zero emissions by 2050. Setting a price on carbon—whether through a carbon tax or a cap-and-invest program—confers a clear market value to emissions reductions that is commensurate with the environmental, societal, and economic benefits that reducing global greenhouse gas pollution provides. This market signal will better align clean energy policy goals with the costs of currently available technology and enable greater uptake of cleaner LDES technologies over heavier-emitting alternatives, like natural gas peaker plants. Revenue from the carbon pricing program could be used to foster technology innovation (e.g., supporting the development and deployment of nascent LDES technologies) or for other purposes such as lowering government deficits or reducing distortionary taxes.

RATIONALE

As noted in the second recommendation, the current market does not reflect the full value of LDES nor does it compensate LDES asset owners for their environmental benefits.[78] Put differently, the current market-defined value of LDES is far lower than the societal value. Policies such as procurement programs seek to use government payments to substitute for this "missing demand" for environmental benefits, but require substantial outlays of public funds. A price on carbon could help provide the demand signal needed to encourage deployment of LDES, build investor confidence in the value of LDES solutions, and generate revenue for the government.

An economywide carbon price would have benefits beyond developing demand for LDES. Market-based policies can drive innovation and can more cost-effectively reduce emissions than traditional regulations by giving emitters the flexibility to find the lowest-cost options for reductions.[79] For example, a cap-and-trade program enacted in 1990 for the reduction of sulfur dioxide emissions—the primary cause of acid rain—resulted in a rate of emissions reductions that doubled what was predicted from traditional regulation.[80] In terms of carbon pricing, the world's first national carbon tax in Finland is estimated to have reduced carbon emissions 30 percent faster within its first 15 years of existence than a scenario where carbon pricing had not been enacted.[81]

A federal economywide carbon price will level the playing field between carbon-intensive, incumbent resources, like natural gas peaker plants, and newer, non-emitting technologies like LDES. Specifically, carbon pricing will impact the levelized cost of energy for fossil-fired plants and increase their generating costs commensurate with the extent of their greenhouse gas emissions. Increasing market bid prices will reveal greater differences between off-peak and peak electricity market prices, which LDES technologies can capture.[82] A portion of revenues generated by a carbon pricing program could also be used to offset other federally funded LDES programs, such as research and development grants that would help drive down the cost of LDES and related technologies, or for other purposes such as lowering government deficits or reducing distortionary taxes.

INNOVATION LENS

A carbon price would strengthen existing and future prospective policies aimed at accelerating the deployment of LDES and other emerging low-carbon technologies. Like the first three recommendations above, economywide carbon pricing would primarily accelerate innovation by strengthening demand for LDES. It would also support commercialization and deployment of LDES systems in whatever applications prove to be the most cost-effective. In the short run, these applications might include peaking capacity and operating reserves, as existing generators seek to use LDES systems to reduce the amount they must pay under a carbon price. In the long run, a carbon price would also lead to higher demand for zero-emission electricity as some end-users switch away from fossil-fuel combustion and toward the development and use of more low- and zero-carbon generation capacity. The accelerated penetration of variable renewable sources would, in turn, elicit demand for LDES. If some of the revenue generated by this policy were directed to DOE's LDES research, development, and demonstration units, the agency could target these resources to any pressing innovation challenge facing the energy storage industry. While it will take time before LDES solutions are elicited by a carbon price, the demand signal provided by the price will be crucial to meet long-term climate goals.

IMPLEMENTATION

The administration and Congress should examine options and work toward enacting an economywide market-based carbon reduction program that could contribute to the achievement of net-zero emissions by 2050. Work on such a program should include conducting analyses, developing policy principles, drafting legislation, conducting workshop discussions, and holding committee hearings.

CONCLUSION

LDES can play a critical role in enabling higher penetration of renewables, enhancing grid resilience, reducing use of peaker plants, and diversifying the domestic energy storage supply chain. However, the economic and environmental benefits of LDES have yet to be captured in most grid planning, power market, and energy modeling activities. Near-term, near-commercial scale demonstrations of LDES will be essential to driving down the levelized cost of LDES and producing the data, cost-savings, and operational insights that grid managers will need in the long-term.

The policy recommendations in this brief were developed through discussions with stakeholders across the LDES ecosystem, and offer a potential path forward to unlocking the full value of LDES as a climate technology. By pursuing (1) resource adequacy reforms, (2) operational flexibility reforms, (3) clear and distinct state LDES procurement targets, (4) national coordination and acceleration of LDES demonstration projects, and (5) federal economywide carbon pricing, federal- and state-level decision-makers can ensure that power markets and energy regulation will effectively enable widespread and coordinated deployment and commercialization of LDES.

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Additional Resources

Long-duration Energy Storage Technology Working Group (Webpage)
https://www.c2es.org/accelerating-the-us-net-zero-transition/c2es-technology-working-groups/long-duration-energy-storage

Taking the Long View: Unlocking the Value of Long Duration Energy Storage (Blog)
https://www.c2es.org/2024/12/taking-the-long-view-unlocking-the-value-of-long-duration-energy-storage

Investing in long duration energy storage could take Virginia's energy transition to new peaks (Blog)
https://www.c2es.org/2024/06/investing-in-long-duration-energy-storage-could-take-virginias-energy-transition-to-new-peaks

Deploying Long-Duration Energy Storage in Virginia (Brief)
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