GOVERNOR'S
Energy Office

Long-Duration Energy Storage

A review of technology options, key considerations, costs, and scenarios for the use of long-duration energy storage in Maine pursuant to *Public Law 2023, Chapter 374: An Act Relating to Energy Storage and the State's Energy Goals.*

February 2024

This report is available online at maine.gov/energy

The Maine Governor's Energy Office, established in Title 2 MRSA §9 of Maine Statute, is the designated State Energy Office for the State of Maine, charged with carrying out responsibilities of the state relating to energy resources, planning and development. The office serves as the advisor to the Chief Executive on energy policy matters.

Submitted to the Maine Legislature's Joint Standing Committee on
Energy, Utilities and Technology

February 1, 2024

Table of Contents

Purpose

On June 30, 2023, Governor Mills signed into law Public Law 2023, Chapter 374, *An Act Relating to Energy Storage and the State's Energy Goals* (LD 1850). This legislation builds upon the state's existing energy storage goals and makes clear Maine's intention to invest in energy storage infrastructure to increase grid reliability, resiliency, and support the integration of clean energy resources needed to meet the state's climate and clean energy goals in a cost-effective manner.

Section 3 of this legislation directs the Governor's Energy Office (GEO) to study long-duration energy storage, including opportunities for new and emerging long-duration energy storage technologies that may support the state's need for clean, firm power generation in support of the state's climate and clean energy goals. It directs GEO to submit a report, along with any recommendations, to the Joint Standing Committee on Energy, Utilities and Technology (EUT) and lists four topics that the report must address, including:

1. A discussion of technology options for long-duration energy storage, including emerging technologies and a description of their technical operation and commercial viability, that may be feasible within the state and New England between 2023 and 2040;
2. An overview of known cost and performance characteristics, as well as development considerations by technology, such as development timelines, siting requirements or safety considerations;
3. A discussion of scenarios for long-duration energy storage technologies, such as serving as peaking capacity, providing winter reliability or providing benefits through colocation with renewable resources; maximizing transmission infrastructure or deferring transmission upgrades; and
4. Consideration of whether and under what conditions the use of long-duration energy storage would be cost-effective for ratepayers in the state.

This report, submitted by GEO to the EUT Committee, meets the requirements of the law.

Overview of Report

This report, completed with existing GEO staff resources, addresses the topics as laid out by the legislation and references recent publicly available research and reports conducted by such entities as the U.S. Department of Energy (DOE), National Renewable Energy Laboratory (NREL), trade organizations, and other state entities that conduct energy research and policy.

It is organized into six sections preceded by an introduction. The first section discusses how long-duration energy storage is defined in the literature and for the purposes of this report. The next sections address the four topics as laid out by the legislation from a high-level, systems focus. The final section provides a set of policy considerations the Legislature and other state entities may contemplate to build understanding of the opportunities of new and emerging long-duration energy storage technologies and support development of these technologies in a manner that may support Maine's climate and energy goals over the coming decades.

Specifically:

- **Section I** discusses the definition of long-duration energy storage in the literature and for the purposes of this report.
- **Section II** discusses technology options for long-duration energy storage.
- **Section III** discusses known cost and performance characteristics.
- **Section IV** discusses scenarios for the use of long-duration energy storage in Maine.
- **Section V** discusses the cost-effectiveness of long-duration energy storage and potential opportunities for economic development.
- **Section VI** concludes the report with several policy considerations.

An appendix in also included which provides a list of selected resources that include additional information on this topic.

Introduction & Existing Landscape

In Maine statute, an "energy storage system" is defined as "a commercially available technology that uses mechanical, chemical or thermal processes for absorbing energy and storing it for a period of time for use at a later time."[1] It is important to recognize that this definition is both technology and duration neutral. This is salient as the technology landscape for energy storage is evolving rapidly and includes a diverse set of technologies, each with a different set of cost and performance characteristics.

Technologies that store energy can provide significant benefits to the grid and its resiliency. Energy storage can provide backup power during outages and can help customers and grid operators manage electric load; energy storage can reduce renewable curtailment by absorbing excess wind or solar energy when it is being produced, and discharge it later when the energy is needed; energy storage can defer the need to upgrade or build new transmission and distribution infrastructure or it can improve the economics of new builds; and energy storage can reduce peak loads when peaking generators – often utilizing the highest emitting fuels – are called on to produce electricity, reducing emissions and increasing clean electricity consumption. While energy storage is often referred to as a "Swiss Army knife" that can shift to meet the needs of the grid, to provide these different types of services and reap the highest value from energy storage technologies, storage needs access to markets and clear signals to encourage storage operation in the desired manner.

Today, a majority of installed energy storage capacity in the United States comes from hydroelectric pumped storage with just under 23 gigawatts (GW) – primarily built before 2000 – operating across the U.S.[2] In recent years, lithium-ion batteries have made up more than 90 percent of new energy storage installations: between 2010 and the end of 2022, nearly 9 GW of battery storage resources have come online.[3] The U.S. Department of Energy (DOE) expects continued growth of energy storage resources over the next several decades, including 225 to 460 GW of long-duration energy storage resources by 2050 to support net-zero policies and high renewable penetration across the country.[4]

Maine's energy storage market has only more recently begun to grow, with grid-scale deployments of battery energy storage projects first coming online in 2015 and 2016. The state is not a host of any large hydroelectric pumped storage facilities. As of January 2023, Maine had

> Maine law defines an **"energy storage system"** as "a commercially available technology that uses mechanical, chemical or thermal processes for absorbing energy and storing it for a period of time for use at a later time."

---

[1] M.R.S. 35-A §3481

[2] U.S. Energy Information Administration Form 860. *U.S. EIA*, October 2023, https://www.eia.gov/electricity/data/eia860M/.

[3] "Battery Storage in the United States: An Update on Market Trends." *U.S. EIA,* July 24, 2023, https://www.eia.gov/analysis/studies/electricity/batterystorage/.

[4] "Pathways to Commercial Liftoff: Long Duration Energy Storage." *U.S. DOE,* May 2023, https://liftoff.energy.gov/wp-content/uploads/2023/05/20230505-LDES-Pathway-to-Commercial-Liftoff_Public-Webinar-vF_web.pdf.

63 megawatts (MW) of battery energy storage projects connected in front of the meter operating or expected to go into service within the year as illustrated in Table 1. Additional storage capacity, again primarily served by batteries, is operating behind-the-meter across the state. These resources are generally smaller in scale and customer-sited, though a project such as Boothbay Harbor's 0.5 MW advanced lead-acid battery installation, the result of Maine's Non-Wires Alternatives (NWAs) process, is an example of another pathway for storage development that, in this case, addressed local reliability needs as an alternative to a transmission upgrade.

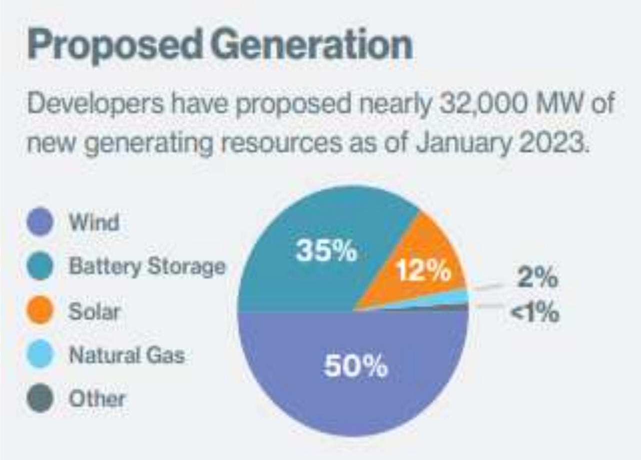
Maine has established energy storage goals of at least 300 MW of installed capacity within the State by the end of 2025 and at least 400 MW by the close of 2030. These targets, the result of bipartisan legislation enacted in 2021, established Maine as the ninth U.S. state with codified energy storage targets, which are significant given the size of the state's electricity load. The state's 2030 goal of 400 MW of operational energy storage represents approximately 17 percent of Maine's peak demand as of 2021.

Table 1. Front-of-the-Meter Storage Projects in Maine[5]

Resource Name	Town	Nameplate Capacity (MW)
Madison BESS	Madison	4.7
William F. Wyman	Yarmouth	16.7
Rumford BESS	Rumford	4.7
Great Lakes Millinocket	Millinocket	20.9
Bonny Eagle Renewable BESS	Hollis Center	8.0
Rumford Renewable BESS	Rumford	8.0
TOTAL		63

Additionally, hundreds of MWs of energy storage resources are at various stages of development in Maine, and across New England 35 percent of the 35,000 MW of proposed resources in the ISO New England (ISO-NE) interconnection queue are battery storage resources.[6] While some attrition is typical, this represents a significant shift away from the historic power generation resource mix in New England which until relatively recently,

Figure 1. Proposed Generating Resources in ISO-NE (ISO-NE)



---

[5] "ISO New England – 2023 Forecast Report of Capacity, Energy, Loads, and Transmission." *ISO-NE*, May 2023, https://www.iso-ne.com/static-assets/documents/2023/05/2023_celt_report.xlsx.

[6] "New England Power Grid 2022-2023 Profile." *ISO-NE*, https://www.iso-ne.com/static-assets/documents/2021/03/new_england_power_grid_regional_profile.pdf.

was driven by coal, oil, and nuclear, and has shifted in recent years primarily to a mix of natural gas, nuclear, and renewables.

The state of Maine has statutory greenhouse gas reduction requirements of 45 percent below 1990 levels by 2030 and 80 percent by 2040, as well as a requirement for carbon neutrality by 2045. To support that goal, in 2019 Governor Janet Mills signed bipartisan legislation that established a Renewable Portfolio Standard (RPS) requiring 80 percent of electricity used in the state be generated by renewable resources by 2030, and a target of 100 percent by 2050. In 2023, Maine crossed the threshold of using more than 50 percent of its electricity from renewable sources. In Governor Mills' 2023 State of the Budget Address, recognizing the progress made to date and the key role of clean energy in controlling costs for consumers and reducing fossil fuel dependence, she announced a new accelerated goal of 100 percent clean energy by 2040.

These policies, as well as the decarbonization policies of Maine's neighboring states, will necessitate substantial new clean energy resource development in the coming decades. As clean energy is deployed, including significant variable renewable resource capacity like solar and wind, continuing to ensure power system reliability, resource adequacy, and resilience will be critical.

Ultimately, Maine and the region's evolving grid mix, load patterns due to the electrification of buildings and transportation, and weather patterns due to climate change are changing the shape and length of the system's peak demand. In this transition to a 100 percent clean electricity system, energy storage resources will likely play a significant role. Energy storage resources rated for four hours or less already provide many services to the grid today, complementing wind and solar resources by shaving peak demand, among other services.

Several policies and programs are in place in Maine today to encourage the development of storage resources in the state to meet Maine's energy storage goals, to provide valuable services to the grid, and to provide resiliency for customers. These include pilots and demand response programs for behind-the-meter storage resources at the Efficiency Maine Trust, the creation of the Maine Energy Storage Program which requires the Governor's Energy Office to propose a procurement for up to 200 MW of utility-scale energy storage, pending Solar For All programs that aim to reduce the specific barriers that low-income Maine people face in accessing the benefits of solar and storage, and a sales and uses tax exemption for large energy storage projects 50 MW or greater.

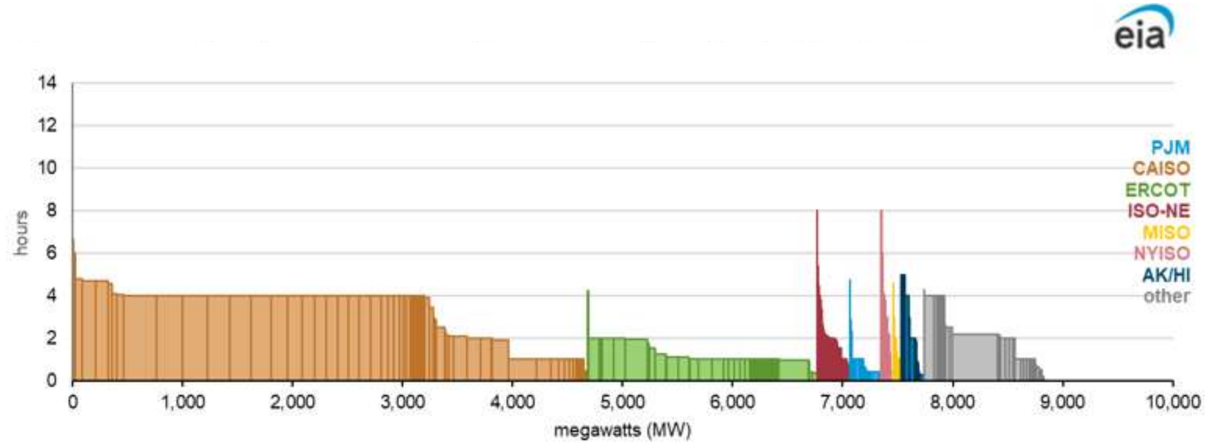
To date, more than 90 percent of energy storage capacity installed in the U.S. since 2010 has a duration of four hours or less.[7] This is a result of several factors including technological capability, cost, existing regional market rules, and the existing set of generators, needs of the electric grid, and customer usage.

---

[7] "Moving Beyond 4-Hour Li-Ion Batteries: Challenges and Opportunities for Long(er)-Duration Energy Storage." *NREL*, September 2023, https://www.nrel.gov/docs/fy23osti/85878.pdf.

Figure 2 illustrates the power and capacity of large-scale battery storage by region as of 2022. ISO-NE has a total installed capacity of 302.2 MW of large-scale battery energy storage with a total duration of 633 megawatt hours (MWh). The average duration of a single project in ISO-NE is 2.3 hours with an average installed capacity of 3 MW and an average energy capacity of 6.3 MWh.[8]

Figure 2. Power capacity and duration of large-scale battery energy storage by region (U.S. EIA 2022)



Data source: U.S. Energy Information Administration, *2022 Form EIA-860 Early Release, Annual Electric Generator Report*

Longer durations of energy storage, in addition to existing shorter duration storage resources, could provide some of the flexibility and firm capacity needs in a future with significant renewable energy penetration, optimizing grid resources across hours, days, or weeks at a time. Long-duration energy storage resources are not widely deployed today, but several technologies are in development. Changes to policy, financing, and market signals, in addition to the changing dynamics of Maine's grid, may support the deployment of longer-duration energy storage resources in the decades ahead. The following sections explore system-level opportunities for long-duration energy storage in Maine and existing barriers to their deployment.

Section I: Defining Long-Duration Energy Storage

Duration in the context of energy storage means the number of hours a storage device or facility can deliver continuous energy at its rated capacity. For example, a fully charged battery with 5 MW of rated capacity and 2-hour duration can deliver 10 MWh of electricity to the grid.

---

[8] "2023 Early Release Battery Storage Figures." *EIA*, June 2023, https://www.eia.gov/analysis/studies/electricity/batterystorage/.

As previously noted, most energy storage resources today have a duration of four hours or less. There are several reasons that this is the case and those reasons will be discussed in greater depth later in this report.

Duration: The number of hours a storage device or facility can deliver continuous energy at its rated capacity. Measured in hours.

Energy capacity: The total amount of energy that can be stored in the system. Measured in watt-hours.

Rated capacity: The maximum instantaneous amount of energy the storage system can deliver. Measured in watts.

To date, there is no standard or universally agreed upon definition of "long-duration" energy storage. Advanced Research Projects Agency-Energy (ARPA-E), an office of DOE that pursues high-potential, high-impact energy technologies for investment and development in advance of becoming commercial, runs a program to develop energy storage systems with a focus on 10 to 100 hour durations to increase grid resilience and performance.[9] DOE's Long Duration Storage Shot initiative also aims to accelerate breakthroughs in energy storage, and to reduce costs of grid-scale technologies, with a focus on durations of 10 hours and greater.[10] NREL recently conducted a literature review of 39 documents that provide definitions of long-duration energy storage. They found most definitions fit into categories of greater than 4 hours, greater than 10 hours, and durations that extend to multiple days. NREL concluded that there was some justification for finding near consensus in defining long-duration as greater than 10 hours.[11]

For the purposes of this report, long-duration will be discussed in a few ways, primarily focusing on the characteristics of a storage resource to provide firm capacity and resource adequacy to meet the needs of Maine's evolving energy system as indicated by the legislative intent of LD 1850. In some places in this report, primarily when discussing specific technologies, distinct durations by hour may be discussed, but when discussing the opportunities of long-duration energy storage more broadly, the report will discuss long-duration storage in terms of resources that:

- Have durations of **greater than four hours**;
- Can provide inter-day or "**diurnal**" energy storage (up to ~12 hours); or
- Have capacities of multiple days or longer, sometimes referred to as "**seasonal**" storage. 100-hour storage is generally discussed as the upper limit of energy storage resource duration.

---

[9] "Duration Addition to electricitY Storage." *ARPA-E*, https://arpa-e.energy.gov/technologies/programs/days. Accessed November, 2023.

[10] "Long Duration Storage Shot." *U.S. DOE*, https://www.energy.gov/eere/long-duration-storage-shot. Accessed November 2023.

[11] "The Challenge of Defining Long-Duration Energy Storage." *NREL*, 2021, https://www.nrel.gov/docs/fy22osti/80583.pdf.

This report has chosen to discuss these categories of long-duration storage, rather than specific hour markers, to be able to discuss the types of circumstances or needs an energy storage system with longer durations than today's average may be able to meet in a future grid where heating and transportation are highly electrified or where the grid is supplied by 100 percent clean energy.

These needs and the availability of technologies with durations of greater than four hours, diurnal, or seasonal will depend heavily on evolving regional demand, renewable energy deployment, market signals, and the economics of competing technologies to provide similar services.

Section II: Technology Options for Long-Duration Energy Storage

In 2022, GEO sponsored the completion of the "Maine Energy Storage Market Assessment" (the Assessment) as directed by P.L. 2021, Chapter 298, *An Act to Advance Energy Storage in Maine*.[12] The Assessment evaluated storage technologies and use cases, assessed the market and policy landscape and hurdles to storage deployment, and performed a cost-benefit analysis for a select set of scenarios. The scenarios demonstrated opportunities to deploy storage in the state over the next decade and focused on commercially and economically available technologies. Though the study was primarily technology neutral, it ultimately modeled lithium-ion batteries in its cost-benefit analysis and predicted batteries will likely comprise most of the storage deployed in Maine in the next five years given continued cost declines, high round trip efficiency, siting flexibility, and the ability to provide fast-response to balance and integrate renewable resources.

However, in its key takeaways, the Assessment also noted that long-duration storage technologies may support New England's need for clean, firm energy in a deeply decarbonized future, and that a range of potential long-duration technologies could provide Maine with low- or zero-carbon dispatchable generation or long-duration energy storage, particularly beyond 2030 as regional carbon targets become stricter and the costs of emerging technologies decline.

As identified by Maine's statutory definition of an energy storage system, there are several different categories of technologies or processes that can store energy for use at a later time including through mechanical, chemical, or thermal processes. Today, commercially available long-duration energy storage resources are very limited, but several promising technologies are in research, development, and demonstration phases.

DOE's ARPA-E initiative focused on developing long-duration storage systems with durations of 10 to 100 hours is currently supporting 11 projects that, if successful, will provide new forms of long-duration stationary electricity storage with a goal of enhancing grid resiliency, providing low-cost energy capacity, supporting grid infrastructure, and enabling a greater share of intermittent renewable resources in the generation mix. Those projects, supported by university research labs and start-up energy companies include solid state thermal batteries,

---

[12] "Maine Energy Storage Market Assessment." *Energy and Environmental Economics, Inc. (E3)*, March 2022. https://www.maine.gov/energy/sites/maine.gov.energy/files/inline-files/GEO_State%20of%20Maine%20Energy%20Storage%20Market%20Assessment_March%202022.pdf.

CO2-based pumped thermal energy storage, aqueous sulfur systems, geomechanical pumped storage, and high-performance flow batteries, among others.[13]

Beyond DOE's ARPA-E program the federal government has invested in several other efforts to support research on long-duration energy storage technologies, recognizing that these resources could play a critical role the decarbonization of the U.S. energy system. Those efforts include the Energy Storage Grand Challenge, the Long Duration Storage Shot, and other programs housed in DOE's Office of Clean Energy Demonstrations. Each of these efforts and investments have a role to play in technology development, evaluation, and commercialization, as well as the development of policy tools and standards for market access and compensation that could be adapted for regional markets.

The list of technologies discussed below is not inclusive of all potentially viable long-duration energy storage technologies that could become available in the coming decades. It represents a sample of the different types of technologies under development that could provide energy storage over long durations in the decades ahead.

Mechanical

Mechanical forms of energy storage include such technologies as hydroelectric pumped storage, compressed air, and flywheels.

Hydroelectric pumped storage is a technologically mature form of energy storage and the most common form of energy storage operating in the U.S. today. Most pumped storage facilities in the U.S. were built in the 1970s, about half of which are still operating today. A typical pumped storage facility pumps water into a storage reservoir during the night, taking advantage of times when both demand and electricity prices are lower than the daytime. When power is needed, water is released from the reservoir and flows downhill through hydroelectric generators at a dam in a lower reservoir. Pumped hydro facilities are generally larger in both capacity and duration than lithium-ion battery storage facilities, however they can be challenging to site, require licensing and relicensing through the Federal Energy Regulatory Commission (FERC), and can consume more energy than they store when pumping water uphill. Maine does not have any existing hydroelectric pumped storage facilities, and no new pumped storage facility has been built in the U.S. since 2012. There are two pumped storage facilities in Massachusetts, located at Northfield Mountain and Bear Swamp, both of which are currently undergoing relicensing through FERC. These facilities are high capacity, 1,000 MW and 600 MW respectively, and have durations of 6-10 hours.[14]

Compressed air energy storage, also referred to as CAES, is similar in concept to pumped hydroelectric storage, but involves air instead of water. CAES requires a large underground area like a cavern or above ground storage reservoirs. When the compressed air is discharged, power is generated as the heated compressed air expands, driving a gas turbine. Only one CAES

---

[13] "Duration Addition to electricitY Storage." *ARPA-E*, https://arpa-e.energy.gov/technologies/programs/days. Accessed November, 2023.

[14] "Charging Forward: Energy Storage in a Net Zero Commonwealth." *Energy and Environmental Economics, Inc. (E3)*, December 2023, https://www.masscec.com/sites/default/files/documents/Charging%20Forward%20%282023%29.pdf.

facility is currently operating in the U.S.—a 100 MW/100MWh facility that compresses air in a salt cavern in Alabama and is operated by the PowerSouth Energy Cooperative.[15]

Flywheels store kinetic energy in a wagon wheel-like rotating mass. As it spins, the motor or other source of power builds torque in the direction of rotation. When discharged, a braking torque is applied to decelerate the flywheel. Historically, flywheels have been used alongside rotating machinery at mills or steam engines for power management, but they can also be standalone machines. There are four flywheels generating power in the U.S. with a total combined capacity of 47 MW/17 MWh.[16]

Chemical

The category of chemical and electro-chemical energy storage technologies includes lithium-ion batteries, flow batteries, and iron-air batteries to name a few, in addition to power-to-gas or power-to-hydrogen.

Lithium-ion batteries are a chemical form of energy storage that have high energy density and efficiency in a relatively small package. They can be modular, mobile, and have a fast-response time. Compared to mechanical energy storage options, lithium-ion batteries have a shorter lifespan due to degradation of their materials. However, they continue to see cost declines and have the potential to expand their market from four hours or less to longer durations. There are already six- and eight-hour lithium-ion variations active today, but according to the Electric Power Research Institute (EPRI), it’s possible longer-durations, up to 24-hours could become cost-competitive in a decade.[17] However beyond costs, technology, supply chain, and regulatory barriers would also likely need to be exceeded for lithium-ion batteries to compete with other long-duration technologies in the future.

Flow batteries offer an alternative to lithium-ion batteries that have a longer lifespan and no capacity degradation during their operation, which may allow them to serve longer durations. However, today they are more expensive and lower density. Flow batteries store energy in liquid electrolytes. When discharged, the liquid is pumped through electrodes from one tank to another, extracting electrons.

Iron-air batteries use inexpensive and abundant materials—iron and air—to generate electricity through the reaction of these materials which create rust, then reversing the reaction by “unrusting” the iron to recharge the battery. These types of batteries require a larger footprint that lithium-ion batteries but offer potential benefits in terms of their material safety and domestic supply chain stability. This is an emerging technology that could provide seasonal storage with active pilot projects in the demonstration phase in the U.S. today. Form Energy, a

---

[15] “Compressed air energy storage technology: Generating electricity out of thin air.” *Baldwin EMC*. https://www.baldwinemc.com/compressed-air-energy-storage-technology-generating-electricity-out-of-thin-air/. Accessed December 2023.

[16] “Electricity explained: Energy storage for electricity generation.” *U.S. EIA*. https://www.eia.gov/energyexplained/electricity/energy-storage-for-electricity-generation.php. Accessed December 2023.

[17] “Alternative technologies ‘may struggle to compete with lithium-ion’ as duration grows.” *Energy Storage News*, March 2022, https://www.energy-storage.news/long-duration-energy-storage-may-struggle-to-compete-with-lithium-ion-as-its-duration-grows/.

Massachusetts-based storage company, has announced several upcoming pilot deployments of its technology, including a partnership with Great River Energy to build a 1 MW/150 MWh pilot in Cambridge, Minnesota with an expected operational date of 2025.[18]

Hydrogen produced with electricity from renewable energy may also have potential to provide Maine and New England with long-duration energy storage. As the power sector becomes cleaner and the costs of hydrogen production technologies like electrolyzers fall, limited hydrogen could be produced and stored in pipes or tanks, then combusted to balance renewable generation or provide low-carbon power during periods of sustained low renewable output as a diurnal or seasonal storage resource. However, the New England region differs from other regions in the United States in that it does not have significant documented geologic storage potential. Hydrogen production and generation could reduce total investment needs for renewables and batteries that would be needed in a future with limited thermal assets. Significant production tax credits were made available to incentivize production of clean hydrogen with passage of the federal Inflation Reduction Act. DOE's Hydrogen Shot initiative seeks to reduce the cost of clean hydrogen by 80 percent to $1 per kilogram near the end of the decade.[19]

Thermal

Thermal technologies can include technologies such as sensible heat, latent heat, and thermochemical heat.

Sensible heat entails heating a material and then discharging the energy by creating steam. The output or capacity of this method is highly dependent on the density and volume of the storage material. This type of storage has been deployed using materials such as molten salt or concrete. Solar-thermal systems use sensible heat storage by taking advantage of excess heat energy produced by solar and storing that heat in fluids such as water or molten salt. There are two operational solar thermal plants in the U.S., one in Arizona and one in Nevada with a combined capacity of 405 MW. This technology can be deployed with a small footprint and has the potential to be scaled for longer durations.

Latent heat relies on a similar concept, but charges and discharges energy through the phase change of a material (solid to liquid or liquid to gas), rather than temperature change. Salts and metals, such as aluminum, are being used in the development of this technology.

Thermochemical storage relies on high temperature processes to drive chemical reactions that break and reform bonds in reactive materials. Energy could be stored in these chemical bonds for significant periods of time. This concept is in the very early stages of development.

Section III: Cost and Performance Characteristics

Each storage technology that has been discussed is at a different level of commercial or market maturity. Each also has different considerations regarding their development timelines, siting

---

[18] "Form Energy Announces Pilot with Great River Energy to Enable the Utility's Transition to an Affordable, Reliable and Renewable Electricity Grid." *Form Energy,* May 2020, https://formenergy.com/wp-content/uploads/2020/05/Form-Energy_-GREPilotPress-Release.pdf.

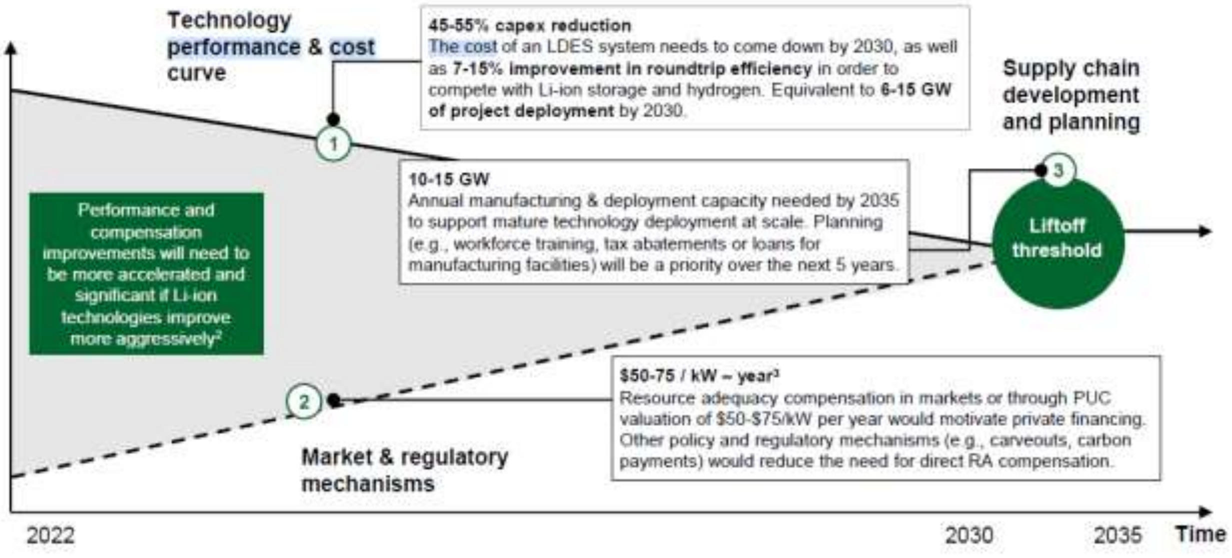
[19] "Hydrogen Shot." *U.S. DOE*, https://www.energy.gov/eere/fuelcells/hydrogen-shot. Accessed December 2023.

needs, scalability, roundtrip efficiency, operational characteristics, safety considerations, and costs.

At the federal level, long-duration energy storage has been recognized as a set of technologies with the potential to play a significant role in achieving a decarbonized power system. In order to accelerate clean energy technologies from development to commercial viability to achieve net-zero emissions by 2050, the U.S. DOE has recently published a series of Liftoff Reports that highlight the role of public and private sector investment in technology deployment.

DOE's *Pathways to Commercial Liftoff: Long Duration Energy Storage* report, published in March 2023, modeled decarbonization pathways for the U.S. power sector to assess the role of long-duration energy storage technologies in this transition from an operational and cost perspective. This analysis estimates that the U.S. grid may need 225-460 GW of long duration energy storage capacity to support net zero goals by 2050, and that long-duration energy storage technologies could result in significant savings and avoided capital expenditures compared to pathways that do not utilize storage capacity. DOE defines "liftoff" as the point where these technologies and their supporting industry no longer require significant public capital and investment to succeed, and when the risk is adequate for private investors to act. The Liftoff report describes the improvements in technology, cost declines, regulatory supports, and developments in domestic supply chains to achieve liftoff of long-duration energy storage technologies in the early- to mid-2030s.

Figure 3: Achieving liftoff in the 2030s will require improvements in technology, cost declines, regulatory supports, and domestic supply chain development (DOE Pathways to Commercial Liftoff: Long Duration Energy Storage)

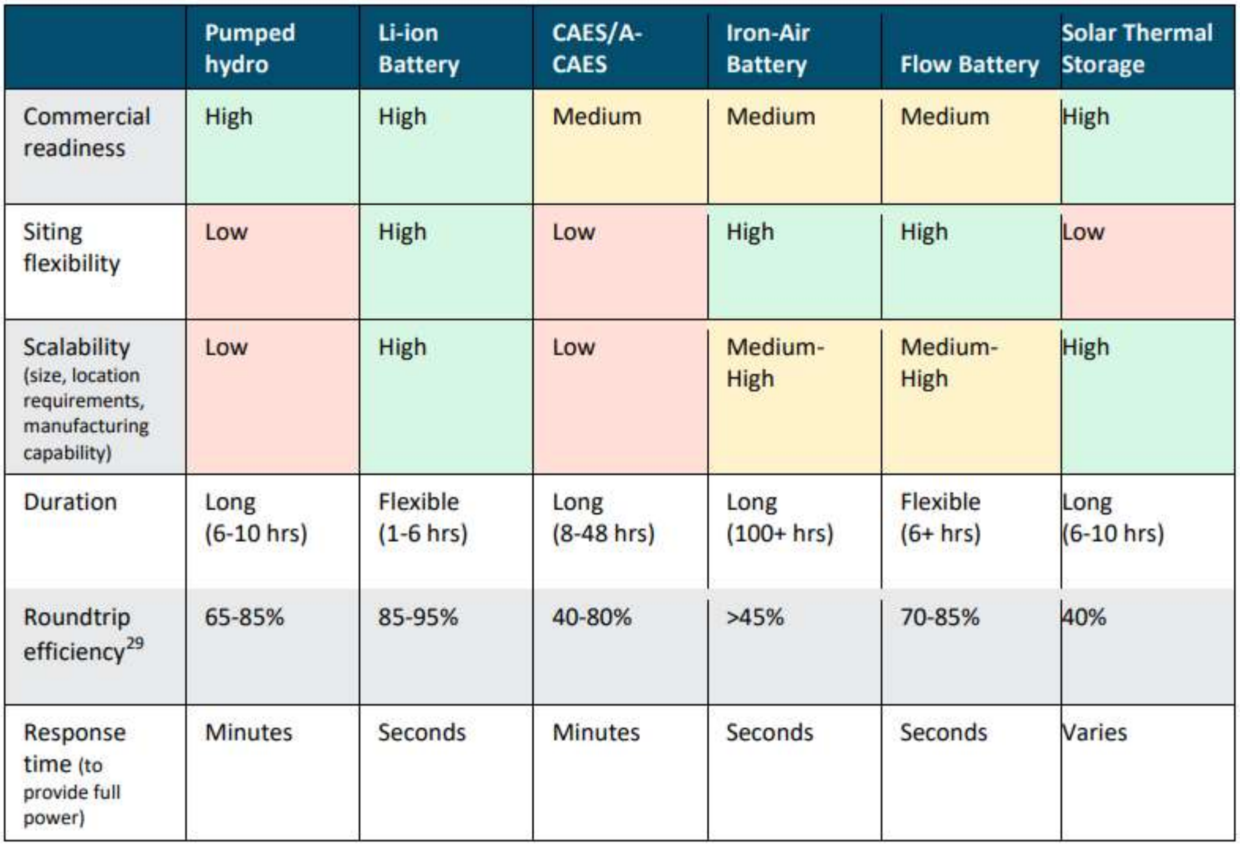


The DOE report highlights the public and private investments that will be needed to support commercialization of long-duration energy storage resources, including in the technology itself and in manufacturing capacity to scale deployment. It's estimated that cost curves must decline by 45-55 percent by 2028-2030 in addition to performance and efficiency improvements.

The development of commercially available and cost-effective long-duration energy storage technologies remains highly uncertain as of 2024, though significant investments are being made at both the federal level and by the private sector to advance these technologies. DOE has identified ambitious cost targets for energy storage technologies through its Energy Storage Grand Challenge Roadmap, including a 90 percent reduction in the levelized cost of storage for long-duration applications compared to a 2020 baseline cost by 2030, reaching a levelized cost of \$0.05/kWh.[20]

Adjustments to state policies and regional market compensation structures may also support the development of compensation structures that support deployment of long-duration energy storage and accelerate private sector confidence in financing of these technologies in the decades ahead. Though not exhaustive, Table 2 summarizes the characteristics of several types of existing and emerging technologies that can store energy for a variety of durations from greater than four hours to diurnal and seasonal storage.[21]

Table 2. Overview of long duration energy storage characteristics by technology (Maine Energy Storage Market Assessment)



	Pumped hydro	Li-ion Battery	CAES/A-CAES	Iron-Air Battery	Flow Battery	Solar Thermal Storage
Commercial readiness	High	High	Medium	Medium	Medium	High
Siting flexibility	Low	High	Low	High	High	Low
Scalability (size, location requirements, manufacturing capability)	Low	High	Low	Medium-High	Medium-High	High
Duration	Long (6-10 hrs)	Flexible (1-6 hrs)	Long (8-48 hrs)	Long (100+ hrs)	Flexible (6+ hrs)	Long (6-10 hrs)
Roundtrip efficiency[29]	65-85%	85-95%	40-80%	>45%	70-85%	40%
Response time (to provide full power)	Minutes	Seconds	Minutes	Seconds	Seconds	Varies

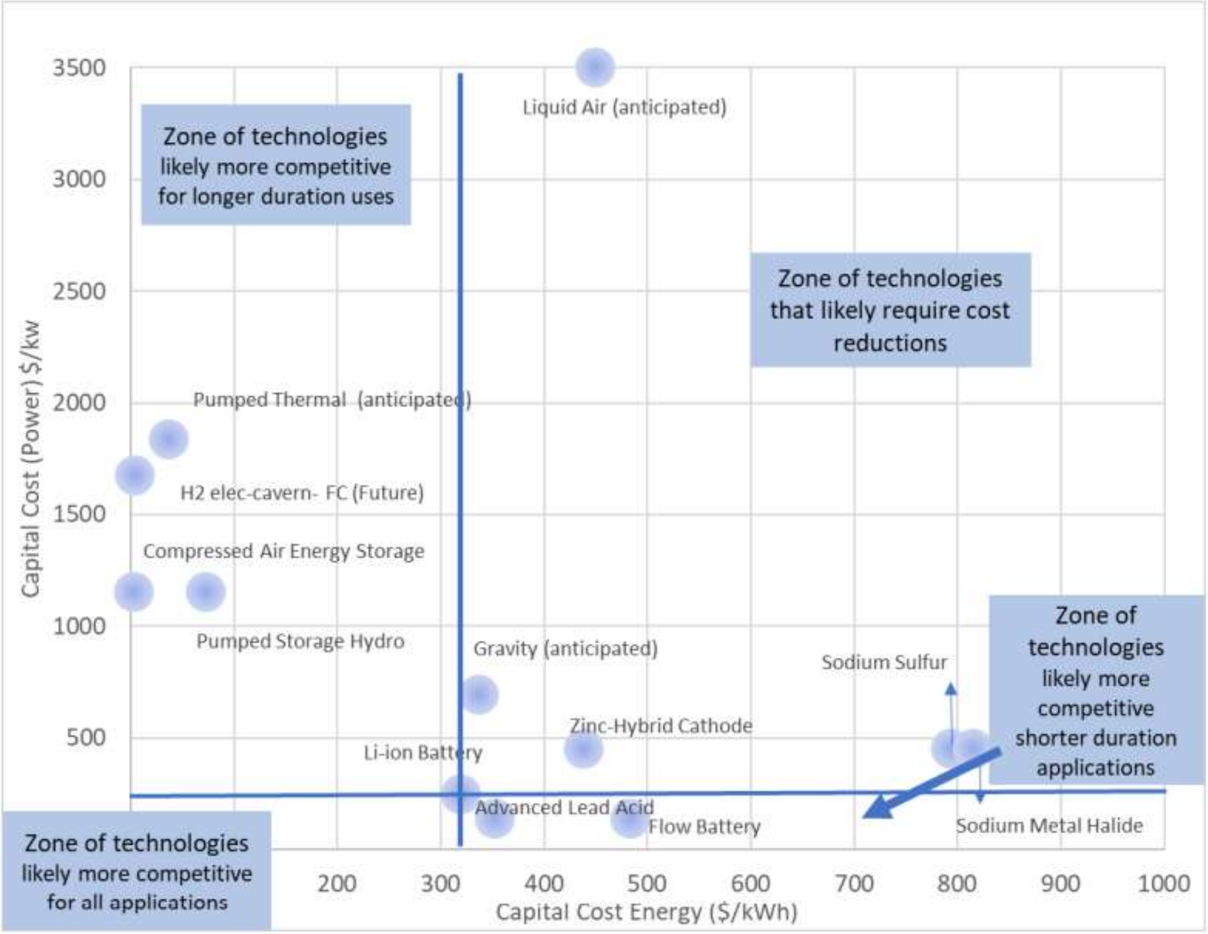
---

[20] "Energy Storage Grand Challenge Roadmap." *U.S. DOE*, December 2020, https://www.energy.gov/sites/default/files/2020/12/f81/Energy%20Storage%20Grand%20Challenge%20Roadmap.pdf.

[21] "Maine Energy Storage Market Assessment." *Energy and Environmental Economics, Inc. (E3)*, March 2022. https://www.maine.gov/energy/sites/maine.gov.energy/files/inline-files/GEO_State%20of%20Maine%20Energy%20Storage%20Market%20Assessment_March%202022.pdf.

Figure 4, drawn from NREL's Storage Futures Study, illustrates the capital costs for energy ($/kWh) compared to the capital costs for capacity or power ($/kW) for a range of energy storage technologies.[22]

Figure 4. Capital costs for energy ($/kWh) vs. capital cost for capacity ($/kw) for a range of storage technologies (NREL Storage Futures Study)



Technologies with higher power costs and lower energy costs may be most competitive for long-duration applications, though NREL's study recognizes anticipated costs factored into the chart have a high likelihood of changing as technologies advance and move toward commercialization.

Like many other generation resources, the value of storage is closely tied to its ability to stack multiple value streams and to receive appropriate signals to optimize both charging and operation.

---

[22] "Storage Futures Study: Key Learnings for the Coming Decades." *NREL,* 2022, https://www.nrel.gov/docs/fy22osti/81779.pdf.

Section IV: Potential Use Cases for Long-Duration Energy Storage in Maine

This section will discuss potential use cases for new and emerging long-duration energy storage technologies in Maine, and the opportunities for these resources to support Maine's need for clean, firm power generation to meet the state's climate and clean energy goals from a high-level, systems perspective. This section will also discuss some of the regulatory barriers in place today that could limit the ability of long-duration energy storage to be adequately compensated for its services.

Two- and four-hour storage can earn compensation for a range of grid services to the electric system today. These resources can participate in wholesale energy markets for energy arbitrage, ancillary services, and in ISO-New England's forward capacity market auction. As more end uses like heating and transportation are electrified and electricity generation is decarbonized through high penetrations of renewables and clean resources, longer durations of storage may be able to support and balance the grid during times of high demand and low renewable output through inter-day or multi-day storage. As grid dynamics evolve in Maine and New England, the value of certain types of grid services may increase and new services that can be provided by long-duration energy storage may emerge. In meeting Maine's 2040 and 2050 emission reduction and clean energy goals, it's likely that the need for resources that can provide the services of capacity, energy arbitrage, and the ability to avoid emissions will be particularly great.

A grid served by a high penetration of variable renewable resources will increase the need for resources that can provide firm capacity to the system. This need for capacity is closely tied to the concept of resource adequacy, which is defined by the U.S. Energy Information Administration (EIA) as "the ability of the electric system to supply the aggregate electrical demand and energy requirements of the end-use customers at all times."[23] While in the vast majority of scenarios a highly decarbonized grid will provide sufficient resource adequacy, in rare instances of multi-day stretches of low wind and solar production, particularly during the winter months when electricity demand for heating will be significant, long-duration storage resources may be able to provide significant value.

Resource adequacy: The ability of the electric system to supply the aggregate electrical demand and energy requirements of the end-use customers at all times.

When this circumstance occurs today, the gap is typically filled by ramping up fossil fuel-fired generators that have onsite fuel stored for this purpose. In New England, coal and oil-fired generators make up approximately 20 percent of the region's electric generating capacity. These facilities are used infrequently but benefit from capacity payments that incentivize them to be available to meet these periodic needs typically in the winter months. In the decades to come, long-duration energy storage could provide this same or similar capacity without the

---

[23] "Glossary: Electricity." *U.S. EIA*, https://www.eia.gov/tools/glossary/?id=electricity. Accessed December 2023.

emissions profile of oil-fired generation. According to ISO-NE, more than 7,000 MW of generating capacity—primarily coal, oil, and nuclear generators—have retired or announced plans to retire as of 2020. ISO-NE predicts another 5,000 MW of coal and oil-fired generation will likely retire in the next several years.[24]

To incentivize long-duration energy storage resources to provide firm capacity, resource adequacy, and electric reliability to the wholesale electric system, the regional capacity market will need to evolve to properly value and compensate the technology for its services. While the use of large amounts of long-duration energy storage for firming capacity may be unlikely in the near term, indications that market rules and signals are evolving to allow for proper compensation could be important to shaping their development for this use.

Historically, the period of peak demand on any given day does not last very long. In Maine, peak demand is generally in the early evening hours. This pattern can be well served by short duration storage resources charged during the day by relatively cheap solar. This common pattern of demand, in addition to falling prices of lithium-ion batteries, has resulted in regional wholesale markets adopting policies that compensate storage resources that can supply four hours of duration. ISO-NE's capacity and ancillary services markets allow storage facilities with durations less than four hours to receive some capacity credit, but do not differentially value and compensate longer-duration energy storage systems or firm zero carbon resources for their potential reliability services.

At present, a 100-hour storage system would receive the same capacity accreditation as a four-hour battery, despite providing the potential additional value of increased firm capacity and the ability to deliver firm supply between days or over several sequential days. Recognizing that New England's power grid is rapidly evolving as economic trends, technological advances, and policies alter the mix of resources providing electricity across the region, since 2022 ISO-NE has been working on a proposal to modify and update the resource capacity accreditation process to enhance the way that capacity contributions from all resource types are measured and valued. Any changes to the current framework which determines how capacity resources can bid into the Forward Capacity Market will ultimately require review and approval by the Federal Energy Regulatory Commission (FERC). Evolving capacity accreditation rules in ISO-NE will play a significant role in incentivizing storage of durations greater than four hours.

As Maine advances beneficial electrification, it is likely that the state will shift from a net summer to a net winter-peaking system within the coming decade. This shift is driven in part by significant new solar generation across the region driving down daytime demand, as well as continued deployment of electrified heating technologies. In June 2023, Maine surpassed its goal of installing 100,000 new heat pumps between 2019 and 2025 two years early and Governor Mills announced a new target of installation of another 175,000 heat pumps by 2027. Increasing electrification and renewable generation deployment, and the associated

---

[24] "New England Power Grid: 2022-2023 Profile." *ISO-NE*, https://www.iso-ne.com/static-assets/documents/2021/03/new_england_power_grid_regional_profile.pdf.

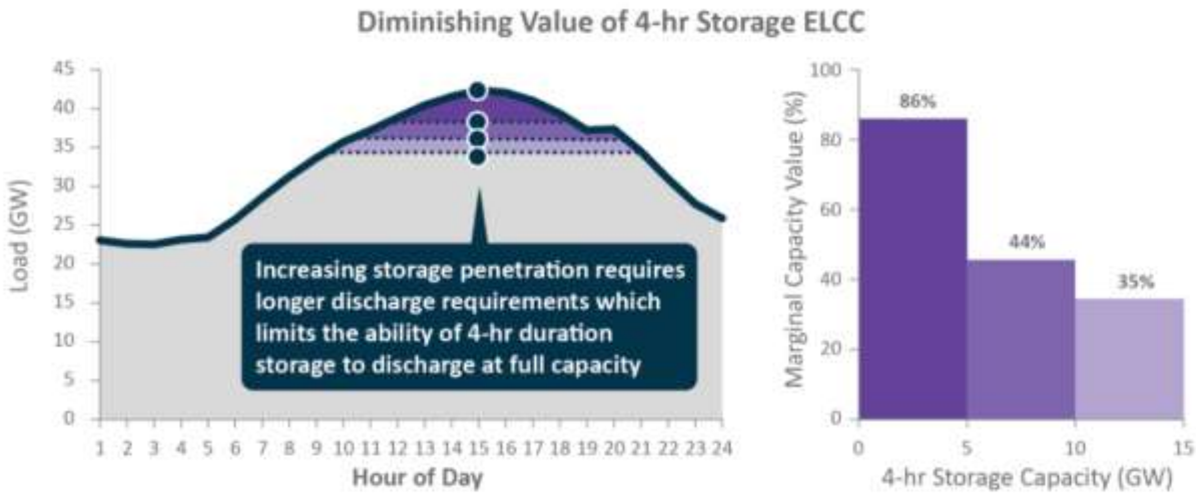
transformation of peak demand trends, will have broad implications across electricity markets, including for energy storage deployment.

In general, as peaks flatten and become longer, the ability of two- or four-hour storage resources to dispatch for the entire period of projected peak is diminished. Furthermore, as storage deployment increases, it can have the effect of further widening net peak load periods, which in turn, drives the need for additional stored energy or energy stored for longer durations. When the net peak widens, there is less opportunity for the energy storage resource to recharge during periods of low wholesale energy prices – typically when renewable energy production is highest.

This phenomenon is illustrated by the concept of ELCC or “effective load carrying capacity.” ELCC, in short, is a measurement of the ability of a resource to produce energy when the grid needs it most, such as during the system peak. Energy storage is a finite resource as it must be charged and recharged like a cellphone, but it’s different than solar and wind in that it is dispatchable. Much of the time, energy storage has a high ELCC because resource owners or operators can choose the moment to dispatch the storage and usually do so when it’s needed most. But as net peak load periods extend beyond the two- or four-hour windows that today’s batteries can handle, the ELCC declines, unless the battery is derated (discharged at a reduced power capacity) or resources with longer storage durations are available. This is illustrated in Figure 5.

ELCC: Effective load carrying capacity is a measurement of the ability of a resource to produce energy when the grid needs it most, such as during the system peak.

Figure 5: Illustrative chart showing the impact of additional storage resources on ELCC (E3)[25]



The addition of longer durations of energy storage could address this challenge at first, but these resources will also see a decline in ELCC overtime. Diurnal and seasonal durations will likely maintain their ELCC for longer and decline over a greater period of time.

Ultimately, the ability of energy storage resources to contribute their full capacity to the regional grid and bolster resource adequacy in a decarbonizing grid is dependent on the makeup of the rest of the resource portfolio. Additional solar resources can narrow the peak demand, reducing the number of hours of storage needed to reduce that peak and increases the chance of the storage asset being able to recharge using solar before the next peak. With the introduction of wind resources, which have a different generation profile than solar, there may be increased opportunities for storage resources to recharge. A diverse mix of resources modifies the net load shape and together, the cumulative set of resources plus storage can increase the ELCC or total capacity contribution of the portfolio. This concept is referred to as a "diversity benefit."

Diversity benefit: The interaction between different types of generating resources that boost their cumulative capacity value or ELCC.

Recent legislation became law in Maine which directs the state to procure up to 3 GW of offshore wind by 2040. The winds in the Gulf of Maine are both strong and consistent, offering significant power potential to Maine and the Northeast states in the decades to come. Day-to-day, wind generation offshore is most productive at night, while it peaks seasonally in the winter. Given these operational characteristics, the diversity benefit of offshore wind plus long-duration storage is likely to be significant. The generation profile of offshore wind is predicted to drive down net peaks in New England across the day, providing several opportunities for longer-duration energy storage to shave peaks by dispatching across multiple hours, and to

---

[25] "Capacity and Reliability Planning in the Era of Decarbonization." *Energy and Environmental Economics, Inc. (E3)*, 2020, https://www.ethree.com/wp-content/uploads/2020/08/E3-Practical-Application-of-ELCC.pdf.

soak up clean, low-cost excess energy that can be used for those periodic winter lulls with high demand and low generation.

Long-duration energy storage resources strategically co-located at grid locations onshore that face congestion can also reduce curtailment, increase the value of existing renewables, and reduce the total capacity needs of the system. Long-duration storage can serve as a partial alternative to transmission upgrades, for example, by relieving congestion in locations where transmission infrastructure is fully or nearly fully utilized. But in other cases, it can be used to improve the business case for the utilization of new transmission developed to access remote renewable energy resources. For example, northern Maine has significant high quality wind resources, but limited transmission infrastructure to transmit that low-cost power to the regional grid. Given the capacity factor of wind, a transmission line may be challenged to use its full capacity most of the time, but co-located energy storage could increase the utilization of a new transmission line and lower the cost of delivered energy per unit.

FERC recently approve changes to ISO-NE's tariff that allow it to consider battery storage for transmission functions. Approval of storage as transmission-only assets (SATOAs) allows storage facilities that are planned and operated as transmission assets to recover costs through transmission rates.[26] This is another example of where evolving market rules could signal new opportunities for long-duration energy storage resources to develop for specific use cases.

In summary, the growth of renewables in Maine and New England will likely drive changes in system shape and the length of peaks, which in turn may increase the need for and value of energy storage in the years ahead. Storage can also increase the use of renewables and drive emissions reductions and ratepayer savings. Storage plus a diverse renewable portfolio can increase the combined capacity value of the resource portfolio as a whole.

Section V: Cost-effectiveness of Long-Duration Energy Storage & Economic Development Opportunities

As previously discussed, similar to many other generation resources, the value of storage is closely tied to its ability to access and stack multiple value streams. Cost-benefit analysis results from Maine's Energy Storage Market Assessment show cost-effectiveness for wholesale, grid-connected storage, but emphasize again, that technology cost declines and ensuring the ability to monetize multiple value streams will be important. As of 2024, most long-duration energy storage resources have not yet reached commercial viability and remain too costly to scale for use today, but as revenue streams associated with higher penetrations of renewables materialize, new opportunities may help facilitate the deployment of long-duration energy storage which in turn could drive reductions in wholesale energy costs and reduce the total infrastructure needs and costs to ratepayers of expanding Maine's grid to meet the state's clean energy and emission reduction goals.

---

[26] "FERC Accepts ISO-NE Filing to Allow Storage as a Tx-Only Asset." *RTO Insider*, October 2023, https://www.rtoinsider.com/59152-ferc-iso-ne-allow-storage-tx-only-asset/.

As technology options for long-duration energy storage move toward commercialization, it may be helpful in the future for the state to consider doing a focused cost-benefit analysis of promising long-duration energy storage resources to better inform Maine's understanding of these technologies on the state and its electricity system, the impacts of investments on different parties such as the owner or the ratepayer, and to inform policy and program design.

Significant federal funding and incentives have recently become available to support lower cost deployment of clean energy resources through the Inflation Reduction Act (IRA). These incentives will substantially bolster short-duration lithium-ion battery storage resources which will likely continue to be the most popular storage technology for several years to come while research and development funds made available by the Bipartisan Infrastructure Law (BIL) and other DOE programs, as well as pilots supported by states and the private sector, will be important for moving new and emerging long-duration energy storage technologies toward commercialization at declining costs.

Federal legislation like IRA and BIL are also driving interest and investment in the building of domestic supply chains and manufacturing of clean energy technologies and energy storage resources through credit options, adders, or requirements for domestic content. A challenge faced by lithium-ion batteries today is their reliance on foreign minerals and materials for their construction which can drive material costs, access issues, and total project cost. Through support of a range of storage technologies, meeting national, regional, and state goals may be less vulnerable to the volatility of a single supply chain. Several of the long-duration energy storage technologies discussed in earlier sections of this report require fewer critical minerals or materials that are difficult to source domestically.

DOE's Liftoff report estimates that if the market for long-duration energy storage can achieve liftoff in the early- to mid-2030s, it has the potential to generate up to 2.1 million job-years in engineering and construction with a $530 billion economic benefit over the next 25 years. According to the 2023 U.S. Energy & Employment Report (USEER), there were more than 81,000 U.S. jobs working with electrochemical battery storage (72,923) and hydroelectric pumped storage (8,333) in 2022. Battery storage jobs increased by 4.6 percent or 3,225 jobs in 2022. More than half of battery storage jobs are in construction, while about one fifth are in manufacturing.[27] A diversified field of long-duration energy storage technologies could increase jobs opportunities in energy storage in both construction and non-construction jobs.

Section VI: Policy Considerations & Conclusion

To achieve Maine's climate and clean energy goals, the state will need substantial new clean energy resources in the coming decades. As clean energy is deployed, including significant variable renewable resource capacity like solar and wind, ensuring power system reliability, resource adequacy, and resilience will be critical. Two- and four-hour storage, primarily served by lithium-ion batteries, will help provide these services in the years to come, but as peak demands shift to winter and net peak loads widen, longer-duration energy storage resources could play a significant role in providing flexible, clean, firm power at all hours of the day—even

---

[27] "United States Energy & Employment Report 2023." *U.S. DOE*, June 2023, https://www.energy.gov/sites/default/files/2023-06/2023%20USEER%20REPORT-v2.pdf.

during high-demand, low-production periods of time which may occur between days or across several days—and in maximizing the usefulness of investments in new clean resources and new transmission. This report discussed several technology options that may be able to provide long-duration energy storage in the coming decades.

While there are many promising long-duration energy storage resources in development today—each with different characteristics, operating profiles, and costs—many aren't yet commercially viable or at scale to provide their services in a cost-effective manner. Some of the technologies discussed may be better suited to Maine and its geography than others. All of these resources face existing technology barriers, as well as regulatory and policy barriers to optimal deployment.

However, significant investments are being made at both the federal level and by the private sector to advance these technologies, with goals of achieving "liftoff" in the early- to mid-2030s, and regional markets are also signaling opportunities to evaluate and modify market rules to more accurately compensate new technologies for new services to the grid. Liftoff for long-duration energy storage technologies in the early- to mid-2030s would align well with forecasts made in the Maine Energy Storage Market Assessment, which highlights the potential for long-duration energy storage technologies to provide Maine with clean dispatchable generation, particularly beyond 2030 when state and regional clean energy targets increase and technology costs are anticipated to decline. To meet this timeline and the long lead time needed for project development, Maine should continue monitoring and seeking opportunities to cost-effectively advance short duration energy storage in the near-term and look for opportunities to build understanding of and reduce costs for long-duration storage now and in the years ahead. As Maine and New England's electricity generation resource mix evolves, the value that long-duration energy storage might offer in terms of reliability and resiliency could be considerable; planning efforts that combine considerations of storage and capacity resources could be highly beneficial.

As Maine pursues its short and long-term clean energy and emission reduction goals, the state will consider the following actions related to long-duration energy storage:

- **Continue to support technology neutral approaches to storage policy goals, while recognizing duration priorities may evolve with technology and energy system changes.** The current definition of energy storage in Maine law, as well as Maine's energy storage deployment goals, are both technology and duration neutral. Maintaining a technology neutral approach will be important as the landscape for energy storage is evolving rapidly and includes a diverse set of technologies, each with a different set of cost and performance characteristics. The GEO is tasked by law with periodically evaluating and updating the state's storage goals. Given the emerging importance of long-duration energy storage in cost-effectively meeting energy needs, the state may consider goals for long-duration storage deployment if appropriate.

  - For example, California has a procurement target for 1,500 MW of additional storage by 2024 and a target of 1 GW of long-duration energy storage resources with durations of at least 8 hours by 2026.

- **Track storage deployments in New England and Maine, including key characteristics such as technology and duration.** The state of Maine should monitor storage deployments in Maine and the New England region to maintain awareness of market development, technology maturation, and primary use cases for energy storage resources with durations greater than 4 hours. This should include regular updates of installed capacity from appropriate entities (such as ISO-NE, electric utilities, and installers) to ensure deployments are tracked and reported effectively.

- **Monitor federal and private-sector investments in research, development, and demonstration of long-duration energy storage technologies.** The state should keep abreast of technology developments and cost-reductions resulting from federal research and investments, as well as public-private partnerships in R&D.

- **Seek opportunities to engage in federally funded pilot projects for long-duration energy storage technologies.** Pilot projects can accelerate the deployment and cost-effectiveness of new and emerging technologies. The state of Maine should consider seeking federal funding to support deployment of pilot-scale long-duration energy storage projects in the state that demonstrate the feasibility of these technologies to provide resource adequacy and renewable resource integration, and that may provide economic or workforce development opportunities to the state.

- **Consider joint procurements of energy storage resources, including long-duration energy storage resources, in future resource procurements to capitalize on diversity benefit.** Maine's upcoming and future procurements, including offshore wind, may benefit from resource pairing with energy storage resources to minimize curtailment and fully integrate new clean capacity.

- **Participate in advancing regional market design improvements to ensure fair compensation for storage resources that contribute to cost-effectively meeting electricity needs.** The state should monitor and consider engaging in ISO-NE's process to review and modify its regional resource capacity accreditation process to ensure that capacity contributions from all resource types, including long-duration energy storage, are measured and valued adequately.

Appendix: Sources of Additional Information

This report cites several recent publications from the U.S. Department of Energy, the National Renewable Energy Laboratory, trade organizations, and other states that are also evaluating the opportunities for long-duration energy storage in supporting national, regional, and state decarbonization targets between now and 2050. These resources helped inform this Maine-based evaluation, and will continue to serve as helpful resources as technology, regulatory, and policy landscapes evolve in the years to come.

Links to some of those publications are included below:

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

U.S. Department of Energy:
United States Energy & Employment Report 2023 (June 2023)

National Renewable Energy Laboratory:
Storage Futures Study (Multiple Publications)

Long Duration Energy Storage Council:
The Journey To Net-Zero: An Action Plan To Unlock A Secure, Net-Zero Power System (June 2022)

Maine Governor's Energy Office:
Maine Energy Storage Market Assessment (March 2022)

Massachusetts Clean Energy Center:
Charging Forward: Energy Storage in a Net Zero Commonwealth (December 2023)

New York State Energy Research and Development Authority:
New York's 6 GW Energy Storage Roadmap: Policy Options for Continued Growth in Energy Storage (December 2022)