U.S. DEPARTMENT OF
ENERGY

Potential Benefits of High-Power, High-Capacity Batteries

January 2020

United States Department of Energy
Washington, DC 20585

Executive Summary

The ability of the United States (U.S.) electric power system (i.e., the electric grid) to reliably meet customer demand is crucial to our economy and national security. The increasing adoption of variable generation technologies and dynamic changes in customer demand are creating the need for enhanced grid flexibility to ensure the continued reliability, resilience, and security of the electric power system. Batteries and other energy storage technologies that have the capability to both supply and absorb electrical power (bidirectional electrical energy storage) can provide flexibility by helping to balance electrical supply and demand.

Report Scope and Approach

This report describes opportunities for high-power, high-capacity batteries to increase the resilience of the U.S. electric power system and to help integrate higher levels of variable renewable energy (VRE). These opportunities can be addressed through multiple pathways based on technology and grid architecture options that include battery storage. By describing the opportunities in terms of grid services and dimensional requirements, this report aims to align system needs with the storage options best suited to fill those needs.

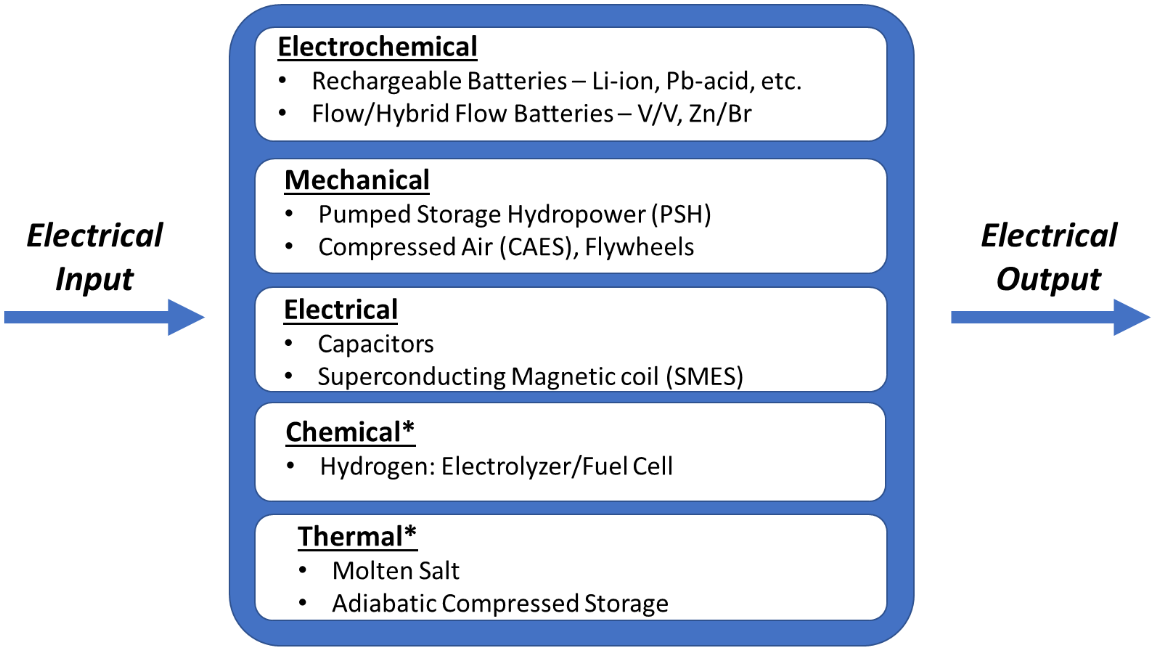
Dimensional requirements for storage technologies vary by duration (intra-hour, intraday, weekly, and seasonally) and discrete market applications (e.g., power reliability, demand charge management, or electric energy time shift). This report describes the suitability of viable energy storage technology options to fulfill these requirements, including technology maturity and examples of notable deployments.

The report also describes efforts by the U.S. Department of Energy (DOE), industry, and other grid stakeholders to improve an understanding of battery capabilities, validate new storage applications, and pursue opportunities to develop advanced technology solutions. These efforts include studies of adoption scenarios, technology gaps, the effect of policies, and the current market and regulatory landscape. The U.S. energy innovation ecosystem continues to invest in research and development (R&D), modeling, testing, field demonstrations, and technical assistance that can enlarge the set of available options and help policymakers connect emerging opportunities with an appropriate set of solutions. On the technology side, in addition to batteries themselves, these efforts extend to power electronics and controls associated with battery systems. Although not a focus of this report, robust implementation would require sufficient manufacturing capabilities and production capacity for the technology solutions envisioned.

This report also identifies a suite of technologies and solutions that offer the potential to fulfill resilience and variable renewable energy (VRE) integration objectives. Other energy storage technologies such as pumped storage hydropower (PSH) and non-storage options that deliver similar services may ultimately compete in the same marketplace. Battery storage systems are the fastest-growing segment of the grid storage market and are expected to be largely responsible for its continued growth due to their highly dispatchable and bidirectional electrical storage capabilities. Having a suite of storage technologies with different technical attributes will enable operators across the country to use the most efficient and robust options based on their current resources and needs. When discussing potential applications, this report uses the terms “technology options” and “energy storage” to highlight opportunities for all technologies that can provide bi-directional electrical energy storage capabilities.

Bidirectional electrical energy storage systems can be classified by the medium used to store electrical energy until it is needed by the grid. In general, an electrical energy storage system is a system capable of absorbing electric energy, storing that energy for a period of time, and dispatching the stored energy in the form of electricity. It can use a mechanical, electrical, chemical, electrochemical, thermal, or other relevant process to store such energy. For example, electrical energy from the grid can be stored mechanically, as in the case of flywheels, or electrochemically via battery technologies. A summary of potential bidirectional electrical energy storage pathways are depicted in the figure.

Examples of Electrical Energy Storage Mediums



**Alternate pathways besides electrical output may be more efficient for these technologies.*

For the past decade, battery storage systems have been the fastest-growing segment of the grid storage market and are expected to be largely responsible for its continued growth. There are two primary architectural options for battery storage deployment to enable increased renewables integration as well as grid reliability and resilience. One approach is to use smaller batteries distributed throughout the grid that can provide power and flexibility for individual homes, businesses, and critical infrastructure. This type of distributed approach to resilience could take the form of distributed storage systems, microgrids, and rooftop solar installed in combination with energy storage. The second approach is to install larger centralized batteries that can provide utility-scale services to grid operators. This centralized approach to resilience could take the form of standalone storage systems or storage in combination with generators.[1] Advancements in high-power, high-capacity batteries will enhance opportunities for large-scale deployment of both distributed and centralized grid storage.

Today, a major obstacle to widespread adoption of battery storage is the lack of a comprehensive valuation framework capable of capturing the entire suite of grid services battery storage systems can provide. A single battery system can provide multiple grid services, but often the combined, or stacked, benefits are not well defined and lead to underestimating the total value of the investment. Existing market and tariffs do not fully capture the value of the range of services that storage could provide. Enabling battery storage systems to fully realize multiple benefit streams enables a more complete evaluation of the entire value proposition. The lack of commonly accepted valuation metrics for certain grid services—including grid resilience—makes it difficult for potential energy storage customers to fully evaluate the value proposition of battery storage. Relatively few customers can develop sufficient internal metrics for risk and return on batteries that only provide resilience benefits. Combining the value of resilience with operational savings or revenues would enable more potential energy storage customers to economically justify their purchases.

Rising levels of variable renewable generation, such as solar and wind energy, are projected to continue through the coming decades. As the penetration of variable renewable generation increases, technologies that provide additional flexibility will become more valuable.[2] Today's commercially available batteries are well suited to provide power to balance the grid in the milliseconds-to-minutes timescale. Batteries can provide many functions that facilitate variable renewable generation integration, including frequency response, voltage support, load following/ramping support, and frequency regulation. High-capacity, high-power batteries can also provide power for minutes to hours, which enables time shifting of electrical energy from periods of high electrical generation to periods of high demand. When fully developed, the next generation of high-capacity, high-power batteries could economically provide energy for hours to days and augment wind and solar photovoltaic generation resources with characteristics similar to conventional dispatchable generators.

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[1] Other measures to enhance resilience include improvements to infrastructure hardening, forecasting, regional coordination, emergency preparedness, smart grid technologies, combined heat and power systems, and building energy efficiency.

[2] Resource-specific strategies to address the challenges posed by high penetrations of variable generation include overbuilding and curtailing renewables, improving generator dispatchability, increasing the flexibility of load/demand (including through demand response), and energy storage. Centralized or utility-scale options to increase grid flexibility include changes in market design and regulatory frameworks; planning and deployment of grid infrastructure and information and control technology; and coupling of the electricity, fuel, and transport sectors.

DOE, the power industry, and other grid stakeholders continue to improve their understanding of battery capabilities, validate new storage applications, and pursue opportunities to develop technology solutions. These efforts include studies of adoption scenarios, technology gaps, the effects of policies, and the current market and regulatory landscape. The U.S. energy innovation ecosystem continues to invest in research and development, modeling, testing, and technical assistance that aims to enlarge the set of available options and help policymakers connect emerging opportunities with an appropriate set of solutions.

With benefits extending to transportation, the grid, and throughout the economy, DOE has proactively developed new tools and technologies to accelerate energy storage development. The DOE Office of Electricity has been leading efforts to develop the next generation of high-capacity, high-power stationary batteries to support the long-term resiliency needs for the U.S. grid. Research aimed at increasing the energy density or capacity of flow batteries and other technologies through the use of low-cost earth-abundant materials seeks to enable these systems to provide longer duration services like time-shifting of renewable resources, while also continuing to support grid stability.

Other DOE storage activities include the Grid Modernization Initiative, the Advanced Energy Storage Initiative, and the Grid Storage Launchpad (GSL). In May of 2019, DOE issued its most recent Grid Modernization Lab Call, with Energy Storage and System Flexibility as one of the major topic areas. The lab call emphasized developing the storage functions that enhance system resilience and flexibility. The Advanced Energy Storage Initiative will build an integrated DOE R&D strategy and establish aggressive, achievable, and comparable goals for cost-competitive energy storage services and applications. The proposed GSL intends to extend U.S. R&D leadership in energy storage through validation, collaboration, and acceleration. By validating new technologies at earlier maturity stages, the GSL will lower the time and expense of storage chemistry innovations. Through university and the commercial sector collaboration, the GSL will augment the industry with enhanced testing protocols and in-operando characterization capabilities. Finally, the GSL will accelerate and de-risk new technologies by propagating rigorous grid performance requirements to all stages of storage development, from benchtop to systems.

In addition to improvements in battery technologies, improvements in power electronic converters, secure control systems, and packaging are also needed to enable next-generation batteries to realize their full potential. DOE investments in battery safety, reliability improvements, and performance validation have enabled greater industry acceptance of the technology. Additionally, the Office of Electricity’s North American Energy Resiliency Model (NAERM) is advancing the Nation’s understanding of the strategic use and placement of energy storage systems, including batteries, within the energy sector. The comprehensive resilience model developed under the NAERM Initiative offers an analytical framework of the resiliency risks within the energy sector and defines contingency scenarios where energy storage systems can help mitigate these risks. This information will help better define the valuation of energy storage systems beyond the services battery storage provides today.

While a variety of storage and other grid technologies could ultimately meet the long-term resilience needs for the U.S. grid, battery storage technologies in particular are expected to have a significant role because of their versatility in delivering multiple grid services when needed. Today, energy storage technologies are being deployed to support select grid services as their cost-benefit profile and technical capabilities allow. As outlined in this report, ongoing and future developments to deliver lower cost, higher performance, and safer battery systems can facilitate new technology adoption and improve the inherent resilience of a fast-changing U.S. grid.

DOE activities continue to reduce the cost of energy storage technologies and ensure that these technologies can safely and reliably provide the desired services. Further analysis to understand technology adoption scenarios, application values, and system reliability will facilitate the benefits that come with continued adoption of energy storage. Energy storage is expected to be a core element in the suite of technological and architectural options that can provide economic, resilience, and reliability advantages for a wide variety of future scenarios.

POTENTIAL BENEFITS OF HIGH-POWER, HIGH-CAPACITY BATTERIES

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I. Energy Storage Grid Functions

A technology's ability to provide increased resilience or to facilitate VRE generation depends on its ability to provide the discrete services relevant to each application. This section, excerpted and adapted from the 2015 DOE/Electric Power Research Institute (EPRI) Energy Storage Handbook in Collaboration with the National Rural Electric Cooperative Association (NRECA),[3] enumerates and describes the suitability of energy storage in providing many of these services. In this document, the term *services* denotes distinct capabilities that can be supplied by a grid resource such as energy storage. Organized markets often provide discrete payments for these services. Inside and outside of organized markets, definitions for these services can be found in tariffs, such as those on file with the Federal Energy Regulatory Commission (FERC). The term *application* denotes an overall objective that can be accomplished through a collection of services.

Table 1 summarizes the dimensional requirements across grid services in terms of the ranges of system size, needed duration, and minimum cycles per year. The table also identifies some of the most common energy storage applications in the transmission, distribution, and customer domains. The system size describes how quickly energy can be put into or extracted from the battery. The duration measures the amount of energy that batteries need to store. A service that requires a duration of minutes or seconds requires much less battery energy capacity than a service requiring a duration of hours. The cycles per year refers to the number of times the battery is expected to be charged and discharged to provide a given grid service. The cycle frequency is important because batteries have a finite cycle life. As explained in Section V of this report, some storage technologies may be more cost-effective than others based on the requirements for size, duration, and cycles per year.

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[3] Sandia National Laboratories, "DOE/EPRI Energy Storage Handbook in Collaboration with NRECA," SAND2015-1002, February 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf

Table 1. Grid functions for energy storage and associated system requirements.

Grid Function		Typical System Size	System Dimensional Requirements	
Category	**Service**		**Needed Duration**	**Minimum Cycles/Year**
Bulk Energy Services	Electric energy time shift (arbitrage)	1–500 MW	<1-12 hours	> 250
	Electric supply capacity	1–500 MW	2–6 hours	5–100
Ancillary Services	Frequency regulation	10–40 MW	15 minutes–1 hour	250–10,000
	Spinning, non-spinning, and supplemental reserves	10–100 MW	15 minutes–1 hour	20–50
	Voltage support	1–10 mega volt-ampere reactive	Not Applicable	Not Applicable
	Black start	5–50 MW	15 minutes–1 hour	10–20
	Load following/ramping support for renewables	1–100 MW	15 minutes–1 hour	Varies Widely
	Frequency response	> 20 MW	<1 minute	Varies Widely
Transmission Infrastructure Applications	Transmission upgrade deferral	10–100+ MW	2–8 hours	10–50
	Transmission congestion relief	1–100+ MW	1–4 hours	50–100
Distribution Infrastructure Applications	Distribution upgrade deferral	500 kW–10 MW	Varies Widely	Varies Widely
Customer Energy Management Applications	Power quality	100 kW–10 MW	10 seconds–15 minutes	10–200
	Power reliability	1 kW–10 MW	Varies Widely	Varies Widely
	Retail energy time shift	1 kW–1 MW	1–6 hours	50–250
	Demand charge management	50 kW–10 MW	1–4 hours	50–500

Note: Table data do not include Pumped Storage Hydropower.

I.A. Bulk Energy Services

Electric Energy Time shift (Arbitrage)

Electric energy time shift involves purchasing inexpensive electric energy, available during periods when costs are low, to charge the storage system so that the stored energy can be used or sold later when the costs are high. Alternatively, storage can provide similar time-shift services by storing excess energy production, which would otherwise be curtailed, from renewable resources such as wind or photovoltaic (PV) generation. The functional operation of the storage system is similar in both cases and they are treated interchangeably in this report. [4]

Electric Supply Capacity

Energy storage could be used to defer the need to deploy new central station generation capacity or reduce the need to purchase capacity in the wholesale electricity marketplace. The operating profile for storage used as supply capacity (characterized by annual hours of

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[4] Sandia National Laboratories, "DOE/EPRI Energy Storage Handbook in Collaboration with NRECA," SAND2015-1002, February 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf, page 2.

operation, frequency of operation, and duration of operation for each use) is specific to the market and location. For example, if capacity is priced per hour, then storage plant duration is flexible. If prices require that the capacity resource be available for a specified duration for each occurrence (e.g., 5 hours) or require operation during an entire time period (e.g., 12:00 p.m. to 5:00 p.m.), then the storage resource must be sized to accommodate those requirements. [5]

I.B. Ancillary Services

Frequency Regulation

Frequency regulation is used to reconcile momentary differences caused by fluctuations in generation and loads. The primary reasons for including frequency regulation in the power system are to maintain the grid frequency in compliance with the North American Electric Reliability Corporation's (NERC's) Real Power Balancing Control Performance (BAL-001) and Disturbance Control Performance (BAL-002) Standards.[6,7] In 2011, one of the earliest FERC orders to recognize the speed and accuracy of energy storage required organized markets to differentiate frequency regulation payments by delivered performance.[8]

The rapid-response characteristic (i.e., fast ramp rate) of most storage systems, especially those based on high-power batteries, makes it valuable as a frequency regulation resource. The equivalent benefit of frequency regulation from storage with a fast ramp rate (e.g., flywheels, capacitors, and some battery types) is on the order of two times that provided by conventional generation because it can follow the frequency regulation signal more accurately.[9]

Spinning, Non-Spinning, and Supplemental Reserves

The electric grid requires an operating reserve capacity that can be called on when normal electric supply resources become unavailable. FERC, NERC, and the organized markets have varying definitions and performance requirements for operating reserves.[10] Terms used for these services include spinning reserve, synchronized reserve, non-spinning reserve, non-

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[5] Sandia National Laboratories, "DOE/EPRI Energy Storage Handbook in Collaboration with NRECA," SAND2015-1002, February 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf, page 3-4.

[6] NERC, "Standard BAL-001-2 — Real Power Balancing Control Performance." https://www.nerc.com/files/BAL-001-2.pdf

[7] NERC. "Standard BAL-002-3 – Disturbance Control Standard." https://www.nerc.com/pa/Stand/Reliability%20Standards/BAL-002-3.pdf

[8] 137 FERC ¶ 61,064, "Frequency Regulation Compensation in the Organized Wholesale Power Markets," October 20, 2011.

[9] Sandia National Laboratories, "DOE/EPRI Energy Storage Handbook in Collaboration with NRECA," SAND2015-1002, February 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf, page 6.

[10] NERC, Ancillary Services Matrix. https://www.nerc.com/docs/pc/ivgtf/NERC_ancillary_services%20ERCOT%20IESO%20NYISO%20MISO%20PJM%20SPP%20WECC%2012%2014.pdf

synchronized reserve, and supplemental reserve. Response times for these services generally range from under 10 minutes to more than an hour from dispatch signal to full output.[11]

Voltage Support

Electric grid operators must maintain voltage within specified limits, and system operators need voltage support resources so that the transmission system can be operated in a stable manner. Normally, designated power plants are used to control voltage by modulating their reactive power output; however, strategically placed energy storage systems within the grid could also provide reactive power, in addition to energy storage functionality.[12]

Black Start

After a blackout, most generators need external power to turn on the pumps, sensors, and control equipment necessary to bring the plant back online, a process known as *black start*. Energy storage systems of the proper size and characteristics can be used as a black start resource.[13] Black start service payments can be competitive, cost-based, or bundled with other payments.[14]

Load Following/Ramping Support for Renewables

For load-following applications, energy storage systems should be able to quickly inject or absorb power from the grid without significant performance penalties (such as efficiency losses). Most renewable applications will have a specified up and down ramp rate in MW/minute and the time duration of the ramp for energy storage applications. Both the Midcontinent Independent System Operator (MISO) and the California Independent System Operator (CAISO) have implemented ramp-specific compensation mechanisms.[15,16]

Frequency Response

Frequency response is very similar to frequency regulation, except the needed response time is much shorter (seconds to less than a minute) when there is a sudden loss of a generation or a transmission line.[17] Various generator response actions are needed to counteract this sudden imbalance between load and generation to maintain system frequency and stability of the grid.

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[11] NERC, Ancillary Services Matrix. https://www.nerc.com/docs/pc/ivgtf/NERC_ancillary_services%20ERCOT%20IESO%20NYISO%20MISO%20PJM%20SPP%20WECC%2012%2014.pdf

[12] Sandia National Laboratories, "DOE/EPRI Energy Storage Handbook in Collaboration with NRECA," SAND2015-1002, February 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf, page 9.

[13] Sandia National Laboratories, "DOE/EPRI Energy Storage Handbook in Collaboration with NRECA," SAND2015-1002, February 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf, page 10.

[14] FERC and NERC Staff, "Recommended Study: Blackstart Resources Availability," May 2018. https://www.ferc.gov/legal/staff-reports/2018/bsr-report.pdf

[15] 149 FERC ¶ 61,095, "Midcontinent Independent System Operator, Inc.," October 31, 2014.

[16] 156 FERC ¶ 61,226, "California Independent System Operator Corporation," September 26, 2016.

[17] Sandia National Laboratories, "DOE/EPRI Energy Storage Handbook in Collaboration with NRECA," SAND2015-1002, February 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf, page 14.

Primary frequency response occurs within initial seconds to enable generation units to increase/decrease their power output. This is followed by the longer duration secondary frequency control response that spans a half-minute to several minutes.[18] In 2018, FERC began requiring new "large and small generating facilities…to install, maintain, and operate equipment capable of providing primary frequency response as a condition of interconnection."[19]

I.C. Transmission Infrastructure Applications

Transmission Upgrade Deferral

Transmission upgrade deferral involves delaying or avoiding the need for investments in transmission system upgrades by using energy storage systems to time-shift energy.[20] In some cases, installing a small amount of energy storage downstream from the nearly overloaded transmission component could defer the upgrade for a few years.[21]

Transmission Congestion Relief

Transmission congestion occurs when available least-cost energy cannot be delivered to loads because transmission facilities do not have enough capacity to deliver that energy.[22] Transmission congestion may lead to increased costs or locational marginal pricing for wholesale electricity at certain transmission nodes.[23] Like transmission upgrade deferral, congestion relief can be accomplished by time-shifting energy using storage. Electricity would be stored when there is no transmission congestion and would be discharged during peak demand periods to reduce peak transmission capacity requirements and congestion charges.[24]

I.D. Distribution Infrastructure Applications

Distribution Upgrade Deferral

Distribution upgrade deferral involves using storage to delay or avoid investments that would otherwise be necessary to ensure adequate distribution capacity to serve load requirements.

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[18] Sandia National Laboratories, "DOE/EPRI Energy Storage Handbook in Collaboration with NRECA," SAND2015-1002, February 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf, page 14.

[19] Order 842, 162 FERC ¶ 61,128, "Essential Reliability Services and the Evolving Bulk-Power System—Primary Frequency Response," February 15, 2018.

[20] Sandia National Laboratories, "DOE/EPRI Energy Storage Handbook in Collaboration with NRECA," SAND2015-1002, February 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf, page 16.

[21] American Public Power Association, "Arizona utility taps storage over traditional grid upgrade," August 14, 2017. https://www.publicpower.org/periodical/article/arizona-utility-taps-storage-over-traditional-grid-upgrade

[22] Sandia National Laboratories, "DOE/EPRI Energy Storage Handbook in Collaboration with NRECA," SAND2015-1002, February 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf, page 17.

[23] U.S. Department of Energy, "National Electric Transmission Congestion Study," September 2015. https://www.energy.gov/sites/prod/files/2015/09/f26/2015%20National%20Electric%20Transmission%20Congestion%20Study_0.pdf

[24] Sandia National Laboratories, "DOE/EPRI Energy Storage Handbook in Collaboration with NRECA," SAND2015-1002, February 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf, page 17.

The upgrade deferral could be a replacement of an aging or overstressed distribution transformer at a substation or upgrading distribution lines with higher capacity conductors.[25] For most feeders within a distribution system, the highest loads occur just a few days per year, for just a few hours per year, allowing energy storage systems to provide significant benefits with limited discharge requirements.[26]

I.E. Customer Energy Management Applications

Power Quality

When placed upstream of customer onsite loads, energy storage systems can protect against short-duration events that affect the quality of power. Some manifestations of poor power quality include the following:

- Variations in voltage magnitude (e.g., short-term spikes or dips, longer-term surges, or sags)
- Variations in the primary 60-hertz frequency at which power is delivered
- Low power factor (voltage and current excessively out of phase with each other)
- Harmonics (the presence of currents or voltages at frequencies other than the primary frequency)
- Interruptions in service of any duration, ranging from a fraction of a second to several seconds.[27]

Typically, the discharge duration required for the power quality use ranges from a few seconds to a few minutes.

Power Reliability

A storage system can effectively support customer loads when a total loss of power from the source utility occurs. This support requires the storage system and customer loads to island during the utility outage and re-synchronize with the utility when power is restored. The energy capacity of the storage system relative to the size of the load determines the time duration that the storage can supply the load. This duration can be extended by supplementing the storage system with onsite generation assets.[28]

Retail Energy Time Shift

Retail electric energy time shift involves the use of storage to reduce overall costs for electricity. Customers charge the storage system during off-peak times when the retail electric

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[25] Sandia National Laboratories, "DOE/EPRI Energy Storage Handbook in Collaboration with NRECA," SAND2015-1002, February 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf, page 19.

[26] Sandia National Laboratories, "DOE/EPRI Energy Storage Handbook in Collaboration with NRECA," SAND2015-1002, February 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf, page 20.

[27] Sandia National Laboratories, "DOE/EPRI Energy Storage Handbook in Collaboration with NRECA," SAND2015-1002, February 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf, page 21.

[28] Sandia National Laboratories, "DOE/EPRI Energy Storage Handbook in Collaboration with NRECA," SAND2015-1002, February 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf, page 22.

energy price is low and then discharge the energy during periods when on-peak time of use energy prices apply.[29] The maximum discharge duration in this case is determined based on the relevant tariff. A study of over 3000 U.S. residential utility rates found a limited number of tariffs that would provide a significant financial incentive for storage-based time shifting.[30]

Demand Charge Management

The energy time shift capability of electricity storage can be used to reduce customer demand during peak periods.[31] To avoid a demand charge, load must be reduced during all hours a specified demand charge period (e.g., 11:00 a.m. to 5:00 p.m.) and on specified days. In many cases, the demand charge is assessed if load is present during just one 15-minute period during times of the day and during months when demand charges apply.[32]

I.F. Summary of Grid Functions

Table 2 summarizes the services and applications listed in this section and qualitatively identifies the current ability of existing technology to provide each. Energy storage, and battery-based energy storage in particular, is highly suitable to provide a variety of grid functions. The subsequent sections will highlight the services that are important for resilience or VRE generation applications.

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[29] Sandia National Laboratories, "DOE/EPRI Energy Storage Handbook in Collaboration with NRECA," SAND2015-1002, February 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf, page 23.

[30] A. Breckel, "Electricity Bill Savings Opportunities from Distributed Electric Storage," presented at the 2015 Grid of the Future Symposium, International Council on Large Electric Systems, October 2015.

[31] Sandia National Laboratories, "DOE/EPRI Energy Storage Handbook in Collaboration with NRECA," SAND2015-1002, February 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf, page 24.

[32] Sandia National Laboratories, "DOE/EPRI Energy Storage Handbook in Collaboration with NRECA," SAND2015-1002, February 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf, page 24.

Table 2: Energy storage technologies' current suitability for grid functions[33, 34, 35]

		Bidirectional Energy Storage								Other Technologies	
		Batteries									
		Li-ion batteries	Sodium-based batteries	Lead-acid batteries	Flow batteries	Pumped storage hydropower	Compressed air	Flywheels	Electrochemical capacitors	Thermal storage	Demand response
Bulk Energy Services	Electric Energy Time shift (Arbitrage)	●	●	●	●	●	◉	○	○	◉	○
	Electric Supply Capacity	●	◉	◉	●	●	◉	◉	○	◉	◉
Ancillary Services	Frequency Regulation	●	●	●	●	●	●	●	◉	○	◉
	Spinning, Non-Spinning, and Supplemental Reserves	●	●	●	●	●	●	●	○	○	◉
	Voltage Support	●	●	●	●	●	◉	◉	○	○	○
	Black Start	●	●	●	●	●	◉	○	○	○	○
	Load Following/Ramping Support for Renewables	●	●	●	●	●	◉	◉	○	○	◉
	Frequency Response	●	◉	◉	◉	◉	◉	●	◉	○	○
Transmission Infrastructure Applications	Transmission Upgrade Deferral	●	●	●	●	○	○	○	○	○	○
	Transmission Congestion Relief	●	●	◉	●	○	○	○	○	○	○
Distribution Infrastructure Applications	Distribution Upgrade Deferral	◉	◉	●	◉	○	○	○	○	○	○
Customer Energy Management Applications	Power Quality	●	◉	◉	◉	○	○	●	●	○	○
	Power Reliability	●	●	●	●	○	○	◉	○	○	○
	Retail Energy Time shift	◉	◉	◉	◉	◉	◉	○	○	◉	◉
	Demand Charge Management	◉	◉	◉	◉	◉	◉	○	○	◉	◉

Key:

● - Technology is highly suitable for the application.

◉ - Technology may be limited or non-optimized for the application.

○ - Technology is not well-suited for the application.

Note: For a more quantitative view of the relationship between storage technologies and grid applications, see the DOE/EPRI Energy Storage Handbook.[36]

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[33] U.S. Department of Energy, "Grid Energy Storage," December 2013. https://www.energy.gov/sites/prod/files/2014/09/f18/Grid%20Energy%20Storage%20December%202013.pdf

[34] PJM Interconnection, "PJM's Evolving Resource Mix and System Reliability," March 30, 2017. https://www.pjm.com/~/media/library/reports-notices/special-reports/20170330-pjms-evolving-resource-mix-and-system-reliability.ashx

[35] Milligan Grid Solutions, "Sources of Grid Reliability Services," 2018. http://milligangridsolutions.com/Sources%20of%20Essential%20Reliability%20Grid%20Services%20Fact%20Sheet.pdf

[36] Sandia National Laboratories, "DOE/EPRI Energy Storage Handbook in Collaboration with NRECA," SAND2015-1002, February 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf

II. Energy Storage and Grid Resilience

II.A. Architectural Options

The U.S. grid faces stresses from weather, physical, and cyber threats; however, its resilience is challenged by these stresses. Unplanned outages can leave millions of customers without power, result in significant economic damages, and compromise national security. While the U.S. has not experienced a major outage caused by a physical or cyber-attack, the advancing threats directed at our critical energy infrastructure are increasing the risk of such attacks.[37,38]

As set forth in Presidential Policy Directive 21,[39] resilience is defined as "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruption. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents."[40] The following section examines distributed and centralized approaches for resilience through the use of energy storage.[41]

Distributed Resilience

To avoid the loss of electrical power during utility outages, local backup power can be provided through distributed energy resources (DERs). With onsite DERs available, local services have less risk of being disrupted when the bulk power system, including transmission and distribution facilities, is interrupted. For example, adding DER to municipal buildings is one way of ensuring continuity of government functions during power outages. DER in other locations can also promote wider community resilience, especially for buildings providing critical services, such as hospitals. In addition to the resilience benefits, the following examples of distributed

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[37] Worldwide Threat Assessment of the US Intelligence Community, 2019. https://www.odni.gov/index.php/newsroom/congressional-testimonies/item/1947-statement-for-the-record-worldwide-threat-assessment-of-the-us-intelligence-community

[38] "Worldwide Threat Assessment of the US Intelligence Community," Daniel R. Coats, Director of National Intelligence, January 29, 2019. https://www.dni.gov/files/ODNI/documents/2019-ATA-SFR---SSCI.pdf

[39] Presidential Policy Directive. https://www.dhs.gov/sites/default/files/publications/ISC-PPD-21-Implementation-White-Paper-2015-508.pdf

[40] U.S. Department of Energy, "Talking Points for Assistant Secretary Bruce J. Walker," June 11, 2018. https://www.energy.gov/sites/prod/files/2018/07/f53/Walker%2006-11-18%20SEARUC%20Remarks%20-%20As%20Prepared.pdf

[41] Note in the following discussion, while energy storage technologies are an important element for grid resilience, energy storage itself is not a source of generation and therefore must be charged by another resource to provide resilience through an extended event.

infrastructure, including both storage and non-storage options, can lead to co-benefits such energy savings, grid support services, and improved local air quality.[42,43]

Distributed energy storage can be deployed as standalone storage systems or integrated with rooftop solar systems and microgrids.[44]

Solar-plus-storage. Solar PV systems generate electricity directly from solar energy. The solar PV cells generate direct current (DC) electricity, which is then typically connected to an inverter to convert the DC electricity into alternating current (AC) electricity. A PV system's inverter will send power to the grid and most will automatically disconnect the system when an outage affects the grid for technical, safety, and regulatory reasons.[45] However, the addition of energy storage, in conjunction with specially designed inverters, can be included in solar PV installations to allow the system to be islandable or to operate when power from the interconnected grid is unavailable. Such systems are called "solar-plus-storage" or "resilient PV" and have resilience benefits by being able to provide some power during system outages.[46,47] Such systems are becoming increasingly common as the prices of solar power and energy storage have dropped dramatically and as resilience becomes an increasingly important goal. For example, following Hurricane Maria, the Federal Emergency Management Agency installed 10,000 residential solar-plus-storage systems between September 2017 and September 2018, largely due to an emphasis on resilience.[48]

Standalone Storage. While solar-plus-storage can be considered distributed storage, standalone energy storage is also an option. Standalone storage power reliability is currently most prevalent in the form of battery-based uninterruptible power supply (UPS) systems. UPS systems are often found in telecommunications and data centers but are less common in other commercial, industrial, and residential applications.[49]

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[42] Center for Climate and Energy Solutions, "Resilience Strategies for Power Outages," August 2018. https://www.c2es.org/site/assets/uploads/2018/08/resilience-strategies-power-outages.pdf

[43] AECOM, "Energy Systems for Island Resilience, Case Study: Guam," 2018. https://www.districtenergy.org/HigherLogic/System/DownloadDocumentFile.ashx?DocumentFileKey=543866ca-1ba2-555e-1411-e974d471021f&forceDialog=0

[44] In addition to the use of batteries, these systems also use advanced capabilities of power electronics (including inverters), which convert the AC of the grid to DC for the battery.

[45] Third Sun Solar, "Does solar work in a blackout?" May 29, 2013. https://thirdsunsolar.com/residential/does-solar-work-in-a-blackout/

[46] Center for Climate and Energy Solutions, "Resilience Strategies for Power Outages," August 2018. https://www.c2es.org/site/assets/uploads/2018/08/resilience-strategies-power-outages.pdf

[47] National Renewable Energy Laboratory and City University of New York, "New York Solar Smart DG Hub-Resilient Solar Project: Economic and Resiliency Impact of PV and Storage on New York Critical Infrastructure," NREL/TP-7A40-66617, June 2016. https://www.nrel.gov/docs/fy16osti/66617.pdf

[48] Bloomberg BNA, "Rooftop Solar Nearly Doubles in Puerto Rico One Year after Maria," 2018. https://news.bloombergenvironment.com/environment-and-energy/rooftop-solar-nearly-doubles-in-puerto-rico-one-year-after-maria

[49] Bloomberg New Energy Finance, "Standby Power for Telecoms and Data Centers (Part 1): a Primer," April 5, 2017.

Cities are also beginning to consider how battery electric vehicles (EVs) and fuel cell vehicles can serve as potential devices to promote resilience to power outages. Future vehicle-to-building and vehicle-to-grid interfaces can use vehicle batteries or fuel cells to power buildings or portion of the grid. EVs can access a redundant fuel source when motor fuel distribution is disrupted, as can happen following very large storms like hurricanes. Early EV adopters were able to charge their vehicles and avoid long lines at gas stations that affected most drivers in the New York City region after Hurricane Sandy.[50]

Microgrids. Industries, local communities, and utilities are also investing in microgrids that include energy storage to back up critical infrastructures. Microgrids can comprise a combination of fossil generation assets, renewable energy assets, and storage to provide a diversified resource mix that can supply loads during an outage. Fossil generation assets with onsite fuel supplies enable longer-term outage mitigation and can cover periods of low renewable generation. Solar and wind resources in a microgrid decrease fuel usage when generating and can provide power during disruptions in fuel supply. Energy storage added to a microgrid mitigates the variability of the renewable energy, provides electrical power while fossil assets are starting up, and enables more efficient operation of all generation assets. During normal conditions, the renewable generation assets and storage enable valuable services, such as demand charge reduction, and reduce electricity consumption during normal operation.

Centralized Resilience

Enhancing resilience at the bulk power level can involve the use of a variety of infrastructure hardening techniques and mitigation options and an expanding range of technology options such as larger, centralized systems or utility-scale energy storage. These sets of options allow increased capabilities for asset owners and grid operators during and after adverse events.

Utility-scale energy storage can improve system resilience, either as standalone systems or in combination with generators. Energy storage systems have recently demonstrated black start capabilities by restoring power to generators and power lines after a grid disruption and the ability to provide critical ancillary services during difficult conditions.[51,52,53,54]

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[50] Center for Climate and Energy Solutions, “Resilience Strategies for Power Outages,” August 2018. https://www.c2es.org/site/assets/uploads/2018/08/resilience-strategies-power-outages.pdf

[51] Energy Storage News, “California battery’s black start capability hailed as ‘major accomplishment in the energy industry’,” May 17, 2017. https://www.energy-storage.news/news/california-batterys-black-start-capability-hailed-as-major-accomplishment-I

[52] “Imperial Irrigation District brings 30-MW battery storage system online.” https://www.publicpower.org/periodical/article/imperial-irrigation-district-brings-30-mw-battery-storage-system-online

[53] Fluence, “Case Study Storm Resilience: Energy Storage Provides Grid Resilience during Severe Storm Conditions,” 2018. https://www.energy.gov/sites/prod/files/2018/10/f56/1.1%20Resilience%20Panel_Olnick_10-17-18.pdf
https://cdn2.hubspot.net/hubfs/2810531/Collateral/AES%20Collateral/Fluence%20Case%20Study%20-%20Storm%20Resilience.pdf

[54] Sandia National Laboratories, “DOE/EPRI Energy Storage Handbook in Collaboration with NRECA,” SAND2015-1002, February 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf

Energy storage can also play a role in addressing resilience challenges to the natural gas pipeline system. In 2017, the Western Electricity Coordinating Council (WECC) commissioned an evaluation of the reliability of the gas/electric interface in the Western Interconnection. In one of the scenarios involving a disruption to a critical section of pipeline, researchers estimated that a new 14-15 GW 4-hour battery storage would mitigate all unserved energy. Researchers recommended using a combination of mitigation options including improved forecasting and regional coordination.[55]

II.B. Functional Requirements

To improve grid resilience, a number of functional capabilities are required. The following section highlights the grid services (described in Section II) that are particularly relevant for high-power, high-capacity battery applications for resilience.

Black Start. Pumped hydro storage assets have been relied on by grid operators for decades to provide black start capabilities during partial or complete outages. Recently, battery-based energy storage technologies have also demonstrated black start capabilities at scale. In 2017, a 5 MW battery in Germany was the first battery-based storage system designed to restore or black-start the local grid after a disruption. Later in 2017, a California utility successfully demonstrated the use of a 33 MW–20 MWh battery to black start a natural gas plant. After a blackout, the batteries are used to help start up power plants. Once those plants are online, the batteries absorb excess power, helping to balance generation and load as the system is restored.[56]

Frequency Regulation and Related Ancillary Services. Utility-scale storage assets can provide grid operators with more flexible options to manage the grid, including frequency regulation, voltage support, frequency response, and other ancillary services.[57] For example, most storage systems can provide fast ramp rates that make them valuable as a frequency regulation or frequency response resource. In contrast, conventional, large thermal generation units incur significant wear and tear when they provide the variable power output needed for frequency regulation. Studies have shown that the storage systems of 20 MW or larger can be twice as

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[55] Wood Mackenzie, "Western Interconnection Gas-Electric Interface Study," August 15, 2018. https://www.nerc.com/gov/bot/MRC/Agenda%20Highlights%20nad%20Minutes%202013/MRC-Presentation-Package-August-15-2018.pdf

[56] Energy Storage News, "California battery's black start capability hailed as 'major accomplishment in the energy industry'," May 17, 2017. https://www.energy-storage.news/news/california-batterys-black-start-capability-hailed-as-major-accomplishment-I

[57] Fluence, "Case Study Storm Resilience: Energy Storage Provides Grid Resilience during Severe Storm Conditions," 2018. https://cdn2.hubspot.net/hubfs/2810531/Collateral/AES%20Collateral/Fluence%20Case%20Study%20-%20Storm%20Resilience.pdf

effective as a conventional thermal generator in providing effective frequency response when there is a sudden loss of a generation unit or a transmission line.[58]

Voltage Support. Normally, designated power plants are used to generate reactive power to offset reactance—or the opposition to alternating current flow—in the grid. Strategically situated energy storage systems, centralized or distributed, could provide effective reactive power support.[59]

Energy Time Shifting. To be a source of power reliability, a technology option such as energy storage must provide enough power for critical loads for the duration of a power outage. According to data reported to the U.S. Energy Information Administration (EIA), electric power for U.S. customers was interrupted for an average of 7.8 hours (470 minutes) in 2017, nearly double the average total duration of interruptions experienced in 2016. In 2017, the average customer experienced 1.4 interruptions counting major events and 1.0 interruption excluding major events.[60] Therefore, in most cases, several hours of storage duration would be required to assist with the average power interruption. Energy storage technologies are used to reduce the impact of these interruptions, especially in critical applications.

II.C. Other Considerations

System Design. Storage installations can be used to keep a facility operational during a grid outage if they can safely isolate from the grid during an outage. This functionality requires a more complex design and installation process.[61] While designed to provide resilience capabilities, most storage systems are financially justified on energy efficiency and cost savings.

System Economics. As the cost of storage continues to decrease, potential customers will be able to economically justify investment in storage systems by combining the value of resilience with operational savings or revenues. Utilities and regulators are increasingly exploring more conventional applications that expand the ability to monetize storage functions, such as demand charge reduction, distribution deferral, or real-time pricing. Some technology vendors have zero upfront cost business models whereby the customer receives the storage asset for free and shares its energy savings or demand response income with the vendor.[62] In this

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[58] Sandia National Laboratories, "DOE/EPRI Energy Storage Handbook in Collaboration with NRECA," SAND2015-1002, February 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf p. 15.

[59] Sandia National Laboratories, "DOE/EPRI Energy Storage Handbook in Collaboration with NRECA," SAND2015-1002, February 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf p. 9.

[60] U.S. Energy Information Administration, "Today in Energy: Average U.S. electricity customer interruptions totaled nearly 8 hours in 2017," November 30, 2018. https://www.eia.gov/todayinenergy/detail.php?id=37652

[61] Energy Storage News, "Investing in energy storage for resiliency: the business case in the U.S," August 28, 2018. https://www.energy-storage.news/blogs/investing-in-energy-storage-for-resiliency-the-business-case

[62] Energy Storage News, "Investing in energy storage for resiliency: the business case in the U.S," August 28, 2018. https://www.energy-storage.news/blogs/investing-in-energy-storage-for-resiliency-the-business-case

arrangement, the customer also benefits by being able to use the storage system to supply local loads during grid outages.

Identifying the functional requirements for resilience applications for most potential storage customers is limited by a lack of defined economic value for resilience. Markets and tariffs do not currently reflect resilience values. The lack of a transparent resilience value to the end user causes most backup power systems to be designed and installed based on their expected economic return during normal grid-connected operations. Although these systems will provide some measure of added resilience, often no hard monetary value is assigned, which is to say that the systems are expected to provide an economic return before resilience is considered.[63] According to a recent report by the DOE Electricity Advisory Council, there is still a need for market designers and regulators to understand the technology and determine the best methods to value storage as a reliability and resiliency solution.[64] At a most basic level, the addition of storage can increase a utility's overall resource diversification, thus increasing its resilience in the face of disruptive events. Storage can also enhance resilience by enabling optimization of existing generation, transmission, and distribution assets and providing restoration and startup services. In some states, storage is increasingly being considered an option in emergency-related energy planning.[65]

II.D. Adoption Scenarios

There are currently few projections of storage deployment solely for resilience applications, mainly due to the lack of widely accepted valuations for resilience. However, researchers are continuing to study the potential role of energy storage in supporting grid resilience.

U.S. DOE-Funded Studies

Researchers are currently developing a variety of tools and methodologies to allow grid owners, customers, and policymakers to assess how variations of distributed storage and microgrids, such as the optimal amount of storage to pair with solar generation, could help meet resilience goals. These nascent tools and methodologies will also help quantify the respective economic

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[63] National Renewable Energy Laboratory and City University of New York, "New York Solar Smart DG Hub-Resilient Solar Project: Economic and Resiliency Impact of PV and Storage on New York Critical Infrastructure," NREL/TP-7A40-66617, June 2016. https://www.nrel.gov/docs/fy16osti/66617.pdf

[64] U.S. Department of Energy Electricity Advisory Committee, "Securing the 21st–Century Grid: The Potential Role of Storage in Providing Resilience, Reliability, and Security Services," June 25, 2018. https://www.energy.gov/sites/prod/files/2018/06/f53/EAC_Role%20of%20Storage%20in%20Providing%20Resilience%20Reliability%20Security%20Services%20%28June%202018%29_0.pdf

[65] U.S. Department of Energy Electricity Advisory Committee, "Securing the 21st–Century Grid: The Potential Role of Storage in Providing Resilience, Reliability, and Security Services," June 25, 2018. https://www.energy.gov/sites/prod/files/2018/06/f53/EAC_Role%20of%20Storage%20in%20Providing%20Resilience%20Reliability%20Security%20Services%20%28June%202018%29_0.pdf

costs and benefits of these variations.[66,67,68] As more pilot and demonstration projects are tested by adverse events, the real-world data on these costs, benefits, and designs will feed back into improved sets of tools and methodologies.

In addition, a recent program under the DOE Grid Modernization Laboratory Consortium looked at the grid architecture required for high resiliency. In these architectures, smoothing power variations via energy storage is valued as a resilience-improving measure. By including energy storage as a core infrastructure investment for resilience and operational purposes, operators no longer need to look at the potential of stacking economic benefits to justify adding storage to the grid.[69,70]

DOE has also established the NAERM Initiative focused on developing a comprehensive resilience modeling system for the North American energy sector infrastructure. Contingency analysis tools within NAERM will enable situational awareness of the impact of threats and identify effective strategies—like the deployment of energy storage—that can mitigate these threats.

Industry Studies

A storage developer published a case study of a storage system's ability to contribute to grid resilience under difficult conditions. During Hurricane Irma in 2017, almost 40 percent of the generation assets in the Dominican Republic were forced to shut down and several transmission and distribution circuits were cut off, putting additional stress on the system. During some periods in the storm, only a few power plants and two 10 MW/5 MWh battery energy storage systems remained online. As severe storm conditions created significant deviations in grid frequency, the energy storage systems provided rapid response to counteract these deviations and maintain the target frequency. The additional power output delivered by the energy storage arrays during the storm was estimated to be equivalent to instantaneously adding a 30 MW thermal power plant.[71]

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[66] Pacific Northwest National Laboratory, "Microgrid Component Optimization for Resiliency Tool," PNNL-SA-139908, December 6, 2018. https://nelha.hawaii.gov/wp-content/uploads/2018/12/21.-Sarah-Newman_PNNL.pdf

[67] Department of Defense OASD (Energy, Installations & Environment), "Department of Defense Installation Energy: OSD Energy Resilience Overview Energy Planning for Resilient Military Installations," December 5, 2017. https://www.acq.osd.mil/eie/Downloads/IE/20171205%20Energy%20Planning%20for%20Resilient%20Military%20Installations.pdf

[68] Greentech Media, "Resilient Solar: New York and San Francisco Study Solar With Batteries as a Resiliency Solution," April 24, 2018. https://www.greentechmedia.com/articles/read/resilient-solar-power

[69] Pacific Northwest National Laboratory, "Distribution Storage Networks," PNNL-26598, June 2017. https://gridarchitecture.pnnl.gov/media/advanced/Distribution_Storage_Networks_v0.3_PNNL.pdf

[70] Pacific Northwest National Laboratory, "Defending the Electric Grid from IoT," PNNL-26621, May 2017. https://gridarchitecture.pnnl.gov/media/advanced/Defending_the_Electric_Grid_from_IoT.pdf

[71] Fluence, "Case Study Storm Resilience: Energy Storage Provides Grid Resilience during Severe Storm Conditions," 2018. https://cdn2.hubspot.net/hubfs/2810531/Collateral/AES%20Collateral/Fluence%20Case%20Study%20-%20Storm%20Resilience.pdf

III. Energy Storage Enabling Deployment of Renewables

VRE generation technologies such as solar and wind produce highly variable output, with power changes of over 80 percent on the minutes-to-hours timescale.[72] Relatively low amounts of VRE can be managed with modest adjustments, such as improved resource forecasting, improved grid codes (interconnection standards), better real-time information flow on VRE output, and sensible planning of geographical dispersion and balancing of wind and solar power installations (which often have complementary generation profiles).[73] Very high levels of VRE may create challenges for system balancing over periods of hours, days, and seasons;[74] however, aggregation of VRE generation over a large geographical area greatly reduces the net variability in the seconds-to-hours timeframe. As the penetration of inverter-based VRE generation increases and displaces generators with mechanical inertia, fast-responding energy resources including battery storage systems could be used to stabilize the system during and after major disturbances such as transmission faults or unplanned generation outages. The specific challenges associated with integrating high percentages of VRE and the mix of solutions selected vary from place to place and depend on the flexibility of existing systems.

III.A. Architectural Options

High VRE penetration will require grid flexibility that can be obtained from existing and new energy resources and enhanced markets and system operation practices. Studies undertaken in several countries, including Australia, Canada, China, the United States, and European countries, have assessed the impacts of high deployment of variable generation and the range of mitigation options. The potential roles of high-power, high-capacity batteries in high VRE scenarios are described below.

Energy storage technologies increase system reliability and flexibility by decoupling demand and supply of electricity within a given time dimension. For example, long-duration energy storage could store days of variable wind and solar in a future (ca. post-2030) regional electricity grid.[75] On a timescale of seconds to hours, energy storage is currently providing the types of short-duration services that can help lower the cost of VRE integration.

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[72] U.S. Department of Energy Advanced Research Projects Agency - Energy, “GRIDS Program Overview.” https://arpa-e.energy.gov/sites/default/files/documents/files/GRIDS_ProgramOverview.pdf

[73] E. Hsieh and R. Anderson, “Grid flexibility: The quiet revolution,” The Electricity Journal, Volume 30, Issue 2, March 2017, Pages 1-8. https://www.osti.gov/pages/servlets/purl/1352338

[74] Renewable Energy Policy Network for the 21st Century, “Renewables 2018 Global Status Report,” 2018. http://www.ren21.net/wp-content/uploads/2018/06/17-8652_GSR2018_FullReport_web_-1.pdf

[75] U.S. Department of Energy Advanced Research Projects Agency - Energy, “Duration Addition to electricitY Storage (DAYS) Overview.” https://arpa-e.energy.gov/sites/default/files/documents/files/DAYS_ProgramOverview_FINAL.pdf

Integrated Storage

Deployment of DERs such as integrated solar-plus-storage installations on industrial, commercial, and residential sites is increasingly common. Rapidly declining cost curves for variable generation and energy storage suggests potentially economically driven growth (on an unsubsidized basis) on the U.S. grid beginning in the 2020s, starting in the Southwest.[76]

Standalone Storage

Standalone utility-scale energy storage can advance VRE integration in several ways: it smooths fluctuating output from wind and solar power, and it enables the shifting of supply to better align with demand by storing electricity that is produced when it is not needed and releasing it when demand is higher. This could significantly reduce the need for renewable energy curtailment. Storage can also provide ancillary services with appropriate market incentives and controls.[77]

Other Options

To date, most of the flexibility in the grid has been provided by the generation fleet. Transmission interconnections also play a key role in flexibility by enabling access to a larger fleet of generation resources. Improving power flow control or building new transmission lines can improve system flexibility. Additional flexibility could be obtained by operating existing transmission assets more efficiently, for example by taking advantage of dynamic power transfer ratings.[78]

A number of technologies can act as flexible energy resources. A flexible energy resource is a system that can shift the demand for electricity in time, enhancing the ability to control generation output, or provide additional ancillary services to the grid. For example, demand response enabled water heaters can shift demand for electricity, and smart inverters can enable PV generation to provide additional services to the grid.

Several studies have also shown that implementation of appropriate flexibility options, including energy storage, demand response, and coordination of system operation, is critical to

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[76] Bloomberg New Energy Finance, "Co-located Solar & Storage: Southwest Story," September 17, 2018.

[77] Renewable Energy Policy Network for the 21st Century, "Renewables 2018 Global Status Report," 2018. https://www.ren21.net/wp-content/uploads/2019/08/Full-Report-2018.pdf

[78] M.J. Baumann, "Battery storage systems as balancing option in intermittent renewable energy systems - A transdisciplinary approach under the frame of Constructive Technology Assessment," July 2017. https://run.unl.pt/bitstream/10362/31566/1/Baumann_2017.pdf

making high-penetration PV and other VRE resources part of a reliable, resilient, and cost-effective electricity grid.[79,80,81,82,83]

Solar and wind over-generation has led to the implementation of curtailment in the United States and other countries. One potential strategy is to allow unconstrained buildout of variable renewable capacity and accept that excess generation will be curtailed as needed.[84] In the future, high-power, high-capacity energy storage will likely be used to economically store and time-shift a portion of the renewable energy that would otherwise be curtailed.

Another category of options includes measures to improve VRE forecasting, aggregating different types of variable resources across larger geographical areas, and improved generation dispatch and reserve management.[85] Flexibility can also be increased by improving system operations through changes in market design and regulatory frameworks; improved planning and deployment of grid infrastructure, flexible generation, and information and control technologies; expanded demand response capability; and coordination of the electricity, thermal, and transport sectors.[86] Each method has unique advantages and limitations, particularly as systems are scaled to longer durations. The relative importance of storage versus other approaches will depend on the costs of storage, geographic region (where resources such as transmission capacity differ), policies, and other factors.[87]

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[79] National Renewable Energy Laboratory, "Exploration of High-Penetration Renewable Electricity Futures. Vol. 1 of Renewable Electricity Futures Study," NREL/TP-6A20-52409-1, 2012. https://www.nrel.gov/docs/fy12osti/52409-1.pdf

[80] National Renewable Energy Laboratory, "On the Path to SunShot: Emerging Issues and Challenges in Integrating Solar with the Distribution System," NREL/TP-5D00-65331, 2016. http://www.nrel.gov/docs/fy16osti/65331.pdf

[81] National Renewable Energy Laboratory, "On the Path to SunShot: Emerging Issues and Challenges in Integrating High Levels of Solar into the Electrical Generation and Transmission System," NREL/TP-6A20-65800, 2016. http://www.nrel.gov/docs/fy16osti/65800.pdf

[82] National Renewable Energy Laboratory, "Energy Storage Requirements for Achieving 50% Solar Photovoltaic Energy Penetration in California," NREL/TP-6A20-66595, August 2016. https://www.nrel.gov/docs/fy16osti/66595.pdf

[83] National Renewable Energy Laboratory, "2018 U.S. Utility-Scale Photovoltaics-Plus-Energy Storage System Costs Benchmark," NREL/TP-6A20-71714, November 2018. https://www.nrel.gov/docs/fy19osti/71714.pdf

[84] "Minnesota study finds it cheaper to curtail solar than to add storage," January 2019. https://www.utilitydive.com/news/minnesota-study-finds-it-cheaper-to-curtail-solar-than-to-add-storage/546467/

[85] National Renewable Energy Laboratory, "Integrating Variable Renewable Energy: Challenges and Solutions," September 2013. https://www.nrel.gov/docs/fy13osti/60451.pdf

[86] Renewable Energy Policy Network for the 21st Century, "Renewables 2018 Global Status Report," 2018. http://www.ren21.net/wp-content/uploads/2018/06/17-8652_GSR2018_FullReport_web_-1.pdf

[87] U.S. Department of Energy Advanced Research Projects Agency - Energy, "Duration Addition to electricitY Storage (DAYS) Overview." https://arpa-e.energy.gov/sites/default/files/documents/files/DAYS_ProgramOverview_FINAL.pdf

III.B. Functional Requirements

To facilitate high levels of deployment of renewables, technology options must be able to provide grid support on the order of seconds to minutes of power for many types of ancillary services, including frequency response, frequency regulation, ramping, and load following.[88]

Frequency Response. The ability of the power system to maintain stability and synchronism among all elements following a large disturbance is a major constraint on operations in many grids. In the Western U.S. and Texas systems, the level of VRE deployment and displacement of conventional generation has required an evolution of controls and operational practices to maintain system stability.[89] New frequency-responsive controls on variable energy resources and especially energy storage are effective at improving frequency response after the loss of utility-scale generation.[90]

Energy Time Shifting. A resource must be able to deliver energy on the order of hours for electric energy time shifting (i.e., arbitrage). Technology options for energy time shifting need as much energy as possible in the form of high energy-to-power ratios.[91] To mimic the operating patterns that most benefit renewables, some analysts specify that energy storage needs dispatch durations of at least 4 hours.[92]

Long-duration energy storage systems that could time-shift energy over weeks or seasons can augment wind and solar PV resources to perform similarly to baseload and dispatchable fossil fuel generators. Highly dispatchable VRE generator-plus-storage assets, enabled by substantial quantities of stored electricity and proper sizing of power components, would provide significantly more value to the grid compared to today's storage systems that are typically limited to durations of 4 to 6 hours or less. Depending on the location (e.g., Maine vs. Arizona), asset type (e.g., solar vs. wind), and desired output shape (e.g., peaker vs. baseload), storage systems with tens to approximately 100 hours of duration can in many cases support electricity

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[88] Sandia National Laboratories, "DOE/EPRI Energy Storage Handbook in Collaboration with NRECA," SAND2015-1002, February 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf

[89] National Renewable Energy Laboratory, "Western Wind and Solar Integration Study Phase 3A – Low Levels of Synchronous Generation," NREL/TP-5D00-64822, November 2015. https://www.nrel.gov/docs/fy16osti/64822.pdf

[90] National Renewable Energy Laboratory, "Western Wind and Solar Integration Study Phase 3 – Frequency Response and Transient Stability," NREL/SR-5D00-62906, December 2014. https://www.nrel.gov/docs/fy15osti/62906.pdf

[91] The energy-to-power ratio is an important characteristic of a battery system. Conventional generation technologies are often characterized in terms of power capacity, which is the maximum instantaneous amount of power output and is measured in units such as megawatts. However, batteries are limited by the time they can sustain power output before they need to recharge. The duration is the length of time that a storage system can sustain power output at its maximum discharge rate, typically expressed in hours. The energy capacity of the battery storage system is the total amount of energy that can be stored or discharged by the battery storage system and is measured in units such as megawatt hours.

[92] Bloomberg New Energy Finance, "Will Batteries Bolster Renewable Returns?" September 6, 2017.

delivery across greater than 90 percent of the hours in a given year, assuming the rated power of storage is commensurate with the desired output power.[93]

III.C. Adoption Scenarios

Aggressive renewable portfolio standards (RPSs) are driving some jurisdictions to explicitly incentivize the adoption of energy storage. For example, California already experiences solar and wind curtailment at certain times of the day and year. As the state moves toward its RPS targets, storage could help address these challenges.[94,95,96] Long-duration storage technologies will support greater integration of renewable energy on the grid. Today, pumped hydro and compressed air energy storage (CAES) can provide long-duration storage. However, deployment feasibility is limited to specific locations with favorable geology, topology, and hydrological resources. Other technologies with fewer deployment constraints, including flow and reversible thermal storage, may have the potential to deliver similar discharge durations.[97]

Other reports also note that increasing renewable deployment and RPS requirements are driving an increase in the value of longer-term energy storage. For example, Platts indicates an economic potential for battery storage in most states and all Regional Transmission Organizations (RTOs) and Independent System Operators (ISOs) by the end of the next decade, driven by the deployment of variable generation (wind and solar) that can increase the price spread and volatility and system needs for flexibility.[98] The EIA projects 34 GW in utility-scale battery storage by 2050, in conjunction with increases in wind and solar deployments (Figure 1).[99]

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[93] U.S. Department of Energy Advanced Research Projects Agency - Energy, "Duration Addition to electricitY Storage (DAYS) Overview." https://arpa-e.energy.gov/sites/default/files/documents/files/DAYS_ProgramOverview_FINAL.pdf

[94] U.S. Government Accountability Office, "ENERGY STORAGE Information on Challenges to Deployment for Electricity Grid Operations and Efforts to Address Them," GAO-18-402, May 2018. https://www.gao.gov/assets/700/691983.pdf

[95] Greentech Media, "Can California Achieve 100% Renewable Electricity by 2040? Jerry Brown Thinks So," December 15, 2017. https://www.greentechmedia.com/squared/state-bulletin/california-100-renewables-2040-governor-brown

[96] R. Golden and B. Paulos, "Curtailment of Renewable Energy in California and Beyond," The Electricity Journal, Vol.28, Issue 6, Pages 36-50, July 2015. https://www.sciencedirect.com/science/article/pii/S1040619015001372

[97] U.S. Government Accountability Office, "ENERGY STORAGE Information on Challenges to Deployment for Electricity Grid Operations and Efforts to Address Them," GAO-18-402, May 2018. https://www.gao.gov/assets/700/691983.pdf

[98] Platts, "U.S. Power Storage Outlook," December 11, 2018.

[99] U.S. Energy Information Administration, "Annual Energy Outlook 2018 with projections to 2050," February 6, 2018. https://www.eia.gov/outlooks/aeo/pdf/AEO2018.pdf

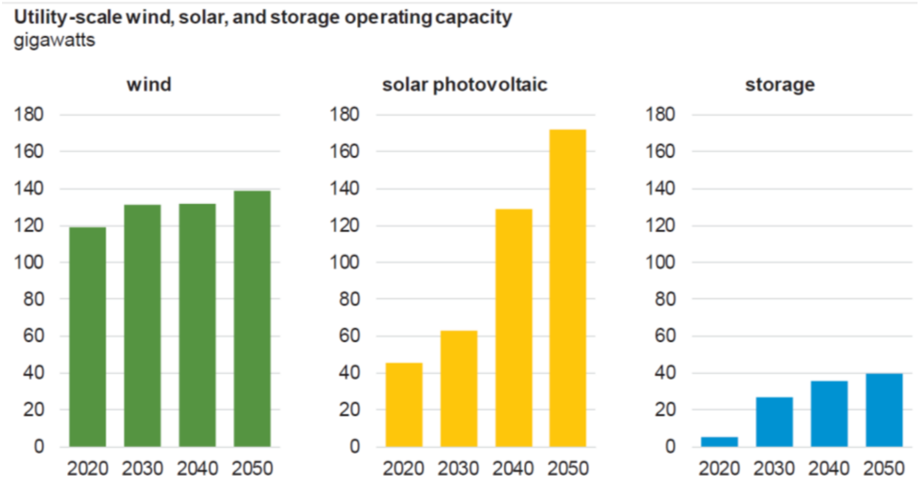

Figure 1: Projected utility-scale wind, solar, and storage operating capacity in 2020, 2030, 2040, and 2050.[100]

Today, the International Energy Agency (IEA) finds that ancillary services and energy shifting (often alongside variable generation) are key higher value applications for energy storage. Although energy storage continues to be used for ancillary services over the IEA's forecast period, it is a relatively shallow opportunity. By 2030, the primary use case of frequency regulation is projected to account for 10–15 percent of total global battery storage capacity.[101] Renewable capacity firming at the utility scale is projected to account for 11–14 percent of total global battery storage capacity in 2030.[102] Energy shifting of renewables could become the leading application by 2040.[103]

DOE-Funded Studies

A number of studies have considered the technical and, to a more limited extent, economic potential for energy storage to enable high levels of variable generation. While all studies concluded that more energy storage could support these high-variable generation scenarios, a number of assumptions and potential tradeoffs are inherent in estimating an optimal amount of energy storage in these scenarios.

A National Renewable Energy Laboratory (NREL) study considered a future scenario with 33 percent wind and solar generation in the electric power system of the Western U.S. This study looked at the impact of displacing synchronous thermal generation with wind under highly

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[100] U.S. Energy Information Administration, "Annual Energy Outlook 2018 with projections to 2050," February 6, 2018. https://www.eia.gov/outlooks/aeo/pdf/AEO2018.pdf

[101] International Renewable Energy Agency, "Electricity Storage and Renewables: Costs and Markets to 2030," October 2017. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf

[102] International Renewable Energy Agency, "Electricity Storage and Renewables: Costs and Markets to 2030," October 2017. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf

[103] International Renewable Energy Agency, "Electricity Storage and Renewables: Costs and Markets to 2030," October 2017. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf

stressed, weak system conditions.[104] A related NREL report looked at dynamic performance of the grid in the fractions of a second to 1 minute following a large disturbance (e.g., loss of a large power plant or a major transmission line) and identified mitigation measures such as transmission reinforcements, storage, advanced control capabilities, or other alternatives.[105] Both studies concluded that, with good system planning, sound engineering practices, and commercially available technologies, the Western Interconnection can withstand the crucial first minute after grid disturbances with high penetrations of wind and solar.[106,107] New frequency-responsive controls on wind, utility-scale solar PV, concentrating solar thermal power, and energy storage are effective at improving frequency response after the loss of approximately 2,750 MW of utility-scale generation, the largest generation contingency in the Western Interconnection. Grid-wide stability concerns with high penetrations of wind and solar still merit further study.[108]

Another NREL study examined the potential role of storage in minimizing PV curtailment under 50 percent solar adoption in California. This study aimed for a target level of curtailment that would keep the incremental cost of additional PV below the estimated variable cost of a combined-cycle generator in 2030, or about seven cents per kWh.[109] The study also examined the impact of increased generator flexibility, demand response, exports, and EVs and found that these measures can greatly increase the potential penetration of PV; however, even a very flexible power system will likely need additional storage beyond what is expected to be built by 2020 to enable 50 percent penetration of PV.[110]

The study also considered adoption of as many as 6.4 million EVs, a number equal to 25 percent of California's light-duty vehicle fleet, with the assumption that the majority of these vehicles can be optimally charged to maximize use of mid-day PV generation. In a high-flexibility case with low-cost PV (3 cents/kWh), the storage that will be installed by 2020 is sufficient to support 40 percent PV. Achieving 50 percent PV would require about 15 GW of additional storage capacity to be built by 2030. If California can substantially increase grid operational flexibility but not achieve either wide-scale deployment of EVs or a substantially decreased PV

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[104] National Renewable Energy Laboratory, "Western Wind and Solar Integration Study Phase 3A – Low Levels of Synchronous Generation," NREL/TP-5D00-64822, November 2015. https://www.nrel.gov/docs/fy16osti/64822.pdf

[105] National Renewable Energy Laboratory, "Western Wind and Solar Integration Study Phase 3 – Frequency Response and Transient Stability," NREL/SR-5D00-62906, December 2014. https://www.nrel.gov/docs/fy15osti/62906.pdf

[106] National Renewable Energy Laboratory, "Western Wind and Solar Integration Study Phase 3A – Low Levels of Synchronous Generation," NREL/TP-5D00-64822, November 2015. https://www.nrel.gov/docs/fy16osti/64822.pdf

[107] National Renewable Energy Laboratory, "Western Wind and Solar Integration Study Phase 3 – Frequency Response and Transient Stability," NREL/SR-5D00-62906, December 2014. https://www.nrel.gov/docs/fy15osti/62906.pdf

[108] National Renewable Energy Laboratory, "Western Wind and Solar Integration Study Phase 3A – Low Levels of Synchronous Generation," NREL/TP-5D00-64822, November 2015. https://www.nrel.gov/docs/fy16osti/64822.pdf

[109] National Renewable Energy Laboratory, "Energy Storage Requirements for Achieving 50% Solar Photovoltaic Energy Penetration in California," NREL/TP-6A20-66595, August 2016. https://www.nrel.gov/docs/fy16osti/66595.pdf

[110] National Renewable Energy Laboratory, "Energy Storage Requirements for Achieving 50% Solar Photovoltaic Energy Penetration in California," NREL/TP-6A20-66595, August 2016. https://www.nrel.gov/docs/fy16osti/66595.pdf

cost, about 10 GW of new storage capacity would be required to achieve 40 percent PV and about 28 GW of new storage would be required to achieve 50 percent PV.[111]

Industry Studies

In recent years, many operators have initiated studies to evaluate system needs under high levels of VRE integration. For example, the California Independent System Operator found that under a 50 percent RPS target, large-scale storage resources could provide "significant benefits to the system," including a reduction in renewable curtailment and overall lowering system production costs.[112] In conducting its Renewable Integration Impact Assessment, the Midcontinent Independent System Operator (MISO) has found that integration complexity increases "sharply from 30 percent – 40 percent renewable penetration."[113] MISO continues to evaluate how new solutions, including energy storage, can help manage this complexity.[114] Finally, in its 2017 Integrated Resource Plan (IRP), the utility Public Service Company of New Mexico (PNM) evaluated the potential contribution of energy storage to increasing renewable energy generation.[115] PNM's IRP pioneered the use of a new metric, $\text{LOLE}_{\text{FLEX}}$, and concluded they would require additional flexible generating capacity to accommodate additional renewable resource supplies beyond 20 percent.[116]

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[111] National Renewable Energy Laboratory, "Energy Storage Requirements for Achieving 50% Solar Photovoltaic Energy Penetration in California," NREL/TP-6A20-66595, August 2016. https://www.nrel.gov/docs/fy16osti/66595.pdf

[112] California ISO, "Supplemental Sensitivity Analysis: Benefits Analysis of Large Energy Storage," January 4, 2018. https://www.caiso.com/Documents/SupplementalSensitivityAnalysis-BenefitsAnalysisofLargeEnergyStorage.pdf

[113] Midcontinent ISO, "RIIA Phase 2 Interim Results," November 28, 2018. https://cdn.misoenergy.org/20181128%20RIIA%20Workshop%20Presentation295441.pdf

[114] Midcontinent ISO, "Renewable Integration Impact Assessment (RIIA) Assumptions Document," December 2018, https://cdn.misoenergy.org/RIIA%20Assumptions%20Doc_v6301579.pdf

[115] Public Service Company of New Mexico, "PNM 2017-2036 Integrated Resource Plan," July 3, 2017. https://www.pnm.com/documents/396023/396193/PNM+2017+IRP+Final.pdf/eae4efd7-3de5-47b4-b686-1ab37641b4ed

[116] Public Service Company of New Mexico, "PNM 2017-2036 Integrated Resource Plan," July 3, 2017. https://www.pnm.com/documents/396023/396193/PNM+2017+IRP+Final.pdf/eae4efd7-3de5-47b4-b686-1ab37641b4ed

IV. Technology Options

To set the “potential benefits of high-power, high-capacity batteries” in a wider context, this section reviews both the overall market for energy storage and battery-specific technologies. It also describes relevant, ongoing R&D activities.

IV.A. Future Projections of Energy Storage Deployment

Projections of future energy storage growth depend on both the need for storage services or applications and the technology available to provide those services. The cost of storage is also a key factor. This section highlights several studies that provide an estimate of the overall market potential for energy storage. In many cases, this market potential is disaggregated by application, function, or technology type.

Bloomberg New Energy Finance projects that the size of the U.S. grid storage market could grow from 1.1 GW/1.4 GWh installed at the end of 2017 to 146 GW/470 GWh of storage by the end of 2040 (see Figure 2).[117]

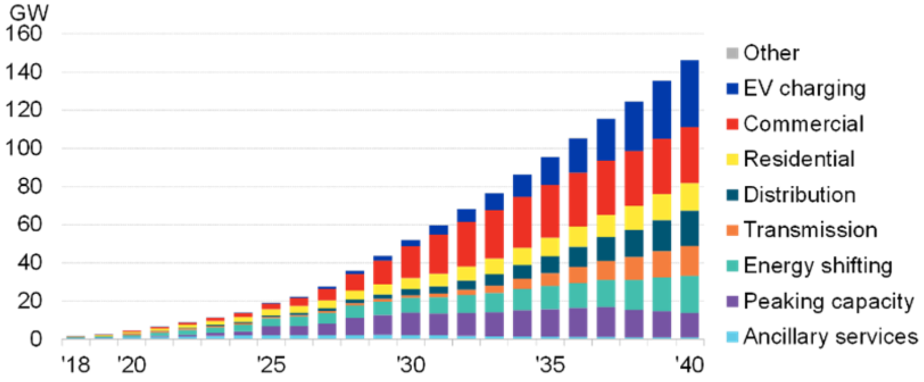

Figure 2: Projected U.S. cumulative grid storage market size by primary application based on power output.[118]

McKinsey recently assessed the cost of batteries and other grid flexibility options that can shift variable generation on a $/MWh shifted basis and concluded that by or before 2030, batteries could compare favorably with traditional supply-side options like constructing a combined cycle gas turbine generator and some traditional demand-side options (see Figure 3).[119]

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[117] Bloomberg New Energy Finance, “2018 Long-Term Energy Storage Outlook,” November 15, 2018.

[118] Bloomberg New Energy Finance, “2018 Long-Term Energy Storage Outlook,” November 15, 2018.

[119] McKinsey, “Less carbon means more flexibility: Recognizing the rise of new resources in the electricity mix,” October 2018. https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/less-carbon-means-more-flexibility-recognizing-the-rise-of-new-resources-in-the-electricity-mix

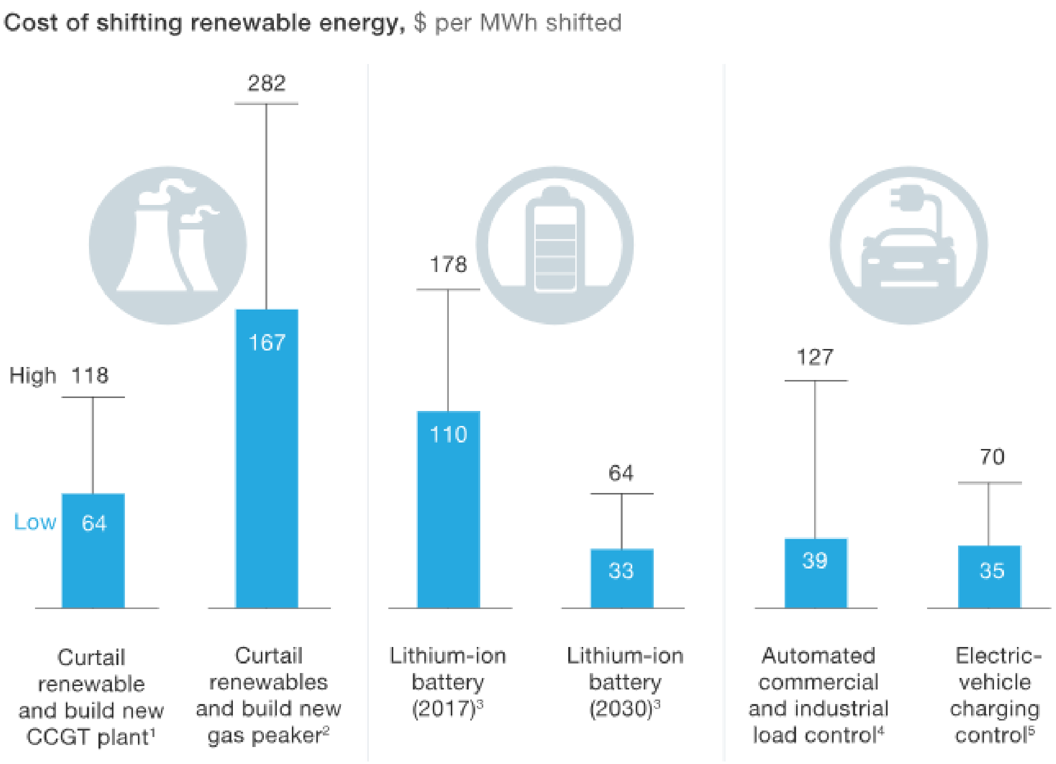

Figure 3: Cost estimates of technology options for shifting renewable energy.[120]

The DOE Advanced Research Projects Agency – Energy (ARPA-E) has also estimated the size of the U.S. energy storage market with respect to variable generation needs, based on the timescales of net (load plus generation) variability:[121]

(a) Seconds to minutes of power for voltage and frequency support. For this application, power reserve capacity on the order of up to 5–7 percent of generation on the grid (about 20–50 GW nationally) is necessary, depending on time of day and season of the year.

(b) Minutes to hours of power for smoothing and firming variable generation. For this application, reserve power for up to 1-hour duration providing standby support at a power rating on the order of 20 percent of the power from variable sources. According to a recent FERC's Energy Infrastructure Update, the installed capacity of wind and solar generation in the U.S. stood at nearly 140 GW as of May 2019.[122] Based on the ARPA-E estimate, a total storage capacity of 27 GWh would be needed today for smoothing and firming. With further developments, high-power, high-

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[120] McKinsey, "Less carbon means more flexibility: Recognizing the rise of new resources in the electricity mix," October 2018. https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/less-carbon-means-more-flexibility-recognizing-the-rise-of-new-resources-in-the-electricity-mix

[121] U.S. Department of Energy Advanced Research Projects Agency - Energy, "GRIDS Program Overview." https://arpa-e.energy.gov/sites/default/files/documents/files/GRIDS_ProgramOverview.pdf

[122] FERC Energy Infrastructure Update. https://www.ferc.gov/legal/staff-reports/2019/may-energy-infrastructure.pdf

capacity battery storage systems could economically provide a significant portion of this need.

(c) Hours to days of power for daily energy peak shifting. For this application power capacity, on the order of 200 GW and 1,000 GWh would be necessary for up to 20 percent variable generation. Future high power, very-high-capacity battery storage systems could meet a portion of these needs.

Global analyses describe similar trends. The International Renewable Energy Agency (IRENA) predicts that global electricity storage capacity will triple by 2030 if countries proceed to double the share of renewable generation in the world's energy system. The total stock of electricity storage capacity in energy terms will need to grow from an estimated 4.67 TWh in 2017 to 11.89–15.72 TWh (155–227 percent higher than in 2017) if the share of renewable energy in the energy system is to be doubled by 2030. Total battery capacity in stationary applications could increase from a current estimate of 11 GWh to 100–421 GWh in 2030.[123] The report also highlights the significant potential for growth in applications behind the meter, notably in order to increase the self-consumption of rooftop solar PV. The largest market for battery electrical storage in the period to 2030 may be the pairing of batteries with new small-scale solar PV systems. Behind-the-meter storage could become the primary use case for 60–64 percent of total battery storage energy capacity in stationary applications in 2030.[124] Despite rapid growth in stationary energy storage, batteries developed for commercial electronics and EVs are expected to dominate battery development with stationary storage comprising only 7 percent of the overall battery market by 2040.[125]

The aforementioned studies point to the increasing deployment of energy storage for both front-of-the-meter and utility-scale storage deployments. A comparison of the current energy storage growth projections in terms of GW and GWh is shown in Figure 4 and Figure 5, respectively, for several jurisdictions. All studies project roughly an order of magnitude increase in storage deployment over the next decade. While increased deployment of energy storage can enhance grid resiliency and improve renewables integration, there are other potential benefits to increased deployment of energy storage. For example, the Energy Storage Association's 35x25 Vision[126] projects that 35 GW of energy storage development by 2025 can lead to $985M in operational savings to the grid and create 50,000 new jobs in the sector.

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[123] International Renewable Energy Agency, "Electricity Storage and Renewables: Costs and Markets to 2030," October 2017. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf

[124] International Renewable Energy Agency, "Electricity Storage and Renewables: Costs and Markets to 2030," October 2017. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf

[125] Bloomberg New Energy Finance, "2018 Long-Term Energy Storage Outlook," November 15, 2018.

[126] Energy Storage Association, "35X25: A Vision for Energy Storage." http://energystorage.org/system/files/attachments/esa_vision_2025_final.pdf

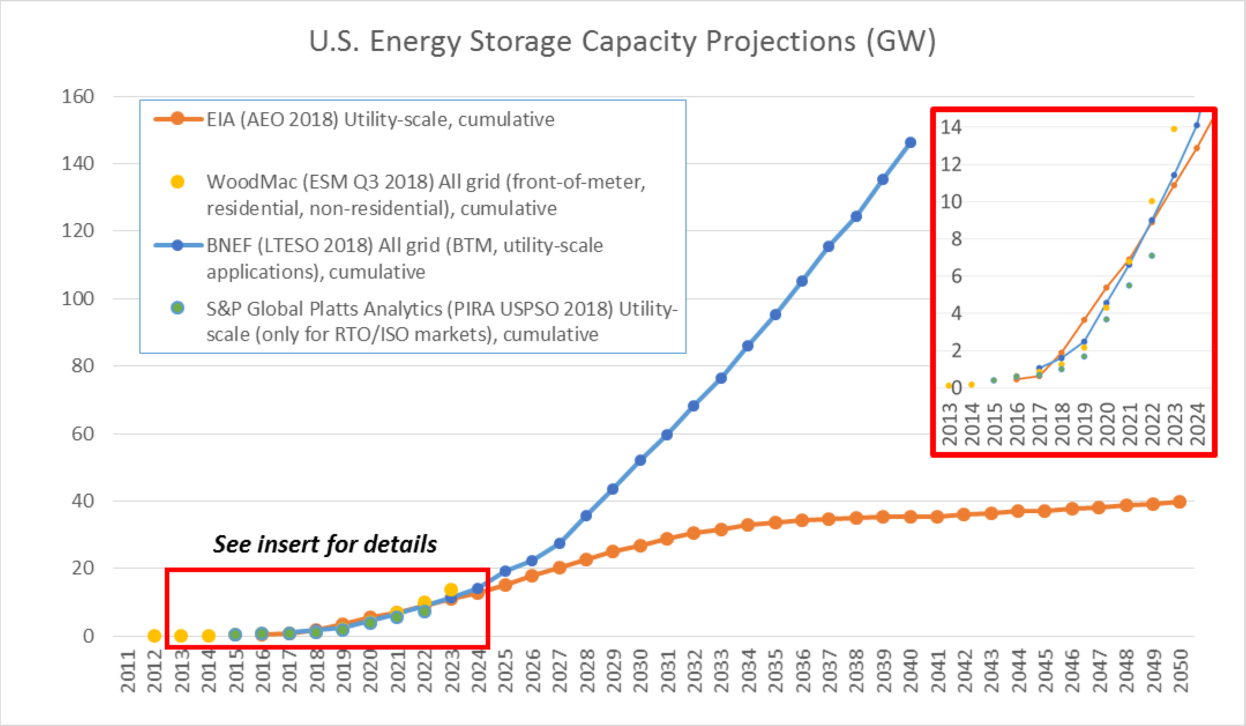

Figure 4: Compilation of U.S. energy storage capacity (GW) projections (2011–2050)[127, 128, 129, 130]

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[127] U.S. Energy Information Administration, "Annual Energy Outlook 2018 with projections to 2050," February 6, 2018. https://www.eia.gov/outlooks/aeo/pdf/AEO2018.pdf

[128] Wood Mackenzie, "U.S. Energy Storage Monitor: Q3 2018 Full Report," September, 2018.

[129] Bloomberg New Energy Finance, "2018 Long-Term Energy Storage Outlook," November 15, 2018.

[130] S&P Global Platts Analytics, "U.S. Power Storage Outlook," December 11, 2018. , ©2018 S&P Global Inc.

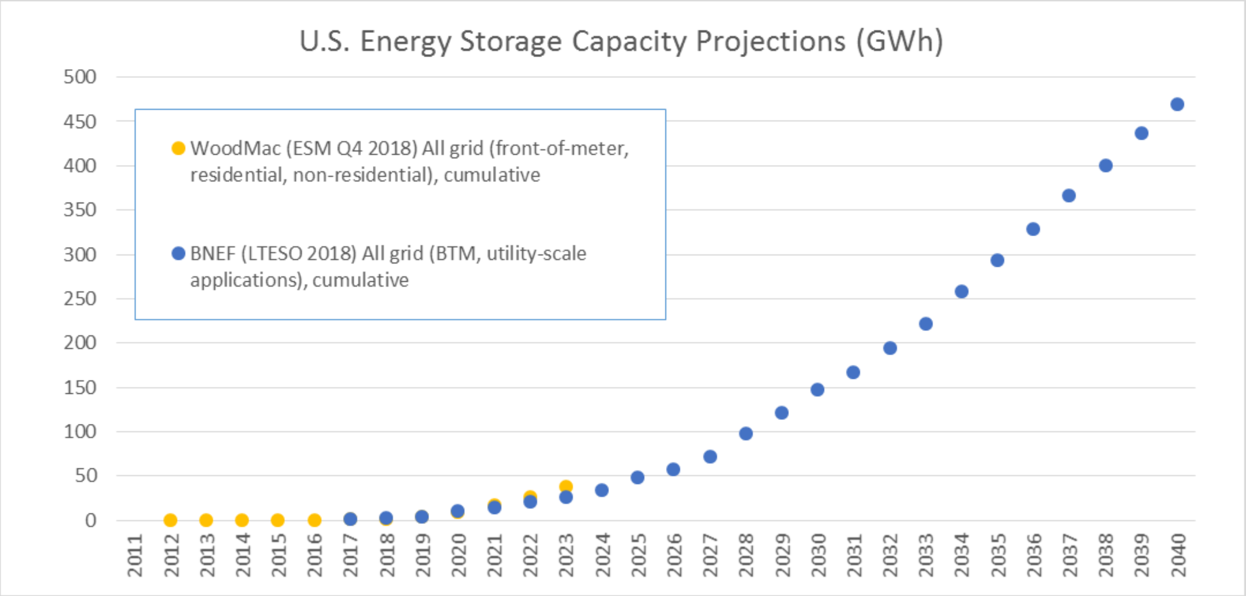

Figure 5: Compilation of U.S. energy storage capacity (GWh) projections (2011-2040)[131, 132]

IV.B. Energy Storage Mediums/Battery Chemistries

This section provides and overview of the most common energy storage technologies and provides an overview of each technology's capabilities, maturity level, deployment case studies, projections, and relevant DOE efforts. Today, lithium-ion, sodium, flow, lead-acid, and zinc-based technologies account for most of the current and planned battery deployments on the grid. Figure 6 highlights the range of power and discharge duration of these battery systems as currently listed in the DOE Energy Storage database.[133] Among battery technologies, lithium-ion technologies tend to dominate shorter duration (0.25–1 hour), high-power deployments such as frequency regulation, but more recent systems have increased both the power and duration capability of the technology. Sodium-sulfur and flow batteries are more prevalent as required discharge durations exceed 4 hours.

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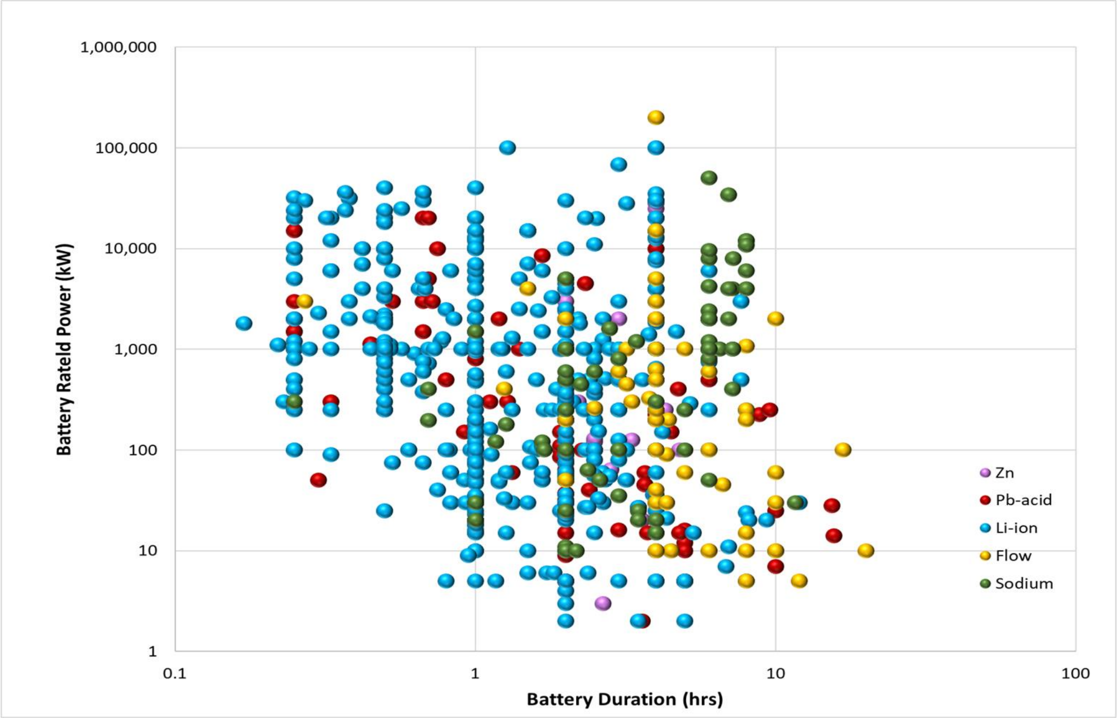
[131] Wood Mackenzie Power & Renewables and Energy Storage Association, "U.S. energy storage monitor Q4 2018 full report," December, 2018.

[132] Bloomberg New Energy Finance, "2018 Long-Term Energy Storage Outlook," November 15, 2018.

[133] DOE Global Energy Storage Database. https://www.energystorageexchange.org/



Source: US DoE Energy Storage Database, March 2019, https://www.energystorageexchange.org/
Based on Shell International Exploration & Production (US) Inc.; analysis presented by Shell 11 March 2019, ARPA-e DAYS

Figure 6. Power (kW) duration (hr) characteristics of existing battery-based energy storage installations by chemistry as listed in the DOE Energy Storage Database.

Figure 7 provides a more qualitative view for the indicative discharge durations and power capabilities of various battery chemistries available today. Zinc, lead-acid, and lithium-ion batteries are typically used for applications ranging from minutes to hours, while flow and sodium batteries are used for applications of several hours or more. For applications that require days or weeks of storage durations, DOE is supporting work to develop new emerging technologies.

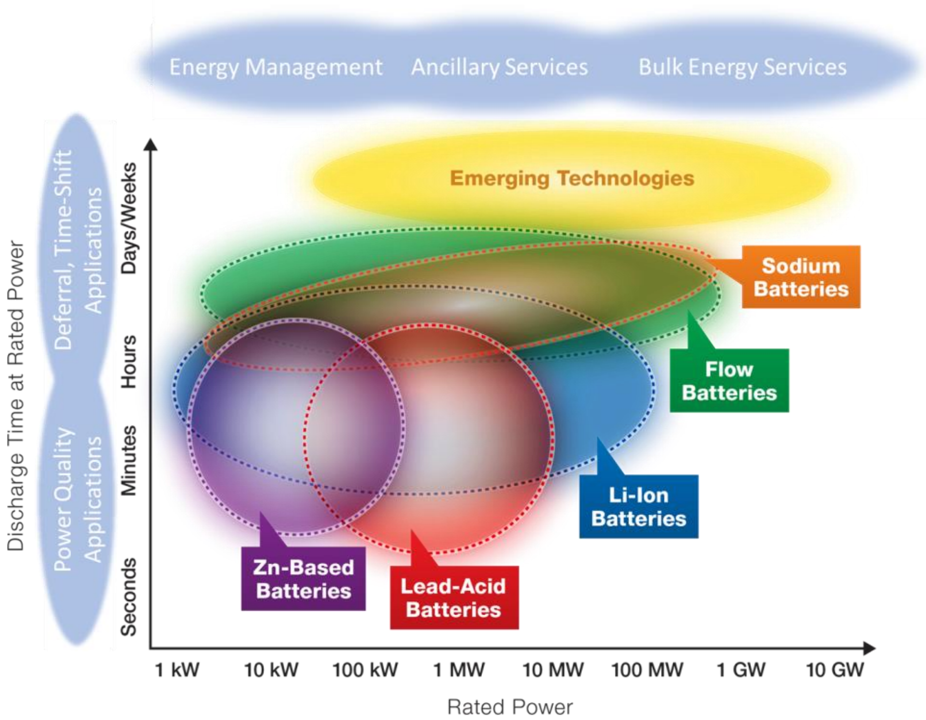


Figure 7. Power-duration graphs with various *battery-based energy storage technologies*, aligned with typical technological power and duration characteristics that align with categories of grid applications (examples).[134]

Figure 8 illustrates battery energy storage alongside a variety of energy storage technologies, including capacitors, flywheels, compressed air, and pumped hydro. Flywheels and capacitors are suitable for very short durations, while pumped hydro and compressed air have the capability to provide very long storage durations.

Appendix B provides details on many of these technologies and highlights the DOE R&D activities to increase the ability of batteries to provide higher power and longer duration capabilities. DOE research in electrical energy storage is coordinated by Federal staff participation in cross-DOE program and proposal reviews, advisory committee meetings, responses to congressional requests, and regular meetings that include office leadership.

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[134] Based on data from DOE Global Energy Storage Database. https://www.energystorageexchange.org/ developed for Figure 6 of this report.

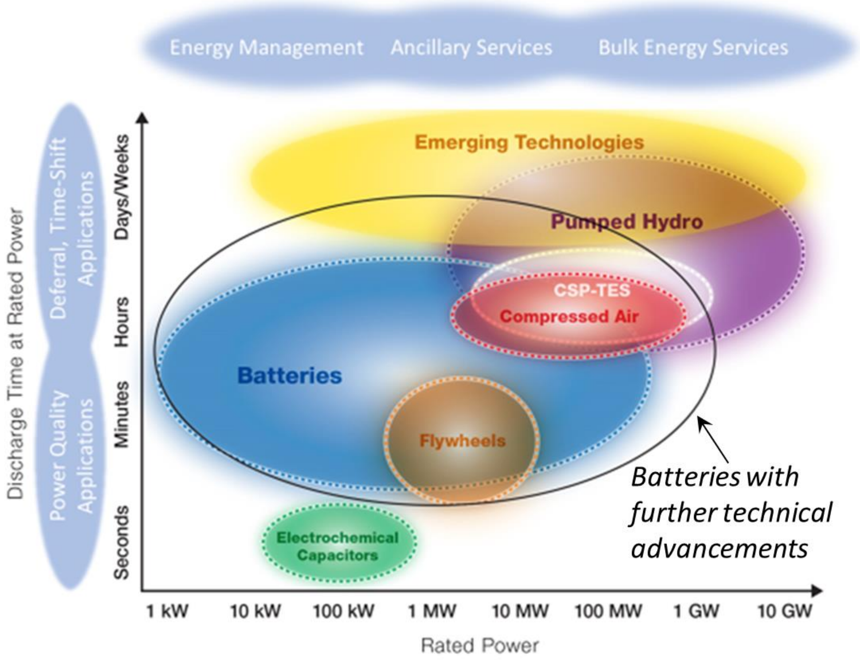

Figure 8. Power-duration graphs of *various energy storage technologies* aligned with typical technological power and duration characteristics that align with categories of grid applications (examples).[135]

Bidirectional versus Unidirectional Energy Storage

At a most basic level, energy storage technologies can be categorized by their ability to both store and deliver electricity. Bidirectional electrical energy storage is defined by the ability of technologies to both receive and deliver electricity to the power grid directly. Unidirectional storage technologies are typically focused on either delivering or extracting energy but are unable to accomplish both. For example, coal and natural gas reserves may be considered a form of unidirectional chemical energy storage where the energy is stored in the fuel until needed to generate electricity. Thermal energy storage on the other hand often uses lower-cost electricity to preheat and cool, avoiding the need to do so during peak demand. Continuing efforts are underway to identify economically viable methods to reverse the stored thermal energy into usable electricity.

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[135] Based on data from DOE Global Energy Storage Database. https://www.energystorageexchange.org/ developed for Figure 6 of this report.

IV.C. Other Adoption Gaps

Information Gap Evaluation

Valuing investments in energy storage must consider both the cost and the benefits, but assessing the potential benefits and costs of storage can prove challenging.[136] In general, most participants perceive missing valuation of provided energy storage services as a primary obstacle for market diffusion of stationary batteries.[137]

Quantifying Benefits. Benefits can be difficult to quantify, as they depend on the application, location, and ability to capture multiple benefits. Specifically, the compensation for services that storage can provide reflects local market conditions, and these vary across regions. In addition, the value of certain storage applications can be harder to quantify than for others. For example, if a utility is considering deployment of storage to defer an investment in a transmission and distribution infrastructure upgrade, then determining the value of the storage asset involves analyzing the avoided cost of that investment, which is quantifiable. However, it is more difficult to quantify the value of less tangible benefits of storage, such as improvements to operational flexibility and grid resilience, which are not monetized and are therefore difficult to quantify.[138]

Limited Information on Cost. Sufficient information on the cost of storage systems is not readily available, limiting utilities' ability to include storage in modeling and investment decisions, according to some stakeholders. Energy storage system price and cost data vary among sources and are often aggregated to protect proprietary interests. There is also limited information about project costs, operational conditions, and performance of energy storage systems. In addition, uncertainty exists about the future cost outlook and pace of technological maturity.[139]

Life Expectancy. For certain storage technologies, much is still unknown about their useful life, which depends on the number of charge and discharge cycles, calendar life, and other technical parameters. Reliable and validated lifetimes of an asset are necessary for accurately estimating the complete life-cycle costs and benefits. Given the fact that battery technologies are evolving,

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[136] U.S. Government Accountability Office (GAO), "ENERGY STORAGE Information on Challenges to Deployment for Electricity Grid Operations and Efforts to Address Them," GAO-18-402, May 2018. https://www.gao.gov/assets/700/691983.pdf

[137] M.J. Baumann, "Battery storage systems as balancing option in intermittent renewable energy systems - A transdisciplinary approach under the frame of Constructive Technology Assessment," July 2017. https://run.unl.pt/bitstream/10362/31566/1/Baumann_2017.pdf

[138] U.S. Government Accountability Office, "ENERGY STORAGE Information on Challenges to Deployment for Electricity Grid Operations and Efforts to Address Them," GAO-18-402, May 2018. https://www.gao.gov/assets/700/691983.pdf

[139] U.S. Government Accountability Office, "ENERGY STORAGE Information on Challenges to Deployment for Electricity Grid Operations and Efforts to Address Them," GAO-18-402, May 2018. https://www.gao.gov/assets/700/691983.pdf

the lack of data makes it more challenging for utilities to estimate expected costs and benefits to justify their investment expense.[140]

Modeling Gap Evaluation

Numerous modeling studies have demonstrated that electricity storage systems with up to approximately 8 hours of duration can significantly increase the amount of energy from wind and solar that can be used on a large regional grid such as in California or Texas.[141,142] Most studies of high wind and solar penetrations consider levels up to about 50 percent on an annual energy basis and often include simplifying assumptions such as large-scale geographic averaging, lossless and limitless transmission, and perfect generation forecasting. Even with such simplifications, modeling results indicate that increasing the duration of electricity storage will allow greater penetration of low-cost wind and solar resources. As a corollary, achieving high levels of variable renewable penetration could require multiday electrical energy storage and even seasonal energy arbitrage in extreme cases. However, additional modeling work is needed to accurately quantify the impact of long-duration energy storage on wind and solar penetration at the regional level and should include realistic handling of grid power flow constraints, network stability, contingency requirements, opportunity costs of curtailed energy, limits to load flexibility, and other parameters necessary to capture the full complexity of delivering power within a large electricity system.[143]

Cost and Performance Gap Evaluation

Cost. Cost is the longstanding challenge for stationary electricity storage versus other grid options described in the introduction section above.[144] Decisions to invest in energy storage often consider costs, benefits, and competing options. While the cost of some technologies has fallen in recent years, the overall initial capital cost of storage systems—including all the system components, installation, and integration costs—can still present an investment barrier when compared to more traditional resources available to electric utilities.[145]

Existing installations of PSH, CAES, and other advanced grid-scale modular energy storage technologies (batteries, flow batteries, etc.) add up to 176 GW globally (as of 2017), which is

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[140] U.S. Government Accountability Office, "ENERGY STORAGE Information on Challenges to Deployment for Electricity Grid Operations and Efforts to Address Them," GAO-18-402, May 2018. https://www.gao.gov/assets/700/691983.pdf

[141] U.S. Department of Energy Advanced Research Projects Agency - Energy, "Duration Addition to electricitY Storage (DAYS) Overview." https://arpa-e.energy.gov/sites/default/files/documents/files/DAYS_ProgramOverview_FINAL.pdf

[142] National Renewable Energy Laboratory (NREL), "Energy Storage Requirements for Achieving 50% Solar Photovoltaic Energy Penetration in California," NREL/TP-6A20-66595, August 2016. https://www.nrel.gov/docs/fy16osti/66595.pdf

[143] U.S. Department of Energy Advanced Research Projects Agency - Energy, "Duration Addition to electricitY Storage (DAYS) Overview." https://arpa-e.energy.gov/sites/default/files/documents/files/DAYS_ProgramOverview_FINAL.pdf

[144] U.S. Department of Energy Advanced Research Projects Agency - Energy, "Duration Addition to electricitY Storage (DAYS) Overview." https://arpa-e.energy.gov/sites/default/files/documents/files/DAYS_ProgramOverview_FINAL.pdf

[145] U.S. Government Accountability Office, "ENERGY STORAGE Information on Challenges to Deployment for Electricity Grid Operations and Efforts to Address Them," GAO-18-402, May 2018. https://www.gao.gov/assets/700/691983.pdf

less than 2 percent of the world's electric power production capacity.[146] The widespread deployment of these technologies is primarily limited by the high capital cost of existing storage technologies. Hence, alternative technical approaches providing equivalent energy and power are needed to address the challenge of grid-scale energy storage.[147]

While the cost of lithium-ion batteries has declined in recent years, the battery is only one component of an energy storage system. The cost of the balance of plant components and other costs to integrate storage with the grid can be substantial and are not declining as quickly as the cost of storage devices. In addition to the cost of the storage device, plant component costs include power conversion electronics, software, and monitoring and control systems, among others, that are essential to maintain the health and safety of the entire system.[148]

Energy and Power Density. The most interesting area for battery technologies is seconds-to-multiple-hour applications as balancing of variable generation. Energy density is seen as an essential factor for battery storage in transportation but not for stationary applications as these are characterized by a low degree of restrictions on weight or space. Power density is perceived as more critical, especially when it comes to short-term balancing as in the case of primary frequency regulation.[149]

Round-Trip Energy Efficiency and Cycle Life. In general, DOE has targeted development of distributed energy storage systems with an installed capital cost of < $100/kWh and a lifetime of > 5000 cycles in order to be comparable to PSH. While hydropower can operate for up to 20,000 charge and discharge cycles before an overhaul is required, new storage technologies should be able to operate up to at least 5,000 charge and discharge cycles without degradation in power or storage capacity. This number of cycles represents a useful life of approximately 10 years, the minimum required for initial use in a utility environment.[150]

Critical Materials. Key materials for battery storage systems include lithium, nickel, cobalt, and manganese for lithium-ion batteries and vanadium for vanadium-redox batteries. With increases in global demand for batteries and limited alternatives, both lithium and cobalt could experience increasing supply constraints, and both are in a period of increasing prices or price volatility. The market response for cobalt in particular may be limited because of complex market dynamics in the Democratic Republic of the Congo, which is the largest global

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[146] Center for Climate and Energy Solutions, "Electric Energy Storage." https://www.c2es.org/content/electric-energy-storage/

[147] U.S. Department of Energy Advanced Research Projects Agency - Energy, "GRIDS Program Overview." https://arpa-e.energy.gov/sites/default/files/documents/files/GRIDS_ProgramOverview.pdf

[148] U.S. Government Accountability Office (GAO), "ENERGY STORAGE Information on Challenges to Deployment for Electricity Grid Operations and Efforts to Address Them," GAO-18-402, May 2018. https://www.gao.gov/assets/700/691983.pdf

[149] M.J. Baumann, "Battery storage systems as balancing option in intermittent renewable energy systems - A transdisciplinary approach under the frame of Constructive Technology Assessment," July 2017. https://run.unl.pt/bitstream/10362/31566/1/Baumann_2017.pdf

[150] U.S. Department of Energy Advanced Research Projects Agency - Energy, "GRIDS Program Overview." https://arpa-e.energy.gov/sites/default/files/documents/files/GRIDS_ProgramOverview.pdf

supplier.[151] In addition, cobalt is co-produced with zinc, which is currently seeing a decline in global demand. The DOE Advanced Manufacturing Office Critical Materials Institute is undertaking efforts to address supply issues for these critical materials.[152]

V. Conclusion

The challenges of integrating increased variable generation resources, responding to dynamic changes in customer demand, and building resilience to natural or human-induced adverse events are driving the need for enhanced capabilities in the U.S. electric power system. Bidirectional electrical energy storage technologies that supply and absorb electrical power could play a central role in both providing the necessary buffer between electrical supply and demand and providing stored electrical capacity to mitigate outages.

High-power, high-capacity batteries have the potential to substantially increase the adoption of storage to support both system resilience and future VRE deployment. Future technical advances that would help achieve resilience and renewable integration objectives include reducing cost and increasing efficiency, life expectancy, and energy density for stationary applications. A strategy for implementing battery technology should also consider long-term industry sustainability factors, including addressing critical materials supply issues.

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[151] Blood Batteries - Cobalt and the Congo, September 2018. https://www.forbes.com/sites/jamesconca/2018/09/26/blood-batteries-cobalt-and-the-congo/#58d3ab27cc6e

[152] The Ames Laboratory, "The Critical Materials Institute." https://cmi.ameslab.gov/about

APPENDIX A: Acronyms and Abbreviations

AC	alternating current
ARPA-E	Advanced Research Projects Agency – Energy
CAES	compressed air energy storage
CAISO	California Independent System Operator
DC	direct current
DER	distributed energy resource
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
EPRI	Electric Power Research Institute
EV	electric vehicle
FERC	Federal Energy Regulatory Commission
GRIDS	Grid-Scale Rampable Intermittent Dispatchable Storage
GSL	Grid Storage Launchpad
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
IRP	Integrated Resource Plan
ISO	Independent System Operator
LOLE	loss of load expectation
MISO	Midcontinent Independent System Operator
NAERM	North American Energy Resiliency Model
NERC	North American Electric Reliability Corporation
NRECA	National Rural Electric Cooperative Association
NREL	National Renewable Energy Laboratory
PNM	Public Service Company of New Mexico
PSH	pumped storage hydropower
PV	photovoltaic
R&D	research and development
RFB	redox-flow battery
RPS	renewable portfolio standard
RTO	Regional Transmission Organization
SDG&E	San Diego Gas and Electric
UPS	uninterruptible power supply
VRE	variable renewable energy
WPTO	Water Power Technologies Office

APPENDIX B: DOE Battery Technology Activities

DOE is undertaking a range of R&D activities to increase the ability of batteries to provide higher power and longer duration capabilities. Not every storage or battery technology is represented in the following sections. Rather, this summary focuses on those technologies that are currently being deployed or are active research areas within the DOE program offices. DOE research in electrical energy storage is coordinated by Federal staff participation in cross-DOE program and proposal reviews, advisory committee meetings, responses to congressional requests, and regular meetings that include office leadership. In its fiscal year 2020 budget, DOE proposed the Advanced Energy Storage Initiative, which seeks to establish stronger cross-office activities and shared technology targets.

Lithium-ion Batteries

Ability to Provide Functional Requirements

Lithium-ion batteries are one of the most widely used technologies for portable electronics due to their high energy density and cycling performance. These systems store electrical energy in electrodes that can accommodate lithium within their atomic structure, called intercalation or insertion compounds. Most commercial lithium-ion batteries are generally comprised of a graphite anode, a lithium containing transition metal oxide or phosphate cathode, and a non-aqueous lithium-ion conducting liquid electrolyte. When using a graphite anode, cells are often characterized by the different cathode materials used (e.g., $LiCoO_2$, $LiNi_xMn_yCo_zO_2$, $LiNi_xCo_yAl_zO_2$, or $LiFePO_4$). On charging, Li^+ ions are removed from the cathode, transferred across the electrolyte, and intercalated between the graphite layers in the anode. The reverse of this process discharges the battery and enables electrical flow when connected to an external circuit. In 2008, one of the first utility-connected lithium-ion storage systems[153] was installed to provide frequency regulation services. Early grid-connected systems focused on higher power (~10 MW) and shorter discharge durations (< 1 hour) that made them an ideal solution for frequency regulation and other services that required a fast injection of power over a shorter period of time.

Today's Technology Maturity Level

Early deployments to serve the frequency regulation markets in PJM (the electricity balancing authority for Pennsylvania, New Jersey, and Maryland) had discharge durations as short as 15 minutes. Further reductions in battery costs have enabled longer duration systems to be economically deployed. In response to the Aliso Canyon gas leak in 2016, 70 MW of lithium-ion energy storage systems were deployed, all with 4-hour discharge durations.[154] Currently the largest (by power rating) lithium-ion grid-scale storage system was installed by Tesla in

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[153] AES Innovation History. http://innovation.aes.com/innovation-history/default.aspx

[154] "Tesla, Greensmith, AES Deploy Aliso Canyon Battery Storage in Record Time," January 2017. https://www.greentechmedia.com/articles/read/aliso-canyon-emergency-batteries-officially-up-and-running-from-tesla-green

November 2017 in Hornsdale, Australia. The 100 MW/129 MWh storage system is paired with a 315 MW wind farm.[155]

Constraints on Architecture

The power capability of a lithium-ion cell, or any battery chemistry, is inversely proportional to the resistance within the cell components to the transport of charged lithium-ions between the two electrodes. Energy capacity is limited by the amount of accessible electrode materials. Higher power, short-duration cells typically have thinner electrodes, whereas longer duration systems require more material (thicker electrodes) that are often difficult to fully utilize. Because of the inherent high energy density of lithium-ion cells, typical form factors for individual cells are designed with a high surface-area-to-thickness ratio to ensure adequate dissipation of heat. Excessive heat generation in the cell can lead to breakdown of the organic electrolyte into flammable gaseous components that may combust in certain conditions. Modules comprised of racks of individual cells are designed to maximize heat dissipation from the cells while reducing the potential of fire propagating from one cell to another. Future technology drivers for EVs and consumer electronics will continue to push for higher energy densities, indicating that future form factors will likely remain constrained by the need to dissipate the heat generated during the charge/discharge cycle. This architectural constraint will require MW scale grid systems to be composed of hundreds of thousands of individual cells, potentially limiting future cost reductions for complete systems due to the need to individually connect each small cell. An architecture based on higher capacity battery cells would address these constraints.

Deployment Examples

Since the early PJM deployments, increasing emphasis has been placed on pairing lithium-ion and other storage technologies with renewables and other DERs to enhance local resiliency. Specific to the interest of this report, several deployment examples are presented below in which battery energy storage enabled more efficient renewables integration and improved local resiliency.

- In 2016, Sterling Municipal Light Department of Massachusetts, with support from DOE and the Massachusetts Clean Energy Commission, installed a 2 MW/3.9 MWh lithium-ion battery storage system integrated with 2 MW of solar generation that can island the Sterling police station and dispatch center for up to 12 days in the event of power outages. In addition to providing resilience to these facilities, the battery storage system is also being used during normal operation to reduce monthly and annual demand charges for the municipality to ISO New England. In 2017, these savings amounted to $400,000 and generated a 6.7-year unsubsidized payback period for the utility.[156]

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[155] "South Australia's Tesla battery on track to make back a third of cost in a year," September 2018. https://www.theguardian.com/technology/2018/sep/27/south-australias-tesla-battery-on-track-to-make-back-a-third-of-cost-in-a-year/

[156] Clean Energy Group Case study, "Sterling Municipal Light Dept. Energy Storage System." https://www.cleanegroup.org/ceg-projects/resilient-power-project/featured-installations/sterling-energy-storage/

- In 2010, DOE and the California Energy Commission supported San Diego Gas and Electric's Borrego Springs Microgrid Demonstration Project. This project combined 1.5 MW/3.5 MWh of battery energy storage with about 3 MW of rooftop solar and 26 MW of third-party solar. In April 2013, the microgrid successfully provided power to 1,225 customers for about 6 hours and provided power to 1,060 customers for 25 hours during an outage. During normal operation, the battery storage system is employed in improving operation of the utility's grid and facilitating integration of 26 MW of solar energy.[157] In 2018, the California Energy Commission announced the award of 10 new microgrid demonstration projects around the state.

- The Imperial Irrigation District battery + gas plant black start project is a 30 MW/20 MWh lithium-ion battery system installed to mitigate stability and power quality issues as renewable energy resources are integrated into the local grid. The project also provided resilience benefits by demonstrating the ability to black start or restore power to units at its El Centro natural gas plant without relying on external transmission lines or generation.[158] According to the utility, the operation was "the first time in history that a battery energy storage system black-started a generator in an operational situation."[159]

- Arizona Public Service Punkin Center battery project for transmission and distribution deferral demonstrated ratepayers save 50 percent compared with the traditional upgrading of the distribution grid to serve a small town. Modest yet persistent 1–2 percent load growth in the town was set to overload the sole transmission line serving the community in the middle of the Tonto National Forest.[160,161] The project provides local power to residents of Punkin during 20–30 peak power demand days per year, postponing the need for an upgraded feeder line. On other days, the project provides grid services to Arizona Public Service.

- Marine Corps Air Station Miramar developed a microgrid that can power the entire installation for 3 weeks, using two 1.4 MW natural gas generators, two 1.8 MW diesel

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[157] "Borrego Springs: California's First Renewable Energy Based Community Microgrid," February 2019 California Energy Commission Report. https://www.energy.ca.gov/2019publications/CEC-500-2019-013/CEC-500-2019-013.pdf

[158] American Public Power Association, "Imperial Irrigation District brings 30-MW battery storage system online," October 28, 2016. https://www.publicpower.org/periodical/article/imperial-irrigation-district-brings-30-mw-battery-storage-system-online

[159] Energy Storage News, "California battery's black start capability hailed as 'major accomplishment in the energy industry'," May 17, 2017. https://www.energy-storage.news/news/california-batterys-black-start-capability-hailed-as-major-accomplishment-I

[160] American Public Power Association, "Arizona utility taps storage over traditional grid upgrade," August 14, 2017. https://www.publicpower.org/periodical/article/arizona-utility-taps-storage-over-traditional-grid-upgrade

[161] Utility Dive, "APS to deploy 8 MWh of battery storage to defer transmission investment," August 9, 2017. https://www.utilitydive.com/news/aps-to-deploy-8-mwh-of-battery-storage-to-defer-transmission-investment/448965/

generators, battery storage, and two 1.6 MW landfill-gas-fueled generators. There is also more than 1.2 MW of solar PV installed within the islandable area of the microgrid.[162]

Deployment Projections

Growth in lithium-ion as a grid-scale storage solution has been enabled by the increased global manufacturing capacity installed to meet the demand for consumer electronics and EVs. Improvements in manufacturing have led to lower costs for individual cells and assembly of cells (or packs). While the batteries comprise a major portion of the total installed cost for an energy storage system, additional equipment such as power electronics, balance or plant, site preparation, or grid interconnection upgrades must be considered when evaluating the financial viability of an operational energy storage system. Tracking of lithium-ion pack costs by the DOE Vehicle Technologies Program shows a > 50 percent reduction in pricing over the past 5 years (Figure 9).[163]

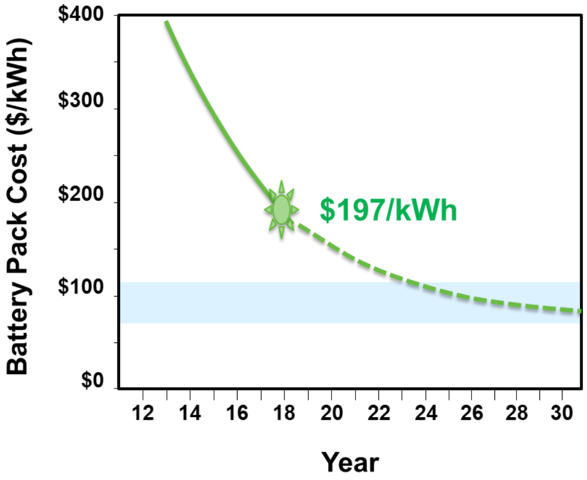

Figure 9. Lithium-ion battery cost reduction from DOE Vehicle Technologies Program.

These cost reductions have enabled lithium-ion-based energy storage systems to move beyond providing only high-value ancillary services like frequency regulation and enabling significant application in pairing with renewable resources to stabilize energy production. According to Bloomberg projections, even with continued growth, the stationary energy storage market will account for less than 7 percent of the overall lithium-ion market by 2024.[164] The market trends represented in Figure 10 imply that future R&D investments for lithium-ion batteries may continue to be dominated by consumer and EV applications.

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[162] "Beyond the Fence Line: Strengthening Military Capabilities through Energy Resilience Partnerships," p. 16.

[163] DOE Vehicle Technologies Program.

[164] Bloomberg New Energy Finance, "Department of Energy BNEF Analyst Day," February 22, 2018.

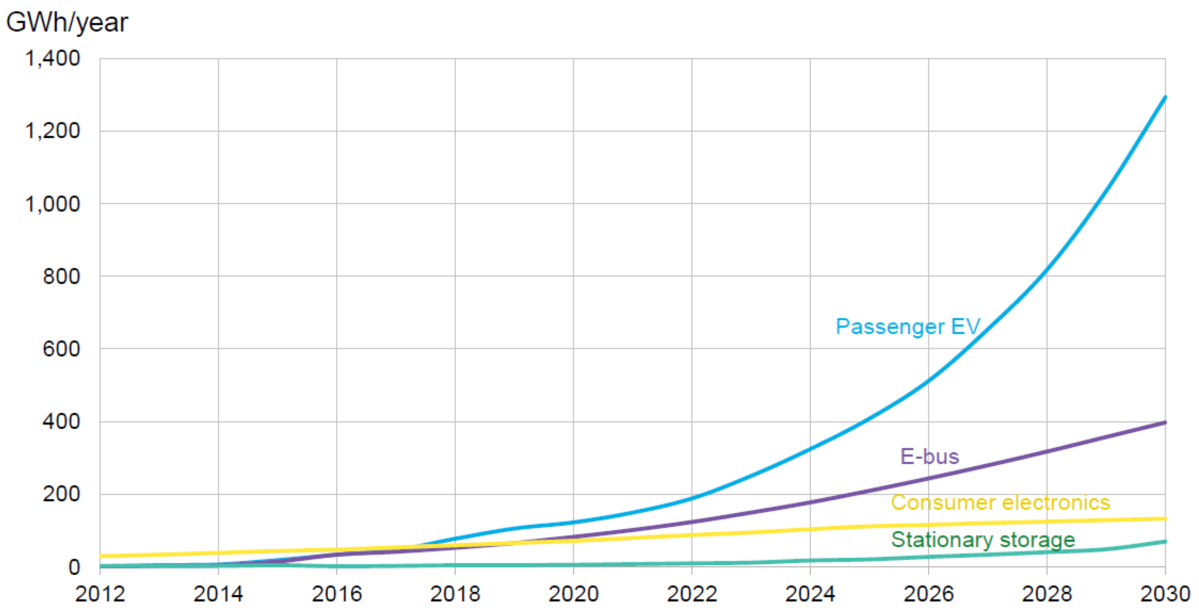

Figure 10. Projected annual battery demand by sector.[165]

DOE Activity

DOE Office of Energy Efficiency and Renewable Energy's Vehicle Technologies Program has played a critical role in advancing the state of battery technologies for EV applications. Early research by the department led to the nickel-metal-hydride batteries used in the first-generation EVs. In the past decade, the program's battery development efforts have focused on early-stage materials and cell architectures that can significantly reduce cost of lithium-ion systems. Today, R&D programs like the Battery500 Consortium are developing the next generation of lithium-based batteries that use a metallic-lithium anode to increase the energy density of a cell to allow for longer duration operation for the same weight of batteries. While significant technology challenges remain, if successful, the Battery500 Consortium could enable batteries with twice the energy per weight at a cost of < $100/kWh.

Additional R&D efforts by the program are evaluating the impacts of an EV fast-charging infrastructure on battery chemistries and grid stability and how lithium-ion systems can be recycled after their useful life to reduce long-term environmental impacts and supply chain constraints. For lithium-ion batteries, the most pressing supply chain risk is cobalt. The Vehicle Technologies Program has established the ReCell R&D Center and the Battery Recycling Prize to maximize recycling value from end-of-life batteries by recovering cathode and anode material. The Battery Recycling Prize, a jointly funded effort with the Vehicle Technologies Program and the Advanced Manufacturing Office, targets recovering 90 percent of lithium-ion batteries at their end of life. More information on these battery programs can be found at https://www.energy.gov/eere/vehicles/batteries.

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[165] Bloomberg New Energy Finance, "Department of Energy BNEF Analyst Day," February 22, 2018.

The DOE Office of Electricity's Energy Storage Program is leading efforts to understand the reliability, safety, and use of lithium-ion technologies deployed in the field. With the primary market for technologies focused on non-grid applications, the Office of Electricity is actively developing the knowledge base on how this technology performs under actual and simulated grid duty cycles. DOE supports field demonstrations of lithium-ion technology with state and regional stakeholders to assess the optimal use and economic potential under local operating conditions to better inform large-scale planning models. The program also conducts R&D to determine the expected lifetime of the different lithium-ion chemistries (and other technologies) under various grid duty cycles to give potential storage owners a greater level of confidence in the technology. Finally, the program is actively engaged in understanding the safety and operation of energy storage systems through its Energy Storage Safety Collaborative.[166] The Collaborative works with a broad group of stakeholders—from academia, R&D, codes officials, and first responders—to understand risks and mitigate the frequency and severity of potential incidents. Additional information on the Energy Storage Program can be found at https://www.energy.gov/oe/activities/technology-development/energy-storage with additional technical details at https://www.sandia.gov/ess-ssl/. In addition to these R&D activities to better define the safety and reliability of lithium-ion technologies, DOE also conducts R&D on advanced power electronics to lower the cost and improve reliability of converting the DC of the battery to the AC of the grid.

In addition to these efforts, both the Office of Electricity and Vehicle Technologies Program are supporting early-stage research into replacing the traditional materials in lithium-ion technologies with the more abundant sodium technologies while retaining the lithium-ion manufacturing process. The rising cost of lithium and supply chain concerns have prompted research into alternative materials that can be substituted for lithium in traditional lithium-ion batteries. Sodium—as the sixth most abundant element in the earth's crust—is readily available and possess a similar chemistry to lithium that favors quick adaptability to the current manufacturing infrastructure. Due to the fact that sodium-ion is relatively heavier, energy densities are lower than lithium-ion, which limits their potential market to applications that are less sensitive to high energy densities. Commercialization of sodium-ion technology is in the early stages, with a few companies overcoming some of the challenges of cell design and electrode balancing to develop pilot demonstrations. Continued research within several DOE offices is focused on identifying materials and cell chemistries that can enable sodium-based systems to have comparable energy density and lifecycle performance to today's lithium-ion while eliminating the cost and supply chain constraints of lithium.

Sodium-Metal-Based Batteries

Ability to Provide Functional Requirements

The sodium-ion technology mentioned above substitutes sodium-based compounds for lithium and does not require substantive changes to the lithium-ion manufacturing process. Battery technologies such as sodium-sulfur and sodium-metal-halide (or Zebra) batteries, however, use

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[166] DOE Energy Storage Safety Collaborative. https://www.sandia.gov/energystoragesafety-ssl/

a molten-sodium anode and thus require significantly different cell architectures to function. Both sodium-sulfur and sodium-metal-halide technologies have achieved commercial deployment on the grid with sodium-sulfur technology being the dominant sodium-metal-based energy storage solution. Both technologies use a solid ceramic electrolyte to transfer charge between a molten-sodium anode and a sulfur (sodium-sulfur) or metal-halide (sodium-metal-halide) cathode. Because the ceramic electrolyte has poor conductivity at room temperature and the necessity for keeping electrode materials in the molten state, these systems typically operate around 300–350˚C, requiring additional insulation and protection. As an analogue to a sodium-sulfur battery, sodium-metal-halide batteries use a transition metal halide (e.g., $NiCl_2$) as the cathode material instead of sulfur and operate at around 280°C. In addition to the ceramic electrolyte, sodium-metal-halide batteries also require a secondary molten salt electrolyte to facilitate charge transport in the cathode. Because of the use of the relatively expensive nickel as the cathode, the cost of sodium-metal-halide batteries is typically higher than for sodium-sulfur batteries.

Today's Technology Maturity Level

Sodium-sulfur batteries, developed by Ford in the 1970s and commercialized in Japan, were the most prevalent grid-scale battery system until the recent rise of lithium-ion technologies. Sodium-sulfur battery technology is typically characterized by longer discharge durations (6–8 hours), high energy density (~150 Wh/kg), and long cycle life (4000 cycles). Sodium-metal-halide batteries have been developed with discharge durations of up to 4 hours and have relatively high energy density (~100 Wh/kg) and long cycle life (3000 cycles). Vendor options for both technologies are limited, with a single commercial vendor of MW scale sodium-sulfur battery systems exists today. Other companies are producing storage solutions based on sodium-metal-halide technology in the 5–150 kW range or have since abandoned technology development in 2015 to focus on lithium-ion technologies.

Constraints on Architecture

Because a higher operating temperature is required to keep the sodium anode and cathode materials in a molten state, high-temperature sodium battery systems require additional precautions to ensure the sodium metal does not violently react if exposed to an oxidant. In sodium-metal-halide technology, the molten secondary electrolyte in the cathode provides additional protection by reducing when exposed to molten sodium and suppressing thermal runaway during failure. The higher temperature operation of these systems places additional constraints on the technology since they must be operated routinely or the parasitic losses to keep the system at temperature can overwhelm any economic benefits. However, the higher temperature and system operations required to remain at temperature make the technologies insensitive to extreme temperature conditions that can impact battery chemistries designed to operate around normal ambient conditions.

Deployment Examples

There are currently 20 MW/125 MWh[167] of sodium-sulfur battery systems installed in the United States with typical discharge duration of 6 to 7 hours. These systems have been deployed by U.S. utilities to provide a variety of grid services and upgrade deferrals. The following is a selection of sodium-sulfur deployments:

- The largest operational sodium-sulfur battery system in the world was commissioned in 2016 in Fukuoka, Japan, is rated at 50 MW/300 MWh, and helps to integrate a large solar array.[168]
- American Electric Power was an early adopter of sodium-sulfur technology for grid energy storage, installing the first demonstration of a sodium-sulfur battery system in 2002. The 2 MW/14 MWh system in Milton, West Virginia, was installed in 2009 to provide backup power and defer upgrades to a local substation. From 2009–2017, the storage system deferred nearly $15M in substation investments while providing outage mitigation to 700 customers. A 2017 software upgrade is now enabling the same storage system to provide frequency regulation services to PJM.[169]
- In 2010, Electric Transmission Texas and American Electric Power installed a 4 MW/24 MWh sodium-sulfur energy storage system in Presidio, Texas, to provide outage mitigation and address power fluctuations caused by an aging, single transmission line running to the town.[170]

Deployment Projections

Sodium-based battery storage accounted for 12 percent of the U.S. installed large-scale energy capacity (MWh) at the end of 2016.[171] Future projections for sodium-based systems are difficult given the limited number of technology vendors and lack of cost parity with lithium-ion systems for shorter (< 4 hour) duration storage solutions. However, as a proven technology with up to 8-hour discharge duration, sodium-sulfur technology will likely continue to have a presence in the future energy storage landscape. In January 2019, United Arab Emirates announced the deployment of a 108 MW/648 MWh sodium-sulfur battery in Abu Dhabi.[172] The storage system will enable load balancing across the city and mitigate power fluctuation from PV installations.

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[167] NGK NaS Energy Storage System. https://www.ngk.co.jp/nas/

[168] “The World's Largest NAS System helps balance supply and demand of Kyusyu's growing solar generation.” https://www.ngk.co.jp/nas/case_studies/buzen/

[169] “Software upgrade to old sodium battery marks shift in AEP's storage strategy,” May 2017. https://www.utilitydive.com/news/software-upgrade-to-old-sodium-battery-marks-shift-in-aeps-storage-strateg/442223/

[170] “Texas Pioneers Energy Storage in Giant Battery,” March 2010. https://news.nationalgeographic.com/news/2010/03/100325-presidio-texas-battery/

[171] U.S. Energy Information Administration, “U.S. Battery Storage Market Trends,” May 2018 p. 8. https://www.eia.gov/analysis/studies/electricity/batterystorage/pdf/battery_storage.pdf .

[172] “UAE integrates 648MWh of sodium sulfur batteries in one swoop,” January 2019. https://www.energy-storage.news/news/uae-integrates-648mwh-of-sodium-sulfur-batteries-in-one-swoop

Because of the elevated operating temperature of the sodium-sulfur battery, it is insensitive to local temperature conditions that might impact operation of other storage solutions.

DOE Activity

R&D supported by DOE's Office of Electricity Energy Storage Program is working to address some of the technical barriers limiting the current development of molten sodium-based battery technologies. Because of their high operating temperature, traditional sodium batteries require higher cost materials and manufacturing processes. Research efforts at DOE National Laboratories are working on novel metal-halide-based chemistries and designs that operate between 150–200˚C. This lower temperature operation enables using lower cost materials and mass-producible manufacturing process. Additionally, lowering the operating temperature has also been shown to increase the operational life of these technologies compared to current technologies.

Lead-Acid Batteries

Ability to Provide Functional Requirements

All lead-acid designs share the same basic chemistry: a lead-dioxide positive electrode, a metallic-lead negative electrode, and sulfuric-acid-based electrolyte. Traditional lead-acid batteries for motive application lack the discharge duration for grid-scale storage, but several advancements in the technology have enabled their usefulness for storage applications. Advanced lead-acid technologies typically employ carbon additions to anode to improve performance and lifetime.

Today's Technology Maturity Level

Invented in 1859, lead-acid batteries are the oldest form of rechargeable battery technology with wide application as engine starters and industrial backup. An analysis of the rechargeable battery market share by Avicenne Energy (Figure 11) shows the dominance of lead-acid technology in the overall rechargeable battery market.[173]

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[173] "Lithium-ion Battery Raw Material Supply and Demand 2016-2015," presented June 2017. http://www.avicenne.com/pdf/Lithium-Ion%20Battery%20Raw%20Material%20Supply%20and%20Demand%202016-2025%20C.%20Pillot%20-%20M.%20Sanders%20Presentation%20at%20AABC-US%20San%20Francisco%20June%202017.pdf

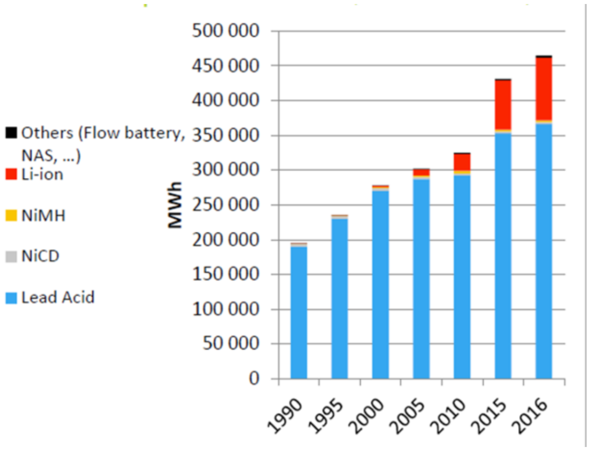

Figure 11: Rechargeable battery market share.[176]

One of the earliest MW scale energy storage systems deployed on the grid (installed in 1997) was based on lead-acid technology, but recent growth in stationary deployments has been centered on UPS systems for telecommunications and backup power applications.

Constraints on Architecture

The design and architecture of lead-acid batteries is very mature. Inherently, lead-acid technologies are low energy density (~30 Wh/l), containing about tenfold less energy by volume than lithium-ion technologies. Overall, capital costs for lead-acid systems are one of the lowest on a $/kWh basis; however, these systems typically use a smaller range of their available capacity (e.g., 30–70 percent state of charge compared to 5–95 percent for lithium-ion), which increases the cycle life of the technology but also increases the levelized cost by requiring more batteries for a given power and energy output. Current recycling rates for lead-acid batteries are > 99 percent in the United States[174] due to the high lead content contained in the battery (65 percent lead by weight) and environmental regulations.[175]

Deployment Examples

To date, most grid-scale storage applications using lead-acid technology have ranged from 1–3 MW with discharge durations around an hour.

- In 1997, a 1.6 MW/1.0 MWh lead-acid system was installed in the island community of Metlakatla, Alaska, to reduce the nearly $1M/year cost associated with operating diesel generators for peak demand. The system is integrated with a hydroelectric generator that

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[174] "Study finds nearly 100 percent recycling rate for lead batteries," November 2017. https://www.recyclingtoday.com/article/battery-council-international-lead-battery-recycling/

[175] G.J. May et al. "Lead batteries for utility energy storage: A review," Journal of Energy Storage 15 (2018) p.155.

maintains the charge on the battery system. The system is still operational with complete battery replacement occurring in 2008 after nearly 12 years of operation.[176]

- In 1988, Southern California Edison installed a 10 MW/40 MWh lead-acid battery at a substation in Chino, California. This demonstration project was operational for 9 years and was used to demonstrate the technical feasibility of the system to provide grid services such as peak shaving, transmission line support, and spinning reserve. The storage system was able to switch from idle to full charge/discharge in less than 20 milliseconds.[177]
- PNM, in conjunction with DOE and EPRI, installed a 250 kW/1.0 MWh advanced lead-acid energy storage system as a smart grid demonstration. The project showed that the battery storage system could provide load shifting and intermittency mitigation of a 0.5 MW PV array connected to the storage system.
- A microgrid project at Fort Bliss, Texas, includes an advanced lead-acid battery rated at 300 kW. In addition to seamless transition during grid failure, the system also provides support services including power factor correction and area frequency regulation services to the local electrical system operator while it is connected to the electric grid, providing increased reliability and security to Ft. Bliss.[178]

DOE Activity

Given the maturity of lead-acid technology DOE has limited R&D programs. As with other technologies, DOE is investigating the impact of typical grid duty cycles on the lifetime and performance of these systems to better inform the technology development process.

Redox-Flow Batteries.

Ability to Provide Functional Requirements

A redox-flow battery (RFB), as schematically shown in Figure 12, is a unique type of rechargeable battery architecture in which the electrochemical energy is typically stored in two soluble redox couples contained in external electrolyte tanks.[179]

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[176] "Examination of VRLA cells sampled from a battery energy storage system (BESS) after 30-months of operations," SAND02000-1453C.

[177] G.J. May et al. "Lead batteries for utility energy storage: A review," Journal of Energy Storage 15 (2018) p.145–157.

[178] Fort Bliss Energy Storage System. http://www.princetonpower.com/images/casestudies/pdfs/FortBliss_CaseStudy_September2015.pdf

[179] Z. Yang, et al "Electrochemical Energy Storage for Green Grid," Chem. Rev. 2011, 111, p 3577–3613.

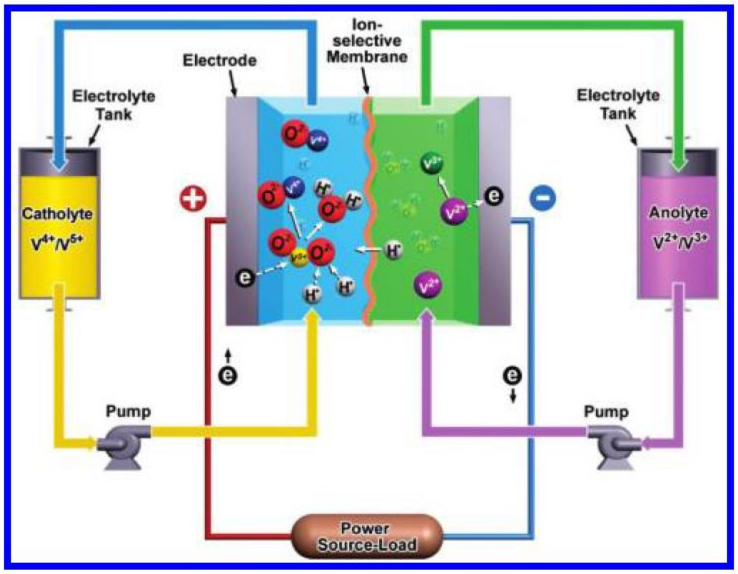

Figure 12. Schematic of an all-vanadium RFB as an example of RFBs (or regenerative fuel cells).[180][181]

Liquid electrolytes are pumped from the storage tanks through electrodes where the chemical energy in the electrolyte is converted to electrical energy (discharge) or vice versa (charge). The electrolytes flowing through the cathode and anode are often different and referred to as anolyte and catholyte, respectively. Between the anode and cathode compartments is a membrane (or separator) that selectively allows cross-transport of a charge-carrying species (e.g., H^+, Cl^-) to maintain electrical neutrality and electrolyte balance. In traditional battery designs like lithium-ion, the stored energy is directly related to the amount of electrode material and increasing the power capacity of these systems also increases the energy capacity as more cells are added. In redox-flow systems the power and energy capacity can be designed separately. The power (kW) of the system is determined by the size of the electrodes and the number of cells in a stack, whereas the energy storage capacity (kWh) is determined by the concentration and volume of the electrolyte. Both energy and power can be easily adjusted for storage from a few hours to days, depending on the application. This flexibility makes RFBs an attractive technology for grid-scale applications where both high-power and high-energy services are being provided by the same storage system. The basic RFB design is also flexible in the chemistries it can accommodate. Any multivalent element that can be dissolved in a solution can potentially be used in RFB design.

Today's Technology Maturity Level

To date, vanadium-based and hybrid zinc-bromine flow batteries have achieved the most commercial success, with other technologies based on iron-chrome and polysulfide-bromine having been demonstrated but falling short of commercialization. Vanadium flow batteries use the ability of vanadium to exist in four distinct electrically charged species to serve as both the anolyte and catholyte, limiting the impact of species crossover on battery performance. The

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[180] Yang, et. al, Chem. Rev. 2011, 111, p. 3683

[181] Z. Yang, et al "Electrochemical Energy Storage for Green Grid," Chem. Rev. 2011, 111, p 3577–3613

technology was first demonstrated in the 1980s by Maria Skyllas-Kazacos at the University of New South Wales, with various generations of the technology having attempted field demonstrations and commercialization. In the past decade, the technology has re-emerged as a candidate for grid-scale storage applications due to its long cycle life and effective use of available state-of-charge range. Replacing the flowing anolyte with a metal electrode (e.g., zinc in $Zn\text{-}Br_2$ and iron in Fe/Fe^{2+} technologies) increases the number of chemistries available for use, but also couples the power and energy reducing the operational flexibility. Zinc-based hybrid flow batteries are one of the more promising systems for medium- to large-scale energy storage applications, with advantages in safety, cost, cell voltage, and energy density. Zinc-hybrid systems have the highest energy content due to the high solubility of zinc ions (> 10 M) and the solid negative electrode.[182]

Constraints on Architecture

Traditional flow battery technologies, like vanadium flow batteries, consist of a collection of serially connected cells arranged in a stack where the electrochemical reactions occur and external storage tanks containing anolyte and catholyte. This decoupling of power and energy creates a great deal of flexibility in the design architecture as the size of the stack (relating to flow battery power) and tanks (the energy content of flow batteries) can be independently adjusted depending on the application. Individual cells in a stack can approach a square meter in active area and typically operate at ~1.0 V to prevent hydrolysis of the aqueous solution. Because of this architecture, flow batteries typically provide lower voltage and higher currents to the DC-AC inverter, the reverse of what is delivered by lithium-ion systems. In addition, most flow battery components are comprised of polymer materials that can be manufactured by traditional molding processes that greatly reduce the cost of production.

Deployment Examples

- In the United States, the largest vanadium flow battery system is 2 MW/8 MWh located in Everett, Washington, and operated by Snohomish Public Utility District.[183] The mixed-acid vanadium chemistry was developed as part of the DOE Office of Electricity Energy Storage Program.

- An all-iron flow battery is currently on test at Fort Leonard Word in Missouri for the U.S. Army Corps of Engineers. Because the system uses a neutral pH electrolyte, the 60 kW/220 kWh containerized flow battery can be transported dry with water added onsite to activate the battery. The ability to add and remove water from the system locally greatly reduces

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[182] Li B, Z Nie, M Vijayakumar, G Li, J Liu, VL Sprenkle, W Wang. "Ambipolar zinc-polyiodide electrolyte for a high-energy density aqueous redox flow battery," Nature Communications 6 article number 6303, February 2015.

[183] "Washington state's new 8 megawatt-hour flow battery is the largest of its kind," April 2017. https://arstechnica.com/information-technology/2017/04/washington-states-new-8-megawatt-hour-flow-battery-is-the-largest-of-its-kind/

weight for easier transport to forward-operating bases.[184] Technology development and demonstration were supported through a 5-year ARPA-E award under the 2012 Grid-Scale Rampable Intermittent Dispatchable Storage (GRIDS) program.

- Using high-power cells developed as part of the ARPA-E GRIDS program, a 0.5 MW/3 MWh vanadium flow battery was deployed at a high school in Massachusetts to store energy from the school's wind turbine and other local power generation.[185]
- A 200 kW/1,000 kWh Zn-Br_2 hybrid system has been deployed at the Amandelbult mine in South Africa.[186]

Deployment Projections

While flow batteries currently comprise < 1 percent of the deployed energy storage systems in the world, the operational flexibility, long life, and potential for long-term cost reductions make it a viable candidate for future grid-scale deployments. Two of the largest battery storage systems in the world are currently under construction in China and are based on the vanadium flow battery system. The first is a 200 MW/800 MWh system in Dalian that will be used for peak shaving application and load center.[187] A second 100 MW/500 MWh project is proposed in the Hubei Province to provide peaking power to the region.[188]

DOE Activity

While vanadium flow batteries have achieved initial commercial deployment, further R&D efforts are needed to push the technology to lower cost. Efforts by the DOE Office of Electricity to increase performance and reduce the cost of advanced systems demonstrated that the technology may be able to achieve costs < $300/kWh when deployed at scale.[189] However, the analysis shows that greater than 50 percent of the cost of a vanadium flow battery system (including the balance of plant and power electronics) is contained within the cost of the

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[184] "The Life and Death Value of Energy Storage in Military Microgrids," January 2017. https://microgridknowledge.com/military-microgrids-ess/

[185] "Vionx, National Grid, and US Department of Energy Complete Installation of one of the World's Most Advanced Flow Batteries at Holy Name High School, Worcester, Mass," October 2017. https://www.vionxenergy.com/vionx-national-grid-and-us-department-of-energy-complete-installation-of-one-of-the-worlds-most-advanced-flow-batteries-at-holy-name-high-school-worcester-m/

[186] "Primus Power installing eight EnergyPod battery systems at Amandelbult mine," April 2018. https://im-mining.com/2018/04/23/primus-power-installing-eight-energypod-battery-systems-amandelbult-mine/

[187] "200MW/800MWh Energy Storage Station to be Built with RONGKE POWER's Vanadium Flow Battery," May 2016. http://www.uetechnologies.com/news/71-200mw-800mwh-energy-storage-station-to-be-built-with-rongke-power-s-vanadium-flow-battery

[188] "China's biggest flow battery project so far is underway with hundreds more megawatts to come," November 2018. https://www.energy-storage.news/news/chinas-biggest-flow-battery-project-so-far-is-underway-with-hundreds-more-m

[189] Pacific Northwest National Laboratory, "High Current Density Redox Flow Batteries for Stationary Electrical Energy Storage PNNL-23819-4", September 2016. https://energystorage.pnnl.gov/pdf/PNNL-23819-4.pdf

vanadium raw materials.[190] Future capital cost reductions will require replacing vanadium with lower cost raw materials to approach the $100/kWh targets required for wider scale deployment of energy storage.

One approach being developed by the DOE Office of Electricity Energy Storage Program is to replace vanadium with lower cost, easy to synthesize, redox active-organic molecules. A critical design aspect is ensuring these organic redox systems use existing RFB manufacturing capabilities necessitating that new technologies are water soluble with similar concentrations, viscosities, and performance to today's RFBs. Designing these new organic systems to be soluble in water—called aqueous soluble organics—not only ensures these systems are compatible with existing RFB infrastructure but also provide inherent fire safety. Recent research efforts identified a phenazine-based anolyte that offers significant potential for lower cost while demonstrating equivalent performance to state-of-the-art vanadium systems.[191] Additional research will be required to demonstrate the technology is suitable for scale-up and field applications.

ARPA-E, through several energy storage-based solicitations such as GRIDS, OPEN 2012, and Integration and Optimization of Novel Ion-Conducting Solids programs, has supported several high-risk but transformational flow battery technologies. Technologies based on iron, organics, zinc, and lithium slurries have been moved to greater commercial viability by enabling multi-kW scale prototypes to be demonstrated. Recently, ARPA-E awarded four new flow battery projects under its Duration Addition to electricitY Storage (DAYS) program. DAYS focused on economically extending the discharge capacity of flow batteries into the 10- to 100-hour range via means such as reducing the capital cost of the flow battery stack and enabling inexpensive active materials such as sulfur and manganese with low crossover through the central membrane.[192]

The DOE Office of Science also supports basic research in electrical energy storage applicable to both transportation and grid storage technologies like flow batteries. The strategic directions are currently driven by the report from the 2017 Basic Research Needs for Next-Generation Electrical Energy Storage Workshop.[193] This workshop included engagement from the DOE energy technology offices with participation from the broad academic, National Laboratory, and industrial research communities. The research priorities focus on fundamental science underpinning batteries for grid energy storage and transportation, such as using advanced synthesis to tailor structures, tuning functionality of materials and chemistry, reducing

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[190] Next Generation Redox Flow Battery Development at PNNL. https://www.sandia.gov/ess-ssl/docs/pr_conferences/2015/EESAT%202%20Wednesday/Sprenkle.pdf

[191] A. Hollas, et al, "A biomimetic high-capacity phenazine-based anolyte for aqueous organic redox flow batteries" Nature Energy 3, p. 508.

[192] U.S. Department of Energy Advanced Research Projects Agency - Energy, "GRIDS Program Overview." https://arpa-e.energy.gov/sites/default/files/documents/files/GRIDS_ProgramOverview.pdf

[193] Basic Research Needs for Next Generation Electrical Energy Storage https://science.osti.gov/-/media/bes/pdf/reports/2017/BRN_NGEES_rpt.pdf?la=en&hash=AE01DA34A0F1F17E42261F0B7BC416868C9C51AB

detrimental chemistries that degrade performance, and using advanced analytical and modeling tools to probe reactions across a wide range of temporal and spatial scales. Fundamental research efforts include the Joint Center for Energy Storage Research,[194] an Energy Innovation Hub; Energy Frontier Research Centers; and single-investigator and small group research.

Zinc-Based Technologies

Ability to Provide Functional Requirements

In addition to the aforementioned hybrid flow battery based on a zinc anode, several other non-flow battery chemistries use low-cost zinc as a critical element of construction. Zinc-nickel technology is composed of a zinc-based anode, an alkaline electrolyte, and a nickel-hydroxide cathode. This technology is characterized by high power densities with energy densities in between lead-acid and lithium-ion technologies. The higher energy density and longer cycle life have made them attractive alternatives in UPS and automotive applications where lead-acid systems have been primarily used and may enable them to find application for shorter duration grid services. Another promising zinc-based chemistry currently being developed for grid-scale applications is based on the traditional Zn-MnO_2 alkaline batteries. These cells use a zinc anode, an alkaline electrolyte, and a manganese-oxide cathode; this chemistry is the basis of most disposable batteries currently on the market. Modifications to the chemistry have enabled reversible charging of the cells. When combined with estimated materials cost of < $20/kWh, a long shelf life, and an established manufacturing supply chain in the United States, these batteries are a potential candidate for low-cost grid storage.

Today's Technology Maturity Level

Zinc-nickel batteries, invented by Edison in 1901, are still being developed today as a low-cost rechargeable storage solution to replace lead-acid batteries in applications requiring high power and longer lifetimes. Several commercial entities in the United States are pursuing development of the technology. Traditional Zn-MnO_2, or "alkaline" batteries, are one of the most produced battery chemistries in the world.

Constraints on Architecture

Manufacturing lines for rechargeable Zn-MnO_2 chemistries use the same materials and construction with modification to the chemistry to enable rechargeability.

Deployment Examples

- The Georgia Department of Transportation has deployed 40 zinc-nickel systems in the greater Atlanta area as UPSs for traffic lights citing the enhanced reliability over lead-acid technologies.[195]

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[194] Joint Center for Energy Storage Research. https://www.jcesr.org/

[195] Atlanta's Regional Traffic Operations Program. https://www.zincfive.com/atlanta-georgia-qa

- A 200 kW/800 kWh $Zn\text{-}MnO_2$ system has been deployed in the basement of Steinman Hall at the City University of New York campus. This demonstration project supports peak load management and demand response to reduce electrical consumption.[196]

Deployment Projections

Zinc-nickel technologies are expected to compete in the $40B market for existing lead-acid technologies,[197] while $Zn\text{-}MnO_2$ technologies are expected to compete for stationary storage applications requiring 3 to 4 hours of discharge duration. Inherent safety advantages resulting from both chemistries having a water-based electrolyte and low energy density may enable them for indoor applications where risk of fire is more of a concern.

DOE Activity

Recent R&D efforts supported by ARPA-E and the Office of Electricity have focused on advancing reversible $Zn\text{-}MnO_2$ technology to the state of commercial viability. Early support by ARPA-E in New York enabled maturation of the technology and pilot-scale production of first-generation products. The DOE Office of Electricity Energy Storage Program is supporting validation of the technology in selected field trials and R&D focused on improving materials utilization and development of lower cost materials to further the cost-performance position of the technology. Longer term R&D is focused on using the full capability of $Zn\text{-}MnO_2$ systems and demonstrating cells with energy densities of 200 Wh/l and a cell cost lower than $50/kWh. These developments will enable the technology to compete with higher energy density technologies but at significantly lower costs and improved safety.

Utilizing Zn^{2+} and other multivalent cations in battery technologies (e.g., Mg^{2+}, Fe^{2+}) offer the potential of delivering more than one electron for every charge and discharge cycle, thereby increasing materials efficiency and potentially lower cost storage options. Research efforts on divalent materials are being conducted across the Office of Electricity, ARPA-E, and the Office of Science's Joint Center for Energy Storage Research.

Electrochemical Capacitors

Ability to Provide Functional Requirements

Electrochemical capacitor technology, sometimes referred to as "supercapacitors" or "ultracapacitors," directly stores electrical charge on the surface of a material rather than converting the charge to another form, such as chemical energy in batteries. This makes supercapacitors highly reversible and efficient, with extremely fast response times (typically < 1

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[196] Understanding Zinc-Manganese Systems. https://naatbatt.org/wp-content/uploads/2018/11/6_E_Cowles-Understanding-Zinc-Manganese-Dioxide-Systems_Slides_Cowles.pdf

[197] Avicenne Energy, "The Rechargeable Battery Market and Main Trends 2011-2020," March 2018.

second).[198] The technology is ideally suited for short-duration, high-power applications such as frequency regulation and voltage stabilization.

Today's Technology Maturity Level

The electric double-layer effort used in supercapacitors was first documented in 1957, but not actively developed until nearly a decade later.[199] Today, supercapacitors are a mature technology with common commercial deployments seen in multiple industrial sectors including automotive.

Constraints on Architecture

The devices may have longer useful lives since there is little breakdown in the electrochemical capacitor's ability to store energy electrostatically. Currently, electrochemical capacitors can store significantly more energy than dielectric and electrolytic capacitors; however, the technology is still cost prohibitive.[200]

Deployment Examples

- At the University of California San Diego, a 28 kW ultracapacitor is installed to facilitate smoothing of PV intermittency and is coupled with solar forecasting systems.[201]

- Supercapacitor technology has been demonstrated to provide fast injection of reactive power. The system can respond in less than 50 milliseconds to help stabilize grid operations.[202]

Deployment Projections

According to Polaris Market Research, the global ultracapacitor market is expected to reach $8B by 2026 supported by growth in the EV and smart meter markets.[203]

DOE Activity

As evidenced by current market size, electrochemical capacitor technology is a relatively mature technology with most R&D efforts conducted by industry for product improvements. Select R&D efforts within DOE are focused on extending the discharge duration or temperature

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[198] J. Miller, "Perspective on electrochemical capacitor energy storage," Applied Surface Science 460 (2018) p 3–7.

[199] Tecate Group, "Ultracapacitors & Supercapacitors." https://www.tecategroup.com/ultracapacitors-supercapacitors/ultracapacitor-FAQ.php

[200] DOE Grid Energy Storage, December 2013. https://www.energy.gov/sites/prod/files/2014/09/f18/Grid%20Energy%20Storage%20December%202013.pdf.

[201] W. Torre, "Design and Integration of a 2.5MW/5MWh Energy Storage System on University of California, San Diego's 42 MW Microgrid," September 2015. https://www.sandia.gov/ess-ssl/docs/pr_conferences/2015/PR%204/2-Torre.pdf

[202] T&D World, "Siemens Launches Frequency Stabilizer to Support Power Grids in Milliseconds," September 2018. https://www.tdworld.com/test-and-measurement/siemens-launches-frequency-stabilizer-support-power-grids-milliseconds

[203] Polaris Market Research. "Ultracapacitors Market Share," September 2018. http://abnews-wire.blogspot.com/2018/10/ultracapacitors-market-to-surpass-usd.html

stability of these technologies to enable more efficient operation of the power electronics used in energy storage systems.

Pumped Storage Hydropower

Ability to Provide Functional Requirements

PSH currently accounts for about 95 percent of utility-scale storage deployments currently representing 21.6 GW[204] of capacity in the United States and > 130 GW worldwide.[205] PSH provides large-scale energy storage, enabling balancing of variable renewable resources such as wind and solar PV on timescales from seconds to seasons, and it can also provide a suite of non-energy services to support reliable grid operation. While PSH was originally deployed principally to balance load variability so nuclear plants could operate as stable baseload generation, there is evidence the role of PSH is evolving to provide greater flexibility in response to increasing penetration of variable renewables. In recent years, for example, some PSH plants have switched their operations entirely to cycle twice per day rather than once to balance excess solar PV generation in the middle of the day.[206]

PSH employs off-peak electricity to pump water to an upper reservoir to store energy and releasing water through a hydroelectric turbine into the lower reservoir. Figure 13 shows a cutaway view of a typical PSH plant.[207] PSH systems are classified as open-loop if they require continuous connection to a natural body of water, and closed-loop when upper and lower reservoirs are independent of continuous connection to natural bodies of water. These systems typically utilize > 70 percent of their available capacity and can have response times from standstill to generation of 1–2 minutes. The time required to switch from generation to pumping mode are typically 4–7 minutes.[208,209]

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[204] 2017 Hydropower Market Report. p. 1 https://www.energy.gov/sites/prod/files/2018/04/f51/Hydropower%20Market%20Report.pdf

[205] 2017 Hydropower Market Report. p. 4 https://www.energy.gov/sites/prod/files/2018/04/f51/Hydropower%20Market%20Report.pdf

[206] 2017 Hydropower Market Report: p. 69 https://www.energy.gov/sites/prod/files/2018/04/f51/Hydropower%20Market%20Report.pdf

[207] Sandia National Laboratories, “DOE/EPRI Energy Storage Handbook in Collaboration with NRECA,” SAND2015-1002, February 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf, p. 15.

[208] Modeling and Analysis of Value of Advanced Pumped Storage Hydropower in the United States. Argonne National Lab, 2014. https://ceeesa.es.anl.gov/projects/psh/psh.html

[209] R. O’Neil, Pumped Storage Hydropower Overview, Presented at First Solar, September 2018.

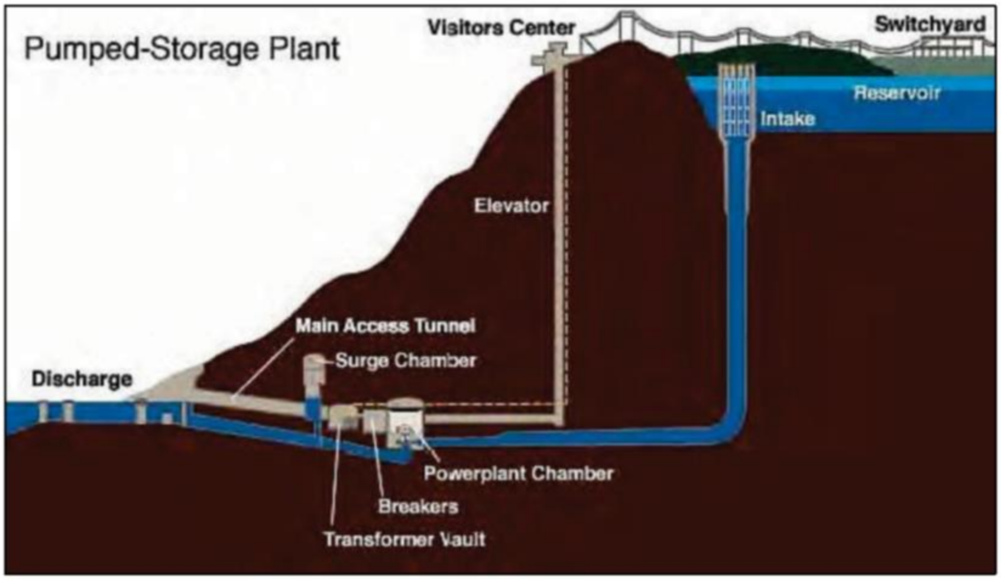

Figure 13. Cutaway diagram of a typical pumped hydro plant.

Today's Technology Maturity Level

PSH technology has the highest capacity of all current storage technologies because its size is limited only by the size of the available upper and lower reservoirs. As seen in Figure 14, deployment of PHS peaked in the 1970s before significant concerns over land and water usage limited further deployments.[210] However, given PSH capabilities to generate GW scale power with 10+ hour duration, it remains an attractive option for large-scale energy storage and provision of other grid services.

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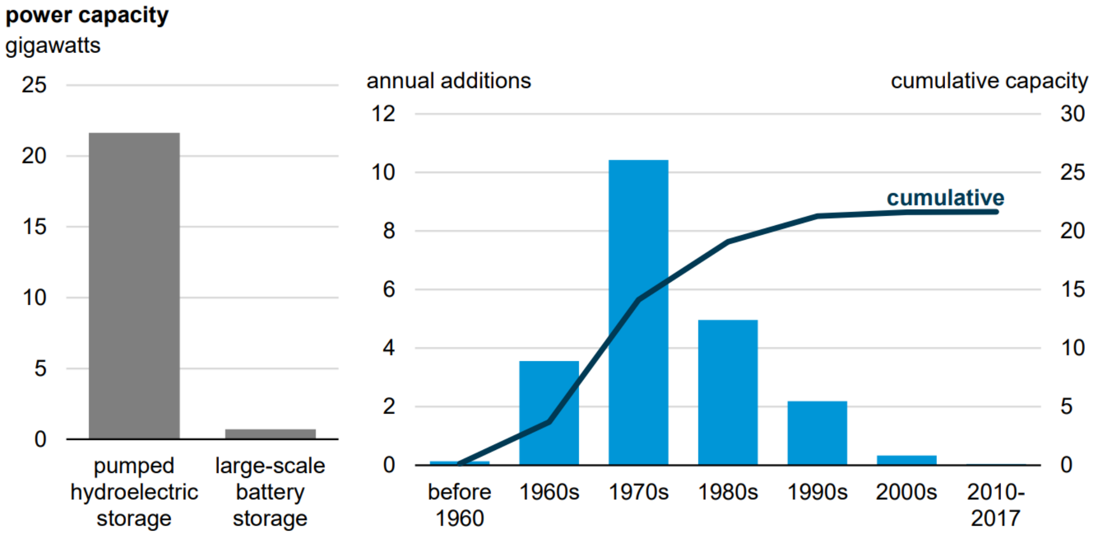
[210] Preliminary Monthly Electric Generator Inventory (based on Form EIA-860M as a supplement to Form EIA-860).



Source: U.S. Energy Information Administration, Form EIA-860M, *Preliminary Monthly Electric Generator Inventory*

Figure 14. U.S. Hydroelectric pumped storage capacity (1960–2017).[211]

Despite the relative technological maturity of PSH as an energy storage technology, a critical challenge is accurately understanding the value PSH provides to the system. PSH can offer a full range of services to the system, from GWs of capacity and GWhs of energy to fast-response reliability services and inertia. Co-optimizing provision of these services, some of which can be provided simultaneously and many of which involve tradeoffs with other services, is highly complex. Furthermore, the large size of some PSH plants can demand power system models that accommodate price-maker rather than price-taker approaches. Understanding the full stack of system values that PSH can provide, particularly as operations change, is an active area of research.

Constraints on Architecture

The most significant constraint on PHS deployments is obtaining suitable available land for the upper and lower reservoirs. Closed-loop systems that are not connected to a natural water source have less environmental impact and therefore greater flexibility in siting options. Closed-loop systems are the predominant technology being explored for future developments. Round-trip efficiencies, historically around 70 percent, have been improved over the years, with future R&D efforts by DOE targeting systems capable of > 80 percent round-trip efficiencies.

For suitable sites, PSH deployments still face a number of barriers, including return on investment, capital costs, and time to commissioning. Return on investment can be highly uncertain because of the long asset lifetime for PSH; given the rapid rate of changes in electricity markets and generation mixes, use cases valuable today may change significantly over the 50+ year asset lifetime. High initial capital costs are a significant barrier for PSH, even while variable costs are low. Long time to commissioning adds to the uncertainty and difficulty

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[211] U.S. Energy Information Administration, "U.S. Battery Storage Market Trends," May 2018 p. 19.

of deploying new PSH plants; a ballpark estimate of total time from project initiation to operation is 10 years.

Deployment Examples

Forty-three PSH plants in the United States provide over 95 percent of the Nation's utility-scale electrical energy storage capability.[212] The largest projects are all open-loop facilities.

- The largest PSH system in the country (by power rating) is located in Bath County, Virginia, and began operation in 1985. The system has a net generating capacity of 3 GW and covers nearly 264 acres in its upper reservoir.[213]
- The Helms PSH project outside Fresno, California, has a maximum power output of 1.2 GW and ~140 GWh of energy capacity. Constructed in 1984, the facility has reversed its pumping profile within the past 5 years to accommodate the growing impact of renewable energy. Historically, the Helms PSH system was charged at night, but increased solar deployments have led to charging the system during the day to balance excess generation capacity.[214]

Deployment Projections

According to the DOE Water Power Technologies Office (WPTO), 48 PSH projects were in development by the end of 2017, with 40 projects in the preliminary permitting stage, 6 seeking FERC authorization, and 2 having received licenses. The average rating of these deployments is 290 MW and more than 90 percent of the proposed projects are located in or close to states with policies requiring increases in renewable generation.[215]

DOE Activity

The WPTO supports development of innovative hydropower and PSH technologies to enable low-cost, reliable power for the Nation's electric grid. Given the challenges and opportunities associated with PSH operation, valuation, and deployment, WPTO's technology development and research activities are advancing fundamental understandings of the potential benefits of existing and prospective advanced PSH facilities. New technologies such as small modular PSH systems can reduce the geographical footprint and enable MW scale PSH systems to be deployed, while advances in ternary PSH systems improve capacity utilization and increase response time and efficiency.

The hydropower subprogram continues research to quantify and understand the economic value of the services provided by hydropower and PSH, and the additional costs or technical requirements of operating hydropower systems in a changing grid. This research includes

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[212] Hydropower Market Report, https://www.energy.gov/eere/water/hydropower-market-report

[213] Bath County Pumped Storage Station, https://www.dominionenergy.com/company/making-energy/renewable-generation/water/bath-county-pumped-storage-station

[214] 2017 Hydropower Market Report. p. 69. https://www.energy.gov/sites/prod/files/2018/04/f51/Hydropower%20Market%20Report.pdf

[215] 2017 Hydropower Market Report. p. 3. https://www.energy.gov/sites/prod/files/2018/04/f51/Hydropower%20Market%20Report.pdf

understanding the value of hydropower and PSH under future electric system conditions, quantifying the effect of flexibility constraints on plant capabilities and performance (e.g., from variations in water flows, plant designs, or license conditions), addressing critical technical barriers to effective operation of hydropower resources for reliability and economic dispatch, and identifying technology solutions that will preserve or enable hydropower capabilities to deliver services or system benefits competitively. In addition, the subprogram continues to drive innovation in the design of PSH, as traditional designs are capital intensive, limited in where they can be sited, and difficult to finance. New transformative designs could reduce capital investment requirements, expand siting possibilities, and shorten development timeframes for new facilities, thus creating incentive for private investment. Ongoing analytical efforts include techno-economic analysis of the value of services that PSH can provide to the grid and work to understand new possible use cases for PSH in the evolving electricity system.

Compressed Air Energy Storage (CAES)

Ability to Provide Functional Requirements

CAES systems use off-peak electricity to compress air and store it in a reservoir, either underground in a suitable cavern or in an above-ground pressure vessel. When electricity is needed, the compressed air is heated, expanded, and directed through an expander or conventional turbine generator to produce electricity. A complete CAES system comprises compressors, expanders, air reservoirs, combustor, motor/generator, and a control system.

Today's Technology Maturity Level

CAES was first proposed in 1949. The first system was placed into operation in 1978 in Huntorf, Germany,[216] making it one of the older technologies deployed for grid-scale energy storage.

Constraints on Architecture

The primary constraint for underground CAES is the limited appropriate geologic formations in a given utility's service area. As an underground technology, it has less environmental impact than PSH. Above-ground CAES technologies using pipes or pressure vessels do not have the geologic limitations but in general have been found to be more expensive on a $/kWh scale compared to other storage technologies.[217]

Deployment Example

One of two reservoir CAES systems in the world is in McIntosh, Alabama, and has been in operation since 1991. The plant has a generation capacity of 110 MW, a storage capacity in excess of 2000 MWh, and is capable of continuously delivering its full-power output for up to 26 hours.[218]

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[216] J. Wang, et al, "Overview of Compressed Air Energy Storage and Technology Development," Energies 2017, 10, 991.

[217] Sandia National Laboratories, "DOE/EPRI Energy Storage Handbook in Collaboration with NRECA," SAND2015-1002, February 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf, page 40.

[218] PowerSouth: Compressed Air Energy Storage. http://www.powersouth.com/wp-content/uploads/2017/07/CAES-Brochure-FINAL.pdf

Deployment Projections

Novel technologies based on CAES principles such as liquid air energy storage and adiabatic CAES are currently under development and, if proven cost effective, may enable greater adoption of long-duration CAES technology in the grid.

DOE Activity

The Office of Electricity supported demonstration efforts of modular CAES technology under American Recovery and Reinvestment Act grants beginning in 2010, which were unable to demonstrate financial viability.[219] Early-stage R&D on potential novel designs that can overcome technical and economic barriers is limited.

Flywheels

Ability to Provide Functional Requirements

Flywheels store energy in the form of the angular momentum of a spinning mass called a rotor and are charged and discharged electrically using a dual-purpose motor/generator connected to the rotor. Most flywheel systems use a containment vessel around the rotor for improved safety and performance. Flywheels are characterized by fast response times (around 4 ms), long cycle life, and high power density,[220] making them ideal candidates for power quality applications like frequency regulation. The kinetic energy (and storage capacity) of the flywheel is directly proportional to the mass of the rotor, making these systems very heavy. Modern flywheels may require 1 metric ton of mass to generate 25 kWh.[221]

Today's Technology Maturity Level

Flywheel technologies have long been used in industry to dampen variations in electric loads. Many shapes of flywheel have been used ranging from the wagon-wheel configuration found in stationary steam engines to the mass-produced, multipurpose disks found in modern automotive engines.

Constraints on Architecture

Flywheels self-discharge at a much higher rate than other storage mediums and can be hazardous if not designed for safety. One of the most significant constraints on the storage architecture is the lack of installed manufacturing base to support lower cost systems.

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[219] "Energy Storage Activities in the United States Electricity Grid", May 2011 https://www.energy.gov/sites/prod/files/oeprod/DocumentsandMedia/FINAL_DOE_Report-Storage_Activities_5-1-11.pdf

[220] M.E. Amiryar and K.R. Pullen, "A Review of Flywheel Energy Storage System Technologies and Their Applications", Appl. Sci. 2017, 7, 286; doi:10.3390/app7030286

[221] D. Bender, "Flywheels", Sandia National Laboratories, May 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-3976.pdf

Deployment Examples

- A 20 MW flywheel in Stephentown, New York, provides frequency regulation services for the New York ISO. The facility began operation in 2011 and is composed of 200 flywheels, each with an energy storage capacity of 100 kW.

- Chugach Electric Association in Anchorage, Alaska, has installed a hybrid battery and flywheel energy storage system. The flywheel provides rapid injection of power to stabilize voltage and frequency and can deliver 18 MW-secs of energy within 1 millisecond. With the flywheel providing fast-response services, the 2 MW/0.5 MWh lithium-ion battery provides longer term storage services to enable greater integration of a 17 MW wind farm on Fire Island, Alaska.[222]

Deployment Projections

Energy storage applications requiring high power for short periods will continue to be a potential market for flywheels if costs can remain competitive with electrochemical technologies.

DOE Activity

The Office of Electricity has active R&D supporting development of new materials that can enable the mass requirements for flywheels at a much lower cost while achieving similar performance and reliability standards to today’s technology. ARPA-E has also supported several novel flywheel technologies aimed at lower costs and longer durations.

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[222] R. Walton “Alaskan microgrid to pair battery, flywheel storage systems for Anchorage area,” February 2017. https://www.utilitydive.com/news/alaskan-microgrid-to-pair-battery-flywheel-storage-systems-for-anchorage-a/435609/