



Independent Statistics & Analysis
U.S. Energy Information
Administration

Battery Storage in the United States: An Update on Market Trends

July 2020



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List of Acronyms

AEO	<i>Annual Energy Outlook</i>
AK/HI	Alaska and Hawaii
CAES	Compressed-Air Energy Storage
CAISO	California Independent System Operator
CPUC	California Public Utility Commission
CSP	Concentrated Solar Power
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
ERCOT	Electric Reliability Council of Texas
FERC	Federal Energy Regulatory Commission
GW	Gigawatt
IOU	Investor-owned utilities
ITC	Investment tax credit
IPP	Independent power producer
IRP	Integrated resource plan
ISO-NE	Independent System Operator of New England
kW	Kilowatt
kWh	Kilowatthour
LADWP	Los Angeles Department of Water and Power
MISO	Mid-Continent Independent System Operator
MW	Megawatt
MWh	Megawatthour
PGE	Pacific Gas and Electric
PJM	PJM Interconnection
PPA	Power purchase agreement
SCE	Southern California Edison
SDGE	San Diego Gas and Electric
SGIP	Self-Generation Incentive Program
SMUD	Sacramento Municipal Utility District

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Executive Summary

Large-scale battery storage systems are increasingly being used across the power grid in the United States. In 2010, 7 battery storage systems accounted for only 59 megawatts (MW) of power capacity, the maximum amount of power output a battery can provide in any instant, in the United States. By 2015, 49 systems accounted for 351 MW of power capacity. This growth continued at an increased rate for the next three years, and the total number of operational battery storage systems has more than doubled to 125 for a total of 869 MW of installed power capacity as of the end of 2018.

This report explores trends in battery storage capacity additions in the United States and describes the state of the market as of 2018, including information on applications, cost, ongoing trends, and market and policy drivers. These observations consider both power capacity and energy capacity, the total amount of energy that can be stored by a battery system. Some key observations are as follows:

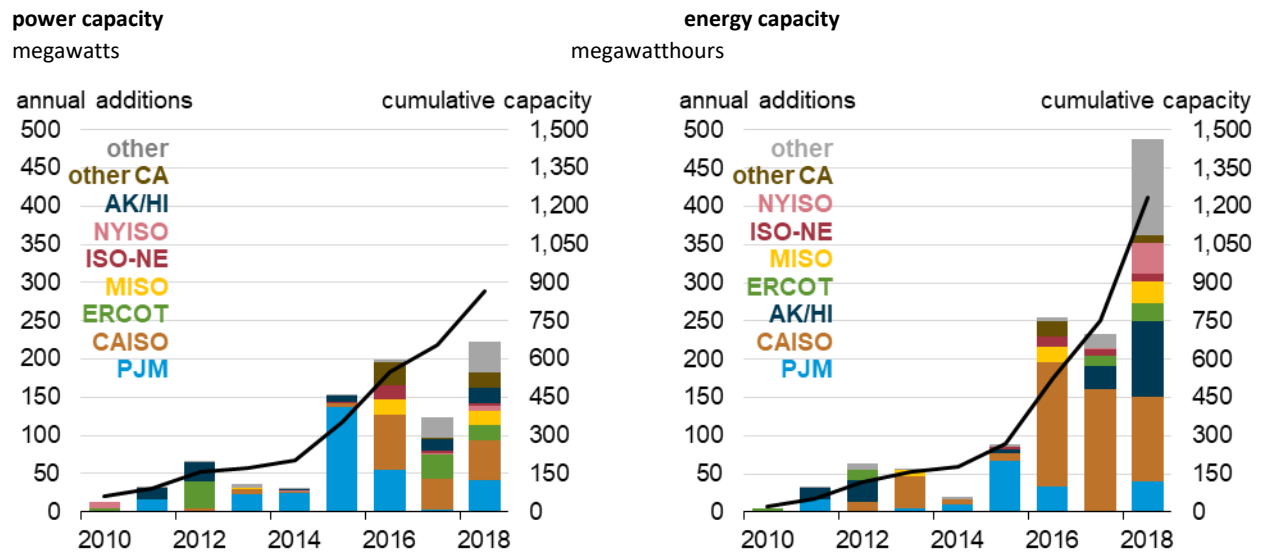
At the end of 2018, 869 megawatts (MW) of power capacity,¹ representing 1,236 megawatthours (MWh) of energy capacity,² of large-scale³ battery storage was in operation in the United States.

- Over 90% of large-scale battery storage power capacity in the United States was provided by batteries based on lithium-ion chemistries.
- About 73% of large-scale battery storage power capacity in the United States, representing 70% of energy capacity, was installed in states covered by independent system operators (ISOs) or regional transmission organizations (RTOs).
- Alaska and Hawaii, with comparatively smaller electrical systems that account for 1% of total grid capacity in the United States, accounted for 12% of the power capacity in 2018, or 14% of large-scale battery energy capacity.
- Historically, the majority of annual battery installations have occurred within the PJM Interconnection (PJM), which manages energy and capacity markets and the transmission grid in 13 eastern and Midwestern states and the District of Columbia, and California Independent System Operator (CAISO) territories. However, in 2018, over 58% (130 MW) of power capacity additions, representing 69% (337 MWh) of energy capacity additions, were installed in states outside of those areas.

¹ As the maximum instantaneous amount of power output, power capacity is measured in units such as megawatts (MW)

² As the total amount of energy that can be stored or discharged by a battery storage system, energy capacity is measured in megawatt-hours (MWh)

³ Large-scale refers to systems that are grid connected and have a nameplate power capacity greater than 1 MW.

Figure ES1. Large-scale battery storage capacity by region (2010–2018)

Sources: U.S. Energy Information Administration, Form EIA-860M, [Preliminary Monthly Electric Generator Inventory](#); U.S. Energy Information Administration, Form EIA-860, [Annual Electric Generator Report](#)

Approximately one third (32%) of large-scale battery storage power capacity (and 14% of energy capacity) in the United States in 2018 was installed in PJM.

- In 2012, PJM created a new frequency regulation market product for fast-responding resources, the conditions of which were favorable for battery storage. However, changes implemented in 2017 in PJM's market rules have reduced the number of battery installations in the region.
- Most existing large-scale battery storage power capacity in PJM is owned by independent power producers (IPPs) providing power-oriented frequency regulation services.

Installations in CAISO accounted for 21% of existing large-scale battery storage power capacity in the United States in 2018, but they accounted for 41% of existing energy capacity.

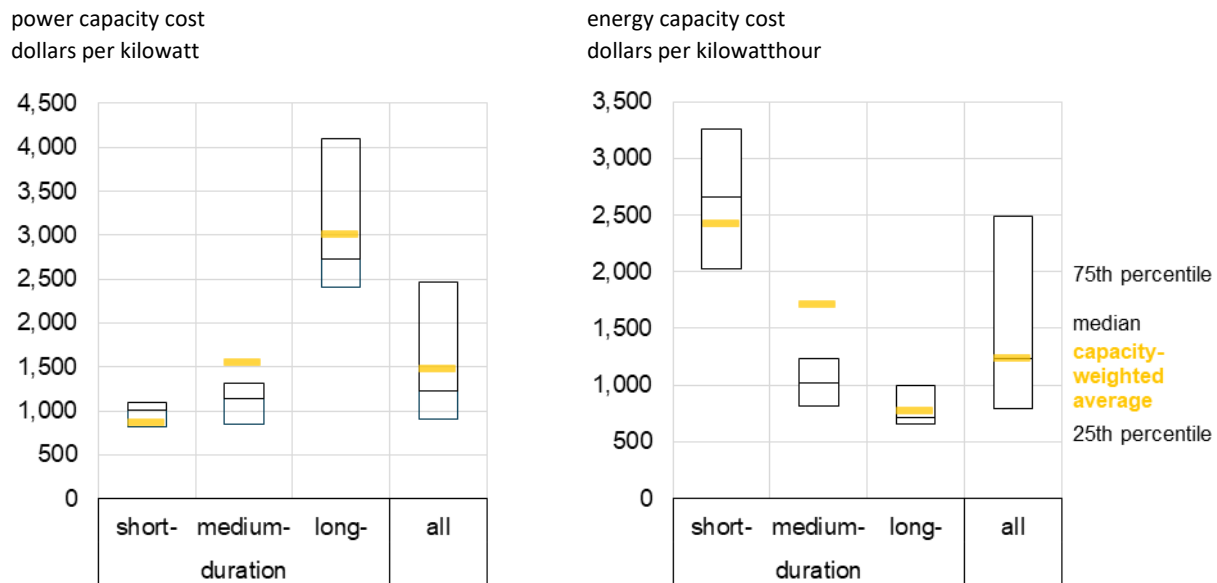
- In 2013, the California Public Utility Commission (CPUC) implemented [Assembly Bill 2514](#) by mandating that the state's investor-owned utilities procure 1,325 MW of energy storage by 2020.
- Large-scale installations in California tend to provide energy-oriented services and tend to serve a wider array of applications than systems in PJM.
- Four California utilities held nearly 90% of small-scale⁴ storage power capacity in the United States in 2018.

⁴ Small-scale refers to systems connected to the distribution network and have a nameplate power capacity less than 1 MW.

Battery storage costs have been driven by technical characteristics such as the power and energy capacity of a system.

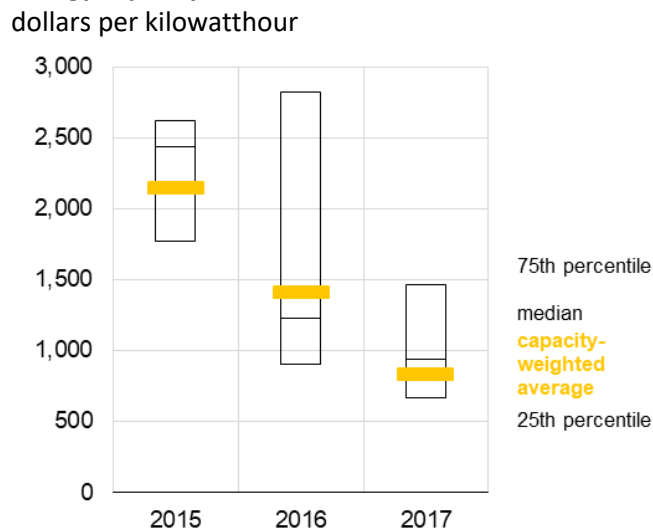
- On a per-unit of power capacity basis, total installed system costs for batteries of shorter duration have been less expensive than long-duration systems (Figure ES2).
- In terms of costs per-unit of energy capacity, the reverse has been true—longer duration batteries have typically had lower normalized costs compared with shorter-duration batteries (Figure ES2).
- Over time, average costs per-unit of energy capacity have decreased by 61% between 2015 and 2017, from \$2,153/kWh to \$834/kWh (Figure ES3).

Figure ES2. Total installed cost of large-scale battery storage systems by duration (2013 -2017)



Source: U.S. Energy Information Administration, Form EIA-860, *Annual Electric Generator Report*

Figure ES3. Total installed cost of large-scale battery storage systems by year energy capacity costs



Source: U.S. Energy Information Administration, Form EIA-860, *Annual Electric Generator Report*

Introduction

This report examines trends in the installation of batteries for large-scale electricity storage in the United States by describing the current state of the market, including information on applications, costs, and market and policy drivers.

This report focuses on battery storage technologies, although other energy storage technologies are addressed in the appendix. Electrical, thermal, mechanical, and electrochemical technologies can be used to store energy.

The capacity of battery storage is measured in two ways: *power capacity* and *energy capacity*. Generation is often characterized in terms of power capacity, which is the maximum amount of power output possible in any instant, measured in this report as megawatts (MW). However, batteries can sustain power output for only so long before they need to recharge. The *duration* of a battery 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 defined as the total amount of energy that can be stored or discharged by the battery storage system, and is measured in this report as megawatthours (MWh).

Hydroelectric pumped storage, a form of mechanical energy storage, accounts for most (97%) large-scale energy storage power capacity in the United States. However, installation of new large-scale energy storage facilities since 2003 have been almost exclusively electrochemical, or battery storage.

This report explores trends in both large-scale and small-scale battery storage systems. EIA defines large-scale (or utility-scale) systems as being connected directly to the electricity grid and having a nameplate power capacity (the maximum rated output of a generator, usually indicated on a nameplate physically attached to the generator) greater than 1 MW. Small-scale refers to systems that have less than 1 MW in power capacity. Such systems are typically connected to a distribution network, the portion of the electrical system that delivers electricity to end-users.⁵

⁵ Large-scale and small-scale reporting conventions are derived from the reporting requirements of the EIA *Electric Generators Report* (Form EIA-860) survey and the EIA *Electric Power Industry Report* (Form EIA-861) survey. The reporting cut-offs for these surveys are based entirely on the power capacity of the generator.

Large-Scale Battery Storage Trends

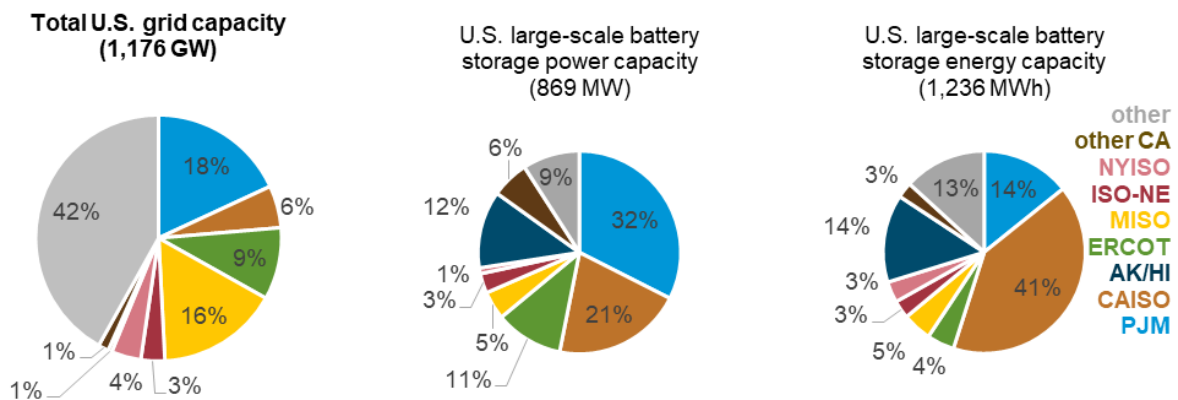
The first large-scale⁶ battery storage installation recorded by EIA in the United States that was still in operation in 2018 entered service in 2003. Only 59 MW of power capacity from large-scale battery storage systems were installed between 2003 and 2010. However, this sector has experienced growth in recent years. Between 2011 and 2018 there were 810 MW of power capacity from large-scale battery storage added leaving a total of 869 MW battery storage power capacity operational by the end of 2018.

Most of existing U.S. power capacity has been installed by independent power producers in the PJM Interconnection (PJM), which coordinates the movement of electricity through all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and the District of Columbia. Regulated utilities in the California Independent System Operator (CAISO) territory have procured significant amounts of storage capacity as well. The United States observed a new record for annual power capacity additions in 2018 when it saw 222 MW of large-scale battery storage installed, breaking the previous record of 199 MW added in 2016.

Regional Trends

As shown in Figure 1, about 73% of large-scale battery storage power capacity and 70% of energy capacity in the United States is installed in areas covered by independent system operators (ISOs) or regional transmission organizations (RTOs)⁷. The ISOs and RTOs, depicted in Figure 2, account for 58% of total grid capacity in the United States and have the largest shares of storage capacity relative to their shares of installed grid capacity. The disproportionate share of large-scale battery storage across the ISOs and RTOs may result from differences in market design and state policies (See Market and Policy Drivers section).

Figure 1. Large-scale power and energy capacity by region (2018)

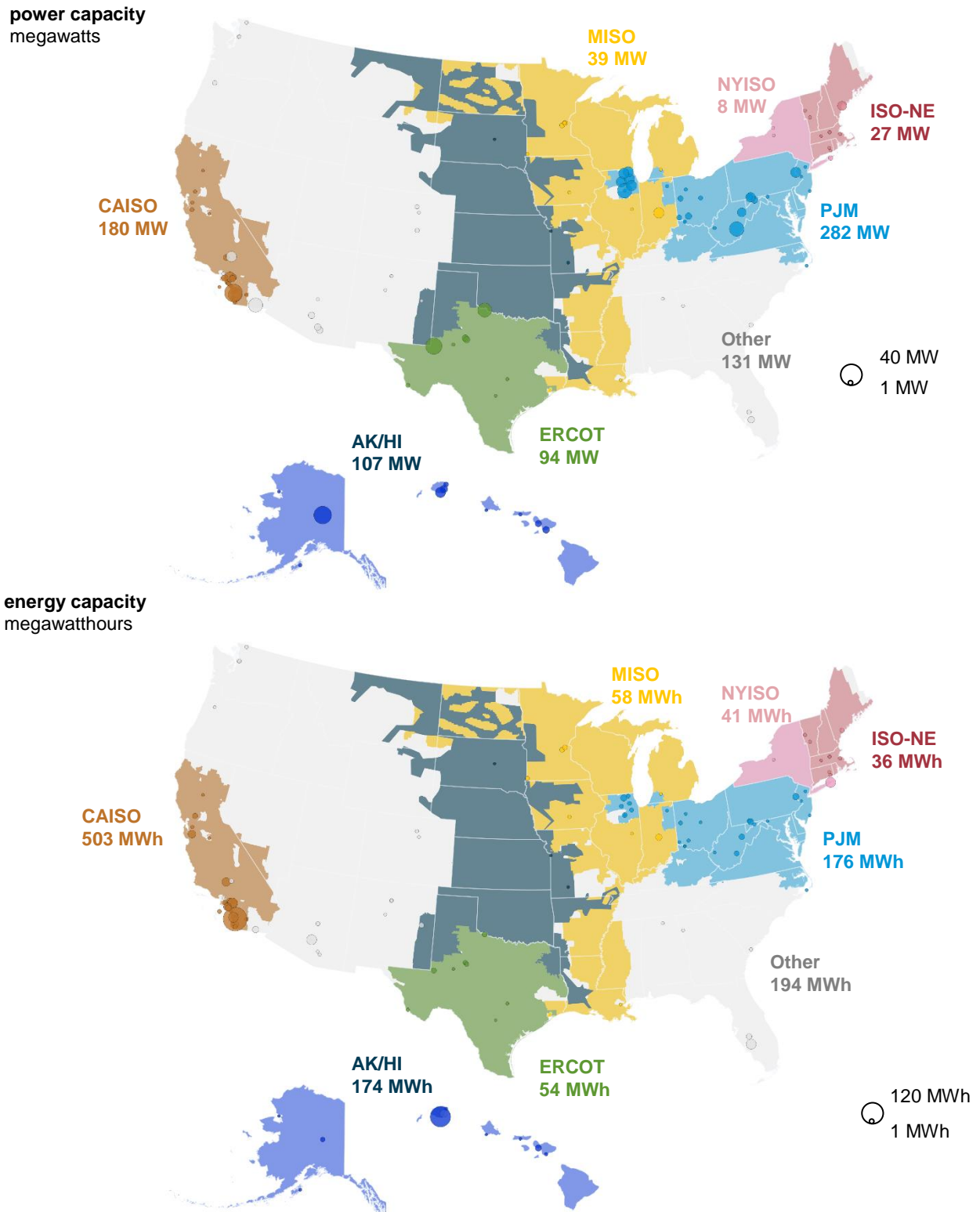


Sources: U.S. Energy Information Administration, Form EIA-860M, *Preliminary Monthly Electric Generator Inventory*; U.S. Energy Information Administration, Form EIA-860, *Annual Electric Generator Report*

⁶ Large-scale refers to systems that are grid connected and have a nameplate power capacity greater than 1 MW.

⁷ ISOs and RTOs are independent, federally regulated non-profit organizations that ensure reliability and optimize supply and demand bids for wholesale electric power.

Figure 2 Large-scale battery storage installations by region (2018)



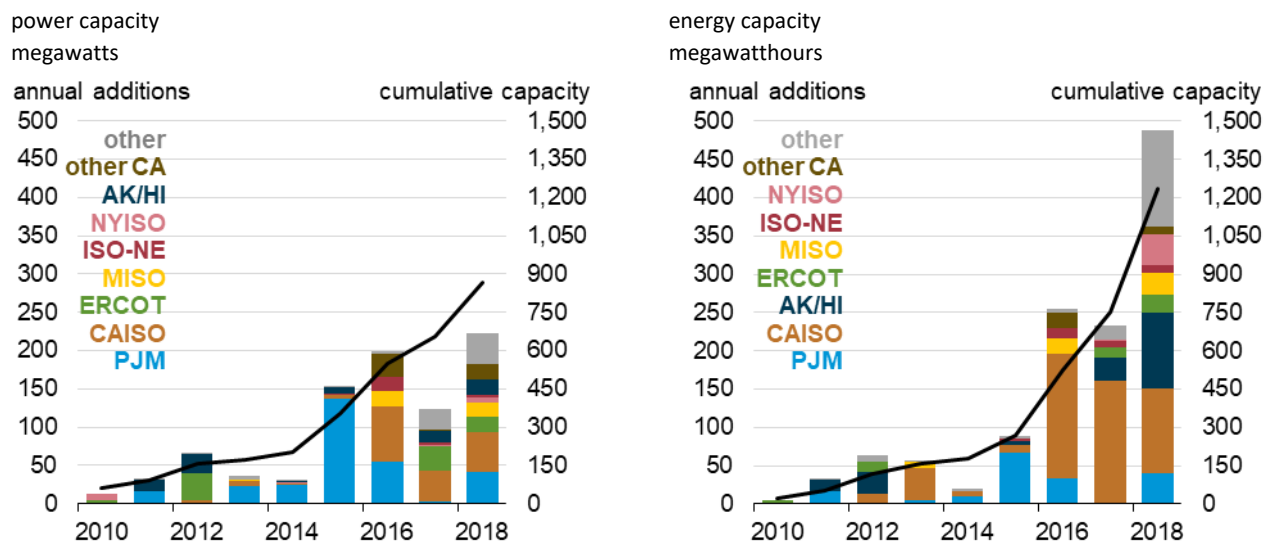
Sources: U.S. Energy Information Administration, Form EIA-860M, *Preliminary Monthly Electric Generator Inventory*; U.S. Energy Information Administration, Form EIA-860, *Annual Electric Generator Report*

Notes: Energy capacity data for large-scale battery storage installed in 2018 are based on preliminary estimates.

Between 2003 and 2018, 922 MW of large-scale battery storage power capacity across 134 systems was installed in the United States, three-quarters of which was installed between 2015 and 2018. More than 30% of existing large-scale battery storage power capacity as of 2018 was located in the PJM Interconnection (Figure 2), most of which was built from 2014-2016. This was most likely the result of changes in [PJM’s market](#) for frequency regulation (a grid service that helps balance momentary differences between electricity demand and supply within the transmission grid) in 2012 which created a specific requirement for fast response resources, such as batteries. In 2015, PJM put a cap on the market share for fast responding resources due to grid reliability concerns,⁸ and PJM has had relatively flat storage growth since these changes were implemented.

Installations in PJM tend to be power-oriented with larger capacities but shorter durations to serve frequency regulation applications. In 2018, large-scale battery storage installations in PJM had an average power capacity of 10.8 MW and an average duration of 45 minutes. This matches the average duration that was observed in 2017 for PJM.

Figure 3. Large-scale battery storage capacity by region (2003–2018)



Sources: U.S. Energy Information Administration, Form EIA-860M, [Preliminary Monthly Electric Generator Inventory](#); U.S. Energy Information Administration, Form EIA-860, [Annual Electric Generator Report](#)

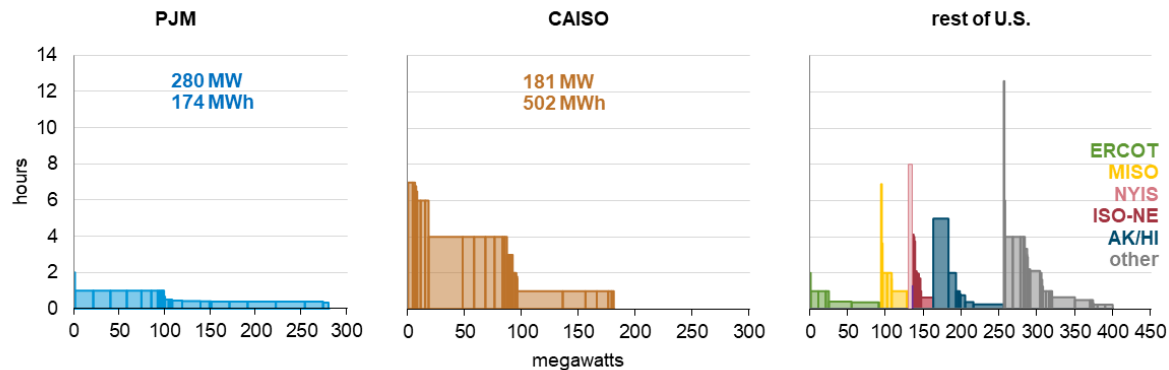
Although installations in CAISO accounted for 21% of existing large-scale battery storage power capacity in the United States in 2018, they accounted for 41% of existing energy capacity (Figure 3). California’s need for battery storage has been for reliability purposes, so large-scale battery storage installations tend to be energy-oriented with small power capacities but long durations.

In 2018, large-scale battery storage installations in CAISO had an average power capacity of 6 MW and duration of 3.5 hours (Figure 4). This is longer than the average duration of 3.2 hours in CAISO in 2017. Other markets in the United States show a mix of power- and energy-oriented battery installations.

⁸ FERC Docket No. ER19-1651-000, PJM Interconnection ORDER ON CONTESTED SETTLEMENT, https://elibrary.ferc.gov/idmws/file_list.asp?document_id=14845834

Of the power capacity in California, 37% was procured by Southern California Edison and San Diego Gas and Electric to address reliability risks as a result of constraints on the natural gas supply following a leak at Aliso Canyon, a major natural gas storage facility in the region. The [California Public Utilities Commission \(CPUC\) requires](#) generation resources to provide at least four hours of output to contribute to reliability reserves. As a result, large-scale battery storage installations in California tend to need larger energy capacities to qualify as reliability resources. (See Market and Policy Drivers for more information on California’s activities related to energy storage.)

Figure 4. Power capacity and duration of large-scale battery storage by region (2018)



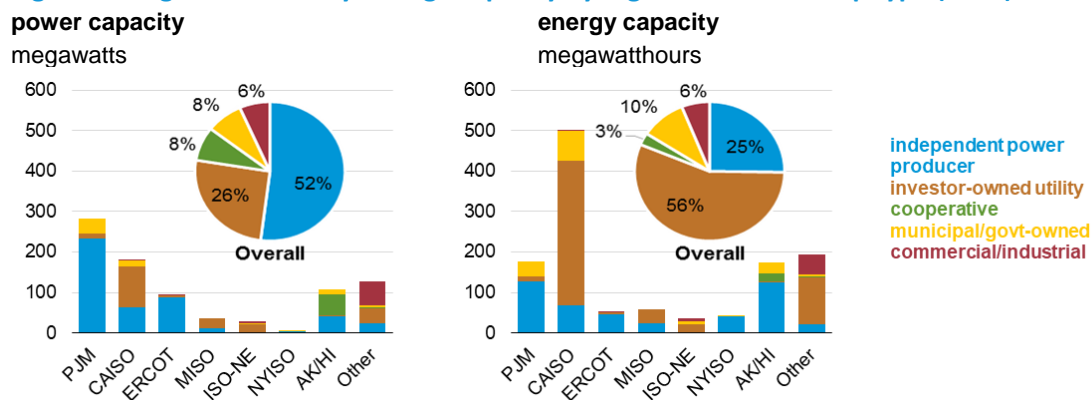
Source: U.S. Energy Information Administration, Form EIA-860M, [Preliminary Monthly Electric Generator Inventory](#); U.S. Energy Information Administration, Form EIA-860, [Annual Electric Generator Report](#)

Note: Energy capacity data for large-scale battery storage installed in 2018 are based on preliminary estimates. Duration is calculated by dividing nameplate energy capacity (in megawatthours [MWh]) by maximum discharge rate (in megawatts [MW]), except in cases where the maximum discharge rate was not available, in which case the nameplate rating was used instead.

Ownership Trends

At the end of 2018, slightly more than half (52%) of the existing power capacity of large-scale battery storage in the United States was owned by independent power producers (IPPs) while more than half (56%) of large-scale battery storage in terms of energy capacity was owned by investor-owned utilities (IOUs) (Figure 5). This ownership structure reflects the dominance of IPPs in PJM with its power-oriented storage applications and the IOU ownership of energy-oriented reliability assets in CAISO.

Figure 5. Large-scale battery storage capacity by region and ownership type (2018)



Source: U.S. Energy Information Administration, Form EIA-860, [Annual Electric Generator Report](#)

Although there are relatively fewer large-scale battery storage installations outside of PJM and CAISO, some noteworthy points emerge in other regions. Most (94%) of the installations in the Electric Reliability Council of Texas (ERCOT), which is regulated by the Public Utility Commission of Texas, are owned by IPPs. Of the eight installations in Mid-Continent Independent System Operator (MISO), six are owned by IOUs. In Alaska, most large-scale battery storage energy capacity is owned by IPPs, while the power capacity is split between cooperatives and IPPs. State-owned utilities in the U.S. own 8% of large-scale battery storage power capacity, driven by a single large (30 MW/20 MWh) installation in southern California owned by the Imperial Irrigation District.

Chemistry Trends

Chemistry Descriptions

Battery storage technologies make use of several different battery chemistries. The most common that have seen large-scale deployment^{9,10,11} in the United States include:

- **Lithium-ion** technology, which represented more than 90% of the installed power and energy capacity of large-scale battery storage in operation in the United States at the end of 2018. Lithium-ion batteries have high-cycle efficiency (they don't lose much energy between recharge and discharge) and fast response times. In addition, their high energy density (stored energy per unit of weight) makes them the current battery of choice for most portable electronic and electric vehicle applications.
- **Nickel-based** batteries were used in some of the earliest large-scale battery storage installations in the United States, including a 2003 system added in Fairbanks, Alaska. Since then, the deployment of this battery chemistry has been limited. Nickel-based batteries typically have high energy density and reliability but relatively low cycle life (fewer recharge/discharge cycles before degrading performance beyond specifications for the application).
- **Sodium-based** battery storage accounted for 2% of the installed large-scale power capacity and 6% of the installed large-scale energy capacity in the United States at the end of 2018. Sodium based battery storage is an established technology based on abundant materials with a long cycle life suitable for long-discharge applications. These systems require high operating temperatures as they utilize molten sodium to operate (~300°C).
- **Lead acid** is one of the oldest forms of battery storage; its development began in the mid-1800s. Lead acid is widely used as a starter battery in vehicles. Lead acid covered only 1% of large-scale battery storage capacity installed at the end of 2018 in the United States and has seen limited grid-scale deployment because of its relatively low energy density and cycle life.
- **Flow battery** systems have one or more chemical components that are dissolved in a liquid solution. The chemical solutions are typically stored in tanks and separated by a membrane. The overall battery capacity is determined by tank size and can be expanded to meet different applications. They have a long cycle life, and their operational lifetime is projected to be long. At the end of 2018, flow batteries represented less than 1% of the installed power and energy capacity of large-scale battery storage in the United States.

⁹ Akhil, Abbas A., et al. *DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA*. January 2015. <http://www.sandia.gov/ess/publications/SAND2015-1002.pdf>

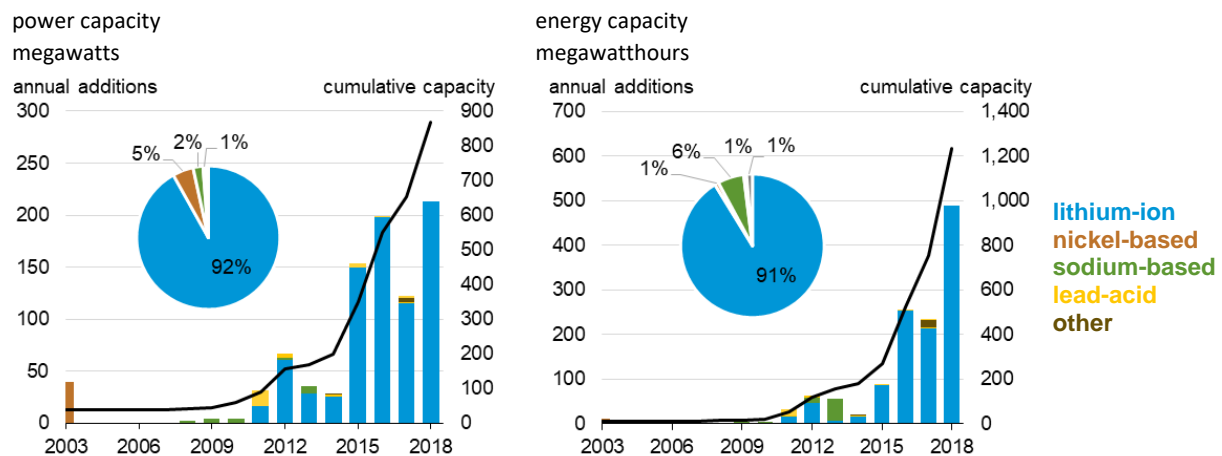
¹⁰ Chen, Haisheng, et al. *Progress in electrical energy storage system: A critical review*. Progress in Natural Science, March 2009.

¹¹ Luo, Xing, et al. Overview of current development in electrical energy storage technologies and the application potential in power system operation. Applied Energy, January 2015

Chemistry Trends

The earliest large-scale battery storage installations in the United States used nickel-based and sodium-based chemistries (Figure 6). However, since 2011, most installations have opted for lithium-ion batteries, including retrofits of older systems that initially relied on different chemistries. For example, in 2012, Duke Energy added 36 MW of lead-acid battery storage to its Notrees wind power facility in West Texas. When the lead-acid batteries were first installed, the battery system participated in the region's frequency regulation market, which required rapid charging and discharging that significantly degraded the batteries. In 2016, Duke Energy replaced the original lead-acid batteries with better performing lithium-ion batteries.¹²

Figure 6. Large-scale battery storage capacity by chemistry (2003–2018)



Source: U.S. Energy Information Administration, Form EIA-860, *Annual Electric Generator Report*

Flow batteries are an emerging energy storage technology. The first large-scale flow battery storage system in the United States was installed in Washington in 2016 by Avista Utilities. Two more flow batteries were installed in 2017 by electric utilities in Washington and California. The vanadium based electrolyte used in these flow battery systems is stored in large tanks and pumped through a separately connected electrode system. This configuration allows for greater energy capacities at lower prices, but it lowers the round trip efficiency¹³ of the stored electricity as a result of the operation of the pumps.¹⁴ Other battery storage chemistries and technologies are in different phases of development but have yet to see significant deployment in large-scale grid applications in the United States.

¹² Duke Energy, *Duke Energy to upgrade its Notrees Energy Storage System*, June 2015, <https://news.duke-energy.com/releases/duke-energy-to-upgrade-its-notrees-energy-storage-system>

¹³ Round-trip efficiency is the battery system efficiency over one cycle, measured as the amount of energy discharged to a specified depth over the amount of energy consumed to bring the system back up to its specified initial state of charge.

¹⁴ Amerseco, Inc., *Demonstrating the Benefits of Long-Duration, Low-Cost Flow Battery Storage in a Renewable Microgrid*, December 2019, <https://www.serdp-estcp.org/Program-Areas/Installation-Energy-and-Water/Energy/Microgrids-and-Storage/EW19-5312>

Current Applications

Batteries have both physical and operational constraints, such as power output and discharge duration. These constraints affect individual battery technology choices that are often made with the intent of optimizing the delivery of certain types of services or providing specific applications to the electricity grid. In some cases it is also possible or even necessary to combine applications to maximize the value of the system. For a more complete discussion, please refer to the reference work cited below.

Application Descriptions

The leading types of existing battery applications¹⁵ include the following:

- **Frequency regulation** helps balance momentary differences between electricity demand and supply within the transmission grid, often in order to help maintain interconnection frequencies close to 60 Hertz.
- **Spinning reserve** is the unused dispatchable generating capacity of online assets that provides grid frequency management, which may be available to use during a significant frequency disturbance, such as during an unexpected loss of generation capacity. This reserve ensures system operation and availability. Dispatchable generators are those that can be turned on or off in order to meet immediate needs of the system.
- **Voltage or reactive power support** ensures the quality of power delivered by maintaining the local voltage within specified limits by serving as a source or sink of reactive power (the portion of electricity that establishes and sustains the electric and magnetic fields of alternating-current equipment).
- **Load following** supplies (discharges) or absorbs (charges) power to compensate for load variations—this application is a power balancing application, also known as a form of ramp rate control.
- **System peak shaving** reduces or defers the need to build new central generation capacity or purchase capacity in the wholesale electricity market, often during times of peak demand.
- **Arbitrage** occurs when batteries charge during periods when electrical energy is less expensive and discharge when prices for electricity are high, also referred to as electrical energy time-shift.
- **Load management** provides a demand side customer-related service, such as power quality, power reliability (grid-connected or microgrid operation), retail electrical energy time-shift, demand charge management, or renewable power consumption maximization (charging the battery storage system during periods when renewable energy is greatest so as to consume the maximum renewable energy from the battery system, i.e. charging with solar during the day or charging with wind during high wind periods).
- **Storing excess wind and solar generation** reduces the rate of change of the power output from a non-dispatchable generator in order to comply with local grid requirements related to grid stability or prevent over production or over-production penalties. Non-dispatchable generators cannot be turned on or off in order to meet immediate needs and are often intermittent resources (generators with output controlled by the natural variability of the energy source, for example wind and solar).

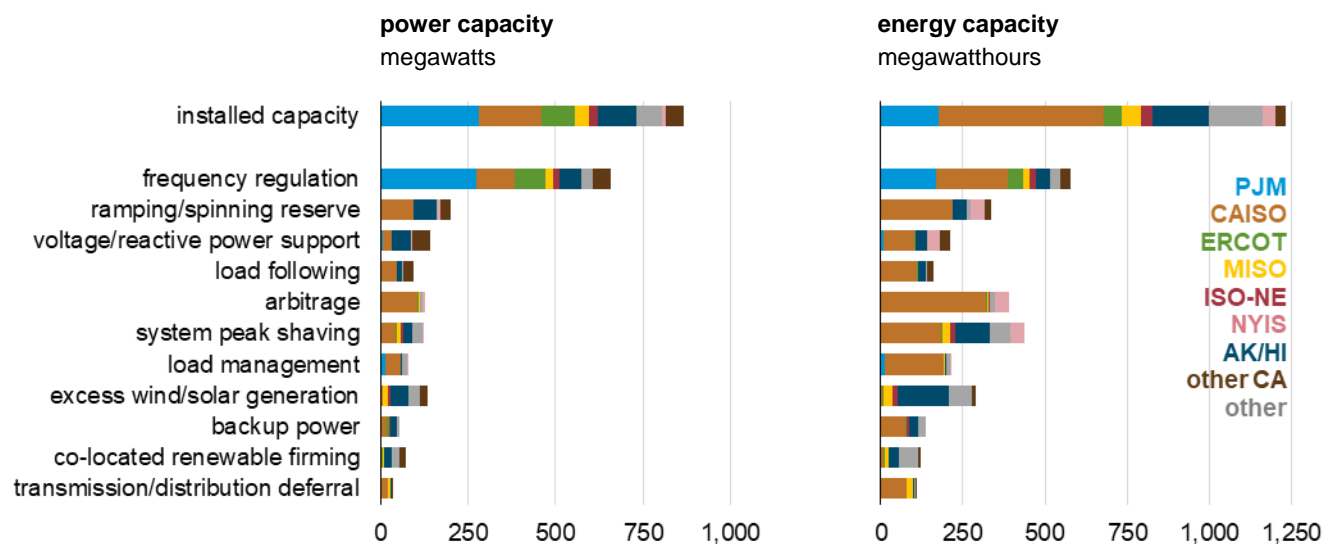
¹⁵ DNV-GL, *Recommended Practices: Safety, operation and performance of grid-connected energy storage systems*, September 2017, https://rules.dnvgl.com/docs/pdf/DNVGL/RP/2017-09/DNVGL-RP-0043.pdf?_ga=2.80787476.2095102769.1516371272-888917498.1516371272

- **Backup power**, following a catastrophic failure of a grid, provides an active reserve of power and energy that can be used to energize transmission and distribution lines, provides start-up power for generators, or provides a reference frequency.
- **Transmission and distribution deferral** keeps the loading of the transmission or distribution system equipment below a specified maximum. This application allows for delays in transmission upgrades, avoids the need to upgrade a transmission system completely, or avoids congestion-related costs and charges.
- **Co-located generator firming** provides constant output power over a certain period of time of a combined generator and energy storage system. Often the generator in this case is a non-dispatchable renewable generator (for example, wind or solar).

Applications by Region

Figure 7 illustrates the total amount of power and energy capacity that was available for each application in the United States in 2018. In the United States, 75% of large-scale battery storage power capacity provides frequency regulation, which helps systems quickly balance unexpected differences in electricity supply and demand. Installations in PJM have driven this trend, where a specific market product for fast-ramping frequency regulation led independent power producers to rapidly deploy large-scale battery storage. Installations in CAISO as of 2018 tended to serve a wider array of applications than those in PJM because many had been procured by regulated utilities to serve multiple applications without necessarily being directly compensated for each application through market mechanisms.

Figure 7. Applications served by large-scale battery storage (2018)



Source: U.S. Energy Information Administration, Form EIA-860, *Annual Electric Generator Report*

Figure 7 is based on information provided by EIA-860 survey respondents regarding their market region and the applications that battery storage systems provided in 2018. A survey respondent was permitted to select more than one application provided by each battery system.

EIA-860 survey respondents reported that storage in PJM was used for primarily only one application (frequency regulation), while batteries installed in CAISO were used for several (2.7 applications on average). Batteries installed in Alaska and Hawaii were diversely used (4.0 applications on average).

Battery Storage Costs

Costs for battery storage technologies depend on technical characteristics such as the power capacity and energy capacity of a system.

Cost Background

This discussion of costs is divided into three main categories based on the nameplate duration of the battery storage system, which is the ratio of nameplate energy capacity to nameplate power capacity.

- The short-duration battery storage category includes systems with less than 0.5 hours of nameplate duration.
- The medium-duration battery storage category includes systems with nameplate durations ranging between 0.5 hours and 2.0 hours.
- The long-duration battery storage category includes all systems with more than 2.0 hours of nameplate duration.

The average characteristics of the categorized sample data are summarized in Table 1. These categorizations are used in this report to illustrate the importance of defining the system characteristics when discussing costs, especially regarding power capacity versus energy capacity. The reported capital cost values are from large-scale battery storage systems installed across the United States between 2013 and 2017 and include multiple reported battery chemistries.

As shown in Table 1, for costs reported between 2013 and 2017, short-duration battery storage systems had an average power capacity of 11.7 MW, medium-duration systems had an average capacity of 7.2 MW, and long-duration battery storage systems had 6 MW. The average energy capacity for the short- and medium-duration battery storage systems were 4.2 and 6.6 MWh, respectively. The average for the long-duration battery storage systems was 23.5 MWh, between 4 and 6 times more than the average energy capacity of short and medium duration battery storage systems.

Table 1. Sample characteristics of capital cost estimates for large-scale battery storage by duration (2013 -2017)

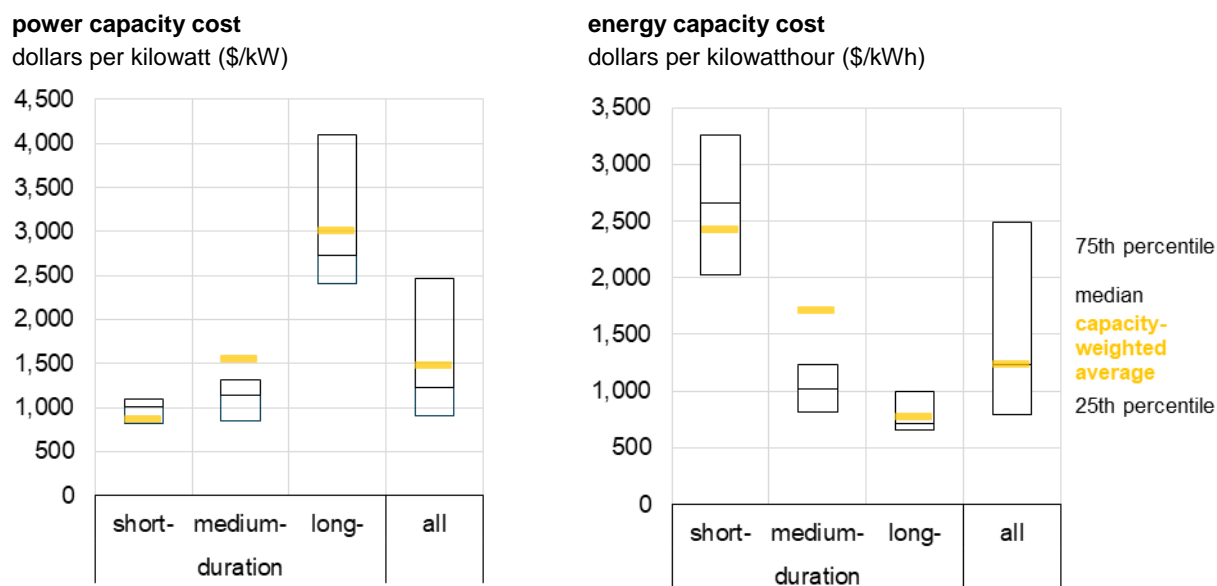
	Short- duration <0.5 hours	Medium- duration 0.5–2 hours	Long- duration >2 hours
Number of battery systems with reported costs available	22	20	16
Average of nameplate power capacity, megawatts (MW)	11.7	7.2	6.0
Average of nameplate energy capacity, megawatthours (MWh)	4.2	6.6	23.5
Average of nameplate duration, hours	0.4	1.1	4.2
Capacity-weighted cost per unit power capacity, dollars per kilowatts (\$/kW)	864	1,554	3,006
Capacity-weighted cost per unit energy capacity, dollars per kilowatthour (\$/kWh)	2,425	1,710	772

Source: U.S. Energy Information Administration, Form EIA-860, *Annual Electric Generator Report*

Cost Results

Based on costs reported between 2013 and 2017, battery systems with shorter durations typically had lower normalized power capacity costs measured in dollars per kilowatt (\$/kW) than batteries with longer nameplate durations (Figure 8). The opposite was generally true when examining normalized energy capacity costs measured in dollars per kilowatthour (\$/kWh) because total system costs for longer-duration systems are spread out over more stored energy. Nonetheless, the range of normalized cost values was driven by technological and site-specific requirements.

Figure 8. Total installed cost of large-scale battery storage systems by duration (2013 -2017)



Source: U.S. Energy Information Administration, Form EIA-860, *Annual Electric Generator Report*

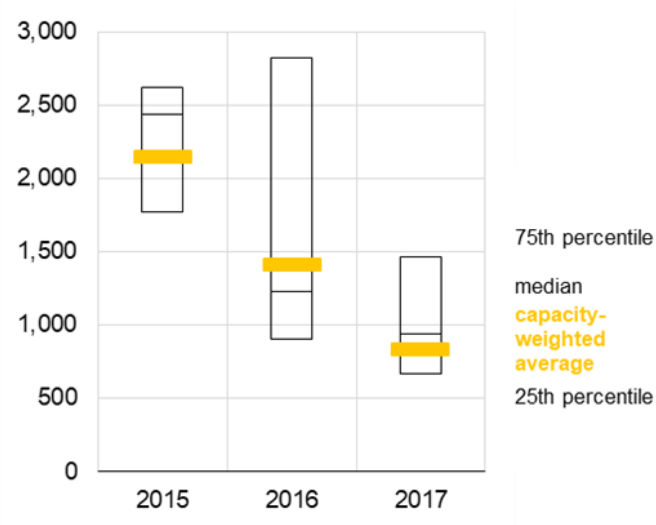
Normalized energy capacity costs have decreased over time (Table 2, Figure 9). The capacity-weighted average installed cost of large-scale batteries fell by 34% from \$2,153/kWh in 2015 to \$1,417/kWh in 2016. This trend continued into 2017 with another decrease in average installed costs of 41% to \$834/kWh. This trend ultimately resulted in a total 61% decrease in average installed costs between 2015 and 2017.

Table 2. Sample characteristics of capital cost estimates for large-scale battery storage by year

	2015	2016	2017
Number of battery systems with reported costs available	10	21	22
Average of nameplate power capacity, megawatts (MW)	12.7	10.4	5.6
Average of nameplate energy capacity, megawatt-hours (MWh)	5.4	12.2	10.6
Average of nameplate duration, hours	0.5	1.5	1.8
Capacity-weighted cost per unit power capacity, dollars per kilowatts (\$/kW)	913	1,664	1,587
Capacity-weighted cost per unit energy capacity, dollars per kilowatthour (\$/kWh)	2,153	1,417	834

Source: U.S. Energy Information Administration, Form EIA-860, *Annual Electric Generator Report*

Figure 9. Total installed cost of large-scale battery storage systems by year
energy capacity costs
dollars per kilowatthour



Source: U.S. Energy Information Administration, Form EIA-860, *Annual Electric Generator Report*

Note: Cost observations for installation years 2013 and 2014 were dropped from this figure as a result of small sample sizes for those respective years.

Unlike non-storage technologies, battery storage can supply and consume energy at different times of the day, creating a combination of cost and revenue streams that makes it challenging to directly compare to generation technologies. They are not stand-alone generation sources and must buy electricity supplied by other generators to recharge and cover the round-trip efficiency losses experienced during cycles of charging and discharging.

There are two major challenges in determining the profitability and cost of battery storage systems. First, quantifying the competitiveness of a battery storage technology with other technologies operating on the grid must consider the individual markets that the storage technology is planning to be used in and what revenue opportunities exist for the technology. The second challenge involves the degradation of the system over time, which is the lasting and continuous decrease in either a battery's power or energy performance or both and is linked to use or age of a battery component or system.

The performance can be characterized by the full cycle power input and output at an agreed-upon charge/discharge rate. There are two general options that can be employed to ensure reliable performance during a storage system's lifetime:

- **Overbuilding:** adding more storage or discharge capacity behind the inverter than is needed, so that as the system ages it will maintain a capacity at or above the contracted capacity required of the system.
- **Continual Upgrades:** replacing some portion of the storage system to maintain the agreed-upon performance during its lifetime.

The two approaches to meeting performance requirements affect the installed capital costs of the system. Overbuilding storage capacity leads to a higher initial installed capital cost, while continual

upgrades lead to higher operation and maintenance costs throughout the lifetime of the storage facility. Therefore, comparing only the normalized capital cost of various battery systems, as shown in [Figure 8](#), does not capture the variation in the lifetime costs. The costs collected and presented in this report are not sufficient to capture all of these nuances.

Other Cost Metrics

In addition to the capital costs presented in this section, EIA has observed trends in battery storage costs arising from the negotiated price of electricity for projects that are financed through power purchase agreements (PPAs). PPAs are contracts between electricity suppliers and electricity buyers (or offtakers) at a fixed price per unit of electricity delivered. They represent a predictable, long-term source of revenue to the project. The negotiated electricity prices under a PPA are heavily influenced by each project's specifications, contract terms, and other localized factors. Observing PPA prices can give an indication of cost trends over time; however, PPA prices are not comparable to total capital costs of the system.

Small-Scale Energy Storage Trends

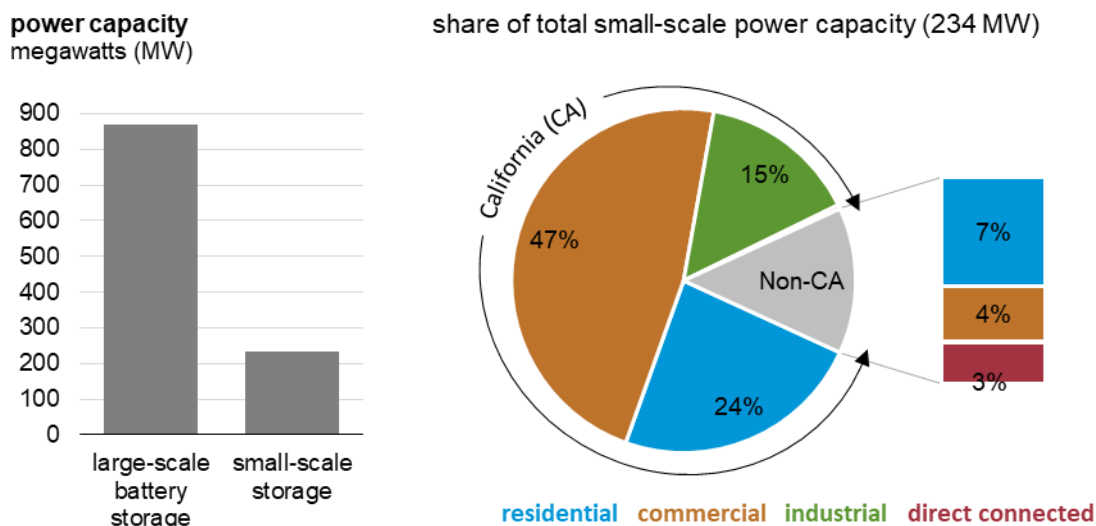
In 2018, utilities reported 234 MW of existing small-scale storage power capacity in the United States. A little more than 50% of this capacity was installed in the commercial sector, 31% was installed in the residential sector, and 15% was installed in the industrial sector. The remaining 3% was directly connected to the distribution grid, such as by the utility at their own distribution substation.

The data collected for small-scale applications depend on the electric utility’s access to information about installations in its territory. If end users of storage systems are installing systems for purposes where the system would not interact with the distribution network—for example back-up applications—the electricity distribution utility may not know about those system installations. Utilities collect information on small-scale storage systems primarily through inter-connection agreements. Because these agreements are designed by the utilities, the information about storage units may not be collected in a consistent format across all utilities.

Small-Scale Energy Storage Trends in California

As shown in Figure 10, in 2018, 86% of reported small-scale storage power capacity in the United States was in California and, specifically, was owned by six utilities: Southern California Edison (SCE), Pacific Gas and Electric (PGE), San Diego Gas and Electric (SDGE), Los Angeles Department of Water and Power (LADWP), Sacramento Municipal Utility District (SMUD), and City of Moreno Valley. In 2018, most installations of small-scale storage in the commercial sector in California were in SCE’s territory (64% of such capacity) and SDGE’s territory (22%). Most installations (95%) of small-scale storage in the industrial sector in California were in PGE’s territory.

Figure 10. Small-scale energy storage capacity by sector (2018)



Source: U.S. Energy Information Administration, Form EIA-861, *Annual Electric Power Industry Report*

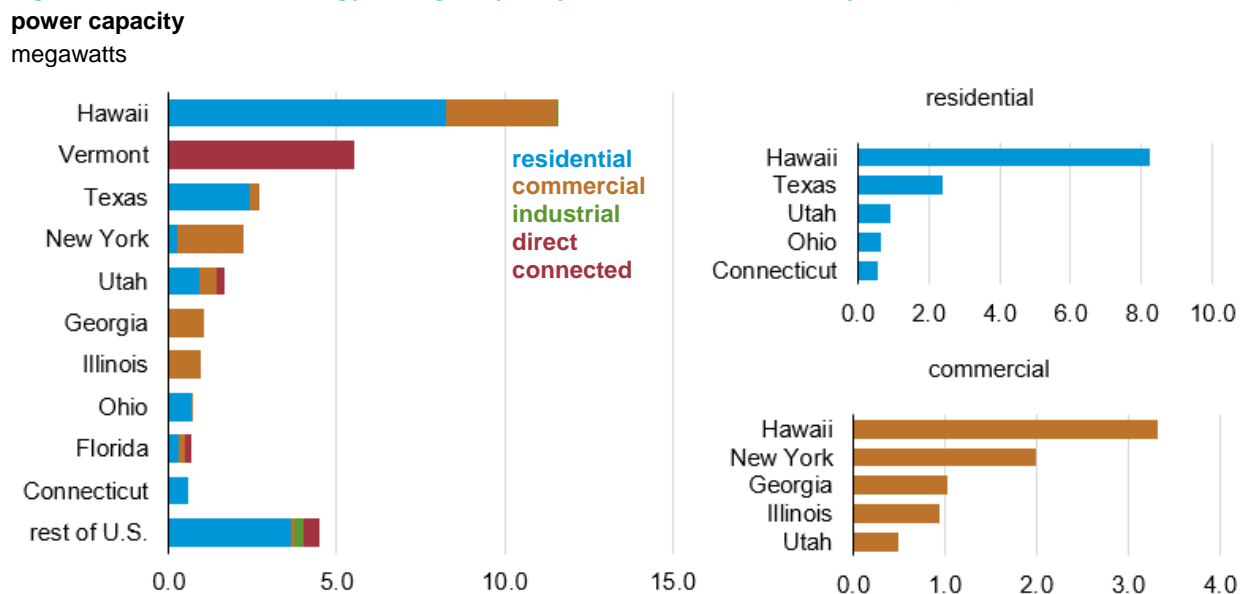
Note: Data collected on small-scale storage may include forms of energy storage other than batteries. Direct-connected storage is not located at an ultimate customer’s site but is in front of the meter or connected directly to a distribution system or both. Direct-connected storage in California and industrial storage outside of California are less than 1% of the total and are therefore not depicted in the figure.

California’s large share of small-scale energy storage power capacity can be attributed to the state’s [Self-Generation Incentive Program](#) (SGIP), which provides financial incentives for installing customer-sited distributed generation. Installations receiving rebates through SGIP contribute to California’s 2013 energy storage mandate ([Assembly Bill 2514](#)), which requires 200 MW of customer-sited energy storage to be installed by 2024. In May 2017, the California Public Utilities Commission implemented [Assembly Bill 2868](#) by ordering SCE, PGE, and SDGE to procure up to an additional 500 MW of distributed energy storage, including no more than 125 MW of customer-sited energy storage.

Small-Scale Energy Storage Trends in the Rest of the United States

After California, the states with the most small-scale storage power capacity in 2018 were Hawaii, Vermont, and Texas, and much of this capacity was installed in the residential sector (Figure 11). Minimal small-scale storage power capacity in the industrial sector existed outside of California. In the commercial sector, small-scale storage was mostly available in Hawaii and New York, as well as other states, notably in Georgia, Illinois, and Utah.

Figure 11. Small-scale energy storage capacity outside of California by sector (2018)



Source: U.S. Energy Information Administration, Form EIA-861, [Annual Electric Power Industry Report](#)

Small-scale energy storage systems are typically owned by end-users. Direct-connected storage systems are installations not located at an ultimate customer’s site but rather in front of the meter or connected directly to a distribution system or both. In Vermont, Green Mountain Power Corporation reported the largest amount of direct-connected battery storage power capacity. Green Mountain operated front-of-the-meter battery storage systems for customers that totaled 5.5 MW of power capacity in 2018.

Market and Policy Drivers

As discussed previously, battery storage is technologically capable of serving many applications, each with benefits for one or more participants in the electricity system, including transmission and distribution system operators, generation resources, and consumers. However, the functional ability of storage to serve these applications can be limited or not well defined under existing market rules and other policies. This situation has begun to change as the technology has matured and industry stakeholders in some regions have gained experience financing, procuring, and operating storage installations. Most of the activity has been led by wholesale market operators and state-level regulators.

Wholesale Market Rules

[ISOs and RTOs](#) are independent, federally-regulated non-profit organizations that ensure reliability and optimize supply and demand bids for wholesale electric power. They are technology neutral and must ensure market rules do not unfairly preclude any resources from participating, as enforced by the Federal Energy Regulatory Commission (FERC). Many existing market rules may not take into account the unique operating parameters and physical constraints of battery storage as both a consumer and producer of electricity. However, recent actions by FERC and ISOs/RTOs have begun to carve a path for storage to participate in the individual markets.

A notable example is [FERC Order 755](#), issued in 2011, which required ISO/RTO markets to provide compensation to resources that can provide faster-ramping frequency regulation. As a result of Order 755, PJM split its frequency regulation market into a fast-ramping service and a slower-ramping service. By the end of 2015, more than 180 MW of large-scale battery storage capacity had come online in the PJM territory. However, in 2015 PJM began observing operational issues due to overdependence on the fast-ramping regulation service, which mainly consisted of resources such as batteries with duration restrictions, as opposed to the slower-ramping service, which generally consisted of resources which could be operated much longer (but took longer to come online)¹⁶. PJM thus changed its frequency regulation signals, and installations of large-scale battery storage in the region stalled since PJM made these changes.

Other system operators have also implemented relevant changes to market rules, including developing unique asset classes for storage, specifying participation models, lowering minimum size requirements, allowing for aggregation, and defining duration requirements. However, these regions have not seen large-scale battery storage deployment at the same level as PJM. In February 2018, FERC issued [Order No. 841](#) requiring system operators to remove barriers to the participation of electric storage resources in the capacity, energy, and ancillary services markets. Each ISO/RTO under FERC jurisdiction was required to revise its tariff to include market rules that recognize the physical and operational characteristics of electric storage resources and to implement the revisions upon FERC's approval of

¹⁶ PJM, "Fast Response Regulation (RegD) Resources Operational Impact," July 01, 2017. <https://www.pjm.com/~media/committees-groups/committees/oc/20150701-rpi/20150701-fast-response-regulation-resources-operational-impact-problem-statement.ashx>

tariff compliance. As of May 2020, all ISO/RTO's had filed multiple tariff revisions but none have been fully approved by FERC.

State-Level Policy Actions

Other than FERC activities described in the previous section, federal policies involving energy storage have been limited.¹⁷ Most policy actions involving energy storage have been at the state level and include setting procurement mandates, establishing incentives, and requiring incorporation of storage into long-term planning mechanisms.

Policy Actions in California

California has introduced several measures related to energy storage. In 2013, the California Public Utility Commission (CPUC) implemented [Assembly Bill 2514](#) by setting a mandate for its investor-owned utilities to procure 1,325 MW of energy storage across the transmission, distribution, and customer levels by 2020. All of the capacity must be operational by 2024. In May 2017, CPUC implemented [Assembly Bill 2868](#) by ordering its investor-owned utilities to procure up to an additional 500 MW of distributed energy storage, including no more than 125 MW of customer-sited energy storage. The [Self-Generation Incentive Program](#), which provides financial incentives for installing customer-sited distributed generation, has designated \$48.5 million in rebates for residential storage systems 10 kW or smaller and \$329.5 million for storage systems larger than 10 kW.

Press reports in 2017 indicated that 100 MW, or about 37% of existing battery storage power capacity in California, was installed in response to a leak at the Aliso Canyon Natural Gas Storage Facility outside Los Angeles in October 2015.¹⁸ According to these reports, in May 2016, to help address resulting reliability risks as a result of constraints on natural gas supply, the CPUC authorized the Southern California Edison electric utility to hold an expedited solicitation for energy storage. As a result, 62 MW of battery storage capacity was added to the system in December 2016. In addition, the CPUC expedited an ongoing procurement of 38 MW of battery storage by San Diego Gas and Electric, which was installed in early 2017.

Policy Actions in the Rest of the United States

As of May 2020, five states besides California have also set energy storage mandates or targets. In 2015, Oregon passed [House Bill 2193-B](#), directing two electric utilities to each procure 5 MWh of storage energy capacity by 2020. In August 2018, Massachusetts enacted [House Bill 4857](#) (“An Act to Advance Clean Energy”), directing the Massachusetts Department of Energy Resources set an energy storage target of 1,000 MWh by 2025. In October 2018, [New York announced a target of 3,000 MW of energy storage by 2030](#). In May 2018, New Jersey enacted the [Clean Energy Act](#), P.L. 2018, which set a target of 2,000 MW of energy storage by 2030. In February 2020, Virginia passed [House Bill 1526](#), which set a 3,100 MW energy storage goal by 2035. In addition, some states, such as Nevada, allow storage systems

¹⁷ One exception is the investment tax credit (ITC), which is a credit to income tax liability proportional to the capital expenditures originally intended for certain renewable energy technologies, including solar and wind. Energy storage installed at a solar or wind facility can be considered part of the energy property of the facility and can receive a portion of the tax credit.

¹⁸ Green Tech Media, “Tesla, Greensmith, AES Deploy Aliso Canyon Battery Storage in Record Time,” January 31, 2017, <https://www.greentechmedia.com/articles/read/aliso-canyon-emergency-batteries-officially-up-and-running-from-tesla-green#gs.bvJdDKY>

to be included in state-level renewable portfolio standards. Aside from targets, some states have provided financial incentives for energy storage installations, including grants, support for pilot projects, and tax incentives. In 2018, Maryland passed [Senate Bill 758](#), offering a tax credit of 30% on the installed costs for residential and commercial systems.

Many states require utilities to produce integrated resource plans (IRPs) that demonstrate each utility's ability to meet long-term demand projections using a combination of generation, transmission, and energy efficiency investments, while minimizing costs. Incorporating storage into IRPs can be a challenge because storage is different from conventional electricity generators and demand-side resources. For example, storage has unique operational constraints, can be interconnected at various points throughout the system, can serve a variety of applications, and is faced with policy and regulatory uncertainty that may affect system profitability. Nonetheless, some states have begun to require utilities to include storage in integrated resource plans, including Arizona, California, Connecticut, Colorado, Florida, Indiana, Kentucky, Massachusetts, New Mexico, North Carolina, Oregon, Utah, Virginia, and Washington. New York and Vermont include storage in their state energy plans.¹⁹

¹⁹ PV Magazine, "Utilities are increasingly planning for energy storage," December 7, 2017, <https://pv-magazine-usa.com/2017/12/07/utilities-are-increasingly-planning-for-energy-storage-w-charts/>

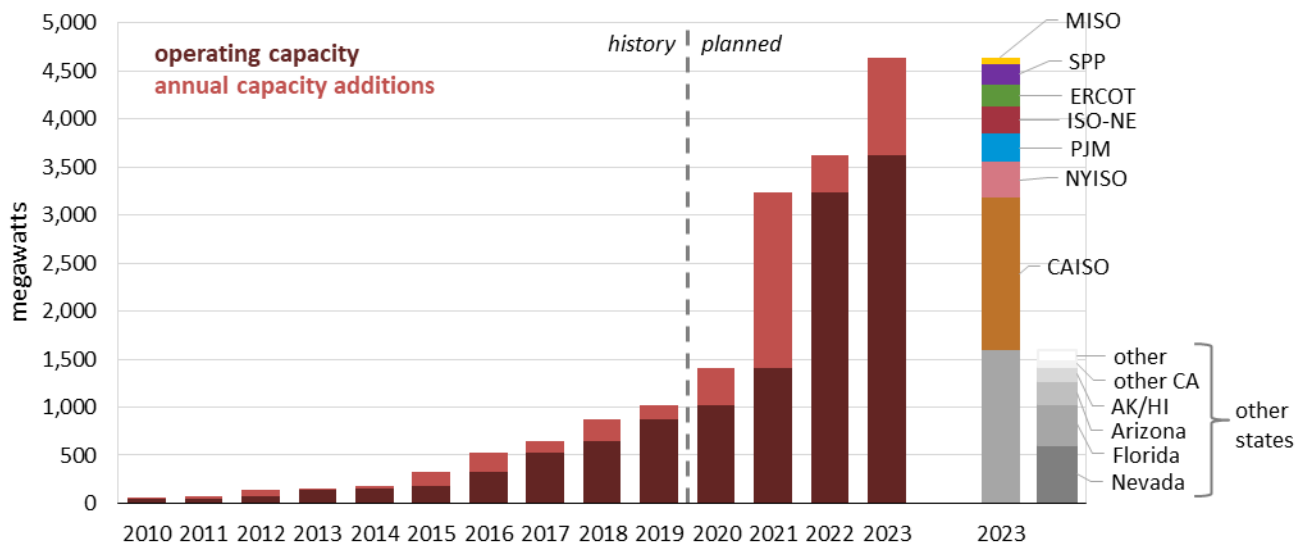
Ongoing Trends

For the short term, EIA assesses future battery capacity installation trends using planned generator additions reported by project developers, both for stand-alone battery storage systems and for those co-located with other electricity generating technologies such as solar or wind. EIA provides long-term projections on future battery capacity installations in the *Annual Energy Outlook*.

Near-Term Planned Capacity Additions (2020–23)

As of December 2019, project developers reported to EIA that they planned to make 3,616 MW of large-scale battery storage operational in the United States between 2020 and 2023. Given the short planning period required to install a storage facility, the reported planned capacity does not necessarily reflect all the possible builds during this period, but the reported planned capacity can be used as an indicator of trends.

Figure 12. Large-scale battery storage cumulative power capacity (2010–2023)



Source: U.S. Energy Information Administration, Form EIA-860M, [Preliminary Monthly Electric Generator Inventory](#)

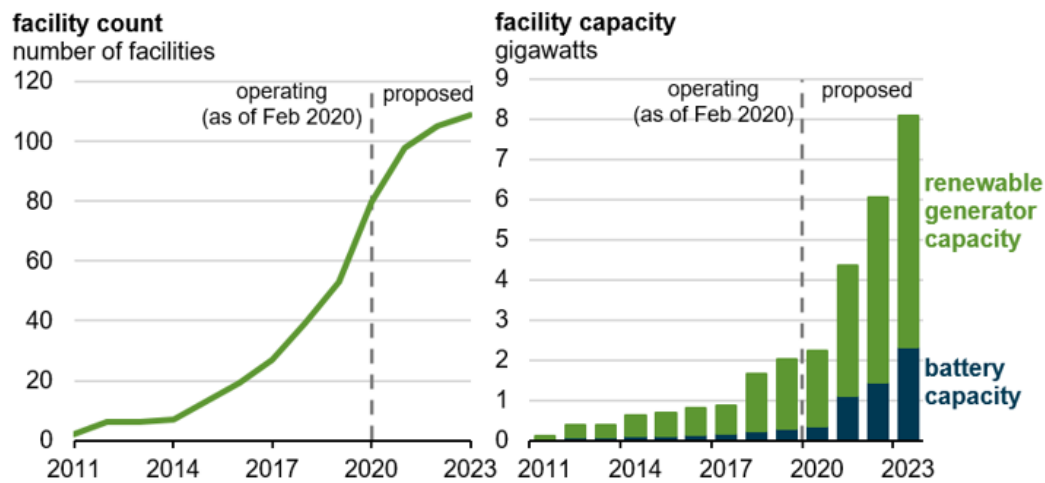
California accounted for 38% of planned battery storage power capacity reported as of December 2019. These planned additions put California in line to meet its energy storage mandate (Assembly Bill 2514), which requires its investor owned utilities to install 1,325 MW of energy storage across the transmission, distribution, and customer levels by 2024. New York and Massachusetts also have state mandates for energy storage and have planned battery storage projects in the upcoming years. Virginia and New Jersey have mandates but have not reported any planned energy storage builds to EIA (See Market and Policy Drivers for more information). Several states without policy mandates show relatively strong growth in storage in the upcoming years, including Nevada, Florida, and Arizona.

Co-Located Battery Storage Projects

Pairing renewable energy power plants with energy storage is a trend of increasing importance as the cost of energy storage declines. The number of solar and wind generation sites co-located with battery

storage systems has increased from 19 paired sites in 2016 to 53 sites in 2019. Data reported for proposed projects suggest that the number of co-located sites may double by 2023 from 2019 levels.

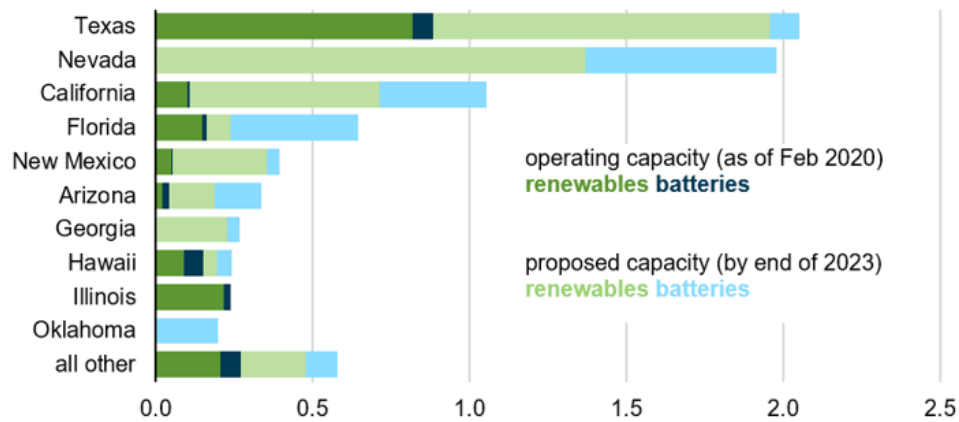
Figure 13. Count and capacity of renewable plus storage facilities (2011–2023)



Source: U.S. Energy Information Administration, Form EIA-860M, [Preliminary Monthly Electric Generator Inventory](#); U.S. Energy Information Administration, Form EIA-860, [Annual Electric Generator Report](#).

Among the benefits of these co-located projects, the most critical is the ability to take advantage of common onsite infrastructure to store renewable-generated energy produced during periods of low electricity prices and low demand, and later supply that stored energy to the grid when both demand and electricity prices are higher. Solar and wind technologies are the more common generators that benefit from battery storage because of their intermittent operation. The benefits of later pairing battery storage can also be realized even after the renewable energy power plant has initially entered into operation. More than 25 solar and wind power plants have added battery storage systems after their original operation date. As of February 2020, more than 90% of the operating capacity from co-located battery and renewable generation sites were located in nine states. Texas had the most co-located battery storage capacity with 886 MW (renewable plus storage capacity) as of February 2020 (Figure 14). On average, existing co-located projects have a renewable nameplate capacity to battery power capacity ratio of 6:1, and planned projects have a power capacity ratio of 2:1. As of 2019, 10 of the 53 co-located facilities accounted for more than half of the combined renewable and battery storage capacity. Of all operating battery storage capacity in the United States as of 2019, 25% was installed in paired systems, while of all the operating solar capacity in the United States, only 2% was in paired with an energy storage system. By December 2023, 2.3 gigawatts (GW) of the 4.9 GW (47%) of operating battery storage is planned to be paired onsite with renewable generation.

Figure 14. Operating and planned renewable plus storage capacity, top 10 states
power capacity
 gigawatts



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

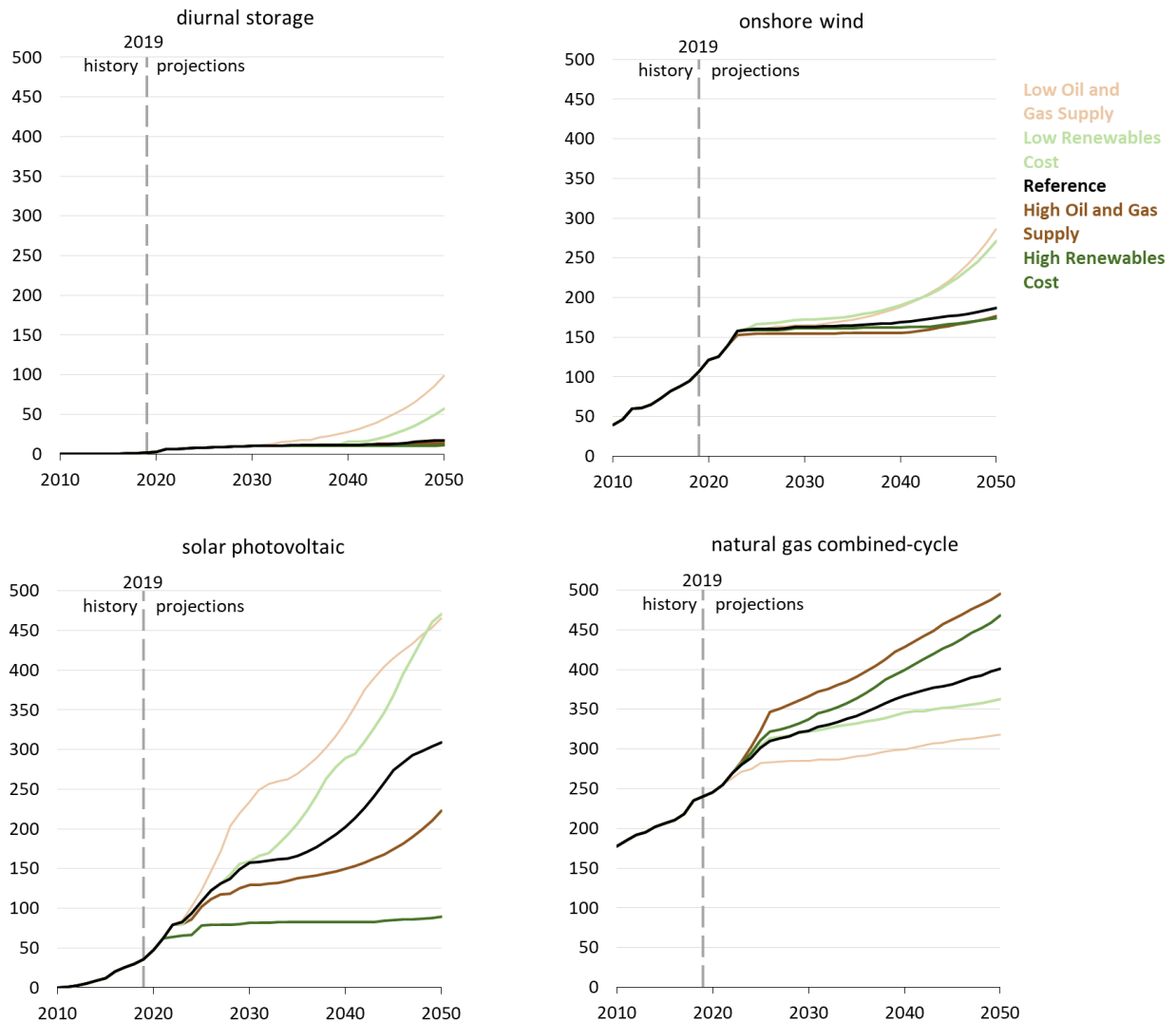
Long-Term Projected Capacity Additions (2020–2050)

The *Annual Energy Outlook 2020 (AEO2020)* provides projections to 2050 on the supply and demand needs for energy markets in the United States. The Reference case, which assumes implementation of current U.S. laws and policies, projects large-scale battery storage capacity to grow from 1 GW in 2019 to 17 GW in 2050 (Figure 15Figure 14).

In addition to the Reference case, AEO2020 examines the sensitivity of model results to changes in various assumptions. In the Low Renewables Cost case, where the costs of renewable technologies are assumed to decline at a faster rate, ending at 40% lower than the Reference case by 2050, higher levels of energy storage support increased solar and wind capacity additions. In the Low Oil and Gas Supply case, less availability of natural gas results in higher natural gas prices. Because natural gas-fired combined-cycle generating units and solar facilities compete with each other, increased natural gas prices promote the growth of solar and thus storage as in the Low Renewables Cost case. In addition, the high price of natural gas used by combustion turbine peaking units allows more market opportunity for energy arbitrage, which also supports the growth of energy storage. These factors contribute to the Low Oil and Gas Supply case showing the most storage capacity additions of any of the AEO2020 projections.

Figure 15. AEO2020 power capacity by case and selected technology, 2050

power capacity
gigawatts

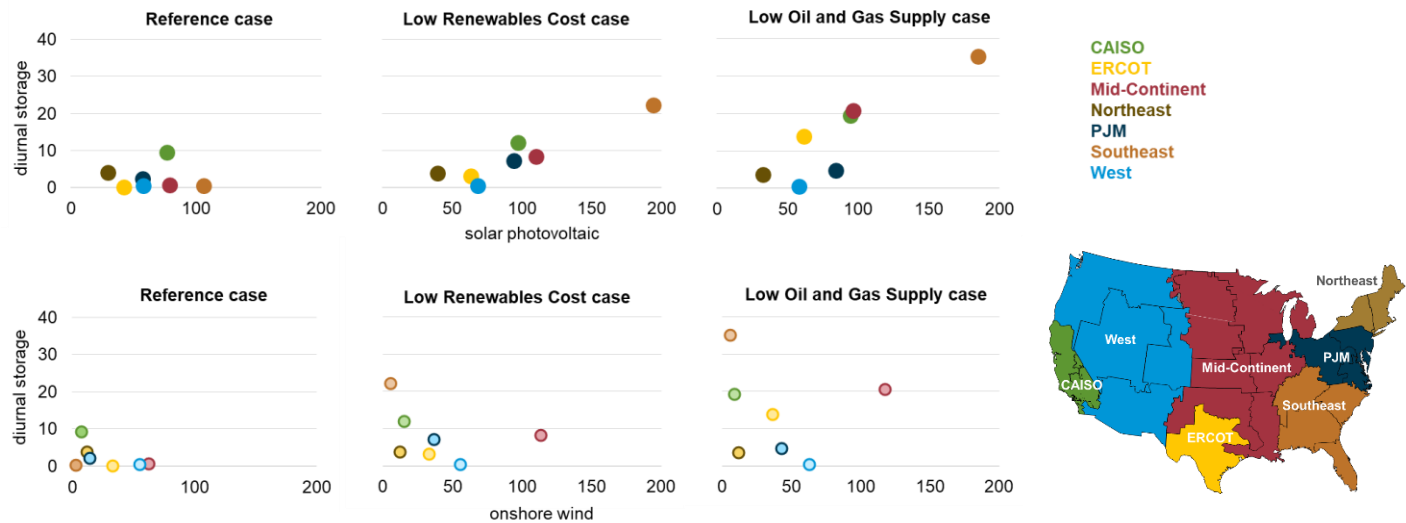


Source: U.S. Energy Information Administration, [Annual Energy Outlook 2020](#)

When looking at the regional trends in the Reference case and side cases (Figure 16), growth in energy storage capacity follows growth in solar photovoltaic (PV) capacity, but it does not correlate strongly with growth in wind generation capacity. The Southeast region is very sensitive to the varying assumptions in the side cases, showing strong growth relative to the Reference case in both the Low Oil and Gas Supply case and Low Renewables Cost case. All cases show limited storage growth in the Northeast, PJM, and West regions.

Figure 16. AEO2020 regional diurnal storage versus solar photovoltaic power and wind capacity, 2050

power capacity
gigawatts



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2020*

Because long-term planning models are designed to deliver multi-decade results with many complex interactions, modelers often have to simplify their modeling of energy storage technologies. One simplification that has significant consequences for the representation of energy storage technologies is the temporal resolution of the model. EIA’s AEO2020 included energy storage as a four-hour battery system that can be used to avoid curtailments of excess solar- and wind-generated electricity, shift energy within a day, and help meet regional reliability requirements; however, modeling sub-hourly markets, such as battery systems participating in frequency response, remains a challenge. As a result, EIA’s AEO projections as shown do not represent all of the available storage technology options nor the full suite of applications that storage can serve. See the list of possible applications for storage in the [Current Applications](#) section of this report.

EIA has been collaborating with other modeling entities on a multi-model comparison²⁰ to enhance the representation of technologies that challenge conventional long-term planning model design, such as wind, solar, and energy storage. The representation of battery storage in the AEO will continue to develop as the markets and applications for energy storage evolve.

²⁰ Cole, Wesley, et al, *Variable Renewable Energy in Long-Term Planning Models: A Multi-Model Perspective*, November 2017, <https://www.energy.gov/eere/analysis/downloads/variable-renewable-energy-long-term-planning-models-multi-model-perspective>.

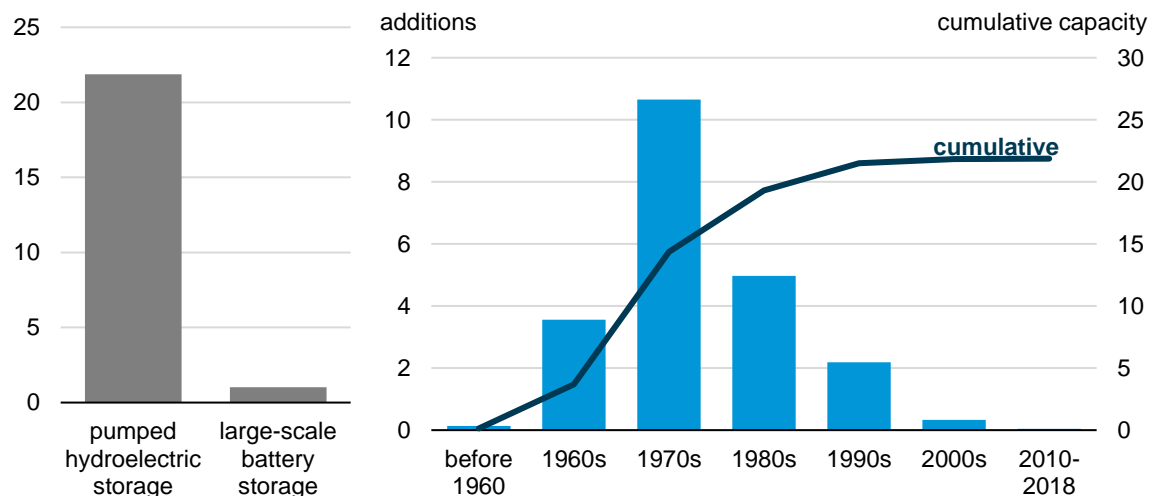
Appendix A: Other Storage Technologies

This report has focused primarily on electrochemical energy (or battery) storage; however, energy storage can take other forms including electrical, thermal, and mechanical. Electrical energy storage includes capacitors and superconductors. Thermal storage includes water, ice, molten salts, and ceramics. Mechanical includes technologies such as hydroelectric pumped storage, flywheels, and compressed-air energy storage (CAES).

Hydroelectric pumped storage uses electricity to pump water into an elevated reservoir so it can be used to drive a hydroelectric turbine when electricity is needed. Although the United States has significantly more operating hydroelectric pumped storage capacity than battery storage capacity, most of it was installed in the 1970s and early 1980s (Figure 17). California, Virginia, and South Carolina account for most of the existing hydroelectric pumped storage capacity. The largest single facility in the United States was installed in 1985 in Bath County, Virginia, and has a capacity of 3 GW.

Figure 17. Hydroelectric pumped storage capacity (1960–2018)

power capacity
gigawatts



Source: U.S. Energy Information Administration, Form EIA-860, *Annual Electric Generator Report*

Flywheels store energy by using an electric motor to speed up a spinning mass, which can then be used later to spin a turbine to produce electricity. To reduce losses, the mass is spinning in a nearly frictionless enclosure. Flywheels are well suited to provide power-oriented applications that require many charge and discharge cycles. Three large-scale flywheel systems are currently operating in the United States: a 20 MW system in New York, a 20 MW system in Pennsylvania, and a 2 MW system in Alaska. One standby flywheel system of 5 MW currently exists in Texas.

CAES uses electricity to compress air and store it in an underground cavern. The air is then expanded through a turbine when electricity is needed. The only operable large-scale CAES system in the United States is a 110 MW system that was installed in Alabama in 1991 by PowerSouth Energy Cooperative.

The Apex Bethel Energy Center is a 317 MW CAES system in Texas that is expected to enter operation in 2022.

Thermal storage systems take excess energy produced during the day to heat salt or other materials that can be used later to power a steam turbine. Thermal storage can also be used as a distributed energy resource, for example, by chilling water overnight to use for space cooling during summer days. All existing large-scale thermal energy storage in the United States uses concentrated solar power (CSP) technology. CSP reflects rays from the sun to a receiver to produce steam directly or to heat up alternative fluids, which are used to generate steam through a heat exchanger. The steam is then run through a turbine to generate electricity. Some of these alternative heat transfer or storage fluids can store energy for long durations, and they can be used to generate steam and electricity at night using thermal solar energy gathered during the day. Of the eight CSP projects currently in operation (totaling 1,775 MW) only Arizona Solar One LLC's Solana Generating Station plant in Arizona (295 MW) and Tonopah Solar Energy LLC's Crescent Dunes Solar Energy plant in Nevada (110 MW) employ energy storage.

Other energy storage technologies are in different phases of development but have yet to see significant deployment in large-scale grid applications.