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U.S. Battery Storage Market Trends

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List of Acronyms

AEO	Annual Energy Outlook
AK/HI	Alaska and Hawaii
CAES	Compressed-Air Energy Storage
CAISO	California Independent System Operator
CPUC	California Public Utility Commission
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	Investment-owned utilities
ITC	Investment Tax Credit
IPP	Independent power producers
ISO-NE	Independent System Operator of New England
KIUC	Kauai Island Utility Cooperative
kW	Kilowatt
kWh	Kilowatthour
MISO	Mid-Continent Independent System Operator
MW	Megawatt
MWh	Megawatthour
PGE	Pacific Gas and Electric
PJM	Pennsylvania-New Jersey-Maryland 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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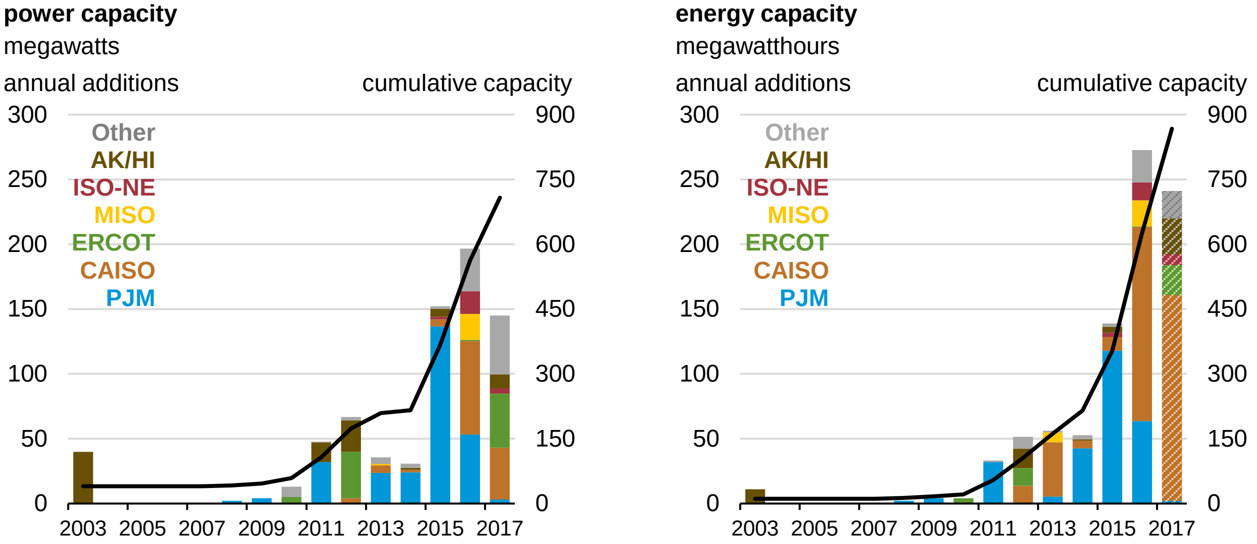
Executive Summary

This report explores trends in U.S. battery storage capacity additions and describes the current state of the market, including information on applications, cost, and market and policy drivers. There are a number of key takeaways:

- At the end of 2017, 708 megawatts (MW) of power capacity,[1] representing 867 megawatthours (MWh) of energy capacity,[2] of large-scale[3] battery storage capacity was in operation.
- Over 80% of U.S. large-scale battery storage power capacity is currently provided by batteries based on lithium-ion chemistries.
- About 90% of large-scale battery storage in the United States is installed in regions covered by five of the seven organized independent system operators (ISOs) or regional transmission organizations (RTOs) and in Alaska and Hawaii (AK/HI).

Figure ES1. U.S. Large-Scale Battery Storage Capacity by Region (2003–2017)



Notes: 2017 energy capacity data for large-scale battery storage are based on preliminary estimates; energy capacity annual additions do not include 26 MW of since-retired batteries because energy capacity is not reported for retired generators
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.*

- Nearly 40% of existing large-scale battery storage power capacity (and 31% of energy capacity) lies in the Pennsylvania-New Jersey-Maryland Interconnection (PJM), which runs energy and capacity markets and the transmission grid in 13 eastern states and the District of Columbia.
    - In 2012, PJM created a new frequency regulation market product for fast-responding resources, the conditions of which were favorable for battery storage. However, recent changes in PJM's market rules have slowed battery installations in the region.
    - Most existing large-scale battery storage power capacity in PJM is owned by independent power producers providing power-oriented frequency regulation services.

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

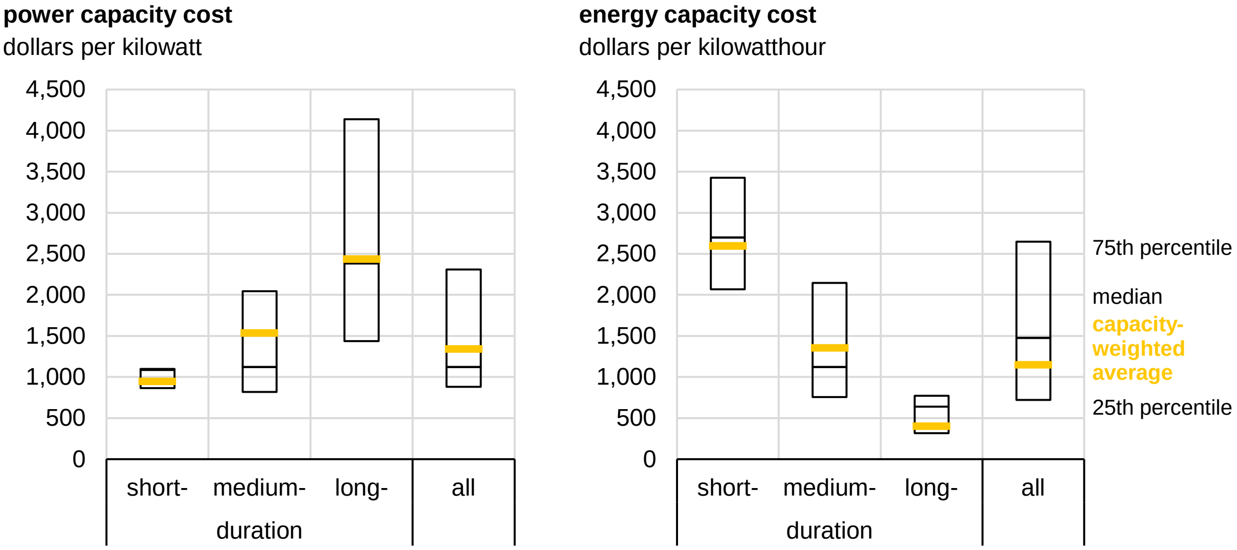
[2] Energy capacity of the storage system is the total amount of energy that can be stored or discharged by the battery storage system and is measured in megawatt-hours (MWh)

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

- Installations in California Independent System Operator (CAISO) territory accounted for 18% of existing U.S. large-scale battery storage power capacity in 2017, but they accounted for 44% of existing energy capacity.
    - In 2013, the California Public Utility Commission (CPUC) implemented Assembly Bill 2514 by setting a mandate for the state's investor-owned utilities to 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.
    - In addition, nearly 90% of reported small-scale[4] storage power capacity in the United States was reported by four California utilities.

- Costs for battery storage technologies depend on technical characteristics such as the power and energy capacity of a system.
    - In general, total installed system costs for batteries of shorter duration are less expensive than long-duration systems on a per-unit of power capacity basis.
    - In terms of costs per-unit of energy capacity, the reverse is true—the longer duration batteries will typically have lower normalized costs compared with shorter-duration batteries.

Figure ES2. Total Installed Cost of Large-Scale Battery Storage Systems by Duration



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

- Battery storage can serve many applications. However, the functional ability of storage to serve these applications has traditionally been not well defined under existing market rules and policies. As the technology has matured and as the industry stakeholders in some regions have gained experience financing, procuring, and operating storage installations, the situation has changed and more clarity has begun to be provided. Most of the activity has been led by specific ISOs/RTOs and state-level regulators.

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

Introduction

This report examines trends in U.S. battery storage capacity installations and describes the current state of the market, including information on applications, cost, as well as market and policy drivers for recent battery storage installations.

Many types of technologies can store energy, including electrical, thermal, mechanical, and electrochemical technologies. Hydroelectric pumped storage, a form of mechanical energy storage, accounts for the greatest share of large-scale energy storage power capacity in the United States. However, large-scale energy storage capacity additions since 2003 have been almost exclusively electrochemical (or battery) storage. For this reason, most this report focuses on battery storage technologies, although other energy storage technologies are addressed in the appendix.

An important distinction for battery storage is the difference between power and energy capacity. 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 (MW). 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 megawatthours (MWh).

This report explores trends in both large-scale and small-scale battery storage systems. Large-scale (or utility-scale) systems are connected to the grid and have a nameplate power capacity greater than 1 MW. Small-scale refers to systems that are less than 1 MW in power capacity and are typically connected to a distribution network.[5]

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[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 and not on location with respect to the customer meter, distribution network, or wholesale grid.

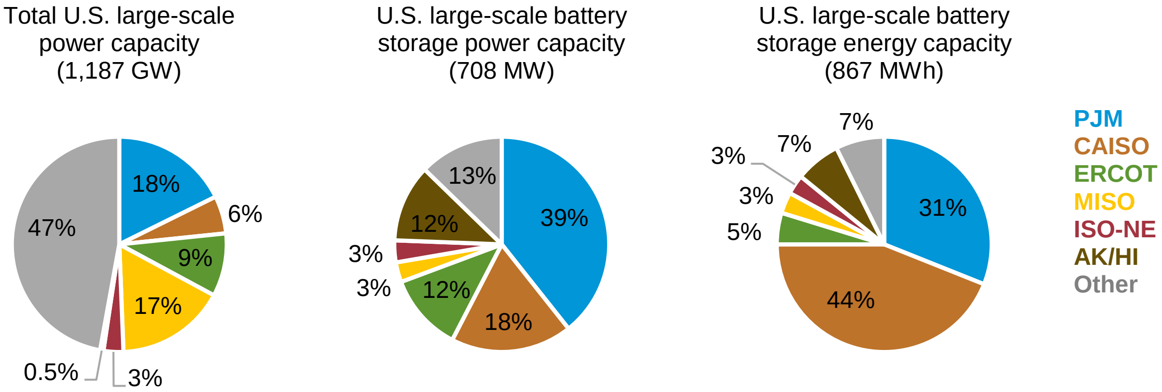
Large-Scale Battery Storage Trends

The first large-scale[6] battery storage installation in the United States that was still in operation as of 2017 entered service in 2003. Installed power capacity has nearly doubled every two years since 2011, and by the end of 2017, 708 MW was in operation. Independent power producers in the Pennsylvania-New Jersey-Maryland interconnection (PJM), which covers all or part of 13 eastern states and the District of Columbia, have installed most of the existing power capacity, but regulated utilities in the California Independent System Operator (CAISO) territory have procured significant amounts of energy-oriented capacity as well. In 2016, annual U.S. power capacity additions reached an all-time high when 197 MW of large-scale battery storage was installed. Most U.S. installations use lithium-ion batteries, but design parameters such as power capacity, energy capacity, and duration vary by region and by project.

Regional Trends

As shown in Figure 1, about 90% of large-scale battery storage capacity in the United States is installed in the regions covered by five of the seven organized independent system operators (ISOs) or regional transmission organizations (RTOs)[7] and the non-contiguous states of Alaska and Hawaii (AK/HI). These regions account for 53% of total U.S. large-scale power capacity and have the largest shares of storage capacity relative to their shares of total installed capacity. The disproportionate share of large-scale battery storage in these regions results from differences in market design and policies.

Figure 1. Large-Scale U.S. Power and Energy Capacity by Region (2017)



Notes: Energy capacity data for large-scale battery storage installed in 2017 are based on preliminary estimates.
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.*

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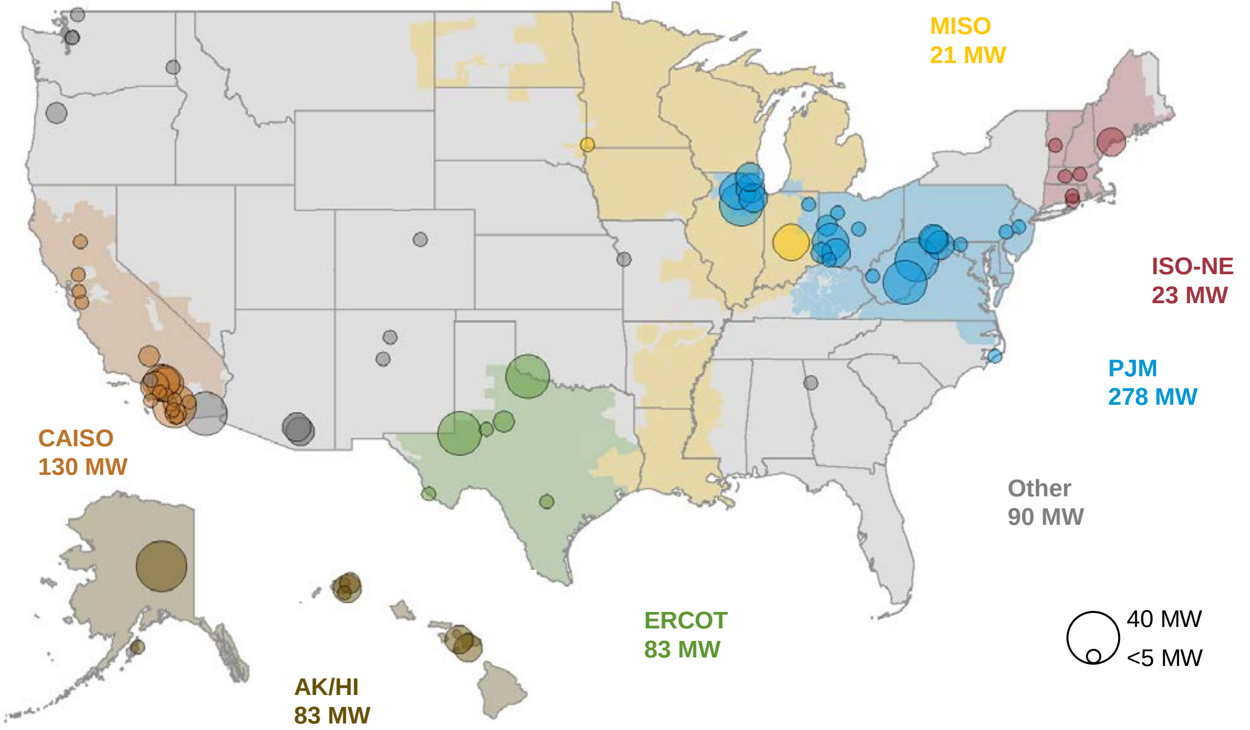
[6] Large-scale refers to systems that are grid connected and have a nameplate power capacity greater than 1 MW.

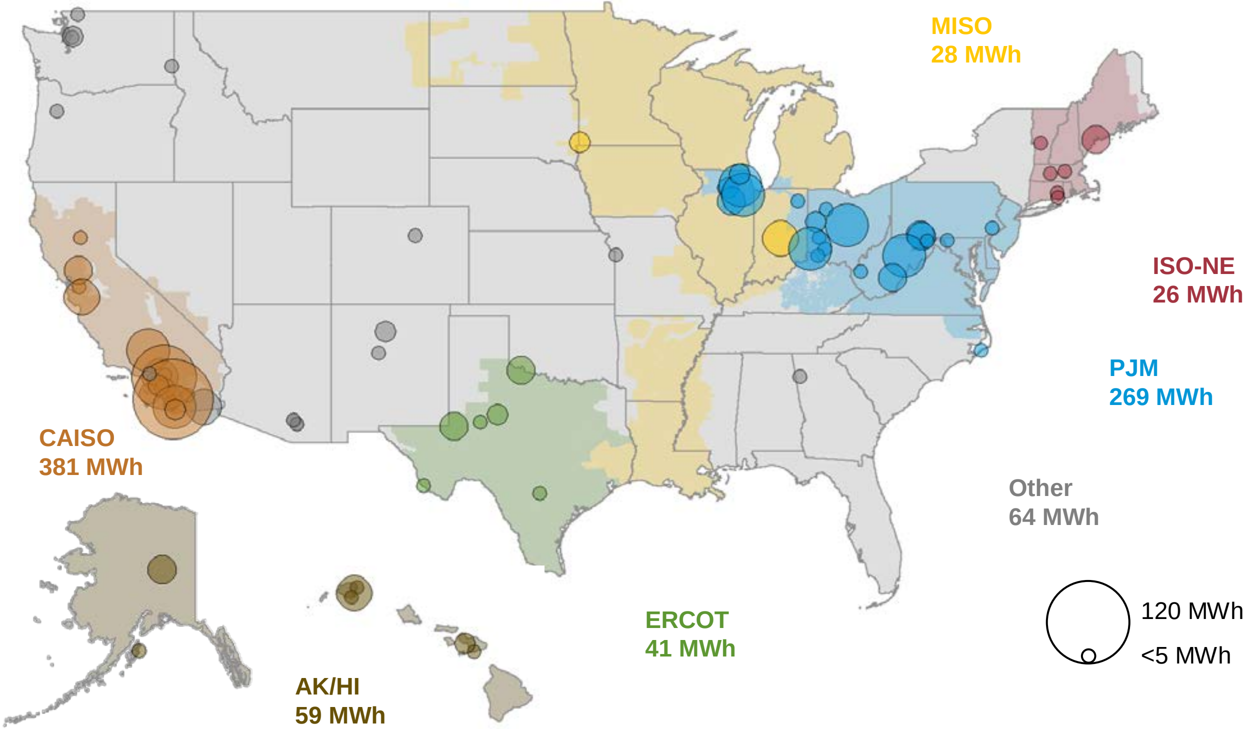
[7] ISOs and RTOs, are independent, federally regulated non-profit organizations that ensure reliability and optimize supply and demand bids for wholesale electric power. The Electric Reliability Council of Texas (ERCOT) is regulated by the Public Utility Commission of Texas.

Figure 2. U.S. Large-Scale Battery Storage Installations by Region (2017)

power capacity
megawatts



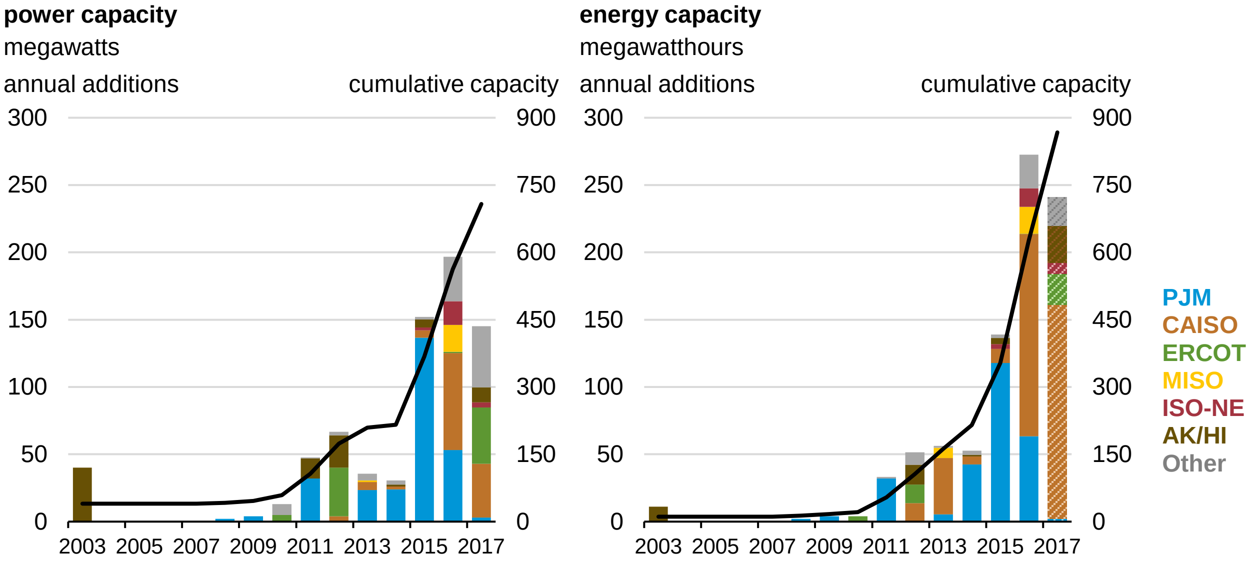
energy capacity
megawatthours



Notes: Energy capacity data for large-scale battery storage installed in 2017 are based on preliminary estimates.
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.*

Between 2003 and 2017, 734 MW of large-scale battery storage power capacity was installed in the United States, two-thirds of which was installed in the past three years. Nearly 40% of existing large-scale battery storage power capacity lies in the PJM Interconnection, shown in Figure 2. In 2012, PJM created a new frequency regulation market for fast-responding resources, the conditions of which were especially favorable for battery storage.

Figure 3. U.S. Large-Scale Battery Storage Capacity by Region (2003–2017)

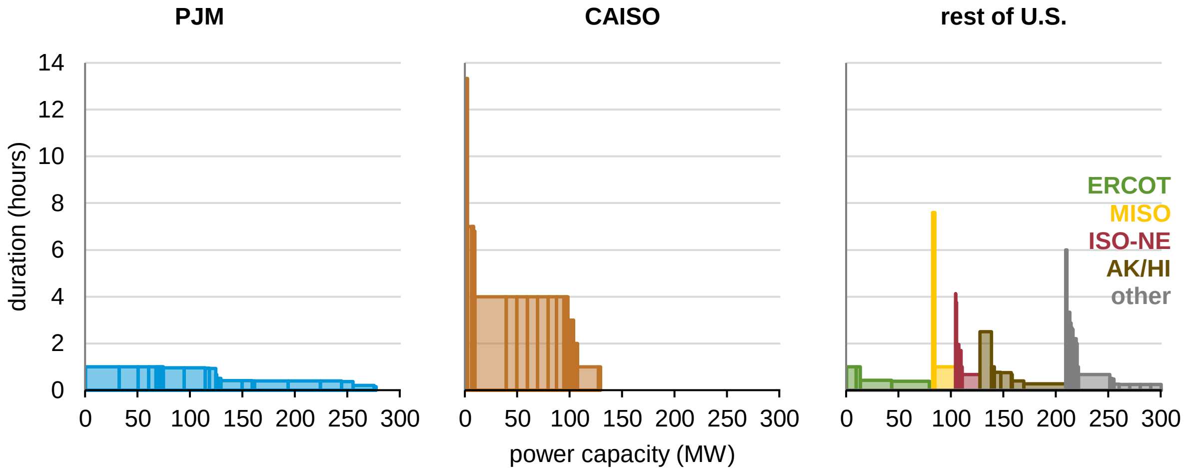


Notes: Energy capacity data for large-scale battery storage installed in 2017 are based on preliminary estimates. Energy capacity additions do not include 26 MW of since-retired batteries since energy capacity is not reported for retired generators.
Sources: U.S. Energy Information Administration, Form EIA-860M, *Preliminary Monthly Electric Generator Inventory*; U.S. Energy Information Administration, Form EIA-860, *Annual Electric Generator Report.*

Although installations in CAISO account for 18% of existing U.S. large-scale battery storage power capacity, they account for 44% of existing energy capacity in 2017, as illustrated in Figure 3. Of the power capacity in California, 62% was procured by two electric utilities, Southern California Edison and San Diego Gas and Electric, to help address reliability risks as a result of constraints on the natural gas supply following a leak at a major natural gas storage facility in the region. The California Public Utilities Commission 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 the section on market and policy drivers for more information on California's activities related to energy storage.)

Given the trend in California of using battery storage for applications such as reliability, large-scale battery storage installations in California tend to be energy-oriented with small power capacities and long durations. Large-scale battery storage installations in CAISO have an average power capacity of 5 MW and an average duration of 4 hours, as shown in Figure 4. Installations in PJM, however, tend to be power-oriented with larger capacities and shorter durations to serve frequency regulation applications. Large-scale battery storage installations in PJM have an average power capacity of 12 MW and an average duration of less than 45 minutes. Other markets in the U.S. show a mix of power- and energy-oriented battery installations.

Figure 4. Power Capacity and Duration of U.S. Large-Scale Battery Storage by Region (2017)

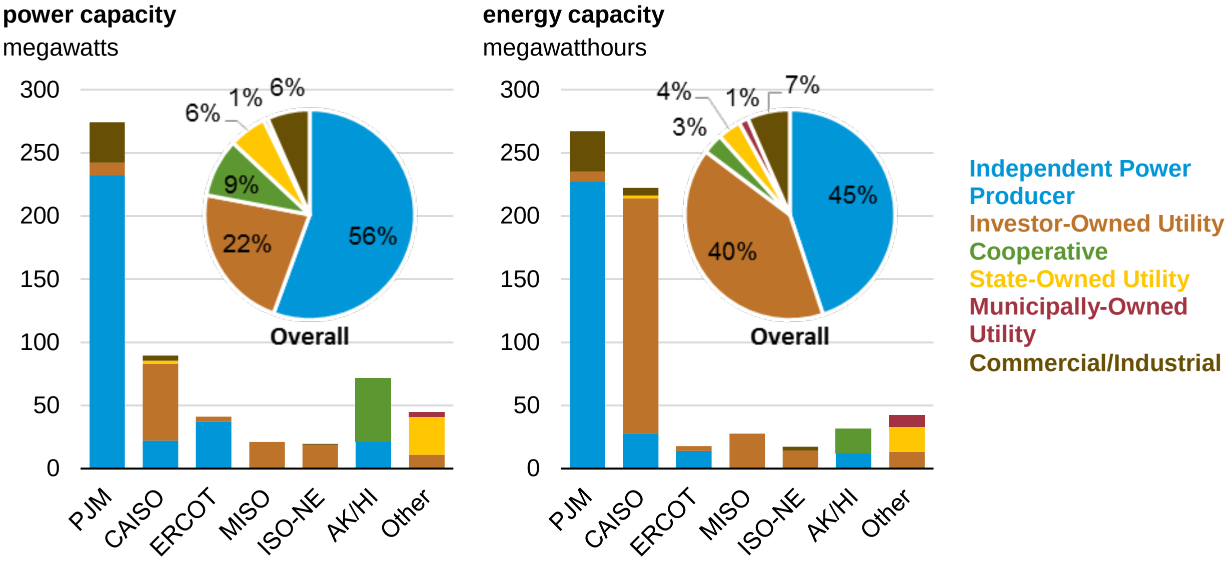


Note: Energy capacity data for large-scale battery storage installed in 2017 are based on preliminary estimates. Duration is calculated by dividing nameplate energy capacity (in MWh) by maximum discharge rate (in MW), except in cases where the maximum discharge rate was not available, in which case the nameplate rating was used instead.
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*.

Ownership Trends

At the end of 2016, more than half of existing U.S. large-scale battery storage power capacity was owned by independent power producers (IPPs). As shown in Figure 5, overall ownership of U.S. large-scale battery storage in terms of energy capacity is more balanced between IPPs and investor-owned utilities (IOUs). This ownership trend reflects the dominance of IPPs in PJM, with its power-oriented storage applications as well as the IOU ownership of energy-oriented reliability assets in CAISO.

Figure 5. U.S. Large-Scale Battery Storage Capacity by Region and Ownership Type (2016)



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

With relatively few large-scale battery storage installations outside of PJM and CAISO, it is difficult to anticipate how ownership type in other regions may develop. Nonetheless, some noteworthy points emerge. The five installations in the Mid-Continent Independent System Operator (MISO) and Independent System Operator of New England (ISO-NE) are mostly owned by IOUs. In Alaska, most large-scale battery storage capacity is owned by cooperatives, which is a relatively common ownership type for generation assets in the state. State-owned utilities own 6% 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

Battery storage encompasses several different battery chemistries, including lithium-ion, nickel-based, sodium-based, lead acid, and flow batteries.

Chemistry Descriptions

Some existing battery storage chemistries that have seen grid-scale deployment[8,9,10] include:

- Lithium-ion represented more than 80% of the installed power and energy capacity of large-scale battery storage in operation in the United States at the end of 2016. Lithium-ion batteries have high-cycle efficiency and fast response times. In addition, their high energy density makes them the current battery of choice for the portable electronic and electric vehicle industries.
- Nickel-based batteries were used in some of the earliest U.S. large-scale battery storage systems installed, including a 2003 system added in Fairbanks, Alaska. Since then, limited deployment of this battery chemistry has occurred in the United States. Nickel-based batteries typically have high energy density and reliability but relatively low cycle life.
- Sodium-based battery storage accounted for 3% of the installed large-scale power capacity and 12% of the installed large-scale energy capacity in the United States at the end of 2016. This type of battery storage is a mature technology based on abundant materials with a long cycle life that is suitable for long-discharge applications. These systems are based on molten electrolyte materials and require high operating temperatures (~300°C).
- Lead acid is one of the oldest forms of battery storage, with development beginning in the mid-1800s. Lead acid is a mature technology that is widely used in passenger vehicles. Lead acid covered only 2%–3% of large-scale battery storage capacity installed in the United States at the end of 2016 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 long cycle life, and their operational lifetime is projected to be long. Within the United States at the end of 2016, flow batteries represented less than 1% of the installed power and energy capacity of large-scale battery storage.

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[8] 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

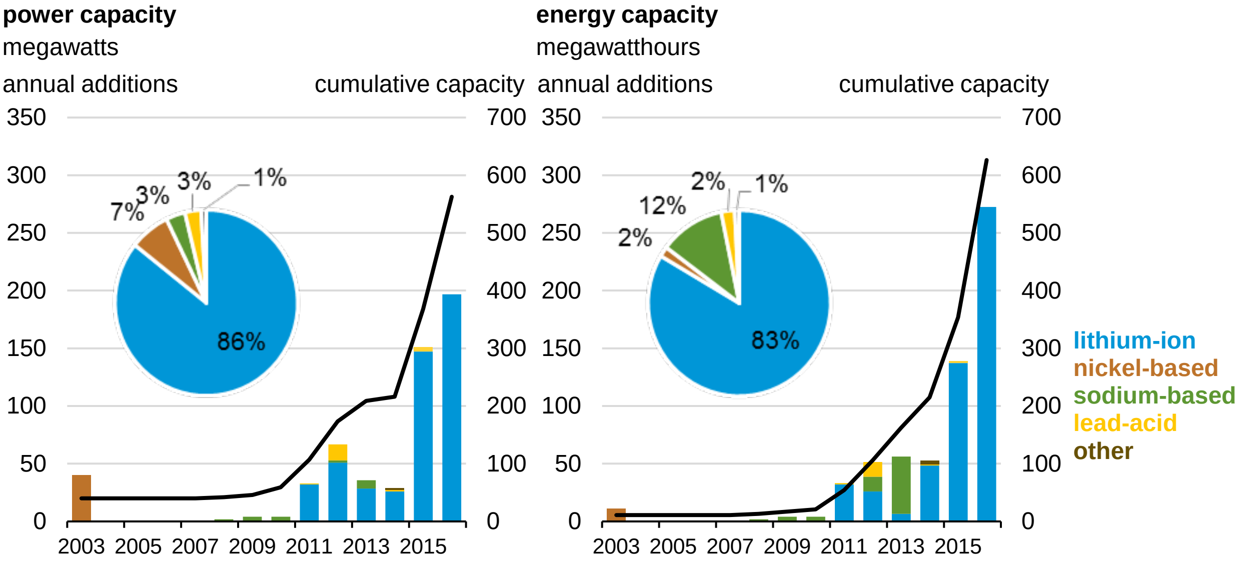
[9] Chen, Haisheng, et al. *Progress in electrical energy storage system: A critical review*. Progress in Natural Science, March 2009.

[10] 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

A number of trends exist in battery chemistry.

Figure 6. U.S. Large-Scale Battery Storage Capacity by Chemistry (2003–2016)



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

The earliest large-scale battery storage installations in the United States used nickel-based and sodium-based batteries, as seen in 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 lithium-ion batteries.[11]

Flow batteries are an emerging battery storage technology. In 2016, Avista Utilities installed the first U.S. large-scale flow battery storage system in Washington State. Two more flow batteries were installed in 2017 by electric utilities in Washington and California. Other battery storage chemistries are in different phases of development but have yet to see significant deployment in large-scale grid applications.

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[11] 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

Current Applications

Batteries have physical and operational constraints such as power output and discharge duration. These constraints are often designed with the intent of optimizing the delivery of certain types of services or applications to the grid. It is also possible and sometimes necessary to combine applications to maximize the value of the system.

Application Descriptions

Some existing batteries applications and their definitions[12] include

- Frequency regulation helps balance momentary differences between demand and supply, often in response to deviations in the interconnection frequency from 60 Hertz.
- Spinning reserve provides synchronized capacity for grid frequency management, which may be available to use during a significant frequency disturbance. For example, during an unexpected unavailability of generation capacity. This reserve ensures system operation and availability.
- 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.
- Load following supplies (discharges) or absorbs (charges) power to compensate for load variations—this 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 station generation capacity or purchase capacity in the wholesale electricity market, often in times of high (peak) demand.
- Load management provides a 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.
- Storing excess wind and solar generation reduces the rate of change of the power output from a non-dispatchable generator (e.g., wind or solar) in order to comply with local grid codes related to grid stability or prevent over production or over-production penalties.
- Arbitrage occurs when batteries charge with inexpensive electrical energy and discharge when prices for electricity are high, also referred to as electrical energy time-shift.
- 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 lower than a specified maximum. This allows for delays or completely avoids the need to upgrade a transmission system 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 (e.g., wind or solar).

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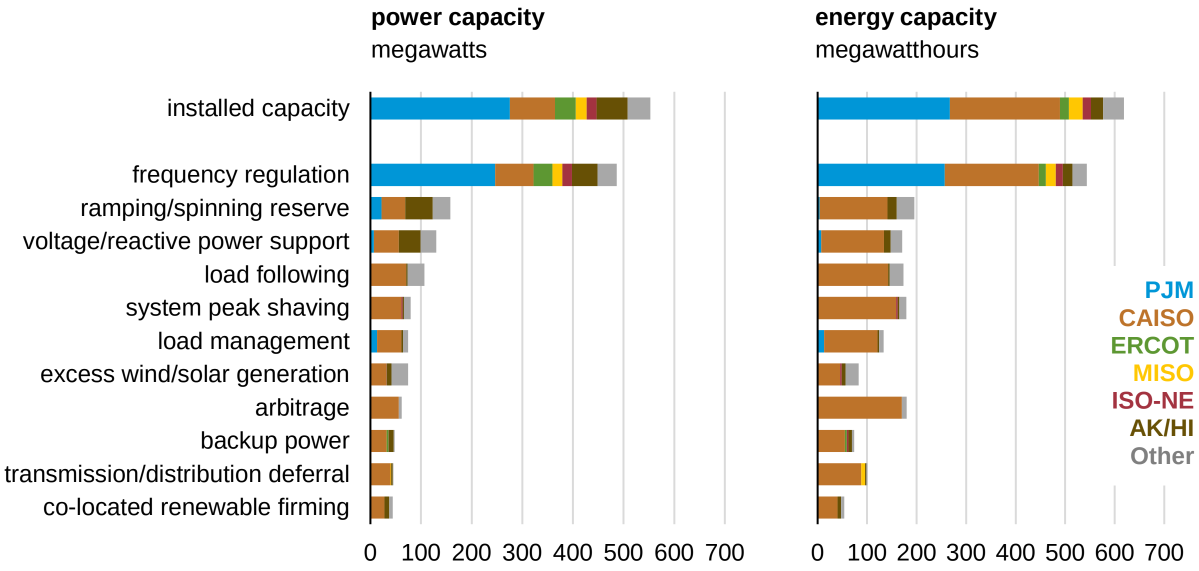
[12] DNV-GL, *Recommended Practices: Safety, operation and performance of grid-connected energy storage systems*, September 2017, https://rules.dnvgl.com/docs/pdf/DNVGL/RP/2017-09/DNVGL-RP-0043.pdf?_ga=2.80787476.2095102769.1516371272-888917498.1516371272

Applications by Region

Figure 7 illustrates the total amount of power and energy capacity that is available for each application. In the United States, 88% of large-scale battery storage power capacity provides frequency regulation, which helps electric systems quickly balance frequency when unexpected differences in electricity supply and demand occur. Installations in PJM, where a specific market product for fast-ramping frequency regulation has led independent power producers to rapidly deploy large-scale battery storage, have largely driven this trend. Installations in CAISO tend to serve a wider array of applications than those in PJM because many have 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 U.S. Large-Scale Battery Storage (2016)



Note: The figure does not include a 10 MW/7.5 MWh battery storage unit located in Maui, Hawaii, which did not report any applications in 2016.

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

Figure 12 (included in the appendix) illustrates how each battery reports the applications that they provide, sorted by region and power capacity of the battery system. PJM batteries selected 1.1 applications on average, while CAISO batteries selected 4.4 applications on average. Figure 13 and Figure 14 combine the information in Figure 7 (above) and Figure 12 to show the power capacity and then the energy capacity totals available to serve each application as selected by the individual battery systems reporting in 2016.

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

The discussion of costs can be 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. Short-duration battery storage systems refer to 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 –2.0 hours, while the long-duration category includes all systems with more than 2.0 hours of nameplate duration.

The average characteristics of the duration-binned sample data are summarized in Table 1. Given the small sample size for each bin (between 8–10 reported units), the values should be used with caution. No conclusions about the state of the industry as a whole can be drawn from these values. Instead, they are used in this report to illustrate the importance of defining the system characteristics when discussing costs, especially in terms of 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 2016 and include multiple reported battery chemistries. As a result, these reported values do not necessarily reflect trends in time or technology-specific tradeoffs.

As shown in Table 1, short-duration battery storage systems have an average power capacity of 13 MW, with medium-duration systems slightly higher at 13.8 MW. The average system size in terms of power capacity for the long-duration battery storage systems is much smaller, at 2.7 MW. In contrast, the average energy capacity for the medium- and long-duration battery storage systems both exceed 15 MWh, while the average for the short-duration battery storage systems, at 4.7 MWh, is one-third the size of the longer duration systems.

Table 1. Sample Characteristics of Capital Cost Estimates for Large-Scale Battery Storage by Duration

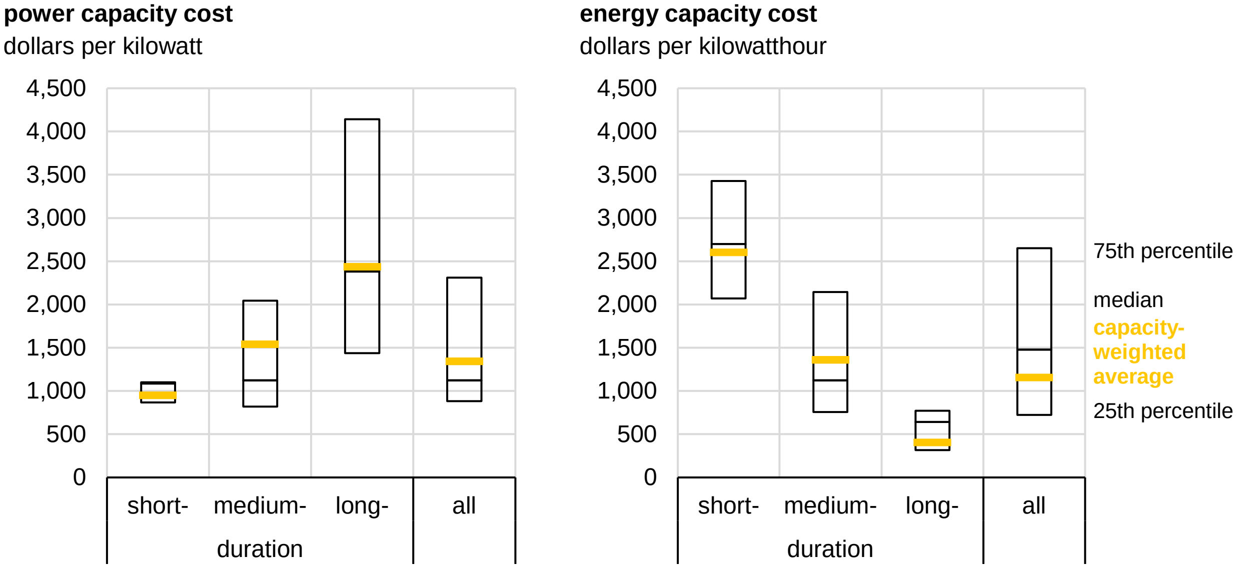
	short-duration <0.5 hours	**medium-duration** 0.5-2 hours	**long-duration** >2 hours
Number of battery systems reported	10	10	8
Average of nameplate power capacity, megawatts (MW)	13.0	13.8	2.7
Average of nameplate energy capacity, megawatthours (MWh)	4.7	15.6	16.7
Average of nameplate duration, hours	0.4	1.1	5.6
Capacity-weighted cost per unit power capacity, dollars per kilowatts ($/kW)	944	1,533	2,430
Capacity-weighted cost per unit energy capacity, dollars per kilowatthour ($/kWh)	2,597	1,352	399

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

Cost Results

As shown in Figure 8, battery systems with shorter durations will typically have lower normalized power capacity costs ($/kW) than batteries with longer nameplate durations. The opposite is generally true when examining normalized energy capacity costs ($/kWh), as the total system costs for longer-duration systems are spread out over a larger basis of stored energy. Nonetheless, the range of normalized cost values is driven by technological and site-specific requirements.

Figure 8. Total Installed Cost of Large-Scale Battery Storage Systems by Duration



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

Unlike non-storage technologies, battery storage can supply and consume energy at different times of the day, creating an unusual combination of cost and revenue streams that make direct comparisons to other generation technologies challenging. They are not stand-alone generation sources and must buy electricity supplied by other generators to recharge and cover the round-trip efficiency[13] losses experienced during cycles of charging and discharging.

There are two challenges. First, quantifying the competitiveness of a battery storage technology with other technologies operating on the grid therefore must consider the individual markets that the storage technology is planning to be used in and what revenue opportunities exist for the technology. Another challenge in determining the costs of battery storage systems involves the degradation of the system over time. Degradation is the lasting and continuous decrease in either or both a battery's power or energy performance linked to use or age of a battery component or system. Owners of battery storage systems typically contract for a certain level of performance at specified intervals in the battery system's lifetime. The performance can sometimes be characterized by the full cycle power input and output at an agreed-upon charge/discharge rate.

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[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.

Storage system operators can deliver the agreed-upon performance of the system over its lifetime in one of two ways:

- 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 later in its lifetime.
- Continual upgrades, replacing some portion of it to maintain the agreed-upon performance over its lifetime.

The two approaches to meeting performance requirements affect the installed capital costs of the system. The first approach will lead to a higher initial installed capital cost, while the second will lead to a higher operation and maintenance cost 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 necessarily 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

Outside of the capital costs presented in this section, trends in prices for battery storage can be observed in the negotiated price of electricity for projects that are financed through power purchase agreements (PPAs). PPAs are projects that are owned and operated by entities that supply electricity to a customer—typically an electric utility—at a fixed price per unit of electricity delivered. These prices are heavily influenced by each project's specifications, contract terms, and other localized factors. PPAs are different from capital costs and are not necessarily reflective of total capital costs of the system.

A few recent examples of PPA prices for projects that pair solar with battery storage systems include:

- In May 2017, SolarCity (a subsidiary of Tesla) partnered with the Kauai Island Utility Cooperative (KIUC) to install a 15 MW solar array paired with an 11 MW battery storage system. The project was financed using a 20-year PPA at a price of $139/MWh.[14]
- In early 2017, KIUC signed a PPA with AES corporation at $110/MWh to finance a 28 MW solar array paired with a 20 MW/100 MWh battery system that is slated to come online by the end of 2018.[15]
- In May 2017, NextEra Energy entered into a 20-year PPA with Tucson Electric Power to finance a 100 MW solar array paired with a 30 MW/120 MWh energy storage system—the agreed-upon price was $45/MWh.[16]
- In December 2017, Xcel Energy's Colorado utility subsidiary announced the results of a recent solicitation where the median bid price for solar-plus-storage projects was $36/MWh and the median bid price for wind-plus-storage projects was $21/MWh.[17]

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[14] Bloomberg, "Tesla Completes Hawaii Storage Project That Sells Solar at Night," March 8, 2017, https://www.bloomberg.com/news/articles/2017-03-08/tesla-completes-hawaii-storage-project-that-sells-solar-at-night.

[15] Utility Dive, "Hawaii co-op signs deal for solar+storage project at 11¢/kWh," January 10, 2017, https://www.utilitydive.com/news/hawaii-co-op-signs-deal-for-solarstorage-project-at-11kwh/433744/.

[16] Utility Dive, "Updated: Tucson Electric signs solar + storage PPA for 'less than 4.5¢/kWh'," May 23, 2017, https://www.utilitydive.com/news/updated-tucson-electric-signs-solar-storage-ppa-for-less-than-45kwh/443293/.

[17] Utility Dive, "Renewable plus storage bids in Xcel Colorado solicitation could set low-price benchmark," January 16, 2018, https://www.utilitydive.com/news/renewable-plus-storage-bids-in-xcel-colorado-solicitation-could-set-low-pri/514566/.

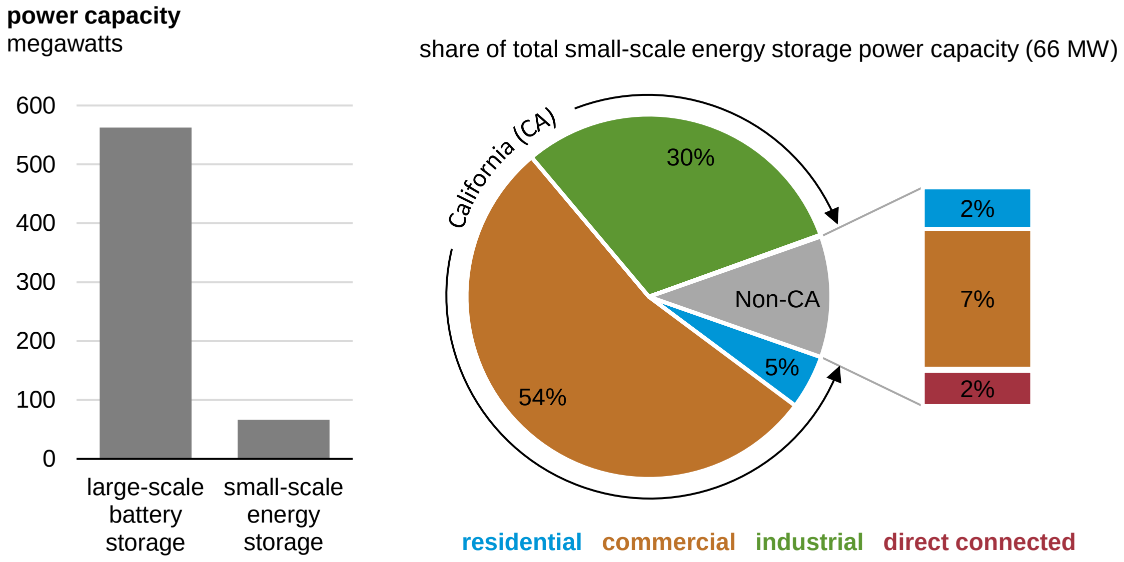
Small-Scale Energy Storage Trends

In 2016, U.S. utilities reported 66 MW of existing small-scale storage power capacity. More than 60% of this capacity was installed in the commercial sector, and 31% was installed in the industrial sector.

Small-Scale Energy Storage Trends in California

As shown in Figure 9, nearly 90% of reported small-scale storage power capacity in the United States is in California and, specifically, owned by four utilities: Southern California Edison (SCE), Pacific Gas and Electric (PGE), San Diego Gas and Electric (SDGE), and Sacramento Municipal Utility District (SMUD). Most installations of small-scale storage in the commercial sector in California are in SCE's and SDGE's territories, with 50% and 38% of such capacity, respectively. Most installations (71%) of small-scale storage in the industrial sector in California are in PGE's territory.

Figure 9. U.S. Small-Scale Energy Storage Capacity by Sector (2016)



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 are in front of the meter and/or connected directly to a distribution system.
Source: U.S. Energy Information Administration, Form EIA-861, *Annual Electric Power Industry Report*

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. SGIP provided rebates to 49 MW of storage through the end of 2016,[18] which is 83% of all reported small-scale storage power capacity in California. Installations receiving rebates through SGIP contribute to California's 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.

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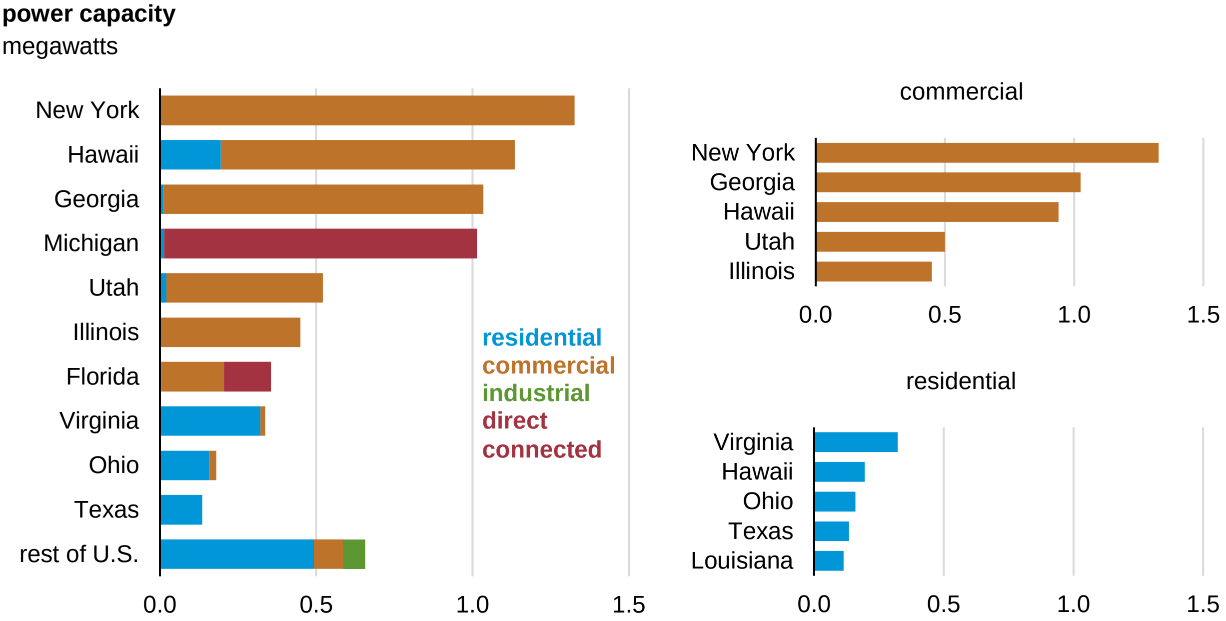
[18] Itron, *2018 SGIP Advanced Energy Storage Impact Evaluation* (Davis, CA: Itron, August 31, 2017), http://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=6442454964.

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

After California, the states with the most small-scale storage power capacity are New York, Hawaii, and Georgia, with most of this capacity installed in the commercial sector, as shown in Figure 10. Little small-scale storage power capacity in the industrial sector exists outside of California. In the residential sector, small-scale storage is available in other states, especially in Virginia, Hawaii, Ohio, Texas, and Louisiana.

Figure 10. U.S. Small-Scale Energy Storage Capacity Outside of California by Sector (2016)



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

Small-scale energy storage system ownership is typically discussed in terms of the end-use sector. Direct-connected storage systems are installations not located at an ultimate customer's site but rather in front of the meter and/or connected directly to a distribution system. In Michigan, DTE Electric Company is reporting the largest amount of direct-connected battery storage power capacity. They operate 21 community energy storage systems, which include 18 25-kW (50-kWh) storage units, a 500-kW battery storage device integrated with a 500-kW solar system, and two energy storage systems using repurposed electric vehicle batteries.[19]

The data collected for small-scale applications depend on the electric utility's access to information about installations in their 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 distribution utility may not have knowledge of those system installations. Utilities also 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.

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[19] DTE Energy, *DTE Energy Advanced Implementation of Energy Storage Technologies* (Detroit, MI: DTE Energy, 2015), https://www.smartgrid.gov/files/OE0000229_DTE_FinalRep_2016_03_16.pdf.

Market and Policy Drivers

As discussed previously, battery storage is physically 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 the 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/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 ISOs/RTOs have begun to carve a path for storage to participate in their markets.

A notable example is FERC Order 755, issued in 2011, which required ISO/RTO markets to provide compensation to resources having the ability to provide faster-ramping frequency regulation. As a result of Order 755, PJM split its frequency regulation market into two services: 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, PJM began observing operational issues in its frequency regulation market structure and has since changed its frequency regulation signals. Installations of large-scale battery storage in the region have plateaued since PJM made these changes.

Other system operators have 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 must revise its tariff to include market rules that recognize the physical and operational characteristics of electric storage resources.

State-Level Policy Actions

Other than FERC activities described in the previous section, to date federal policies involving energy storage have been limited[20] and most policy actions involving energy storage have been at the state level. State-level policy actions include setting procurement mandates, establishing incentives, and requiring incorporation of storage into long-term planning mechanisms.

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[20] One exception to this 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.

Policy Actions in California

To date, California has introduced the most 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.

More than 60% of the 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. In May 2016, to help address reliability risks due to constraints on natural gas supply, CPUC authorized the Southern California Edison electric utility to hold an expedited solicitation for energy storage. By December 2016, 62 MW of battery storage capacity was added to the system. CPUC also expedited ongoing procurement of 38 MW of battery storage by San Diego Gas and Electric[21], which was installed in early 2017.

Policy Actions in the Rest of the United States

As of May 2018, three states besides California have also set energy storage mandates or targets. In 2015, Oregon passed a law directing two electric utilities to each procure 5 MWh of storage energy capacity by 2020. In June 2017, the Massachusetts Department of Energy Resources set an energy storage target of 200 MWh by 2020. And, in January 2018, New York announced a target of 1.5 GW of energy storage by 2025. In addition, some states, such as Nevada, allow storage systems to be included in renewable portfolio standards. Aside from targets, some states have provided financial incentives for energy storage including grants, support for pilot projects, and tax incentives. In 2018, Maryland began to offer a tax credit of 30% on the installed costs for residential and commercial systems.

Many states require utilities to produce integrated resource plans 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 these plans can be a challenge because storage is different from conventional 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 a shifting landscape of policies and regulations 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[22].

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[21] 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

[22] 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/

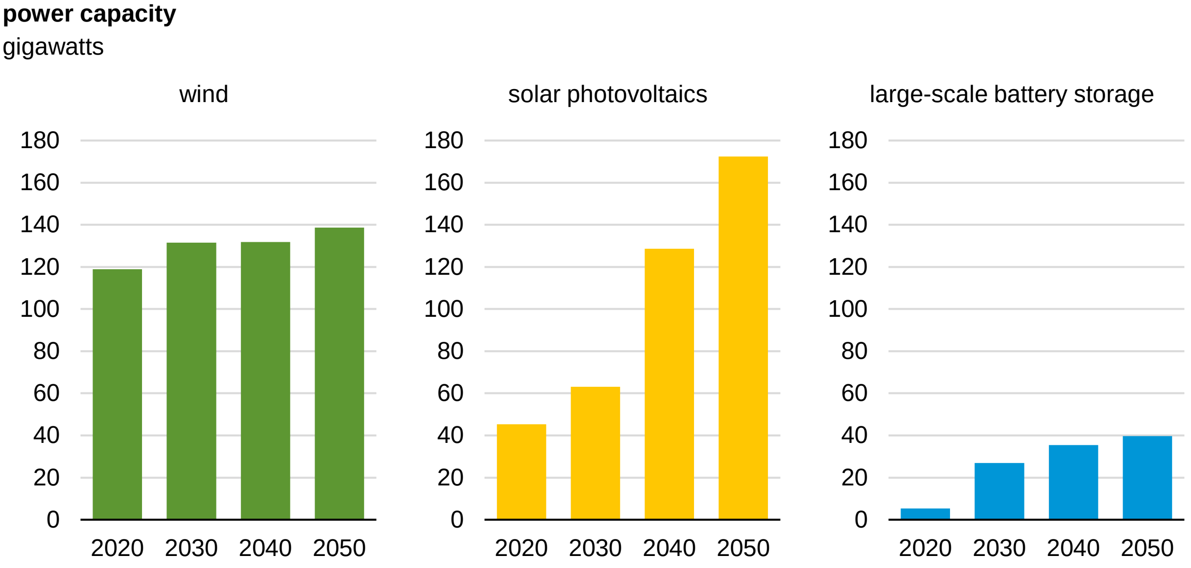
Future Trends

As of December 2017, project developers report to EIA that 239 MW of large-scale battery storage is expected to become operational in the United States between 2018 and 2021. Given the short planning period required to install a storage facility, the reported planned capacity does not necessarily reflect the entirety of builds over this period, but the estimates can be used as an indicator of trends.

California accounts for 77% of planned large-scale battery storage currently reported. In 2013, California set an 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. (See the section on market and policy drivers for more information.)

The *Annual Energy Outlook* (AEO), provides projections to 2050 on the supply and demand needs for energy markets in the United States. The 2018 AEO report was the first year to include operational or capacity projections of energy storage outside of pumped hydroelectric storage in the model results. The Reference case, which assumes implementation of current U.S. laws and policies, projects large-scale wind capacity growth of 50 gigawatts (GW) and large-scale solar photovoltaic capacity growth of nearly 150 GW by 2050. Over this same period, large-scale battery storage capacity is projected to grow to 40 GW, as shown Figure 11. In the longer term, wind and solar growth are projected to support economic opportunities for storage systems that can provide several hours of storage and enable renewable generation produced during the hours with high wind or solar output to supply electricity at times of peak electricity demand.

Figure 11. U.S. Large-Scale Wind, Solar, and Battery Storage Capacity Projections (2020–2050)



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2018*

Challenges exist when modeling energy storage technologies in long-term planning models. Because these models are designed to deliver multi-decade results, simplifications in the structure of the model often occur. One simplification that has significant consequences for the representation of energy storage technologies is the temporal resolution of the model. AEO2018 included energy storage as a 4-

hour battery system that can be utilized 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 for many long-term planning models. As a result, the AEO projections 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 an earlier section of this report.

EIA is collaborating with other modeling entities on a multi-model comparison[23] 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.

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[23] 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.

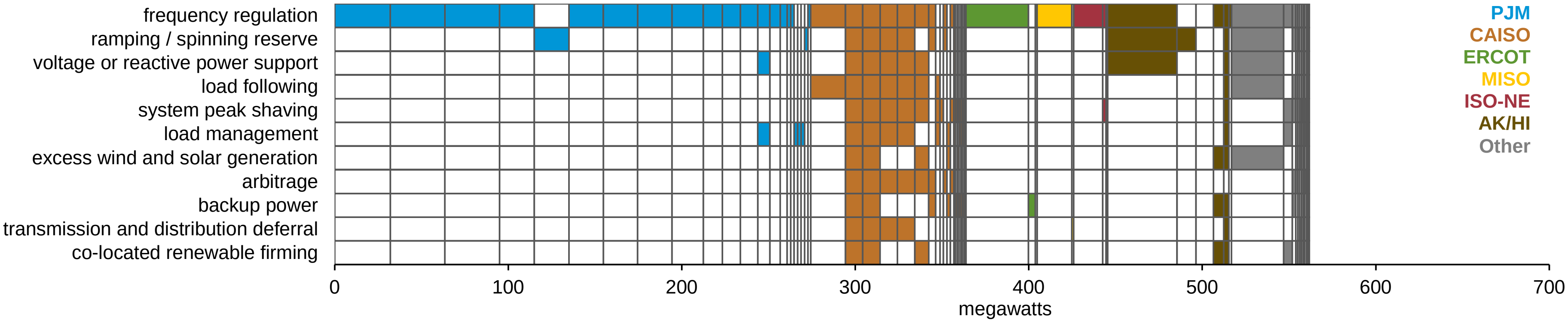
Appendix

Appendix A: Applications Additional Figures

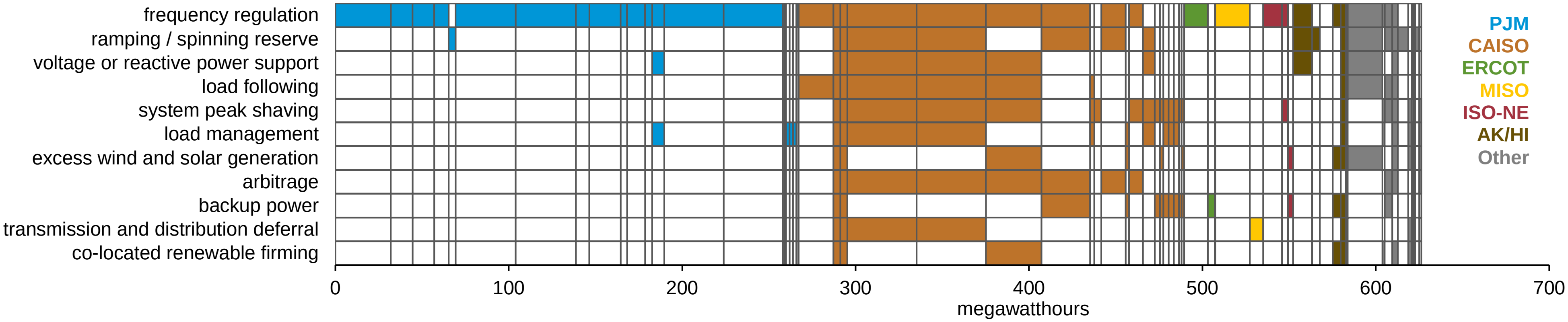
This appendix includes additional figures illustration the selected use cases for energy storage in the existing fleet.

Figure 12. Applications Served by U.S. Large-Scale Battery Storage (2016)

power capacity
megawatts



energy capacity
megawatthours

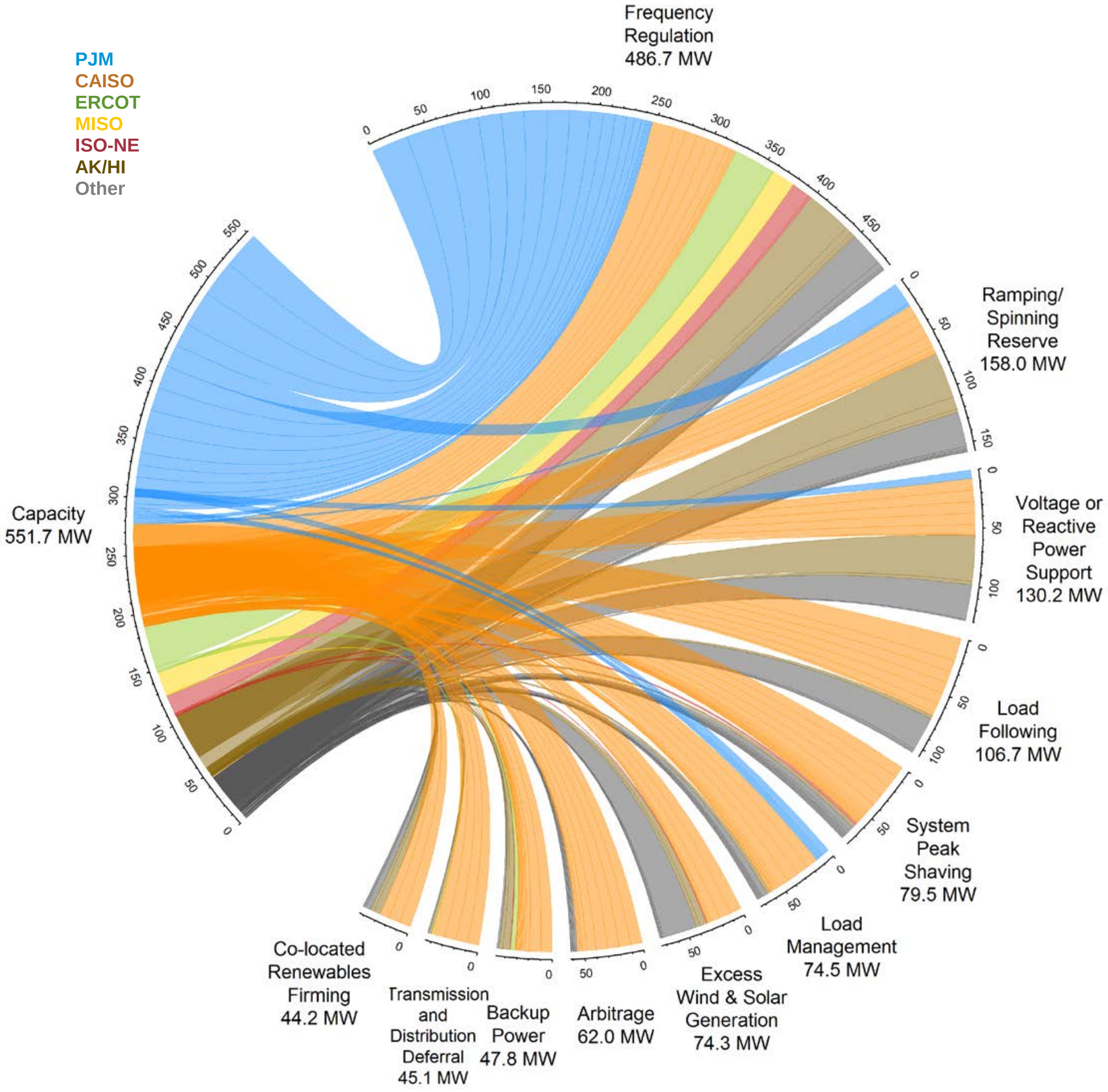


Note: Each column represents a single-battery installation, and filled boxes indicate which application(s) it served in 2016.
Source: U.S. Energy Information Administration, Form EIA-860, Annual Electric Generator Report

Figure 13. U.S. Large-Scale Battery Storage Capacity and Applications Served (2016)

power capacity

megawatts

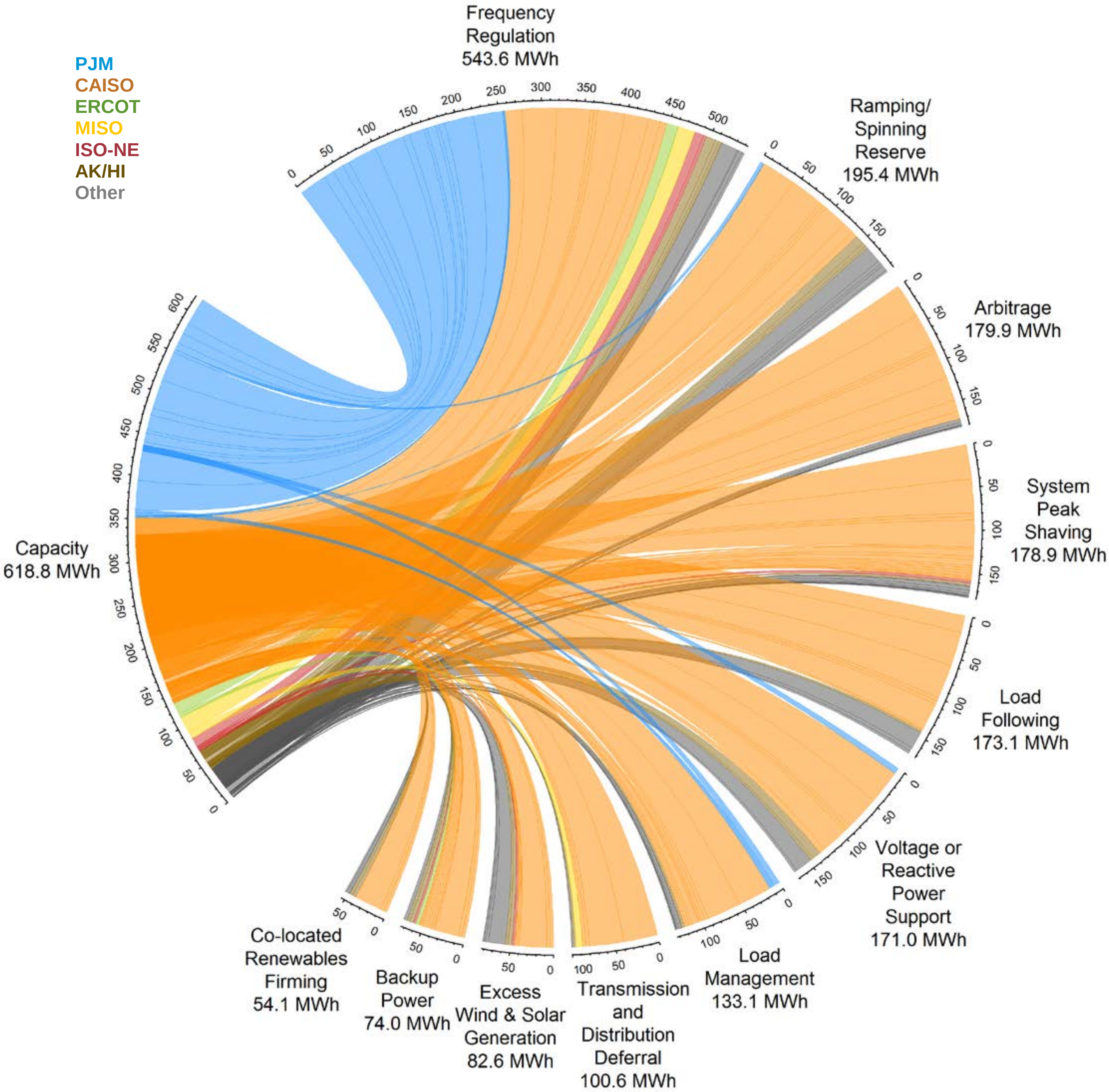


Note: The figure does not include a 10 MW/7.5 MWh battery storage unit located in Maui, Hawaii, which did not report any applications in 2016.

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

Figure 14. U.S. Large-Scale Battery Storage Capacity and Applications Served (2016)

energy capacity
megawatthours



Note: The figure does not include a 10 MW/7.5 MWh battery storage unit located in Maui, Hawaii, which did not report any applications in 2016.
Source: U.S. Energy Information Administration, Form EIA-860, *Annual Electric Generator Report*

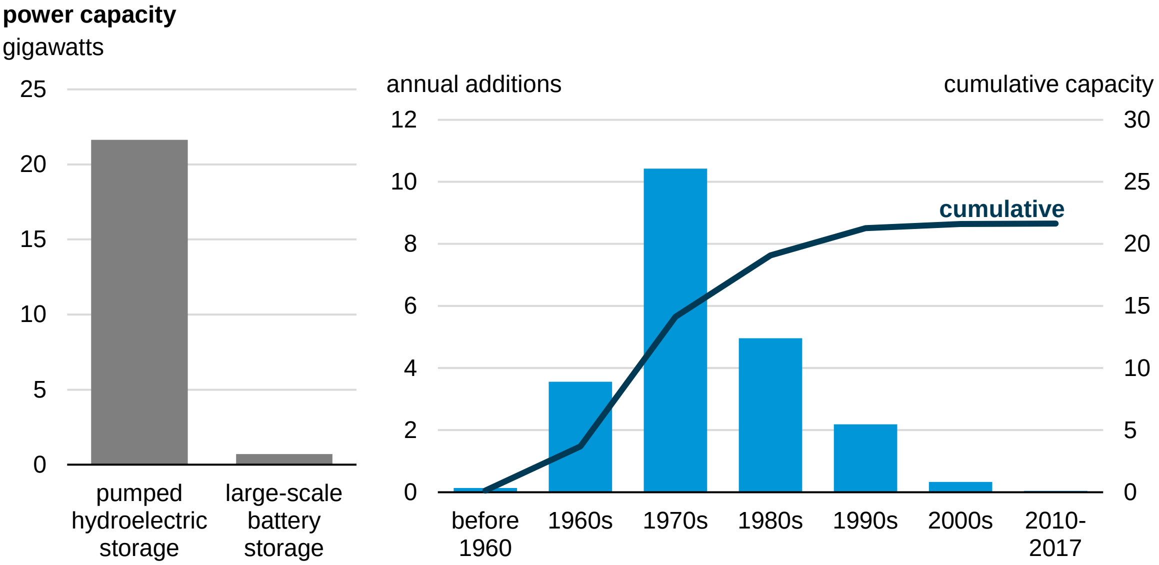
Appendix B: Other Storage Technologies

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).

To date, large-scale thermal storage has only been utilized in conjunction with solar thermal power plants. These systems take the excess energy produced during the day to heat salt or other materials that can be used later to power a steam turbine. Two large-scale solar thermal systems with storage are currently operating in the United States. The 280 MW Solana Generating Station in Arizona was installed in 2013, and the 125 MW Crescent Dunes facility in Nevada was installed in 2015. Thermal storage can also be utilized as a distributed energy resource, for example, by chilling water overnight to use for space cooling during summer days.

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. Figure 15 illustrates that, although the United States has significantly more operating hydroelectric pumped storage than battery storage, most of it was installed in the 1970s and early 1980s. California, Virginia, and South Carolina account for the largest shares of existing U.S. hydroelectric pumped storage capacity. The largest single facility in the United States was installed in 1985 in Bath County, VA and has a capacity of 3 GW.

Figure 15. U.S. Hydroelectric Pumped Storage Capacity (1960–2017)



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

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 flywheel system, the 20 MW Energy Nuevo Storage Farm, is expected to be installed in California in 2020.

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 2020.

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