MSCE Energy Infrastructure Energy Storage Brief

MSCE Energy Infrastructure Brief on Utility-Scale Energy Storage

Topics

- Types of Energy Storage
- Electrical Services Provided by Energy Storage
- Pumped Storage Hydropower
- Lithium-ion Batteries
- Useful Websites

Types of Energy Storage

There are four main types of energy storage. Electrochemical storage primarily in batteries, mechanical storage of potential or kinetic energy primarily pumped-storage hydro but also flywheels for rapid regulation of voltage and frequency, thermal storage using lenses to concentrate sunlight to heat a fluid to produce steam, and chemical storage by creating hydrogen primarily through electrolysis of water. The table below summarizes the main U.S. storage systems in 2022. Most of the largest systems use electricity from the power grid as their charging source. However, in recent years many battery storage systems are directly coupled to renewable energy facilities that are also used as a charging source. Gross generation is the amount of energy supplied by the storage system and net generation is gross generation minus both the electricity used to recharge the storage system and the electricity consumed to operate the storage system itself.

U.S. utility-scale energy storage systems for electricity generation, 2022

Storage system	Number of plants and of generators	Power capacity MW	Energy capacity MWh	Gross generation MWh	Net generation MWh
pumped-storage hydro	40–152	22,008	NA	22,459,700	-6,033,905
batteries	403–429	8,842	11,105	2,913,805	-539,294
solar-thermal	2–3	405	NA	NA	NA
compressed-air	1–2	110	110h	NA	57
flywheels	4–5	47	17	NA	0

Data source: U.S. Energy Information Administration, *Preliminary Monthly Electric Generator Inventory* (Form EIA-860m) and *Power Plant Operations Report* (Form EIA-923), February 2023
Note: Includes facilities with at least 1 megawatt (MW) of total nameplate capacity operational at end of 2022; MWh is megawatthours; NA is not available.

Energy storage for electricity generation - U.S. Energy Information Administration (EIA)

The largest storage system in the U.S. in terms of gross electrical generation is based on mechanical storage, namely pumped storage, i.e., pumping water from a lower reservoir located at the power house to an elevated reservoir connected to the powerhouse. The fastest growing storage system is electrochemical storage, specifically the use of batteries to directly store electricity for later use. Other storage systems, namely mechanical storage of potential energy as compressed air in underground caverns and storage of focused sunlight into a thermal reservoir, are less prevalent.

Chemical storage of hydrogen is an evolving technology. In this brief, we will primarily focus on batteries and on pumped storage hydropower (PSH) storage systems.

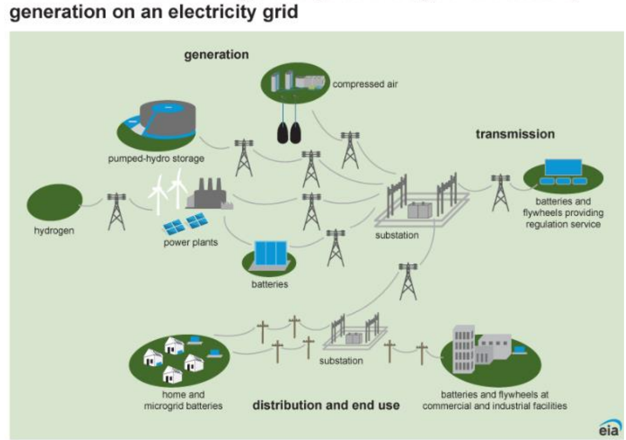
Electrical Services Provided by Energy Storage

The major services provided by energy storage systems are briefly discussed below. More detailed information can be found at [Electricity storage technologies can be used for energy management and power quality - U.S. Energy Information Administration (EIA)](). There is a distinction between power storage systems and energy storage systems. Power systems focus on short-term storage operating from fractions of a second to a few minutes. Energy storage systems focus on longer-term storage operating on the time scale of hours.

- *Balancing power generation and power consumption*. Power generators are synchronously connected to the grid. However, an excess of generated power relative to demand leads to an increase in the power generator's rotational speed and an increase in the AC frequency of the electricity. A decrease in generated power relative to demand leads to a decrease in AC frequency. The voltage also needs to remain constant. These changes occur on short timescales requiring rapid-response technologies from flywheels and capacitors to smaller capacity battery systems.
- *Peak electricity energy demand shaving*. Storing electricity during low demand periods and discharging electricity during high demand periods can help to flatten out daily load shapes. This is especially true for battery storage systems at intermittent solar and wind energy resources. This storage operates over time periods of an hour or more and can include pumped storage hydro systems as well as batteries.
- *Reducing end*-user *energy demand and demand charges*. Commercial and industrial users can use onsite storage systems to reduce electricity demand from the grid. The associated demand charges are usually based on their highest electricity consumption during peak demand periods.
- *Back-up energy storage*. Consumer-owned storage systems can provide electricity during electricity outages.

This figure illustrates the general locations of several energy and power storage systems on an electricity grid. Batteries are located all across the electrical grid, ranging from power generation sites to transmission substations and end user management systems.

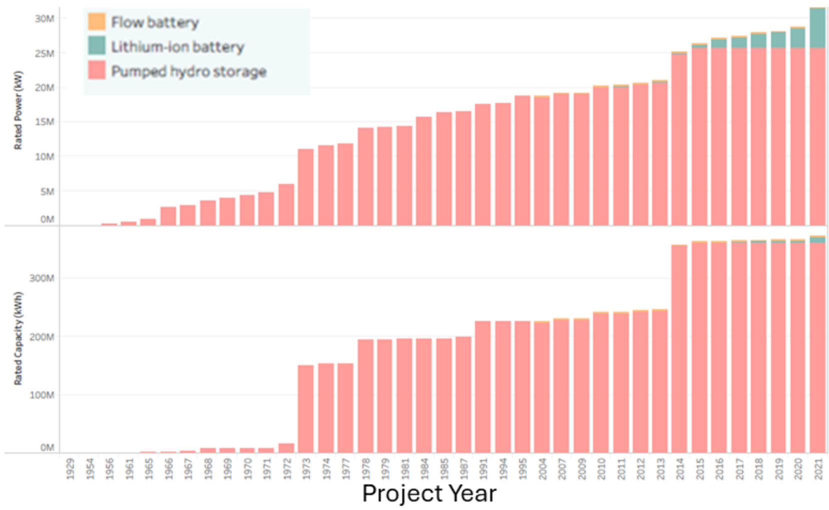
General locations of energy storage technologies for electricity generation on an electricity grid



Source: U.S. Energy Information Administration
Note: Hydrogen, and batteries at homes, neighborhoods, and at commerical and industrial facilities are presented here as potential energy storage technologies to supply electricity to electric power grids.

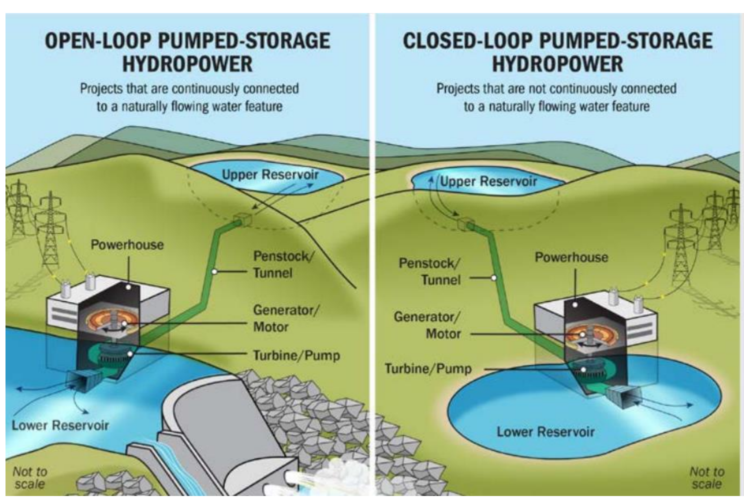
Pumped Storage Hydropower (PSH)

As discussed earlier, PSH is the major electrical energy storage technology in the U.S. in terms of total energy and power storage capacity. This is clearly shown in the figure below depicting the cumulative sum of energy and power storage installations by year and technology. It is only in recent years that batteries have begun to make a noticeable contribution. Battery storage is discussed in the next section.

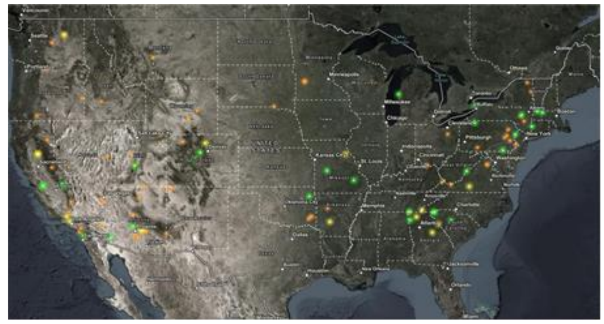


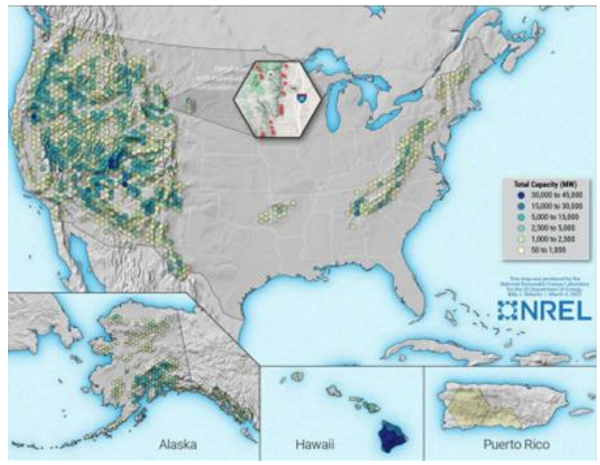
DOE Global Energy Storage Database (sandia.gov)

The figure below illustrates the general concept of open-loop and closed-loop PSH (2019-2020 Water Power Technologies Office Accomplishments (energy.gov)). All utility scale systems in the U.S. are open loop, although closed loop systems are gaining increased interest due to their potentially smaller environmental impacts on river systems.



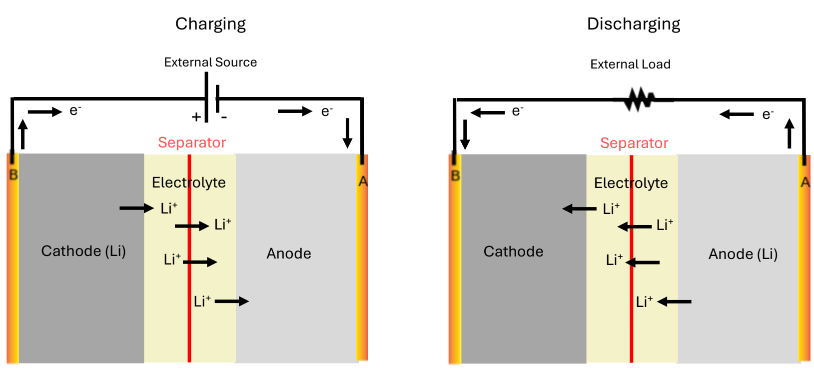
The top figure shows the locations of existing open-loop PSH facilities either as part of a conventional hydropower dam (yellow dots) or as an independent system (green dots). The orange dots represent planned PSH facilities based on information from Oak Ridge National Laboratory (Pumped Storage Hydropower Policy and Market Tool (arcgis.com)). The bottom figure shows the location of *potential* closed-loop PSH sites by total capacity according to an evaluation by the National Renewable Energy Laboratory (Closed-Loop Pumped Storage Hydropower Resource Assessment for the United States. Final Report on HydroWIRES Project D1: Improving Hydropower and PSH Representations in Capacity Expansion Models (nrel.gov)). Because closed-loop systems are not connected to continuously flowing water, they have greater siting options than open-loop systems.





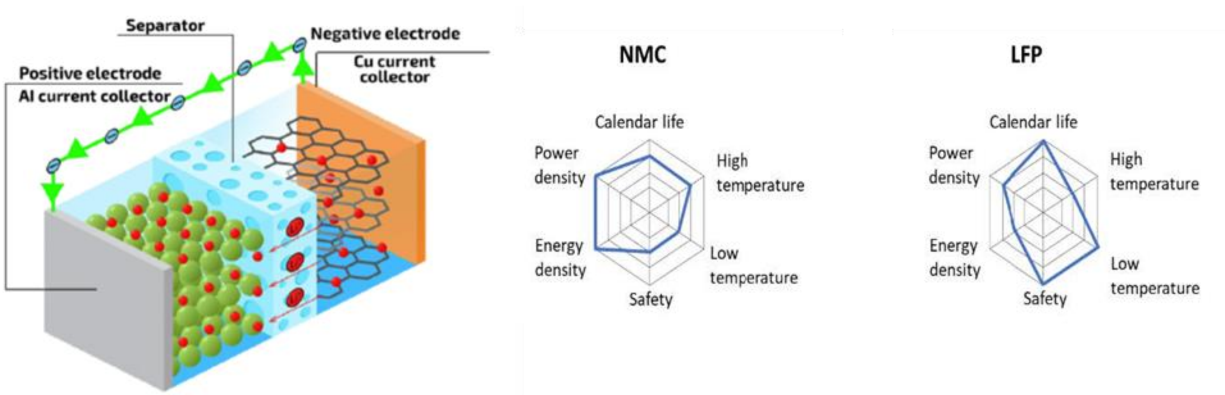
Lithium-ion Batteries

The figure below shows the basic elements of a lithium-ion battery including the positively charged cathode, the negatively charged anode, and the liquid electrolyte that is between them. The electrolyte solution contains a lithium salt dissolved in an organic solvent. The porous separator keeps the anode and cathode from directly contacting each other while also allowing the lithium ions that are dissolved in the electrolyte solution to pass through in one direction or the other depending on whether the battery is charging or discharging.



A: negatively charged copper current collector
B: positively charged aluminum current collector

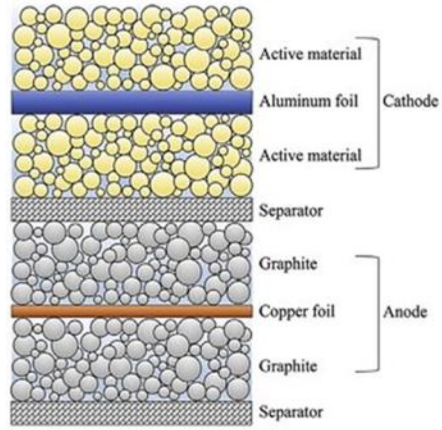
The figure below depicts a lithium-ion battery unit in its discharge mode. The negative anode typically consists of graphitic carbon (black hexagon structure) connected to a copper current collector. The positive cathode consists of a metallic compound (green dots) connected to an aluminum current collector that allows lithium ions (red dots) to be either captured or released depending on charging or discharging mode. The porous separator is also shown and typically consists of a porous plastic structure. The metallic cathode compound usually is used to describe the battery. The most common cathodes in current use in utility scale batteries are composed of either nickel, manganese and cobalt in various combinations with lithium (NMC batteries) or composed of lithium iron phosphate (LFP batteries). The general characteristics of both battery types are also summarized in the figure. NMC batteries have high energy density (typically ~300 watt-hours per kilogram) compared to LFP batteries with lower energy density (~160 Wh/kg). However, LFP batteries have a longer calendar life before replacement, perform better at low environmental temperatures, and are less prone to catching fire.



DOE ESHB Chapter 3: Lithium-Ion Batteries (sandia.gov)

To improve the above battery characteristics, active research has focused on replacing the liquid electrolyte with either a gel electrolyte (semisolid-state battery) or a solid electrolyte (solid-state battery). In both cases, this results in both a higher electrical conductivity of the lithium ions passing through the electrolyte and improved safety due to greatly increased fire safety and more rapid charging rates. The semi-solid battery is seen as a bridge technology as they can be manufactured on conventional battery technology production lines while the solid-state battery manufacturing technologies are being developed. The semi-solid LFP battery has a reported operating energy density of 260 Wh/kg. It has already been deployed in utility-scale storage facilities (World's first grid-scale, semi-solid-state energy storage project goes online – pv magazine International (pv-magazine.com)).

During manufacturing, the positive and negative electrodes and separator are separately pressed into thin films along with metal foil current collectors to form the basic battery unit (see figure). The units are then layered together and enclosed in a sealed container that also contains the electrolyte to form a battery cell. Cell geometry can either be cylindrical or rectangular. The cells are then combined in series to form modules that are electrically connected and placed in a hard, rectangular case to protect against excess heating and vibration. The number of cells in parallel and series used to create a module depends on a specific manufacturer's design. Due to their geometry, rectangular cells (referred to as prismatic cells) can pack more electrolytes into their volume than cylindrical cells. The modules are then connected in series to form a battery pack of the desired voltage, and these packs are connected in parallel for the desired energy and power ratings. The connected packs are typically placed in large storage containers for further protection against the elements as shown in the figure.



www.researchgate.net/figure/a-Repeatable-unit-RVE-of-a-lithium-ion-battery-and-cross-sections-of-the-components_fig1_322199599

Energy Storage Manufacturing Analysis | Advanced Manufacturing Research | NREL

Useful Websites

- Department of Energy Electrical Energy Storage Program DOE Office of Electricity Energy Storage Program – Sandia National Laboratories
- U.S. DOE Energy Storage Handbook U.S. DOE Energy Storage Handbook – DOE Office of Electricity Energy Storage Program (sandia.gov)
- Cost Projections for Utility-Scale Battery Storage: 2023 Update Cost Projections for Utility-Scale Battery Storage: 2023 Update (nrel.gov)
- Long-duration Storage Technology Strategy Assessments Storage Innovations 2030 | Department of Energy
- QuEST: An open-source platform for Energy Storage Analytics QuESt 2.0 – Open-source platform for Energy Storage Analytics – DOE Office of Electricity Energy Storage Program (sandia.gov)
- UW MSCE Energy Infrastructure, https://www.energy-infrastructure.uw.edu/