# Science Module: Energy Storage

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ENERGY INITIATIVE

#### WHAT IT DOES

Energy storage systems have the potential to solve many of the problems that plague the electrical grid. Producers of conventional energy sources (e.g., fossil fuels, nuclear, etc.) have to predict how much electricity to produce on any given day in order to meet consumer demand and produce a reliable grid. This means that if demand is less or more than the amount generated, there could be issues caused by too much (e.g., grid instabilities or damage to end-user electronics) or too little electricity (e.g., brownouts and blackouts). Energy storage systems can be used for ancillary services such as frequency regulation to solve issues caused by over-generation of electricity. They can also be used to store excess electricity produced during periods of lower demand and provide electricity to meet consumer needs during higher demand hours or support the grid during periods of too little energy generation.

#### BACKGROUND

While traditional grid technologies rely on the generate-and-distribute model, energy storage systems are a method to convert generated electricity into stored energy for use at a later time. Consequently, energy storage systems are ideal partners for renewable energy sources that tend to be intermittent, such as solar and wind power. For example, energy storage paired with solar power systems can store the excess electricity produced during the middle of the day and release the collected electricity during peak demand hours in the evening. This process is known as time-shifting and is a solution to the so-called "duck curve," or how solar production drops off in the evening at the same time that consumers demand more electricity as they come home from work. The coupling of solar or wind plus energy storage has made these systems price competitive with traditional power plants in recent utility bids, such as the development of an Xcel Energy solicitation for combined solar/wind and storage project bids in Colorado.

A wide variety of technologies are being explored and used for energy storage today. The two most adopted technologies are gravitational and electrochemical systems. Each of these methods have been successfully deployed for large (utility) and small (residential) scale operations. Various other technologies, which will be discussed in a later science module and are outlined in Table 1 below, are in the development phase. These include compressed air energy storage, thermal energy storage, and mechanical (flywheel) systems.

| Energy storage type | Specific technologies |
|---|---|
| Gravitational | Pumped hydroelectric, solid mass |
| Electrochemical | Batteries (lead-acid, Na-S, NiCd, Li-ion), flow batteries, capacitors |
| Compressed air | Compressed air energy storage, cryogenic air storage |
| Mechanical | Flywheel systems |
| Thermal | Molten salt, slush tanks, Native earth/bedrock, Eutectic metals, phase-change materials |

*Table 1. Energy storage systems*

## History of Adoption and Policy

Pumped-storage hydropower (PSH) systems have been in use in the United States for nearly a century, providing a method to meet peak demand needs and regulate the frequency of the electricity grid. In contrast, battery energy storage systems have only been integrated over the past 20 years, as shown in Figure 1. The first battery systems were based on lead-acid batteries, with the more recent systems adopting lithium-ion (Li-ion) batteries as the material of choice.

*Figure 1. Energy storage installations in US, 1929-2018. Source: Department of Energy Global Energy Storage Database*

While the technology exists to deploy energy storage systems on a wider scale, there have been both economic and policy roadblocks that have inhibited this deployment. As energy storage systems can provide a variety of services, from frequency regulation to peak-load support, it can be difficult to define a market and craft regulations that capture that flexibility. This undefined market and regulatory landscape creates risk for potential developers and has limited the overall growth of the energy storage system industry.

Over the past twenty years, there have been several developments that have and will likely continue to grow the energy storage industry. One such development is the expansion of the Department of Energy's (DOE) research thrust into energy storage systems. In 1996, the small Utility Battery Storage program was expanded at Sandia National Laboratories into the fully-fledged Energy Storage Systems research program. This program has supported industry and academic research to further the competitiveness of energy storage systems at the utility scale.

On the policy side, the Federal Energy Regulatory Commission (FERC) has passed several orders that have increased the adoption of energy storage systems. In particular, Orders No. 1000 and No. 755, both passed in 2011, have been influential in the implementation of energy storage technologies. Orders No. 1000 mandated the need for more efficient electricity transmission systems and Order No. 755 improved the compensation system for services other than power generation. Additionally, the 2009 American Recovery and Reinvestment Act (ARRA) extended federal government funding to develop new energy storage technologies – particularly batteries – which was a driving force for the adoption of Li-ion batteries in new battery-based energy storage systems. Most recently, in February of 2018, FERC passed a ruling that will likely change market rules to increase the involvement of energy storage systems in wholesale electricity markets.

**RELEVANT SCIENCE**

## Gravitational Energy Storage Systems

Gravitational energy storage systems are relatively simple: electricity is used to move a mass (liquid or solid) to a higher elevation to store that electricity as gravitational potential energy. That mass may then be allowed to fall back down and turn a turbine, generating electricity. The pumped-storage hydropower (PSH) system is the most common gravitational energy storage system in use today. A schematic of this system is shown in Figure 2. While the schematic implies that the reservoirs are closed systems, PSH plants are typically open-loop, or use partially natural formations as reservoirs.

*Figure 2. Schematic of a pumped hydroelectric storage system. Source: Department of Energy (adapted)*

In a PSH system, water is pumped from a lower reservoir to an upper reservoir during periods of low electricity demand, and the water falls back to the lower reservoir through electricity-generating turbines to provide power during high-demand hours. These systems can provide utility-scale power, have high (greater than 80%) round trip (electricity in to electricity out) efficiencies, and power can be extracted from PSH systems relatively quickly. These advantages, combined with the mature technology of water pumps and turbines, have contributed to the use of PSH systems across the country over the past 100 years. The largest PSH system in the world, the Bath County Pumped Storage Station, is located in Virginia. The station has a 3 GW power capacity (comparable to large traditional coal-fired power plants) and has been operational since 1985.

While PSH systems are a widespread technology, there are several disadvantages that must be noted. In particular, these stations typically require the damming of a natural water source to create a reservoir. The creation of a reservoir can cause drastic changes in the surrounding area and can impact or displace the population of the area. Constant raising and lowering of water levels may also cause erosion and generate silt, both of which can have negative ecological consequences.

## Electrochemical Energy Storage Systems

In electrochemical energy storage systems such as batteries and electrochemical capacitors, electricity (or electrical energy) is converted to and stored as chemical energy without the need for any mechanical movement. Batteries and electrochemical capacitors have the same basic design: two electrodes (or electrical contacts) separated by an electrolyte, which allows for the movement of charged atoms (or ions) but not electrical current. Within electrochemical energy storage systems, batteries have become the dominant technology. Lithium ion (Li-ion) batteries are used in most battery-based energy storage systems today, and have applications both on small microgrid systems and full utility-scale systems. A schematic of the operational mechanism of Li-ion batteries is shown in Figure 3.

*Figure 3. Diagram of lithium ion battery discharge and charge cycles. Source: Department of Energy (adapted)*

As shown in the diagram, during the charging process of a Li-ion battery, lithium ions are transferred from the positive electrode (cathode) to the negative electrode (anode) where they each pick up an electron that is supplied by the external electrical current. This external current is either the excess electricity produced by the electrical grid or from a connected renewable energy source, such as a solar panel or wind turbine. During the discharge cycle, lithium ions can then be split from the electrons and transferred back across the electrolyte from the anode to the cathode, converting the stored chemical energy back to electrical energy.

Generally, electrochemical energy storage systems are implemented for uses other than utility-scale bulk energy storage, namely for ancillary services such as frequency regulation. Electricity is typically transmitted in its alternating current (AC) form at a specific and tightly controlled frequency (60 Hz in the US). However, the frequency of the current can change during the transit between the power plant and the end-user, therefore, frequency regulation services are necessary to govern the alternating current. As batteries can be rapidly discharged (i.e., in seconds to minutes), they can respond to voltage and frequency variations in the electrical grid which, without the battery support, could lead to grid instabilities.

Batteries have a much shorter overall lifetime and significantly lower energy density (amount of energy produced per weight) than other energy storage systems. The shortened lifetime of batteries is due to degradation of the electrolyte and electrodes. As energy storage systems are long-term projects that compete with traditional power generation sources, the limited lifetime of batteries and the lower energy density may pose significant hurdles to the further development of battery-based energy storage systems past ancillary service applications.

Although battery-based energy storage systems are not ideal, there have been many successful examples of both small and large-scale projects. In San Francisco, JP Morgan has installed 500 kW of Tesla-produced Li-ion batteries to create a microgrid, providing clean energy storage and lowering dependence on the grid for the One Maritime Plaza building. The Notrees Battery Storage Project in Texas – an addition made to the Notrees Wind Power project in 2013 – is composed of a 36 MW Li-ion energy storage system, which is used to store excess energy produced by the 153 MW wind power plant during low demand hours and then distribute that energy during high demand hours.

## Future of Energy Storage Systems

One of the most recent developments in energy storage systems is hydrogen energy storage. In this kind of system, electrical energy is used to split water into oxygen and hydrogen by electrolysis. The hydrogen can be stored in pressurized or temperature-controlled vessels (small-scale) or in underground salt caverns (utility-scale). That hydrogen can then be converted back to electricity in fuel cells or by being burnt in a more traditional power plant. While the use of hydrogen for grid-scale energy storage is still in the research and development phase, there is a growing interest in hydrogen energy storage systems as they have a much higher energy storage capacity than batteries on the small-scale and pumped-storage hydropower on the utility scale.

There are multiple reasons to be hopeful for the future prospects of energy storage systems. From the policy perspective, the recent FERC ruling to establish markets for energy storage systems will remove some of the economic ambiguity and risk associated with the development of energy storage projects. The establishment of defined markets for energy storage systems should promote the inclusion of energy storage in electrical grids across the country. On the technology side, projections by the Energy Storage Association, a trade organization, and GTMResearch, an energy market research group, show that the amount of deployed energy storage will increase eightfold over the next four years and will be a $3 billion industry by 2022. The advantages and benefits to the electrical grid provided by energy storage will continue to increase the deployment of both small and large-scale energy storage systems in the future.

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**ENERGY SUBCATEGORY**

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**RECOMMENDED CITATION**

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