Chapter 9

Energy storage

Energy storage, the capture of energy produced at one time for use at a later time, is not a new concept. Without understanding the details, man has long understood that when wood is burned, something stored within the wood changes and heat is released. In more modern times the need for storage to steady the output from a variable energy source such as wind was widely recognized. Since the discovery of electricity generation by Michael Faraday in 1820 people have sought ways to store that energy for use on demand. Without such storage, or use in some other way (e.g., to heat water, bricks, or phase change materials that store heat, refrigerate water to create ice, or electrolyze water to create and store hydrogen), the energy delivered by electricity is lost.

9.1 STORAGE AND GRIDS

Today, with modern societies increasingly dependent on energy services delivered by electricity, the need for electric energy

The chapter is from the book *Water, Energy, and Environment: A Primer*, Allan R. Hoffman (Author).
doi: 10.2166/9781780409658_0151

storage technologies has become critical. Try to imagine life without your mobile telephone or computer. The Energy Storage Association, a national trade association for the energy storage industry, describes its importance as follows: 'Energy storage fundamentally improves the way we generate, deliver, and consume electricity. Energy storage helps during emergencies like power outages from storms, equipment failures, accidents or even terrorist attacks. But the game-changing nature of energy storage is its ability to balance power supply and demand instantaneously – within milliseconds – which makes power networks more resilient, efficient, and cleaner than ever before.' The Smart Electric Power Alliance is even more concise: 'The role of energy storage can be summed up in two words: grid empowerment.'

Because electric grids must balance supply and demand, and because demand is highly variable and hard to control, the balancing is achieved routinely by controlling the output of electricity generators. If these generators are variable, for example, solar and wind, and their grid contributions become significant, achieving the balance is more difficult, and a means of compensating for these variations is needed. This is one important role that storage plays.

9.2 TYPES OF STORAGE

Energy storage comes in many different forms and can provide short or long-term storage. The different forms can be divided into seven broad categories (58):

- Traditional and Advanced Batteries: a range of electrochemical storage devices, including advanced chemistry batteries and capacitors
- Flow Batteries: batteries where the energy is stored directly in the electrolyte solution for longer cycle life and quicker response times

- Flywheels: mechanical devices that use rotational energy to store and deliver electricity
- Superconducting Magnetic Energy Storage: energy is stored in persistent magnetic fields
- Compressed Air Energy Storage: uses compressed air to create an energy reserve
- Pumped Storage Hydropower: uses water stored at an elevated height to create an energy reserve
- Thermal Storage: capturing heat and cold to create energy on demand

9.2.1 Traditional and advanced batteries

Traditional batteries are those that have been in use for many years – for example, lead–acid batteries, which are still the dominant battery storage technology today.

9.2.1.1 Lead–acid

They are widely used in cars, trucks and many other applications because of their low cost, high power (power per unit volume), and high reliability.

Disadvantages are low energy density (stored energy per unit volume), large size and weight, and the need for an acid electrolyte. Lead (Pb) is also a toxic material when inhaled or ingested. Research to improve lead–acid batteries has been underway for more than a century, and considerable progress has been made – for example, lead–acid batteries that require no maintenance, and widespread recycling of used batteries to recover the Pb electrodes. Further progress is anticipated.

9.2.1.2 Sodium sulfur

Sodium sulfur batteries, which operate at high temperatures (300–350°C) use molten sulfur as the positive electrode and molten sodium as the negative electrode.

They are separated by a solid ceramic barrier that serves as the electrolyte. It was developed in the 1960s by the Ford Motor Company and subsequently sold to the Japanese company NGK. It has now been widely demonstrated in Japan, and more than 270 MW of peak shaving capacity has been installed. US utilities are beginning to explore the technology for peak shaving, backup power, firming up intermittent wind power, and other applications.

9.2.1.3 Nickel–cadmium

Nickel–cadmium (Ni–cad) batteries have been in commercial production since 1910. They are a traditional battery type that, while not known for high energy density or low first cost, provides a simple-to-manage, long-lived and reliable electricity storage option. For many years, in small battery form, they were a primary electricity source for mobile devices.

9.2.1.4 Lithium-ion

Most battery attention today is focused on a relatively new development, lithium-ion (Li-ion) batteries. They were first developed in Japan and released to the market in 1991. Initial applications were in consumer markets, but today many companies are examining the use of large collections of Li-ion battery cells for use in other energy storage applications. These include their use in passenger electric vehicles (3–3.5 miles of travel per kWh of stored energy), residential and business storage of solar-generated electricity, and multi-megawatt containerized batteries for utility applications.

Li-ion batteries are widely used today because they have high energy density: ‘pound for pound they’re some of the most energetic rechargeable batteries available.’ For example, it takes six kilograms of lead–acid battery to store the same energy as one kilogram of Li-ion battery. They also hold their charge well (today’s Li-ion batteries lose about 5% per month), have no memory effect (removing the need to fully discharge the battery before recharging), can handle hundreds to thousands of charge–recharge cycles, and have good round-trip electrical efficiency.

Li-ion batteries do have a downside: they are sensitive to heat, can't be fully discharged, are still costly (although costs are coming down rapidly), and battery cells with certain chemical formulations can occasionally burst into flame if damaged or otherwise overstressed. The term 'lithium-ion' refers not to a single chemistry but to a number of chemical combinations where lithium ions are transferred between the electrodes during the charge–discharge cycles. The lithium ions are derived from electrode materials that contain lithium compounds, and different compounds present different cell voltages, energy densities, lifetime, and safety characteristics. Battery management systems are required – Li-ion batteries lack the ability to dissipate overcharge energy – and safety characteristics are a function of system design and control algorithms, regardless of battery cell chemistry.

9.2.1.5 Supercapacitors

Supercapacitors, also a relatively new battery technology, store energy in electric fields created by stored electric charge. They fill a gap between ordinary capacitors and rechargeable batteries. Because the charge is stored physically, with no chemical or phase change occurring, the charge–discharge processes are fast and highly reversible.

They can be repeated over and over again, with virtually no limit, at high round-trip efficiency. Depending on the design, supercapacitors (also called ultracapacitors) can have reasonably high energy densities and can deliver quick bursts of energy during peak power demands. Because of these characteristics they are now widely used as low-current power sources for computer memories, medical devices, and in cars, buses, trains, cranes and elevators, including energy recovery from braking. As a result, the number of market applications and manufacturers is growing steadily.

9.2.2 Flow batteries

Flow batteries are large-scale rechargeable energy storage systems where rechargeability is provided by chemical compounds dissolved in liquids which, when mixed together, generate electricity.

A major advantage of flow batteries is that they can be recharged quickly by replacing the electrolyte liquid while allowing recovery of the active chemical components in the used electrolyte. By storing energy in the electrolyte fluid they differ from conventional batteries, in which energy is stored as electrode material.

Redox (reduction/oxidation) flow batteries are particularly well suited to storing large amounts of energy – for example, the surplus energy created by solar or wind power generation – and are on the verge of wide application in the electric utility industry. The energy storage materials are liquids that are stored in separate tanks, and when energy is needed the liquids are pumped through a 'stack' where they interact to generate electricity. Many different chemical liquids have been tested for flow battery operation, with most current attention being focused on vanadium compounds. Disadvantages are that flow batteries have relatively low round-trip efficiencies, long response times, and the ratio of power to energy is fixed at the design stage. Because of vanadium cost concerns other chemical possibilities are being examined, for example, zinc–bromine, zinc–chlorine, and iron–chromium.

An important flexibility in the design of flow batteries is that the energy storage capability, that is, the size of the storage tanks, can be tailored to the need of the particular application. They are well suited for a broad range of applications, with power requirements ranging from tens of kilowatts to tens of megawatts, and energy storage requirements ranging from several hundred kWh to hundreds of megawatt-hours. They are also easy to control and maintain, and fluid flow can be stopped quickly in an emergency situation.

9.2.3 Flywheels

Flywheels store energy by using electrical power to accelerate a cylindrical assembly called a rotor (the flywheel) to a very high speed and maintaining the energy in the system via rotational motion. The rotational energy is converted back to electricity by slowing down the flywheel. The flywheel system itself is a kinetic, or mechanical, battery, spinning at very high speeds to store energy that is instantly available when needed.

At the core of most modern-day flywheels is a carbon-fiber composite rim, supported by a metal hub and shaft, with a motor/generator mounted on the shaft. Together, the rim, hub, shaft and motor/generator assembly form the rotor. When charging (i.e., absorbing energy), the flywheel's motor acts like an electrical load and draws power from the grid to accelerate the rotor to a higher speed. When discharging, the motor is switched into generator mode, and the inertial energy of the rotor drives the generator which, in turn, creates electricity that is then injected back into the grid. Multiple flywheels may be connected together to provide various megawatt-level power capacities.

To illustrate the industry's current capabilities, one major flywheel manufacturer offers a high-performance rotor assembly that is sealed in a vacuum chamber and spins at up to 16,000 rpm. At that rotational speed, the speed at the rim would be approximately Mach 2, about 1500 mph, if it were operated in a normal atmosphere. At that speed the rotor must be enclosed in a high vacuum to reduce friction and energy losses. To reduce losses even further, the rotor is levitated with a combination of permanent magnets and an electromagnetic bearing. At 16,000 rpm the flywheel can store and deliver 25 kWh of extractable energy. Advanced flywheel energy systems can spin at speeds from 20,000 to over 50,000 rpm in a vacuum enclosure. Such flywheels can come up to speed in a matter of minutes.

In addition to providing a steady source of electricity, a flywheel may also be used to supply short pulses of energy at high power levels that exceed the abilities of its own energy source. This is achieved by accumulating energy in the flywheel over a period of time, at a rate that is compatible with the energy source, and then releasing energy at a much higher rate over a relatively short time when it is needed.

An obvious issue associated with flywheels is catastrophic failure. With rotors moving at high rotational speeds and the flywheel structure experiencing large physical stresses, what would happen if a flywheel flew apart? The industry addresses this possibility by using in-ground concrete foundations to ensure a stable platform to support each high-speed spinning mass. This ensures that any problem with a single flywheel is contained and cannot affect other units.

Advantages of a flywheel are high energy density and substantial durability that allows them to be cycled frequently with no degradation in performance. They also have very fast response and charge/discharge rates, being able to go from full discharge to full charge quickly. They are particularly well suited for high-power, relatively low-energy applications.

9.2.4 Superconducting magnetic energy storage (SMES)

Superconducting magnetic energy storage (SMES) devices store energy in the magnetic field of a circulating dc electrical current in a superconducting coil. The cooled superconductor (at liquid nitrogen temperatures or lower) has no electrical resistance and the current continues indefinitely unless its energy is tapped by discharging the coil. A typical SMES device has three parts, a coil of wire that can become superconducting, a cryogenic cooler that cools the superconducting wire below its transition temperature at which it loses its electrical resistance, and power conditioning circuitry that allows for charging and discharging the coil.

Its advantages are ultra-fast charge and discharge times, no moving parts, nearly unlimited cycling capability, and an energy recovery rate greater than 95%. Disadvantages are the cost of the specialized wire, the need for continuous cooling to very low temperatures, large-area coils needed for appreciable energy storage, and the possibility of a sudden, large energy release if the wire's superconducting state is lost. SMES devices are often used to provide grid stability in distribution systems and for power quality at manufacturing plants requiring ultra-clean power (e.g., microchip production lines). At present 1 MWh SMES units are common and a 20 MWh engineering test model is under development.

9.2.5 Compressed air energy storage (CAES)

Compressed air energy storage (CAES) utilizes surplus electricity to compress air to high pressures in underground caverns or other large storage vessels, which can then be heated and released as needed to power expansion turbines that generate electricity.

One interesting feature of CAES is that, while being compressed from atmospheric pressure (14.7 psi/101 kPa) to storage pressures of about 1000 psi, the air heats up strongly (to more than 1000°F, 538°C). Some of this heat can be removed by cooling to protect the multi-stage air compressors, or stored thermally and used for subsequent adiabatic expansion of the stored air. Energy is also added to the compressed air during the expansion/power generation cycle by heating with natural gas. Gases other than air, for example, carbon dioxide, can be used as well.

CAES systems were first built in the 1870s in Europe and Argentina. The first utility-scale CAES project was the 1978

290 MW Hunters Plant in Germany, using an excavated salt dome as the storage container. In 1991 a 110 MW plant with a capacity of 26 hours was built in McIntosh, Alabama. The world's third CAES project, opened in 2012, was a 2 MW facility in Gaines, Texas. More recently, the Utah-based Intermountain Power Project has announced a 1.2 GW CAES project in underground salt domes, with the first 300 MW to serve as storage for solar PV power. The next 900 MW will serve as storage for anticipated new wind energy generation. The US DOE is also supporting several proposed CAES projects in California and New York.

9.2.6 Pumped storage

Pumped storage uses surplus, low-cost electricity, usually at night, to pump water from a lower reservoir to a higher one, and then this water is allowed to run downhill through turbines to generate electricity as needed.

It is a form of hydroelectricity, but the upper reservoirs used with pumped storage are quite small when compared with conventional hydroelectric dams of similar power capacity, and generating periods are often less than half a day. Because of the large scale possible in such schemes pumped storage is – based on MW installed – the most common type of utility storage today. As of 2017 total installed global capacity was 184 GW, of which 25 GW was in the US (59).

The round-trip efficiency of pumped storage is in the range 70–80%, but such losses are compensated for financially by its ability to offer electricity to the grid during periods of peak demand when electricity prices are highest.

The main disadvantage of pumped storage is the need for sites offering both geographical height and water availability, usually in hilly or mountainous regions. They are often areas of natural beauty, and therefore subject to public opposition.

In many ways pumped storage is similar to CAES in that surplus electricity is used to store energy in a large reservoir. It should also be noted that the substance moved against gravity to a higher level (and therefore to a higher potential energy) doesn't have to be water. Some companies today are revisiting a concept first proposed in the mid-19th century whereby a windmill would be employed to raise a quantity of iron balls, and these balls would then be allowed to fall into buckets on one side of a wheel, causing the wheel to rotate and thus drive a machine. Modern versions of this concept substitute gravel for iron balls and the mechanical system drives a turbine and generates electricity.

9.2.7 Thermal storage

Thermal storage allows us to store energy in the form of heat or cold for use at another time. Power-generating examples include modern solar thermal power plants which use concentrated sunlight to produce all of their energy during daylight hours. Surplus energy produced during these hours can be stored thermally in the form of hot oil or molten salt, and other higher-temperature storage schemes are being explored. Another approach is to use off-peak electricity to cool water or create ice, which can be used in a building's cooling system to lower air-conditioning electricity demand during the day. Both types of thermal storage are in use today.

9.3 APPLICATIONS

Energy storage systems can be used to deliver a broad range of benefits to both the electrical grid and the grid's customers. For customers these include backup power, increased self-consumption of PV-generated electricity, reduction of peak demand charges, and optimized management of time-of-use utility rates. For utilities, energy storage provides a range of important ancillary services such as frequency and voltage control, peak shaving, deferral of investments in distribution and transmission infrastructure, relief of transmission congestion, adequacy of supply, energy arbitrage (buying electricity at a lower price and selling at a higher price), spinning/non-spinning reserve, and energy for black start after a shutdown.

Historically, energy storage has been expensive, and initial attempts at evaluating its economic value have focused on single applications of the type mentioned above. Early studies concluded that storage was too costly for widespread use. Nevertheless, several recent studies have questioned this conclusion, pointing out that storage batteries and other storage devices can be used for more than one purpose, each with its own revenue potential (60, 61). They point out that focusing just on levelized cost of energy (LCOE), the usual metric used in comparing electricity costs, can be misleading. When applied to energy storage such an approach fails to take into account the full range of values and revenue benefits offered by storage, and that the full economic value offered by a storage technology varies depending on the application. This perspective can change the financial viability of energy storage projects, and the broad conclusion now is that energy storage should be evaluated as a totally new and different entity. Admittedly, evaluating the economics of energy storage is difficult. For example, batteries are not strictly a supply or demand-side technology, but rather can serve as either load or generation depending on whether they are charging or discharging. In many cases today storage devices are used for only a small fraction of their availability, and they could be used for more so-called ‘stacked’ applications.

9.4 COSTS

The cost of energy storage is a rapidly moving target, as more and more companies announce storage products, and consumers and utilities begin to appreciate the full value of storage technologies. Today, costs are falling and markets are expanding rapidly. $230/kWh has been identified as the price point at which battery storage wins out over conventional fossil fuel generation. This cost point should be reached in markets within the next few years, and is expected to decrease further to $100/kWh. Significant market growth is anticipated in storage of solar-generated electricity by households and businesses, utility-scale applications, and use in electric and hybrid-electric vehicles. The market research firm HIS expects the energy storage market to increase from its 2017 installation rate of 6 GW to an annual installation rate of over 40 GW by 2022.

9.5 FUNDAMENTAL CHANGE

What is becoming increasingly clear is that energy storage is bringing fundamental change to the electrical energy system. Over the past century and more, we developed electrical grids throughout the world that immediately consumed what they produced, and managed that by overproducing a bit to make sure that backup exists in case of unforeseen outages. However, if you have energy storage there is no need to overproduce and no need for backup reserves. It allows you to store electricity and use it as needed.