Article 2: Key Concepts in Electricity Storage

Scope: This article provides an introduction to some of the key concepts and vocabulary associated with electricity storage. For the full set of articles as well as information about the contributing authors, please visit http://acee.princeton.edu/distillates.

Storage is a widespread phenomenon. Every garage and closet is a storage site. The inventory of a business consists of stored items. In the energy domain, oil in large cylindrical tanks at the edge of a city is stored energy. So is the wood in the trunk of a tree, the water in a reservoir behind a dam, and the heat in a tank containing molten salt made very hot by concentrated sunlight. Here, we are confining attention to the storage of electricity. To qualify, energy must enter and exit the storage system as electricity.

We are also confining attention here to storage related to electric power, which is one of the three major frontiers for electricity storage today, alongside storage for vehicles and for consumer electronics. A crucial difference is that both weight and volume matter far less for electric power applications. Many storage concepts that have potential for power systems can be quickly ruled out for the other two domains.

The feature of electricity storage systems that distinguishes them from electricity generators is their ability not only to produce electricity, but also to take it in. Batteries are the electricity storage systems that many people think of first. There are many other systems, however, and the goal here is to provide the generic vocabulary applicable to all forms of electricity storage. Toward that end, we introduce, in two pairs, four widely used storage metrics that determine the suitability of energy storage systems for grid applications: power & capacity, and round-trip efficiency & cycle life. We then relate this vocabulary to costs.

Power and capacity

The *power* of a storage system, P, is the rate at which energy flows through it, in or out. It is usually measured in watts (W). The *energy storage capacity* of a storage system, E, is the maximum amount of energy that it can store and release. It is often measured in watt-hours (Wh). A bathtub, for example, is a storage system for water. Its "power" would be the maximum rate at which the spigot and drain can let water flow in and out. Its "capacity" would be the amount of water the tub can hold.

Together, the power and the capacity determine how long it will take to fill (charge) or empty (discharge) the energy storage system. Specifically, dividing the capacity by the power tells us the *duration,* d, of filling or emptying: $d = E/P$. Thus, a system with an energy storage capacity of 1,000 Wh and a power of 100 W will empty or fill in 10 hours, while a storage system with the same capacity but a power of 10,000 W will empty or fill in six minutes. Thus, to determine the time to empty or fill a storage system, both the capacity and power must be specified. The time to empty or fill provides a guide as to how a storage system will be used. An energy storage system based on transferring water back and forth between two large reservoirs at different altitudes ("pumped storage") will typically take many hours to complete the transfer in either direction. Pumped storage is suitable for situations where power is desired many hours after it can be produced, such as occurs when wind is strong at night but demand is strong during the day. Batteries chargeable and dischargeable over many hours are included in systems that provide 24-hour electricity for a remote home with a rooftop solar collector and no connection to any electric grid.

Another important parameter for storage systems is how quickly the power can "ramp" up or down – how responsive the storage system is. Battery and flywheel storage systems can change the rate at which they can absorb or deliver energy so rapidly (changing the power level in or out by as much as a few percent per second) that they are competing with gas-turbine generating systems that can also vary their power output, but not as quickly.

The distinction between the two units just introduced that are amounts of time – the time required for full discharge and the time required to ramp up and down – have exact analogs when distance substitutes for electric charge: How far a car can travel, starting with a full gas tank, before the tank is empty is the discharge time. If the car can go from zero to 60 miles per hour in six seconds, six seconds is a measure of the ramp time.

Scientific notation allows a compact way to discuss larger amounts of power: thousands of watts (kilowatts, kW), millions of watts (megawatts, MW), and billions of watts (gigawatts, GW). Similarly, to discuss storage capacity: thousands of watt-hours (kilowatt-hours, kWh), millions of watt-hours (megawatt-hours, MWh), and billions of watt-hours (gigawatt-hours, GWh). For vehicle applications, it is useful to know that one horsepower = 746 watts and that car engines typically deliver upwards of 100 horsepower. Thus, a battery for driving an electric car will deliver at least tens of kilowatts of power, while its range will be determined by its storage capacity in kilowatt-hours. “Grid-scale storage” requires, roughly, storage capacity greater than one MWh.

For vehicle and consumer electronics applications, the most common metrics modify the power and capacity units introduced here by dividing then by either mass or volume, thereby conveying the implications for situations where portability is critical. One finds units like watts per kilogram (W/kg) and kilowatt hours per cubic meter (kWh/m^3). We will not be using these units here.

Round-trip efficiency and cycle life

An *ideal* cycle for an electricity storage system is a sequence where some amount of electricity is used to add energy to the storage system and then exactly the same amount of electricity is produced when energy is extracted from the storage system while it returns to a state that is exactly the same as the initial state.

In all real cycles, this cannot happen: not all of the electricity stored can be retrieved, and the initial state is somewhat modified. During charging, electricity taken from the grid is converted into another form of energy, e.g. lifting water, compressing air, spinning a flywheel, separating electrical charges, making/breaking chemical bonds. During discharging, whichever the process, it must be reversed. In all cases these conversion processes have irreversibilities such as resistances in circuits, friction in flywheel bearings, and friction in pipes carrying water between an upper and a lower reservoir. The result is that heat is produced and less electricity can be extracted from a storage system than was put into it, when the system returns to its initial state. The *round-trip efficiency* is the energy delivered, divided by the energy received.

The rate of filling impacts the round-trip efficiency – usually less capacity can be accessed when a storage system is filled very quickly compared to very slowly. Therefore, power and *useful* capacity are not independent. The round-trip efficiency will also be less after a storage device is filled and emptied many times, compared to its value when the storage device is new. The *cycle life* is the number of cycles of filling and emptying before the performance falls below some predetermined level.

Not surprisingly, the round-trip efficiency and the cycle life strongly affect the value of a storage device and are the object of much research. In principle, storage elements can be replaced several times during the period of operation of a storage system, but this constrains system design and is usually undesirable. If a storage system needs to swap its storage elements for new ones every five years, for example, and it is competing with a generator that can run for 20 years, the cost of four storage elements needs to be factored into the cost comparison. Replacement costs can represent a significant portion of total lifetime system costs.

The fractional “state of charge” (SOC) of a storage device (a term most commonly used for batteries but applicable to all storage systems) is the energy stored at that moment divided by the maximum energy that can be stored. One refers to a deep discharge cycle when a storage system is emptied and filled almost completely; for example, the SOC might go back and forth between 0.9 and 0.1. A discharge cycle might be called shallow if the SOC varies between 0.6 and 0.4. The cycle life of a storage system will generally be longer – sometimes *much* longer – when a storage system undergoes only shallow cycles rather than deep discharges, because deep discharge, like fast discharge, adds its own irreversibilities that are detrimental to the storage device.

When a storage system can perform adequately for many cycles it is called “reversible,” and if it is a battery it is called “rechargeable.”

Storage system cost

The total cost of an electricity storage system reflects both capital costs and operating costs. For most storage systems the operating cost is a small fraction of the total storage cost, and the focus is on capital costs. The total capital cost, in turn, is often separated into two components: costs associated with moving stored energy in and out (power costs, in $/kW) and costs associated with the size of the storage system (energy costs, in $/kWh). The fractions of the total capital cost assignable to power-related and the energy-related costs vary with the storage technology.

The ability to drive down total costs through research and development (R&D) and commercial deployment depends on how novel the storage system is. For mature technologies such as pumped storage, there may be little opportunity for significant cost reductions, because the required equipment is already in wide commercial use. For newer technologies, costs are likely to fall as a result of the “learning by doing” that accompanies extensive commercial deployment.

The cost of a storage system is traded against the revenue it generates from providing various services. It is useful to distinguish between services that provide benefits immediately and only after some time passes. Storage can provide immediate benefits by absorbing energy when demand falls and thereby enabling operating generators not to curtail their power, which can be costly. Storage can provide delayed benefits by decoupling electricity production from electricity delivery, thereby enabling the shifting of energy delivery from an earlier time to a later time. Both benefits can also be provided by power generators, so storage faces similar competition in both cases. Immediate benefits provided by storage systems can also be provided by a generator already running on the grid that is able to reduce its output quickly. Delayed benefits of storage can also be provided by running a generator at the later time.

Chemical storage presents a special case, because the stored energy can be directed toward another market. Suppose electricity is stored as hydrogen via the electrolysis of water. At a later time, the hydrogen can be combined with oxygen (e.g., in a fuel cell) to produce electricity (perhaps with a round-trip efficiency of two-thirds). However, the hydrogen can also be sold for use in the production of chemicals. In this case, the storage function is undermined. The sale of hydrogen becomes an off-ramp of electricity storage.