PDHonline Course E320 (4 PDH)

Energy Storage Technology

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Energy Storage Technology

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Introduction: "Bottling Electricity"

Electricity is one of the major commodities in our economy and it is one of the few commodities that never had an economical or practical method to store the product. Electric power is produced and delivered at virtually the instant it is demanded. Generation and transmission systems must be designed to meet the peak instantaneous demand that may occur on the system. Considering a little extra capacity for reliability, this has resulted in a model where the capacity factor of the entire system is less than 50%. Although it is difficult to store electricity directly, electric energy can be stored in other forms, such as potential, chemical, or kinetic energy. Advanced energy storage technologies based on these principles are emerging as a potential resource in supporting an efficient electricity market. The term *energy storage* refers specifically to the capability of storing energy that has already been generated as electricity and controllably releasing it for use at another time.

Only about 2.5% of the total electric power delivered in the United States passes through energy storage, almost all of which is pumped hydroelectric storage. The restructuring of the electricity industry, along with increased requirements for power reliability and quality, has made utility-scale energy storage a subject of current interest.

Although the present-day electric grid operates effectively without storage, cost-effective ways of storing electrical energy can help make the grid more efficient and reliable. *Electric energy storage* (EES) can be used to accumulate excess electricity generated at off-peak hours and discharge it at peak hours. This application could yield significant benefits including a reduced need for peak generation and reduced strain on transmission and distribution networks. energy storage can also provide critically important ancillary services such as grid frequency regulation, voltage support, and operating reserves, thereby enhancing grid stability and reliability.

Technical applications of energy storage include grid stabilization, grid operational support, power quality and reliability, load shifting, and compensating for the variability of renewable energy sources. Restructured electricity markets provide opportunities for energy storage to participate in energy arbitrage and ancillary services.

The first application of large-scale energy storage in the United States occurred in 1929, when the first pumped hydroelectric power plant was placed into service. Pumping water from a lower elevation to a higher elevation was the most practical way to store large amounts of energy that could then be released during periods of high, or peak, demand. These power plants are still used to help manage grid frequency and provide clean reserve generation, known as ancillary services. During a 30-year period from the late 1950s to the late 1980s, approximately 19,500 MW of pumped hydroelectric storage facilities were brought into service in the United States. By 2000, about 3% of the total power delivered by the nation's grid was supplied through these energy storage facilities. Because of the need for significant elevation changes in pumped hydroelectric plant designs, the number of environmentally acceptable sites for future pumped hydroelectric facilities is limited. The siting of new plants will face the same objections that the siting of new transmission lines faces today.

Another energy storage technology is *compressed air energy storage* (CAES). A CAES demonstration power plant was placed in service in the early 1990s and has proven to be effective. Underground formations, such as salt domes and depleted gas fields, can be adapted for use with CAES technology. These systems appear to be practical in a power range from above 100 MW up to several thousand MW.

The most common form of energy storage in use today is based on batteries. The is a large installed base of lead acid batteries in UPS system. The rapid growth of the information age has spawned the construction of data centers to support the Internet and communications centers. These facilities are sensitive to power supply disruptions, so large battery-powered protection systems have been and will continue to be deployed to achieve a high level of protection. Powering these types of loads currently accounts for over 1.5% of the total utility power consumption in the United States.

There are several other electrochemical technologies in use for electric backup power applications. These battery technologies are also being investigated or deployed for utility-scale applications. Battery technologies include lithium ion, sodium sulfur, zinc-bromine, vanadium redox, and polysulfide-bromide redox flow batteries, among others.

The two main classes of batteries in this distributed energy storage category are flow batteries and high-temperature batteries such as sodium sulfur and sodium nickel chloride batteries. Industry experts have found that, unlike lead-acid batteries, these devices can cycle daily and have useful operating lives in the range of 10 to 20 years. These systems can be designed for charge/discharge durations up to eight hours per day. All these devices are scaled chemistries with no emissions and quiet operation.

Flow battery technology utilizes an active element in a liquid electrolyte that is pumped through a membrane like a fuel cell to produce an electrical current. The system's power rating is determined by the size and number of membranes, and the runtime (hours) is based on the gallons of electrolyte pumped through the membranes. Pumping in one direction produces power from the battery, and reversing the flow charges the system.

High-temperature batteries operate above 250C and utilize molten materials to serve as the positive and negative elements of the battery. These chemistries produce battery systems with very high-power densities that serve well for storing large amounts of energy. The Sodium-Sulfur battery, such as the unit shown on the right, is currently being deployed in the United States by several large utilities in demonstration projects.

Other energy storage devices such as flywheels and supercapacitors are being applied for power quality applications and frequency regulation for utilities and other load-balancing uses to reduce emissions from diesel generator-powered devices such as port cranes. For these systems, energy storage is measured in minutes.

One energy storage technology that may be the future of utility energy storage is Plug-in Hybrid Electric Vehicles (PHEVs). The acceptance of these vehicles and the ensuing rate of adoption by the public will determine the timing of their impact on the overall power demand of the utility grid. Assuming most charging of PHEVs occurs at night, the relative impact on the grid over time should be positive in conjunction with the anticipated significant growth of wind energy. Uncontrolled daytime or early evening charging by PHEVs, by contrast, could pose challenges to system economics and capacity, as the extra demand could increase congestion or peak use.

There are many benefits to deploying energy storage technologies into the nation's grid. Energy storage can provide:

- A means to improve grid optimization for bulk power production.
- A way to facilitate power system balancing in systems that have variable or diurnal renewable energy sources.
- Facilitation of integration of plug-in hybrid electric vehicle (PHEV) power demands with the grid.
- A way to defer investments in transmission and distribution (T&D) infrastructure to meet peak loads for a time.

- A resource providing ancillary services directly to grid/market operators.

Depending upon the principal application of the energy storage technology, energy storage may be viewed as a generation, transmission, distribution, or end-user resource.

Pumped hydroelectric and CAES technologies are considered bulk power energy storage systems. In contrast, new classes of batteries have been developed that are considered suitable for smaller applications and are referred to as "distributed" utility storage systems. (In this context, the term "distributed" is used as a differentiation from "large centralized" energy storage technologies, analogous to large-centralized power plants.) The term *distributed energy* storage means deployment of these devices close to load centers, transmission system points of reinforcement, or renewable generation sources, typically in or near utility substations. In other contexts, the term "distributed" denotes location on distribution feeder circuits or at consumer premises behind the meter.

Full integration of new sources of energy demand coupled with the overall increase in electricity use is a major challenge facing the designers of the electric grid of the future. Energy storage technologies need to be examined closely to understand where storage can add value to the overall electricity infrastructure. Examples of the value of energy storage technologies could include capital deferral, energy maintenance during *islanding*, and better utilization of generation in coordination with the variable output nature of renewable energy generation.

> **Islanding**: Continuing to power a portion of a grid independently from the utility source.

The ratio of storage energy capacity to charge/discharge power rating, or the duration of the energy storage that is required, varies depending upon the application and favors different technologies accordingly. Energy density, cost, efficiencies, and environmental concerns are additional factors that affect the applicability of different technologies to different purposes. The electric vehicle application drives most R&D for advanced materials today, but it should be noted that it is also the most demanding application and thus the one that justifies higher costs. In the long term, the best energy storage technologies for utility-scale applications may be different from those used for electric-drive vehicles.

Determining the amount and overall value of energy storage that should be added to the grid begins with an examination of the marginal cost of generating electricity. The electric power industry runs at low capacity factors. This level of capacity has been acceptable to the industry because generation resources have traditionally been more cost-effective sources of capacity than energy storage resources. The growth of renewable energy will likely lead to even lower capacity factors for traditional generation sources.

Many of the drivers for a Smart grid are based on a desire to improve capacity factors by shifting the demand curve through either incentives or controls. Beyond some point that remains to be determined, there is likely to be some public resistance to the degree of load shifting entailed in the deployment of demand response programs. Energy storage technology offers another path to help balance the system to adapt production to demand while improving capacity factors.

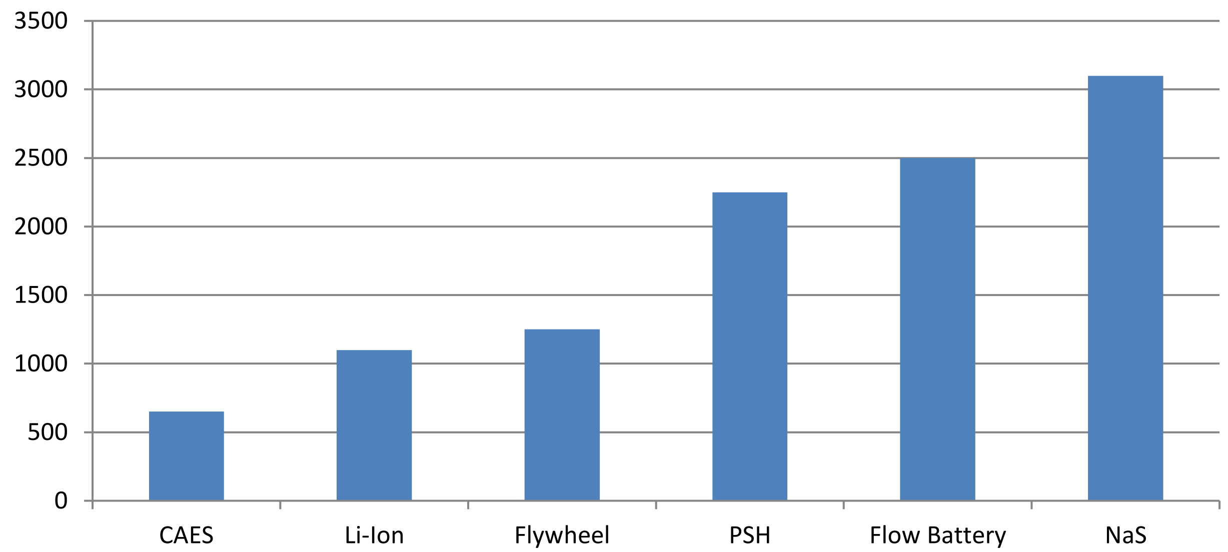
Another positive aspect of the implementation of energy storage technologies is the potential to capture and store electricity from wind energy when there is a lack of transmission infrastructure. For example, wind curtailment has already become common in Texas because of a lack of transmission capacity to move that power from western Texas to load centers in other parts of the state. In many regions, including Texas, transmission projects are moving forward to better connect wind power plants with load centers, although energy storage technologies may have potential value in the interim. In addition, as wind power deployment increases, wind output may begin to exceed electricity demand during certain times of the year, which would necessitate curtailment. This problem may also be aggravated by inflexible nuclear and coal power plants that have limited ability to decrease their output, given the difficulty of powering up or powering down these large baseload facilities.

Wind is a growing contributor of energy, but only a small, insignificant contributor to electrical generating capacity. Wind power's intermittency— which results in generation that is not dispatchable—is well documented. The output of a wind farm can vary from zero to the full rated output of the facility. This is an issue even with large wind farms, which have some self-compensating ability because they are geographically dispersed. For modern wind turbine farms, the yearly average capacity factor—the portion of time they produce full output—is around 40%. As the percentage contribution of wind grows, so does its effect on the grid, creating problems of frequency stabilization and system reliability. Energy storage options could be employed to supplement or compensate for the variability of the wind power's output.

Much like wind energy, photovoltaic energy is also an intermittent source of electricity. The output from a solar array will vary with the location, weather conditions, and time of day. It also varies throughout the day, increasing from morning to midday and dropping off in the afternoon. In many cases, photovoltaic energy production does not coincident with late afternoon summer peak demands that most utilities experience. There is also the intermittency caused by passing cloud cover, which can momentarily reduce a photovoltaic array's output to virtually zero. Energy storage can smooth the output of photovoltaics by filling the shoulder period—the afternoon drop-off of power from the sun. It can also buffer the effect of momentary power loss due to passing cloud cover. Because the output from a solar array is DC, it does not require the AC to DC conversion that wind energy needs. This allows direct connection of the battery to the solar DC bus through electronics, but without AC/DC conversion. The capital cost should therefore be less and the efficiency higher than those of wind power conversion equipment.

In analyzing energy storage alternatives, Figure 1 shows the current cost estimates for various types of energy storage technologies available today. Except for CAES, all other forms of energy storage have no emissions associated with the energy discharge cycle. CAES systems burn a mixture of compressed air and natural gas to generate power. CAES technology requires fuel costs for discharging, which are not captured in Figure 1. If the system operated on compressed air alone, the costs per kilowatt (kW) would be approximately three times greater.

Figure 1
Cost Estimates for select ESS Technologies



Energy storage technology types can be divided into two categories based on their economically practical duration: those with *hours of runtime*, and those with *minutes of runtime*. Currently, flywheels and batteries rated for smaller amounts of energy are appearing in the grid today for ancillary service use such as frequency regulation. All other energy storage technologies can provide hours of energy runtime in addition to use in ancillary services such as frequency regulation.

Chapter 1
Energy Storage Applications

In this chapter we will look at the applications of electric energy storage systems to the utility grid. We will look at the benefits to the three sectors on the utility industry which are,

- Generation
- Transmission & Distribution
- End-Users

Electricity has traditionally been used at the time at which it is generated. It is not often stored, even though energy storage would allow for the optimization of power generation. Currently, the United States has adapted generation to match peak load, resulting in low capacity factors for the electric power industry, as much of the capacity is used infrequently to meet peak demand. The shift in generation resources from fossil fuels to renewable energy resources as a source of electric power will aggravate this low capacity factor because wind power is often strongest at times when electric demand is low. When used to levelize the production/demand mismatch over various time domains, energy storage technologies have several generation applications. In addition, storage also has transmission applications that improve transmission capacity and reliability.

Energy storage applications may offer potential benefits to the transmission and distribution (T&D) system because of the ability of modern power electronics, and some electro-chemistries, to change from full discharge to full charge, or vice versa, extremely rapidly. These characteristics enable energy storage to be considered as a means of improving transmission grid reliability or increasing effective transmission capacity. At the distribution level, energy storage can be used in substation applications to improve system power factors and economics and can also be used as a reliability enhancement tool and a way to defer capital expansion by accommodating peak load conditions.

Energy storage can also be used to alleviate diurnal or other congestion patterns and, in effect, store energy until the transmission system able to deliver the energy to the location where it is needed.

One area in which energy storage technologies could provide great benefits is in conjunction with renewable energy resources. By storing energy from variable resources such as wind and solar power, energy storage could provide firm generation from these units, allow the energy produced to be used more efficiently, and provide ancillary transmission benefits.

At the end-use level, energy storage technologies can be used to capture distributed renewable generation—photovoltaic solar or wind power—and store it until it is needed, both for off-grid and grid-connected applications. As such, end-user energy storage technology applications also have the potential benefit of improving grid utilization, especially if end-user energy storage can be coordinated with utility operations. One example of such coordination is the use of energy storage in large commercial buildings to allow peak shaving and demand response to occur without reducing actual building services and heating, ventilation, and air conditioning (HVAC).

A potential benefit of an end-user energy storage technology is *vehicle-to-grid* (V2G) technology, whereby plug-in hybrid electric vehicles (PHEVs), with the added capability of discharging back to the grid, are used to improve grid utilization, levelize demand, and improve reliability. Because expectations for PHEV deployment are so high, there is great interest in the electric power utility industry about the potential for V2G to provide many of the benefits of energy storage at the distribution and end-user level.

There are also high-value benefits to niche energy storage applications associated with specific end-use sectors. Specific industrial applications will be developed as megawatt-scale energy storage technology becomes proven and economic and that will provide added benefits of energy storage technologies.

Generation Applications

The following is a summary of a few of the key areas where electric energy storage systems may benefit the electric utility grid from the generator to the end-user.

Energy storage can help with grid stabilization by assisting with the grid's return to its normal operation after a disturbance. Energy storage can be used to remedy three forms of instability: rotor angle instability; voltage instability; and frequency excursions.

In addition to stabilizing the grid after disturbances, energy storage can also be used to support normal operations of the grid. Four types of support operations can be performed with energy storage,

1. Frequency Regulation Services: Energy storage can be used to inject and absorb power to maintain grid frequency in the face of fluctuations in generation and load.

2. Contingency Reserves: At the transmission level, contingency reserve includes spinning (or synchronous) and supplemental (non-synchronous) reserve units, that provide power for up to two hours in response to a sudden loss of generation or a transmission outage.

3. Voltage Support: Voltage support involves the injection or absorption of reactive power (VARs) into the grid to maintain system voltage within the optimal range. Energy storage systems use power-conditioning electronics to convert the power output of the storage technology to the appropriate voltage and frequency for the grid.

4. Black Start: Black start units provide the ability to start up from a shutdown condition without support from the grid, and then energize the grid to allow other units to start up. A properly sized energy storage system can provide black start capabilities, provided it is close enough to a generator.

Energy storage can also help to improve power quality and reliability. Most grid-related power quality events are voltage sags and interruptions with durations of less than two seconds, phenomena that lend themselves to energy storage-based solutions.

Load shifting is another area where energy storage is utilized during periods of low demand and releasing the stored energy during periods of high demand. Load sifting comes in several different forms; the most common is peak shaving. Peak shaving describes the use of energy storage to reduce peak demand in an area. It is usually proposed when the peak demand for a system is much higher than the average load, and when the peak demand occurs relatively rarely. Peak shaving allows a utility to defer the investment required to upgrade the capacity of the network. The economic viability of energy storage for peak shaving depends on several factors, particularly the rate of load growth.

This section further discusses the potential benefits of energy storage across different infrastructure and time domains and gives some indications of the performance characteristics required by each application and the estimated economic gains. Table 1 summarizes generation applications and their benefits.

Table 1
Generation Applications

Activity	Definition	Nature of Benefit	Benefit Magnitude	Power Requirements (Max)	Duration Requirements	Other Requirements	Structural Issues
Governor response	Generator autonomous dynamic response to frequency	Renewable sources lack governor response, which is essential for system stability. Increasing conventional unit governor response for renewable sources will cost the markets	Compensate for lack of renewable sources governor response	1–5% of associated generation	Seconds to a few minutes	Sub-second response	None; standards for renewable governor response are lacking
Regulation	Second by second adjustment of power production to match load and schedules and regulate system frequency	Regulation is a defined ancillary service with annual costs to markets on the order of millions of dollars. Storage can displace conventional fossil generation for this purpose and free up generation capacity for energy production. Renewable generation typically lacks regulation capability	0.2–0.5% system wholesale energy costs	1–2% of system peak overall	15–30 minutes duration is required to be effective	Rapid (<10 sec) response	Regulation often overlaps short-term balancing energy. Control algorithms can be adjusted to exploit fast storage response and use storage first for regulation
Balancing energy/ Real-time dispatch	Adjustment of production economically/market based on a minute-by-minute basis to match demand	In some markets hourly schedule changes cause "spikes" in balancing requirements and prices. Storage used for this purpose would mitigate the spikes. Renewable volatility is expected to greatly increase balancing energy needs, which would increase prices and reduce capacity available for base/scheduled energy production; storage can mitigate this problem	2– 3% of today's wholesale costs; benefit is to reduce costs and potentially avoid increases to renewable penetration growth	Balancing is 2–3% of system energy today and may double with large renewable penetration	1 hour or more	Charge efficiencies must be settled in the real-time markets, so efficiency becomes an important attribute	None; standards for renewable governor response are lacking

Table 1 (Continued)

Application	Definition	Nature of Benefit	Benefit Magnitude	Power Requirements (Max)	Duration Requirements	Other Requirements	Structural Issues
Reserve augmentation	Conventional generation provides spinning and operating reserve as back-up against the failure of resources	Storage can provide short-term reserves and enable slower generation to participate, freeing up additional capacity from economic units online	Conventional generators charge an "opportunity cost" when providing reserves – this cost can be avoided	Spinning reserve is typically matched to the largest unit in a control area or congestion zone; typically, 1000–1500 MW	15–30 minutes if backed up by slower generation	Storage must be kept in a state of charge to supply reserves	Unexplored territory except for hydroelectric resources
Intra-day production shifting	Some renewable energy resources have intra-day behavior (e.g., mountain wind locations) which impose scheduling and load matching challenges	Storing renewable production for several hours will utilize more renewable energy and reduce peak fossil production	Depending upon the amount and daily variability of renewable sources this can be a large economic benefit	Depends upon specific resources. Could be a range of 30–50% of resource maximum power capacity	Hours	Energy capacity must be economic against the value of energy captured	Eligibility for Investment Tax Credits should be considered
Diurnal renewable levelizing	Diurnal renewable levelizing	Storing renewable energy resources from daily peak production for use at peak load hours	Depending upon the amount and daily variability of renewable sources this can be a large economic benefit	Can be as much as 50% of renewable resource production	6–12 hours	Energy capacity must be economic against the value of energy captured	None
Weekly production levelizing	Weekly production levelizing	Store production on weekends for weekday use	Pumped hydro is the vehicle for this today and provides large benefits	Can be 20–30% of peak load for two days	48 hours	Needs large energy storage capacities; only pumped hydro proven for this today	None
Seasonal production levelizing	Seasonal production levelizing	Store seasonal resources for use in peak load seasons	Hydroelectric facilities provide this	Typical only of large hydro reservoirs today	Months		None

Source: DOE Energy Advisory Committee's Energy Storage Technology subcommittee.

Many of the generation services that are potential energy storage applications are existing energy market-defined products (e.g., ancillary services and balancing energy), and as such, market costs for these services are readily available. Where markets are not deregulated, the amount of energy storage capacity that could be used is roughly linked to system or generator sizes. In most cases, the overall economic benefits can be used to finance energy storage technology projects via normal market mechanisms.

When benefits are described as alleviating conventional generation capacity to provide energy, it is because the provision of an ancillary service requires that the generator operate at less than full capacity. Thus, the owner of that generator incurs an opportunity cost in that the margins on production are decreased; this cost is a large part of the pricing demanded for ancillary provision, especially at peak load. In some cases, generating units that are not "in the market" and would be uneconomical are used to provide ancillary services, generally at higher prices.
Replacing these units with energy storage technologies would reduce these costs and the associated emissions from these units, potentially enabling the retirement of older power plants.

Some of the applications are already under early commercial development; several merchant energy storage developers are piloting fast energy storage technologies for use in system regulation. In addition, some wind developers that experience curtailment due to insufficient transmission capacities are investigating energy storage solutions.

Transmission and Distribution Applications

Transmission capacity to bring remote generation to load centers is currently limited, although new transmission infrastructure is being planned and built in many areas. Increasingly, new generation must be sited far from population centers, which can place additional strain on the grid. Wind power generation is often located in remote or rural locations, which requires the installation of new transmission. Because wind resources typically have capacity factors of around 40%, it is often the case that associated new transmission rated at the full power capacity of the renewable resource is not economical.

For some wind power projects, it may be cost-effective to either, build transmission capacity for slightly less than the full nameplate capacity of the project and simply curtail output during the small number of hours per year when output exceeds the available transmission capacity, or to add energy storage to enable the dispatch of the energy at a different time.

Energy storage technologies may provide a way to capture power production that would otherwise be curtailed and reserve it for a time when the transmission grid is not loaded to capacity. Energy storage also affords the transmission owner/grid operator a chance to defer transmission expansion for a period; transmission capacity is generally not incrementally increased. This ability to defer transmission expansion is an example of energy storage providing mutual benefits to generation and transmission. However, the costs of energy storage options need to be compared to other options, including the construction of new transmission infrastructure, that benefit all generators as well as consumers via enhanced reliability and lower overall costs.

Transmission congestion is already an issue in many parts of the country. Congestion charges are typically considered as part of fuel cost adjustments by most regulated load-serving entities and can be tens to hundreds of millions of dollars each month. The impact of congestion is to force the use of expensive generation resources closer to the load center instead of less expensive coal and hydroelectric resources, which can be used in remote locations. Therefore, large-scale energy storage is another way to mitigate transmission congestion if the economics are viable.

A special case of congestion relief occurs when the limiting transfer capacities are not the physical capacities of the transmission paths in question, but rather are reliability limits arising from post-contingency loading or stability conditions. In the western United States, system dynamic and transient stability limits impose restrictions on the north-south power flows, below the physical limits of the transmission lines. In the Northeast, post-contingency voltage conditions similarly limit transfers below the physical capacities.

Fast energy storage has the potential, yet unexplored or validated, to relieve many of these reliability limitations. In the event of a contingency, the inverter-based storage could theoretically respond in a period of power system cycles and provide a stability or voltage augmentation. The economic value of relieving these reliability limits is considerable, making this potential role one that should be studied. Allowing the transmission circuits to be loaded to full thermal limits could result in increased power transfers for better economics and would be important as new generation sources are located far from load centers. This improvement could be a bridge until expanded transmission capacity is permitted and constructed and would similarly provide capacity factor benefits to some new transmission facilities.

At the distribution level, energy storage can provide benefits similar to those it provides at the generation and transmission levels: providing local peak power/time shifting capabilities, grid reinforcement against peak and against reliability incidents, and specialized power electronics-based benefits.

While pumped hydroelectric facilities can only be located where suitable dam sites can be created, and compressed air energy storage (CAES) may be difficult to site in volume in any suburban/urban area, other technologies, particularly dry batteries, lend themselves to distributed deployment in basements and garages. Table 2 shows the potential applications of energy storage in the transmission and distribution systems.

Table 2
Transmission & Distribution Applications

Application	Benefit	Quantification	Power Requirements	Duration Requirements	Issues
Transmission capacity factor for renewable sources	Capture renewable production and deliver when transmission capacity is available	20–50% of renewable capacity	20–30% of renewable peak production	6–12 hours	Uncertain long-term economics as capacity is built
Transmission congestion relief	Generalized application of above	Potentially large in localized applications	Equal to typical congested power on path	Hours	Uncertain long-term economics as capacity is built
Transmission reliability limit relaxation	Specialized technical version of congestion relief relying on fast storage	$10 - $100 million	0-1000 MW	Seconds to 15 minutes	Unexplored and need rigorous analysis and demonstration
Transmission capital deferral	Relieve short-term congestion	Several years carrying costs		Hours	site specific
Substation peak load/Backup	Defer transformer upgrades due to peak load growth	$M per station for 2–5 years deferral	2–10 MW	Hours	Economics unanalyzed
Voltage support	Storage can provide local real power at high power factor	Economics need analysis	Varies with application	Varies with application	Cost compared with alternative solutions
Reliability enhancement	Provide down-circuit supply while outages are restored	Outage costs vary depending on duration and consumer	2–10 MW	Hours	Economics unanalyzed

While the deployment of energy storage technologies on distribution systems can offer all the benefits available from larger storage units at transmission and generation levels, it can also offer some additional value. The flattening of demand on station transformers and circuits enables the deferral of distribution upgrade capital. In addition, the availability of the stored backup power closer to the end-use consumer at the distribution level would offer inherently higher service reliability than what could be offered with energy storage at transmission or generation levels. Due to the nonlinear nature of T&D losses, diurnal peak shaving of energy storage devices would reduce T&D losses. The closer the energy storage is located to load, the greater the reduction in T&D losses, particularly given that a high percentage of the T&D losses are on the distribution circuits. Another additional value of distribution-level energy storage, compared to larger units deployed at transmission and generation levels, is the inherent increased security and reliability in storing energy in multiple locations instead of concentrating them in fewer large centers. A unique distribution system has significant value and should be considered in locating energy storage devices.

End-User Applications

Energy storage can be used as an asset for commercial and industrial end-users. For these applications, the device may be utilized as a standalone asset or in combination with distributed generation (DG).

For residential end-users, energy storage can add value as a backup power device, providing power during outages for vital appliances. In addition, it can play a role with renewable energy, such as rooftop solar power, as a way to store excess renewable energy production for use when the renewable energy resource is unavailable (i.e., when the sun is not shining or the wind is not blowing), allowing the consumer to avoid using grid energy at those times. Of course, grid electricity may be a more cost-effective option for maintaining power during these periods.

For commercial end-users, energy storage technologies can fill a unique niche in providing backup power for short-term interruptions. Typically, a facility will use DG technologies to supply backup power. However, many interruptions are often short in duration and happen before a generation device can "ramp up." In combination with DG, energy storage can provide ride-through protection for short-term interruptions and serve as a bridge to a facility generator in case of long-term outage. This short-term storage market is the very mature uninterruptible power supply (UPS) market arena that is currently booming.

UPS devices have been used by commercial end-users with specialized reliability requirements. With environmentally and economically attractive energy storage, possibly assisted economically by price arbitraging and linkages to demand response, this application may become increasingly relevant for other commercial end-users.

Energy storage can be considered simply another "generation option" for an end-user. Today's user may be able to use all power sources—the grid, energy storage, and DG—in combination to optimize usage and costs for power, and as a result, maximize economics and profits. If, in the future, the utility decouples rates and implements a demand or capacity charge, the user may be able to pay a lower demand charge if they are willing to accept curtailed service for essentials only—when the renewable production is absent and the energy storage is exhausted. Energy storage technology can serve individual residences or even a micro-grid serving several commercial users.

It is also conceivable that energy storage technologies, interconnected with end-user-controlled demand-side resources and DG, will be used to shift grid demand to low-priced periods and avoid peak real-time prices. Again, this is also a viable application for commercial as well as residential users. It is anticipated that significant PHEV penetration will lead to such applications, as consumers realize the desirability of charging their vehicles at off-peak prices.

There is also the possibility for the linkage of end-user energy storage with utility operations to achieve some of the same benefits as described in the T&D application section. Because of the costs of control interconnection and the need for some assurance that the energy storage technology will perform when needed, this system is likely to first appear in high value/high-density locations, such as downtown urban underground networks. The operational problems of underground networks and the high costs of capital expansion and energy in these areas make inter-controlled end-user DG and energy storage an interesting opportunity for the T&D utility. This opportunity implies that end-user energy storage can discharge back to the grid via a net metering scheme under utility control.

One of the most appealing benefits of deploying a Smart grid is that the "smart" technologies can be used to shift or control demand to reduce peaks. Some demand response programs require altering consumer behavior, although other demand response programs can operate automatically and without the consumer being aware of its deployment. A virtue of energy storage technology is that it can accomplish the same supply/demand balancing without imposing behavioral constraints on consumers. On the other hand, the benefit of demand response measures is that they are typically lower in cost.

Demand response is increasingly a market resource, incorporating the provision of ancillary services such as reserves and real-time energy, as well as some demand response aggregators that aim to provide system regulation. Utility-scale energy storage coupled with demand response provides the aggregator a higher responsiveness and certainty of response, making demand response participation in ancillary services markets more attractive.

As with distributed generation, energy storage at the end-user site is a natural complement to demand response applications and has the chance to play a vital role in demand response programs. Ultimately, end-users may use their storage in net metering situations, as some renewable energy resources are used today, to sell power back to the grid at peak times. Whether energy storage economics will make this option viable is not yet known.

Other niche applications for energy storage technologies include cranes, container ports, and other applications characterized by short bursts of peaking power in which managing local demand and/or losses is of value.

These niche applications are mentioned only to illustrate that many other high-values, end-user applications will come forth once the energy storage technology is proven effective. Table 3 shows the end-user applications and value propositions that could be derived from energy storage.

Table 3
End-User Applications

Application	Benefit	Quantification	Power Requirement	Duration
Storing renewable distributed generation (DG) production	Capture DG production for use when wanted and reduce grid consumption; mitigate capacity charges as well	Benefit up to value of renewable energy at peak hour's pricing	Equal to local DG peak production	Hours
Time shifting of demand to avoid peak prices	Avoid high real-time prices at peak	$100/MWh or more	Equal or less than peak load	Hours
Price arbitraging in real-time pricing situation	Same as for storage in generation balancing energy	May mitigate high ramping balancing costs	As desired	30 minutes
Reliability enhancement	Avoid interruptions	Linked to value of production and cost of interruption	Equal to peak load protected	Minutes to hours
Utility reliability enhancement	Allow utility control for targeted enhancement	Linked to utility capital deferral	Equal to peak load typically	Minutes to hours
Plug-in hybrid electric vehicle Integration	Lower cost of charging by only using off-peak power	Lower cost of driving plus utility capital deferral	Equal to vehicle power draw	Hours
Demand response integration	Make demand response participation in markets more attractive	Not quantified yet	Like demand response / load management that is replaced	Minutes to hours
Renewable demand response	Renewable volatility and difficulty of control make them unreliable for demand response applications. Storage can be an enabler	Not quantified yet	Like demand response / load management that is replaced	Minutes to hours
Railroad acceleration support	Avoid significant variable (I^2R) losses	Catenary losses are 15–20%	10 MW per station	Minutes to hours

Source: DOE Energy Advisory Committee's Energy Storage Technology subcommittee.

Chapter 2
Battery Energy Storage

Batteries systems are one of the commercially available methods to provide energy storage and they can provide varying sizes of energy storage. The types of battery systems that may be employed in utility energy storage systems include, lead-acid, nickel cadmium, nickel metal hydride, lithium-ion, lithium titanate, lithium iron phosphate, zebras, sodium sulfur, vanadium, and zinc bromine. Battery storage encompasses several different battery chemistries, including lithium-ion, nickel-based, sodium-based, lead acid, and flow batteries.

Some existing battery storage chemistries that have seen grid-scale deployment include:

- Lithium-ion represents more than 80% of the installed power and energy capacity of largescale battery storage in operation in the United States. 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. 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. 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 (300C).

- Lead acid is one of the oldest forms of battery storage, with development beginning in the 1800s. Lead acid is a mature technology that is widely used in passenger vehicles. Lead acid provides less than 3 percent of large-scale battery storage capacity installed in the United States and has 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. At present, flow batteries represented less than one percent of the installed power and energy capacity of large-scale battery storage though this is an interesting technology to watch.

Figure 2 shows the current installed capacity of large-scale battery storage systems.

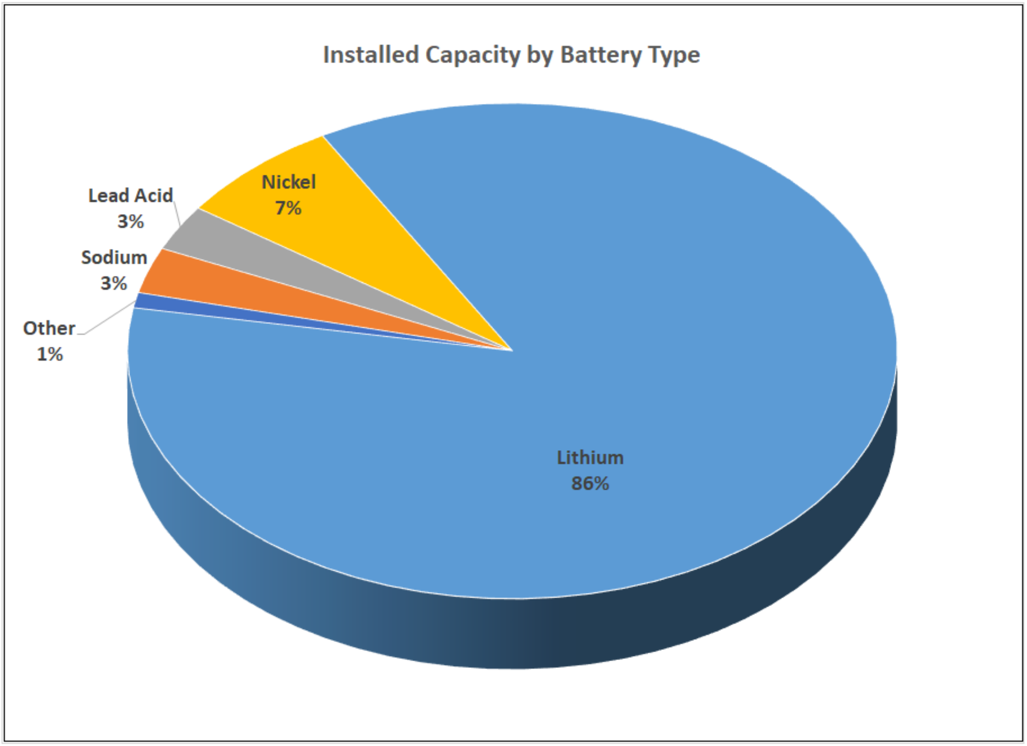


Figure 2

The earliest large-scale battery storage installations in the United States used nickel-based and sodium-based batteries. However, since 2011, most installations have opted for lithium-ion batteries, including retrofits of older systems that initially relied on different chemistries.

Flow batteries are an emerging battery storage technology. 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.

Battery Storage Costs

Costs for battery storage technologies depend on technical characteristics such as the power capacity and energy capacity of a system. Battery storage systems are generally divided into the following categories based on nameplate duration. They are,

- Short Duration - <30 minutes
- Medium Duration - 30 minutes to two hours
- Long Duration - Greater than two hours

Table 4 shows the characteristics of battery storages systems based on their duration category.

Table 4
Battery Characteristics by Duration Category

Duration	Capacity (MW)	Energy Capacity (MWH)	Duration (Hours)	Capacity Cost ($/Kw)	Energy Cost ($/Kwh)
Short	13	4.7	0.4	944	2,597
Medium	13.8	15.6	1.1	1,533	1,352
Long	2.7	16.7	5.6	2,430	399
Costs are in 2016 dollars.					

As shown in Table 4, short-duration battery storage systems have an average power capacity of 13 MW and 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.

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* losses experienced during cycles of charging and discharging.

> ***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.

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.

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

The following is an overview of the most common battery types.

Lead Acid

Lead-acid batteries, like the one shown on the right, are the most common type of secondary, or rechargeable, battery in use. They are used in a variety of applications including starting, lighting, and ignition (SLI) loads in automobiles and UPS systems. Lead acid batteries are economical and can tolerate a wide range of operating conditions.

These batteries can produce either high currents or low currents over a wide range of temperatures and they have a good shelf life. They are heavy, and most are flooded cell units, which require regular maintenance.

The chemical process in a lead-acid battery involves the oxidation of the metal anode, which releases negatively charged electrons and positively charged ions. The electrons travel through an external circuit to the cathode where the electrons combine with the material in the cathode.

The chemical process at the cathode is called a reduction reaction and it also releases a negatively charged metal-oxide ion. This ion causes a water molecule in the electrolyte to split into a hydrogen ion and a hydroxide ion. The hydrogen ion, which is positively charged, combines with the negatively charged metal-oxide ion. The hydroxide ion, which is negatively charged, combines with the positively charged metal ion at the anode forming a water molecule and metal-oxide molecule. When the anode becomes fully oxidized or when the cathode becomes completed reduced, the chemical reaction stops, and the battery has discharged all its potential energy. The positive electrode is lead-dioxide (PBO_2), and the negative electrode is lead (Pb). The electrolyte is a mixture of sulfuric acid.

The plates in a lead-acid battery are made up of a grid and a paste. The grid is a lead or lead alloy, and the paste is the active material that holds the charge. The density and porosity of the paste and the physical dimensions of the plate determine the capacity and discharge rate of the battery plate. For instance, high discharge rates require plates with a thin, porous paste whereas; high capacity batteries require thicker, denser plates. SLI batteries require thin plates for the high starting currents and standby batteries require thick plates with a denser paste to tolerate deeper discharge cycles.

The traditional lead-acid battery is known as a flooded cell and the lead plates are immersed in a solution of electrolyte. Flooded cell batteries vent gases during the discharge process and water must be added periodically to make up for lost electrolyte. Some of the newer flooded cell batteries, known as low maintenance batteries, come with enough extra electrolyte to make up for the electrolyte that will be lost during the life of the battery.

A newer design of lead-acid battery is known as a sealed-lead battery. In sealed-lead batteries the oxygen recombines with the lead and hydrogen to recreate water in the electrolyte. The separator in a sealed lead battery is some type of fibrous glass mat that is wetted with electrolyte. The design allows the gas by-products of the discharge cycle to recombine within the battery and thereby preventing the loss of electrolyte. Sealed-lead batteries must have a safety vent to prevent dangerous pressure buildups that might occur during overzealous recharging.

Lead-acid batteries are usually classified for SLI, deep cycle, or standby applications. SLI is starting, lighting, and ignition applications that require short, high current applications such as when turning an automobile starter. Deep-cycle batteries are designed for prolonged discharges such as boat trolling motors and golf carts and are well suited for utility scale energy storage projects.

The fundamental weakness of the flooded-cell battery for utility-scale energy storage projects is that it tolerates only 150 to 200 charge/discharge cycles before it is irreversibly damaged. However, a deep-cycle battery can tolerate discharge to as much as 80% of its rated capacity, with a cycle life of from 1,000 to 1,500 deep cycles. The deep-cycle battery tends to lose water at a faster rate than other types of lead-acid battery and needs frequent maintenance. Its self-discharge rate is also high. This battery is relatively expensive.

An SLI battery is discharged only occasionally with only a few amp-hours of capacity removed during discharge, but the discharge rate is extremely high. Except for starting, an SLI battery is normally in a trickle charge mode. Since little capacity is used during starting, the plates in an SLI battery can be thin. Therefore, SLI batteries tend to have many thin plates with a large surface area exposed to the electrolyte to handle the heavy discharge currents.

A deep cycle battery is charged, removed from its charging source, and then nearly totally discharged before recharging. Deep discharging creates large stresses in the plates, which causes the active material on the plates to pull away from the plates and fall to the bottom of the battery. Therefore, a deep cycle battery must be designed to account for the potential pull away of the active material from the plates. To minimize pull away the plate separators are thicker, there are fewer plates than an SLI battery, and the battery has room below the plates to accommodate waste material that pulls away from the plates and settles in the bottom of the battery case.

Lead-acid batteries suffer significant loss of life at high temperatures. At 35 degrees Celsius a lead-acid battery may only have half its normal life.

Nickel-Cadmium

A nickel cadmium, or Ni-Cad, battery is a type of rechargeable battery. Ni-Cad batteries have a reputation as a rugged, durable, energy source with good cycling capability and a broad discharge range. NiCad batteries are available either vented or sealed. The *vented NiCad* battery is designed for applications that require robust energy storage with long operating lifetimes and minimal maintenance. This form of the battery is currently used in several large electrical energy storage systems. The *sealed NiCad* battery is primarily used in small consumer products.

Ni-Cad's use nickel hydroxide for the positive electrode, cadmium for the negative electrode, and have an alkaline electrolyte. Typical Ni-Cad's are designed with the negative electrode larger than the positive electrode so that the gas generated at the positive electrode is absorbed by reacting with the excess material at the negative electrode. Therefore, the battery will not have to vent the gas.

Ni-Cad's have high storage density and the ability to deliver extremely high load currents on demand. They can be recharged very quickly provided appropriate safeguards are employed to prevent battery damage. They have low internal resistance, which enables them to deliver high discharge currents.

Modern Ni-Cad batteries can accept around 500 charge/discharge cycles before the service life becomes unacceptably short. The end of life for Ni-Cad's is usually characterized by an increase in internal resistance, which shortens the service life. An alternative failure mode is an internal short, which renders the battery completely inoperative.

When compared to primary batteries, Ni-Cad's do not have long service maintenance. Ni-Cad's will self-discharge in about six months and will self-discharge even quicker at high temperatures. A Ni-Cad will lose approximately 10% of its capacity within 24 hours after charging and will discharge to 1.1 volts within about six-months. Although superior to the lead-acid battery in performance, the NiCad battery has a higher rate of self-discharge, so constant charge maintenance is required. The NiCad battery can withstand a greater depth of discharge than can the lead-acid battery.

The NiCad battery is more tolerant of over-discharging or overcharging than lead-acid batteries. It is more tolerant of extreme temperature variation than is the lead-acid battery. It can also operate at subzero temperatures.

A problem with Ni-Cad's is the so called "memory effect". If a Ni-Cad does not routinely deliver a significant portion of its stored capacity the storage capacity will gradually decrease. The memory effect is caused by a crystalline structure known as dendrites forming on the separator films, which reduces capacity and may damage the separator causing small "shorts' within the battery.

Ni-Cad batteries are a mature technology and are low maintenance with excellent charge/discharge characteristics, good round-trip efficiency, and good cycling capability. Ni-Cads cost more than lead-acid batteries, have a high rate of self-discharge, and have low energy density. Some types suffer from the memory effect of previous charge/discharge cycles.

Nickel Metal Hydride

Nickel metal hydride (NiMH) batteries are an alternative to Ni-Cad batteries. The most common application for nickel metal hydride batteries are heavy power requirement portable electronic equipment such as portable PC's that require long run times.

The design of NiMH batteries is almost identical to Ni-Cad's except that a hydrogen absorbing negative electrode is used instead of a cadmium electrode. Nickel oxyhydroxide (NiOOH) is the active material in the positive electrode. The negative electrode is hydrogen in the form of a metal hydride that is capable of a reversible absorbing/desorbing reaction during charge and discharge. The electrolyte is an alkaline solution of diluted potassium hydroxide and in a sealed design most of the electrolyte liquid is absorbed by the separator and electrodes. The separator is usually a nylon blend material. NiMH batteries have a re-sealable safety to vent gases during overcharge. During normal operation and charging the oxygen recombination cycle can recombine gases and maintaining pressure equilibrium within the battery.

NiMH batteries will maintain a constant voltage during discharge until the capacity is nearly exhausted at which point the voltage drops rapidly. If the discharge current is excessive the battery voltage will deteriorate, and the rated capacity will be negatively impacted. Temperature can have a significant impact on battery performance and in cold temperatures the capacity is dramatically shortened.

Charging a NiMH battery is like Ni-Cad's except the voltage transitions are not as defined as with Ni-Cad's so care must be taken not to overcharge and damage the battery. Due to the more subtle changes in the voltage profile during charging, the charging circuits must be more sophisticated than those used for Ni-Cad's. NiMH batteries accept fast charges rather well.

The chemical process of NiMH batteries is exothermic meaning that heat is given off during the charging process. When a NiMH cell reaches full charge most of the charging current is converted to heat and the cell temperature and pressure increase rapidly. Since the voltage peak in NiMH's is not as significant as with Ni-Cad's and with the dramatic temperature increase at full charge, temperature sensing is the most reliable method of determining charge status.

NiMH batteries can operate effectively for over 500 cycles. Cell deterioration is in the form of increased internal resistance or a reduction of active material available for the chemical reaction.

Voltage depression, or memory effect, has only a slight impact on NiMH batteries. The "memory" characteristic of Ni-Cad's is not a significant issue with NiMH's. An advantage of NiMH batteries is that a normal discharge and recharge cycle will restore the chemicals in the cells to the original state, thereby erasing any memory effect. During discharge the battery should not be allowed to discharge too deeply to prevent cell reversal.

Like NiCad's, NiMH batteries are also a mature technology. They require little maintenance and have good energy density and charge/discharge cycling characteristics. They also do not suffer from memory effects. NiMH batteries are higher cost than lead-acid or Ni-Cad's and have a high self-discharge rate. Although the NiMH battery is a significant improvement over the

NiCad battery in energy density and has no "memory" issues, it has a much greater rate of self-discharge (30% per month), making it unsuitable for many applications.

Lithium Ion

Lithium ion batteries are the most widely used rechargeable battery. They are lightweight, have a high voltage rating, and an extremely good energy density. Newer types of Lithium ion batteries are being applied in PHEV applications.

The energy density of Li-Ion batteries is greater than either Ni-Cad's or NiMH batteries. Unlike Ni-Cad's, Li-Ion batteries do not suffer from voltage depression (memory). The discharge characteristic of Li-Ion batteries is like Ni-Cad's, which is flat over most of its service life.

Li-Ion batteries can be constructed in either cylindrical or prismatic forms. The prismatic can also be manufactured with a polymer "pouch." This form is commonly referred to as lithium polymer. The change in shape and material offers reduced weight and compactness.

The three primary components of a lithium-ion battery are the anode, cathode, and electrolyte, for which a variety of materials may be used. The most popular material for the anode is graphite. The cathode is generally one of three materials: lithium cobalt oxide, lithium iron phosphate, or lithium manganese oxide. Depending on the choice of material for the anode, cathode, and electrolyte, the voltage, capacity, life, and safety of a lithium-ion battery can change dramatically. The typical energy density of an Li-Ion battery is 150 Wh/kg.

During discharge, the current flows within the battery (when the external circuit is connected) from the anode to the cathode, as in any type of battery: the internal process is the movement of Lithium ions from the anode to the cathode, through the electrolyte and separator diaphragm.

When charging, an external electrical power source forces the current to pass in the reverse direction; the positive terminal from the charging circuit has to be connected to the cathode of the battery, and the anode has to be connected to the negative terminal of the external circuit. The lithium ions then migrate from the cathode to the anode, where they become embedded in the porous electrode material in a process known as intercalation.

The electrolyte is generally based on formulations containing manganese or cobalt salts. Pure lithium, like sodium, is very reactive. It will vigorously react with water to form lithium hydroxide and hydrogen gas is liberated. Thus, water is rigidly excluded from the battery pack by using a sealed container.

The internal resistance of lithium-ion batteries is high compared to other rechargeable chemistries such as nickel-metal hydride and nickel-cadmium. It increases with both cycling and age. Rising internal resistance causes the voltage at the terminals to drop under load, reducing the maximum current that can be drawn from them. Eventually they reach a point at which the battery can no longer operate for an adequate period.

The advantages of lithium-ion batteries include the ability to form the batteries into a wide variety of shapes and sizes so as to efficiently fill available space in the devices they power, they are light, the chemistry allows a high open circuit voltage to be obtained, they do not suffer from the memory effect, and they also have a self-discharge rate of approximately 5-10% per month, compared with over 30% per month for nickel metal hydride batteries.

The disadvantages include a relatively poor cycle life, high charge levels and elevated temperatures that hasten permanent capacity loss for lithium-ion batteries, they are can be extremely dangerous if mistreated, they may explode if overheated or if charged to an excessively high voltage, and they may be irreversibly damaged if discharged below a certain voltage.

Li-ion technology is being studied closely for application in megawatt-level storage. The high energy density, lack of memory effects, minimal environmental concerns, and self-monitoring/zero-maintenance qualities of this technology lend themselves to the utility industry.

Lithium Titanate

A lithium titanate battery is a form of Lithium-ion battery that is faster to charge than lithium-ion batteries. Instead of the carbon normally used for the anode of a lithium-ion battery a lithium-titanate anode is used in a lithium titanate battery and manganese is used for the cathode. In addition to faster charging, the lithium titanate battery operates well at low temperatures, have long life, and can be safely discharged completely.

Lithium Iron Phosphate

The lithium iron phosphate (LFP) battery is a form of a lithium ion battery, which uses lithium iron phosphate ($LiFePO4$) as a cathode material. Lithium iron phosphate is gaining market acceptance because of its low cost, non-toxicity, the high abundance of iron, its excellent thermal stability, safety characteristics, good electrochemical performance, and high specific capacity. The specific energy density is 90 Wh/kg.

The key barrier to commercialization was its intrinsically low electrical conductivity. This problem, however, was then overcome partly by reducing the particle size and effectively coating the lithium iron phosphate particles with conductive materials such as carbon.

The lithium iron phosphate battery uses a lithium-ion-derived chemistry and shares many of its advantages and disadvantages with other lithium ion battery chemistries. The key advantages for Lithium iron phosphate when compared with lithium ion (LiCoO2) batteries are improved safety through higher resistance to thermal runaway, longer cycle and calendar life, higher current or peak-power rating, and use of iron and phosphate which have lower environmental impact than cobalt.

The specific energy of a LFP battery is somewhat lower than that of a lithium ion battery. New LFPs have been found to fail prematurely if they are deep cycled too early. Rapid charging will shorten the batteries lifespan. Many brands of LFP's have a low discharge rate compared with lead-acid or lithium ion.

Lithium iron phosphate is an intrinsically safer cathode material than lithium ion. The chemistry of lithium iron phosphate batteries makes it difficult to release oxygen from the electrode, which reduces the risk of fire and the battery is resistant to over-charge damage. Only under extreme heating (generally over 800 °C) does breakdown occur and this bond stability greatly reduces the risk of thermal runaway when compared with lithium ion.

Zebra

The sodium nickel chloride battery is popularly known as the Zebra battery. Zebra is short for Zeolite Battery Research Africa Project. The technical name for the battery is the Na-NiCl2 battery.

Molten salt batteries are a class of high temperature electric battery that uses molten salts as an electrolyte. They offer both a higher energy density as well as a higher power density by means of a high conductivity molten salt electrolyte. They are used in services where high energy density and high-power density are required. These features make rechargeable molten salt batteries a promising technology for powering electric vehicles.

The Zebra battery operates at 250°C and utilizes molten sodium chloroaluminate (NaAlCl4), which has a melting point of 157°C, as the electrolyte. The negative electrode is molten sodium. The positive electrode is nickel in the discharged state and nickel chloride in the charged state. Because nickel and nickel chloride are nearly insoluble in neutral and basic melts, intimate contact is allowed, providing little resistance to charge transfer. Since both sodium chloroaluminate and sodium are liquid at the operating temperature, a sodium-conducting β-alumina ceramic is used to separate the liquid sodium from the molten sodium chloroaluminate.

The Zebra battery has a specific energy density of 90 Wh/kg. The β-alumina solid electrolyte is very stable, both to sodium metal and the sodium chloroaluminate. Lifetimes of over 1,500 cycles and five years have been demonstrated with full-sized batteries, and over 3,000 cycles and eight years with 10- and 20-cell modules.

When not in use, Zebra batteries are typically left under charge so that they will remain molten and be ready for use when needed. If shut down and allowed to solidify, a reheating process must be initiated that may require up to two days to restore the battery pack to the desired temperature and impart a full charge. This reheating time varies depending on the state-of-charge of the batteries at the time of their shut down, battery-pack temperature, and power available for reheating. After a full shut down of the battery pack, three to four days will usually elapse before a fully charged battery pack loses enough energy to cool and solidify.

The Zebra battery has high energy density and cycle times of 1,500 or greater and utilize low-cost materials. The batteries are expensive and must be maintained at high temperatures. Zebra batteries have not reached the mature market stage yet.

Sodium Sulfur

A sodium-sulfur (NaS) battery is a high temperature battery that consists of molten sulfur (S) electrode and a sodium (Na) anode that are separated by a solid beta alumina ceramic electrolyte. The sodium-sulfur battery has a high energy density, high efficiency of charge/discharge and long cycle life. Because of high operating temperatures (300 to 350°C) and their highly corrosive makeup, sodium-sulfur cells are primarily suitable for large-scale non-mobile applications such as grid energy storage.

The cell is usually made in a tall cylindrical configuration. The entire cell is enclosed by a steel casing that is protected, usually by chromium and molybdenum, from corrosion on the inside. This outside container serves as the positive electrode, while the liquid sodium serves as the negative electrode. The container is sealed at the top with an airtight alumina lid. An essential part of the cell is the presence of a beta-alumina sodium ion exchange membrane, which selectively conducts sodium ions. The cell becomes more economical with increasing size. In commercial applications the cells are arranged in blocks for better conservation of heat and are encased in a vacuum-insulated box.

The battery has a solid membrane between anode and cathode, compared with liquid metal batteries where the anode, the cathode, and the membrane are liquids. During the discharge phase, molten elemental sodium at the core serves as the anode, meaning that the sodium donates electrons to the external circuit. The sodium is separated by a beta-alumina solid electrolyte cylinder from the container of sulfur, which is fabricated from an inert metal serving as the cathode. The sulfur is absorbed in a carbon sponge. The beta-alumina solid electrolyte is a good conductor of sodium ions, but a poor conductor of electrons, so avoids self-discharge. When sodium gives off an electron, the sodium ion migrates to the sulfur container. The electron drives an electric current through the molten sodium to the contact, through the electrical load and back to the sulfur container. Here, another electron reacts with sulfur to form sodium polysulfide.

As the cell discharges, the sodium level drops. During the charging phase the reverse process takes place. When the system is fully operational the heat produced by charging and discharging cycles is sufficient to maintain operating temperatures and usually no external source is required.

Pure sodium presents a hazard because it spontaneously burns/explodes in contact with water, thus the system must be protected from moisture. In modern sodium-sulfur cells, sealing techniques make fires unlikely.

The battery temperature must be kept above 250°C. If it can cool below approximately 160°C, the electrolyte will freeze, irreversibly damaging the cell. During discharge, heating is not necessary since the electrochemical reaction is exothermic and generates enough heat to maintain temperature. During recharging and in the stand-by mode, electrical resistance heaters located in the module walls maintain the module's temperature.

Sodium-sulfur batteries have exceptional cycling capacity, good energy density, high reliability, and good longevity. In addition, Sodium-sulfur batteries have round-trip efficiencies of 75-80%. Disadvantages are that the units are expensive and must operate at high temperatures.

Vanadium

The Vanadium (VRB) battery is based on a vanadium-based reduction-oxidation (redox) regenerative fuel cell that converts chemical energy to electrical energy. Energy is stored chemically in different ionic forms of vanadium in a dilute sulfuric acid electrolyte. The electrolyte is pumped from separate plastic storage tanks into flow cells across a proton exchange membrane (PEM), where one form of electrolyte is electrochemically oxidized and the other is electrochemically reduced. This creates a current that is collected by electrodes and made available to an external circuit. The reaction is reversible, allowing the battery to be charged, discharged, and recharged. The vanadium redox battery is known as a *flow battery* because the electrolyte is a liquid that flows through a power cell that converts chemical energy to electricity.

The vanadium redox battery exploits the ability of vanadium to exist in solution in four different oxidation states and uses this property to make a battery that has just one electro-active element instead of two.

A VRB battery consists of two electrolyte tanks containing active vanadium species in different oxidation states. These energy-bearing liquids are circulated through a cell stack by pumps. A stack consists of many cells, each of which contains two half-cells that are separated by a membrane. In the half-cells, the electrochemical reactions take place on inert carbon felt polymer composite electrodes from which current may be used to charge or discharge the battery. The problem that had prevented the development of flow batteries prior to the VRB was the cross-contamination of the electrolytes. When two liquid electrolytes made of different substances are separated by a membrane, eventually the membrane is permeated and the two substances mix, making the battery useless. This problem was solved by using the same element on both sides of the battery. Although cross-contamination still occurs, it is essentially the same element, thus eliminating contamination as a problem. Because of this, the vanadium electrolyte can function indefinitely.

Other useful properties of vanadium flow batteries are their fast response to changing loads and their extremely large overload capacities. Studies have shown that they can achieve a response time of under one-half millisecond for a 100% load change and allowed overloads of as much as 400% for 10 seconds. Round trip efficiency is around 75%.

Current production vanadium redox batteries achieve an energy density of about 25 Wh/kg of electrolyte. This energy density is quite low as compared to other rechargeable battery types.

The extremely large capacities possible from vanadium redox batteries make them well suited to use in large power storage applications such as helping to average out the production of highly variable generation sources such as wind or solar power, or to help generators cope with large surges in demand. Their extremely rapid response times also make them superbly well suited to UPS type applications, where they can be used to replace lead-acid batteries and even diesel generators.

The separate power and energy sections make it possible to add storage capacity simply by adding tanks and electrolyte. This is an important attribute for matching a battery to an application that may require additional capacity later.

The advantages of the vanadium redox battery are that it can offer almost unlimited capacity simply by using larger and larger storage tanks, it can be left completely discharged for long periods with no ill effects, it can be recharged simply by replacing the electrolyte if no power source is available to charge it, and if the electrolytes are accidentally mixed the battery suffers no permanent damage.

The disadvantages with vanadium redox technology are a relatively poor energy-to-volume ratio, and the system complexity in comparison with standard storage batteries.

Zinc Bromine


Photo Credit: ZBB Technologies

The zinc-bromine (ZnBr) flow battery holds promise in both performance and cost. The primary features of the zinc-bromine battery are: Good energy density, excellent depth of discharge, good cycle life, and capable of storing megawatt levels of power.

The zinc-bromine flow battery is a type of hybrid flow battery. A solution of zinc bromide is stored in two tanks. When the battery is charged or discharged the electrolyte is pumped through a reactor stack and back into the tanks. One tank is used to store the electrolyte for the positive electrode reactions and the other for the negative. Zinc-bromine batteries have an energy density of around 50 Wh/kg.

The electrolyte is composed of zinc bromide salt dissolved in water. During charge, metallic zinc is plated from the electrolyte solution onto the negative electrode surfaces in the cell stacks. Bromide is converted to bromine at the positive electrode surface of the cell stack and is immediately stored as safe, chemically complex organic phase in the electrolyte tank.

During charging zinc is electroplated onto conductive electrodes, while at the same time bromine is formed. On discharge the reverse process occurs, the metallic zinc plated on the negative electrodes dissolves in the electrolyte and is available to be plated again at the next charge cycle. In the fully discharged state, it can be left indefinitely for later charge without damage.

The Zinc-bromine battery's AC round-trip efficiency is approximately 75%. An agent in the electrolyte is used to reduce the reactivity and vapor pressure of the elemental bromine, which minimizes the self-discharge of the battery and significantly improves safety. Zinc is not a toxic metal and the battery contains no concentration of bromine. The battery stacks are made from recyclable plastics. The cycling capability of the Zinc-bromine battery is excellent at 10,000 cycles at 80% depth of discharge.

In summary, the Zinc-bromine battery has a high energy density relative to lead-acid batteries, can achieve 100% depth of discharge capability on a daily basis, has a high cycle life of greater than 2,000 cycles, and does not have shelf life limitations.

Chapter 3
Non-Electrochemical Storage

In Chapter 2 we looked at electrochemical, or battery, storage options. In this chapter we will look at a few of the non-electrochemical storage options including compressed air systems, pumped storage hydro power plants, flywheels, thermal storage, and ultra-capacitors.

Compressed Air

Compressed Air Energy Storage (CAES) refers to the compression of air to be used later as energy source. It can be stored during periods of low energy demand, and for use in meeting periods of higher demand. Compressed air systems use about 40% less energy than a traditional combined-cycle gas turbine by injecting compressed air into the input fuel to the turbine.

Off-peak electrical power is used to compress air into an underground air-storage “vessel” and later the air is used to feed a gas-fired turbine generator complex to generate electricity during on-peak times.

Air is stored in mass quantity in underground in a cavern created by solution mining or an abandoned mine. Plants are designed to operate on a daily cycle, charging at night and discharging during the day. The extra heat of compression is removed from the air with inter-coolers following compression and is dissipated into the atmosphere as waste. These plants have efficiencies of 50-55%.

When gas is compressed some of the compression work goes into heating the gas. If this heat is then lost to the surroundings, and assuming the same quantity of heat is not added back to the gas upon expansion, the energy storage efficiency will be reduced. Energy storage systems often use large natural underground caverns. This is the preferred system design, due to the large gas volume, and thus the large quantity of energy that can be stored with only a small change in pressure. The cavern space can be compressed, and the resulting temperature change and heat losses are small.

Advantages of compressed air over electric storage are the longer lifetime of pressure vessels compared to batteries and the lower toxicity of the materials used. Costs are thus potentially lower, however advanced pressure vessels are costly to develop and safety-test and at present are more expensive than mass-produced batteries.

Compressed air energy storage can be a hybrid power generation system, with the stored compressed air mixed with a fuel suitable for an internal combustion engine. For example, natural gas or biogas can be added, then combusted to heat the compressed air, and then expanded in a conventional gas turbine engine.

Pumped Storage Hydro

Pumped storage hydroelectricity is a type of hydroelectric power generation used by some power plants for load balancing. The method stores energy in the form of water, pumped from a lower elevation reservoir to a higher elevation. Low-cost off-peak electric power is used to run the pumps. During periods of high electrical demand, the stored water is released through turbines. Although the losses of the pumping process make the plant a net consumer of energy overall, the system increases revenue by selling more electricity during periods of peak demand, when electricity prices are highest. Pumped storage is the largest-capacity form of grid energy storage now available.

At times of low electrical demand, excess generation capacity is used to pump water into the higher reservoir. When there is higher demand, water is released back into the lower reservoir through a turbine, generating electricity. Reversible turbine/generator assemblies act as pump and turbine. Some facilities use abandoned mines as the lower reservoir, but many use the height difference between two natural bodies of water or artificial reservoirs. Pure pumped-storage plants just shift the water between reservoirs, but combined pump-storage plants also generate their own electricity like conventional hydroelectric plants through natural streamflow.

Considering evaporation losses from the exposed water surface and conversion losses, approximately 70% of the electrical energy used to pump the water into the elevated reservoir can be regained. The relatively low energy density of pumped storage systems requires either a large body of water or a large variation in height and finding a suitable site can limit its use.

This system may be economical because it flattens out load variations on the power grid, permitting thermal power stations such as coal-fired plants and nuclear power plants and renewable energy power plants that provide base-load electricity to continue operating at peak efficiency, while reducing the need for "peaking" power plants that use costly fuels. However, capital costs for purpose-built pumped storage hydro systems are high.

Along with energy management, pumped storage systems help control electrical network frequency and provide reserve generation. Thermal plants cannot respond quickly to sudden changes in electrical demand, potentially causing frequency and voltage instability. Pumped storage plants, like other hydroelectric plants, can respond to load changes within seconds.

A new use for pumped storage is to level the fluctuating output of intermittent power sources. The pumped storage absorbs load at times of high output and low demand, while providing additional peak capacity. Increased wind generation may increase the likelihood of such occurrences. It is particularly likely that pumped storage will become especially important as a balance for very large-scale photovoltaic generation.

Flywheels

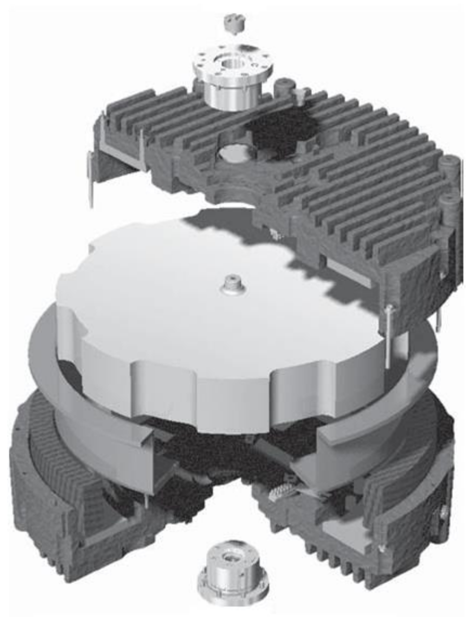


Photo Credit: ActivePower, Inc

Flywheel Energy Storage Systems (FES) store energy in the angular momentum of a spinning mass. During charge, the flywheel is spun up by a motor with the input of electrical energy; during discharge, the same motor acts as a generator, producing electricity from the rotational energy of the flywheel. Most products are capable of several hundred thousand full charge-discharge cycles and enjoy much better cycle life than batteries.

They are capable of high cycle efficiencies of over 90%. Since the energy sizing of a flywheel system is dependent on the size and speed of the rotor, and the power rating is dependent on the motor-generator, power and energy can be sized independently. One flywheel design is constructed of carbon and fiberglass composites to withstand up to 22,500 revolutions/min. The flywheel is housed in a vacuum sealed steel container and employs a high-speed magnetic lift system to minimize friction. Flywheels are designed to shut down benignly in case of failure, and the composite material is designed to disintegrate in case of failure to avoid potential injuries.

Advanced FES systems have rotors made of high strength carbon-composite filaments, suspended by magnetic bearings, and spinning 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 — much quicker than some other forms of energy storage.

Flywheel power storage systems in current production have storage capacities comparable to batteries and faster discharge rates. They are mainly used to provide load leveling for large battery systems, such as an uninterruptible power supply for data centers.

Flywheel maintenance in general runs about one-half the cost of traditional battery UPS systems. Newer flywheel systems completely levitate the spinning mass using maintenance-free magnetic bearings, thus eliminating mechanical bearing maintenance and failures.

In utility operations, flywheels can provide frequency regulation. Lower carbon emissions, faster response times and ability to buy power at off-peak hours are among some advantages of using flywheels instead of traditional sources of energy for peaking power plants. Currently, high-speed flywheel systems rated for 1,000 kW for 15 minutes are being deployed for frequency regulation.

Flywheels are not affected by temperature changes as are chemical rechargeable batteries, nor do they suffer from memory effect. They are also less potentially damaging to the environment, being made of largely inert or benign materials. Another advantage of flywheels is that by a simple measurement of the rotation speed it is possible to know the exact amount of energy stored.

Recently, flywheels have been proposed for longer duration applications and one such design is a proposed 20-MW flywheel energy storage system for frequency regulation applications at the transmission level.

Flywheels have a cycle life of 100,000 - 2,000,000 cycles based on design specifications. The service life estimate is based on the cycle life and expected usage for various market applications.

Thermal energy storage

Thermal energy storage may refer to technologies that store energy in a thermal reservoir for later reuse. They can be employed to balance energy demand between daytime and nighttime. The thermal reservoir may be maintained at a temperature above or below than that of the ambient environment.

The principal application today is the production of ice, chilled water, at night, which is then used to cool environments during the day.

Thermal energy storage technologies store heat, usually from active solar collectors, in an insulated repository for later use in space heating, domestic or process hot water, or to generate electricity.

Thermal energy storage is made practical by the large heat-of-fusion of water; One metric ton of water, just one cubic meter, can store 317k BTUs. In fact, ice was originally transported from mountains to cities for use as a coolant, and the original definition of a "ton" of cooling capacity was the heat to melt one ton of ice every 24 hours.

The most widely used form of this technology is in large building or campus-wide air conditioning or chilled water systems. Air conditioning systems, especially in commercial buildings, are the most significant contributors to the peak electrical loads seen on hot summer days. In this application a relatively standard chiller is run at night to produce a pile of ice. Water is circulated through the pile during the day to produce chilled water that would normally be the daytime output of the chillers.

The efficiency of air conditioning chillers is measured by their coefficient of performance (COP). In theory, thermal storage systems could make chillers more efficient because heat is discharged into colder nighttime air rather than warmer daytime air. In practice, this advantage is overcome by the heat losses while making and melting the ice.

There are still some advantages to society from air conditioning thermal storage. The fuel used at night to produce electricity is a domestic resource in most countries, so that less imported fuel is used. This process also has been shown in studies to significantly reduce the emissions associated with producing the power for air conditioners, since inefficient "peaker" plants are replaced by low emission base load facilities in the evening. The plants that produce this power are often more efficient than the gas turbines that provide peaking power during the day. And because the load factor on the plants is higher, fewer plants are needed to service the load.

A new twist on this technology uses ice as a condensing medium for refrigerant. In this case, regular refrigerant is pumped to coils where it is used. Instead of needing a compressor to convert it back into a liquid, however, the low temperature of the ice is used to chill the refrigerant back into a liquid. This type of system allows existing refrigerant based HVAC equipment to be converted to thermal energy storage systems, something that could not previously be easily done with chill water technology. In addition, unlike water-cooled chill water systems that do not experience a tremendous difference in efficiency from day to night, this new class of equipment typically displaces daytime operation of air-cooled condensing units. In areas where there is a significant difference between peak daytime temperatures and off-peak temperatures, this type of unit is typically more energy efficient than the equipment it is replacing.

Super-Capacitors

Electric double-layer (EDL) capacitors, also known as supercapacitors, are electrochemical capacitors that have an unusually high energy density when compared to common capacitors, typically on the order of thousands of times greater than a high capacity electrolytic capacitor. Larger double-layer capacitors have capacities up to 5,000 farads. These supercapacitors look and perform like battery storage technologies. The highest energy density is 30 Wh/kg.

EDL capacitors have a variety of commercial applications, notably in "energy smoothing" and momentary-load devices. They have applications as energy-storage devices used in vehicles and for smaller applications like home solar systems where extremely fast charging is a valuable feature.

Photo Courtesy of Maxwell Technologies

In a conventional capacitor energy is stored by the removal of electrons, from one metal plate and depositing them on another. This charge separation creates a potential between the two plates, which can be harnessed in an external circuit. The total energy stored in this fashion is proportional to both the amount of charge stored and the potential between the plates. The amount of charge stored is essentially a function of size and the material properties of the plates, while the potential between the plates is limited by dielectric breakdown of the substance separating the plates. Different materials sandwiched between the plates to separate them result in different voltages to be stored. Optimizing the material leads to higher energy densities for any given size of capacitor.

EDL capacitors do not have a conventional dielectric. Rather than two separate plates separated by an intervening substance, these capacitors use "plates" that are in fact two layers of the same substrate, and their electrical properties, the so-called *electrical double layer*, result in the effective separation of charge despite the vanishingly thin physical separation of the layers. The lack of need for a bulky layer of dielectric permits the packing of "plates" with much larger surface area into a given size, resulting in extraordinarily high capacitances in practical-sized packages.

In an electrical double layer, each layer by itself is quite conductive, but the physics at the interface where the layers are effectively in contact means that no significant current can flow between the layers. However, the double layer can withstand only a low voltage, which means that electric double-layer capacitors rated for higher voltages must be made of matched series-connected individual EDLCs, much like series-connected cells in higher-voltage batteries.

In general, EDL capacitors improve storage density using activated charcoal in place of the conventional insulating barrier. Activated charcoal is a powder made up of extremely small and very rough particles, which in bulk form a low-density volume of particles with holes between them that resembles a sponge. The overall surface area of even a thin layer of such a material is many times greater than a traditional material like aluminum, allowing many more charge carriers to be stored in any given volume.

EDL capacitors have much higher *power density* than batteries. Power density combines the energy density with the speed that the energy can be delivered to the load. Batteries, which are based on the movement of charge carriers in a liquid electrolyte, have relatively slow charge and discharge times. Capacitors, on the other hand, can be charged or discharged at a rate that is typically limited by current heating of the electrodes. While existing EDL capacitors have energy densities of only 10% of a conventional battery, their power density is generally 10 to 100 times as great.

The advantages of supercapacitors include long life, with little degradation over hundreds of thousands of cycles, low cost per cycle, good reversibility, very high rates of charge and discharge, extremely low internal resistance, high output power, high specific power, and rapid charging. The disadvantages include the amount of energy stored per unit weight is considerably lower than that of an electrochemical battery, low working voltage, has the highest dielectric absorption of any type of capacitor, has a high self-discharge, and cells have low voltages.

Chapter 4
Plug-in Electric Hybrid Vehicles

This chapter takes a somewhat futuristic look at the potential impact of a significant penetration of Plug-in Hybrid Electric Vehicles (PHEVs) both in terms of increased demand on the electric power delivery system and the possible benefits of the distributed energy storage this technology can offer. Using a PHEV to provide energy storage is called vehicle-to-grid (V2G) power.

A hybrid electric vehicle (HEV), such as the Toyota Prius, has both an electric motor and a combustion engine. The battery pack is small because the electric drive is used only for assisting acceleration and generally managing the alternations that occur between electric and engine power. This system provides good overall performance using a smaller combustion engine. This configuration improves fuel economy by 20–35%, allows for optimized operation of the engine, can capture braking energy, and store it in the battery, and can reduce engine emissions due to improved engine control. The batteries sustain their charge during the driving cycle and are not normally designed to be capable of accepting a charge from the grid. The HEV, like conventional automobiles with only combustion engines, has a range limited only by the size of the fuel tank.

A PHEV is an HEV with a much larger battery pack and the ability to operate for 20–40 miles in an electric-only mode. The combustion engines are smaller and can be optimized by functioning as a generator that charges the batteries using onboard fuel. PHEVs store enough electricity, presumably from an overnight charge, to permit the first 40 or so miles to be driven solely on electric power. Beyond this range, PHEVs function like HEVs—they are intended to be charged from the grid, and the small combustion engine would only be used when the automobile's battery is substantially depleted of charge.

Utilities are moving to Smart grid technologies—technologies with embedded computers that collectively can provide a network of distributed intelligence. The Smart grid will incorporate standardized communication protocols, affording significant interoperability with other devices. It will be integrated with a smart electricity infrastructure at the distribution level, with the energy management system at the transmission level, and with grid operations and planning. One study suggests that "with parallel advances in smart vehicles and the smart grid, PHEVs will become an integral part of the distribution system itself within 20 years, providing storage, emergency supply, and grid stability."

At present, most experts agree that the adoption of PHEVs will begin in the short term with vehicle charging managed by pricing that encourages charging in off-peak times. This grid-to-vehicle concept gives cost benefits to those agreeing to charge their vehicles at night, thus filling in the load valley, and penalizes those charging during the day.

Owning a PHEV and recharging it every night for a minimum charge would increase the average consumer's electric consumption by approximately 50%. While this is an energy load, it is also a potential source of energy storage. If it is assumed that there is a uniform distribution of battery charge, that automobiles are driven on average two hours per day, and that the automobiles are available for use by a utility when they are not being driven, then there would be significant energy capacity stored in the PHEV's. This capability is valuable to the electric power grid for peak shaving, valley filling, and reserve spinning for guarding against losses due to contingencies.

A major challenge to consider is how PHEV usage will interact with high levels of renewable energy generation capacity, especially wind and solar power. Some types of renewable energy generation have strong diurnal characteristics, which are obvious with sunlight limitations for solar power and which vary somewhat according to geography for wind power. If the PHEV charging load matches peak renewable energy production, then the electric power industry will be provided with an ideal situation. If the PHEV charging does not match daily renewable energy generation cycles well, then the mismatch is problematic, and deployment of energy storage technology has an even more important role.

The next logical stage of infrastructure development is the vehicle-to-home (V2H) and/or the vehicle-to-building (V2B) concept. Here, a PHEV would have the ability to communicate with the home or small businesses. The PHEV battery might be operated in a way that makes it available for emergency backup for the home or business in addition to allowing the home to manage its charge/discharge schedule. Optimization of onsite renewable energy sources would be a strong benefit because the consumer could take advantage of the additional production of the on-site energy, such as wind power at night, when there is minimal demand from the home or business.

In the long term, the envisioned V2G concept allows for full bidirectional controlled flow between the vehicle and the grid. Control of the bidirectional electric flow could include payments to owners for use of their automobile batteries for load leveling or regulation and for spinning reserve. Because the flow of energy is bidirectional, electric service providers can benefit in addition to PHEV owners by controlling or at least monitoring the flow between PHEVs and the grid.

Summary

Except for pumped storage hydro and perhaps compressed air energy systems, utility-scale energy storage systems are not widely deployed. However, with the restructuring of the electric utility industry and the increase use of variable energy sources such as wind and photovoltaics, utility-scale energy storage systems are receiving a lot of interest.

Batteries, thermal storage, flywheel storage, supercapacitors, pumped storage hydro, compressed air energy systems, and even plug-in hybrid electric vehicles are all potential storage mechanisms for utility scale energy storage systems.

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