Quadrennial Technology Review 2015

## **Chapter 3:** Enabling Modernization of the Electric Power System

# Technology Assessments

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U.S. DEPARTMENT OF
ENERGY

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# Electric Energy Storage

## **Chapter 3:** Technology Assessments

## Introduction

Electric energy storage technologies (EESTs) have the potential to significantly improve the operating capabilities of the grid as well as mitigate infrastructure investments. The key characteristic of energy storage technologies is their ability to store electricity produced at one time for use at another time, balancing supply and demand. This capability can be used to address a number of challenges facing the power sector today, including the increased variability and uncertainty that accompanies greater reliance on intermittent generating technologies, as well as improve economic dispatch, efficiency, and power quality.

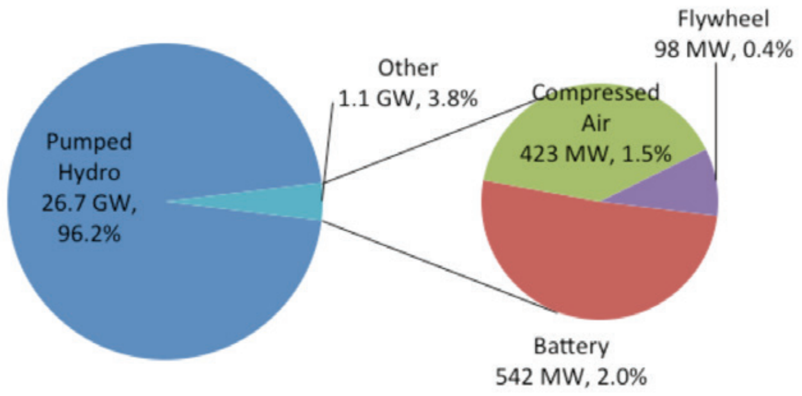
EESTs can support system balancing and economic dispatch on the bulk transmission system and regulation of power quality and coordination of distributed energy resources on distribution systems. EESTs can also be located in local communities or behind the customer meter to contribute to emergency preparedness and resiliency. Deployment of these technologies, along with other innovative solutions, including advanced control software, can enhance the grid's capabilities and flexibility.

This white paper examines the state of EESTs and opportunities for improvement. The scope of this assessment includes stationary energy storage technologies that are interconnected to the grid and are characterized by a bidirectional power transfer capability and the ability to discharge on command. The technologies of focus include bulk energy technologies, including pumped hydropower storage (PHS) and compressed air energy storage (CAES); battery technologies, including lead acid, sodium sulfur, lithium ion, and flow designs; power technologies, including flywheels, superconducting magnetic energy storage, and electrochemical capacitors (ECs); and hydrogen energy storage (HES). Excluded from this review are mobile storage technologies (e.g., electric vehicle applications) and thermal storage (e.g., concentrated solar thermal, ice storage, water heaters, and building thermal inertia). The latter technologies are addressed in the context of the Flexible and Distributed Energy Resources white paper. The remainder of this paper examines the state of EESTs, including the state of the market for storage technologies, applications and challenges influencing the technologies development, and the state of individual technologies and potential opportunities for research and development (R&D).

### State of the Electric Energy Storage Technology Market

The U.S. Department of Energy's (DOE) Global Energy Storage Database reports approximately 300 electric energy storage projects (deployed and anticipated) in the United States as illustrated in Figure 3.C.1, with a projected cumulative operational capacity of 29 gigawatts (GW).[1] Pumped hydropower storage dominates this mix at 96% of the total. This reflects the larger unit size of PHS units and their established role in the electric power system. Compressed air energy storage, batteries, and flywheels constitute the remaining 4% of the storage capacity. Recent additions of storage include 12 projects totaling 59 megawatts (MW) of storage capacity funded by the American Recovery and Reinvestment Act (ARRA) Smart Grid Demonstration Program.[2] Worldwide, about 140 GW of large-scale grid connected energy storage is installed. Trends internationally are similar to domestic ones—the majority of this capacity (~99%) being PHS with the remaining being a mix of battery, CAES, flywheels, and hydrogen storage.[3]

**Figure 3.C.1** Rated Power of U.S. Grid Storage Projects 2014 (Including Announced Projects)



The market demand for storage technologies is strong. One study estimates the global market for utility-scale energy storage is expected to grow to $15.6 billion annually in 2024 from $675 million annually today.[4] This reflects nearly 700 MW of energy storage projects (excluding PHS) recently announced, with the majority located in North America (436 MW) and nearly half of that in California. Asia Pacific and Western Europe are also leading regions, with 165 MW and 95 MW of new projects announced, respectively.[5] Other forecasts estimate the global energy storage market to have annual installations of 6 GW in 2017 and over 40 GW by 2022, with the United States capturing the majority of these installations.[6]

Most prominent among international technology development activities was the commercialization of high temperature sodium-sulfur (NaS) batteries achieved through a sustained R&D effort in Japan. More recently, demonstration projects in Europe and Canada reflect a broad range of technologies and applications, including hydrogen energy storage systems.[7,8,9,10] China and India are actively pursuing electric energy storage programs to support the rapid growth in their electric energy needs and address access and reliability issues. There are lessons to be learned from these global activities and research advances that can be leveraged domestically.

## Applications

There are a wide variety of EESTs and each can provide a range of services to the electric grid as shown in Table 3.C.1.[11] It is important to evaluate the potential for "stacking" multiple services that a technology is able to provide, thereby maximizing its benefits and providing the grid with greater operational flexibility. For example, a 2012 Pacific Northwest National Laboratory (PNNL) study indicated that, on the margin, for every additional unit of wind power capacity added in the Western Electricity Coordinating Council (WECC) region, approximately 0.07 to 0.22 units of intra-hour balancing need to be added.[12] This increased operating reserve could be met by additional generation units, demand response, other distributed energy resources, or storage technologies.

Each electric storage technology has its own performance characteristics that make it optimally suited for certain grid applications versus others, as illustrated in Figure 3.C.2. The suitability of a storage technology is determined primarily by its power and energy capacity and the rate at which these can be stored and delivered. Other characteristics to consider are round-trip efficiency (how much energy is lost from charging and discharging), cycle life (how many times the technology can charge and discharge at a particular depth of discharge [e.g., 80% or 100%]), safety, and ramp rate (how fast the technology can respond to a command).

EESTs have the unique ability to serve as a source of power as well as act as a load. Some technologies also have the ability to produce alternating current (AC) and direct current (DC) power. Compared to conventional thermal generation units, some electric storage technologies are able to respond significantly faster to control signals and utilize their full capacity rating in a shorter time frame. In contrast, the minimum generation constraint and inertia of thermal generation limits operational flexibility and can lead to suboptimal economic dispatch. Storage technologies may also provide reactive power compensation, which can assist in voltage

**Table 3.C.1** Grid Services That Energy Storage Could Provide[13]

**Bulk Energy Services**

- Electric Energy Time-Shift (Arbitrage)
- Electric Supply Capacity

**Ancillary Services**

- Regulation
- Spinning, Non-Spinning and Supplemental Reserves
- Voltage Support
- Black Start
- Other Related uses

**Transmission Infrastructure Services**

- Transmission Upgrade Deferral
- Transmission Congestion Relief

**Distribution Infrastructure Services**

- Distribution Upgrade Deferral
- Voltage Support

**Customer Energy Management Services**

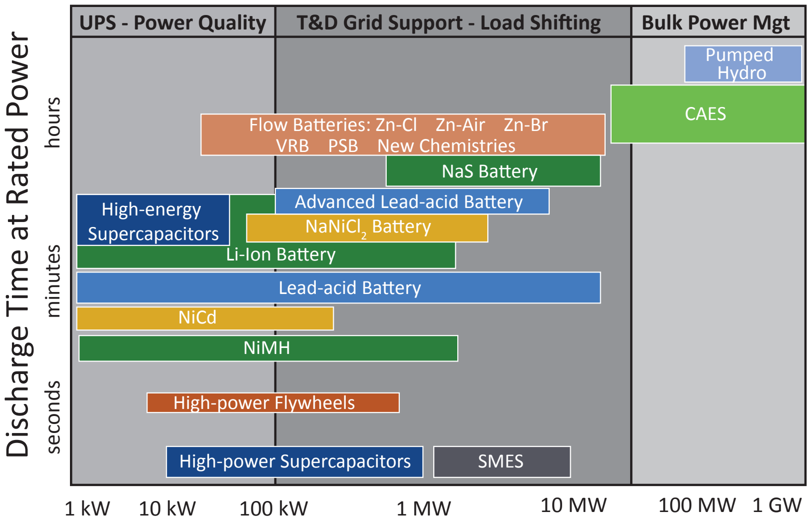
- Power Quality
- Power Reliability
- Retail Electric Energy Time-Shift
- Demand Charge Management

support and system stability and help manage operating behavior of other grid and customer assets. All of these capabilities provide increased flexibility, leading to improved reliability and greater efficiency in the electric power system.

Storage technologies can help balance system supply and demand and reduce curtailments of renewable resources imposed for operational reasons. At higher penetrations of variable renewable resources, some conventional generators will be forced to ramp down during periods of low load to maintain system balance.[14] There are technical limits to how much power plants of all types can be turned down. For example, large coal plants are often restricted to operating in the range of 50%–100% of full capacity. If base load generators cannot reduce output or some other use cannot be found for the excess generation, these low/zero marginal cost and emissions-free resources will be curtailed, a problem in some areas of the country today (namely Texas, the Midwest, and the Pacific Northwest). EESTs provide one set of solutions to minimizing curtailment by storing excess

**Figure 3.C.2** Representative Energy Storage Technologies for Different Applications

Credit: Sandia National Laboratories



renewable electricity during times of low system load or by providing electricity during times of high system load, removing the need to dispatch conventional units that are partially loaded.

Realizing and monetizing the value of the various services that storage can provide will improve the cost-competitiveness of storage as compared with alternatives. Part of the challenge is identifying and clarifying the multiple-use cases and associated values. Numerous studies have quantified the benefits of EESTs. These values were substantial across the various value streams.[15] EESTs also provide societal benefits that are less readily quantified, such as reduced reliance on fossil fuel and increased energy security, reduced air emissions, and improved business productivity.[16] Facility location is another important aspect of the value proposition of storage. Strategically located units in either bulk or distributed settings can yield significantly higher benefits.[17]

## Challenges

While there are many benefits associated with the development and demonstration of EESTs, there are still many challenges. Four key barriers that currently limit the widespread deployment of electric energy storage are (1) lack of cost-competitive systems, (2) need for validated performance and safety, (3) development of equitable regulatory environments, and (4) widespread industry acceptance.[18] The remainder of this section examines each of these issues in more detail.

### Cost-competitiveness

Energy storage technology costs—including all subsystem components, installation, and integration costs—are the primary barrier to the deployment of energy storage resources.[19] Energy storage components, such as battery chemistries or the spinning mass in a flywheel, constitute only about 30% to 40% of the total system cost. A full understanding of the life-cycle investment (e.g., including site acquisition and preparation, system design and engineering, permitting and commissioning, and operations and maintenance) is needed to understand hardware and balance-of-system cost levels required to achieve the desired cost and performance targets in Table 3.C.2.

**Table 3.C.2** Cost and Performance Targets for Electric Energy Storage Technologies[20]

| | |
|---|---|
| **Range of Baselines** | **System capital cost by energy:** \$800-\$10,000/kWh<br>**Levelized cost:** 1-64¢/kWh/cycle<br>**System efficiency:** 75%–92%<br>**Cycle life:** 4,500-225,000 over life of plant<br>**System capital cost by power:** \$300-\$4,600/kW |
| **Near-term Targets** | **System capital cost by energy:** under \$250/kWh<br>**Levelized cost:** under 20¢/kWh/cycle<br>**System efficiency:** over 75%<br>**Cycle life:** more than 4,000 cycles<br>**System capital cost by power:** under \$1,750/kW |
| **Long-term Targets** | **System capital cost by energy:** under \$150/kWh<br>**Levelized cost:** under 10¢/kWh/cycle<br>**System efficiency:** over 80%<br>**Cycle life:** more than 5,000 cycles<br>**System capital cost by power:** under \$1,250/kW |

## Validated Performance and Safety

A process for evaluating and reporting the performance of electric energy storage systems on a unified basis is needed to give investors and insurers confidence in the safety, reliability, and performance of these new technologies. For example, there is significant uncertainty over the usable life of batteries, which directly impacts investment calculations. Another issue that affects the viability of batteries is the availability of a battery health monitoring system that can improve longevity, facilitate maintenance, and enhance controllability. Real-time monitoring of battery conditions that enable optimal operation and early detection of potential failures can improve performance and safety. A preliminary protocol for performance testing of grid energy storage technologies was developed in 2012 and updated in 2014.[21] Combining this testing protocol with industry-accepted codes and performance standards can lead to a wider acceptance of these technologies.

The operational safety of large electric energy storage systems is also a concern. Greater emphasis should be placed on science-based safety testing procedures and developing and codifying design practices that incorporate safety standards. Given the scale of grid storage systems, computational modeling must be part of the solution to extend results and insights from smaller-scale safety testing. Proactive and predictive safety approaches are necessary to ensure that the risk of failure and loss is minimized. Safety validation techniques, incident preparedness, safety codes, standards, and regulations are required to address this challenge. [22,23]

## Equitable Regulatory Environments

Because EESTs can act as a source of energy, a load, a transmission or distribution asset, and a provider of ancillary services, they reside in a gray area as to whether a particular installation would be regulated by public utility commissions. Storage technology developers and owners may operate in regulatory environments that are a combination of competitive market pricing and cost of service regulation, adding to the uncertainty. Regulatory restrictions and lack of clarity in accounting practices and requirements may prevent a utility or developer from obtaining revenue with a resource providing service under multiple classifications.[24] There is a need for comprehensive study of, and research on, regulatory and market designs and their effects on various storage technologies. This information will improve understanding between technology developers, device and system vendors, utilities, market managers, and regulators.[25]

While there have been some opportunities with frequency regulation, there are still many regulatory and market uncertainties surrounding the economics of different applications and the lack of an established revenue generation model that dissuade broader investment. Understanding how these technologies can monetize services individually and in combination will be important to establishing equitable market and regulatory environments. An additional consideration is the fact that the economics and the design parameters for a particular storage technology are intertwined. Energy storage systems are designed to meet duty cycles and specifications for the use cases for which they can economically provide services.

## Industry Acceptance

Industry adoption and acceptance of EESTs requires confidence that, once deployed, technologies will perform as promised and deliver benefits as predicted. System operators today have limited experience with using newer storage resources, and there is significant uncertainty in how the various technologies will actually be used in practice and how they will perform over time for different applications. Use case development and validated control algorithms that employ newer EESTs effectively and profitably could encourage greater investments. An additional barrier to industry adoption of EESTs is the interoperability of existing storage solutions. While there are a few standards under development and current standards are being modified, a more coordinated process of promoting, developing, and demonstrating standards would enable plug-and-play solutions.

The ability to model the operational use of storage and its economics can also limit storage deployment. Current planning tools used by utilities do not have the capability to adequately analyze certain EESTs as an option for transmission or distribution applications. Developing and integrating proper models into tools that are currently used by utilities (rather than developing stand-alone tools) could increase industry acceptance for newer technologies. The lack of models and tools based on nondeterministic methods that can, for example, account for the effects of market and system uncertainties is also a limitation. Such tools could lead to improved energy storage operation, resource assessment, and decision making.[26]

## Technology Status

There are numerous EESTs that differ in capabilities and applications that are summarized in Table 3.C.3. This paper organizes these various technologies into four broad categories: (1) bulk energy storage technologies (including PHS and CAES), (2) battery technologies, (3) power technologies, and (4) hydrogen energy storage. Challenges for the various EESTs are also included in Table 3.C.3. The remainder of this white paper describes the state of the various technologies and the research and development opportunities for each.

**Table 3.C.3** Summary of Technology Types, Applications, and Challenges[32]

| Technology | Primary Application | State of the Technology | Challenges |
|---|---|---|---|
| Bulk Energy Storage Technologies | | | |
| Pumped Hydro Storage | ■ Energy management<br>■ Backup and seasonal reserves<br>■ Regulation service during generation<br>■ Regulation service through variable speed pumps during pumping | ■ Developed and mature technology<br>■ Very high ramp rate<br>■ Currently most cost-effective form of storage | ■ Geographically limited<br>■ Plant site<br>■ Environmental impacts<br>■ High overall project cost |
| Compressed Air Energy Storage | ■ Energy management<br>■ Backup and seasonal reserves<br>■ Renewable integration | ■ Better ramp rates than gas turbine plants<br>■ Established technology in operation since the 1970s | ■ Better ramp rates than gas turbine plants<br>■ Established technology in operation since the 1970s |
| Battery Technologies | | | |
| Advanced Lead-Acid | ■ Load leveling and regulation<br>■ Grid stabilization | ■ Mature battery technology<br>■ Low cost<br>■ High recycled content<br>■ Good battery life | ■ Limited depth of discharge<br>■ Low energy density<br>■ Large footprint<br>■ Electrode corrosion limits useful life |
| NaS | ■ Power quality<br>■ Congestion relief<br>■ Renewable source integration | ■ High energy density<br>■ Long discharge cycles<br>■ Fast response<br>■ Long life<br>■ Good scaling potential | ■ Operating temperature required between 250° and 300°C<br>■ Liquid containment issues (corrosion and brittle glass seals) |

**Table 3.C.3** Summary of Technology Types, Applications, and Challenges[32] (continued)

| Technology | Primary Application | State of the Technology | Challenges |
|---|---|---|---|
| Battery Technologies | | | |
| Lithium-ion | ■ Power quality<br>■ Frequency regulation | ■ High energy densities<br>■ Good cycle life<br>■ High charge/discharge efficiency | ■ High production cost—scalability<br>■ Sensitive to over temperature, overcharge, and internal pressure buildup<br>■ Intolerance to deep discharges |
| Flow Batteries | ■ Ramping<br>■ Peak shaving/time shifting<br>■ Frequency regulation<br>■ Power quality | ■ High number of discharge cycles<br>■ Lower charge/discharge efficiencies<br>■ Very long life | ■ Developing technology, not mature for commercial scale development<br>■ Complicated design<br>■ Lower energy density |
| Hydrogen Energy Storage | | | |
| | ■ Frequency regulation<br>■ Load leveling<br>■ Peak shifting<br>■ Relieving curtailed renewables | ■ Scalable and deployable<br>■ Multi-sector integration—as clean power, as low carbon heat, as hydrogen fuel for transport<br>■ Seasonal storage potential<br>■ Rapid response | ■ Codes and standards<br>■ Total system efficiency |

Additionally, the concept of hybrid storage solutions is a research theme that may result in technologies with better performance and value proposition than individual storage technologies in isolation. For example, hybridization of batteries with ECs could improve the number of cycles a battery can perform without degrading lifetimes. Additionally, this combined system would allow a wider range of power levels with the ECs handling short bursts of power while the battery portion handles longer power demands.[27] Other examples include the combination of supercapacitors or flywheels with battery storage systems for optimal performance.[28,29] The optimization of hydrogen-based storage and fuel cells is another area of research with respect to hybrid systems.[30,31]

## Bulk Energy Storage Technologies

### Pumped Hydro Storage

PHS is a large, mature, and commercial utility-scale technology currently used at many locations in the United States and around the world.[33,34] PHS facilities are capable of discharge times in tens of hours and come in high-power modules that can reach 1,000 MW. Projects may be practically sized up to 4,000 MW and operate at about 76%–85% efficiency, depending on design. PHS plants have long lives, on the order of 50–60 years, and are quite reliable. As a general rule of thumb, a reservoir one kilometer in diameter, 25 meters deep, and with an average head of 200 meters would hold enough water to generate 10,000 MWh.

In recent years, the technology has advanced greatly and now includes improved efficiencies, with modern reversible pump-turbines, adjustable speed pumped turbines, new equipment controls such as static frequency converters, and generator insulation systems as well as improved underground tunneling construction methods and design capabilities.[35] New capabilities of PHS made possible by the use of variable speed pumping are opening up the potential for the provision of additional services that may be used to assist in the integration of variable generation sources.[36] New turbine designs, optimized operations, and better controls can also increase the efficiency of these systems.

PHS currently employs off-peak electricity to pump water from one reservoir to another reservoir at a higher elevation, converting electricity into potential energy. When required, water is released from the upper reservoir through a hydroelectric turbine into the lower reservoir to generate electricity. A new approach locates reservoirs in areas that are physically separated from existing river systems; such "closed-loop" pumped storage projects present minimal to no impact to existing aquatic systems and can be optimally located where needed to support the grid. In addition, the feasibility of modular units, using commercial off-the-shelf components to achieve reductions in deployment costs, is being investigated by DOE.[37] Another research area includes subsurface pumped storage, where facilities are located in abandoned mines, caverns, man-made reservoirs and storage tanks, and gravity pumped hydro storage technology.[38]

In addition to technology development, there are numerous activities that support the modeling and analysis of pumped hydropower storage. Recently, Argonne National Laboratories (ANL) analyzed the value of PHS and the various services it could provide to the grid. ANL has also performed substantial work in developing advanced models for PHS. Additionally, the National Renewable Energy Laboratory in collaboration with ANL conducted analysis of the impact of market scheduling and dispatch of PHS.[39,40] These studies are important to understanding how the integration of advanced technologies will impact the overall system and can lead to improved operations.

## Compressed Air Energy Storage

Storage of compressed air in tanks for powering tools and locomotives goes back to the late 1800s; however, the first grid-scale CAES plant did not open until 1978 in Germany. The 290 MW Huntorf plant in Germany uses two solution-mined salt caverns for storing air that is compressed overnight when electricity prices are low.[41] Energy is recovered when the compressed air is channeled with natural gas to the combustion chamber to generate electricity as needed. The air storage capacity for the Huntorf plant can produce at full capacity for about three hours each day. Since a gas turbine is used with the air release, it is difficult to determine system efficiency. The 110 MW McIntosh plant in Alabama is the second commercial CAES facility in the world, in operation since 1991. Greater deployment of cavern-CAES technology is limited because it requires a relatively rare geologic setting in which to make sealed caverns to store the pressurized air.

CAES projects typically require economies of scale to be cost-effective and thus require substantial capital investment.[42] While there are no fundamental challenges with existing technologies, the engineering can be complex and must be customized for each project, adding to costs. Project economics could be improved if heat loss during compression could be recovered to reheat the air prior to expansion in the turbine, thereby improving overall system efficiency.

While earlier CAES systems are typically located underground and run on fossil fuel, next-generation CAES systems can potentially run exclusively on emission-free sources and are not dependent on geologic factors for site selection. Major recent developments in CAES include newly patented technologies, such as the isothermal compressed air energy storage system, a mist-cooled system that enables aboveground storage, a water-gas encompassing vessel energy storage system, storage in porous rocks, and an advanced adiabatic compressed air storage system.[43, 44, 45, 46, 47]

ARRA (2009) provided DOE with funds to accelerate CAES projects under the Smart Grid Demonstration Program, including isothermal CAES concepts as well as improvements in CAES in existing salt caverns. These activities have advanced the development and demonstration of more geographically flexible and aboveground systems.[48]

Porous media-CAES (PM-CAES) does not require a solution-mined salt dome, making the potential opportunities for this technology significantly larger. In PM-CAES, air is injected directly into the pore space of a reservoir rock such as sandstone, analogous to the underground storage of natural gas. The physics of PM-CAES has been described and simulated recently,[49] and there is currently a large-scale demonstration project in progress in California.[50] As more natural gas reservoirs become depleted from the shale gas industry, there is a growing opportunity for PM-CAES because the reservoirs have already demonstrated storage integrity.

A similar technology to CAES is liquid air energy storage (LAES), also called cryogenic energy storage, which uses electricity to liquefy air that is stored in a tank. The liquid air is gasified via heat exchange with ambient air or waste heat from an industrial process. Rapid re-gasification drives a turbine, generating electricity. LAES uses off-the-shelf components and has no geographical constraints. A 350 kW pilot plant has been operating since 2011 in the United Kingdom, hosted by an industrial site.[51] The UK Department of Energy and Climate Change recently announced funding for further R&D.[52]

Fundamental research is needed for PM-CAES to understand the impact of air storage on surrounding regions, such as the development of pressure gradients. The injection and withdrawal from the reservoir could cause coupled hydro-geomechanical processes (e.g., induced seismicity and possibly hydraulic fracturing) that need to be characterized, especially to evaluate the long-term feasibility of PM-CAES with daily cycles. In addition, there are opportunities to advance the work being done on adiabatic CAES technologies. Adiabatic and advanced adiabatic CAES systems use the heat generated during the compression phase by storing it in a transitional media, such as water. When generating electricity, the compressed air and stored heat are recombined and expanded through a turbine. No additional fuel is required, increasing efficiency and eliminating $CO_2$ emissions.

## Battery Technologies

Batteries are a broad family of devices that store and release electric energy through electrochemical reactions. Performance characteristics of these technologies will differ, depending on the design and chemistry, but most are lower-powered systems with discharge times ranging from a few minutes to six hours or longer. Battery storage technologies can be much more flexible in terms of capabilities and siting compared with PHS and CAES.

There are many different battery technologies that are currently available for commercial applications and have been successfully deployed in both distributed and centralized applications in various sizes. The more mature technologies include lead-acid batteries (including lead-carbon batteries),[53] NaS batteries, and lithium-ion (Li-ion) batteries. However, they have not yet realized widespread deployment owing to challenges in energy density, power performance, lifetime, charging capabilities, safety, and system cost. However, the potential for new battery types and chemistries remains very high, and there is potential for very high energy densities to be achieved at relatively low cost. Advanced Research Projects Agency-Energy's (ARPA-E) Advanced Management and Protection of Energy Storage Devices program is working on advanced sensing, control, and power management technologies to improve the performance, safety, and lifetime of battery systems exclusively through system-level innovations. ARPA-E has also sponsored several energy storage projects in the past, including metal-air ionic liquid, planar sodium-beta, high density lithium, zinc-manganese oxide, and liquid metal batteries.[54, 55] DOE's Joint Center for Energy Storage Research (JCESR), an Energy Innovation Hub, is focused on advancing the fundamental research needed for next-generation energy storage technologies.[56]

## Lead-Acid Batteries

Lead-acid batteries are the oldest form of rechargeable battery technology and are widely used in cars, boats, planes, and uninterruptible power supplies, among other applications. All lead-acid designs share the same basic chemistry: the positive electrode is composed of lead-dioxide ($PbO_2$), the negative electrode is composed of metallic lead (Pb), and the electrolyte is a sulfuric acid solution. Despite its maturity, there have been very few utility applications for this technology owing to its costs, large volume, cycle-life limitations, perceived reliability issues (stemming from maintenance requirements), and relatively heavy weight.

Next-generation lead-acid technologies are divided into two types: (1) lead-carbon and (2) advanced lead-acid. Lead-carbon technologies use a design approach that includes carbon, in one form or another, to improve the performance of the technology. Lead-carbon batteries exhibit a high charge and discharge rate with no apparent detrimental effects that are typically experienced in traditional vented lead-acid batteries. This characteristic allows lead-carbon batteries to deliver and accept high current rates only available with higher-cost nickel metal-hydride and Li-ion batteries. There are several lead-carbon technologies moving into the market, each with a different implementation of carbon integrated with the negative electrode.

Advanced lead-acid technologies are conventional valve-regulated lead-acid batteries combined with other technologies to address shortcomings. Some new characteristics include a brief burst of high power followed by a sustained discharge at lower current. The integrated features of an EC give these technologies a fast response, similar to flywheels or Li-ion batteries. Advanced lead-acid systems from a number of companies are currently in early field trial demonstrations. These advances may make them more suited to certain grid applications.

## Sodium-Sulfur Batteries

NaS batteries are a commercial technology with applications in distribution grid support, wind power integration, and other high-value grid services. NaS batteries are only available in multiples of 1-MW/6-MWh units, with installations typically in the range of 2–10 MW. U.S. utilities have installed about 9 MW of NaS batteries for peak shaving and firming wind installations and have plans to install another 9 MW.[57]

NaS batteries have significant potential for broader use on the grid because of long discharge times (approximately six hours), their relatively high round-trip efficiencies, and their ability to quickly respond to control signals for regulation or improving power quality. However, NaS batteries use hazardous materials, including metallic sodium, which is combustible if exposed to water. The safety concerns and the need to operate at elevated temperatures pose risks and extra costs for this technology. Research opportunities include advances in chemistries, materials, and designs to reduce operating temperatures and improve safety features.

A related technology—sodium sulfur chloride batteries—are also high temperature devices but possess advantages over conventional NaS batteries, such as enhanced safety. Two battery original equipment manufacturer suppliers are deploying systems ranging from 50 kW to 1 MW. Several fully integrated systems are planned for utility grid support and renewable integration.

## Lithium-Ion Batteries

In the past two years, Li-ion batteries have emerged as the fastest-growing technology for electric energy storage. Compared with the long history of lead-acid batteries, Li-ion technology is relatively new. Li-ion batteries are commonly found in consumer electronic products, which make up most of the global production volume of 10 to 12 GWh per year. Leveraging the material technology and commercial availability for consumer electronic applications, Li-ion is now being positioned as the leading platform for plug-in hybrid electric vehicles (PHEVs) and all-electric vehicles. Transportation applications use larger-format cells and packs with energy capacities of 15 to 20 kWh for PHEVs and up to about 85 kWh for all-electric vehicles.

The large manufacturing scale of Li-ion batteries (estimated to be approximately 30 GWh by 2015) could result in lower-cost battery packs. These packs can be integrated into systems for grid services that require less than four hours of storage capacity. Many Li-ion systems have been deployed across the world in early field trials to gain experience in siting, grid integration, and operation. Li-ion systems dominate the current deployment landscape for grid-scale electric energy storage in the United States. This technology has potential for cost reductions with the 1.3 GW energy storage mandate in California and the recent announcement of Tesla's Gigafactory. [58]

There are many different Li-ion chemistries that can be leveraged for grid-scale applications, each with differing power-versus-energy characteristics. Lithium-sulfur chemistries offer the potential for greater energy densities than Li-ion batteries.[59] Various technology configurations exist, with some using a flexible membrane made of sulfur-carbon nanotubes as a cathode, increasing the energy density. Other types of nanomaterials and nanostructures are being leveraged that show enhanced results compared with conventional batteries. [60]

## Flow Batteries

A principal advantage of most flow battery systems is that their power and energy ratings can be scaled independently, making them more flexible to design and modify for alternative uses. In contrast with other batteries with solid electrodes and a liquid electrolyte, in flow batteries the electrodes are liquid and the electrolyte is a solid. This design allows for the energy storage capacity to simply scale with the volume of the liquid electrode. Significant U.S. industry and DOE investment over the past 40 years has led to better understanding of the advantages and limitations of the available chemistries.

Despite recent breakthroughs in performance and thermal tolerance of different designs and chemistries, flow batteries have not yet achieved significant market adoption, although new designs are now being introduced. Current technologies range from vanadium flow to plating-type batteries, but owing to the lack of MW-scale demonstrations, these batteries have not gained substantial commercial traction in the United States. Of the various flow battery technologies still in the demonstration phase, the largest single system is only rated at 0.6 MW.[61] However, this is changing with Modesto Irrigation District, which is hosting an ARRA-funded redox flow battery project (25MW/75MWh) and at least several other technologies (different chemistries) are being installed at capacities of 1 MW or greater in the United States.

Flow battery projects are being launched overseas, with systems up to 5 MW in size and a total deployed capacity of 20 MW. China and Japan have committed over $200 million to flow battery projects, and Europe is following suit with numerous smaller projects. The interest in flow batteries stems from several potential advantages over traditional batteries: deep discharges, high cycle life, and extremely long unit life. Flow batteries face obstacles with low energy density and integrated design requirements. While there are commercial providers who offer small (5 kW) redox flow units, the economics of redox flow batteries favors larger unit sizes, and it is difficult for them to compete at sub-MW scale. If advances in this technology continue as expected, flow batteries may be commercially deployable in the United States within the next few years.

A range of other flow battery chemistries with unique properties are in the early stages of development. Iron chromium flow batteries are in the R&D stage but are moving toward early field demonstrations. This system uses liquid reactants, requires only a small volume that is electrically active, and has hydraulically balanced cells with no volume change during cycling. Such features allow for less complex design and simpler controls. Zinc-bromine flow batteries consist of solid zinc in the charged state and dissolved zinc in the discharged state, while the bromine is always dissolved in the aqueous electrolyte. Electric utilities in the United States plan early trials of this technology with 0.5–1.0 MW systems for grid support and reliability.[62,63] Zinc polyiodide batteries are showing greater promise, with high energy density, and designs that are free from strong acids and corrosive components.[64] Other less expensive alternatives to vanadium flow batteries include research in cheap organic chemicals such as quinones, which could be partnered with a standard liquid electrode such as bromine.

## Power Technologies

### Flywheels

Flywheels store energy in a spinning mass called a rotor. Electric energy is converted to kinetic energy and converted back through the use of a bidirectional power conversion system. Flywheels can be charged and discharged relatively quickly, on the order of seconds, meaning they can be used for high-powered applications, such as frequency regulation, power quality, and uninterruptible power supply (UPS) applications. Since the rotor is constantly moving, standby power losses from friction and round-trip efficiency become critical design parameters. New approaches using new materials, including superconductors, are becoming available that can be used to levitate the flywheel and hold it rigidly in position without any physical contact. When the flywheel is operating in vacuum, losses from friction are dramatically reduced. Most modern flywheel systems have some type of containment enclosure for safety and performance-enhancement purposes.

Flywheels generally exhibit excellent cycle life compared with other EESTs, with most developers estimating an excess of 100,000 full charge-discharge cycles. Although flywheels have power densities 5 to 10 times that of batteries—meaning they require much less space to store a comparable amount of power—there are practical limitations to the amount of energy (kWh) that can be stored. Flywheels generally have significantly lower energy densities than a number of battery types. Properly sizing this technology will be critical to their economic success.[65]

Benefits of using flywheels include their low maintenance requirements, life spans of up to 20 years, emissions-free operation, fast response times, and the absence of toxic components. Disadvantages of flywheels include high acquisition costs, low storage capacity, and high self-discharge (3%–20% per hour).[66, 67] Advanced flywheel designs such as the Helix module could offer high power, short duration, and fast response (1 MW for 90 seconds and greater than 80% roundtrip storage efficiency) capable of over a million cycles.[68] Opportunities for advanced designs and new materials can lead to reduced friction and increased rotor strength, improving efficiencies and energy capacity.

### Superconducting Magnetic Energy Storage

Superconducting magnetic energy storage (SMES) is a commercial technology that stores electric energy in a magnetic field. Each unit employs a superconducting coil, a power conversion system, and a cooling system. The cooling system chills the coil below the superconducting transition temperature so that electrical currents flow without resistance or loss of energy. Electric energy is stored in the DC magnetic field of the solenoid made up of the superconducting coil. Most SMES technologies have high cycle life and power densities but low energy density. The high costs make them best suited for supplying short bursts of electricity into the energy system for regulation services. SMES currently has the highest round-trip efficiency of any electric energy storage device but is costly to manufacture and maintain. Additionally, the cooling equipment will introduce parasitic losses, and the limited number of grid demonstrations may limit advances. However, the major commercial success of very large, high field magnets for magnetic resonance imaging, nuclear magnetic resonance, and industrial processing and their attendant universal acceptance augers well for both SMES design and acceptance.

Future prospects of low-cost SMES systems depend largely on the discovery of suitable materials with superconducting properties at room temperature. Presently, development focuses on micro-SMES systems with capacities of up to 10 kWh for power quality and UPS sources. ARPA-E has funded a SMES demonstration project capable of deployment in medium-voltage networks at 15–36 kV.[69]

### Electrochemical Capacitors

Capacitors store electricity directly as electrical charge rather than converting the energy into another form (e.g., chemical energy in batteries and kinetic energy in flywheels). This principle makes the electric energy storage process fast, reversible, and efficient.[70] Due to these characteristics, capacitors can be very useful in applications such as frequency regulation and voltage stabilization. These technologies may also have longer useful lives because there is little degradation in the capacitors' ability to store energy electrostatically over time.

Currently, ECs can store significantly more electric energy than dielectric and electrolytic capacitors but are still cost prohibitive.[71] Ruthenium oxide is a material that has excellent properties for making capacitors, but high costs limit large-scale deployment. On the other hand, carbon-based materials are low cost but exhibit high internal resistance, limiting their suitability in high power applications. Research in composite materials that combine low resistivity and high capacitance could lead to development of next generation, low-cost capacitors. Nanoparticle coatings, nanostructures, and other material innovations can further enhance the performance of capacitors for grid applications.[72, 73]

## Hydrogen Energy Storage Systems

HES systems involve multiple processes, pathways, and end-user markets that do not come into play for batteries, CAES, or PHS. HES systems may provide a broad range of energy services in addition to storing grid electricity as hydrogen for later conversion back to electricity. HES systems can serve as an option to avoid curtailment of renewable resources by producing hydrogen with excess electricity. Unlike other energy storage technologies, HES systems allow the flexibility of deploying hydrogen to other markets and customers.

HES systems typically involve the production of hydrogen from electricity via "electrolyzers," in which electrical energy is used to split water molecules into hydrogen and oxygen gas. This process is equivalent to "charging" the system; running stored hydrogen through fuel cells or a combustion generator produces electricity, reversing the process. The generated hydrogen can also be used in power-to-gas (P2G) applications or to serve transportation or other industrial end-use markets directly. Currently, such markets include feedstock supply to petroleum refineries, advanced bio refineries, ammonia production facilities, or other industrial processes. Emerging near-term markets include material handling equipment (such as forklifts or airport tugs), backup power supply for telecommunications or remote power systems, and range extenders for battery electric vehicles.

P2G involves either the direct injection of electrolytic hydrogen into natural gas pipelines or the combination of hydrogen with carbon dioxide to produce synthetic methane. At relatively low concentrations (i.e., 2% to 10%) hydrogen may be injected into some natural gas pipeline systems with only minor modifications to supply infrastructure or end-use devices. Several P2G projects are underway; Germany had 22 projects as of 2012.[74, 75]

Some life-cycle cost studies indicate that HES systems can be competitive with battery systems and could be a viable alternative to PHS and CAES for bulk energy applications. However, advances will be needed in the development of these systems to address high costs, low round-trip efficiencies, safety concerns, and the need for high-volume, high-pressure storage tanks.

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# Glossary and Acronyms

| | |
|---|---|
| **Alternating current (AC)** | A type of electrical current in which the direction of the flow of electrons switches back and forth at regular intervals or cycles. |
| **American Recovery and Reinvestment Act (ARRA** | Referred to as the Stimulus or The Recovery Act, was an economic stimulus package enacted by the 111th United States Congress in February 2009 and signed into law on February 17, 2009, by President Barack Obama. |
| **Batteries** | Devices that convert chemical energy into electrical energy using electrodes, immersed in a media (liquids, gels, solids) that support the transport of ions. Each cell contains a positive terminal, or cathode, and a negative terminal, or anode. Electrolytes allow ions to move between the electrodes and terminals, which allows current to flow out of the battery to perform work. |
| **Compressed air energy storage (CAES)** | A way to store energy generated at one time for use at another time using compressed air. |
| **Cycle-life** | A measure of how many times the technology can charge and discharge at a particular depth-of-discharge, e.g., 80% or 100%. |
| **Direct current (DC)** | Electrical current which flows consistently in one direction. The current that flows in a flashlight or another appliance running on batteries is direct current. |
| **Discharge duration** | Discharge duration is how long a storage device can maintain output. |
| **Electrochemical capacitors (EC)** | Devices that physically store an electric charge at their surface electrolyte interface between electrodes. |
| **Lead-dioxide (PbO2)** | In a lead-acid cell, electrons are stored in the positive plate, the active element being lead dioxide (PbO2). The negative plate is composed of pure lead, usually in a sponge form to facilitate the chemical reaction. |
| **Lithium ion battery (Li-ion)** | A battery characterized by a transfer of lithium ions between the electrodes between charge and discharge cycles. |
| **Nickel metal-hydride (Ni-MH) battery** | A nickel–metal hydride battery, abbreviated NiMH or Ni–MH, is a type of rechargeable battery. The chemical reaction at the positive electrode (cathode) is similar to that of the nickel–cadmium cell (NiCd), with both using nickel oxyhydroxide (NiOOH). However, the negative electrodes use a hydrogen-absorbing alloy instead of cadmium. |
| **Redox flow battery** | A class of electrochemical energy storage devices. Redox refers to the chemical reduction and oxidation used to store energy in a liquid electrolyte solution which flows through the cells during charging and discharging. |
| **Sodium-sulfur (NaS) battery** | A type of molten-salt battery constructed from liquid sodium (Na) and sulfur (S) The rechargeable battery gained market share during the 1970s and 1980s, but short service life and high cost dampened the enthusiasm. |
| **Sodium sulfur chloride batteries** | A type of molten-salt battery that can serve as an alternative to the sodium sulfur battery in applications today. |

| | |
|---|---|
| **Pumped hydropower storage (PHS)** | Store energy in the form of water in an upper reservoirs pumped from a lower reservoir. |
| **Ramp rate** | Indicates how fast the technology can respond to a command to increase or decrease output (generation). |
| **Reactive power** | The component of an AC electric power that establishes and sustains the electric and magnetic fields in inductive and capacitive circuit elements. It is measured in VAR. |
| **Round-trip efficiency** | A measure of how much energy is lost from charging and discharging. |
| **Superconducting magnetic energy storage** | Stores energy in the magnetic field created by the flow of direct current in a superconducting coil which has been cryogenically cooled to a temperature below its superconducting critical temperature. |
| **Valve-regulated lead-acid (VRLA) battery** | The VRLA are designed with a low over-voltage potential to prohibit the battery from reaching its gas-generating potential during charge. Excess charging would cause gassing and water depletion. Consequently, these batteries can never be charged to their full potential. |
| **Vented lead-acid (VLA) battery** | A VRLA battery (valve-regulated lead-acid battery), more commonly known as a sealed battery or maintenance free battery, is a type of lead-acid rechargeable battery. The VLA battery is not sealed. |
| **Hydrogen energy storage (HES)** | A system where electricity is converted into hydrogen by electrolysis and stored in pressurized vessels and re-electrified in fuel cells or in combined cycle power plants. |
| **Cryogenic energy storage (CES)** | The use of low temperature (cryogenic) liquids such as liquid air or liquid nitrogen as energy storage. |
| **Lead-carbon batteries** | A multi-celled asymmetrically supercapacitive lead-acid-carbon hybrid battery. |
| **Power-to-gas (P2G)** | A technology that converts electrical power to a gas fuel. There are currently three methods in use; all use electricity to split water into hydrogen and oxygen by means of electrolysis. |
| **Superconducting Magnetic Energy Storage (SMES)** | SMES systems store energy in the magnetic field created by the flow of direct current in a superconducting coil which has been cryogenically cooled to a temperature below its superconducting critical temperature. |
| **Zinc polyiodide batteries** | New flow battery that uses an electrolyte that has more than two times the energy density of the next-best flow battery |