# Challenges of Electricity Storage Technologies

***A Report from the APS Panel on Public Affairs Committee on Energy and Environment***

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*Panel on Public Affairs*

For the report online, go to www.aps.org/policy/reports/popa-reports/upload/Energy_2007_Report_ElectricityStorageReport.pdf

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## I. Executive Summary (Policy Supplement)

**Potential Impact of Advanced Energy Storage**

Advanced electricity storage technologies have potential for significant environmental, economic and energy diversity benefits:

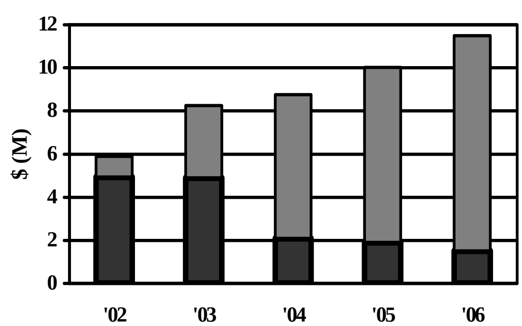
- *Reducing the Need for Reserve Power Plants:* Electricity storage technologies can provide an effective method of responding to daily fluctuations in demand. Electricity produced at off-peak hours can be stored and used later to meet demand spikes, thereby reducing the need for expensive, aging, and relatively dirty fossil-fired reserve generation plants.

- *Cutting the Cost of Power Failures:* As a result of the aging U.S. electricity grid, electricity outages cost the U.S. approximately $79 billion annually with 2/3 of that cost due to interruptions under 5 minutes. In particular, power fluctuations as short as tens of milliseconds cause computer-based systems to fail, crippling an economy that is increasingly reliant on digital technology. Electricity storage technologies can provide power to the grid to "bridge" gaps and smooth out short-term fluctuations until backup generation sources can be brought online.

- *Enabling Renewable Energy:* The sun and wind are the two largest sustainable sources of carbon-free power, but both are intermittent, varying widely in the energy that they can provide at any one time during the day. Electricity storage technologies can smooth out this variability and allow unused electricity to be dispatched at a later time.

**Current Status**

There are currently six promising energy storage technologies: pumped hydropower, compressed air energy storage, batteries, flywheels, superconducting magnetic energy storage, and electrochemical capacitors. These technologies have basic research components that fall naturally with the DOE's Office of Basic Energy Sciences, and development and deployment components that are being advanced primarily through the DOE's Energy Storage Program. The Energy Storage Program has leveraged its modest funds (shown in the figure) with states, utilities, and industry to achieve limited penetration of some energy storage technologies.




Funding levels of the Energy Storage Program of the DOE Office of Electricity Distribution and Energy Reliability over the last 5 years. Light regions indicate funds earmarked for specific projects.

- **Pumped Hydropower:** At a pumped hydro facility, water is pumped into a storage reservoir at high elevation during times when electricity is inexpensive and in low demand. Stored water is then released and used to power hydroelectric turbines when demand for power is high. Pumped storage hydropower is currently the most widely implemented storage technology in the U.S. and the world. In the United States, 38 plants provide 19 gigawatts of power. New developments in pumps and turbines allowing for adjustable water flow rates have increased the flexibility and efficiency of pumped storage hydroelectric power; however, some limitations, such as suitable geographic siting and facility size/capacity, still exist.

  - *R&D opportunities*: Power electronics and computer modeling/simulation

- **Compressed Air Energy Storage:** CAES uses high efficiency compressors to force air into underground reservoirs, such as mined caverns. When the commercial demand for power is high, the stored air is allowed to expand to atmospheric pressure through turbines connected to electric generators that provide power to the grid. Currently, there are 2 large-scale demonstration plants in operation, one in Germany and one in Alabama. In addition to these large-scale facilities, CAES can also be adapted for use in distributed, small-scale operations through the use of high-pressure tanks or pipes.
  - *R&D opportunities*: Demonstration projects and computer modeling.

- **Batteries:** Batteries have the potential to span a broad range of energy storage applications due in part to their portability, ease of use and variable storage capacity. In particular, they can stabilize electrical systems by rapidly providing extra power and by smoothing out ripples in voltage and frequency. Currently, numerous batteries including lead-acid, flow, sodium-sulfur, and lithium-ion all have commercial applications. However, many battery types have only limited market penetration, are expensive, or have short lifetimes.
  - *R&D opportunities:* Materials research, manufacturing techniques, demo projects.

- **Flywheels:** Flywheels store energy in a spinning disk on a metal shaft. Increases in the speed of rotation, the mass of the disk and locating more of the mass closer to the rim of the disk will increase the amount of energy stored. Two generations of flywheels have produced increases in storage capacity through increased disk mass (using steel) and increased rotation speeds (using light weight composite materials for the disk), but these have technical limitations. New prototypes utilize magnetic levitation to increase speed *and* mass while minimizing previous technical issues. This technology is best utilized for applications requiring short discharge time such as stabilizing voltage and frequency. A flywheel farm approach, where several devices are networked together, could allow for adaptation to large-scale energy management. Flywheels necessary for wider commercial energy storage applications are primarily limited by materials properties and cost.
  - *R&D opportunities*: Materials research

- **Superconducting Magnetic Energy Storage:** These devices are composed of superconducting windings that allow electric current to be stored indefinitely with little resistive energy losses. When the stored energy is needed, these devices can be discharged almost instantaneously with high power output over short time periods. Increasing the size of the windings can increase the amount of stored energy. However larger coils present a challenge because the associated increase in magnetic field becomes more difficult to contain. Further, the windings only exhibit the necessary superconducting property at low temperature; therefore, expensive coolants are needed to make the current devices operable.
  - *R&D opportunities:* Materials research and demonstration projects.

- **Electrochemical Capacitors:** Electrochemical capacitors store energy in the form of two oppositely charged electrodes separated by an ionic solution. They are suitable for fast-response, short-duration applications, such as backup power during brief outages. They are excellent for stabilizing voltage and frequency. By proper networking, these devices might be used for longer time-scale applications. Electrochemical capacitors have several advantages including a temperature-independent response, low maintenance and long projected lifetimes (up to 20 years), but they suffer from relatively high cost.
    - *R&D opportunities:* Materials research and manufacturing techniques.

- **Power Electronics:** While not a storage device explicitly, power conversion systems (PCS) are a vital part of any electricity storage system, because they serve as the interface between the storage system (typically running on DC current) and the electricity grid (delivering AC current). A PCS is able to make the necessary conversions so that the stored energy can be taken from or returned to the grid in the correct phase (AC/DC), frequency and level of demand. Systems using silicon carbide or diamond-based components exhibit superior performance. However, the high cost of these materials makes their widespread use undesirable since the cost of the PCS can range from 20-60% of the overall cost of the energy storage system**.**
    - *R&D opportunities:* Materials research, manufacturing techniques, and demonstration projects.

- **Additional Technologies**: Other technologies, such as reversible hydrogen fuel cells (RFC), may also provide breakthroughs in storage capacity. However, the current efficiency of commercial RFCs precludes their use in storage applications.

**Broadening the Electricity Storage Program:**

The APS Panel on Public Affairs explored the various components of a balanced program in a workshop with representatives from the national labs and the utility sector, along with an economist and university scientists. The Panel concluded that the six primary electricity storage technologies are at varying stages of maturity and that achieving the potential economic and environmental benefits of electricity storage will require a comprehensive and balanced strategy. Basic research, demonstration projects, incentives and regulation are all necessary elements that can be used to advance energy storage technologies. In fact, demonstration projects and regulatory incentives may have as much impact on technological penetration of electricity storage at this stage as basic research to bring down cost and raise efficiency.

Each of the program elements is considered below:

- **Basic Research:** The panel determined that there are five areas where fundamental research has a high potential for making electricity storage safe, practical and economical. These areas are materials research, power control systems, computer modeling, manufacturing techniques, and systems integration. Each of these areas is examined in detail in the full report. Much of this research is of interest not only to the DOE but also to the DOD, NASA and the NSF.

- **Demonstration Projects:** Many electric utility companies consider cost-shared demonstration projects the single most important step the government can take to advance electricity storage technology. Demonstration projects would further encourage the utilities to deploy electricity storage systems by confirming that these systems can be integrated safely, seamlessly and reliably with existing systems. To this end, the utilities traditionally demand that a new technology, such as energy storage, be proven in the field by means of several installed plants operated successfully for at least a substantial fraction of their intended lifetime, typically on the order of ten or more years.

- **Regulatory Incentives:** Pricing and regulatory policies in the electricity industry create barriers to deployment of electricity storage technologies. Careful consideration of these barriers is critical to both long-term innovation and to the success of any DOE initiative in electricity storage. For example, some industrial electricity customers would be interested in storage technologies that smooth out the short-term electricity fluctuations that cripple their manufacturing plants. Residential customers would be uninterested in the service. A pricing policy allowing commercial customers to pay a premium for better service might cover the costs of deploying storage technologies. Another consideration is that many states retain restrictions on the specific roles that customers and industries can play in generating and distributing electricity. Electricity storage technologies cross traditional boundaries of generation, transmission and distribution; hence, easing ownership restrictions may encourage storage technology deployment.

**Conclusions:**
Given the potential environmental and economic benefits of electricity storage technologies, DOE should consider broadening the existing program. For a broader program to be successful, it must achieve a balance among basic research, demonstration projects, and regulatory incentives. To strike the appropriate balance among the various program elements, DOE should evaluate any larger initiative with significant input from the utility sector, state and regional utility regulators, and principal investigators from universities, national laboratories and industry. Regarding regulatory incentives in particular, since they can have a large impact on advancing electricity storage, DOE should convene a separate panel of experts to study regulatory, ownership and pricing policies that impact electricity storage.

In addition, DOE should include in these discussions representatives from other federal agencies whose portfolios include research that is needed for electricity storage technologies. The APS Panel determined that there would be substantial overlap with the interests of the Department of Defense, NASA and the National Science Foundation.

## II. Introduction: Benefits of Electricity Storage

Rising fuel costs, geopolitical unrest, and increasing concern about global climate change have focused attention on reducing our dependence on fossil fuels, replacing them with alternative energy sources, and improving the efficiency of existing generating plants. Advanced electricity storage technologies can make significant contributions to these goals in several ways. Table A (Appendix A) gives a quantitative picture of the requirements for each technology. We recognize that the costs of deploying electricity storage technologies will ultimately play a critical role in determining how the utility companies will use them. However, the issue of determining acceptable costs lies beyond the expertise of the authors of this report and appears to be controversial within the industry. Therefore this report will not treat this issue.

### Matching Electricity Supply to Load Demand

Consumer demand for power varies throughout the day as well as seasonally, but many power plants have limited ability to make rapid changes in their outputs in response to such demand-side fluctuations. For example, nuclear plants reliably provide baseline power but cannot respond rapidly to demand spikes. Pumped hydroelectric plants respond quickly to changes in load demand but account for only 2.5% of the U.S. generation. The cost to construct and maintain the additional power plants solely for the purpose of meeting peak demand is high and the environmental impact of these plants is great. Thus storage can improve the efficiency of the generating system by filling in demand valleys and shaving demand peaks.

Energy storage technologies can provide an economical and environmentally advantageous method of responding to daily fluctuations in demand as long as the storage system is not charged by energy generated from fossil fuel. Electricity produced at off-peak hours can be stored and used later to meet demand spikes, thereby reducing the need for expensive reserve generation plants and using existing power plants more efficiently. In particular, electricity storage will be required if we are to take full advantage of the use of nuclear power generation.

Nuclear power plants provide 20% of U.S. electricity and they operate at a capacity factor of 90% because they are cheap to operate and more expensive to build than either coal or gas turbine plants. Nuclear power plants are not used to follow the fluctuations of load in the U.S. because (1) it is more cost effective to use all of their capacity to provide base load, and (2) the NRC does not allow it although it is done over a limited range in France. Currently, load following is done mostly by gas-fired plants although in some parts of the country, New England for example, pumped hydro is already used for load following. Replacing gas plants with electricity storage could be a significant benefit to the environment if the energy storage device is not charged by power produced from fossil fuel. For further discussion of the additional benefits of storage technologies, see the EPRI-DOE *Handbook of Energy Storage for Transmission and Distribution Applications.*

### Providing Backup Power to Prevent Outages

The aging U.S. grid infrastructure suffers from occasional rolling blackouts, most recently in California and Texas. In August 2003, there was a major blackout of the northeastern U.S. and Canada affecting 50 million customers. A recent study estimated that electricity outages cost the U.S. approximately $79 billion annually, with 2/3 of that cost due to interruptions under 5 minutes.[1] Storage can provide power to the grid to "bridge" gaps until backup generation

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[1] K. LaCommare and J. Eto, Lawrence Berkeley National Laboratory Report no. LBNL-55718, *Understanding the Cost of Power Interruptions to U.S. Electricity Consumers,* Sept. 2004, http://repositories.cdlib.org/lbnl/LBNL-55718.

sources can be brought online. For more information on the importance of digital power, see http://enduse.lbl.gov/Projects/InfoTech.html.

A storage device can be used to provide emergency power in an area that is prone to loss of service. This can allow utility companies the option of delaying expensive upgrades and better planning their investments in the grid. Electricity storage can also provide power to devices such as cell phone towers when the grid is out for times on the order of a day.

Some storage devices such as superconducting magnetic energy storage (SMES), flywheels or capacitors can inject power into the grid in milliseconds which can prevent a system from becoming unstable.

**Enabling Renewable Technologies**

Intermittent renewable energy sources, such as wind, vary widely in the energy that they provide on time scales as short as minutes. Energy storage technologies can smooth out this variability by allowing unused electricity to be stockpiled for later use when generation capacity is too low to meet demand. In this case, the storage system could belong to the local generation system, an individual consumer or a wind or solar farm.

In theory, every megawatt of renewable energy displaces a megawatt of carbon-based generation. However, the intermittency of renewables requires retaining a significant fraction of renewable capability in carbon-based generation to bridge supply valleys. Recently, the California Public Utilities Commission mandated that retail sellers of electricity purchase 20% of their power from renewable sources by 2010, and the New York Public Service Commission is mandating 24% by 2013 although much of this will come from existing hydropower. Electrical energy storage can reduce the need for fossil fuel burning in gas-fired backup generating plants.

No technology is completely environmentally benign. Many storage technologies are still being developed, and possible environmental effects are still unknown. Pumped hydro plants, for example, require large reservoirs behind dams which certainly impact the environment. However, the use of storage can provide options allowing the reduction of carbon dioxide emissions.

Some power commissions require utility companies to purchase electricity generated by consumers if the consumers have produced more electricity than they need. For example, this could be the case for a household with excess solar power generation. Extensive production of distributed power could potentially result in significant fluctuations in electricity production.

**Power Quality**

Power fluctuations as short as tens of milliseconds cause computer-based systems to fail. As the economy becomes increasingly reliant on digital technology, the cost of outages could increase. One analyst projects a potential economic loss of 30¢ on every dollar of electricity generation unless a technology is implemented to smooth out fluctuations, although this may be an extreme case.[2] Very short power outages can be bridged by relatively small but fast energy storage systems.

Many industries such as plants manufacturing integrated circuits and computer-intensive data processors require uninterruptible power supplies (UPS) that also provide extremely stable voltages and frequencies. When the demand for electricity increases, the grid voltage can sag. Storage devices can quickly provide power to the grid and stabilize voltage as well as matching the frequency of electricity from a storage device to that of the grid. Storage devices for these applications must respond very quickly to fluctuations in demand although they will not need to store as much total energy as devices used for the applications above. They are often owned

[2] Presentation made by Dr. Imre Gyuk, Program Manager for Energy Storage in the DOE Office of Electricity Distribution and Energy Reliability, August 14, 2006.

by industries such as chip manufacturers which need very high quality power and are willing to provide their own storage systems. Most consumers do not need power of such high quality.

## III. Technology Requirements

No one storage technology can currently address all applications. Storage technologies handle power ranging from hundreds of kilowatts (kW) up to about ten gigawatts (GW). The charge/discharge time for storage devices ranges from seconds to minutes to hours. Power quality applications need fast-acting storage devices to respond to short, unexpected interruptions in the power supply or sudden changes in the demand for power, while storage devices used for energy management must respond on a longer time scale and must store greater quantities of energy.

The following parameters characterize the performance of storage devices*:

- Quantity of energy stored (commonly kWh or MWh)
- Duration of discharge required (seconds, minutes, hours)
- Power level (kW or MW)
- Response time (milliseconds to minutes)
- Frequency of discharge (number per unit of time, such as per day or year)
- Energy density (facility space and total energy storage capacity)
- Cycle Efficiency (fraction of energy removed that is returned to the grid)
- Cycle life and/or calendar life
- Footprint/compatibility with existing infrastructure
- Ease of implementation
- Transportability
- Cost

*(for quantitative values of some these parameters, see Table A in Appendix A)

Energy storage technologies could be highly beneficial to both the grid and the consumer. However, if these technologies are to be widely adopted, the technologies must also be economically profitable. This report does not directly quantify the benefit to cost ratios for these technologies, but recognizes the importance of this issue as a barrier to implementation. Several reports have addressed the costs and benefits of energy storage technologies. [3]

Storage technologies are at various states of commercial maturity, which can be broken into four stages:

- *Commercial:* At least 5 units installed, with more than 10 years of experience per plant, with demonstrable economic return on investment
- *Pre-commercial*: One or more plants installed as commercial ventures, but lacking either demonstrable benefit or sufficient cumulative time in service to be regarded as commercial

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[3] The issue of acceptable costs for storage technologies is complex and depends on factors outside the expertise of this working group. Although we recognize that the costs of deploying storage technologies is a key issue for utility companies, we do not attempt to treat them here. The following reports treat this issue: *Energy Storage Benefits and Market Analysis Handbook,* James M. Eyer, Joseph J. Iannucci, and Garth P. Corey, Sandia National Laboratory Report no. SAND2004-6177 (December 2004); *Innovative Application of Energy Storage in a Restructured Electricity Marketplace Phase III Final Report,* Joe Iannucci, Jim Eyer and Bill Erdman, Sandia National Laboratory Report no. SAND2003-2546 (March 2005); *Long- vs. Short-Term Energy Storage Technologies Analysis: A Life-Cycle Cost Study*, S. Schoenung and W. Hassenzahl, Sandia National Laboratory Report no. SAND2003-2783 (August 2003).

- *Demonstration:* Some in-grid, in-field experience, but not commercial or pre-commercial as defined above
- *Developmental*: Laboratory units, sub-scale plants, or technologies used in non-utility applications.

Table 1 provides a general survey of the status of various energy storage technologies in the U.S. Few of the technologies, except for pumped hydropower, are at a point where they are able to make significant contributions in transmission and distribution of electricity.

| **Commercial** | **Pre-commercial Prototype** | **Demonstration Stage** | **Developmental** |
|---|---|---|---|
| Pumped Hydro<br><br>Flywheels for power quality applications at the consumer site | CAES<br><br>Lead-Acid Battery[1]<br><br>Ni-Cad Battery[1]<br><br>Sodium-Sulfur Battery<br><br>Flywheel (as load device)<br><br>Micro-SMES (as load device) | Zinc-Bromine Battery<br><br>Flywheel (as grid device)<br><br>Vanadium Redox battery[2]<br><br>Electrochemical capacitor | Lithium-Ion Battery for grid applications<br><br>SMES (as grid device)<br><br>Electrochemical capacitors<br><br>Other advanced batteries |

1. Commercial in utility emergency backup power applications
2. Commercial in telecom applications < 15 kW

**Table 1. Summary of the Developmental Status of Some Key Electricity Storage Devices**

## IV. Current Status of the Technology

There are six electricity storage technologies under consideration for widespread use: pumped hydropower, compressed air energy storage (CAES), batteries, flywheels, superconducting magnetic energy storage (SMES) devices, and electrochemical capacitors (also known as ultra- or supercapacitors). Fig. 1 below summarizes the capability of technologies that exist at the time of this writing. Due to their modular nature, multiple units of a given technology often can be networked to achieve greater power levels, and the figure is based on the capability of a single unit. Detailed data are provided in Table B of Appendix A.

Other storage technologies have been suggested for storage on the grid. The electrolysis of water combined with a hydrogen fuel cell has been suggested. However, the efficiency of electrolysis is currently around 70% and that of commercial fuel cells close to 50% so that the cycle efficiency of the technology is at best 35%. Because this is well below the cycle efficiency of the other technologies considered here, hydrogen fuel cells and electrolysis are not considered in this report. Similarly, V2G in which hybrid cars store and release electricity to the grid depends on battery technologies discussed here and is much farther in the future than the six technologies on which this report is focused.

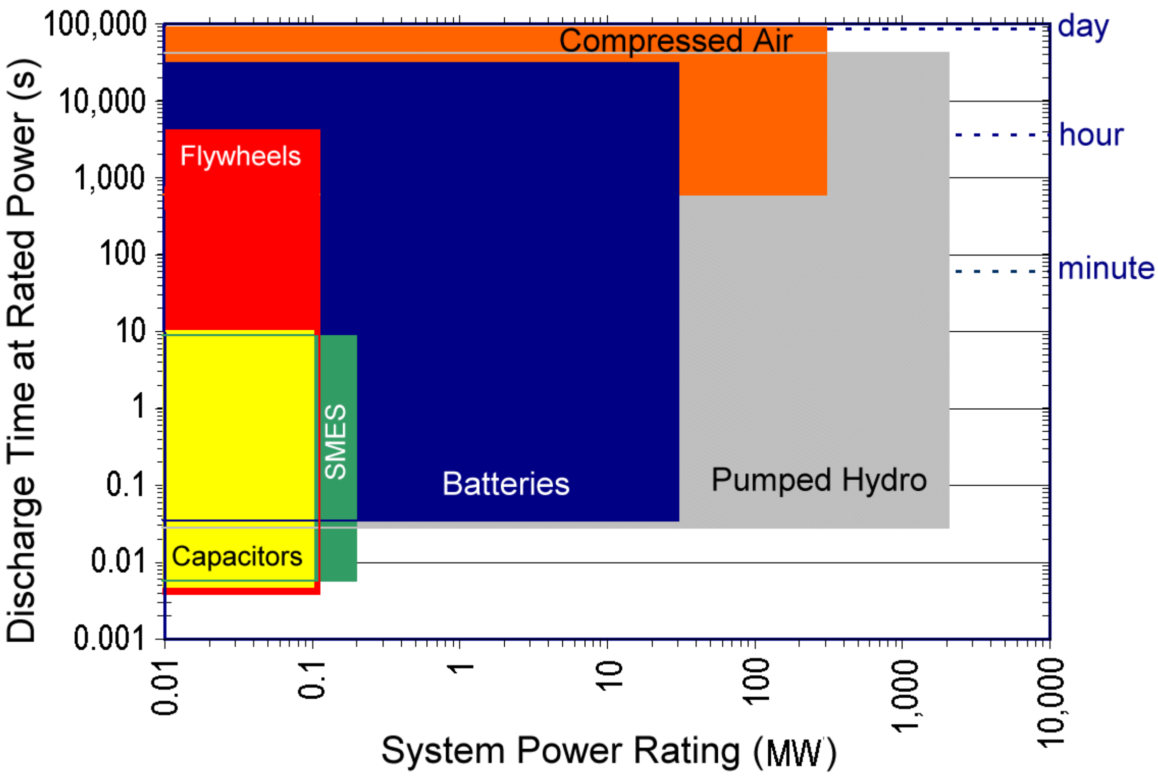


**Fig. 1. Capabilities of Existing Electricity Storage Technologies.**

The following discussion outlines the current technological status and the application areas in which each of the six technologies would have the greatest impact.

**Pumped Hydropower**

Pumped hydropower is currently the most widely implemented storage technology in the U.S. and the world. In the United States, 38 plants provide 19 gigawatts of power. Based upon conventional hydroelectric generators, pumped storage hydroelectric technology is well developed and well-suited for applications requiring large power levels and long discharge times. Water is pumped into a storage reservoir during times of low load and released through turbines to generate power to supply peak demand. Pumped hydro is utilized for situations where a fast supply of power is needed (spinning reserve), for meeting sudden peaks in demand (load following), frequency regulation, and voltage control.

Adjustable speed hydropower uses turbines and pumps that can operate at variable speeds depending upon the supply of, and demand for, electricity. The pump turbines are able to operate over a range of rotation speeds (±10% the speed of a conventional pump turbine) which allows them to vary the amount of electricity they generate by 70% and the amount they store by 40%. They can regulate frequency in the pump mode and in the generation mode. They are faster to start, and their variable frequency allows operators to avoid resonances in the system leading to longer equipment lifetime and less maintenance. Their power output can be changed in times of 10-30 ms.[4] Today, there are more than ten units in commercial operation, none in the U.S. They have demonstrated a 3% increase in overall annual efficiency compared to a single speed system.

An existing conventional single speed pumped storage unit can be converted to adjustable speed operation by replacing several key elements, including its rotor, and installing a new high-speed computerized control system. This was done in Japan on Units 2 and 3 of the TEPCO Yagisawa plant and has proved economically viable.

Pumped hydro also has limitations. It requires a large generation station and a water reservoir close to a power plant. Therefore it is not portable, and the plants are too large for widespread use in distributed generation.

**Compressed Air Energy Storage (CAES)**

Compressed air energy storage uses excess energy from base load plants or wind power to drive high efficiency compressors to force air at high pressure (1200 psia) into underground reservoirs, such as salt domes, aquifers, depleted gas fields or mined caverns. Unlike water, air is compressible under readily achievable conditions. When there is a demand for power, the stored air is heated either through combustion or by using exhaust gas from a power plant. The stored air expands to atmospheric pressure through turbines connected to electric generators that provide power to the grid. The high-power-density turbine expanders are quite compact. Multiple units can be located on a single site.

A 290-MW demonstration compressed air energy storage system in Huntorf, Germany has operated for 25 years, and a 110 MW system has operated in McIntosh, Alabama for 12 years. Both have performed successfully, providing prompt dispatch of power to meet load demands and keep frequency and voltage stable. Research has focused on improving the efficiency of the turbines and the overall operating system by such means as humidifying the air, storing thermal energy generated when the air is compressed, and releasing the air adiabatically through the turbines.

Compressed air energy storage seems to be a natural partner to the wind farms currently under development for electricity generation, since it can operate on a short enough time scale to smooth out the fluctuations that occur naturally in the wind. By developing systems where compressed air is stored in tanks or pipes, perhaps underground for safety, compressed air energy storage can be used by distributed, small scale, generation systems. The small systems have a fast response time and can be paired with flywheels for millisecond responses. The everyday use of high-pressure natural gas pipelines and smaller commercial high-pressure cylinders indicate that these small systems will pose little danger of rupture. However, the construction of many small units will require research on efficient turbines and strong storage containers, for example wrapped pipes.

**Batteries**

Batteries have the potential to span a broad range of energy storage applications.[5] Battery systems for electricity storage use the same principles as batteries used, for example, in automobiles, but in much larger and higher power configurations. Energy storage systems

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[4] Sporild, R*., et al*.: "Economic and Technical Aspects of Adjustable Speed Hydro Machines Applied for Improved Stability in Power Networks," *IEEE-PES 2000 Summer Meeting: July 16-21, IEEE* **4** (2000) 2469-2474.

[5] For example, the 8 MW/7 hour-discharge sodium sulfur (NaS) battery manufactured by NGK Insulators is capable of storing up to 56 MWh of energy and is suitable for large energy storage and distributed generation storage applications. On the other hand, the 27 MW/15 minute-discharge nickel-cadmium battery currently used by the Golden Valley Electric Association in Fairbanks, Alaska has application in the area of power quality.

based upon batteries can be portable, and the utility industry is familiar with them. Batteries are a proven technology in widespread use, including limited application to electrical energy storage in systems greater than 5 MW. Japan currently has more than 55 installations of batteries for storage.

Banks of conventional lead-acid batteries have been applied to stabilize electrical systems by rapidly providing extra power and by keeping voltage and frequency stable. However, they wear out relatively quickly when they are charged and discharged frequently. A number of flow battery systems, for example zinc-bromine and vanadium redox, have seen field trials. Flow battery systems store electrolytes outside the battery and circulate them through the battery cells as they are needed. The battery electrodes provide a substrate for chemical reactions and do not participate in them. Thus, flow batteries are long-lived. Nickel metal hydride (NiMH) batteries also show promise for storage applications but they have lower energy densities and are vulnerable to overcharging.

Successful demonstration projects using sodium sulfur (NaS) batteries have encouraged their adoption by the utility sector. Portable battery storage systems are being used to provide short-term power, for example when a storm cuts power lines to rural locations with few customers. However, the wide-scale use of NaS battery technology for grid applications, like those of all batteries except lead acid, would require at least a 2-fold reduction in current costs.

In recent years, lithium-ion (Li-ion) batteries have enjoyed tremendous popularity in commercial devices such as cell phones and laptop computers due to their high energy density (2-3 times that of nickel-cadmium batteries and up to 4 times that of lead-acid batteries). The higher energy density of Li-ion batteries and their relatively long lifetimes make them cost effective, but the technology has not yet been proven safe on the scale needed for electricity storage. This year saw recalls of laptop computers because of the fire danger posed by Li-ion batteries.

The major challenges in using batteries for electrical storage are to make them both affordable and long-lived. Commercially available battery systems are not adequate for long-term (>10 years) use. Manufacture of batteries requires handling a variety of chemicals and may pose safety and environmental issues. There is unanimous agreement that most large scale battery systems are currently too expensive for widespread deployment, and new manufacturing techniques are needed to reduce their cost.

**Flywheels**

A conventional flywheel stores energy as the kinetic energy of a massive disk spinning on a metal shaft. The amount of energy stored depends upon the linear speed of rotation and the mass of the disk. First-generation flywheels, typically manufactured from steel, increased the mass while maintaining rim speeds on the order of 50 m/s.[6]

The introduction of fiber-composite materials enabled second-generation flywheels to reach rim speeds of 800-1000 m/s.[7] These higher-speed machines are limited by the expansion of the rim, which can be as much as 1-2% at high speeds. The expanding rim separates from the rest of the flywheel. They also experience bending resonances and other dynamical instabilities.

Third-generation flywheels, currently under development, combine high mass with high

[6] For example, the JY-60 Fusion Test Facility in Japan, a 200 MW system is composed of six flywheels, each with a 6.6 m diameter. One flywheel weighs 1,100 tons, reaches rotation speeds of 420-600 revolutions per minute and the rim of the flywheel travels up to 65.7 meters per second.

[7] An example is the Pentadyne ASD Voltage Support Solution from the Pentadyne Power Corporation. It offers 120 kW of power for 20 seconds of discharge. The total system weight is half a ton, the rotation speed is 50,000 rpm, and the maximum tip speed is about 800 m/s.

rotational speed to maximize overall energy storage.[8] One system utilizes a magnetically levitated ring design that resolves many of the design flaws in first- and second-generation flywheels. Using a ring as the rotator eliminates the expansion failure. In addition, the magnetic fields can be adjusted to control the rotational instabilities that arise at high speeds. These systems currently exist as prototypes only.

Short discharge time flywheels are suitable for stabilizing voltage and frequency, while longer duration flywheels may be suitable for damping load fluctuations. However, the high cost and limited capacity of first- and second-generation flywheels has greatly limited the implementation of this technology. A flywheel farm approach could be advantageous for larger-scale energy storage. Current technology could allow forty 25 kW flywheels to operate at 1 MW for 1 hour in one facility.

**Superconducting Magnetic Energy Storage (SMES)**

A SMES is an inductor with superconducting windings. Energy is added or extracted from the magnetic field of the inductor by increasing or decreasing the current in the windings. At steady state, the superconducting windings dissipate no energy, and energy may be stored indefinitely with low loss. The main parts in a SMES are motionless, which results in high reliability and low maintenance. However, superconductors also require refrigeration systems that introduce energy losses and do contain moving parts. (New designs involving pulse tubes have no moving parts.) Power can be discharged almost instantaneously with high power output for a brief period of time with less loss of power than for other technologies.

Discharge times of seconds or less have been demonstrated in currently available systems. Today, several megawatt-level units are used to stabilize voltage and frequency, especially at manufacturing plants requiring ultra-clean power, such as microchip fabrication facilities. As a DOE/BPA demonstration project, a 10 MVA (Megavolt-amperes) SMES device was used to stabilize the 900 mile, alternating current connection between two power companies, BPA and Southern California .

It is possible to network several SMES systems or to build larger single coils to increase the energy available.[9] While larger SMES coils look attractive on paper from the perspectives of physics and economics, they produce large magnetic forces that must be contained. A 24 kV SMES magnet has been tested at Florida State University, as a research system. Containment costs of the high magnetic fields associated with large currents may be a cost driver. Various solutions have been proposed, such as constructing the coils underground to transmit the outward force to bedrock, wrapping the coils in steel, or using toroidal geometries.

The main challenge to SMES is reducing the overall cost of the system. Current technology relies on low temperature superconductors, which require expensive cryogenics. Advances in high-temperature superconductivity will play an important role in moving towards less expensive cryogenics and lower conductor costs. Fortunately, cryogenic costs are falling. However, at this time, the costs of high-temperature superconducting components far outweigh possible savings in cryogenics.

**Electrochemical Capacitors**

Electrochemical capacitors, also known as electric double-layer capacitors, store energy in the form of two oppositely charged electrodes separated by an ionic solution. The energy is

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[8] A typical unit for utility applications would be LaunchPoint Technology's proposed Power Ring, 8 feet in diameter, weighing about 6 tons, with 100kW of power and 2 hours of discharge. The rotational speed would be 7,000 rpm with 822 m/s on the tip of the rim.

[9] In northern Wisconsin, a string of distributed SMES units were deployed to enhance stability of a transmission line that was subjected to uncontrolled fluctuations and voltage collapse due to a large load user.

stored by charge separation as ions are attached to the electrodes to store energy and released as the ions go back into solution. Because of the increase in stored energy with the increase of electrode surface area, research has focused on the development of high surface area electrodes. Symmetric capacitors with activated carbon electrodes are the most widely implemented system. However, much higher energy limits are predicted when one of the electrodes is replaced by a battery-like electrode, for example lithium-titanium-oxide spinel or lead oxide.[10] Such capacitors may have higher operating voltages and greater tolerance to exceeding their design voltage. They also seem to offer packaging and manufacturing advantages that defer costs. These asymmetric capacitors have greater promise for applicability to large stored-energy applications than their symmetric counterparts.

Generally, capacitors are suitable for short-duration applications like providing backup power during brief interruptions. Advanced capacitors are excellent for stabilizing voltage and frequency. By proper networking, they could possibly be used for longer time-scale applications.

Electrochemical capacitors provide high power density, and their performance does not depend upon temperature. They live through charge/discharge cycles with extremely low maintenance, and have projected lifetimes up to 20 years.

This technology is slowly being deployed for some applications. Siemens has developed a storage system that utilizes capacitors to capture and store braking energy of trains,[11] and this concept has been considered for use in automobile technology as well. Although a successful demonstration project of a large 1 MJ, 100 kW uninterruptible power supply (UPS) system using electrochemical capacitors for bridging power was carried out by EPRI Power Electronics Application Center in 2003,[12] experts argue that there is more fundamental research to be done before capacitors are ready for wide scale testing.

Although capacitors are more capable than batteries for at least some applications, they are more expensive. Improved high-speed manufacturing methods for capacitor cell fabrication or the development of cheaper electrode materials could reduce the costs.

Table B in Appendix A provides data on the current capabilities of the electricity storage technologies described above.

**Power Electronics**

A power conversion system (PCS) is a vital part of any electricity storage system, because it serves as the interface between the storage system and the grid. While the grid current is AC, energy storage systems typically release power as DC current. Thus, energy from the grid is converted to DC for storage and back to AC for return to the grid. A PCS matches the frequency of current converted from DC to the frequency of the grid and match grid demand to power released from, or taken in by, the storage device.

Ideally, a PCS operates at high frequency, high voltage, and high current. The best systems have a small footprint, a fast response, high power quality, great efficiency and high reliability. There is room for improvement in all these parameters, and much work remains to be done. Current systems use silicon-based components. Power control systems using wide band gap materials such as silicon carbide or diamond exhibit superior performance. Unfortunately,

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[10] J. P. Zheng, "The Limitations of Energy Density of Battery/Double-Layer Capacitor Asymmetric Cells," *Journal of the Electrochemical Society,* 150, A484 (2003)

[11] For more information on the Siemens SITRAS SES system, see http://www.transportation.siemens.com/ts/en/pub/products/benefits/mt/innovation.htm.

[12] T. Key, "Electro-Chemical Capacitors for Dynamic Correction of Power Quality Problems," *Advanced Capacitor World Summit 2003*, Washington DC (Aug. 11-13, 2003)

silicon carbide is twice as expensive as silicon. Even using silicon, lowering cost is critical because the PCS costs constitute at least 20% of the overall cost of the energy storage system. Technologies currently used for components, packaging, thermal management, and manufacturing do not yet reflect the results of recent research. Power electronic devices, notably switching and controls, are rapidly evolving, and there has been significant progress in low power applications. Storage applications require extending these advances to high power systems. Aside from the materials advances, there is a critical R&D need for manufacturing standard off-the-shelf power control systems that allow flexibility for a variety of applications.

## V. Strategies for Advancing Electricity Storage

Given the range of applications and technologies, there is no "one-size-fits-all" strategy for advancing the role of electricity storage and increasing technological penetration. Basic research, demonstration projects, and regulatory incentives are all important elements of a comprehensive strategy. In fact, demonstration projects and regulatory incentives are key to proving technical benefit and long-term reliability, two prerequisites for wide market penetration in the power generation and delivery sectors. Energy storage utilizes new technologies, and new technologies often need new regulatory policies.

This comprehensive and balanced approach is currently being implemented by the Department of Energy's Energy Storage Program within the Office of Electricity Distribution and Energy Reliability. Established in 1992 under a different name, this program has successfully leveraged its modest funds shown in Fig. 2 with states, utilities, and industry to achieve limited penetration of some energy storage technologies.

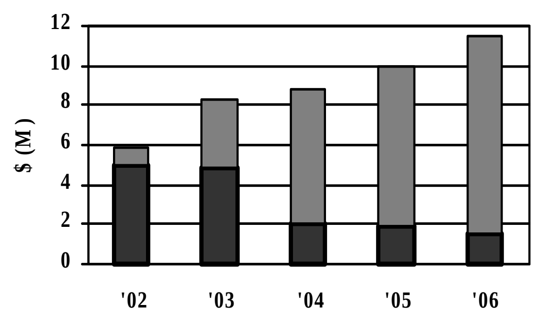


**Fig. 2. Funding for the Energy Storage Program of the DOE Office of Electricity Distribution and Energy Reliability for the last 5 years. Light areas indicate funds earmarked for specific projects.**

In considering a larger initiative for advancing electricity storage technologies, a good balance of R&D and demonstrations should be maintained. Inclusion of regulatory incentives as an integral part of the strategy of advancing these technologies will strengthen such an initiative. Also, the successful advancement of electricity storage technologies will depend heavily upon their seamless integration into the electricity infrastructure. Moreover, the role of electricity storage technologies should be examined carefully when developing the next generation grid.

### Basic Research

There are five areas where fundamental research has a high potential for making electricity storage safe, practical and economical. Research needs to focus on ways of gaining the benefits of electricity storage in the context of the present grid, as well as making storage an integral part of the next-generation grid. Much of the research described below is of interest not only to the Department of Energy but also to the Department of Defense, NASA, NIST, and the National Science Foundation, and careful programmatic integration can ensure that the discoveries made through basic research will further the goals of all four agencies.

1. ***Materials Research*:** Development of new materials has the potential to impact nearly all energy storage technologies. For example, nanomaterials are clearly promising for high surface area applications, such as batteries and electrochemical capacitors. Advancements in nanomaterials may impact technologies where high strength materials are needed, such as flywheels, SMES, and containment vessels for CAES. Advances in superconductivity can yield materials that are easy to manufacture and durable for SMES applications and flywheel bearings. Several current and future storage technologies would benefit from the identification and development of new materials that can support high energy densities. Materials that are made with the goal of applications to electricity storage technologies should have low cost, long lifetime, and the ability to withstand repeated mechanical, thermal and/or electrical cycling. High temperature thermal energy storage materials are of particular interest.

2. ***Power Conversion Systems (PCS):*** A PCS typically contributes over 20% to the overall energy storage system costs and is a critical technology. Current work on SiC-based devices shows promise in improving the overall performance of PCS, but more research is needed in a variety of areas to further optimize these devices. Areas in need of attention include semiconductor switches, device cooling, packaging and methods for integrating multiple energy storage systems with the grid. Due to the modular nature of the technology, it is important to develop and standardize systems, allowing industry to use PCS “off the shelf”.

3. ***Computer Modeling*:** As new electricity storage technologies come into use, the electric power industry will need tools to predict their behaviors as they are integrated into existing transmission and delivery systems. Improved simulation capabilities will allow utilities to better assess which technologies best meet their needs. Many current simulations do not account for renewable energy sources, which will undoubtedly be a part of the next generation transmission and distribution systems. A better understanding of how renewables link to storage systems and integrate into the grid will help increase their penetration.

4. ***Manufacturing Techniques*:** The development of new electricity storage technologies will require novel fabrication techniques for future generations of materials, such as nanomaterials. Particularly in the areas of batteries and capacitors, manufacturing processes will need to be made reliable, inexpensive and safe for workers and the environment. Where possible, the manufacture of components for electricity storage systems should build on the experience of other industries; however, this will not be sufficient, and the development of new techniques should be a high priority.

5. ***Integration:*** If current trends continue, it seems probable that the grid of the future will have to incorporate power generated on a fairly small scale by many renewable technologies, such as wind and photovoltaics. Storage could play an important role in allowing this integration and deeper market penetration. Hence, research is needed on technologies and control systems that will allow this to be done with minimal energy loss and without disrupting the operation of the grid.

**Demonstration Projects**

The utilities have a limited but growing interest in electricity storage. Demonstration projects prove that energy storage systems can be integrated seamlessly with existing systems, are reliable over the long-term, safe, and easy to maintain. The utilities traditionally demand that a new technology, such as energy storage, be proven in the field by means of several installed plants operated successfully for at least a substantial fraction of their intended life-time, typically on the order of ten or more years. Thus, many electric utility companies consider cost-shared demonstration projects the single most important step the government can take to advance and promote energy storage technology.

**Regulatory Incentives**

Pricing and regulatory policies in the electricity industry often create barriers to deployment of energy storage technologies. Careful consideration of these barriers is critical to both long-term innovation and to the success of any DOE initiative in electricity storage. It is also clear that the states play a major role in establishing regulatory policy so incentives will differ in different states. The two examples given below illustrate the connection:

1. ***Pricing Policies:*** Development of pricing policies that allow utilities to charge different rates based on power quality can allocate the costs of implementing and using storage to particular users. Customers, such as manufacturers of digital components whose business depends upon high quality power, would thus pay for a technology that ensures the quality and reliability of the power delivered to their plant. Residential customers would be uninterested in the service. A price geared to the average customer fails to generate payback for an investment in a storage system. One that allows customers to pay a premium for better service might cover its costs. In addition, encouraging time-of-use and peak load pricing policies would encourage the adoption of storage technologies.

2. ***Ownership restrictions*:** Many states retain restrictions on the specific roles that customers and industries can play in generating and distributing electricity. For example, distribution companies cannot own generation facilities, and retail customers are prohibited from establishing small (“mini” or “micro”) distribution systems. At the same time, utilities cannot encourage retail or wholesale customer investments in services traditionally offered by utility companies. Electricity storage technologies cross traditional boundaries of generation, transmission and distribution. Paradoxically, the flexibility of electricity storage also could restrict its deployment, due to the limitations placed on ownership.

## VI. Recommendations

The deployment of electricity storage technologies is not wholly driven by scientific advancement. We believe that demonstrations and incentives must be a substantial component of a successful strategy to advance electricity storage. With this in mind, the following should be done:

**Recommendation 1**

DOE should coordinate a range of activities to address the current and future challenges of electricity storage. A series of workshops and panels to consider basic research opportunities, technology development, and industrial deployment is needed. Key players from numerous relevant areas should be engaged to discuss the current and future challenges of electricity storage. These should include representatives from the following areas: the Office of Management and Budget (OMB), relevant Congressional offices/committees, the utility sector (both those that operate in the restructured and traditionally regulated environment), state and regional utility regulators, and principal investigators from universities, national laboratories and industry.

DOE should reach out to representatives from other federal agencies whose portfolios include research that is needed for electricity storage technologies. It is important to discuss ways in which those agencies could collaborate with DOE on projects applicable both to energy storage technologies and other needs. Such a dialogue would prevent the different funding agencies from duplicating one another's programs.

Given the impact that regulatory incentives can have on advancing electricity storage, DOE should convene a panel of experts to study regulatory, ownership and pricing policies that impact electricity storage. The panel should develop policies to recommend to various state agencies that regulate the electric power industry.

**Recommendation 2**

In considering an initiative on electricity storage, DOE should examine the balance among basic research that promises the creation of new technologies, development based on the results of previous basic research, and demonstration projects on a large enough scale to prove to industry that they are economically viable and technically effective. Clearly, the program will have to use a sliding scale so that government funding decreases as the payoff expected from projects becomes more certain.

With respect to R&D, suggestions in this report outline specific areas where research and demonstration projects have a high probability of accelerating the implementation of energy storage technologies. Emphasis should be placed on the development of small economical electricity storage systems that could be connected to relatively small electricity generators, particularly those deriving their energy from renewable sources.

**Recommendation 3**

To fully capture the benefits of advancements in electricity storage, programs must be carried out in parallel with discussion of the grid. Therefore, DOE should establish a planning group to consider the design of a next-generation electrical grid. By working with the electric power industry and experts from universities and the national laboratories, this group should propose steps needed to upgrade the aging components of the existing and implement new functions such as superconducting cables in urban areas, smart, self-healing power control devices, visualization, monitoring, and modeling.. At the same time, it should consider what technologies, such as renewables and energy storage systems, will be part of a new national grid, if indeed it is to be built. Finally, the group should consider carefully the economic and regulatory policies that would serve to enhance the efficiency of the future grid.

In conclusion, advances in electricity storage are necessary if the U.S. is to optimize its electricity grid and expand the use of renewable power sources. The DOE can play a central role in coordinating efforts to plan strategies, identify basic research opportunities, and implement technologies for electricity storage. Workshops and follow-up activities are major components of this coordination process.

## VII. Appendix A

**Quantitative values for the design and performance requirements of electricity storage technologies by applications.**

**Table A: Requirements for Different Applications of Electricity Storage**

Based on data from Schoenung, Susan B.: *Characteristics and Technologies for Long- vs. Short-Term Energy Storage* (2001) Sandia National Lab Report SAND2001-0765.

| **Application** | **Matching Electricity Supply to Load Demand** | **Providing Backup Power to Prevent Outages** | **Enabling Renewable Technologies** | **Power Quality** |
|---|---|---|---|---|
| **Discharged Power** | < 1MW to 100's of MW | 1 – 200 MW | 20kW to 10 MW | 1 kW to 20MW |
| **Response Time** | < 10min | < 10ms (prompt)<br>< 10 min (conventional) | < 1sec | < 20ms |
| **Energy Stored** | 1 MWh to 1000 MWh | 1 MWh to 1000 MWh | 10 kWh to 200 MWh | 50 to 500 kWh |
| **Need for high efficiency** | High | Medium | High | Low |
| **Need long cycle or calendar life** | High | High | High | Medium |

**Table B: Current Capabilities of Electricity Storage Technologies**

Based mostly on data from Schoenung, Susan B.: *Characteristics and Technologies for Long- vs. Short-Term Energy Storage* (2001) Sandia Report SAND2001-0765, and Kenny Y. C. Cheung, Simon T.H. Cheung, R.G. Navin De Silva, Matti P.T. Juvonen, Roopinder Singh, and Jonathan J. Woo, *Large-Scale Energy Storage Systems*, (2003), http://www.doc.ic.ac.uk/~matti/ise2grp/ .

| **Storage Technology** | **Pumped Hydropower** | **Compressed Air Storage** | **Batteries** | **Flywheels** | **SMES** | **Capacitors** |
|---|---|---|---|---|---|---|
| **Energy Storage Capacity** | < 24,000 MWh | 400 - 7200 MWh | <200 MWh | < 100 kWh | 0.6 kWh | 0.3 kWh |
| **Duration of Discharge at maximum power level** | ~ 12 hours | 4 – 24 hours | 1 – 8 hours | Minutes to 1 hour | 10 s | 10 s |
| **Power Level** | < 2000MW | 100-300 MW | < 30 MW | < 100 kW (each) | 200 kW | 100 kW |
| **Response Time** | 30 ms | 3 -15 min (large scale) | 30 ms | 5 ms | 5 ms | 5 ms |
| **Cycle Efficiency** | 0.87 | 0.8 | 0.70 - 0.85 | 0.93 | 0.95 [1] | 0.95 [1] |
| **Lifetime** | 40 yrs | 30 yrs | 2-10 yrs | 20 yrs | 40 yrs | 40 yrs |

Note: Due to their modular nature, multiple units of a given technology often can be networked to achieve greater power levels.

[1] This number does not include energy lost when a charged capacitor or SMES is neither charging nor discharging.

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