Utility Scale Energy Storage Systems

Benefits, Applications, and Technologies

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Executive Summary

An important characteristic of electricity is that electrical energy cannot be stored directly. Thus, the supply of electricity must be balanced continuously with the demand for it. The constant balancing of supply and demand has significant operational and cost implications. For example, sufficient generating capacity needs to exist to supply the highest level of demand, even though the last increment of capacity will only be needed infrequently and for short periods. Also, the inability to store electricity requires that reserve generating capacity, either in the form of spinning or non-spinning reserves, be maintained to account for changes in the amount of load or unplanned loss of an operating generator.

While it is not possible to store energy in the form of electricity, it is possible to convert electrical energy to another form that can be stored. The stored energy then can be converted back to electricity when it is desired. There are a wide variety of possible forms in which the energy can be stored. Common examples include chemical energy (batteries), kinetic energy (flywheels or compressed air), gravitational potential energy (pumped hydroelectric), and energy in the form of electrical (capacitors) and magnetic fields. From the standpoint of the electrical system, these energy storage methods act as loads while energy is being stored (e.g. while charging a battery) and sources of electricity when the energy is returned to the system (e.g. while discharging a battery).

A limited amount of bulk energy storage, mainly in the form of pumped hydroelectric storage, has long played a role in the United States electric power grid, and storage continues to grow in importance as a component of the electric power infrastructure. Advances in storage technologies and the increasing need for high quality, reliable electric power will likely lead energy storage to become a more substantial component of the electric power grid in the future. Several primary drivers have increased interest in energy storage:

- the increase in peak demand and the need to quickly and efficiently respond to changes in demand given constraints on generation and transmission capacity;
- the need to integrate distributed and intermittent renewable energy resources into the electricity supply system;
- the increasing level of congestion in transmission and distribution systems;
- the role that storage can play in providing ancillary services critical to the efficient and reliable operation of the grid; and
- the increasing need for high quality, reliable power as a result of increased use of consumer power electronics and information and communication systems that are highly sensitive to power fluctuations.

Electricity storage can be deployed to any of the five major subsystems in the electric power system: generation, transmission, substations, distribution, and final consumers. Generators may use traditional fossil fuel resources (such as natural gas or coal), nuclear generation, or renewables (such as hydro, wind, or solar). Storage may play a role at the generator level by providing additional energy when generators are operating at capacity and by storing energy when excess low-cost generating capacity is available. Transmission systems transport electricity at high voltages and often over long distances to utility substations. Storage may play a role at the transmission level by providing additional energy at the receiving end of a congested line and thus alleviating congestion. Step down transformers at utility substations reduce the voltage and transfer the electricity to distribution lines. Storage can play a role at the transformer level by storing energy when the transformer is not operating at capacity and providing energy when needs of the distribution system exceed the transformer capacity. Distribution lines supply electricity to final consumers. Storage can play a role at the consumer level by allowing the consumer to store energy when excess capacity (or low cost electricity) is available and using the stored energy for consumer end uses when capacity is limited (or electricity is costly).

Six potential benefits of incorporating bulk energy storage systems into the electricity grid are: (1) enabling time-shift of energy delivery to facilitate the balancing of electricity supply and load at reduced cost, (2) supplying capacity credit to delay investments in generating capacity, (3) providing grid operational support to facilitate smooth, coordinated operation of the components of the electricity supply system, (4) providing transmission and distribution support to delay investments to upgrade components of the transmission and distribution system, (5) maintaining power quality and reliability by providing energy to the system with very short response times, and (6) allowing integration of intermittent renewables generation by smoothing their energy output over time.

Two aspects of electricity are important to understanding technology and applications of storage: power and energy. Energy can be thought of as a volume (i.e. a kilowatt-hour), while power can be thought of as a rate of flow (i.e. a kilowatt). Some applications, such as load shifting across hours, require a large volume of energy storage capacity. A storage device like pumped hydroelectric power is well suited for this type of application. Other applications, such as real-time voltage stabilization, require a large responsive power capacity. A storage device like a flywheel is well suited for this type of application. So, it is important to match the application with the storage technology.

Additional factors that affect the choice of technology for a particular application are response time, discharge duration, discharge frequency, depth of discharge, and efficiency. Response time is how quickly the storage device can discharge when the need arises. Discharge duration is the length of the period that the storage device can discharge in a single charge-discharge cycle, and discharge frequency is the number of charge-discharge cycles per unit of time. Depth of discharge is the fraction of the storage device's energy capacity that can be drawn down during a charge-discharge cycle. (This is important because some storage devices, particularly batteries, may lose storage capacity over time more quickly depending on whether they are deeply or shallowly discharged in a typical charge-discharge cycle.) The primary measure of efficiency of a storage device is the ratio of the energy output divided by the energy input for a charge-discharge cycle. There also can be secondary measures of efficiency related to losses while the device is not in use.

The efficiency of energy storage devices varies widely across technologies, ranging from about 60 percent to as high as 94 percent. Batteries generally have a lifetime cycle capacity generally in the range of about 5,000 to 10,000 cycles, although a few advanced batteries are rated at over 100,000 cycles. Pumped hydroelectric storage, compressed air energy storage, fly wheels, and capacitors are rated at 10,000 to 100,000 cycles. Pumped hydroelectric storage and compressed air energy storage have the slowest response times – on the order of minutes. Batteries, fly wheels and capacitors have quicker response times – on the order of fractions of a second.

In terms of technological maturity, pumped hydroelectric storage, lead acid batteries and sodium sulfur batteries may be classified as mature technologies. Other technologies that are being actively deployed or in the demonstration phase include lithium ion batteries, advanced lead acid batteries, sodium nickel chloride batteries, sodium ion batteries, flywheels, and compressed air storage. Technologies that span the development through demonstration and deployment phases include flow batteries, and metal-air batteries. Technologies in the research, development and in some cases demonstration phases include superconducting magnetic energy storage, advanced compressed air energy storage, super capacitors, and nano-capacitors.

Given the large number of dimensions of performance that are important for an energy storage device, a direct comparison of device costs is generally not appropriate. A more useful approach is to begin by identifying the application or applications that the device is to serve and then to identify the types of storage devices that are appropriate for that application. For each candidate device, an annualized cost can be estimated based on expected use of the device over its lifetime, which will vary with the application. While somewhat complex, this approach should result in a set of costs that are comparable across technologies for the intended application.

1. Introduction

An important characteristic of electricity is that electrical energy cannot be stored directly. Thus, the supply of electricity must be balanced continuously with the demand for it. The constant balancing of supply and demand has significant operational and cost implications. For example, sufficient generating capacity needs to exist to supply the highest level of demand, even though the last increment of capacity will only be needed infrequently and for short periods. Also, the inability to store electricity requires that reserve generating capacity, either in the form of spinning or non-spinning reserves, be maintained to account for changes in the amount of load or unplanned loss of an operating generator.

While it is not possible to store energy in the form of electricity, it is possible to convert electrical energy to another form that can be stored. The stored energy then can be converted back to electricity when it is desired. There are a wide variety of possible forms in which the energy can be stored. Common examples include chemical energy (batteries), kinetic energy (flywheels or compressed air), gravitational potential energy (pumped hydroelectric), and energy in the form of electrical (capacitors) and magnetic fields. From the standpoint of the electrical system, these energy storage methods act as loads while energy is being stored (e.g. while charging a battery) and sources of electricity when the energy is returned to the system (e.g. while discharging a battery).

A limited amount of bulk energy storage, mainly in the form of pumped hydroelectric storage, has long played a role in the United States electric power grid, and storage continues to grow in importance as a component of the electric power infrastructure. Advances in storage technologies and the needs of the electric power grid enable energy storage to become a more substantial component of the electric power grid of the future. Several primary drivers have increased interest in energy storage:

- the increase in peak demand and the need to respond quickly and efficiently to changes in demand given constraints on generation and transmission capacity;
- the need to integrate distributed and intermittent renewable energy resources into the electricity supply system;
- the need for investments in transmission and distribution systems that are experiencing increasing congestion;
- the need to provide grid ancillary services critical to the efficient and reliable operation of the grid; and
- the increase in the need for high quality, reliable power as a result of increased use of consumer power electronics and information and communication systems that are highly sensitive to power fluctuations.

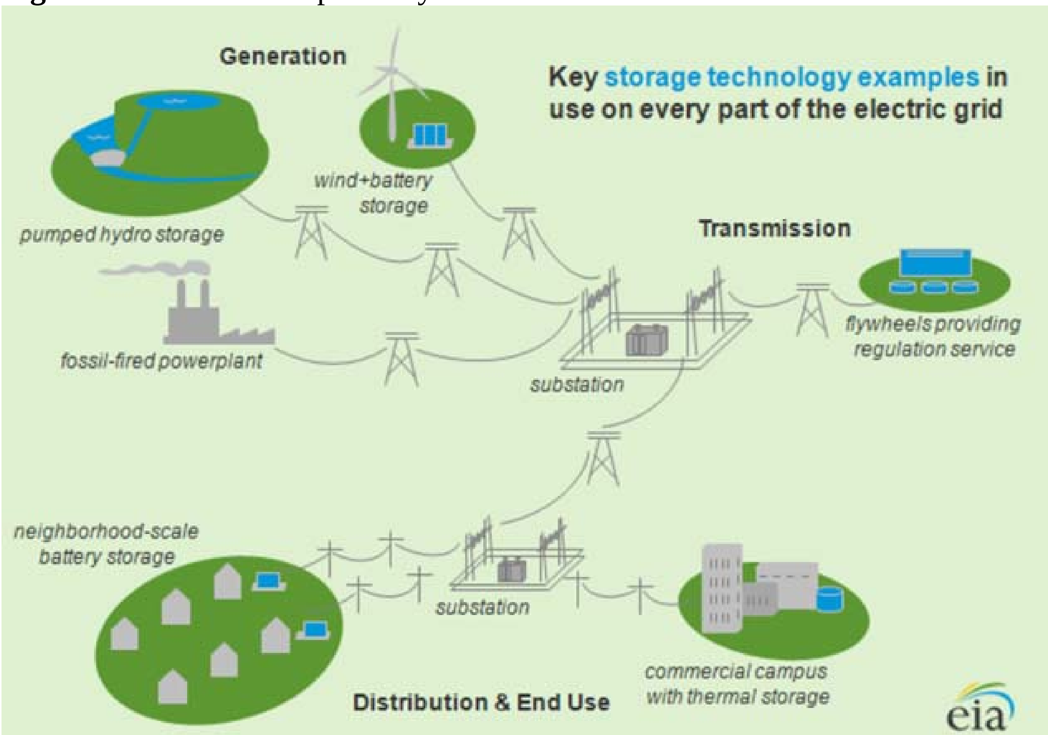
One suggested route to meet these current and future needs is the modernization of the electricity infrastructure, which includes energy storage systems. The energy storage competitive clause of the 2007 Energy Independence and Security Act (42 USC § 17231) makes provisions to modernize the electric power grid infrastructure in order to meet growing demand for high quality, reliable energy and to integrate distributed generation (like wind and solar power) into the electricity supply system. The Code mentions the potential role of energy storage systems as a component of the smart grid. For example, the "deployment and integration of advanced electricity storage," as well as the ability "to accommodate traditional, centralized generation and transmission resources and consumer distributed resources, including distributed generation, renewable generation, energy storage" are proposed as a means to improve the U.S. grid [1].

Renewable generation is a key component in meeting clean energy policy goals. In 2011, Indiana's Clean Energy Law created a voluntary clean energy portfolio standard, known as CHOICE[1] (Comprehensive Hoosier Option to Incentivize Cleaner Energy). CHOICE provides incentives to encourage state utilities to use renewable energy resources, such as wind, for four percent of their total electricity supplied to consumers during the years 2013 to 2018. This percentage increases to seven percent from 2019 to 2024 and ten percent beginning in 2025.

Electricity storage can be deployed to any of the five major subsystems in the electric power system: generation, transmission, substations, distribution, and final consumers (see Figure 1.1). Generators may use traditional fossil fuel resources (such as natural gas or coal), nuclear generation, or renewables (such as hydro, wind, or solar). Transmission systems transport electricity at high voltages and often over long distances to utility substations. Step down transformers at utility substations reduce the voltage and transfer the electricity to distribution lines. Distribution lines supply electricity to final consumers. Variations in the location of the substation and consumers exist, but the general flow of electricity from generation to transmission to distribution to the majority of consumers remains the same.

[1] For more information on the CHOICE and program specifics see Indian Office of Energy Development website [25] or see Indiana Code 8-1-37 [26].

Figure 1.1: The electric power system[2]



This report focuses on six general benefits of incorporating bulk energy storage systems into the electricity grid including: (1) enabling time-shift of energy delivery, (2) supplying capacity credit, (3) providing grid operational support, (4) providing transmission and distribution support, (5) maintaining power quality and reliability, and (6) allowing integration of intermittent renewables generation.

These activities allow utilities to use existing infrastructure and energy resources efficiently to provide a reliable source of high quality electricity to end users. These benefits are defined, and their benefits to utilities are explained below.

(1) Time-shift of Energy Delivery

Common problems for both traditional and renewable generation are balancing generation with load and the inability to realize the cost savings from arbitrage across time. Time shifting energy allows utilities to charge energy storage devices with excess low cost generation and discharge storage during periods of high demand and high generation cost. In essence, storage allows utilities to reduce the impact of time as a constraint to resource availability.

Balancing generation and load using traditional generation plants (fossil fuel, hydroelectric and nuclear) can be costly in terms of capital life expectancy and operational inefficiencies. Frequent adjustment of generation output increases the wear and tear on generators, reduces their expected lifetimes and increases maintenance expenses. This operational scheme also results in both cost and productivity inefficiencies.

[2] Adapted from oncor.com

Arbitrage over time, a power market activity, allows a utility to take advantage of price differences over time. Energy storage may be charged during periods with low cost energy and then discharged during periods with high energy costs. A common application is load leveling (see Figure 1.2). See *(6) Integration of intermittent renewables generation* for further discussion of how this benefit facilitates the integration of renewable generation facilities into the electricity supply system.

Figure 1.2: Daily load leveling[3]

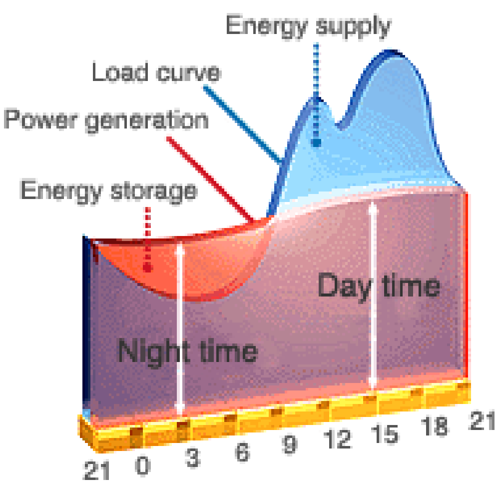
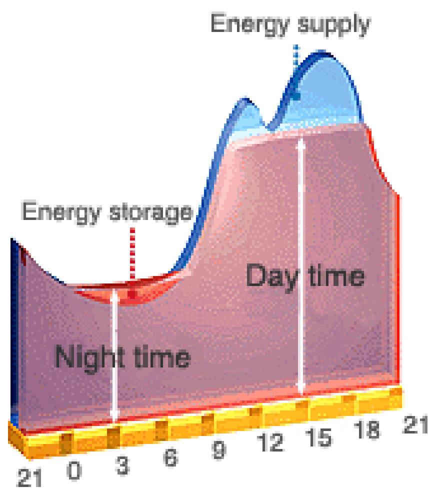


Figure 1.3 Daily peak shaving[4]



(2) Capacity Credit

Another potential problem facing the U.S. electric grid is the adequacy of current grid infrastructure to meet future demand. Capacity credit describes the ability of storage to supply electricity at a location and time that defers the need to upgrade existing generation or transmission infrastructure.

For example, sufficient generation capacity must be available to meet demand each day. In the short run, large plant expansions to increase capacity may be very costly, but existing generation capacity may not be sufficient to meet the expected peak demand.[5] Storage provides extra capacity to shave peak demand in the interim until larger expansions are economically justified (see Figure 1.3).

Storage can also be counted as a capacity credit for congested transmission systems. If energy can be stored at the receiving end of a transmission line that will be congested (at capacity) at a later time, then that energy can be discharged when the line is at capacity, making it appear at the receiving end of the transmission line that more energy can be delivered than would be allowed by the physical line capacity. Storage can also be housed at substations to hold power from transmission lines until it is needed to service loads on distribution lines.

[3] Source: NGK Insulators
[4] Source: NGK Insulators
[5] Peak demand is the maximum level of load over an indicated period. Daily peak demand refers to the maximum load within the day, while annual peak demand refers to the maximum load during the year.

(3) Grid Operational Support

Grid operational support, also called ancillary services, helps maintain power quality and reliability, reduce efficiency losses, and promote the smooth and coordinated operation of grid components. Example applications include voltage and frequency regulation, spinning reserve, and black start. Voltage and frequency regulation ensure power quality and coordination of grid components. Stored power can be used to maintain the proper voltages and frequencies. Storage can act as hot, or immediately available, supply for spinning reserves or as black start supply for recovery from a power outage.

(4) Transmission and Distribution Support

Storage can provide transmission and distribution utilities with a means to regulate power quality, reduce congestion on lines or transformers, and defer infrastructure upgrades. Both transmission and distribution lines operate within optimal voltage and frequency ranges. To maintain steady high quality power, voltage and frequency must be regulated to stay within these ranges. Storage can alternate between absorbing and injecting power to keep voltage and frequency within required ranges.

As discussed in *(2) Capacity credit*, storage may also simultaneously reduce congestion on transmission and distribution lines and defer the need to make structural upgrades in the short run. Reducing congestion reduces load shedding that could occur when the infrastructure is unable to transmit enough power to consumers.

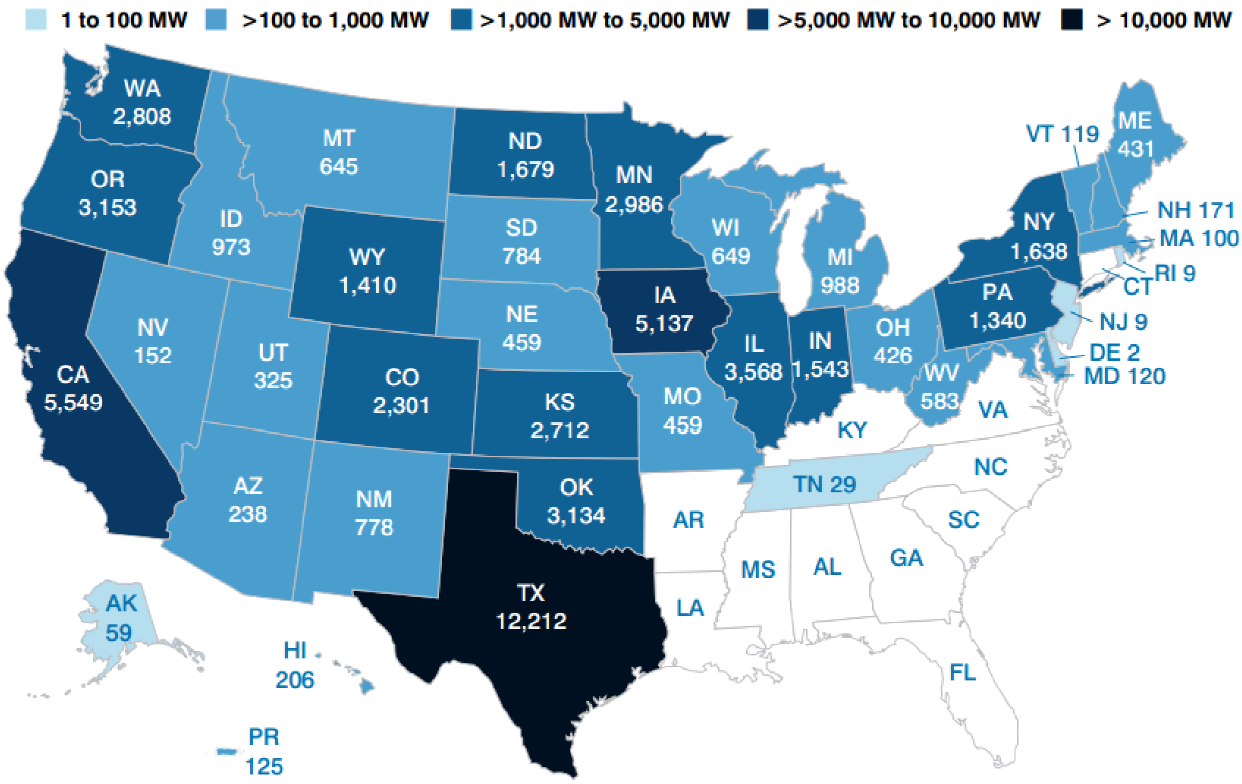
(5) Power Quality and Reliability

Consumers, especially information services, financial, and telecommunications businesses, demand high quality, reliable power to run electronic devices. The stringent efficiency in the operation of the power grid is in large part related to power quality and reliability. As discussed previously, energy storage with fast response times may be used to ensure real time power quality as well as spinning reserves in case of a power quality event or power outage.

(6) Integration of Intermittent Renewables Generation

Wind and solar electricity generation are increasing rapidly in the United States. Wind energy, in particular, is a prominent renewable energy source in Indiana (see Figure 1.4) and has increased rapidly since 2008. Wind and solar energy as sources of electricity generation are by nature intermittent. Both solar and wind energy are sensitive to geographic location and features, time of year, time of day, and weather conditions. These fluctuations in availability and power output make it an unpredictable source of energy supply. Storage may facilitate time-shifting energy in order to balance intermittent renewable generation with load.

Figure 1.4: 2012 United States installed wind generation capacity by state[6]



The imbalance between renewables generation and load has additional financial consequences for renewable generation facility owners. If potential generation exceeds load, curtailment may be necessary, and the profits from shed energy would not be realized. Intermittency in power output also causes frequency and voltage to fluctuate. Storage can smooth these fluctuations to help maintain power quality (as discussed in *(5) Power quality and reliability*) and support the overall functioning of grid components (as discussed in *(3) Grid operational support* and *(4) Transmission and distribution support*).

Although incorporating intermittent renewable generation into the United States' energy portfolio poses many challenges, it also can present advantages over traditional generation. Solar and wind energy generation have lower emissions (external costs) and lower variable operating costs (marginal costs to operate) than fossil fuel plants. Consider Figure 1.5, which provides an illustration of the logic behind a generation dispatch curve. A dispatch curve describes the order in which generation facilities will be deployed in order to meet demand. From an economic perspective, the plants with the lowest variable operating costs should be deployed first or serve base load because utilities will have larger profit margins[7] on the electricity generated at these plants. Generation plants with the highest variable operating (marginal) costs should be deployed last (see Figure 1.5).

[6] Source: American Wind Energy Association "U.S. Wind Industry Fourth Quarter Market Report 2012" (fourth quarter)
[7] A profit margin is the difference between the market price received by the utility for electricity and the cost to the utility of producing that electricity.

Figure 1.5: Logic of a dispatch curve[8]

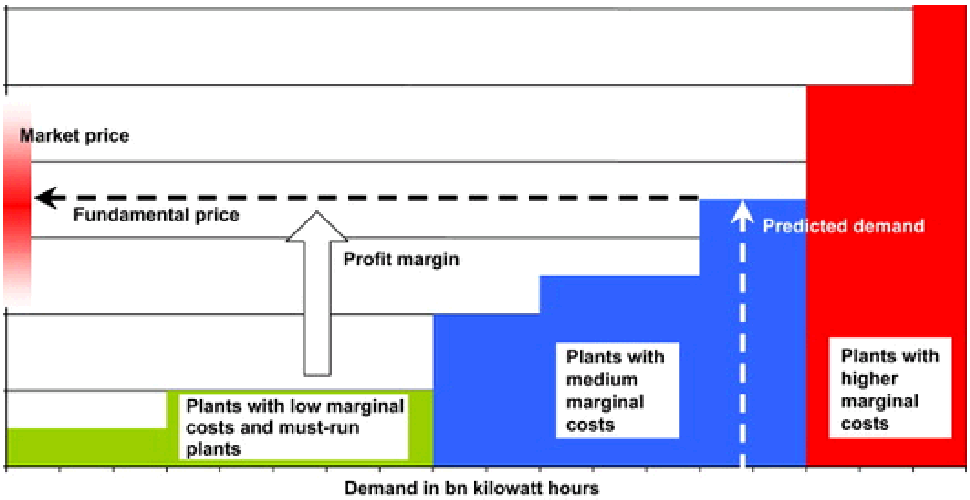
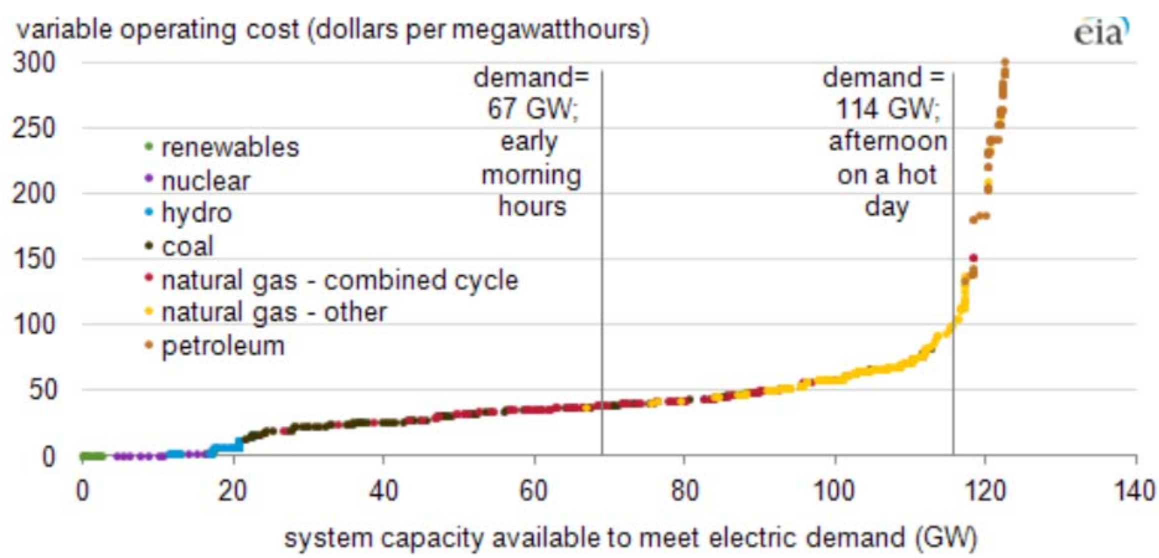


Figure 1.6 portrays a hypothetical generation dispatch curve. Renewables, nuclear, and hydro facilities are the lowest variable operating cost generation sources, followed by fossil fuels with petroleum being the most expensive. This curve reflects the importance of integrating renewables into generation portfolios despite the associated challenges. One such challenge is that some renewables, such as wind and solar, are not viewed as truly dispatchable. This means they may not be available when they are needed, or conversely, they may not be needed when they are available. Storage enables the shift of intermittent renewables across time, making them more dispatchable.

Figure 1.6: Hypothetical dispatch curve for summer 2011[9]



[8] Nestle, Uwe. 2012. *Does the use of nuclear power lead to lower electricity prices? An analysis of the debate in Germany with an international perspective.* Energy Policy, Volume 41, Pages: 152-160. http://www.sciencedirect.com/science/article/pii/S0301421511007324

[9] Source: The U.S. Energy Information Administration (2012). *Electric generator dispatch depends on system demand and the relative cost of operation* http://www.eia.gov/todayinenergy/detail.cfm?id=7590#

The following sections discuss in greater detail (1) important terms and definitions used to describe application and technology attributes, (2) the applications[10] that provide the aforementioned benefits, and (3) a survey of current bulk energy storage technologies and their operational characteristics, cost, and commercial maturity.

[10] The term application refers to the specific use for energy storage (e.g. long duration load shifting).

2. Terms and Definitions

(1) Power vs. Energy

To understand application and storage technology attributes, it is important to distinguish between the terms *energy* and *power*. Energy can be thought of as a quantity or volume whereas power can be thought of as a rate at which the amount of energy changes. Power is measured in kilowatts (kW) or megawatts (MW), while energy is measured in kilowatt-hours (kWh) or megawatt-hours (MWh) – that is an amount of power flowing for a specified period of time.

Applications such as long-duration load shift require a large volume of storage capacity, making energy cost (dollars per kWh or MWh) a particularly important consideration when selecting an appropriate storage technology. Similarly, applications such as grid angular stability and grid voltage stability require power to be absorbed or injected, making power cost (in dollars per kW or MW) a particularly important consideration in choosing the appropriate storage technology. From the cost information in Section 4, it should be noted that energy storage technologies used for power applications have very high energy costs relative to power costs.

It is also important to distinguish between *real power*, *reactive power*, and *pulse power*.[11] The U.S. electric grid is almost entirely an alternating current (AC) system, meaning voltage and current follow a sinusoidal wave pattern. Voltage is positive half the time and negative the other half, while current flows in one direction half the time and the reverse direction the other half. In the United States, these cycles occur 60 times per second (or 60 Hertz). Many components of the electric system will store energy (in the form of magnetic or electrical fields) during one half of the cycle and release the energy during the other half.

Reactive power is power that travels back and forth between components due to the repetitive absorption and release of energy but it does no work. *Real power* is power that is transmitted from an energy source, such as a generator, to do some form of work, such as turning a motor or producing light or heat. It should be noted that not all real power does useful work, such as in the case of heat losses in a transmission line. It should also be noted that while reactive power is not consumed, it can have significant impacts on the network. Reactive power flow does cause the current flowing through the system to increase, which will increase the heat loss and can cause voltage stability problems. Thus, it may be desirable to add components to the system that can provide reactive power support.

Pulse power is the ability to discharge a volume of energy quickly, as opposed to a constant discharge. Energy storage technologies such as capacitors or batteries allow energy to be stored and quickly discharged at high power and high voltage in a pulse.[12]

[11] For a more detailed explanation of real power and reactive power, see Appendix C of *Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide* [24]

[12] For an in depth discussion of pulse power systems see [23].

(2) Response Time and Discharge Duration

Response time is how quickly a storage technology can be brought online and discharge energy. *Discharge duration* is how long a storage device can maintain output. For the most part, technology suitability to perform a specific application will depend on rated power and discharge duration. However, for some applications, such as emergency spinning reserve, response time is also crucial.

(3) Depth of Discharge, Frequency of Discharge, and Efficiency

Depth of discharge refers to the percentage of power discharged relative to full capacity before the storage is recharged. Some technologies are sensitive to depth of discharge. Deep discharge of some electrochemical batteries reduces their life expectancy and may cause physical damage to the battery's cells. Other technologies operate best under full or 100 percent depth of discharge.

Frequency of discharge refers to how often power will be discharged from a storage technology. Some applications only require infrequent discharge (spinning reserve, for example) and others are cycled continuously.

Efficiency is determined by the input to output energy ratio. For most energy storage technologies, energy is lost in the process of being stored and discharged. Energy may also be lost while the device is not in use, and these losses are called standby losses. Standby losses are a measure of efficiency that compares how much of energy used to charge a storage device is lost before discharge. Efficiency can be affected by ambient conditions such as temperature. Some technologies require ancillary devices, which require power, to connect them to the grid. These "parasitic" loads reduce efficiency much like standby losses.

3. Applications

An important factor when evaluating the feasibility of an energy storage technology is the specific application for which the technology will be used. A wide variety of potential applications exist, many with very different technical requirements that may be best met with different technologies. This section categorizes applications via two criteria: duration of discharge and frequency of discharge (see Figure 3.1 and Table 3.1). Some applications may be appropriately categorized for both long and short duration or for both frequent and infrequent discharge. Additionally, it may be advantageous to use a single energy storage installation for more than one application. See Appendix B for a more in-depth explanation of the applications presented here.

Figure 3.1: Discharge duration and discharge frequency matrix

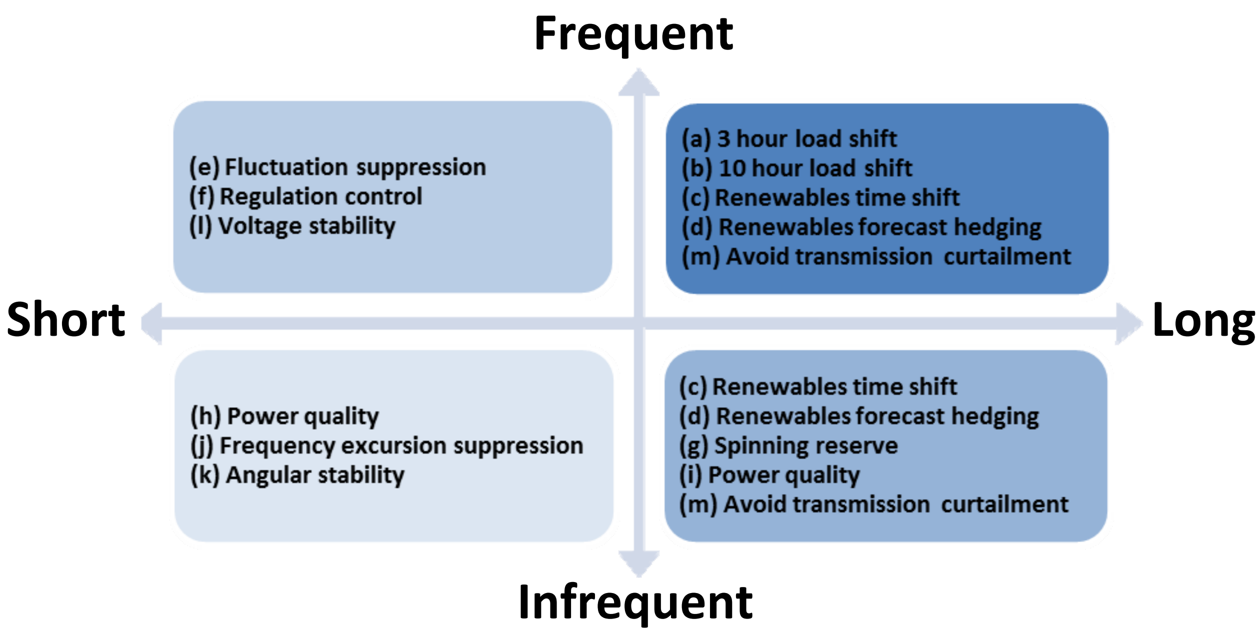


Table 3.1: Application operational requirements

Requirements	Long Discharge Frequent Use	Short Discharge Frequent Use	Long Discharge Infrequent Use	Long Discharge Infrequent Use
Discharge Duration	Hours	Minutes	Hours	Seconds
Response Time	Minutes	Seconds	Minutes	Seconds
Discharge Depth	Deep	Shallow	Deep	Shallow
Min. Cycle Life	Few 1000s	Tens of 1000s	Few 100s	Few 100s
Energy Efficiency	Important	Important	Not Important	Not Important

(1) Long-duration Applications

Long duration applications require sufficient storage capacity to accommodate prolonged discharges (generally one or more hours); these can be thought of as energy applications. Of the six benefits identified in the previous section, the following can be seen in long-duration applications:

- time-shift of energy delivery,
- capacity credit,
- grid operational support,
- power quality and reliability, and
- integration of intermittent renewables generation.

Long-duration applications include:

- *mitigating transmission curtailment* - reducing congestion on the transmission system, thereby allowing more economic generation options to be used;
- *renewables time shifting* - storing energy from renewable sources of generation to better match the temporal pattern of the load;
- *renewables forecast hedging* - mitigating the impact of errors in forecasting the output of renewables generation;
- *load shifting* - storing energy during periods of low demand for use during periods of high demand;
- *power quality and reliability* - maintaining voltage and frequency within normal operating ranges; and
- *spinning reserve* - compensating for unexpected contingencies such as failure of a generating unit.

(2) Short-duration Applications

Unlike long-duration applications, short-duration applications place a premium on the ability to charge or discharge quickly (generally a few seconds to several minutes), and can be thought of as power applications. The following benefits can be seen in short-duration applications:

- time-shift of energy delivery,
- grid operational support,
- transmission and distribution support,
- power quality and reliability, and
- integration of intermittent renewables generation.

Short-duration applications include:

- *power quality and reliability*;
- *regulation control* - maintaining a real-time balance between generation and load;
- *fluctuation suppression* - smoothing out very short-term (milliseconds) variations in voltage and current;

- *frequency excursion suppression* - maintaining system frequency in the face of a generation and load imbalance;
- *grid angular stability* - mitigating power oscillations resulting from loss of generator synchronization; and
- *grid voltage stability* - providing reactive power support to prevent voltage from falling below acceptable levels.

(3) Infrequent Discharge

Applications that are discharged only a few times a month or a year (20 events per year or less) fall into this category. Applications that only use stored energy occasionally can provide the following benefits to the electric power system:

- grid operational support,
- transmission and distribution support,
- power quality and reliability, and
- integration of intermittent renewables generation.

Infrequent discharge applications include:

- *frequency excursion suppression*;
- *grid angular stability*;
- *voltage stability*;
- *spinning reserve*;
- *power quality and reliability*;
- *mitigating transmission curtailment*; and
- *forecast hedging*.

(4) Frequent Discharge

In contrast, frequent discharge applications require stored energy to be discharged and recharged on more than 20 occasions per year or to be cycled continuously. Such applications can provide the following benefits:

- time-shift of energy delivery,
- capacity credit,
- grid operational support,
- transmission and distribution support,
- power quality and reliability, and
- integration of intermittent renewables generation.

Frequent discharge applications include:

- *power quality and reliability*;
- *regulation control*;
- *fluctuation suppression*;

- *load shifting*;
- *mitigating transmission curtailment*;
- *forecast hedging*; and
- *time shifting*.

(5) Combined Applications

There are nine combined applications listed in Table 3.2. Applications are combined based on attractive value propositions, application operational compatibility, and the ability of storage to accommodate all of the combined applications. The combined applications (C1 – C9) list the primary application first, followed by secondary applications that can be simultaneously served together with the primary application (in order of importance). For example, C1 is a combined application in which the primary function is to provide frequency excursion suppression, followed by secondary functions of providing grid angular stability, voltage support, and regulation control. These combined applications may justify the use of storage where serving a single application may not be economical or feasible for other considerations.

Table 3.2: Combined applications

(C1)	**Frequency Excursion Suppression + (**Grid Angular Stability **+** Grid Voltage Stability **+** Regulation Control**)**
(C2)	**Short duration Power Quality + (**Load Shift 10 hours **+** Regulation Control **+** Spinning Reserve**)**
(C3)	**Short duration Power Quality + (**Load Shift 3 hours **+** Regulation Control **+** Spinning Reserve**)**
(C4)	**Long duration Power Quality + (**Load Shift 3 hours **+** Spinning Reserve **+** Regulation Control**)**
(C5)	**Load Shift 10 hours + (**Spinning Reserve **+** Regulation Control**)**
(C6)	**Avoid Transmission Curtailment + (**Frequency Excursion Suppression **+** Regulation Control**)**
(C7)	**Renewable Time Shifting + (**Frequency Excursion Suppression **+** Regulation Control**)**
(C8)	**Forecast Hedging + (**Frequency Excursion Suppression **+** Regulation Control**)**
(C9)	**Fluctuation Suppression + (**Frequency Excursion Suppression **+** Renewable Time Shifting**)**

Table 3.3 describes the technical characteristics required to perform the applications described by comparing required response time, reference duty cycle, energy discharge cycle duty, energy storage system unit power, energy storage system voltage, full power discharge duration, and basis for economic benefits.

For example, consider the technical characteristics of power quality applications (both long and short duration) listed in Table 3.3. The *required response time* (20 milliseconds) and *reference duty cycle* (hot standby) indicate that storage used for power quality applications must be able to react instantaneously to unforeseen deviations of voltage and frequency from optimal ranges. *Energy discharge cycle duty* describes the expected frequency of discharge (on a daily or yearly basis). On average short duration power quality applications are expected to mitigate 100 events per year, as compared to the expectation of only one long duration power quality event per year.

Energy system (ES) unit power and *ES system AC (alternating current) voltage* describe the size and voltage range necessary to provide power quality services. *Full power discharge duration* is the amount of time required to completely empty stored energy at full power. Short duration power quality applications have expected discharge durations of only 5 seconds, whereas for long duration power quality applications it is 4 hours.

Finally, the basis for economic benefits describes the method of calculating a monetary value for each application. For example, the cost of alternate solutions is considered an appropriate representation of the value of power quality applications. For further discussion of the approaches to calculate specific values of storage applications see Appendix A.

Table 3.3: Application technical characteristics

	Required Response Time	Reference Duty Cycle	Energy Discharge Cycle Duty	ES System Unit Power (MW_{AC})	ES System AC Voltage (kV)	Full Power Discharge Duration	Basis for Economic Benefits
3 hour Load Shift	10 minutes	Scheduled 3 hour discharge	60 days/year 1 event/day	1 to 200	4.2 to 115	3 hours	market rates
10 hour Load Shift	10 minutes	Scheduled 10 hour discharge	250 days/year 1 event/day	1 to 200	4.2 to 115	10 hours	market rates
Renewables time shift	1 minute	Optimized by technology	Per reference wind profile	2 to 200	4.2 to 34.5	5 to 12 hours (except CAES; varies)	Various*
Renewables forecast hedging	20 milliseconds	Optimized by technology	Per reference wind profile	2 to 200	4.2 to 34.5	5 to 12 hours (except CAES; varies)	Various*
Fluctuation suppression	20 milliseconds	Continuous cycling	90 cycles/hour	2 to 50	4.2 to 34.5	10 seconds	Various*
Short duration power quality	20 milliseconds	Hot standby	100 events/year 5 events/day 1 event/hour	1 to 50	4.2 to 34.5	5 seconds	cost of alternative solutions
Long duration power quality	20 milliseconds	Hot standby for infrequent events	1 event/year	1 to 50	4.2 to 34.5	4 hours	cost of alternative solutions
Frequency excursion suppression	20 milliseconds	Hot standby	10 events/year 1 event/day	10 to 500	4.2 to 750	15 minute	cost of alternative solutions
Grid frequency support	20 milliseconds		24 events/year 1 event/day	2 to 200	4.2 to 34.5	10 to 30 minutes	Various*
Angular stability	20 milliseconds	Hot standby	10 events/year 1 event/day 20 Cycles/event	10 to 500	4.2 to 750	1 second	cost of alternative solutions
Voltage stability	20 milliseconds	Hot standby	10 events/year 1 event/day	10 to 500	4.2 to 750	1 second	cost of alternative solutions
Transmission curtailment	1 minute	Optimized by technology	Per reference wind profile	2 to 200	4.2 to 34.5	5 to 12 hours (except CAES; varies)	Various*

*indicates various bases for economic benefits of these applications include capitalized costs and benefits of alternative systems, market rates, tax credits, and green price premiums.

4. Technologies

This section contains a survey of current technologies being considered for utility energy storage projects.[13] First, stylized facts about the energy storage market in the United States and the world are presented. Second, storage technologies are described in terms of components and functions, history, technical characteristics, suitability for utility applications, and costs. Finally this section compares technical characteristics, suitability for utility applications, and cost across storage technologies.

Storage has played a role in the United States' electric power infrastructure for more than a century. In the United States, the first pumped hydroelectric plant began operation in the 1920s and was used for load balancing. By the 1950s, isolated power systems began to aggregate into regional power systems capable of delivering bulk generation over long distances. The large scale of electric power system allowed utilities to satisfy growing demand at lower prices. During the 1970s, the energy crisis prompted utilities to consider energy storage in earnest and a resurgence of research and development of storage technologies ensued. After the 1970s, oil and gas prices fell and high efficiency, low cost gas turbines slowed storage research until recent years.

The resurgence in storage research and development can be attributed to fuel price volatility, the penetration of intermittent renewable generation into the U.S. energy portfolio, and the evolution of the power market [2]. Future growth in the number and pace of power market transactions as well as increases in the demand for high quality power will put new pressure on the existing power system infrastructure.

In 2009, the U.S. Department of Energy (DOE) used approximately $185 million from the American Recovery and Reinvestment Act (ARRA) to fund energy storage projects. These projects have a total value of $772 million and will add 537 MW of energy storage capacity to the U.S. grid. Table 4.1 shows DOE-funded projects by intended application and may explain a recent surge in battery and compressed air energy storage research and demonstrations. (For a more detailed list of these projects see Appendix C).

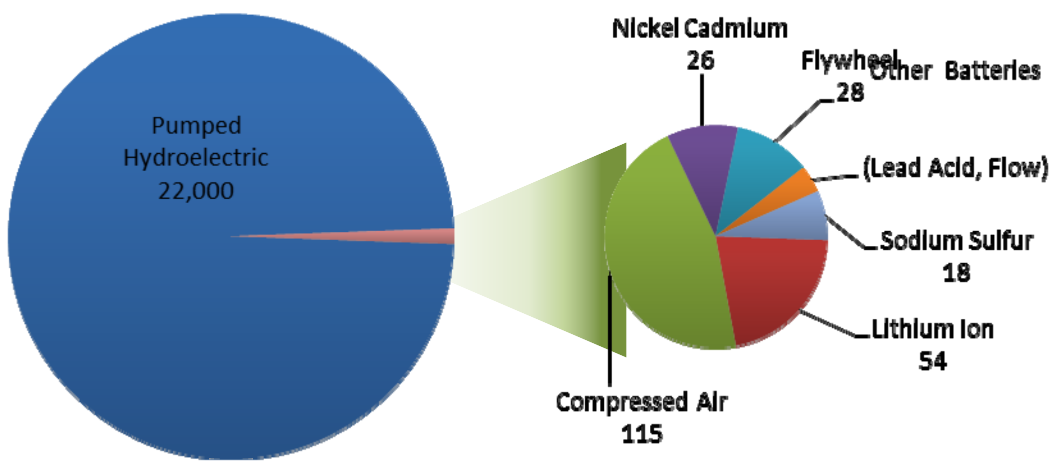
[13] Distributed energy storage technologies behind the consumer's meter are not covered in this report. A small battery at an industrial plant or in a consumer's home is not included, whereas a battery at a utility substation is included.

Table 4.1: ARRA-funded energy storage projects by intended application[14]

Category	Power (MW)	Project Value	DOE funds
Batteries (load shifting & wind integration)	57.0	$145,168,940	$60,784,483
Frequency regulation & ancillary services	20.0	$48,127,957	$24,063,978
Distributed storage for grid support	7.5	$44,468,944	$20,350,142
Compressed air energy storage	450.0	$480,962,403	$54,561,142
Promising technology demonstrations	2.8	$53,075,574	$25,230,027
Total	**537.3**	**$771,803,818**	**$184,989,700**

Today, the vast majority of storage capacity (MW) in the United States (and in the world) is pumped hydroelectric storage. Figure 4.1 shows the composition of energy storage capacity (MW) by technology in the United States.

Figure 4.1: 2011 energy storage capacity (MW) in the United States by technology[15]

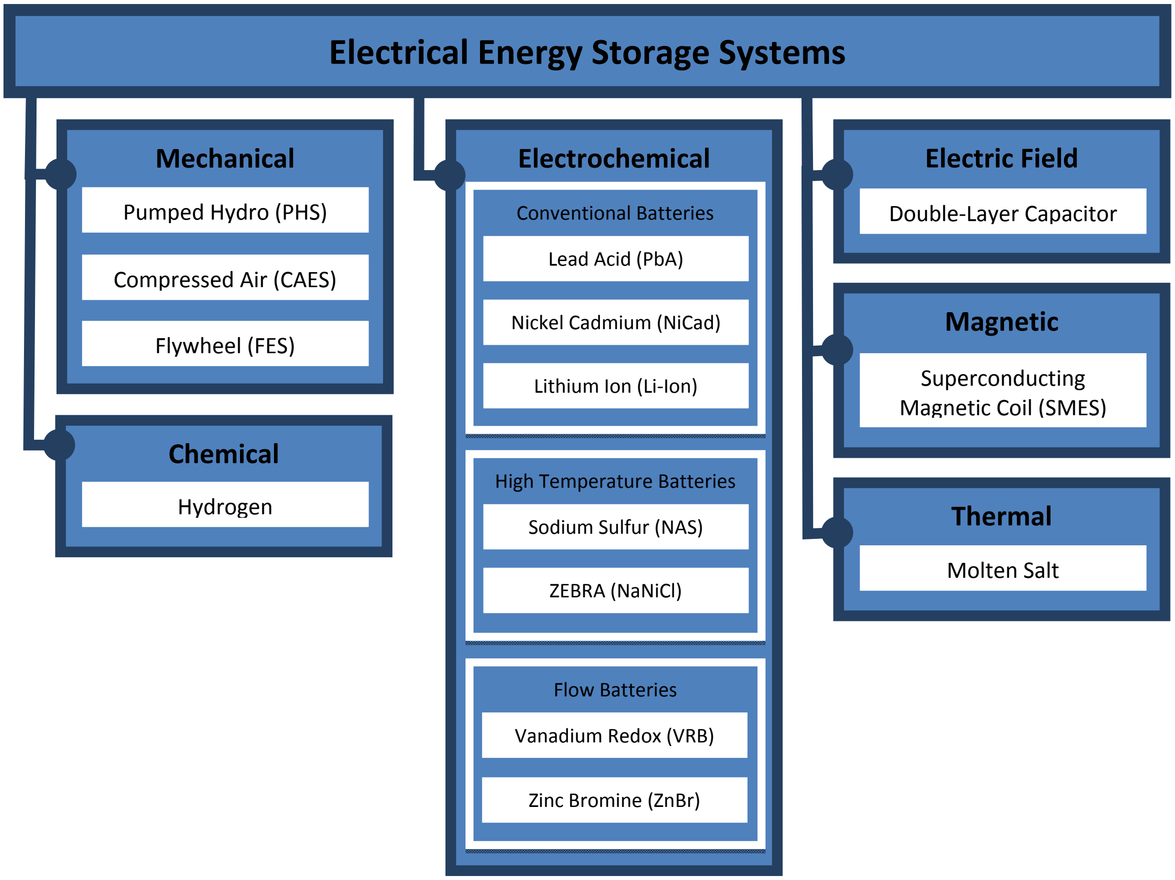


Because electricity is a flow, it must be converted to a storable form such as potential, chemical, kinetic, or thermal energy. For example, electricity is converted to chemical energy when a battery is charged, then returned to electrical energy when the battery is discharged. The proceeding descriptions group storage technologies according to the form of stored energy they employ. These categories are (1) mechanical energy storage; (2) electrochemical (and chemical) energy storage, (3) electrical and magnetic field energy storage, and (4) thermal energy storage (see Figure 4.2).

[14] Adapted from [28]

[15] Data source: Electricity Advisory Committee (2011) *Energy Storage Activities in the United States Electricity Grid*. Information is current as of April 2010. Note: according to a report by Bloomberg Finance developed in partnership with The Business Council for Sustainable Energy entitled *Sustainable Energy in America 2013 Factbook* pumped hydro power capacity in 2011 was 22,300.

Figure 4.2: Classification of energy storage according to energy form [3]



(1) Mechanical

This category of energy storage technologies includes (a) pumped hydroelectric storage, (b) compressed air energy storage, and (c) flywheel energy storage. The term mechanical describes the electricity to stored energy conversion process and specifically includes, potential gravitational energy (pumped hydroelectric storage), pressure potential energy (compressed air energy storage), and rotational kinetic energy (flywheel energy storage). Pumped hydroelectric and compressed air energy storage are primarily energy management technologies, whereas flywheels are primarily used for power applications.

(a) Pumped hydroelectric storage

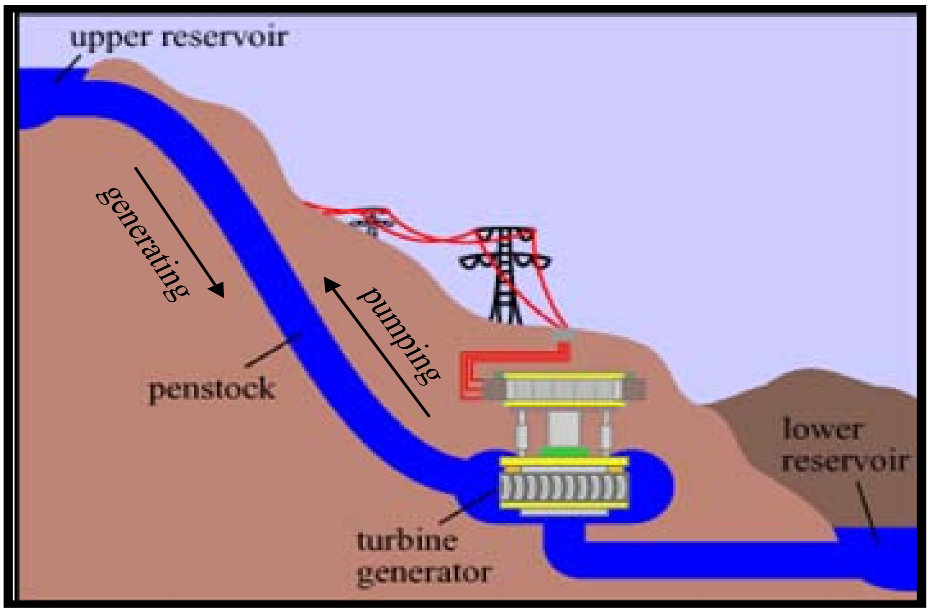
Pumped hydroelectric storage (PHS) is the most mature form of energy storage. In fact, most of the world's (and the United States') energy storage capacity is in the form of pumped hydroelectric storage. Pumped hydroelectric worldwide installed storage capacity is nearly 127 GW (22 of which is in the United States).[16] In part, these large numbers reflect the nature of pumped hydro as an energy management technology, often able to store hundreds to thousands of megawatts per installation. This characteristic makes pumped hydro an ideal technology for load leveling and peak shaving. The first pumped hydroelectric plant in the United States began

[16] Koritarov, Vladimir. Grid-Scale Energy Storage Presentation. March 20, 2013.

operation in 1929 and helped balance generation with load. Since then, pumped hydro systems have also been used for time-shifting, smoothing, and firming[17] of intermittent renewable generation as well as arbitrage over time.

A pumped hydroelectric energy storage system uses electricity to pump water to higher altitude where it is stored as gravitational potential energy. To convert the stored energy back into electricity, water is released and passed back through a turbine/generator on its way to the lower reservoir. When low-cost electricity is available (or during off-peak hours), water is pumped uphill. When electricity is expensive (or during on-peak hours), the downhill flow of water powers the turbine/generator to produce electricity (see Figure 4.3).

Figure 4.3: Pumped hydroelectric energy storage system[18]



Pumped hydro has very low power and energy density, which is the amount of power and energy that can be delivered given its volume. To store such large quantities of low density energy requires both a large area and the proper terrain. These features make building such a large facility and obtaining the proper permits difficult and costly. Pumped hydroelectric facility construction is often constrained by low variation in topographic elevation and water availability. After examining Figure 4.4, it is evident that the state of Indiana does not employ PHS, which is not surprising given its topographic features.

[17] Firming refers to the process which uses a backup resource (in this case stored energy) to supplement intermittent resources' output to ensure total energy output is sufficient to meet customer demand. On the other hand, shaping refers to the process of lowering the output from a supplemental resource when intermittent is generating, storing the excess power for later. [31]
[18] Adapted from: http://www.hk-phy.org/energy/alternate/print/hydro_is_print_e.html

Figure 4.4: Map of existing pumped hydroelectric storage projects in the United States (2009)[19]

Pumped hydro plants may have negative impacts on the surrounding environment, such as forest removal, disturbances of the surrounding watersheds and ecosystems, and the captivity of scarce water resources. However, they have lower emissions than fossil fuel-fired generators [4] and are considered a renewable energy source.

Pumped hydro systems round trip efficiency is between 75 and 78 percent. Energy losses arise from the inefficiencies in the energy conversion process (electricity to gravitational potential energy) and from evaporation and leakage during standby.

Cost estimates are highly situational, often quite different based on siting, construction method, and size. According to the U.S. Energy Information Administration, a 250 MW pumped hydroelectric plant has overnight capital costs of $5,595 (2010 US$) per kW and fixed operating and maintenance (O&M) costs of $13.03 (2010 US$) per kW [4]. Another cost estimate by the Electric Power Research Institute (EPRI) is presented in Table 4.2.

Table 4.2: PHS technical characteristics and costs (2010$)[20]

	Maturity	Capacity (MWh)	Power (MW)	Duration (hrs)	Efficiency (%)	Lifetime (Cycles)	Total cost ($/kW)	Cost ($/kWh)
Grid support (ancillary services) and integration of intermittent renewables								
Small Pumped Hydro	Mature	1,680-5,300	280-530	6-10	80-82	>13,000	2,500-4,300	420-430
Large Pumped Hydro	Mature	5,400-14,000	900-1,400	6-10	80-82	>13,000	1,500-2,700	250-270

[19] Source: http://www.hydroworld.com/articles/hr/print/volume-30/issue-2/article/policies-regulations-whats-so-hard-about-licensing-a-pumped-storage-project.html
[20] Adapted from [22]

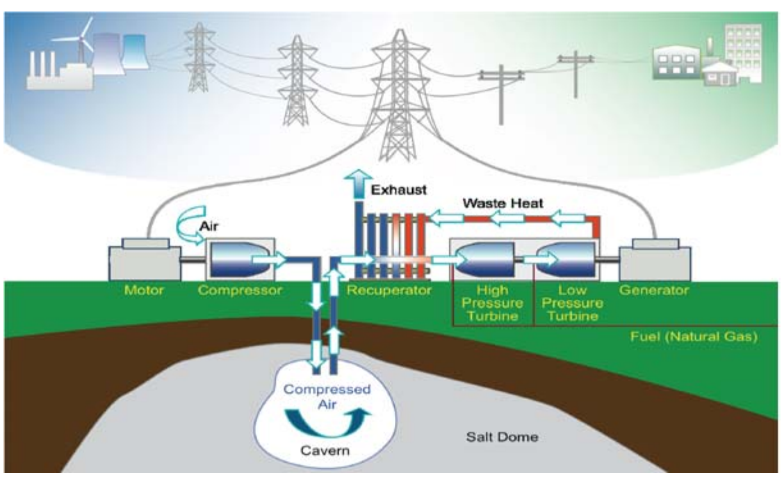
Although pumped hydro systems have large initial costs, these costs are spread over a long life expectancy, much longer than nearly all other available technologies. In comparison to other storage technologies, estimated variable O&M costs per kW are quite low, usually falling quite close to zero [4]. They also do not suffer capacity loss from each charge-discharge cycle as some electrochemical batteries do. Thus, hydro systems are ideal for long discharge and frequent use applications [4].

(b) Compressed air energy storage

Compressed air energy storage (CAES) is a relatively mature energy management technology. Interest in CAES began in the 1970s as oil and gas prices escalated. In 1978, the first CAES facility, located in Huntorf, Germany, began operations. It was used to store off-peak base load energy from a nuclear power plant. Recently, the facility has been used as spinning reserve for industrial customers and to level variable power from integrated wind energy [5]. The second facility, located in McIntosh, Alabama, was built in 1991. Currently, the McIntosh plant serves load management, peaking power, ramping duty, synchronous condenser duty, and spinning reserve applications [5]. Although numerous projects have been proposed and even partially constructed, many of them encountered insurmountable siting problems and were abandoned.

Simple CAES systems use a compressor powered by low cost off-peak power to store the energy as compressed air inside an air-tight vessel. The energy is converted back to electricity by reheating and mixing the cool, pressurized air with fuel. It is then passed through an expansion turbine where it is combusted to drive an electric generator (see Figure 4.5). The compressor/expander pair in a CAES system differs from a conventional combustion turbine (CT) in that the compressor and expander in the CAES system are separate and operate independently while they are mounted on a single shaft in a CT. The compressor in a CT is driven by some of the power generated by the expander. A variety of storage vessels such as salt caverns, hard rock caverns, porous rock formations, abandoned mines, pipes, underwater bladders, and above-ground tanks can be used. Also, a variety of fuels, such as hydrogen, natural gas, gasified biomass, and oil can be used in the combustion process [6].

Figure 4.5: Compressed air energy storage system[21]



[21] Source: http://www.sciencedirect.com/science/article/pii/S1364032108001664

There are two general types of CAES—bulk and small. Bulk CAES is practical for storage needs greater than 5 hours or from one hundred to thousands of MW. A typical storage capacity ranges from 300 to 400 MW over the course of 10 to 30 hours [5]. Large subterranean geological formations are the most economical way to store such a large volume of compressed air [7, 6, 5]. Both existing CAES installations are used for bulk storage. For example, the Huntorf, Germany, facility has a storage capacity of 11 million cubic feet, or 290 MW [5]. It takes 12 hours to charge and up to 4 hours to discharge at maximum capacity with 10 hours of exponentially declining power output [6, 5]. The McIntosh, Alabama facility has a capacity of 19 million cubic feet, or 110 MW, with a maximum of 26 hours output.

Smaller, aboveground systems typically have capacities on the order of 10 to 20 MW and shorter discharge times (less than 5 hours). Small CAES systems use pipes, bladders, or other manmade vessels [5] to store compressed air. Small and bulk CAES capacities and discharge times will also vary significantly depending on siting, construction, and system design.

There are also three major CAES technologies diabatic, adiabatic, and near-isothermal [8, 7]. Diabatic CAES uses heat added during the expansion process to increase the power capacity. Diabatic is the most technologically developed form of CAES and is used in the Huntorf, Germany and McIntosh, Alabama installations [7]. Adiabatic CAES uses a thermal storage device to capture heat expelled in the compression process and then uses the stored thermal energy to reheat the air during the expansion process [7]. Near isothermal CAES technology compresses and expands slowly so that the air temperature remains near constant. This eliminates the need to burn fossil fuels to reheat the air during expansion and substantially increases efficiency [7]. There are several other CAES technologies that incorporate the use of steam or humidification to reduce the storage volume per kWh produced [5]. Other, less well developed, CAES technologies exist in the theoretical or early experimental stages only.[22]

Efficiency estimates vary significantly depending on the specific CAES technology and geologic features. The first source of inefficiency comes from the use of energy in the compression and heating process in diabatic CAES. There are some technological improvements that can reduce the amount of fuel required. For example, the McIntosh, Alabama facility uses a recuperator[23] to reduce fuel consumption by up to 25 percent [5]. In general, efficiency estimates for traditional large CAES systems fall between 73 and 89 percent [6, 5, 8]. Second, if air escapes into surrounding formations and pressure is lost, CAES technology becomes quite inefficient. This has been a major consideration when selecting locations to demonstrate CAES in porous rock formations or abandoned mines. The two existing facilities use salt domes and have not experienced any leaks [5].

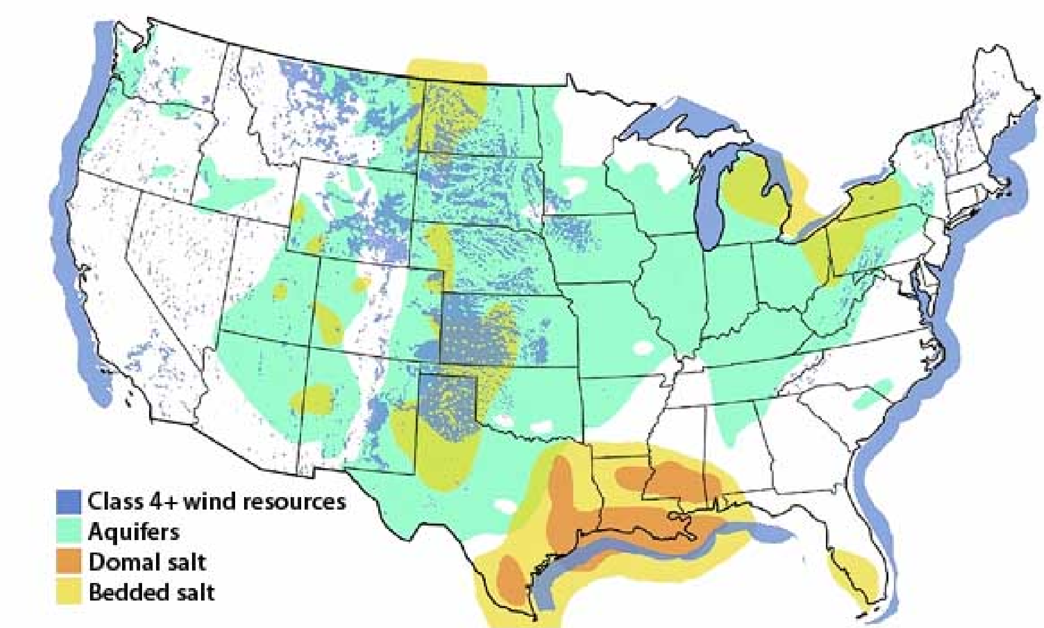
Some safety concerns exist with CAES. First, the high pressures necessary for CAES technology may damage the structural integrity of surrounding geologic formations and cause problems for surrounding above-ground activities. Second, the combination of leftover, flammable hydrocarbons, heat from the compression process, and oxygen creates a potential for explosion [9]. Small CAES systems do not have these drawbacks.

[22] See [7] for more details
[23] A recuperator is a heat exchanger that recovers heat from the products of combustion.

Short (3 hour) and long (10 hour) duration load shifting, regulation control, or a combination of load shifting, regulation control and spinning reserve are deemed suitable for CAES technology [5]. Short and long duration time-shift is particularly useful in peak shaving, load leveling, renewables integration, and electricity arbitrage. Extensive research on the integration of CAES technology with wind generation exists. There are many geographic regions that are suitable for both CAES systems and wind energy generation facilities (Figure 4.6) [6].

Small CAES systems can be used for both short and long duration time shift applications, whereas large CAES systems are best used for long duration time shift applications [5]. Large CAES facilities are best suited for the second application, regulation control. Although typically used for energy applications, CAES has start up times on the order of minutes and is capable of providing black start and spinning reserve services [5]. Both small and large CAES facilities are suited for the combination of load shifting, regulation control, and spinning reserve [5].

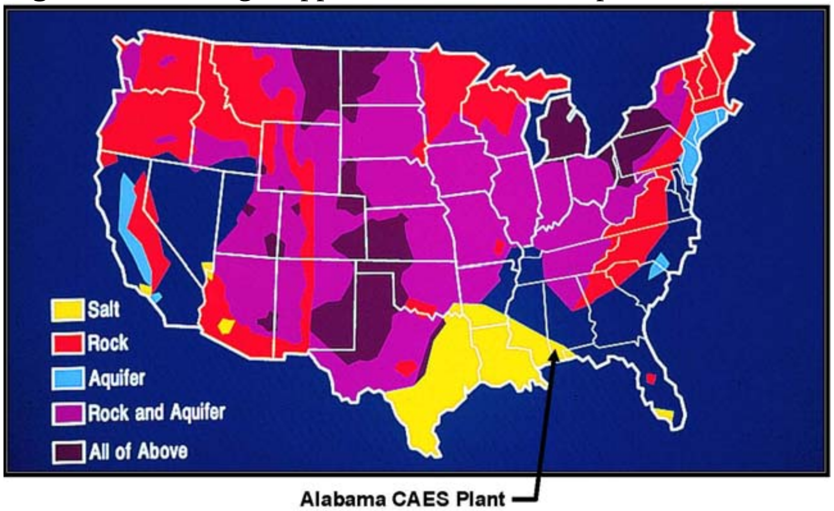
Figure 4.6: Combination wind and CAES opportunities in the United States[24]



Large, subterranean CAES systems face major locational constraints. Although an estimated 80 percent of the United States has favorable geological conditions (Figure 4.7), a much lower percentage is actually suitable for CAES facilities [5]. For this reason, there have been many planned CAES projects that never reached fruition. For example, a 270 MW facility in Des Moines, Iowa progressed eight years before its termination due to geological unsuitability [10]. Similarly, in Matagorda, Texas a 540 MW CAES plant was planned but never completed. Small CAES systems do not face the same geographic restrictions.

[24] Source: http://phys.org/news188048601.html

Figure 4.7: Geologic opportunities for CAES plant sites in the United States



Currently there are several CAES sites in the U.S. in either the planning or development stage. An isothermal 1.5 MW CAES system in Seabrook, New Hampshire is under construction and estimated to be fully operational by 2015. The facility will assist in renewables time-shift and firming, as well as ramping and transmission congestion relief [11]. The New York State Energy Research and Development Authority is also planning to implement a modular CAES system that uses steel piping instead of a subterranean geologic formation. Construction of this 9 MW system in Queens, New York is planned to start sometime in 2013 or 2014 [11]. Finally, Kern County, California plans to build a 300 MW CAES facility in a saline, porous rock, underground formation. The facility will provide electric energy time shift, frequency regulation, reserve capacity (spinning reserve), and renewable capacity firming services [11].

The costs of installing a CAES plant are dependent on facility size, operating technology, containment vessel, fuel prices and intended use. In many ways CAES is similar to PHS, in that it is very site specific and has large up-front costs but low variable O&M costs. Unlike PHS, the prices of fossil fuels are also an important factor in determining the costs of a CAES plant. Because diabatic CAES is not a pure storage technology, the cost of fuel inputs can significantly raise overall costs.

Table 4.3 describes the estimated cost differences for bulk CAES systems in different geologic formations and by mining technique. The manner in which geologic formations are conditioned may impact the cost of the facility. For example, solution mining of salt domes and dry mining of hard rock have large cost differences.

Table 4.3: Capital costs of bulk CAES storage by geology [6]

Geology	Capital Costs
Salt Cavern (Solution Mined)	$1/kWh
Salt Cavern (Dry Mined)	$10/kWh
Hard Rock (Excavated & Existing Mines)	$30/kWh
Porous Rock / Aquifer	$0.10/kWh
Abandoned Limestone or Coalmines	$10/kWh

There are two general CAES sizes, bulk and small, described in terms of energy (MWh) and power (MW) storage capacity. The small units are assumed to use transmission and distribution pipelines previously used for natural gas. These small systems have 10 MW rated power and their costs are described in Table 4.4. The bulk systems are assumed to be in subterranean geologic formations such as those listed in Table 4.3. These bulk systems have 300 MW rated power and their costs are described in Table 4.5. Because of the capacity disparities between bulk and small systems, it is difficult to compare technologies based on total costs. For this reason, the per-unit costs provide a useful measure of the costs per increment of added capacity.

Table 4.4: Small (10 MW) CAES costs by application (2003$)[25]

	Load shift (3hr)	Load shift (10hr)	Avoid Transmission Curtailment*	Renewable Time Shift*	Renewable Forecast Hedging*	C5: Load shift (10hr) + Regualtion Control +Spinning Reserve	C6: Avoid Transmission Curtailment + regulation Control*	C7: Renewables Time shift + Regulation Control*	C8: Renewables Forecast Hedging + Regulation Control*	C9: Frequency Support + Renewable Time Shift*
Capacity (MWh)	30	100	120	100	50	100	120	100	100	80
Initial costs ($/kW)[a]										
CT	270	270	300	300	300	270	300	300	300	300
BOP	160	160	200	200	200	160	200	200	200	200
Storage	120	400	480	400	200	400	480	400	200	400
O&M cost ($/kW-year)[b]										
Fixed	19.0	24.6	32.6	31.0	27.0	24.6	32.6	31.0	27.0	31.0
Variable	4.7	65.0	9.4	21.9	7.5	69.3	26.9	39.4	25.0	17.5
Total Capital Cost (M$)	**5.5**	**8.3**	**9.8**	**9.0**	**7.0**	**8.3**	**9.8**	**9.0**	**7.0**	**9.0**

NOTES: *indicates application estimates are in 2004$

a. Initial costs include acquisition, space, and installation costs. CT means combustion turbine and BOP means balance of plant. Total initial cost can be calculated by multiplying the sum of CT, BOP, and Storage initial costs by the reference power.

b. Fixed O&M costs include projected annual labor, parts, tax, and insurance costs. Variable O&M costs include fuel and other variable consumables and assume a duty cycle appropriate for each application.

[25] Adapted from [5] and [27]

Table 4.5: Bulk (300 MW) CAES costs by application (2003$)[26]

	Regulation Control	Load shift (10hr)	Avoid Transmission Curtailment*	Renewable Time Shift*	Renewable Forecast Hedging*	C5: Load shift (10hr) + Regualtion Control +Spinning Reserve	C6: Avoid Transmission Curtailment + regulation Control*	C7: Renewables Time shift + Regulation Control*	C8: Renewables Forecast Hedging + Regulation Control*
Capacity (MWh)	2,400	3,000	12,000	3,000	1,500	3,000	12,000	3,000	3,000
Initial costs ($/kW)[a]									
CT	270	270	300	300	300	270	300	300	300
BOP	170	170	210	210	210	170	210	210	210
Storage	10	10	70	18	18	10	70	18	18
O&M cost ($/kW-year)[b]									
Fixed	13.0	13.0	24.6	23.6	23.6	13.0	24.6	23.6	23.6
Variable	8.5	58.8	7.8	13.1	4.5	61.3	18.3	23.6	15.0
Total Capital Cost (M$)	**135**	**135**	**174**	**158.3**	**158.3**	**135**	**174**	**158.3**	**158.3**

NOTES: *indicates application estimates are in 2004$
a. Initial costs include acquisition, space, and installation costs. CT means combustion turbine and BOP means balance of plant. Total initial cost can be calculated by multiplying the sum of CT, BOP, and Storage initial costs by the reference power.
b. Fixed O&M costs include projected annual labor, parts, tax, and insurance costs. Variable O&M costs include fuel and other variable consumables and assume a duty cycle appropriate for each application.

Tables 4.4a and 4.4b show the trade-off between storage initial costs and total capital costs. There are economies of scale gains from storing energy in bulk CAES systems reflected in lower initial storage costs. However, bulk systems have much larger up-front, total capital costs. Variable O&M costs for load shifting (10hr), renewable time shift, and combined applications are generally higher than other applications for both bulk and small CAES. Table 4.6 presents a second set of cost estimations according to the benefits the technology will provide.

[26] Adapted from [5] and [27]

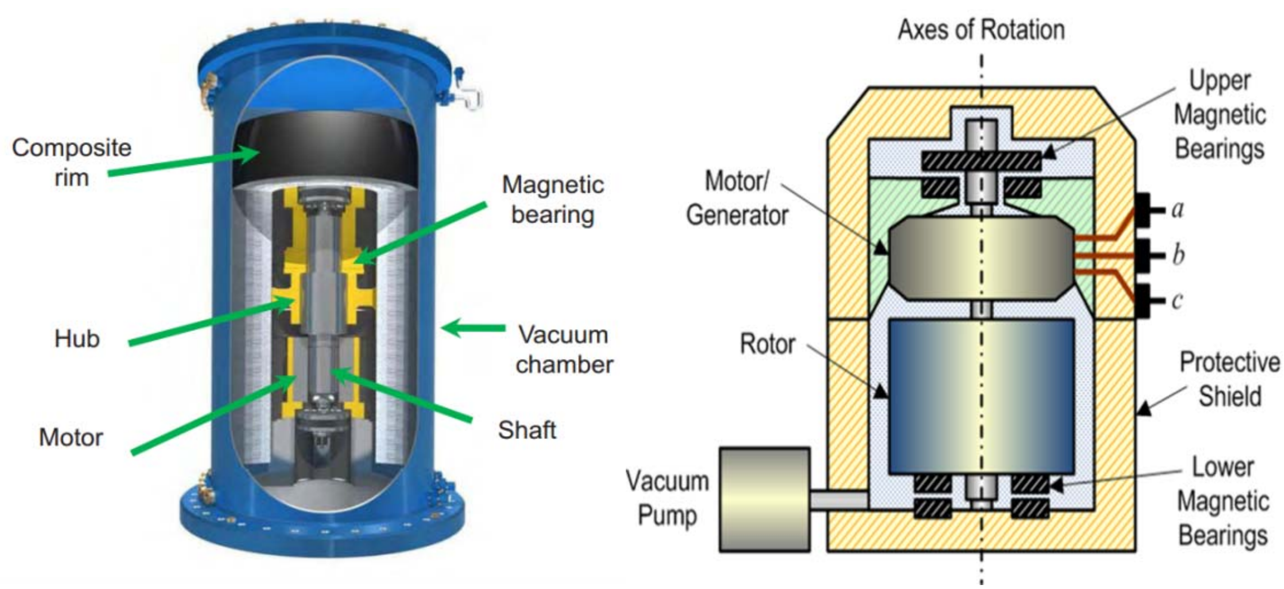
Table 4.6: CAES energy storage costs by benefit (2010$)[27]

	Size	Maturity	Capacity (MWh)	Power (MW)	Duration (hrs)	Lifetime (Cycles)	Total cost ($/kW)	Cost ($/kWh)
Grid support (ancillary services) and integration of intermittent renewables								
CT-CAES[28] (underground)	Small	Demonstration	1,400-3,600	180	8	>13,000	960	120
	Large	Demonstration	1,400-3,600	180	20	>13,000	1,150	160
CAES (underground)	Small	Commercial	1,080	135	8	>13,000	1,000	125
	Large	Commercial	2,700	135	20	>10,000	1,250	60
Time shift, capacity credit, and transmission and distribution support								
CAES (aboveground)	Small	Demonstration	250	50	5	>10,000	1,950-2,150	390-430

(c) Flywheel energy storage

Flywheel energy storage (FES) converts electricity to rotational kinetic energy in the form of the momentum of a spinning mass. This spinning mass, termed a rotor (labeled a composite rim in Figure 4.8), rests on bearings that facilitate its rotation. The rotor and bearings are contained in a sealed housing designed to reduce friction between the rotor and the surrounding environment and provide a safe guard against hazardous failure modes. Friction reducing fluids and a vacuum seal help remove possible sources of friction. To charge, electricity powers a motor-generator that spins a shaft connected to the rotor to store energy. To discharge, the kinetic energy is converted back to electricity by allowing the momentum to power the motor-generator.

Figure 4.8: Flywheel energy storage components[29]



[27] Adapted from [22]
[28] CT-CAES means a combination of a combustion turbine with a CAES system.
[29] Source: http://www.energystorageexchange.org/projects/181. Second image source: http://www.intechopen.com/books/dynamic-modelling/dynamic-modelling-and-control-design-of-advanced-energy-storage-for-power-system-applications

Flywheel technology dates back to the potters' wheel and has been a key component for industrial processes. During the industrial revolution, incorporation of flywheel technology smoothed delivery of variable or pulsating mechanical power output. Flywheel technology was first used in large electric power systems to smooth steam engine generation [5]. Since then, they have been used to maintain power quality and reliability by regulating frequency and providing protection against transient interruptions in the power supply. It was not until the 1960s that flywheels were considered specifically for storage. By the 1970s, rising energy prices fueled alternative energy research including flywheel energy storage. Commercial flywheel systems began to emerge in the 1990s and have continued to gain recognition as a storage specific technology. The largest flywheel can provide 340 MW for 30 seconds and is used for fusion energy research in Japan [5].

The rotor is the most important component of flywheel construction. For example, the rotor mass (diameter and material) impacts the energy capacity. The bearings and casing are designed primarily to reduce friction (energy released as heat) that reduces efficiency and shortens life expectancy. The motor-generator and power electronics characteristics determine the maximum power of fly wheel storage systems. An important characteristic of fly wheel systems is that power and energy capacities are relatively independent from each other. This permits FES devises, much like flow batteries, energy and power capacity to be optimized for specific applications.

There are also variations in the design orientation (vertical and horizontal) and the speed of rotor rotation (high-speed and low-speed). Low-speed steel rotors are able to provide high power output whereas high-speed composite rotors may be used for both high-power and high-energy output. FES used for power applications range between 100 kW to 2 MW with discharge times ranging from 5 to 50 seconds. FES used for energy applications have large-diameter rotors capable of storing 0.5 to 1 kWh of energy. These energy FES systems require more advanced technology than power FES systems to prevent efficiency and standby losses. Round trip efficiency ranges between 70 and 80 percent with standby losses comprising only 1 to 2 percent of the rated power output [5].

Although fly wheel storage systems are able to provide up to an hour of stored energy, they are generally considered short discharge duration technologies. FES systems' defining feature is their instantaneous response time, which makes them a common choice for uninterruptible power supply and power quality applications.

For example, Amber Kinetics has announced a 10 kW fly wheel storage demonstration project in Freemont, California (CAISO) capable of delivering one hour of stored energy at full power [11]. It will be connected to the transmission system to maintain voltage and frequency within required ranges as well as provide spinning reserve. The largest flywheel installation is comprised of 200 spinning mass units capable of delivering 20 MW for 15 minutes at full power [11]. This project by Beacon Power in the Stephentown, New York (NYISO) is used for frequency regulation.

Constraining factors of flywheel systems stem from rotor material strength, weight, and cost, as well as motor-generator size and technology. Life expectancy and expected lifetime cycles hinge on the robustness of the mechanical components, namely the rotor and the bearings, and the cycle duty. Both continuous operation and frequent cycling wear down mechanical components. One way to increase life expectancy and reduce wear and tear on the mechanical components is the use of magnetic bearings that reduce friction (increase efficiency). Commercial fly wheel storage units are expected to last 100,000 charge-discharge cycles.

A few major concerns surround flywheel systems, such as the potential for hazardous contingencies and noise pollution. A possible safety hazard arises when the structural integrity of the rotor or housing is compromised. A piece of the rotor may become loose and propelled by momentum into the surrounding environment, posing danger to personnel or equipment. There is also operating noise that may pose a constraint on the siting of flywheel systems. On the positive side, fly wheel systems do not pose emissions or pollution concerns and have a relatively small area requirement (they have a small footprint).

Because flywheels are generally considered a short duration technology, cost per kWh is very high, while cost per kW is relatively lower. Table 4.7 presents cost estimations for FES systems by applications (2003$s). Table 4.8 presents a second set of cost estimates based on slightly different assumptions.

Table 4.7: Flywheel energy storage system costs by application (2003$)[30]

	Angular Stability	Short Duration Power Quality	Frequency Support*
Capacity (MWh)	0.003	0.006	0.003
Initial costs ($/kW)[a]			
PCS	153	153	345
BOP	100	100	100
Storage	206	206	316
O&M cost ($/kW-year)[b]			
Fixed	18.4	18.4	23.2
Variable	9.1	9.1	12.6
Total Capital Cost (M$)	**4.6**	**4.6**	**1.5**

NOTES: *indicates application estimates are in 2004$
a. Initial costs include acquisition, space, and installation costs. PCS means power conversion system and BOP means balance of plant. Total initial cost can be calculated by multiplying the sum of CT, BOP, and Storage initial costs by the reference power.
b. Fixed O&M costs include projected annual labor, parts, tax, and insurance costs. Variable O&M costs include fuel and other variable consumables and assume a duty cycle appropriate for each application.

30 Adapted from [5]

Table 4.8: Flywheel technical characteristics and costs (2010$)[31]

	Maturity	Capacity (MWh)	Power (MW)	Duration (hrs)	Efficiency (%)	Lifetime (Cycles)	Total cost ($/kW)	Cost ($/kWh)
Grid Support and Power Quality								
Flywheel	Demonstration	5	20	0.25	85-87	>100,000	1,950-2,200	7,800-8,800

(2) Electrochemical Energy Storage

This category contains storage technologies that convert electrical energy into chemical energy when charging. There are two major branches of electrochemical storage technologies, (a) electrochemical batteries and (b) electrochemical capacitors.

(a) Electrochemical batteries

Electrochemical batteries use chemical reactions within a battery cell to facilitate the flow of electrons through a connected load thereby generating an electric current. There are three broad categories of electrochemical batteries: conventional, high temperature, and flow batteries. This section reviews the basic components, functions, and common examples of each category of battery.

Conventional batteries

Conventional batteries are composed of cells which contain two electrodes (a cathode and an anode) and electrolyte in a sealed container. During discharge, a reduction-oxidation reaction occurs in the cell in which electrons migrate from the anode (oxidation) to the cathode (reduction). During recharge, the electrochemical reaction is reversed through the ionization of the electrolyte that connects the anode and cathode. Numerous combinations of electrodes and electrolytes exist for conventional batteries. Common chemistries for conventional battery energy storage projects include: lead-acid, nickel-cadmium, and lithium-ion.

Lead acid battery

Lead acid batteries are the most mature electrochemical energy storage system. Despite low specific energy[32] and power, short cycle life, high maintenance requirements, and toxicity, lead acid batteries persist as a popular choice for energy storage systems because of their low cost and technical maturity. Lead acid batteries have a worldwide installed capacity for electrical power systems applications of approximately 35 MW. Beginning in the 1870s, lead acid batteries were first used for load leveling and peaking in the central electric plants of the time. In recent years, improvements in lead acid technology, such as Ultra battery technologies, have addressed some of these disadvantages.

There are two broad categories of lead acid batteries vented (or flooded) and valve-regulated (or sealed). Flooded lead acid batteries' electrodes are immersed in liquid, and valve-regulated lead acid batteries' use an electrolyte that is immobilized in gel or by an absorbent separator.

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[31] Adapted from [22]
[32] Specific energy is energy per unit of mass which is often measured in Joules per kilogram.

There are three subcategories of vented lead acid batteries: starting, lighting, and ignition (SLI); deep-cycle (or traction); and stationary. Starting, lighting, and ignition flooded lead acid batteries are best suited for short term power quality applications and have relatively short life expectancies ranging from 5 to 7 years (or 30 to 100 cycles at 100 percent depth of discharge). Deep-cycle flooded lead acid batteries are used for deep discharge applications and also have short life expectancies from 3 and 5 years (or up to 1,000 cycles at 100 percent depth of discharge). Stationary flooded lead acid batteries provide power for controls and switching operations and store standby emergency power in utility substations, power generation plants, and telecommunications systems. They have the longest expected life expectancy of the three ranging from 15 to 30 years, and are a common choice for energy storage projects.

There are two subcategories of valve-regulated lead acid batteries: absorbed glass mat (AGM) valve-regulated lead acid batteries and gelled electrolyte valve-regulated lead acid batteries. These batteries are used for uninterruptable power supplies. They also have short life expectancies, typically between 5 and 10 years, and a lower tolerance for abuse than flooded lead acid batteries. Valve-regulated lead acid batteries are sensitive to temperature, overcharge/discharge, corrosion, and water loss and require a float charge[33] in a narrow voltage range. Despite these challenges, valve-regulated lead acid batteries' relatively low costs have allowed them to replace nickel cadmium and nickel iron batteries in some applications.

Lead acid batteries contain two lead alloy electrode grids and a sulfuric acid electrolyte. Typically, a combination of antimony, calcium, tin, or selenium and lead is used to improve the mechanical strength of the cathodes. Lead-antimony alloy is stronger (used for deep cycling applications and where regular maintenance is possible) and lead-calcium alloy is used when corrosion is common (used when replacement is preferred to maintenance).

Lead acid batteries have 2 V nominal voltage and round trip efficiency ranges between 75 and 85 percent [5]. Some difficulties of lead batteries include: self-discharge, sensitivity to temperature, sulfation, hydration, and degradation. These batteries are prone to self-discharge which can be remedied by passing a float charge through the battery while it is idle. Optimal operation is at room temperature, approximately 77°F (25°C). If the temperature drops below -40°F (-40°C), the electrolyte may freeze triggering an explosion, and if the temperature rises too high, the battery may overheat. Sulfation, or the formation of lead sulfate crystals, reduces cell power and energy capacity and may cause physical damage to the electrode. Hydration, the mixing of lead with electrolyte to form lead hydrates, can occur if the battery is left in a low state of charge for prolonged periods and may short circuit the battery. Degradation, in the form of grid corrosion, active material shedding, electrolyte stratification, and low electrolyte level, all lead to ultimate battery failure.

Maintenance requirements for lead acid batteries include: float charging, equalization charging, water replacement and cell post maintenance. As mentioned previously, to prevent self-discharge, voltage is continuously applied to the already charged battery to generate a small current. Equalization charging corrects the inconsistency in state of charge between individual

[33] Float charging is a practice that passes voltage through an already charged battery that is not serving a load at the same rate at which the battery is self-discharging.

battery cells by charging the battery at a high voltage for an extended period of time. Water replacement is only necessary for flooded lead acid batteries (not for valve-regulated lead acid) to compensate for water lost through evaporation and electrolysis.

Additionally, lead acid batteries contain toxic materials that pose environmental and safety hazards. In part due to regulation, lead acid batteries are one of the most recycled products. Regulations typically apply a fee when the battery is purchased which can be used to cover environmental consequences.

Notable improvements to lead acid battery technology include advanced lead acid and thin metal film lead acid. Advanced lead acid technology reduces maintenance requirements, extends life expectancy, and improves cell uniformity which increases both battery life expectancy and cost. One commercial example is the ultra-battery; a hybrid advanced lead acid battery-capacitor that boasts extended life expectancy. Thin metal film lead acid technology applies a new and fairly difficult construction technique to drastically increase power density at the expense of energy density. This research has stagnated due to manufacturing difficulty and short cycle life of these batteries.

Lead acid batteries can be used for the applications grid angular stability, grid voltage stability, grid frequency excursion suppression, short and long duration power quality, as well as several combinations of functions. SLI batteries are often used to provide grid angular stability, grid voltage stability, and short duration power quality, whereas stationary batteries are preferred for grid frequency stability, long duration power quality and combined applications.

Lead acid batteries are considered attractive alternatives both because of technological maturity and availability as well as low relative cost. Costs differ depending on planned use and are summarized in Table 4.9 and Table 4.10. The first three applications are short discharge duration and infrequent discharge applications. They can be considered power applications, and thus power ($/kW) is particularly important when comparing alternative storage option costs. The fourth application is a short duration and frequent discharge application used to maintain power quality. It is evident that frequent discharge implies higher costs. The fifth application is for long duration but infrequent discharge applications, which has the highest cost. The remaining three appropriate applications of PbA (lead acid) technology are combined applications whose cost implications depend on the main application the technology will serve, that is whether it will primarily serve power or energy applications and how often it will be discharged over the course of the year.

Table 4.9: Lead acid battery costs by application (2003$)[34]

	Angular Stability	Voltage Support	Frequency Ecursion Suppression	Short Duration Power Quality	Long Duration Power quality	Frequency Support*	C1: Grid Frequency Support + (Grid Angular Stability + Grid Voltage Support + Regulation Control)	C3: Short duration Power Quality + (Load Shifting-3hr +Regulation Control + Spinninf Reserve)	C4: Long duration Power Quality + (Load Shifting-3hr +Regulation Control + Spinning Reserve)
Capacity (MWh)	0.003	0.003	2.5	0.006	40	3	2.5	10	40
Initial costs ($/kW)[a]									
PCS	153	153	165	153	215	165	165	173	215
BOP	50	50	100	50	100	100	100	100	100
Storage	60	60	315	60	1,258	315	315	315	1,258
O&M cost ($/kW-year)[b]									
Fixed	7.3	7.3	16.5	7.3	43.5	16.5	16.5	17.6	48.8
Variable	6.7	6.7	7.0	6.7	6.9	7.0	7.0	6.5	7.7
NPV disposal costs ($/kW)	13	13	0.8	13	1.8	0.8	0.8	1.4	5.4
Total Capital Cost (M$)	**2.6**	**2.6**	**5.8**	**2.6**	**15.7**	**5.8**	**5.8**	**5.9**	**15.7**

NOTES: *indicates application estimates are in 2004$
a. Initial costs include acquisition, space, and installation costs. PCS means power conversion system and BOP means balance of plant. Total initial cost can be calculated by multiplying the sum of CT, BOP, and Storage initial costs by the reference power.
b. Fixed O&M costs include projected annual labor and parts costs as well as annual tax and insurance costs. Variable O&M costs include fuel and other variable consumables and assume a duty cycle appropriate for each application.

[34] Adapted from [5]

Table 4.10: Lead acid and advanced lead acid battery costs by application (2010$)[35]

	Maturity	Capacity (MWh)	Power (MW)	Duration (hrs)	Efficiency (cycles)	Lifetime (Cycles)	Total cost ($/kW)	Cost ($/kWh)
Grid support (ancillary services) and integration of intermittent renewables								
Advanced Lead Acid	Commercial	200	50	4	85-90	(2200)	1700-1900	425-475
	Commercial	250	20-50	5	85-90	(4500)	4600-4900	920-980
	Demonstration	400	100	4	85-90	(4500)	2700	675
Grid Support and Power Quality								
Advanced Lead Acid	Demonstration	0.25-50	1-100	0.25-1	75-90	(>100,000)	950-1590	2770-3800
Time shift, capacity credit, and transmission and distribution support								
Advanced Lead Acid	Demonstration	3.2-48	1-12	3.2-4	75-90	(4500)	2000-4600	625-1150

Nickel cadmium (NiCd) and other nickel electrode batteries

Unlike lead acid batteries' wet cell construction, nickel electrode batteries are known as dry cell batteries. Each dry cell contains a pair of electrodes, a positive nickel electrode and a negative electrode of cadmium, zinc, hydrogen, iron, or a metal halide. Depending on the chemistry of the negative electrode material, a partition is chosen to separate the two electrodes. After cell construction and packaging, liquid electrolyte is circulated into the porous electrodes. Of the five nickel electrode chemistries, only nickel-cadmium and nickel-iron have utility scale energy storage demonstrations or commercial installations. Of these two, nickel-cadmium remains the most popular for utility energy storage applications and accordingly is discussed in the most detail.

Like lead acid batteries, commercial nickel electrode batteries date back to Thomas Edison's nickel-iron battery which was used for bulk energy storage and electric vehicles. Nickel-cadmium batteries are the most common nickel electrode battery in the utility energy storage industry. Although more costly than lead acid batteries, the relative low cost, high energy density, high power delivery capabilities, hardiness, reliability, and life expectancy of nickel cadmium batteries makes them a popular choice for substation batteries and bulk storage. Approximately 27 MW of installed capacity in the world is being used for electric power systems applications.

Several other nickel electrode battery chemistries are under development, but not yet in commercial use for utility scale storage. Nickel hydrogen batteries have attractive operational features, such as long cycle life, low maintenance requirements, and high reliability, but very high costs. The nickel metal hydride, an offshoot of the nickel hydrogen battery, has many of the same advantages of the NiH_2 battery and lower costs. However, it tends to be less hardy to electrical abuses such as overcharge and high rate discharge than nickel cadmium batteries. These batteries are still in the demonstration stage for utility scale applications. Nickel-zinc is the least commercially mature technology because of low life cycle. It has an advantage over nickel cadmium batteries because of its higher energy density and lower cost. Nickel iron

[35] Adapted from [22]

batteries have lower energy density compared to nickel cadmium. The main disadvantage of nickel cadmium is the cost and toxicity.

Nickel electrode batteries have a nominal voltage of approximately 1.2 V, with the exception of nickel zinc, which has a nominal voltage of 1.5 V. Although on average, nickel electrode battery round trip efficiency ranges from 65 to 85 percent, nickel cadmium batteries typically have much lower efficiency, between 60 and 70 percent (not including losses from ancillary equipment). This range in efficiency stems from differences in electrolyte concentration, charging procedures, stand-by time, and operation temperature. Nickel electrode batteries tend to have relatively higher charge losses resulting from a variety of chemical interactions within the battery cells and deviations from ideal operating temperatures. Like many batteries nickel electrode cells are susceptible to "thermal runaway," a vicious cycle of heating and increased discharge and voltage.

Nickel electrode batteries experience both reversible and irreversible degradation. Reversible forms of degradation are reversed by completely discharging the cell and then recharging. Irreversible degradation varies across electrode types and application but is related to operation temperature and the depth and number of charge/discharge cycles. Some common irreversible degradation sources include: nickel-electrode corrosion, organic material decomposition into the electrolyte, formation of dendrites on the negative electrode, gas barrier failure, and electrode poisoning.

There are three main types (based on electrode construction) of nickel cadmium and nickel-iron batteries: pocket plate, vented sintered-plate, and sealed. Life expectancy for pocket plate industrial nickel cadmium batteries ranges between 800 and 1,000 cycles (80 percent depth of discharge); sintered-plate nickel cadmium batteries may have up to 3,500 cycles at the same depth of discharge; sealed nickel cadmium batteries have shorter cycle lives. This translates to an expected operation life between 10 to 15 years in lightly cycled applications. Nickel iron batteries are the exception; they have long service lives, up to 25 years. Temperature is the main factor that influences life expectancy. A generally accepted rule of thumb is that a 18ºF (10ºC) increase results in 20 percent loss in the calendar year life expectance of a nickel cadmium battery.

Several environmental and safety concerns surround nickel electrode batteries. Foremost is the use of the highly toxic metal cadmium. Regulation, careful monitoring during production, and recycling efficiency have assuaged this concern. Gassing can contribute to pressure build up with the cell and irreparable physical damage to the battery. Finally, nickel electrodes have several maintenance considerations, such as float (trickle) charging, reconditioning, and water addition.

Nickel cadmium batteries are considered an attractive alternative because of technological maturity and availability as well as operational characteristics. Costs differ depending on planned use and are summarized in Table 4.11. Nickel cadmium batteries are best suited for grid angularity stability, grid frequency excursion suppression, short duration power quality, and a couple of combined applications. Although nickel cadmium batteries are not the most expensive batteries they are more costly than lead acid batteries.

Table 4.11: Nickel cadmium battery costs by application (2003$)[36]

	Angular Stability	Frequency Stability	Short Duration Power Quality	Frequency Support*	C1: Grid Frequency Support + (Grid Angular Stability + Grid Voltage Support + Regulation Control)	C3: Short durantion Power Quality + (Load Shifting-3hr +Regulation Control + Spinninf Reserve)
Capacity (MWh)	0.003	2.50	0.006	3	2.50	5
Initial costs ($/kW)[a]						
PCS	153	144	153	144	144	153
BOP	100	100	100	100	100	100
Storage	368	356	368	356	356	640
O&M cost ($/kW-year)[b]						
Fixed	14.8	15.1	14.8	15.1	15.1	26.5
Variable	6.7	6.7	6.7	6.7	6.6	1.0
NPV disposal costs ($/kW)	0.5	0.6	0.5	0.6	0.6	1.2
Total Capital Cost (M$)	6.2	6.0	6.2	**6.0**	6.0	8.9

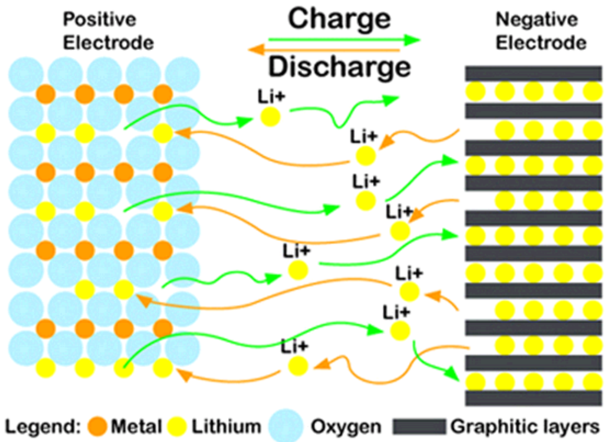
NOTES: *indicates application estimates are in 2004$
a. Initial costs include acquisition, space, and installation costs. PCS means power conversion system and BOP means balance of plant. Total initial cost can be calculated by multiplying the sum of CT, BOP, and Storage initial costs by the reference power.
b. Fixed O&M costs include projected annual labor and parts costs as well as annual tax and insurance costs. Variable O&M costs include fuel and other variable consumables and assume a duty cycle appropriate for each application.

Lithium ion batteries[37]

Lithium ion batteries (Li-Ion) components include: a carbon (graphite) negative electrode, a metal-oxide positive electrode, an organic electrolyte (ether) with dissolved lithium ions, and a micro-porous polymer separator. When the battery is charging, lithium ions flow from the positive metal oxide electrode to the negative graphite electrode. When the battery is discharging the reverse flow of ions takes place (see Figure 4.9).

[36] Adapted from [5]
[37] Not to be confused with lithium batteries. Lithium batteries contain metallic lithium, lithium ion batteries do not.

Figure 4.9: Lithium ion battery function and components[38]



Compared to lead acid batteries, Li-Ion batteries are a much less mature technology. Li-Ion batteries are mostly used in consumer electronics because of their high energy density (low weight), low standby losses, and cycling tolerance. Interest in utility scale Li-Ion batteries did not begin until 1970s, but little new technological development occurred until recent years. Since 2000, Li-Ion batteries have become a popular choice for electric vehicle and aerospace applications. This resurgence in research and development of Li-Ion technology for electric vehicle purposes has also led to interest in demonstrating the battery's potential to perform utility functions.

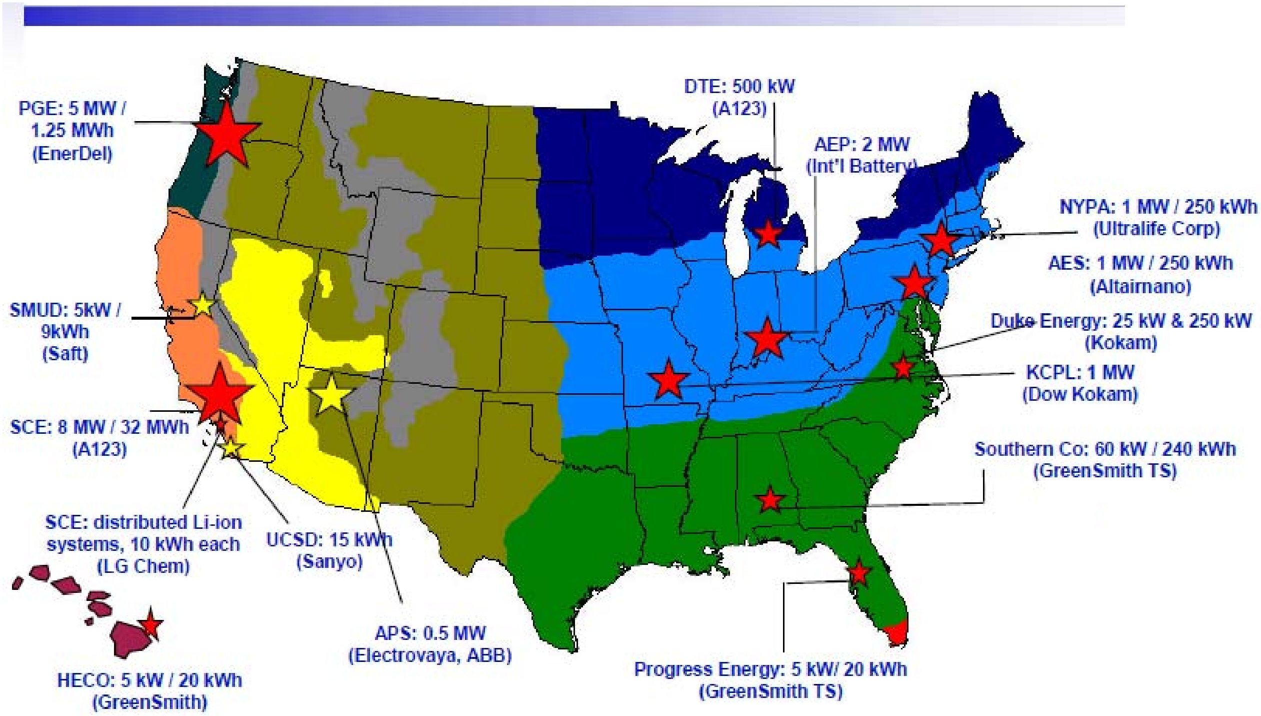
Demonstrations have shown Li-Ion batteries' ability to provide all six of the benefits mentioned in the introduction. For example, a Pacific Northwest smart grid demonstration in Salem, Oregon will provide renewables time shifting, renewables capacity firming, electric energy time shifting, and electric supply capacity. This 5 MW, 1.25 MWh system will be part of a larger smart grid demonstration when complete.

Another example is the SDG&E-Greensmith Li-ion energy storage demonstration project in San Diego, California that will focus on peak shaving and photovoltaic smoothing. A Li-Ion installation in Johnson City, New York proved the ability of Li-Ion batteries to provide frequency regulation.

One of the largest Li-Ion installations in the United States is in Elkins, West Virginia. This facility installed by AES connects 98 MW of wind generation with 32 MW of storage for reserve capacity and renewables integration. A final demonstration worth mentioning is the Tehachapi energy storage project in Tehachapi, California. This project is ARRA-funded and will use an 8 MW, 32 MWh Li-Ion battery to demonstrate voltage support (grid stabilization), avoid transmission curtailment, system reliability, transmission investment deferral, renewable energy transmission effectiveness, system capacity credit, renewable energy smoothing, time shift of wind generation, frequency regulation, spin/non-spin replacement reserves, load following, and energy price arbitrage (see Figure 4.10).

[38] Source: http://www.snupeel.com/wp/research/secondary-battery

Figure 4.10: Map of planned and existing lithium ion battery demonstrations (2009) [12]



Note: The size of the star indicates the size of the project. Yellow stars indicate major auto contracts and red have no auto contracts.

The technical characteristics of Li-Ion batteries are dependent on the electrodes and electrolyte materials but some generalizations can be made. First, because of their high energy density, Li-Ion cells have nominal voltage of 3.7 V. This is much higher than many other battery cell chemistries, which means fewer Li-Ion cells are needed to produce the same power output. Second, like other batteries, they have response times on the order of 20 milliseconds. Third, Li-Ion batteries have relatively high round trip efficiency, usually ranging between 85 to 95 percent [13]. Finally, Li-Ion batteries have expected lifetimes of 2,000 to 3,000 cycles or 10 to 15 years.[39]

Li-Ion batteries have several disadvantages as well. First, the expected lifetime is related to the cycling depth of discharge. Li-Ion batteries should not be used for applications that require full discharge. Second, the metal oxide electrode can become thermally unstable due to over discharge or charge and be subject to thermal runaway if left unchecked. Finally, Li-Ion batteries still face significant cost barriers. Table 4.12 summarizes key technical features and costs associated with Li-Ion batteries. Table 4.13 summarizes Li-Ion costs by benefit (2010$s)

[39] Source: [13]; another source [29] cites Li-Ion batteries have life expectancies of 7000 cycles at 80% depth of discharge.

Table 4.12: Lithium ion battery features[40]

		Li-Ion Battery
Rated Power	(MW)	≤ 10 MW
Lifetime	(yrs)	10-15
	(cycles)	2,000-3,000
Efficiency	(%)	85-95
Power capital cost	($/kW)	$400 - 1,000
Energy capital cost	($/kWh)	$500 - 1,500
Levelized cost of storage	($/kWh)	$0.30 - 0.45
Annual operating costs	($/kW-yr)	$25
Fixed O&M cost	($/kW)	$0.46*
Variable O&M cost	($/kW)	$0.70*

Table 4.13: Lithium Ion battery costs by benefit (2010$s)[41]

	Maturity	Capacity (MWh)	Power (MW)	Duration (hrs)	Efficiency (%)	Lifetime (cycles)	Total cost ($/kW)	Cost ($/kWh)
Power quality, capacity credit, and intermittent renewables integration								
Lithium Ion	Demonstration	0.25-25	1-100	0.25-1	87-92	>100,000	1085-1550	4340-6200
Time shift, capacity credit, and transmission and distribution support								
Lithium Ion	Demonstration	4-24	1-10	2-4	90-94	4,500	1800-4100	900-1700

From these cost tables it is clear that Li-Ion cost estimates vary a great deal and the ranges are quite large. This reflects the degree of uncertainty surrounding possible cost-reducing innovations that may occur in the near future.

High temperature batteries

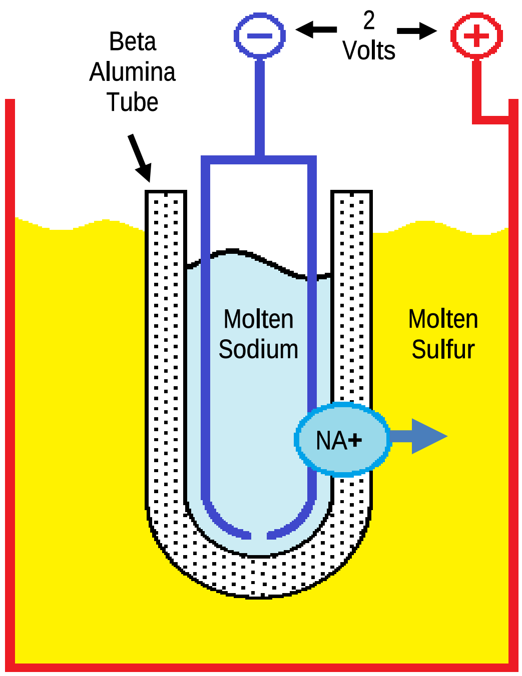
High temperature batteries, or molten salt batteries, contain molten electrodes. Their function and construction is similar to conventional batteries, however they have some features similar to thermal storage. Common chemistries include sodium sulfur (NAS) and sodium nickel chloride (ZEBRA). Sodium sulfur is by far the more common of the two and is discussed below in greater detail.

[40] Adapted from [13]. The * indicates that the information is taken from [30]
[41] Adapted from [22]

Sodium Sulfur Batteries

Sodium sulfur (NAS) battery cells contain a molten sodium (Na) anode (negative electrode), a solid ceramic electrolyte, and a molten sulfur (S) cathode (positive electrode). Positively charged sodium ions flow through the solid ceramic electrolyte into molten sulfur where an electrochemical reaction generates a current (see Figure 4.11). To facilitate ion transfer, the sodium and sulfur are kept molten, at temperatures between 300° and 360°C (572° and 680°F).

Figure 4.11: Sodium sulfur cell construction



NAS batteries are suitable for energy, power, or both energy and power applications [14]. Typically, NAS batteries primary function is long duration energy storage, used for load leveling, arbitrage, "islanding," and renewables output smoothing [15, 8, 16]. However, quick response time (1 millisecond) and the ability to provide pulse power make them suitable for many power quality applications [17, 14].

NAS batteries are officially categorized as commercialized, however they are still in the early stages. While small-scale NAS battery technology is well developed, grid-scale NAS batteries are still in early commercialization. The first utility scale NAS battery demonstration project was hosted by Tokyo Electric Power Company (TEPCO) in 1992, and is still operating. In 2002, NAS batteries became commercially available in Japan, and American Electric Power (AEP) hosted the United States' first utility scale NAS battery demonstration in Gahanna, Ohio.

In 2008 AEP installed a 2 MW, 14 MWh, NAS battery at Churubusco, Indiana which AEP representatives say will be instrumental in testing the ability of the battery to mitigate intermittency from wind power plants [16]. The largest NAS battery planned installation will be at the Noshiro thermal power plant in Northern Japan. Upon completion, this TEPCO project will have 80 MW nominal discharge capacity [18].

TEPCO and NGK have pioneered grid-scale NAS battery use in Japan with much success. In 2011, a NGK NAS battery installed at a Mitsubishi plant caught fire [19]. The incident, raised questions about the maturity of the technology. Despite this incident, NAS battery technology seems to be maturing and gaining acceptance as a bulk energy storage option. As a whole, the rest of the world, including the United States, uses less NAS battery storage than Japan.

NAS battery round trip efficiency ranks relatively high amongst electrochemical batteries. Depending on parasitic loads, operating temperatures, and applications, efficiency ranges from 70 to 90 percent. Demonstration reports note that parasitic loads, such as equipment used to keep the electrodes molten, or power quality applications reduce efficiency [14].

Energy output ranges from 360 kWh to tens of MWh and nominal discharge capacity ranges from 50 kW to 100 MW [17]. A relatively high energy density between 100 and 250 Wh/kg and power density of 260 W/kg allows them to leave a small footprint [3, 17]. The estimated lifespan of an NAS battery is between 10 and 15 years, depending on frequency of use and depth of discharge. Estimates center on 2,500 estimated lifecycles.

NAS batteries are appropriate for both energy and power applications. They can also serve power and energy applications, simultaneously, making them particularly useful. Current installations and demonstrations have showed their suitability for peak shaving, load shifting, power quality control, uninterruptable power systems, "islanding," and storage of intermittent renewables.

NAS batteries typically are charged at night, when demand and costs are relatively low, and are discharged during peak demand when energy costs are relatively high. This effectively shifts some of the peak demand and allows utilities to reduce costs.

Power quality, uninterruptable power systems, and "islanding" are particularly important for utilities serving facilities such as hospitals and airports, online companies, or financial institutions. NAS batteries provide a safety net in which high power quality and emergency power supply is available upon demand. "Islanding," or having a self-contained power source, assures emergency reserve power, but also is able to reduce intermittency associated with renewables [16].

Sodium-Sulfur batteries must operate at extremely high temperatures and can explode if they come into contact with water, making them a safety hazard if not handled properly [19]. Like any battery, toxicity concerns, especially related to decommissioning and disposal, are still major obstacles to widespread installation. Consumers dislike the prospect of batteries located close to residential or highly populated areas.

Because this is still emerging as a commercial grid-scale energy storage technology, cost estimates remain high. As more plants are built and as the batteries use frequency and duration increase, costs are expected to fall. NGK predicts that over time costs will fall to 250 $/kW, however at present they estimate costs to be approximately 600 $/kW [8]. While relatively expensive, NAS batteries cost far less than some of the other available technologies. Table 4.14 indicates NAS costs by application (2003$) and Table 4.15 describes NAS costs by benefit (2010$).

Table 4.14: Sodium sulfur battery costs by application (2003$)[42]

	Short Duration Power Quality	Load Shifting-10 hr	Renewables Forecast Hedging*	C1: Frequency Support + Angular Stability + Voltage Support + Regulation Control	C2: Short Duration Power Quality + load Shifting-10hr + Regulation Control +Spinning Reserve	C3: Short durantion Power Quality + Load Shifting-3hr +Regulation Control + Spinninf Reserve	C4: Long duration Power Quality + Load Shifting-3hr +Regulation Control + Spinning Reserve	C5: Load Shifting-3hr + Regulation Control + Spinning Reserve	C6: Avoid Transmission Curtailment + freguency support + regulation control*	C7: Renewables Time Shift + Frequency support + regulation control*	C8: Renewables Forecast Hedging + frequency support + regulation control*	C9: Fluctuation suppression + frequency support + renewables time shift*
Capacity (MWh)	0.006	100	65	2.5	22	10	40	100	60	78	65	86
Initial costs ($/kW)[a]												
PCS	153	204	239	449	202	202	289	204	239	239	239	239
BOP	100	100	100	100	100	100	100	100	100	100	100	100
Storage	305	1,964	1,382	461	508	508	1,523	1,964	1,523	1,523	1,382	1,523
O&M cost ($/kW-year)[b]												
Fixed	13.8	51.2	39.4	23.1	19.2	19.2	43.2	51.2	42.2	42.2	39.4	42.2
Variable	9.6	13.4	16.9	2.6	2.6	3.9	8.1	9.1	4.5	0.0	0.0	0.0
NPV disposal costs ($/kW)	6.7	43.2	25.4	10.1	11.2	11.2	33.5	43.2	33.5	54.1	54.1	39.5
Total Capital Cost (M$)	5.6	22.7	17.2	10.1	8.1	8.1	19.1	22.7	18.6	18.6	17.2	18.6

NOTES: *indicates application estimates are in 2004$
a. Initial costs include acquisition, space, and installation costs. PCS means power conversion system and BOP means balance of plant. Total initial cost can be calculated by multiplying the sum of CT, BOP, and Storage initial costs by the reference power.
b. Fixed O&M costs include projected annual labor and parts costs as well as annual tax and insurance costs. Variable O&M costs include fuel and other variable consumables and assume a duty cycle appropriate for each application.

Table 4.15: Sodium sulfur battery costs by benefit (2010$)[43]

	Maturity	Capacity (MWh)	Power (MW)	Duration (hrs)	Efficiency (%)	Lifetime (cycles)	Total cost ($/kW)	Cost ($/kWh)
Grid support (ancillary services) and integration of intermittent renewables								
Sodium Sulfur	Commercial	300	50	6	75	4,500	3100-3300	520-550
Time shift, capacity credit, and transmission and distribution support								
Sodium Sulfur	Commercial	7.2	1	7.2	75	4,500	3200-4000	445-555

[42] Adapted from [5]
[43] Adapted from [22]

In contrast to the Li-Ion battery costs, NAS cost ranges are much narrower and lower. This is largely a reflection of the relative maturities of the two technologies.

Sodium nickel chloride (ZEBRA) batteries

Sodium nickel chloride batteries get their nickname ZEBRA from *Zero Emission Battery Research*. Like the NAS battery, it is a molten sodium based battery [3]. It contains a molten sodium negative electrode and a nickel chloride positive electrode. To facilitate ion transfer, the battery operates around 270°C (518°F).

It has been commercially available since 1995. Much of the recent research has been with electric vehicles in mind; however, there is development of ZEBRA systems for renewables integration and load leveling applications.

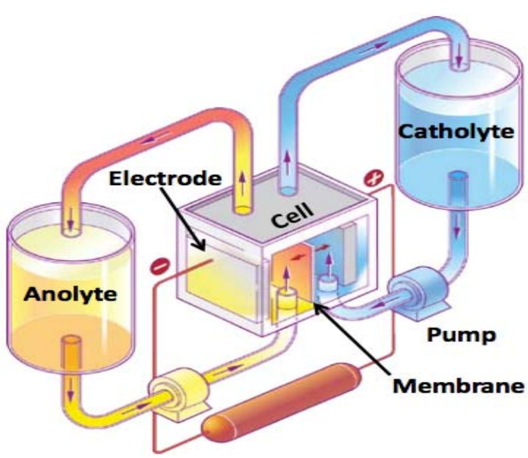
Defining technical characteristics of ZEBRA batteries are rated power between 5 and 500 kW with up to 100 kWh of energy. ZEBRA units have 85-90 percent round trip efficiency, 20 millisecond response times, and expected cycle lives of up to 3,000 cycles at 80 percent depth of discharge.

Some advantages over NAS chemistry includes tolerance of overcharge and discharge, higher cell voltage, and potentially better safety characteristics. In addition due to its high tolerance of short circuits the failure of one cell in a ZEBRA battery does not cause complete failure of the battery.

Flow Batteries

Flow batteries are distinct from both conventional batteries and high temperature batteries because of cell construction, namely, electrolyte material is stored in tanks external to the electrodes. During discharge and charge, electrolyte is pumped from its container into the cell stack to interact with the electrodes (see Figure 4.12). Flow batteries are considered a viable choice for energy applications requiring discharge durations greater than 5 hours because of cost efficiencies with large volumes of relatively inexpensive electrolyte material.

Figure 4.12: Flow battery construction



Unique to flow batteries is the ability to independently vary energy and power capacity. Discharge duration (energy) is determined by the volume of electrolyte, whereas the power ratings are determined by the number of cells. The ease with which electrolyte can be chemically managed and replaced as well as tolerance for overcharge/discharge and partial state of charge makes them resilient to processes that degrade conventional and high temperature batteries' lives.

Disadvantages of flow batteries relate to cost and construction complexity. The addition of pipes, plumbing, tanks, and other non-electrochemical components increase probability and cost of repair and electrolyte leakage. Flow batteries have relatively low power and energy density compared to their conventional and high temperature counterparts. Additionally, there are efficiency losses accrued by auxiliary equipment used to pump electrolytes from tanks to cells.

There are two types of flow batteries: hybrid flow batteries and redox flow batteries. Hybrid flow batteries have one or more electro-active components deposited as a solid layer, and the battery cell contains one battery electrode and one fuel cell electrode. A hybrid flow battery's energy is limited by the size of the battery electrode. Redox flow batteries are a reversible fuel cell in which electro-active components are dissolved in the electrolyte. A redox flow battery's energy is related to electrolyte volume and power is related to electrode area in the cells. Common redox flow battery chemistries include zinc bromine and vanadium. Polysulfide bromine batteries, also known as Regenesys technology, were of interest for energy storage applications, but research halted in 2004, and these chemistries are not currently considered a viable choice.

Vanadium redox flow battery

Vanadium redox flow batteries (VRB) are flow batteries in which vanadium ions are dissolved in an acid aqueous solution. The main components of a VRB are the electrolyte, a carbon felt electrode, an ion exchange membrane that separates the electrolytes, a bipolar plate that separates cells, and the electrolyte tanks, pumps, and piping. Electrolyte is pumped from external storage tanks into the battery cell where an electrochemical reaction between vanadium ions and the carbon felt electrode generates a current. The positive and negative electrolytes are separated within the cell by membrane. An external bipolar plate between each cell conducts the current between cells placed in stacks.

NASA began work on redox battery technology in the 1970s, and in 1984 the University of New South Wales developed a vanadium based redox battery. Several demonstrations have proved the compatibility of vanadium redox battery systems with photovoltaic panel generation (Thailand), wind generation (Australia and Japan), and load-leveling (Japan), power quality and reliability (Castle Valley, Utah)[44]. Currently, there are a few commercially available units, such as a 5 kW unit used to provide back-up power and uninterruptable power supply (UPS).

Like all flow batteries, rated energy and rated power are independently determined. Both the concentration of vanadium ions in the electrolytes and the tank volumes determine the energy storage capacity in a VRB. There are about 20 to 30 watt-hours per liter of electrolyte when the

[44] See [20] for more information about this demonstration site.

battery is fully charged [20]. Flow batteries, including the VRB have a much larger space requirement than other electrochemical storage technologies, for example a VRB system rated at 2.5 MW and 10 MWh requires between 12,000 and 17,000 square feet. This is about twice as large as the estimated space requirements for other electrochemical storage technologies [20]. The electrode surface area determines the power of a VRB system. In contrast to conventional batteries, VRBs are generally useful for energy applications because the volume of electrolyte determines energy capacity. Full power discharge ranges between four and ten hours for systems as of 2006. Each cell has a nominal voltage of 1.4 V and supplies about 26 watts.

The life expectancy for a vanadium redox flow battery cycled 1,000 times a year is 10 to 15 years [20]. The membrane is the life-limiting factor, with the pipes, tanks, and power electronics lasting much longer. Pump and stack maintenance or refurbishment can extend the battery life to 20 years or more. Efficiency losses arise from parasitic loads and heat dissipation. Round trip efficiency ranges between 60 and 70 percent [20]. The electrolyte must be kept at temperatures between 0 and 40°C during operation for optimal efficiency. Response times are nearly instantaneous for the battery itself at 0.35 milliseconds; however, some of the power electronics and pumps have a longer response time. A good approximation of the total VRB system response time is on the order of a few milliseconds, which makes it comparable to other forms of electrochemical energy storage. Table 4.16 contains the technical characteristics of VRB systems serving various applications.

Table 4.16: Technical characteristics of VRB systems by application

Application	Size	Duration	Plant Capacity	Response Time	Duty Cycle	Roundtrip Efficiency	Plant Footprint	Environmental Impact
DR/Peak Shaving	0.5–25 MW	4-8 hours	1 MWh–100 MWh	1-10 min	20-50 events/yr	Low (<70%)	0.002 MW/m2	Low noise; aesthetics depends upon location; medium emissions
Spinning Reserve	1–1000 MW	2 hr	2–2000 MWh	10 min	5–60 events/yr	Low (<70%)	0.002 MW/m2	Low noise; medium emissions
Windfarm Stabilization & Dispatch	100 kW–100 MW	4–8 hours	0.5–800 MWh	1 sec (stability)	Continuous for stability (when operating); 10-50 events/yr for dispatch	Medium (70-90%)	Not a constraint – windplant space available	Low emissions; medium aesthetics

Vanadium redox batteries have two main advantages over other flow battery chemistries. First, the positive and negative electrolytes are the same when the battery is in a discharged state. This has several implications for cost, manufacture, and efficiency. Costs to ship, store, and manage electrolyte are low and the electrolytes will not contaminate each other should they be mixed (the battery will only self-discharge). Second, the sulfuric-based electrolyte does not release poisonous or corrosive vapors like other flow batteries using halide-based electrolytes.

Accordingly, VRBs do not require emissions or fuel handling permits as part of siting costs [20]. The ion exchange membrane, however, is toxic. During decommissioning, the vanadium electrolyte is recycled and does not face the same environmental and restrictions as lead-acid and cadmium disposal.

VRBs have several other advantages over other batteries. First, electrolyte production is relatively simple (vanadium pentoxide powder, sulfuric acid and water), inexpensive, and mobile. Second, VRBs have a tolerance for both overcharge and over-discharge. Because the electrolytes flow through all the cells, overcharge of individual cells is improbable. Similarly, because the electrolytes are practically the same in a low state-of-charge, over-discharge will not damage the cells. Third, vanadium electrolyte does not degrade, and therefore does not need replacement, and overall maintenance is minimal. Generally, only semiannual visual inspection and water replacement is necessary.

Due to energy and power characteristics, VRB are considered useful for utility applications requiring long discharge durations with rated power between 100 kW and 10 MW. Compatible applications include: load shifting (peak shaving), renewables time shifting, fluctuation suppression, forecast hedging, mitigating transmission curtailment, spinning reserve, power quality (especially long duration), voltage support, and frequency excursion suppression. These correlate to four major benefits to the electric power grid: (1) time shift of energy delivery, (2) capacity credit, (4) transmission and distribution operational support, (5) power quality and reliability, and (6) integration of intermittent renewables generation.

Load shifting in this context refers to the ability to shave peak load and would primarily be used to relieve transmission and distribution infrastructure, but it would simultaneously reduce generation capacity needs. A VRB unit can defer capacity upgrades to or the construction of a utility substation. Later, when such substation improvements are economically or environmentally justifiable, the battery can be disassembled for use elsewhere.

Renewables time shifting and fluctuation suppression allow VRB to integrate intermittent renewables generation into the electric power grid. These applications include renewables time shifting, fluctuation suppression, and forecast hedging. This is especially pertinent to wind generation, which is a prominent source of renewable generation in Indiana. A VRB unit would allow wind generators to firm capacity and hedge inaccurate forecasts by absorbing power during surges and injecting power during sags in production. An important implication of this activity is the ability to avoid transmission curtailment.

Finally, VRBs are seen as valuable for power quality and reliability applications including spinning reserve (UPS) and power quality (especially long duration for back-up power). Frequency of discharge for these applications is quite low and in the case of long duration power quality, VRBs have the appropriate energy capacity.

An example demonstration site by PacifiCorp in Castle Valley, Utah[45] is capable of providing 250 kW for 8 hours. In 2003, the VRB system was built there to improve power quality and

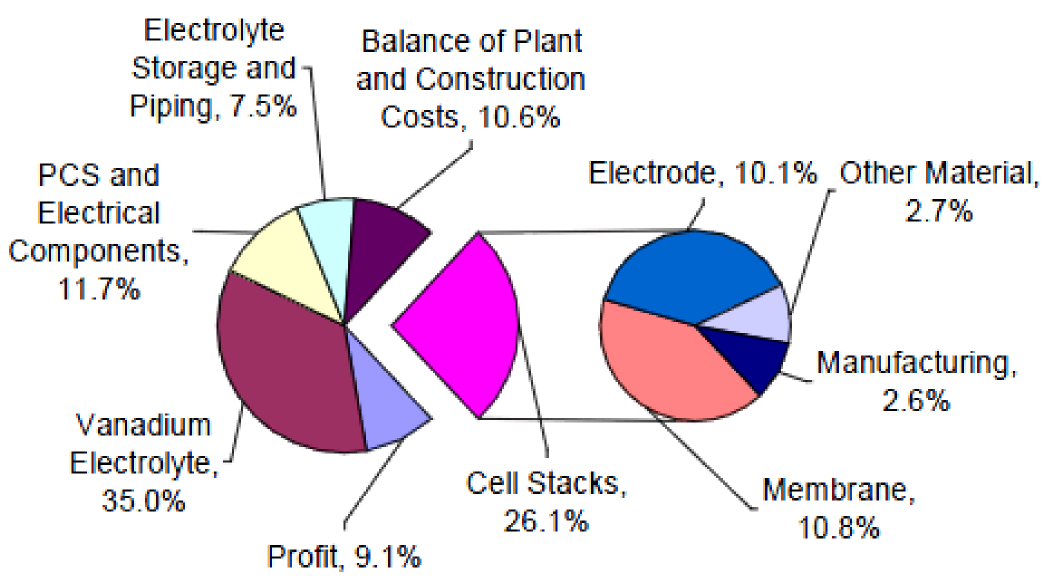
[45] For more information regarding this installation see either [20] or *VRB Energy Storage for Voltage Stabilization: Testing and Evaluation of the PacifiCorp Vanadium Redox Battery Energy Storage System at Castle Valley, Utah* (EPRI 1008434, 2005).

reliability and defer capacity upgrades to a substation. The battery is also able to provide voltage support, which translates to enhanced reliability for consumers and the ability to add new connections for utilities. After a few power enhancements, the battery was able to perform energy arbitrage and has the capacity to provide backup power for the area for up to four hours. Although this facility demonstrated VRB are reliable, some concerns persist that the mechanical pumps and plumbing may be a source of unreliability.

Another project on King Island (near Tasmania) demonstrated the ability of VRB to pair with wind generation to provide a large portion of the island's electricity. The installation has 200 kW for four hours of load shifting and peak power of 400 kW for 10 seconds used for fluctuation mitigation.[46] A similar project at a power plant in Japan paired a 170 kW (with 6 hours of energy) VRB technology with wind generation to provide renewables time shifting and fluctuation suppression. A second Japanese installation uses VRB technology in combination with wind generation to provide fluctuation suppression and frequency excursion suppression. This installation, located on a wind farm, has 4 MW (or pulse power of 6 MW for 30 seconds) and 6 MWh of storage.

VRB systems' costs are largely influenced by the components' costs, specifically the electrolyte and the components of the cell stacks. Figure 4.12 describes the percentage each component contributes to the capital costs of a 1 MW, 8 MWh installation (2006$). Figure 4.13 describes the estimated present cost (in 2006) capital costs of VRB units of different sizes. Because VRB systems are generally useful for energy applications, a dollars per unit of power (kW) measure is likely to be unhelpful. This is because storage systems with the same rated power but different discharge durations (different energy levels) will have different dollar per kW costs. For this reason Figure 4.13 describes power and energy specifications.

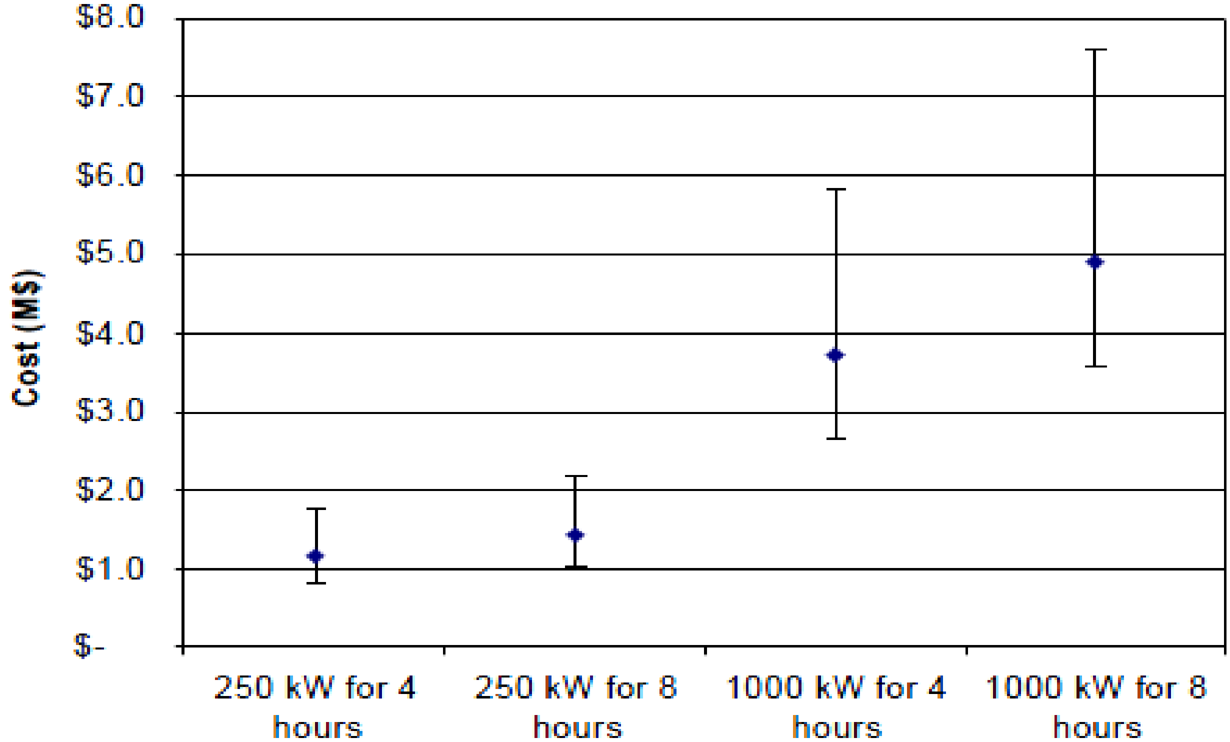
Figure 4.13: Component costs of a VRB as a percentage of total capital cost (2006$) [20]



[46] Fluctuation mitigation technology has been incorporated into many of the wind turbines so the VRB primarily serves to load shift.

Present costs for VRB systems are somewhat uncertain because of component cost variability and system size, but range from $1.1 million (250 kW, 4 hours) to $4.9 million (1 MW, 8 hours).[47] These costs were estimated to fall significantly as the technology matures due to improvements in electrolyte and cell stack manufacturing processes and new sources of raw materials, such as vanadium. One estimate made in 2006 asserted VRB system costs may fall from $1.1 million to $0.8 million (250 kW, 4 hours) and from $4.9 million to $3.2 million (1 MW, 8 hours) [20].

Figure 4.14: Present capital costs estimates of VRB systems [20]



[47] Based on 2006 estimates in [20].

Table 4.17 describes the capital and operating costs of a VRB system in relation to the applications it is performing. Table 4.18 describes the estimated cost of VRB by benefit.

Table 4.17: VRB capital and operating costs (2003$)[48]

	Load Shifting-10 hr	C2: Short Duration Power Quality + load Shifting-10hr + Regulation Control +Spinning Reserve	C3: Short durantion Power Quality + Load Shifting-3hr +Regulation Control + Spinninf Reserve	C4: Long duration Power Quality + Load Shifting-3hr +Regulation Control + Spinning Reserve	C5: Load Shifting-3hr + Regulation Control + Spinning Reserve	C6: Avoid Transmission Curtailment + freguency support + regulation control*	C7: Renewables Time Shift + Frequency support + regulation control*	C8: Renewables Forecast Hedging + frequency support + regulation control*	C9: Fluctuation suppression + frequency support + renewables time shift*
Capacity (MWh)	100	67	20	40	100	90	90	54	83
Initial costs ($/kW)[a]									
PCS	397	311	311	516	397	466	466	466	466
BOP	100	100	100	100	100	100	100	100	100
Storage	2,125	1,417	883	1,825	2,125	2,125	2,125	1,845	1,985
O&M cost ($/kW-year)[b]									
Fixed	54.8	38.8	28.1	51.2	54.8	56.1	56.1	50.5	53.3
Variable	7.0	1.9	4.1	5.2	2.4	-	-	-	-
Total Capital Cost (M$)	26.2	18.3	12.9	24.4	26.2	26.9	26.9	24.1	25.5

NOTES: *indicates application estimates are in 2004$
a. Initial costs include acquisition, space, and installation costs. PCS means power conversion system and BOP means balance of plant. Total initial cost can be calculated by multiplying the sum of CT, BOP, and Storage initial costs by the reference power.
b. Fixed O&M costs include projected annual labor and parts costs as well as annual tax and insurance costs. Variable O&M costs include fuel and other variable consumables and assume a duty cycle appropriate for each application.

Table 4.18: VRB costs by benefit (2010$s)[49]

	Maturity	Capacity (MWh)	Power (MW)	Duration (hrs)	Efficiency (%)	Lifetime (cycles)	Total cost ($/kW)	Cost ($/kWh)
Grid support (ancillary services) and integration of intermittent renewables								
Vanadium Redox	Demonstration	250	50	5	65-75	>10,000	3100-3700	620-740
Time shift, capacity credit, and transmission and distribution support								
Vanadium Redox	Demonstration	4-40	1-10	4	65-70	>10,000	3000-3310	750-830

[48] Adapted from [5]
[49] Adapted from [22]

Zinc bromine flow battery

The zinc bromine flow battery (ZnBr) consists of two bromine electrolytes separated by a nonselective microporous membrane and react with zinc on the electrodes. When the battery is charging, the zinc is deposited onto the electrodes, and as the battery is discharged, the zinc is dissolved back into the aqueous bromine electrolyte. When the battery has been fully discharged, no zinc remains on the electrodes. The two bromine electrolytes are only different in the relative concentration of dissolved elemental bromine.

In 1885, the zinc bromide flow battery was first patented; however, technological development stalled due to problems associated with the electrodes. Research resumed in the 1970s as interest in energy storage systems grew, and continued into the 1990s. Zinc batteries were considered for utility scale storage applications because of the low cost and high energy density of zinc. Flow batteries have the added advantage energy and power capacities that are independent of each other. Although still in earlier stages of development, ZnBr flow batteries exhibit the dual advantages of low cost and high energy density and are commonly considered primarily for energy applications but are also suitable for power applications. Vanadium redox flow batteries are considered more mature and better tested than ZnBr batteries.

Zinc bromide flow batteries have relatively high round trip efficiencies ranging between 70 and 80 percent depending on system design. An important factor affecting efficiency is the uneven buildup of zinc across electrodes and cells during charging. To remedy this problem, the battery is fully discharged, a process called stripping, which dissolves all the zinc in the electrolyte before it is re-deposited during charging. This must be done every 5 to 10 charge-discharge cycles. A typical ZnBr cell has a nominal voltage of 1.8 V and operates at or slightly above room temperature, between 20ºC and 50ºC. Although system temperature does impact efficiency, it is to a lesser degree than some other storage technologies.

The primary life-limiting factor of ZnBr batteries is the extremely corrosive nature of elemental bromine in the electrolyte. Thus, ZnBr energy storage capacity is limited not by the number of operating cycles or the cycle duty, but by the number of hours that the storage system has been in operation. Estimates place ZnBr expected life times around 6,000 hours, which is approximately equivalent to 2,000 cycles at continuous operation and 100 percent depth of discharge.

Another consequence of corrosive liquid bromine in the electrolyte is the possibility of hazardous environmental event or personnel exposure. Although not expected to leak, should some electrolyte contaminate the surrounding area, it could prove hazardous to proximate personnel. The corrosiveness of the liquid bromine is a significant environmental concern when making decommissioning and disposal preparations.

Zinc bromine flow batteries are best suited for load shifting and applications requiring high energy density as opposed to high power density. Example applications currently in use include load shifting (peak shaving) (Japan and Australia), regulation control (load following) (Detroit, Michigan), and renewables time shifting (New York). The Imajuku plant in Fukuoka, Japan is rated at 1 MW and 4 MWh and is directly connected to the grid to perform peak shaving function. The ZnBr system charges during periods of excess generation capacity and discharges when peak load exceeds generation. The system was installed in 1990 and by 1993 it had cycled

1,300 times. Another system in Detroit is located at a utility substation and is used to manage load and relief transmission congestion. It provides capacity upgrade deferral benefits that had allowed a strained transmission system to postpone upgrade expenditures. A 50 kW, 100 kWh system is being used shave peak load and provide power quality in the state of New York.

Costs vary significantly by application and battery size. Table 4.19 describes the costs of a few applications. The Electric Power Research Institute estimates of costs based on size and function are provided in Table 4.20.

Table 4.19: Zinc bromine battery costs by application (2003$)[50]

	Angular Support	Short Duration Power Quality	C3: Short durantion Power Quality + Load Shifting-3hr +Regulation Control + Spinninf Reserve	C4: Long duration Power Quality + Load Shifting-3hr +Regulation Control + Spinning Reserve
Capacity (MWh)	0.003	0.006	8	40
Initial costs ($/kW)[a]				
PCS	173	173	173	476
BOP	100	100	100	100
Storage	366	366	366	1,413
O&M cost ($/kW-year)[b]				
Fixed	12.8	25.8	30.0	39.8
Variable	9.4	9.4	8.8	16.1
Total Capital Cost (M$)	6.4	6.4	6.4	19.9

NOTES: *indicates application estimates are in 2004$
a. Initial costs include acquisition, space, and installation costs. PCS means power conversion system and BOP means balance of plant. Total initial cost can be calculated by multiplying the sum of CT, BOP, and Storage initial costs by the reference power.
b. Fixed O&M costs include projected annual labor and parts costs as well as annual tax and insurance costs. Variable O&M costs include fuel and other variable consumables and assume a duty cycle appropriate for each application.

50 Adapted from [5]

Table 4.20: Zinc bromine battery costs by size and application (2010$)

	Capacity (MWh)	Power (MW)	Duration (hrs)	Efficiency (%)	Lifetime (cycles)	Total Cost ($/kW)	Cost ($/kWh)
Renewables integration	250	50	5	60%	>10,000	1450-1750	290-350
T&D support	5-50	1-10	5	60-65%	>10,000	1670-2015	340-1350
Power quality & reliability	0.625-2.5	0.125-0.5	5	60-65%	>10,000	2200-2420	440-485

(3) Electrical and Magnetic Field Storage

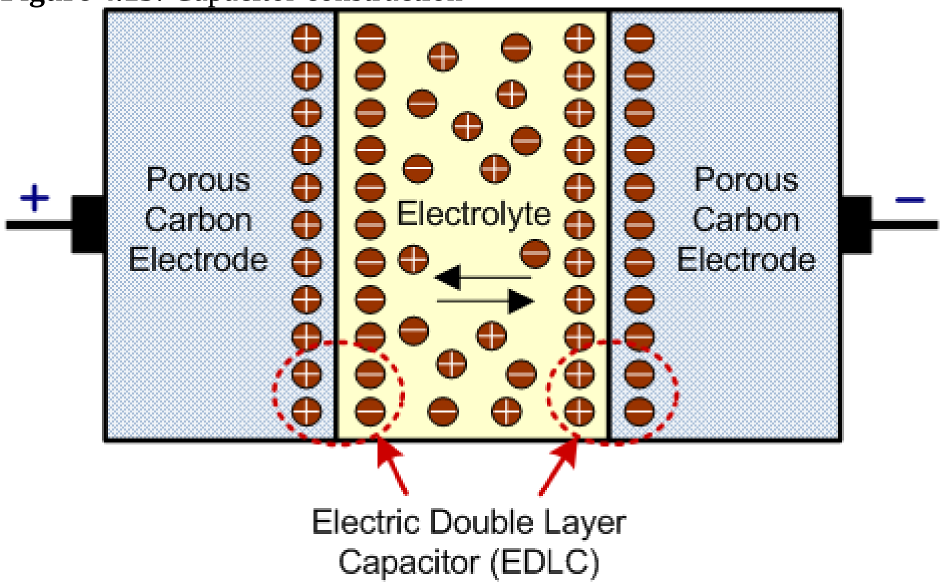
A capacitor, which consists of two electrical conductors separated by a non-conducting material (known as a dielectric), is used to store energy in the form of an electric field. When a voltage is applied across the conductors, opposite electrical charges build up on the conductors, creating an electric field. Energy is stored in the electric field. The capability of the capacitor to store energy is determined by the surface area of the conductors and the distance between. Thus, most capacitors consist of two plates separated by a thin dielectric.

There are three types of capacitors: electrostatic, electrolytic, and electrochemical. An electrolytic capacitor is distinguished from an electrostatic capacitor because it uses a liquid electrolyte as one of the plates.

(a) Electrochemical capacitors

Electrochemical capacitors, also called double layer capacitors (or super-capacitors or ultra-capacitors), are distinct from other capacitors because of their high energy density. Electrochemical capacitors contain: two electrodes, a separator, an electrolyte, two current collectors, and a container. These capacitors store energy statically as opposed to batteries which store energy chemically (see Figure 4.15). Although, they are similar to batteries in that they use aqueous electrolyte and are configured into cells.

Figure 4.15: Capacitor construction[51]



Electrochemical capacitors were discovered in the 1800s. In 1957, General Electric announced a two-terminal charge storage device. By 1979, they were used for computer memory backup applications. They have since evolved and are able to store much more electricity, with some series of electrochemical capacitors having voltages at or above 600 V. These high power levels make it suitable for power quality and intermittent renewables fluctuation suppression applications.

There are two basic double-layer capacitor electrode configurations, symmetric and asymmetric. Symmetric configurations have identical electrodes, while asymmetric designs have different electrodes. See Table 4.21 for a comparison of the technical characteristics of each double-layer capacitor design.

Table 4.21: Double-layer capacitor designs technical characteristics [5]

Electrochemical Capacitor Types	Type I Symmetric /aqueous	Type II Symmetric /organic	Type III Asymmetric /aqueous
Energy density	Low to moderate	Moderate to high	High to very high
Power performance	High	High	Low to high
Cycle life	High	High	High
Self-discharge rate	Low	Low	Very low

Some disadvantages of double layer capacitors include the interdependence of the cells, sensitivity to voltage imbalances between cells and maximum voltage thresholds, and safety issues. First, if just one cell in the string fails, it may lead to the failure of the entire string, in a “domino effect,” or it may lead to a voltage and stress increase on other cells. This leads into the second disadvantage; the cells life expectancies are directly tied to strict maximum voltages.

[51] http://www.intechopen.com/books/dynamic-modelling/dynamic-modelling-and-control-design-of-advanced-energy-storage-for-power-system-applications

Finally, there are many safety issues associated with electrochemical capacitors including electrical, chemical, fire, and explosion hazards. Electrical and chemical hazards are similar to those common to batteries. The voltages of double layer capacitors are often lethal and should be treated with the same precautions as other high voltage devices. Type I and III capacitors have aqueous electrolyte which eliminates the possibility of hazardous fires, but allows for the possibility to chemical burns similar to those from other electrochemical storage devices. Type II poses a potential fire threat and health threats if inhaled, ingested, or contacts skin.

There are also environmental implications due to the lack of recycling programs for electrochemical capacitors. This may contribute to siting, permitting, and disposal costs. See Table 4.22 for an assessment of the costs of double layer capacitors based on function.

Table 4.22: Electrochemical capacitor cost by application (2003$)[52]

	Angular Stability	Voltage Support	Short Duration Power Quality
Capacity (MWh)	0.003	0.003	0.006
Initial costs ($/kW)[a]			
PCS	153	153	153
BOP	100	100	100
Storage	162	162	203
O&M cost ($/kW-year)[b]			
Fixed	11.9	11.9	13.1
Variable	6.7	6.7	6.8
NPV Disposal cost ($/kW)	0.2	0.2	1.5
Total Capital Cost (M$)	4.1	4.1	4.6

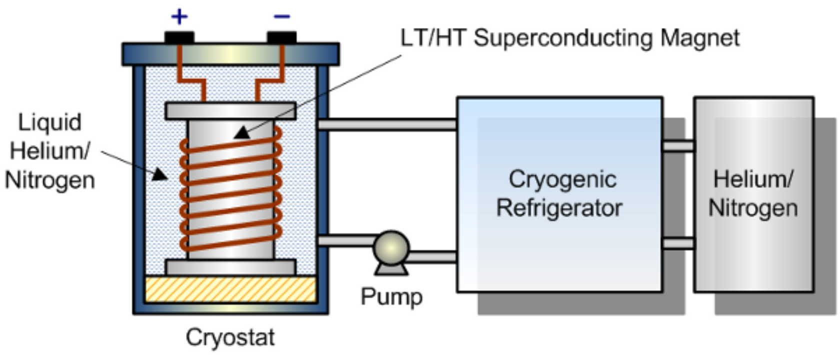
NOTES: *indicates application estimates are in 2004$
a. Initial costs include acquisition, space, and installation costs. PCS means power conversion system and BOP means balance of plant. Total initial cost can be calculated by multiplying the sum of CT, BOP, and Storage initial costs by the reference power.
b. Fixed O&M costs include projected annual labor, parts, tax, and insurance costs. Variable O&M costs include fuel and other variable consumables and assume a duty cycle appropriate for each application.

[52] Adapted from [5]

(b) Superconducting magnetic energy storage

Superconducting Magnetic Energy Storage (SMES) uses the flow of direct current through a cryogenically-cooled, superconducting coil to generate a magnetic field capable of storing energy. In principle, once the superconducting coil is charged, the current will not deteriorate and the magnetic energy can be stored for an indefinite amount of time. The stored energy is released whenever needed by discharging the coil. To keep the magnetic coil cool enough to have superconducting properties, cryogenic refrigeration must be an integral part of the storage system (see Figure 4.16).

Figure 4.16: Superconducting Magnetic Energy Storage[53]



SMES systems have several advantages including "permanent" storage, immediate response, life expectancy that is independent of duty cycle, high efficiency, and high reliability. First, the term permanent implies that stored energy may be held indefinitely; in other words, there are no standby losses. This is because sources of efficiency loss such as heat dissipation, evaporation, etc. do not exist for SMES. Second, SMES is capable of almost instantaneous response, limited only by solid state materials ability to react in a charge/discharge cycle. The charging and discharging of the magnetic field is a much faster process than the mechanical and chemical energy conversion processes involved in other storage technologies. This makes SMES an excellent choice for UPS and power quality applications. Third, SMES life expectancy does not hinge on the number of cycles or the depth of discharge as most electrochemical storage technologies' do. SMES round trip efficiency is above 95 percent. Finally, because there are very few mechanical moving parts there are less sources of failure, making SMES highly reliable.

According to the Electric Power Research Institute's storage technologies handbook published in 2003 [6] the only commercial SMES systems available at that time was the D-SMES system manufactured by American Superconductor. The D-SMES is trailer-mounted system with a capacity to deliver 3 MW for about 1 second and 8 MVAR[54] continuously at 480 Volts (AC). Table 4.23 shows the location and applications of the three D-SMES systems deployed by 2003.

[53] Source: http://www.intechopen.com/books/dynamic-modelling/dynamic-modelling-and-control-design-of-advanced-energy-storage-for-power-system-applications

[54] A volt-ampere reactive (or var) is the fundamental unit of reactive power. One million vars is a megavar (MVAR) and is the reactive power equivalent to a megawatt (MW).

Table 4.23: D-SMES installations in the United States (as of 2003) [5]

Start of Operation	Host	Location	Application
June 2000	Wisconsin Public Service	Northern Wisconsin	Transmission Loop Voltage Stability - 6 Units, installed at distributed locations
July 2000	Alliant Energy	Reedsburg, Wisconsin	Transmission Voltage Stability
May 2002	Entergy	North Texas	Voltage Stability - 2 Units

Prior to making the D-SMES units American Superconductor had manufactured several smaller SMES units designed for power quality applications. These units, designated "Micro"-SMES, were deployed mostly in industrial settings to deal with voltage sag issues. Table 4.24 shows the location and characteristics of these Micro-SMES units.

Table 4.24: Small SMES installations in the United States (as of 2003) [5]

Start of Operation	Customer	Location	Application	Power (Voltage)	Energy, MJ
May 1992	Central Hudson G&E	Fishkill, NY	Semiconductor Testing Facility	500 kVA (480 V_{ac})	1.0
December 1993	Tyndall AFB	Panama City, FL	Five General Military Buildings	500 kVA (480 V_{ac})	1.0
March 1993	CYANCO	Winnemuca, NV	400 HP/4160V Motor at Chemical Plant	500 kVA (4160 V_{ac})	1.0(+)
May 1995	Brookhaven National Laboratory	Upton, NY	Light Source Research Center Ultra-violet Light source, ring, and experiment station	1.4 MVA (480 V_{ac})	2.8
May 1995	McClellan AFB	Sacramento, CA	Semiconductor Chip Mfg. Lab Fiber Optic Mfg. Facility Removed when Base Closed	750 kVA (480 V_{ac})	2.8
July 1996	U.S. Air Force	Tinker AFB, OK	DC Link Support for two 800 kW/1000kVA Ups	1.0 MVA (560 V_{ac})	2.8
June 1997	U.S. Air Force	Tinker AFB, OK	DC Link Support for two 800 kW/1000kVA UPS	1.0 MVA (560 V_{ac})	2.8
April 1997	SAPPI - Stanger	Stanger, South Africa	1000 kVA Paper Machine	1.0 MVA (400 V_{ac})	3.0
May 1997	AmeriMark Plastics	Fairbluff, NC	Plastic Extrusion Plant Removed when plant sold	1.4 MVA (480 V_{ac})	3.0
May 1999	STEWEAG	Gleisdorf, Austria	Automotive Parts Foundry	1.4 MVA (480 V_{ac})	3.0
June 2002	Edison/STM	Agrate, Italy	Semiconductor Processing Facility Voltage Sags - 2 Units	8.0 MVA (480 V_{ac})	3.0
April 2002	EDF	Paris, France	Voltage Sag Protection	8.0 MVA (400 V_{ac})	3.0

Major disadvantages of SMES technology include: refrigeration energy requirements, the use of huge magnetic fields, and system costs. In order to keep the magnetic coils super-cooled, energy inputs must be assigned to run the cryogenic refrigeration unit. Similarly, large magnetic fields pose some concerns. Perhaps one of the most difficult hurtles is the cost of such systems. Table 4.25 contains the cost for SMES by application (2003$s).

Table 4.25: SMES costs by application (2003$s)[55]

	Angular Stability	Voltage Support	Short Duration Power Quality
Capacity (MWh)	0.003	0.003	0.006
Initial costs ($/kW)[a]			
PCS	120	120	150
BOP	50	50	50
Storage	207	207	309
O&M cost ($/kW-year)[b]			
Fixed	14.5	14.5	22.2
Variable	8.7	8.7	12.4
NPV Disposal cost ($/kW)	0	0	0
Total Capital Cost (M$)	3.8	3.8	5.1

NOTES: *indicates application estimates are in 2004$
a. Initial costs include acquisition, space, and installation costs. PCS means power conversion system and BOP means balance of plant. Total initial cost can be calculated by multiplying the sum of CT, BOP, and Storage initial costs by the reference power.
b. Fixed O&M costs include projected annual labor, parts, tax, and insurance costs. Variable O&M costs include fuel and other variable consumables and assume a duty cycle appropriate for each application.

(4) Thermal Energy Storage

There are a number of thermal storage technologies that could be employed to provide benefits to the electric power grid. Only molten salt storage will be described, although the following paragraphs provide a basic overview of thermal storage. The main reason only molten salt storage will be discussed is that most of the other thermal storage technologies are on the consumer's side of the meter.

For example, the most common form of thermal storage, ice energy storage is a standard way to reduce peak demand. The logic is as follows; during the night water is frozen into ice; during the day, the ice is used to cool air conditioning systems thereby reducing the need to draw power from the grid.

Similarly, heat can be added to ceramic bricks or hot water heaters when the energy to do so is available. When energy is required, it can be reclaimed from the stored heat. This is much the same in principle as molten salt thermal storage.

[55] Adapted from [5]

A simple, two-tank, direct molten salt energy storage system utilizes a receiver to reflect sunlight onto a heating chamber. Fluid from a cool tank is pumped to a heating chamber where it is brought to a very high temperature. It is then transferred to a tank containing heated fluid for storage. When heat energy needs to be recovered, it is used to create stream that powers a generator. There are other configurations, but the overall principle remains the same.[56]

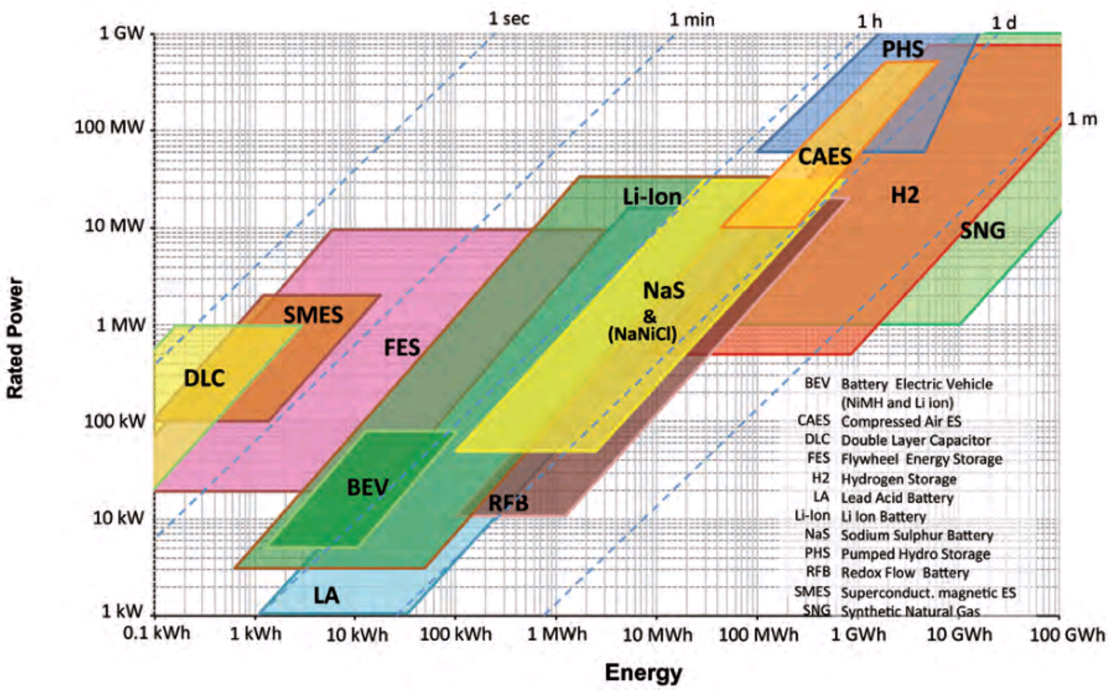
[56] For more information see http://www.eere.energy.gov/basics/renewable_energy/thermal_storage.html

5. Comparison of Technologies

This section brings together the technical characteristics, uses, and costs of the previous discussed storage technologies. The intent is to make general comparisons amongst technologies in order to have a better understanding of the industry as a whole.

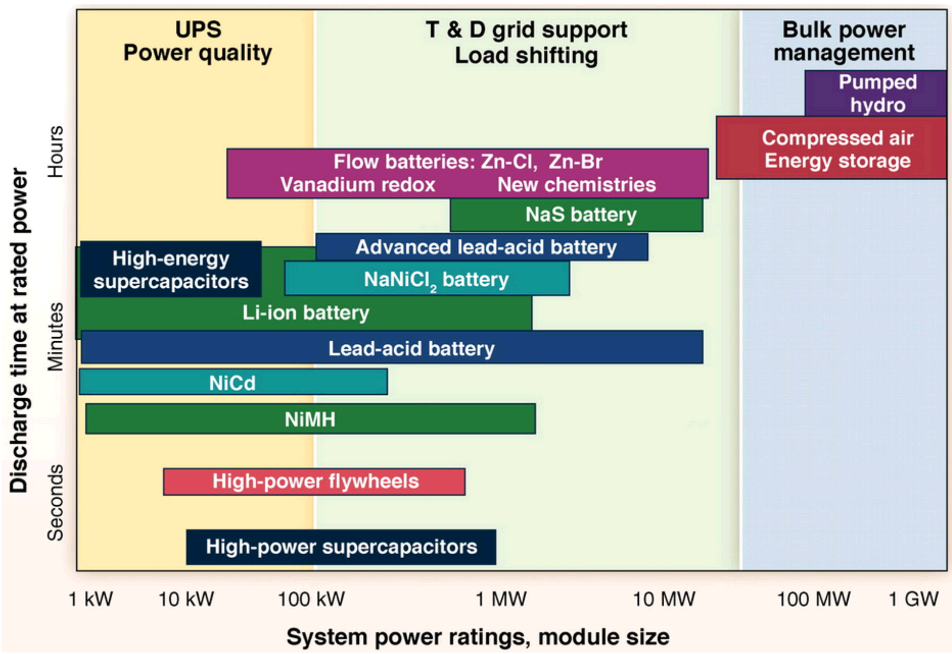
The first round of comparisons will center on rated power, rated energy, and discharge duration (see Figure 5.1). The technologies in the bottom/left (double layer capacitors, SMES, and FES) are primarily used for power applications. As you move to the upper right corner, the technologies approach suitability for energy applications.

Figure 5.1: Rated power, energy, and discharge duration [3]



Second, energy storage technologies can be compared based upon how high their power output is and how quickly they can discharge it. This comparison is useful when considering which technologies are best for providing a particular benefit. Figure 5.2 has three benefit categories, UPS and power quality, transmission and distribution and load shifting, and bulk power management. Again, high-power super-capacitors, FES, and an assortment of electrochemical batteries are appropriate for UPS and power quality. Conversely, PHS and CAES fall under bulk power management.

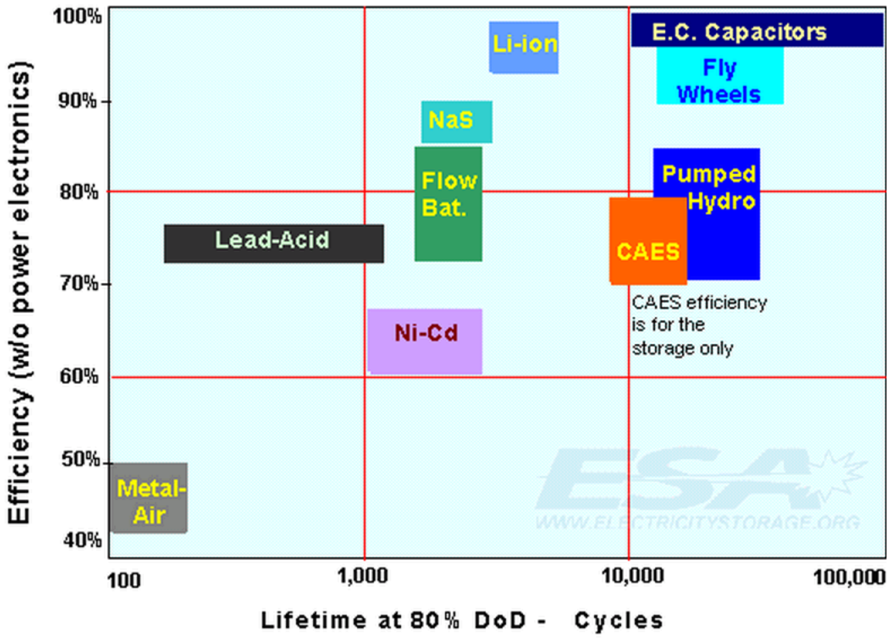
Figure 5.2: Power rating and discharge duration at rated power[57]



[57] Koritarov, Vladimir. Grid-Scale Energy Storage Presentation. March 20, 2013.

Third, the cycle life and the efficiency of storage technologies can be examined (see Figure 5.3). Capacitors have the most efficient lifecycle whereas metal air batteries have the least efficient life cycles. As discussed before, PHS and CAES have very long expected lifetimes that allow them to spread out high initial costs.

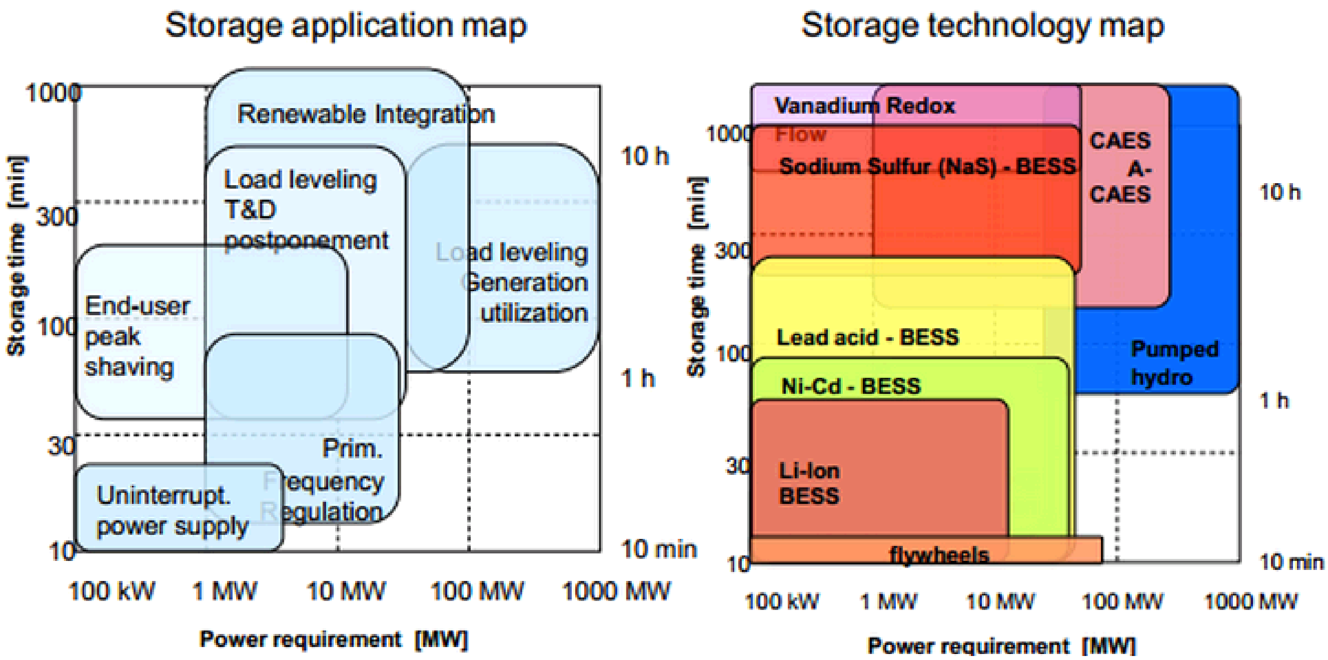
Figure 5.3: Efficient lifecycle of energy storage technologies[58]



[58] Electricity Storage Association

Now, consider the technical characteristics of the applications discussed in section 3 and how they fit with the storage technologies in section 4. Figure 5.4 illustrates both the applications and storage technologies in terms of storage capacity, discharge duration, and rated power. Note that some of the names are different from those used in this report but they describe the same applications.

Figure 5.4: Storage applications and technologies maps



From the above figures, a few commonly paired applications and technologies can be deduced. For example, flywheels are usually considered an attractive technology to provide uninterruptable power supplies. If placed on the same figure these would overlap in terms of storage time and power requirement. Similarly, CAES is often paired with renewable integration and load leveling activities. Finally many electrochemical battery technologies, such as lead acid batteries, nickel cadmium batteries, and lithium ion batteries are used for power quality and frequency regulation applications.

Like Figures 5.1 and 5.2, the upper-right corner of each panel in Figure 5.4 displays energy applications and technologies, whereas the bottom-left corner displays power applications and technologies. See Figure 5.5 to examine the matrix of applications to technologies. The green diamonds indicate compatibility, the yellow circles indicate possible application, and the red squares indicate infeasibility.

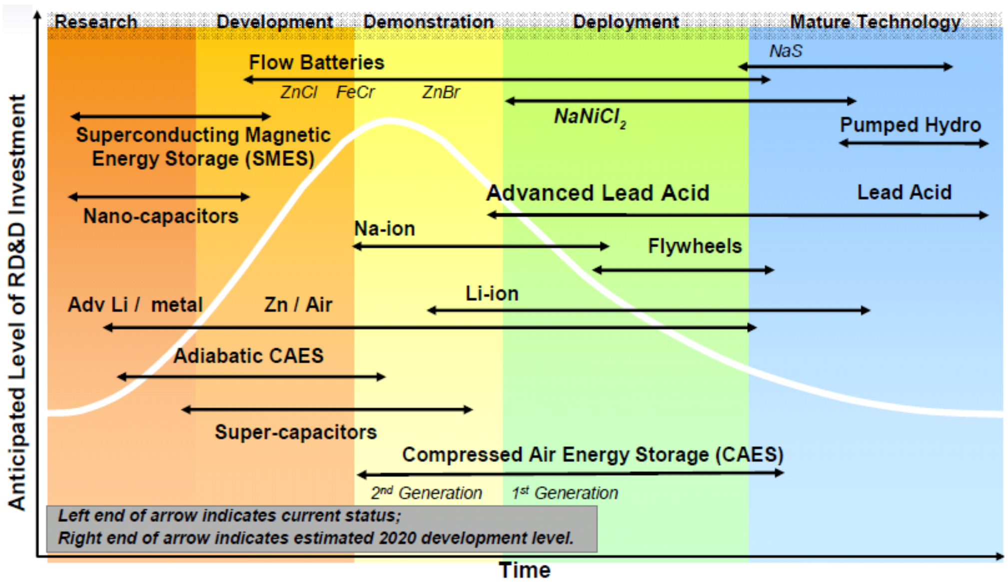
Figure 5.5: Matrix of applications to technologies[59]

Application	Application Requirements			Commercial / Traditional Systems							
	Discharge Duration (hours)		Frequency of Use	Advanced lead acid	Lithium-ion: High energy	Lithium-ion: High power	Sodium nickel chloride (NaNiCl)	Sodium sulfur (NaS)	Thermal: Ice	Vanadium redox flow battery	Zinc bromine
	Low	High									
Microgrid / Islanded Systems											
Supply spinning reserve	0.3	1	Occasional	●	●	■	◆	■	●	●	●
Load following	2	4	Frequent	●	●	■	◆	■	◆	●	●
Peak shifting / Energy time shift	3	7	Frequent	●	●	■	◆	■	◆	●	●
Uninterruptible Power Supply (UPS)											
Service reliability (customer backup)	0.5	2	Occasional	●	●	■	◆	■	■	●	●
UPS			Occasional	◆	◆	◆	●	●	■	●	●
Large renewable											
Renewables time shift	3	6	Frequent	●	●	■	◆	■	◆	●	●
Renewables capacity firming	2	3	Frequent	●	●	■	◆	■	■	●	●
Grid Support											
Frequency regulation / fast regulation	0.3	0.5	Frequent	●	●	◆	●	■	■	●	●
Voltage regulation	0.3	1	Frequent	●	●	◆	●	■	■	●	●
Demand response / Demand charge management	5	8	Frequent	●	●	■	◆	■	◆	●	●
Infrastructure (T&D) deferral	3	6	Occasional	●	●	■	◆	■	●	●	●

[59] Fioravanti, Rick and Ali Nourai (2013) presentation of "Electric Industry Perspectives on Storage"

Before proceeding to cost comparisons the relative maturities of various storage technologies are considered. Figure 5.6 shows the development stages and where on this continuum each technology lies. Keep in mind, maturity typically plays a role in determining costs.

Figure 5.6: A comparison of technology maturity and anticipated R&D expenditure [21]



Now consider the costs comparisions in Figures 5.7 and 5.8. Figure 5.7 compares the power and energy costs of various storage technologies and notes their response times. Generally, energy technologies have lower energy capacity costs and high power capacity costs, as well as slower response times. Batteries, often considered power technologies, have lower power capacity costs and higher energy capacity costs as well as faster response times.

Figure 5.7: Power and energy capital costs and response time

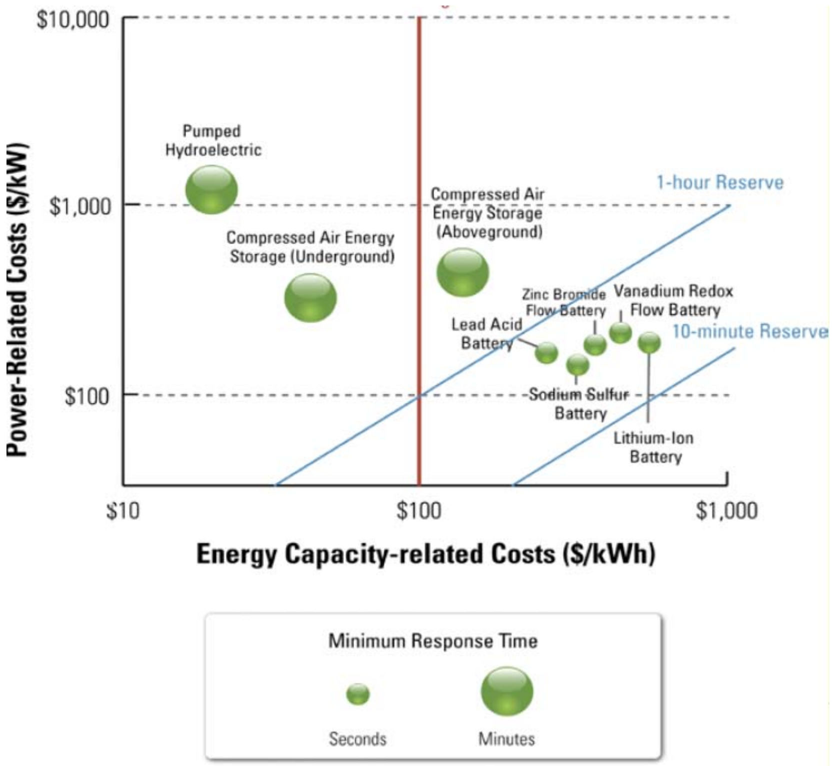


Figure 5.8: Per unit energy and power capital costs by technology

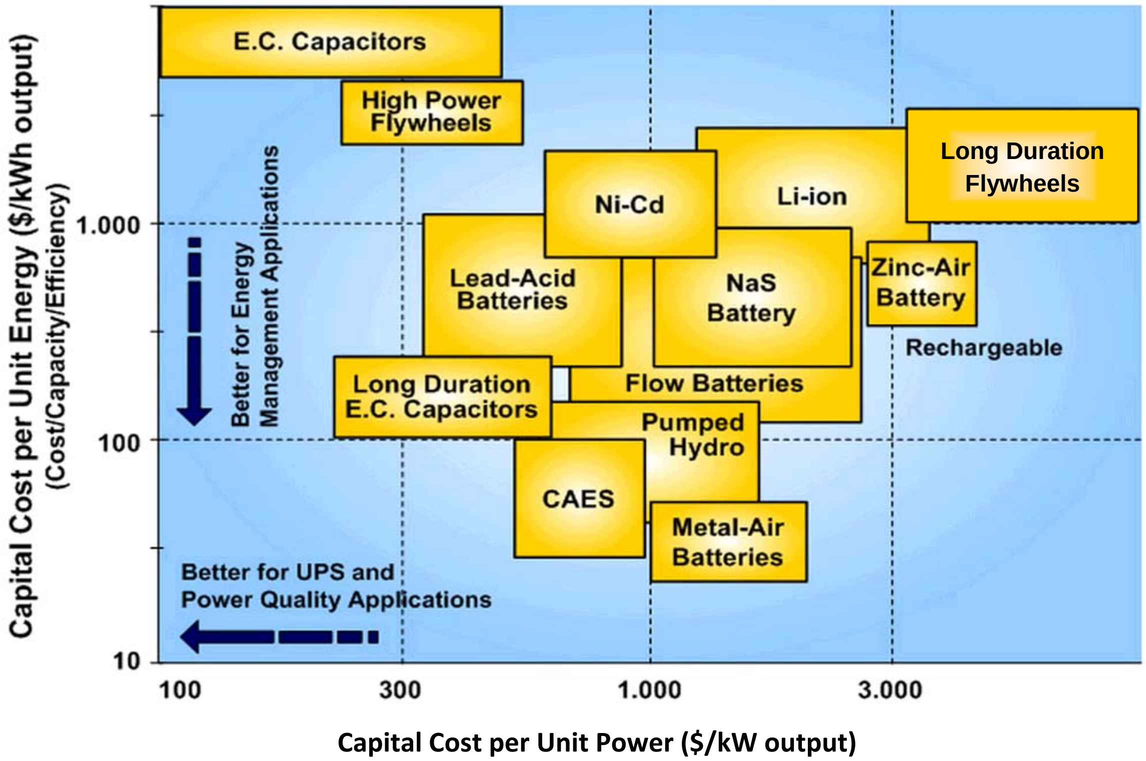


Table 5.1 presents the value (or benefit) associated with a particular storage technology performing within one of four application categories. From an economic perspective, utilities should choose the storage alternative whose value exceeds its cost. Although the values in Table 5.1 should not be emphasized too much (given the considerable uncertainty about the value of storage still exists), they do provide a value which can be compared to the capital costs described in Table 5.1.

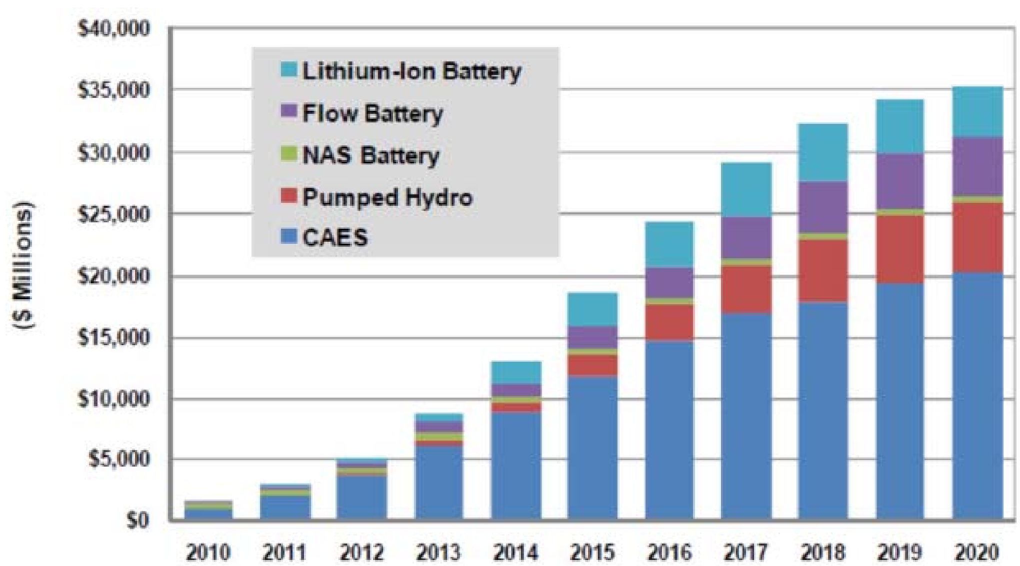
Table 5.1: Present worth cost of 10-year operation in year 1 ($/kW) (2011$)[60] [15]

Table 5. Present Worth Cost of 10-year Operation in Year 1 ($/kw)[1]

Technology/Use	Advanced Lead-acid Battery	Na/S (7.2 hr)	Zn/Br	V-redox	Lead-acid Battery with Carbon-enhanced Electrodes	Li-ion	CAES (8 hrs)	Pumped Hydro (8 hrs)	High-speed Flywheel (15 min)	Supercap (1 min)
Long-duration storage, frequent discharge	2839.26	2527.97	2518.03	3279.34	2017.87	2899.41	1470.10	2399.90		
Long-duration storage, infrequent discharge	1620.37	2438.97	1817.82	2701.41	1559.57	2442.79				
Short-duration storage, frequent discharge	1299.70		905.53	1459.85	669.85	1409.99			965.73	834.62
Short-duration storage, infrequent discharge	704.18		697.78	999.78	625.57	960.48			922.87	793.02

With the benefits from Table 5.1 in mind, consider Figure 5.9 which describes the installed revenue opportunity, or the expected revenues by technology capacity in world markets from 2010 to 2020.

Figure 5.9: Installed revenue opportunity by technology in world markets (2010-2020)



60 For a complete list of assumptions involved in these calculations please see [15].

To summarize the costs presented in the previous sections, see Table 5.2.

Table 5.2: Technology characteristics [22]

- **Wholesale Markets**
- **Wind Integration**
- **Ancillary Services**

Technology Option	Maturity	Capacity (MWh)	Power (MW)	Duration (hrs)	% Efficiency (total cycles)	Total Cost ($/kW)	Cost ($/kW-h)
Pumped Hydro	Mature	1680-5300	280-530	6-10	80-82 (>13,000)	2500-4300	420-430
		5400-14,000	900-1400	6-10		1500-2700	250-270
CT-CAES (underground)	Demo	1440-3600	180	8	See note 1 (>13,000)	960	120
				20		1150	60
CAES (underground)	Commercial	1080	135	8	See note 1 (>13000)	1000	125
		2700		20		1250	60
Sodium-Sulfur	Commercial	300	50	6	75 (4500)	3100-3300	520-550
Advanced Lead-Acid	Commercial	200	50	4	85-90 (2200)	1700-1900	425-475
	Commercial	250	20-50	5	85-90 (4500)	4600-4900	920-980
	Demo	400	100	4	85-90 (4500)	2700	675
Vanadium Redox	Demo	250	50	5	65-75 (>10000)	3100-3700	620-740
Zn/Br Redox	Demo	250	50	5	60 (>10000)	1450-1750	290-350
Fe/Cr Redox	R&D	250	50	5	75 (>10000)	1800-1900	360-380
Zn/air Redox	R&D	250	50	5	75 (>10000)	1440-1700	290-340

- Utility Frequency Regulation
- Power Quality
- Defer Capital Cost Deferral

Technology Option	Maturity	Capacity (MWh)	Power (MW)	Duration (hrs)	% Efficiency (total cycles)	Total Cost ($/kW)	Cost ($/kW-h)
Flywheel	Demo	5	20	0.25	85-87 (>100,000)	1950-2200	7800-8800
Li-ion	Demo	0.25-25	1-100	0.25-1	87-92 (>100,000)	1085-1550	4340-6200
Advanced Lead-Acid	Demo	0.25-50	1-100	0.25-1	75-90 (>100,000)	950-1590	2770-3800

- Utility T&D Substation Grid Support
- Peak Shaving; CapEx Deferral, Reliability
- Dual Mode-Frequency Regulation/RTO Market Participation

Technology Option	Maturity	Capacity (MWh)	Power (MW)	Duration (hrs)	% Efficiency (total cycles)	Total Cost ($/kW)	Cost ($/kW-h)
CAES (aboveground)	Demo	250	50	5	See note 1 (>10,000)	1950-2150	390-430
Advanced Lead-Acid	Demo	3.2-48	1-12	3.2-4	75-90 (4500)	2000-4600	625-1150
Sodium-Sulfur	Commercial	7.2	1	7.2	75 (4500)	3200-4000	445-555
Zn/Br Flow	Demo	5-50	1-10	5	60-65 (>10,000)	1670-2015	340-1350
Vanadium Redox	Demo	4-40	1-10	4	65-70 (>10,000)	3000-3310	750-830
Fe/Cr Flow	R&D	4	1	4	75 (>10000)	1200-1600	300-400
Zn/air	R&D	5.4	1	5.4	75 (4500)	1750-1900	325-350
Li-ion	Demo	4-24	1-10	2-4	90-94 (4500)	1800-4100	900-1700

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Appendix A

Valuation of the Benefits of Energy Storage[61]

SNL Report		EPRI White Paper		PV $/kW-h				PV $/kW			
				SNL Benefits		EPRI Benefits		SNL Benefit		EPRI Benefits	
Application	**Duration**	**Application**	**Duration**	**Low**	**High**	**Target**	**High**	**Low**	**High**	**Target**	**High**
Electric Energy Time-shift	2-8 hrs	Price Arbitrage	2-8 hrs	$50	$350	$67	$100	$400	$700	$134	$800
Electric Supply Capacity	5-6 hrs	System Capacity	5-6 hrs	$60	$142	$44	$121	$359	$710	$220	$726
Area Regulation	1 hr	Regulation (1 hr)	1 hr	$785	$2,010	$255	$426	$785	$2,010	$255	$426
Electric Supply Reserve Capacity	1-2 hrs	Spinning Reserves	1-2 hrs	$29	$225	$80	$110	$57	$225	$80	$220
Voltage Support	1 hr	Voltage Support	1 hr	$400	$400	$9	$24	$400	$400	$9	$24
Transmission Support	1 hr	VAR Support	1 hr	$192	$192	$4	$17	$192	$192	$4	$17
Transmission Congestion Relief	3-6 hrs	Transmission Congestion	3-6 hrs	$5	$47	$38	$368	$31	$141	$114	$2,208
T&D Upgrade Deferral 50th Percentile	3-6 hrs	Defer Transmission Investment	3-6 hrs	$80	$229	$414	$1,074	$481	$687	$1,242	$6,444
T&D Upgrade Deferral 90th Percentile	3-6 hrs	Defer Transmission Investment	3-6 hrs	$127	$360	$414	$1,074	$759	$1,079	$1,242	$6,444
Time-of-use Energy Cost Management	4-6 hrs	Retail TOU Energy Charges	4-6 hrs	$204	$307	$377	$543	$1,226	$1,226	$1,508	$3,258
Demand Charge Management	5-11 hrs	Retail Demand Charges	5-11 hrs	$53	$116	$142	$459	$582	$582	$710	$5,049
Electric Service Reliability	1 hr	Power Reliability	1 hr	$359	$978	$47	$537	$359	$978	$47	$537
Electric Service Power Quality	1 hr	Power Quality	1 hr	$359	$978	$19	$571	$359	$978	$19	$571
Renewables Energy Time-Shift	3-5 hrs	Price Arbitrage	3-5 hrs	$47	$130	$67	$100	$233	$389	$201	$500
Renewables Capacity Firming	2-4 hrs	System Capacity	2-4 hrs	$177	$458	$44	$121	$709	$915	$88	$484
Wind Generation Grid Integration, Short Duration	1 hr	Renewable Energy Integration	1 hr	$500	$1,000	$104	$311	$500	$1,000	$104	$311
Wind Generation Grid Integration, Long Duration	1-6 hrs	Renewable Energy Integration	1-6 hrs	$17	$782	$104	$311	$100	$782	$104	$1,866
Note: SNL included three benefit values, Load Following, Substation On-site Power, and Transmission Support which were not modeled using a similar methodology in the EPRI White Paper.											

[61] Source: EPRI White paper report. See [22]

SNL Report refers to the DOE-Sandia National Laboratories Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide (SAND2010-0815) published in 2010. EPRI document Electricity Energy Storage Technology Option: A White Paper Primer on Applications, Costs, and Benefits (1020676) also published in 2010. The discrepancies in the values placed on specific applications stem from the difference in valuation approaches and underlying assumptions provided below.

The Sandia National Laboratories (SNL) report assumes generic financials:

- 10 years of storage life for all benefits
- 2.5% general inflation
- 10% discount rate

The EPRI White paper report assumes:

- Multiple storage life assumptions based on estimates for each technology
- 10% discount rate but does not escalate benefit values.

For a more detailed explanation of the methodology of the present value calculations listed in the above table, see the EPRI White paper report section entitled, “Comparison to Alternative Energy Storage Benefit Valuations.” The above table is meant to allow a relative comparisons of the benefits of energy storage.

Appendix B

Application Technical Descriptions

This appendix describes the thirteen single applications and nine combined applications of storage technology listed in the applications section of this report. This appendix is intended to explain the function and technical characteristics of each application.

(1) Long-duration Applications

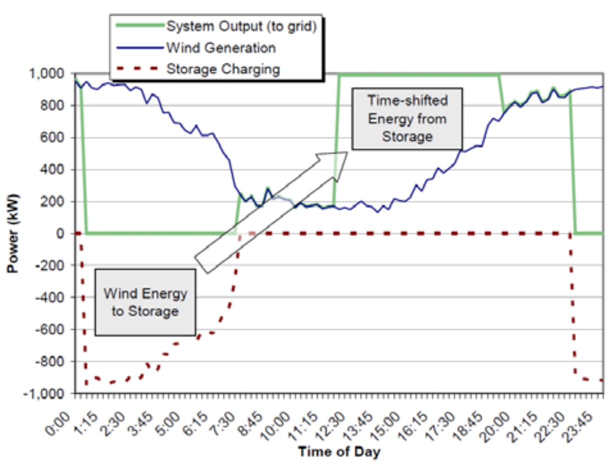
(a) Mitigating transmission congestion

In some circumstances, the optimal flow on a transmission line may exceed its capacity, at which point generation must be curtailed to a level that can be supported by the transmission infrastructure. This can occur when generation is located far from population centers and transmission infrastructure upgrade is not yet economically justified. Energy storage devices can store excess generation until transmission lines clear. This application may require frequent or infrequent discharge depending on site conditions.

(b) Renewables time shifting

The timing of renewable generation often does not match demand. Renewables generation and peak demand typically occur in different periods during the day and year. Wind and solar generation also depend on weather and geographic conditions. Storage removes some of these period specific constraints by storing energy when generation exceeds needs for serving load or releasing stored energy when generation falls short of load. (Time shifting is similar to load shifting. Load shifting is discussed in greater detail in *(d)* and *(e)* below. Also see Figure B1.)

Figure B1: Renewables time shifting with energy storage[62]

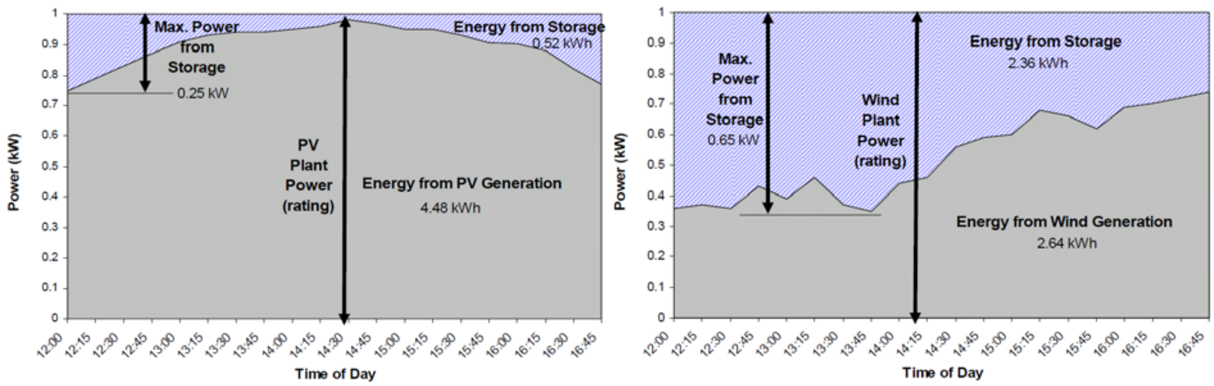


[62] Source: *Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide*. See [24].

(c) Forecast hedging

Because intermittent renewable generation is somewhat unpredictable, output must be forecast in order to facilitate the balancing of generation and load. This is common in the wind and solar generation sectors due to weather variation. Because forecasts are inherently imperfect, some means of modifying the output of the rest of the electricity supply system must be used to balance generation and load when renewables output deviates from the forecast. Energy storage can be used to serve this need for balancing and thus can provide a hedge against deviations from the forecast (See Figure B2).

Figure B2: Firming and smoothing solar and wind generation with energy storage[63]



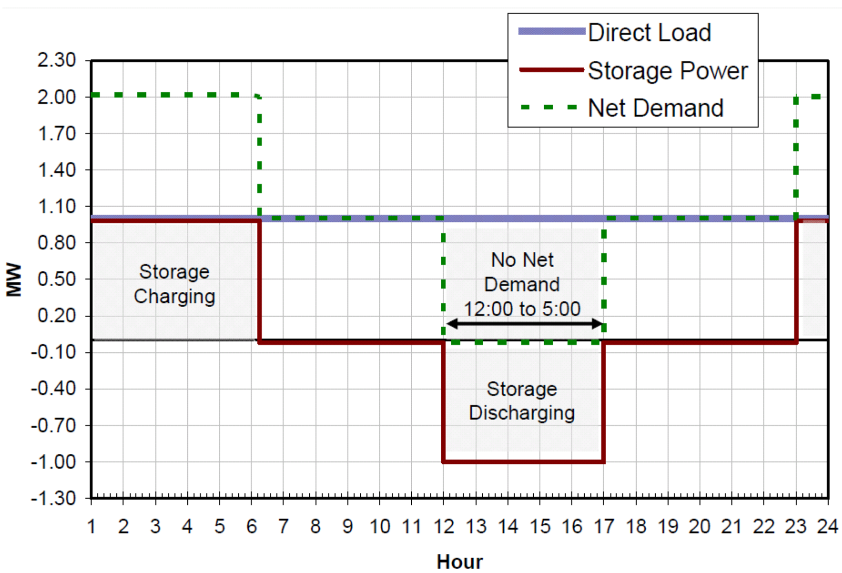
[63] Source: *Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide*. See [24].

(2) Long-duration/Frequent-discharge

(d) 3 hour load shifting and (e) 10 hour load shifting

Load shifting describes the use of energy stored during periods of low demand for periods with high demand. When load is low during the night, excess generation capacity is used to charge energy storage devices. During peak demand hours, stored energy is discharged to augment generation output or transmission and distribution capacity. This allows generation to be more nearly constant over the course of a 24-hour period and reduces peak capacity needs. Using energy storage to simultaneously fill valleys and lower peaks in the load curve allows utilities to defer capacity upgrades, reduce wear and tear on equipment, and reduce system costs (See Figure B3).

Figure B3: Load shifting with energy storage[64]



(3) Long-duration/Infrequent-discharge

(f) Long-duration power quality

When a large or long duration disturbance threatens to reduce power quality for a long period of time, energy storage can provide short-term power quality (i.e., maintain power, voltage, or frequency within optimal operational ranges) as well as several hours of reserve power. A compatible storage device can inject real power for the duration of the sag and seamlessly transition to provide several hours of full power. This application requires adequate storage capacity for industrial and commercial consumers to be able to ride through most of the outage without loss of service, also called full outage protection.

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[64] Source: *Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide*. See [24].

(g) Spinning reserve

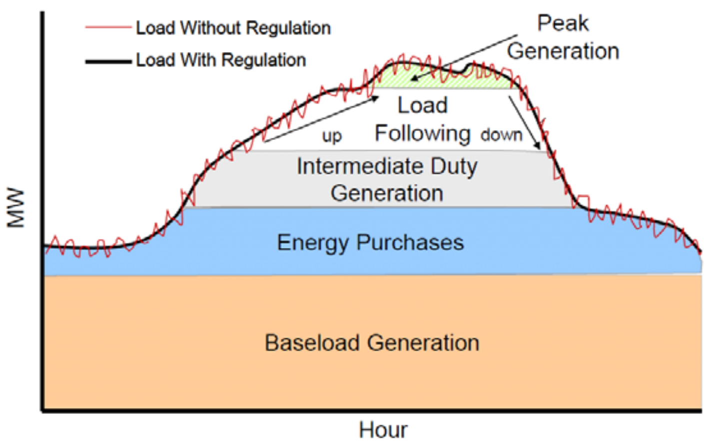
Spinning reserve uses stored energy to compensate for unexpected contingencies. The term spinning reserve used to describe this application encompasses spinning, supplemental, and replacement reserves. Spinning reserve specifically refers to storage that can be made immediately available (i.e., with very fast response time). Supplemental reserves and replacement reserves have slower response times and follow sequentially to provide a few hours of reserve power.

(4) Short-duration/Frequent-discharge

(h) Regulation control

Regulation control involves maintaining a balance between real-time generation and load, also called load following. Adjusting generation to match load continuously can have consequences for equipment life expectancies and cost efficiency. Imbalances between generation and load can also cause frequency deviations that can disrupt both generation equipment and loads.[65] Storage can provide regulation control by providing system frequency regulation in conjunction with load following (see Figure B4).

Figure B4: Regulation control and load following[66]



(i) Fluctuation Suppression

Some types of loads can be very sensitive to deviations from a purely sinusoidal voltage and current in the power system. Energy storage devices can be used to provide high quality power by rapidly charging and discharging in order to smooth out very short-term fluctuations.

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[65] In reality, generation and load are always balanced. If the amount of generation is insufficient to meet the load, energy stored within the system in the form of the rotational kinetic energy of all the motors and generators connected to the system will supply energy to match generation and load. This lost kinetic energy will cause all of the rotating equipment to slow down and frequency will drop. Similarly, if generation is too great, rotating equipment will store the excess energy and frequency will increase.

[66] Source: *Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide*. See [24].

(5) Short-duration/Infrequent-discharge

(j) Short duration power quality

A sag or interruption in voltage can cause power disturbances that negatively impact power quality. This problem can be more common in distribution systems. Energy storage can mitigate voltage sags by injecting real power for up to a few tens of seconds. This application does not require storage to provide enough power for customers to ride through an outage without loss of power.

(k) Frequency excursion suppression

A severe system disturbance associated with an imbalance between generation and load can result in a sustained variance in system frequency outside the nominal range (short-term or long-term). This in turn can cause a loss or shedding of load. They can occur in the generation and renewables sectors, in electrically isolated systems, or in power import terminals where contingencies limit full capacity. Energy storage can restore the generation-load balance and steady frequency by injecting real power or by mobilizing alternate generation.

(l) Grid angular stability

A fault on a transmission component can cause generators to lose synchronism with the grid resulting in grid angular instability. This is most commonly found in long transmission lines. Energy storage may be used to mitigate power oscillations by injecting or absorbing real power. This is done by switching the storage device between charge and discharge modes at the frequency of the oscillations or by introducing "prompt" spinning reserve to increase available transmission capacity.

(m) Grid voltage stability

If there is a shortage of reactive power required by load and load increases, voltage will drop. This is most common where there is transmission congestion or high inductive loads. Energy storage can mitigate degraded voltage by supplying continuous reactive power and injecting real power.

Appendix C

ARRA Funding from DOE

ARRA Energy Storage Demonstrations							
AWARDEE (*TECHNOLOGY*)	**SIZE-POWER (ENERGY)**	**APPLICATION**	**TITLE-DESCRIPTION**	**LOCATION**	**UTILITY**	**FUNDING: ARRA (TOTAL)**	**ESTIMATED COMMISSION-ING DATE**
1. BATTERY STORAGE FOR UTILITY LOAD SHIFTING OR FOR WIND FARM DIURNAL OPERATIONS AND RAMPING CONTROL							
DUKE ENERGY BUSINESS SVCS. *(XTREME)*	24MW *(15MW slow)*	Renewables and Demand	**Notrees Wind Storage** - Deploy a wind energy storage demonstration project at the Notrees Wind power Project in western Texas. The project will demonstrate how energy storage and power storage technologies can help wind power systems address intermittency issues by building a 24 megawatt (MW) hybrid-energy storage system capable of optimizing the flow of energy.	Goldsmith, TX	Duke	$21,806,219 *($43,612,445)*	5/12
PRIMUS POWER *(ZINC-CHLORIDE FLOW BATT.)*	25MW *(75MWhr)*	Renewables	**Wind Firming EnergyFarm™-** Deploy a 25 MW - 75 MWh EnergyFarm for the Modesto Irrigation District in California's Central Valley, replacing a planned $78M / 50 MW fossil fuel plant to compensate for the variable nature of wind energy providing the District with the ability to shift on-peak energy use to off-peak periods.	Alameda, San Ramon, Modesto, CA	Modesto Irrig. Dist.	$14,000,000 *($46,700,000)*	2/13
SOUTHERN CALIF. EDISON CO. *(LITHIUM-ION BATT.)*	8MW *(4 hrs)*	Renewables	**Tehachapi Wind Energy Storage Project** – Deploy and evaluate an 8 MW utility-scale lithium-ion battery technology to improve grid performance and aid in the	Tehachapi, CA	So. Calif. Edison	$24,978,264 *($54,856,495)*	Q1/12

			integration of wind generation into the electric supply. The project will evaluate wider range of applications for li-ion batteries that will spur broader demand for the technology, bringing production to a scale that will make this form of large energy storage more affordable.				
							ARRA Sub-Total: $60,784,483 **(Project Value Sub-Total): $145,168,940**

2. FREQUENCY REGULATION ANCILLARY SERVICES							
BEACON POWER *(FLYWHEELS)*	20MW *(5MWhr)*	Frequency	**Beacon Power 20MW Flywheel Frequency Regulation Plant –** Design, build, test, commission, and operate a utility-scale 20 MW flywheel energy storage frequency regulation plant in either Hazle Township, PA or Chicago Heights, Illinois, and provide frequency regulation services to the grid operator, the PJM Interconnection. The project will also demonstrate the technical, cost and environmental advantages of fast response flywheel-based frequency regulation management.	Stephen-town, NY	PPL Corp. (PA site); Midwest Energy (IL site)	24,063,978 *($48,127,957)*	11/13
							ARRA Sub-Total: $24,063,978 **(*Project Value Sub-Total*): $48,127,957**

3. DISTRIBUTED ENERGY STORAGE FOR GRID SUPPORT							
CITY OF PAINESVILLE *(VANADIUM-REDOX BATT.)*	1MW *(6-8MWhr)*	Coal Efficiency	**Painesville Municipal Power Vanadium Redox Battery Demonstration Program -** Demonstrate 1 MW vanadium redox battery (VRB) storage system at the 32 MW municipal coal fired power plant in Painesville. The project will provide operating data and experience to help the plant maintain its daily power output requirement more efficiently while reducing its carbon footprint.	Painesville, Parma, OH; Johnstown, PA; Alexandria, VA; Evansville, IN; Devens, MA	Painesville Municipal Power	$4,242,570 *($9,666,324)*	12/12
DETROIT EDISON CO. *(LITHIUM-ION BATT.)*	25kW *(20 units of 50 kWhr each)*	Frequency, Demand and Renewables	**Detroit Edison's Advanced Implementation of Community Energy Storage Systems for Grid Support** – Demonstrated proof of concept for aggregated Community Energy Storage Devices in a utility territory. The project is comprised of the following major research objectives: 1) The 20 Community Energy Storage (CES) devices across a utility territory; 2) The installation and use of a centralized communication across the service territory; 3) The integration of a renewable resource with energy storage; 4) The creation of algorithms for dispatching CES devices for peak shaving and demand response; 5) The integration and testing of secondary-use electric vehicle batteries; and 6) The use of Energy storage devices to provide	West Lebanon, Hanover, NH; Saxonville, MA	Detroit Edison	$4,995,271 *($10,887,258)*	7/11

			ancillary services to the power grid.				
EAST PENN MFG. CO. *(ULTRACAPACITOR/ LEAD-ACID BATT.)*	3MW *(1-4MWhr)*	Frequency/ Demand	**Grid-Scale Energy Storage Demonstration for Ancillary Services Using the UltraBattery Technology -** Demonstrate the economic and technical viability of a 3MW grid-scale, advanced energy storage system using the lead-carbon UltraBattery technology to regulate frequency and manage energy demand.	Lyons Station, PA	Met-Ed	$2,543,746 *($5,087,269)*	4/12
PREMIUM POWER CORP. *(ZINC-BROMINE BATT.)*	5-500 kW *(6 hrs)*	Renewables & Micro-grid	**Premium Power Distributed Energy Storage System Demonstration for National Grid and Sacramento Municipal Utility District -** Demonstrate competitively-priced, multi-megawatt, long-duration advanced flow batteries for utility grid applications. This three-year project incorporates engineering of fleet control, manufacturing and installation of five 500-kW/6-hour TransFlow 2000 energy storage systems in California and New York to lower peak energy demand and reduce the costs of power interruptions.	North Reading, MA; Syracuse, NY; Sacramento, Rancho Cordova, CA	National Grid & Sacramento Municipal Utility Dist.	$6,062,552 *($12,514,660)*	4/12
PUBLIC SVC. CO. OF NM (PNM) *(ADVANCED LEAD ACID BATT.)*	500kW *(2.5MWhr)*	Renewables and Modeling	**PV Plus Storage for Simultaneous Voltage Smoothing and Peak Shifting -** Demonstrate how a 2.5MWh Advanced Lead Acid flow battery along with a sophisticated control system turns a 500kW solar PV installation into a reliable, dispatchable distributed generation resource. This hybrid resource will mitigate	Albuquerque NM	PNM	$2,505,931 *($6,313,433)*	8/11

			fluctuations in voltage normally caused by intermittent sources such as PV and wind and simultaneously store more energy for later use when customer demand peaks.				
ARRA Sub-Total: $20,350,070 **(Project Value Sub-Total): $44,468,944**							
4. COMPRESSED AIR ENERGY STORAGE (CAES)							
PACIFIC GAS & ELECTRIC CO. *(CAES)*	300MW *(10 hrs)*	Renewables, Spinning Reserve, VARS	**Advanced Underground CAES Demonstration Project Using a Saline Porous Rock Formation as the Storage Reservoir** - Build and validate the design, performance, and reliability of an advanced, underground 300 MW Compressed Air Energy Storage (CAES) plant using a saline porous rock formation located near Bakersfield, CA as the storage reservoir.	Kern County, CA	Pacific Gas & Electric	$25,000,000 *($355,956,300)*	12/16
ARRA Sub-Total: $25,000,000 **(Project Value Sub-Total): $355,956,300**							
5. DEMONSTRATIONS OF PROMISING ENERGY STORAGE TECHNOLOGIES							
AQUION ENERGY, INC. *(SODIUM-ION BATT.)*	10-100 kWhr	Renewables	**Demonstration of Sodium Ion Battery for Grid Level Applications -** Partner with Carnegie Mellon University to demonstrate a new, low cost, long-life, highly efficient, environmentally friendly, stationary energy storage battery that uses a proven and fully novel cell chemistry. Specifically, an aqueous sodium-ion based electrolyte is used in conjunction	Pittsburgh, PA	AES Duke Energy	$5,179,000 *($10,359,827)*	

			with simple highly scalable electrode materials housed in low cost packaging.				
AMBER KINETICS, INC. *(FLYWHEELS)*	50 kW *(50kWhr)*	Frequency	**Amber Kinetics Flywheel Energy Storage Demonstration -** Develop and demonstrate an innovative flywheel technology for use in grid-connected, low-cost bulk energy storage applications. This demonstration effort, which partners with AFS Trinity, will improve on traditional flywheel systems, resulting in higher efficiency and cost reductions that will be competitive with pumped hydro technologies.	Fremont, CA	(in-house)	$3,694,660 *($10,003,015)*	12/13
RAYTHEON KTECH. *(REDOX FLOW BATT.)*	250kW *(1MWhr)*	Renewables	**Flow Battery Solution for Smart Grid Renewable Energy Applications -** Demonstrate a prototype flow battery system with an intermittent renewable energy source - a helios dual-axis tracker photovoltaic system. The project will combine a proven redox flow battery chemistry with a unique, patented design to yield an energy storage system that meets the combined safety, reliability, and cost requirements for distributed energy storage.	Albuquerque NM; Sunnyvale, Snelling, CA	(none)	$4,764,284 *($9,528,567)*	12/12
SEEO, INC. *(LITHIUM-ION BATT.)*	(25kWhr)	CES	**Solid State Batteries for Grid-Scale Energy Storage -** Develop and deploy a 25kWh prototype battery system based on Seeo's proprietary nanostructured polymer electrolytes. This new class of advanced lithium-ion rechargeable battery will demonstrate the substantial	Berkeley, Van Nuys, CA	PG&E	$6,196,060 *($12,392,120)*	1/13

			improvements offered by solid state lithium-ion technologies for energy density, battery life, safety, and cost. These batteries would be targeted for utility-scale operations, particularly Community Energy Storage projects.				
SUSTAINX *(CAES)*	1MW *(4MWhr)*	Renewables – both	**Demonstration of Isothermal Compressed Air Energy Storage to Support Renewable Energy Production-**Design, build, and deploy a utility-scale, low-cost compressed air energy storage system to support the integration of renewable energy sources onto the grid. The 1 MW/4hr system will store potential energy in the form of compressed air in above-ground industrial pressure facilities. The technology utilizes isothermal gas cycling coupled with staged hydraulic compression and expansion to deliver an efficient and cost-effective energy storage solution.	W. Lebanon, Hanover, NH; Saxonville, MA	AES Energy Storage	$5,396,023 *($10,792,045)*	12/12
							ARRA Sub-Total: $19,653,027 (Project Value Sub-Total): $53,075,574
							ARRA TOTAL FUNDING: $149,851,558 (PROJECT VALUE TOTAL: ($646,797,715)