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Kyle Bradbury

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Chapter 1

Introduction

Efficient and economic energy storage, if implemented in the current power infrastructure on a large scale, could bring about some of the greatest changes in the power industry in decades. By enabling intermittent sources of energy, wind and solar could make their debut en masse, filling fields with wind turbines and deserts with solar arrays. By adding more renewable energy sources to the power mix, there is greater potential for decreases in harmful emissions. Additionally, energy storage would improve the reliability and dynamic stability of the power system by providing stable, abundant energy reserves that require little ramp time and are less susceptible to varying fuel prices or shortages. Energy storage can shift the higher peak load to off-peak hours in order to level the generation requirement, allowing generators to run more efficiently at a stable power level, potentially decreasing the average cost of electricity. Additionally, increased energy storage capacity can defer or avoid generation capacity increases, decrease transmission congestion (and thereby transmission losses), and help enable distributed generation such as residential solar and wind systems.

The list of benefits goes on and on, but what is required to successfully incorporate these systems is an understanding of these technologies and their comparative strengths and weaknesses. The purpose of this document is to address those issues by discussing energy storage in two ways. First, to provide a detailed overview of how each of the energy storage devices work so that the reader is able to get a better feel for the potential benefits and drawbacks of each device. Second, this document is meant to serve as a compilation of the technological and economic parameters of storage devices that have been reported over the past decade. Then, taking these varied reports, provide a single page which summarizes those data in an at-a-glance comparison for those who wish to reference those parameters. All parameters reported here are to the author's knowledge the best representation of the works cited, and are meant as a guide and review.

The remainder of the document is divided up into three chapters. The next chapter discusses some basic energy storage concepts that are common to multiple technologies as well as the methodology for reporting system cost parameters. The chapter that follows provides a brief review of each energy storage system and the parameters of each. The final chapter is the summary of those parameters.

Chapter 2

Storage Technology Basics

This chapter is intended to provide background information on the operation of storage devices that share common principles. Since there are a number of conventional secondary battery technologies and flow batteries used for energy storage, those technologies will be the focus of the following discussion. The mechanisms behind other technologies will be discussed in later sections (including compressed air, pumped hydroelectric, flywheel, superconducting magnetic energy, and electrochemical capacitor storage).

2.1 A Brief Introduction to Batteries

There are so many types of batteries, it becomes difficult to differentiate between them unless there is an understanding of what goes on in a typical unit. Addressing that issue is the purpose of this chapter.

Basics of Electrochemical Cells

To begin at the beginning, the Merriam Webster Dictionary defines a battery as “a number of similar articles, items, or devices arranged, connected, or used together”. This is fitting describing batteries, since many batteries are a collection of interconnected electrochemical cells. The cells are connected in series and/or parallel combinations in order to provide a desired voltage and energy capacity for the collective battery unit. They are typically categorized as primary (non-rechargeable) and secondary (rechargeable) cells. So the key to understanding the battery is understanding how a single electrochemical cell works.

Understanding the Chemistry of Electrochemical Cells

The method by which each cell is able to convert input electrical energy into stored chemical energy, and stored chemical energy into electrical energy is through an oxidation-reduction, or redox reaction. Through oxidation and reduction, electrons are able to be transferred from one substance to another. Through oxidation electrons are lost, and through reduction electrons are gained (so when both oxidation and reduction occur, electrons leave one substance and make their way to another). This process becomes more understandable when we consider the three primary parts of an electrochemical cell: the negative electrode and positive electrode (sometimes referred to as the anode and cathode, respectively, although these descriptors change during charge and discharge)¹, and the electrolyte (the medium for electron transfer between the two electrodes. During charge and discharge externally (between the electrodes and the external circuit) electrons flow, and internally (between the electrodes within the cell) ions flow (cations and anions, or positively and negatively charged ions, respectively, and together this completes an electric circuit. The following descriptions of the cell components come from [1].

¹The use of the terms anode and cathode can sometimes lead to confusion. The flow of electrons is always from the anode to the cathode along a path outside of the cell. Within the cell anions always flow toward the anode and cations always flow towards the cathode. Therefore, during the discharge of an electrochemical cell electrons flow from the negative terminal to the positive terminal through the external load. During discharge inside the cell anions flow to the negative terminal and cations to the positive terminal. Therefore, during discharge the negative terminal is the anode (loss of electrons, so oxidation occurs), and the positive terminal is the cathode (gain of electrons, so reduction occurs). However, during charge, the opposite is true. Electrons flow from the positive terminal to the negative terminal externally, and internally anions flow to the positive terminal and cations to the negative terminal. This implies that during charge, the negative terminal acts as the cathode, and the positive terminal as the anode. However, by convention, the anode is traditionally defined as the negative electrode, and the cathode as the positive electrode. It is important to be aware of the distinction.

1. *Negative electrode*: “The reducing or fuel electrode—which gives up electrons to the external circuit and is oxidized during the electrochemical reaction.”
2. *Positive electrode*: “The oxidizing electrode—which accepts electrons from the external circuit and is reduced during the electrochemical reaction.”
3. *Electrolyte*: “The ionic conductor [this is not to be confused with an electrical conductor]—which provides the medium for transfer of electrons, as ions [charged particles—atoms or molecules], inside the cell between the anode and the cathode. The electrolyte is typically a liquid, such as water or other solvents, with dissolved salts, acids, or alkalis to impart ionic conductivity. Some batteries use solid electrolytes, which are ionic conductors at the operating temperature of the cell.” [1] There is a distinct difference between ionic conductors and electrical conductors - electrical conductors allow for the direct transfer of electrons (in the form of current), ionic conductors allow for the transfer of ions, charged atoms or molecules. If the electrolyte itself were an electrical conductor, this would lead to a short circuit between the cell electrodes, rendering the cell useless.

Charge and Discharge

The basic idea of charge and discharge is that current flows in the wire connected to a load or a power source, and inside the cell, the voltage that is applied causes charged particles to drift from one electrode during charge and discharge, and when they get to the electrode they might be able to give up and electron, or take an electron through a chemical reaction, depending on whether the unit is charging or discharging.

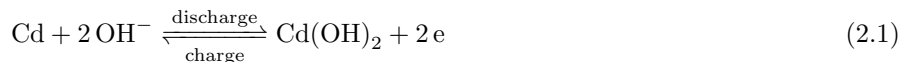
In more detail, when the cell discharges, it is connected to an external load, and electrons flow from the negative terminal through the external load to the positive terminal. Simultaneously within the cell, negatively charged anions flow toward the negative electrode and positively charged cations flow toward the positive electrode to complete the circuit. This is shown visually in the left side of Figure 2.1. Note that since the negative electrode is losing electrons, oxidation occurs at the negative electrode, and since the positive electrode is accepting electrons, reduction is occurring at the positive electrode [1]. As the positively charge cations flow toward the positive electrode, it is becoming more negatively charged since it is accepting electrons traveling from the negative electrode through the load. Since the positive electrode is becoming less positively charged, then the cell is losing energy (as would be expected during discharge).

When the cell recharges these processes are reversed electrons flow from the positive terminal, through the DC power source, to the negative terminal. Within the cell negatively charged particles flow, this time, toward the positive electrode (the anode since oxidation—loss of electrons—occurs here), and cations flow toward the negative electrode (the cathode since reduction—gaining electrons—occurs here). This is shown visually in the right side of Figure 2.1.

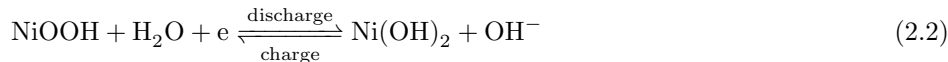
From the perspective of the circuit the anode is where electrons originate and the cathode is where the head to. Since electric current is defined as the direction opposite to that of electron flow, current always flows from the cathode to the anode.

As an example of these processes, consider the reactions in a nickel-cadmium cell. In this case, the negative electrode is composed of cadmium metal, Cd, the positive electrode is nickel hydroxide, Ni(OH)₂, and the electrolyte is typically aqueous potassium hydroxide, KOH(H₂O) [2]. The reactions that occur at the negative electrode and positive electrode during charge and discharge are shown in Equation 2.1 and Equation 2.2 [1], respectively. Notice that at the positive electrode during discharge electrons are gained through reduction (so that electrode acts as the cathode), and at the negative electrode during discharge electrons are lost through oxidation (so that electrode acts as the anode).

Reactions at the negative electrode:



Reactions at the positive electrode:



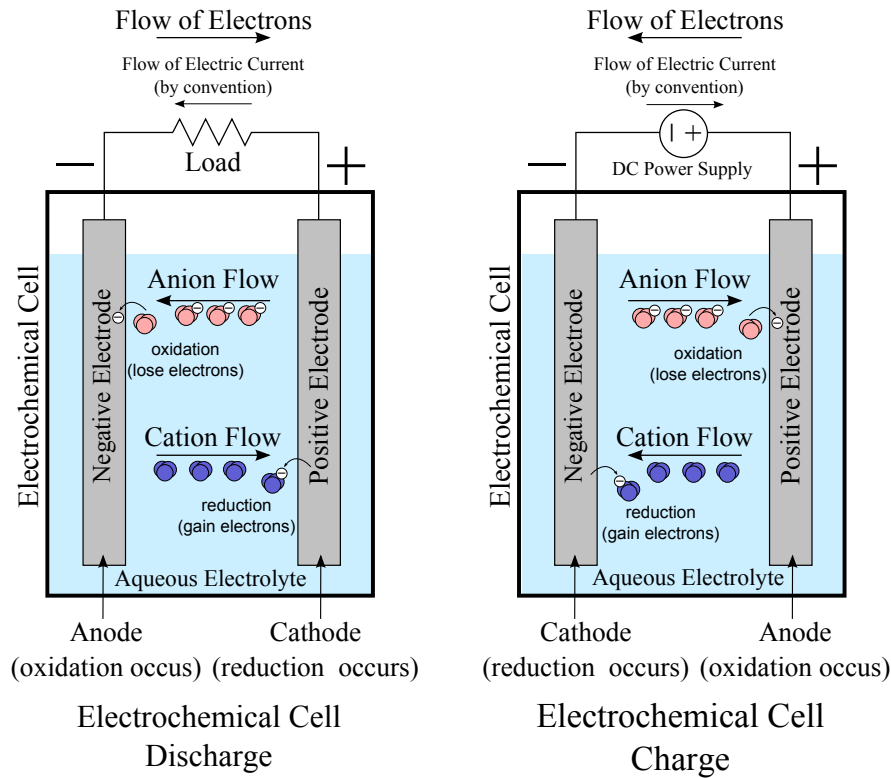
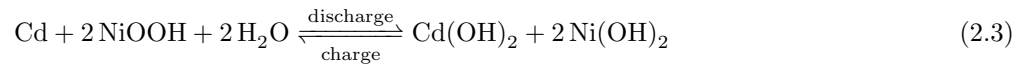


Figure 2.1: Charge and discharge of an electrochemical cell. Adapted from [1]

The net reaction during the charge and discharge process are shown in Equation 2.3.



Chemically, the result of charge and discharge is to change the composition of the cell from one set of chemical species to another, then back again, and ideally the reversibility of this reaction could go on indefinitely, however, the equations presented here are a simplification of the actual reactions that take place, and those are unique for each type of electrochemical cell. The specific degradation modes of each device will be described in later sections for each technology.

Why Do These Reactions Occur?

When an electrochemical cell sits disconnected from a load in an open circuit state (no connection between the terminals to complete the circuit) there is an electromagnetic potential energy difference (voltage) that exists between the electrode with fewer electrons (the positive terminal) and the electrode with more electrons (the negative terminal). Prompting the discharge process is the presence of a conductive path (a load) connected externally between these positive and negative terminals. By completing the circuit, the voltage results in a force applied to the electrons prompting them to flow from the negative electrode to the positive electrode (a flow of electrons being known as current, measured in Amperes), once the electron flow has begun, there is a charge imbalance that leaves the positive and negative electrodes slightly less positively and negatively charged respectively, and this chemical charge imbalance results in the flow of anions to the anode and cations to the cathode to bring the system back toward a state of chemical equilibrium. During this process the potential difference between the two electrodes decreases reflecting the loss of chemical energy stored within the cells, so during discharge energy is delivered from the cells to the load.

During charge a voltage potential is placed across the terminals such that the directions of electron flow and ion flow are reversed, and chemical energy lost during discharge may be restored from the input electrical energy which reverses the chemical reaction and is able to restore the available chemical energy.

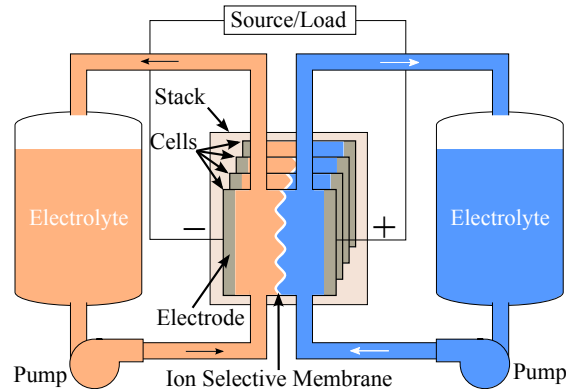


Figure 2.2: Design of a generic flow battery system

Increasing Energy and Power Capacity

The amount of energy that can be stored in an electrochemical cell of the design previously described is limited by the amount of active chemical species in the electrolyte (in the above example this refers to the amount of potassium hydroxide in the aqueous solution) that can be stored within the electrochemical cell. The power capacity of the cell is determined by the surface area of the electrodes, greater surface area means more material in the electrodes for oxidation or reduction (assuming there is enough electrolyte solution to enable the reactions). Therefore, for batteries with fixed cell sizes, the amount of energy and power capacity that each cell is capable of is limited by the amount of electrolyte in the cell, and the electrode size. Since most of these system are of a set size, it's not usually possible to add more electrolyte or to increase the plate size.

Batteries (formed by interconnected cells) can be, themselves, interconnected in series and/or in parallel to increase the power and energy capacity. Series connections increase the energy capacity of the system, while parallel connections increase the energy capacity of the system. Although this is typically done in large-scale battery systems, this does add complexity to the overall system design, and opens the door to more potential points of system failure. There are electrochemical cell designs that do not have this particular design limitation, and they are referred to as flow batteries.

Flow Batteries

This design is sometimes referred to as regenerative fuel cells or redox flow systems [3]. The major difference in the design of flow batteries and that of traditional batteries is that the electrolyte is stored in separate storage tanks and pumped through the electrode compartments (a collection of multiple cells known as the stack) [4]. This means that the energy capacity of this design can be easily increased by simply increasing the amount of electrolyte in the tanks and/or the concentration of that electrolyte. The power capacity can be scaled up by increasing the number of cells in the stack. As opposed to traditional battery designs requiring a large number of series/parallel connections of individual units to get the desired energy and power capacity (a process which presents much greater challenges for scaling-up power and energy capacity), flow battery power and energy capacity are independent and a single system can be designed to meet many specifications [3].

There are a few other differences between flow batteries and conventional designs. Typically, flow batteries have two sets of electrolytes pumped through separate loops, one that flows past the positive electrode and one that flows past the negative electrode. Within the cells, these electrolytes are separated by a microporous separator or an ion conducting membrane [4]. Each of these features can be seen in Figure 2.1. In later sections vanadium redox batteries, polysulfide-bromide batteries, and zinc-bromine batteries will be described, and these are three flow battery designs.

Other Advanced Rechargeable Batteries

Flow batteries are one of three categories identified by [1] as “advanced rechargeable batteries”. The other categories are high-temperature systems, with examples being sodium sulfur and sodium nickel chloride batteries, and lithium systems, with lithium-ion batteries one example. Each of those examples is addressed in greater detail later in the sections that follow.

2.2 Cost Breakdown

In this report, costs for each technology are presented in a common framework such that for any technology, given the desired power and energy requirements of the system, one can estimate the range of total system costs. This methodology has been presented in numerous studies from Sandia National Laboratory, EPRI-DOE, and other organizations studies [2, 3, 5, 6].

Cost Breakdown

System costs are based on many factors and vary widely from system to system. In order to present costs in a systematic fashion, they can be divided into 5 categories:

1. *Energy Storage System Costs* This is the overnight capital cost of the storage device itself, and is typically given in two parts: Power Capacity Cost [\$/kW] and Energy Capacity Cost [\$/kWh]. By dividing the cost this way, there is an inherent assumption that the energy capacity and power capacity are independent, which is not true for all systems. By way of example, this assumption is true for flow batteries and pumped hydroelectric storage, but not true for traditional secondary batteries and flywheels. However, since most systems can be scaled up by interconnecting multiple units in series/parallel combinations, it will be assumed that this methodology correctly approximates the system costs.
2. *Power Conversion System Costs (PCS)* [\$/kW]: This category consists of all components between the storage device and the utility grid including power conditioning equipment, control systems, power lines, transformers, system isolation equipment, and safety sensors.
3. *Balance of Plant Costs (BOP)* [\$/kW]: This category encompasses construction costs and engineering, land, access routes, taxes, permits, and fees.
4. *Operation and Maintenance (OM) Fixed Costs* [\$/kW-yr]: This is an annual costs for the routine maintenance required to keep the system operational. The units for this cost are dollars per kW of installed capacity, per years of operation (so Fixed OM costs of 5\$/kW-yr for a 1kW system would cost \$5 per year).
5. *Operation and Maintenance (OM) Variable Costs* [\$/kWh-delivered]: This is a cost based on the amount of energy delivered by the device that accounts for any costs incurred based on system usage. These costs are typically extremely low for energy storage systems and therefore are assumed to be significantly less than all other costs, and therefore ignored.

It should be noted, that some of the sources of system parameters used in this document [2, 3, 5–7] may have slightly different definitions of which category each component fits in (for example do the transformers fit under PCS or BOP).

Computing the Total System Cost

First the above terms and a few parameters are assigned symbols.

System Costs	
C_{PC}	Power capacity cost [\$/kW]
C_{EC}	Energy capacity cost [\$/kWh]
C_{PCS}	Power conversion system costs (PCS) [\$/kW]
C_{BOP}	Balance of plant costs [\$/kW]
C_{OM}	Operations and maintenance fixed cost [\$/kW-yr]
C_{cap}	Overnight capital cost [\$]
C_{tom}	Total lifetime O&M cost [\$]
C_{tot}	Total system cost [\$]
System Parameters	
P_{max}	Power capacity of the system [kW]
E_{max}	Energy capacity of the system [kWh]
N	Years of operation [years]
r	Discount rate

To compute the total overnight capital cost of the system, multiply the power capacity of the system by the sum of the BOP, PCS, and power capacity costs, then add to it the product of the energy capacity of the system and the energy capacity cost, as shown in Equation 2.4.

$$C_{cap} = P_{max}(C_{BOP} + C_{PCS} + C_{pc}) + E_{max}C_{ec} \quad (2.4)$$

Then the OM costs can be determined by multiplying the OM fixed cost by the power capacity of the system to get an annual OM cost. Adjust this value future O&M costs based on the assumed discount rate over the lifetime of the device to determine the total lifetime OM cost. In this case, summing over the lifetime is equivalent to computing a partial geometric series, which leads to Equation 2.5.

$$C_{tom} = C_{OM}P_{max} \left[\frac{1 - (1 - r)^N}{1 - (1 - r)} \right] \quad (2.5)$$

Lastly, the total lifetime cost of the energy storage system is found by summing the capital cost and lifetime O&M cost together to get the total system cost, shown in Equation 2.6.

$$C_{tot} = C_{occ} + C_{tom} \quad (2.6)$$

Comments on Sources for Costs

Five sources were drawn upon for the collection of cost parameters presented in this report [2,3,5–7], each of which had slightly different methodologies. The collection of parameters presented here is meant as a review of the most relevant studies involving the economic and technological parameters for energy storage systems today, and not as a definitive source in itself. However, care was taken to present the parameters from each source as accurately as possible. To that end, all costs are inflation adjusted to 2010 US dollars. Cost, of course is not always the sole barrier to a technologies implementation, there are often policy-related issues—for more on that subject refer to [8].

Chapter 3

Energy Storage Technologies

This report focuses on the technologies that have either already demonstrated their technological maturity and usefulness, or may be poised to do so in the near future. There are, in fact, a number of technologies that were deliberately not included in this report due to their current round-trip inefficiency (at most 50-60% [7]), which include fuel cells, metal-air batteries, and thermal energy storage).

There are a number of excellent reports that exist providing overviews of the technologies presented here from varying perspectives, including [2, 3, 5, 7, 9], all of which were drawn upon to compile this report.

In the following section, a number of technologies are discussed, organized according to the form of energy that is stored:

Mechanical Energy Storage

- PUMPED HYDROELECTRIC STORAGE: Potential energy of water at different elevations, *Section 3.1*.
- COMPRESSED AIR ENERGY STORAGE: Kinetic energy stored in compressed air, *Section 3.2*.
- FLYWHEEL ENERGY STORAGE: Kinetic energy stored in a rotating disk, *Section 3.3*.

Electrical Energy Storage

- ELECTROCHEMICAL CAPACITORS (SUPERCAPACITORS): Electrostatic energy stored in an electric field (electrostatic energy), *Section 3.4*.
- SUPERCONDUCTING MAGNETIC ENERGY STORAGE: Energy stored in a magnetic field (magnetic energy), *Section 3.5*.

Chemical Energy Storage

- LEAD ACID BATTERIES: Conventional secondary battery, *Section 3.6*.
- NICKEL-ELECTRODE BATTERIES: Conventional secondary battery, *Section 3.7*.
- LITHIUM-ION BATTERIES: Secondary battery, *Section 3.8*.
- SODIUM-SULFUR BATTERIES: Molten salt battery, *Section 3.9*.
- SODIUM NICKEL CHLORIDE BATTERIES (ZEBRA): Molten salt battery, *Section 3.10*.
- ZINC-BROMINE BATTERIES: Flow battery, *Section 3.11*.
- POLYSULFIDE-BROMIDE BATTERIES: Flow battery, *Section 3.12*.
- VANADIUM REDOX BATTERIES: Flow battery, *Section 3.13*.

3.1 Pumped Hydroelectric Storage

The oldest (1929) and most prominent energy storage technology to date has been pumped hydroelectric storage of which there are 20.36 GW of installed capacity in the United States alone [10] across 39 sites with capacities ranging from 50 MW to 2,100 MW [11]. Its simplicity of design, relatively low cost, and similarity in operation to hydroelectric power has made it the industry standard for storage for a century. These systems can quickly ramp up to full load: 10 seconds if the turbine spinning, and 1 minute from standstill [9]. However, they require very specific geographic features that limit unit siting. These systems have high capital cost but very low maintenance costs, and also face criticism due to their significant impact on local wildlife and ecosystems. New designs, however, may be opening the door for additional siting opportunities in the near future.

How it Works As shown in Figure 3.1, PHS consists of two reservoirs with a height differential and a pipe (or penstock) connecting them. To store energy, electricity turns a motor which pumps water from the lower reservoir, up the pipe, to the upper reservoir. To produce energy, water is allowed to flow from the upper reservoir down the pipe through a turbine and into the lower reservoir. The turbine is connected to a generator and as the turbine turns so does the generator, producing electricity. Today, the motor and generator are typically one in the same, since a motor can also act as a generator (in one case it is turned and electricity is produced, in the other electricity is sent in, causing it to turn).

There are two factors that control the power and energy rating of the system: the height difference between the reservoirs (known as the “head”, and the volume of the reservoirs (the “flow”) [9]. The larger the volume of water available and the greater the height, the more energy can be stored. The greater the flow rate through the pipes, the more power can be produced. This comes from the basic physical principle that potential energy due to gravity is proportional to mass times height, with the constant of proportionality being acceleration due to gravity: $E = mgh$. Since power is the time rate of energy, or the derivative of energy, and since gravity and height are constant with time, power can be defined as: $P = \frac{dE}{dt} = \frac{dm}{dt} gh$. So to increase the energy capacity of the system, increase the volume of water and height differential, to increase the power capacity increase the flow rate of water and height differential.

Siting these facilities is complicated in that they require two large reservoirs to be present in close proximity, one higher than the other (and the greater the height differential the better). This type of geologic occurrence is more prevalent in mountainous regions, but in such regions it’s difficult to build these systems, and is typically further from connections to the power grid [9]. If the distance is too great between sites then the connection between the two sites will have to be longer, and likely at a smaller angle (if the reservoirs were side-by-side, the penstock would be nearly vertical) and this would mean more friction between the water and the pipe, losing energy.

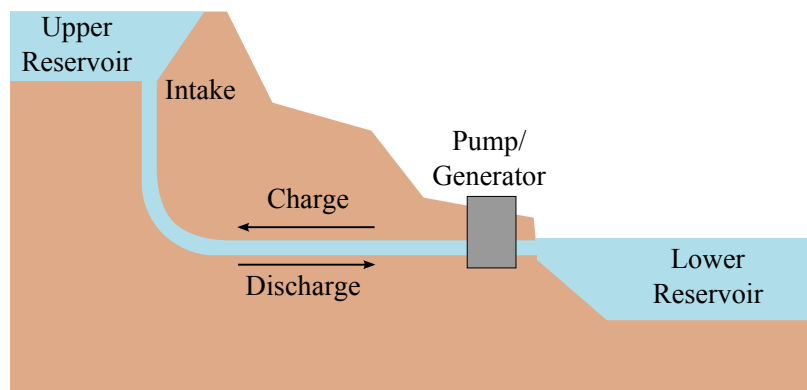


Figure 3.1: Overview of Pumped Hydroelectric Storage (adapted from [7])

Variations A few design alternatives have been proposed:

- **UNDERGROUND PUMPED HYDROELECTRIC STORAGE** In this design the lower reservoir is constructed by excavating rock as far as 300 m underground [9]. The generator/motor is placed in the excavated region underground, and water is pumped from the underground reservoir to the above-ground reservoir. This

design allow for the water to flow vertically, minimizing losses due to friction. The environmental impact of this design on the surface is less because it only requires one reservoir that affects the surface [12]. This design requires specific geographic and geologic structures to be in place for this to be viable at a given site.

- **PUMPED SEAWATER HYDROELECTRIC STORAGE** In this design the lower reservoir is the sea, the rest of the design remains unchanged. One benefit is that this can be implemented in many more locations than other designs since there is so much coastline available. At the same time the use of seawater may lead to corrosion of the equipment, and adding seawater to the upper reservoir may negatively effect the upper reservoir's ecology [9].

System Design Considerations The efficiency of these systems are typically limited most by the efficiency of the pump and turbine [3], although the friction of the water in pipes is another factor. Some of the water will be lost due to evaporation, and this may be considered self-discharge, but similarly, rainfall will help to offset this effect.

Operation & Maintenance The O&M required for this system would be minimal, as these designs are well-understood and have been around for many years. Routine maintenance of the generator and turbine, and cleaning the penstock if required would be expected tasks.

Environmental Impact These systems have significant impacts on the local wildlife, especially if one or both of the reservoirs needs to be constructed. Also, the fluctuating water levels can significantly disrupt the inhabitants of the reservoirs.

Other Resources A number of overviews of this technology exist including [9].

Summary of Device Parameters The following table summarizes the available technoeconomic parameters for PHS from a number of studies from 2000-2010. All monetary values have been adjusted to 2010 dollars. If a value is marked with “-” either the quantity was not found in the corresponding report or the way it was presented was inconsistent with the format used here. For example, the EPRI-DOE report gives total cost in \$/kW or \$/kWh, not a formulation that takes into account both, simultaneously.

	Source:	Schoenung 2003 [5]	EPRI 2003 [2]	Gonzalez 2004 [3]	Schoenung 2008 [6]	Chen 2009 [7]
Techno. Params.	Roundtrip Efficiency [%]	75-78	-	70-85	-	72-85
	Self-discharge [%Energy per day]	-	-	-	-	very small
	Cycle Lifetime [cycles]	-	-	-	-	-
	Expected Lifetime [Years]	n/a	-	30	-	40-60
	Specific Energy [Wh/kg]	-	-	-	-	0.5-1.5
	Specific Power [W/kg]	-	-	-	-	-
	Energy Density [Wh/L]	-	-	-	-	0.5-1.5
	Power Density [W/L]	-	-	-	-	-
Costs	Power Cost [\$/kW]	1190-1250	-	690	-	600-2000
	Energy Cost [\$/kWh]	12	-	0-23	-	5-100
	PCS Cost [\$/kW]	n/a	-	270-580	-	-
	BOP Cost [\$/kW]	4.8	-	included	-	-
	O&M Fixed Cost [\$/kW-y]	3.0	-	4.4	-	-

3.2 Compressed Air Energy Storage (CAES)

In compressed air energy storage systems, off-peak grid power is used pump air underground until it reaches a high pressure. It remains underground in a geologic formation until energy is needed, then it is released and heated, and passing through and turning a turbine, which generates power. CAES systems are essentially high-efficiency combustion turbine plants. In a standard gas turbine, air is compressed, mixed with fuel and combusted. That fluid is then passed through a turbine, which spins a generator producing energy and simultaneously provides the energy for compressing the air. Two-thirds of the energy provided by the fuel goes into compressing the air. So, in CAES systems, the air is already compressed, and therefore uses significantly less fuel. Because of their similarity to standard combustion turbine systems, they are easily integrable into existing power networks. With a ramp rate similar and slightly faster than traditional gas plants, these systems are ideal for meeting peak load.

How it Works The storage process begins as air is passed through a compressor. The motor for the compressor can be either a separate device or the generator operating as a motor (with clutches to switch from the compression train or the turbine train). The compression itself typically takes place through a number of stages to complete the pressurization. Cooling the air occurs between each stage (intercoolers) as well as after the compression (aftercooler), which reduces the volume of the gas to be stored and removes the heat generated during the compression (further reducing the volume of the air [9]).

Once the air is compressed and stored, it may be released when needed to produce power. During discharge, the air is mixed with fuel (such as gas, oil, or hydrogen) and combusted, and is then passed through the turbine stages, at which point the air expands, releasing energy, causing the turbine to spin and thereby driving the generator to produce electricity. Often the hot air from the turbine is then passed through a recuperator to exchange the heat with the compressed air just out of storage. This is shown schematically in Figure 3.2.

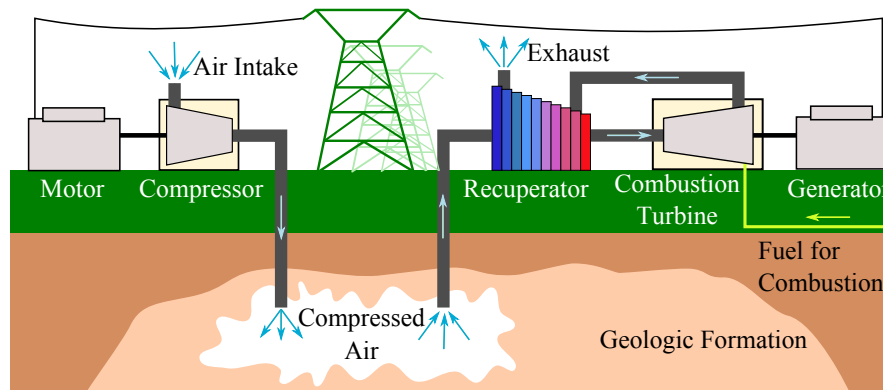


Figure 3.2: Overview of Compressed Air Energy Storage (adapted from [7])

The storage for the air can be in a geologic formation (such as salt caverns from mining, impervious rock formations, porous rock aquifers, or depleted oil or gas wells) and it is estimated that more than 80% of the US has suitable formations for this type of storage [2]. An alternative is in above-ground containers such as series of pipes.

Variations There are two major designs that are considered for this system at present:

- **DIABATIC CAES CYCLE** This is the design described above, and the only variation that has been implemented commercially so far. In this case, the heat that is generated during compression is dissipated into the atmosphere, and upon expansion, the compressed air must be reheated, typically with natural gas. The dissipation of heat and use of fuel to reheat the air upon compression result in overall losses of efficiency, but this design is simpler to implement than adiabatic CAES.
- **ADIABATIC CAES CYCLE** In this design, the heat that is created during compression is stored and used to reheat the air during decompression, reducing, or theoretically eliminating, the need for fuel consumption.
- **HYBRID PLANT** This variation is a system which can operate as both a traditional natural gas plant and a CAES plant. For this design the compressed air would be used to increase the output during peak hours [2], and otherwise, it would function as a traditional gas plant.

System Design Considerations A feature of this system is that the heat rate at maximum load is 2 to 3 times less than a comparable combustion turbine plant [2].

Operation These systems startup within 5-12 minutes with a ramp rate of 30% of maximum load per minute [2].

Maintenance The maintenance requirements are similar to that of a standard combustion turbine natural gas plant of a similar size.

Environmental Impact Since this technology produces emissions from combustion, there is an environmental concern especially compared to emissions-free devices. However, the level of NO_x produced is below 5ppm [2].

Other Resources Summaries of this technology can be found in [2,7,9], with a more detailed treatment in [13].

Summary of Device Parameters The following table summarizes the available technoeconomic parameters for compressed air energy storage systems from a number of studies from 2000-2010. All monetary values have been adjusted to 2010 dollars. If a value is marked with “-” either the quantity was not found in the corresponding report or the way it was presented was inconsistent with the format used here. For example, the EPRI-DOE report gives total cost in \$/kW or \$/kWh, not a formulation that takes into account both, simultaneously.

	Source:	Schoenung 2003 [5]	EPRI 2003 [2]	Gonzalez 2004 [3]	Schoenung 2008 [6]	Chen 2009 [7]
Techno. Params.	Roundtrip Efficiency [%]	73-79	65-85	57-64	-	70-80
	Self-discharge [%Energy per day]	0	n/a	-	-	small
	Cycle Lifetime [cycles]	-	-	-	-	-
	Expected Lifetime [Years]	n/a	30	30	-	20-40
	Specific Energy [Wh/kg]	-	-	-	-	30-60
	Specific Power [W/kg]	-	-	-	-	-
	Energy Density [Wh/L]	-	-	-	-	3-6
	Power Density [W/L]	-	-	-	-	0.5-2
Costs	Power Cost [\$/kW]	510-650	-	490-600	550	400-800
	Energy Cost [\$/kWh]	3.6-140	-	3.5-58	120	2-50
	PCS Cost [\$/kW]	n/a	n/a	270-580	-	-
	BOP Cost [\$/kW]	60	190	46-58	50	-
	O&M Fixed Cost [\$/kW-y]	3.0-12	23-29	1.6-4.3	-	-

3.3 Flywheel Energy Storage

Flywheels have been in existence for centuries, however, over the past few decades they have been considered as forms of bulk energy storage. A simple form of kinetic energy storage, these systems are extremely rapid in their response time and, with recent developments in bearing design, have been able to achieve high efficiencies for short durations of storage. Their disadvantages are that they have a high rate of self discharge due to frictional losses, and their relatively high initial costs.

How it Works Flywheels store energy in rotating discs as kinetic energy in the form of angular momentum. To “charge” this device, energy is used to power a motor which spins the disc, and the disc remains spinning until the energy is needed. At that point the disc is allowed to turn a generator, which produces electricity. The speed of the flywheel increases during charge (adding energy) and decreases during discharge (losing energy).

There are a few important aspects to flywheel design, one being the bearings. The bearings hold the shaft that connects the device to the motor and generator in place while allowing for rotation. Even the best of mechanical bearings create friction, and that friction results in a loss of energy as the flywheel spins. Magnetic bearings have begun to replace mechanical bearings on a number of systems, significantly reducing or eliminating the frictional losses, and therefore the self-discharge.

To determine how much energy a particular device may hold, refer to the equation for the kinetic energy of a spinning mass: $E = \frac{1}{2}I\omega^2$, where I is the moment of inertia and for a solid rotating disc is defined as $I = \frac{1}{2}mr^2$ (m is mass of the disc, and r is the radius of the disc), and ω is the rotational velocity. For a solid rotating disc the above equation becomes: $E = \frac{1}{4}m(r\omega)^2$. This implies that by increasing the maximum speed of the disc the energy capacity is more greatly increased than by increasing the mass of the disc [2].

Variations These devices are categorized into low-speed and high speed designs.

- **LOW SPEED** Most low-speed designs are 10,000 rpm or less, and are typically made of extremely heavy steel discs. The shaft is either vertical or horizontal, and may have mechanical or magnetic bearings.
- **HIGH SPEED** High-speed designs operate above 10,000 rpm, some upwards of 100,000 rpm. Because of the speeds, and associated fatigue failure risks, stronger materials are required, including composites of graphite or fiberglass and therefore also require magnetic bearings and a vertical shaft [2].

System Design Considerations Since flywheels will not necessarily be turning at the correct speed to allow the generator to produce a 60Hz waveform, the output must be processed to resolve this issue. Typically a flywheel will decrease in speed as it is discharging energy, and so to account for this, the AC power out of the generator is typically converted to DC then back from DC to a 60 Hz AC waveform through the use of power electronics, ensuring a consistent output waveform without requiring the flywheel to always be spinning at the right speed.

Another design consideration is that a source of loss is the fluid that the device rotates in. If the rotor is surrounded by air, or another highly viscous fluid, that will be an additional source of friction. Many times the system is enclosed in a vacuum to further reduce such frictional losses.

Lastly, in sizing a system, power and energy capacity can be treated as essentially independent. Power capacity is determined by the power conversion system, and the motor and generator, while the energy capacity is determined by the flywheel mass and speed. Many flywheels are designed to provide high power output for short periods, on the order of 5 to 50 seconds [2].

Operation & Maintenance The component that requires the most maintenance would be the bearings. Typically magnetic bearings are complex systems requiring some care to operate and maintain. Since these devices have hazardous failure modes inspecting these devices for signs of fatigue is critical for preventing catastrophic failure.

Environmental Impact There are little to no negative environmental impacts for flywheels since the materials are benign and are rather compact.

Other Resources Additional sources on flywheels include [2, 9, 14], with a more detailed treatment in [15].

Summary of Device Parameters The following tables summarize the available technoeconomic parameters for flywheel energy storage devices (first low-speed, then high-speed) from a number of studies from 2000-2010. All monetary values have been adjusted to 2010 dollars. If a value is marked with “-” either the quantity was not found in the corresponding report or the way it was presented was inconsistent with the format used here. For example, the EPRI-DOE report gives total cost in \$/kW or \$/kWh, not a formulation that takes into account both, simultaneously.

Low-speed Flywheels						
	Source:	Schoenung 2003 [5]	EPRI 2003 [2]*	Gonzalez 2004 [3]	Schoenung 2008 [6]	Chen 2009 [7]*
Techno. Params.	Roundtrip Efficiency [%]	90	70-80	86	-	90-95
	Self-discharge [%Energy per day]	-	-	-	-	100
	Cycle Lifetime [cycles]	-	100k+	-	-	20k+
	Expected Lifetime [Years]	n/a	n/a	20	-	15
	Specific Energy [Wh/kg]	-	-	-	-	10-30
	Specific Power [W/kg]	-	-	-	-	400-1500
	Energy Density [Wh/L]	-	-	-	-	20-80
	Power Density [W/L]	-	-	-	-	1k-2k
Costs	Power Cost [\$ /kW]	360	-	350	280	250-350
	Energy Cost [\$ /kWh]	60k	-	230-345	380	1k-5k
	PCS Cost [\$ /kW]	110-600	180	270-580	-	-
	BOP Cost [\$ /kW]	-	120	92	0	-
	O&M Fixed Cost [\$ /kW-y]	6.0	22	-	-	-
High-speed Flywheels						
	Source:	Schoenung 2003 [5]	EPRI 2003 [2]*	Gonzalez 2004 [3]	Schoenung 2008 [6]	Chen 2009 [7]*
Techno. Params.	Roundtrip Efficiency [%]	95	70-80	88	-	90-95
	Self-discharge [%Energy per day]	1.25	-	-	-	100
	Cycle Lifetime [cycles]	-	100k+	-	-	20k+
	Expected Lifetime [Years]	16+	n/a	20	-	15
	Specific Energy [Wh/kg]	-	-	-	-	10-30
	Specific Power [W/kg]	-	-	-	-	400-1500
	Energy Density [Wh/L]	-	-	-	-	20-80
	Power Density [W/L]	-	-	-	-	1k-2k
Costs	Power Cost [\$ /kW]	360-400	-	400	300	250-350
	Energy Cost [\$ /kWh]	1.2k-150k	-	580-29k	1k	1k-5k
	PCS Cost [\$ /kW]	110-600	180	270-580	-	-
	BOP Cost [\$ /kW]	0	120	1.2k	0	-
	O&M Fixed Cost [\$ /kW-y]	6.0	22	8.6	-	-

* Denotes that these values were presented in general for flywheels, not specifically low or high speed, so they are included in both tables.

3.4 Electrochemical Capacitors (aka Supercapacitors)

The most confusing part of this technology may be its name, because in different publications it has gone by many names, including: supercapacitor, ultracapacitor, pseudocapacitor, electric double-layer capacitor (EDLC), and gold capacitor. These devices are the descendant of the conventional capacitor (electrostatic or electrolytic), but with the capability to hold orders-of-magnitude more energy (although still less than conventional batteries per volume). Traditional capacitors were typically not considered for large-scale energy storage because of how little energy they could store. Electrochemical capacitors are capable of storing larger quantities of energy in devices that are similar in size to traditional capacitors.

How it Works As electrochemical capacitors are a type of capacitor, first an overview of capacitors is called for. **CONVENTIONAL ELECTROSTATIC CAPACITORS** This is the simplest form of capacitor, and works by storing energy in an electric field. Two plates (electrodes) are placed very close together, but not touching, with either air or other non-conductive material (known as a dielectric) in between the plates. A power source is then connected across the plates which places a voltage across the plates, with one side being positively charged and the other negatively charged. Electrons migrate away from the positively charged plate to the negatively charged plate due to the applied voltage. So, when the power source is removed, there are more electrons on one plate than the other (this is a buildup of charge). But now that the power source is gone, which had caused the electrons to move, now the electrons on the negative plate want to make their way to the positive plate to equalize the charge. This desire of the electron to equalize the charge is their potential to do work, or the stored energy (stored in the electric field).

The amount of energy stored in a capacitor is determined by the voltage applied to the capacitor, V , and the capacitance of the device, C , through the relationship $E = \frac{1}{2}CV^2$. The capacitance is dependent on how the device is designed and is higher when the plates are larger (more surface area for the electrons to collect on), when the plates are closer together, and when the material in between the plates have a higher dielectric constant (which means the material is better for supporting an electric field). So the capacitance is defined as $C = \epsilon \frac{A}{d}$ (where ϵ is the dielectric constant, A is the area of the plates, and d is the distance between the plates).

ELECTROLYTIC CAPACITORS These devices operate essentially the same way as the electrostatic capacitor, except they use an electrolyte as one of the two plates, which means a larger capacitance per unit volume. **ELECTROCHEMICAL CAPACITORS** The design of “supercapacitors” is essentially a hybrid between batteries and capacitors. They have two electrode plates and an electrolyte in between (like batteries) and when a power source is connected, ions make their way to the electrodes with opposite charges due to the electric field (since oppositely charged objects attract). The difference is that a chemical reaction does not occur, merely the ions migrate; so the storage mechanism is still the electric field. Figure 3.4 shows the this idea through the stages of charge. Therefore, unlike batteries that would wear out after being cycled due to numerous chemical reactions, the lifetime of these devices is not significantly impacted by cycling. Also, the electrodes are often made of carbon nanotubes, which, under a microscope, appear as masses of tangled string. This significantly increases the surface area of the electrodes, increasing the storage capacity of these devices significantly. In some devices, every square centimeter of electrode consists of one to two thousand square meters of surface area [2] - this significantly increase the capacitance, and thus energy storage capacity of the device over conventional capacitors.

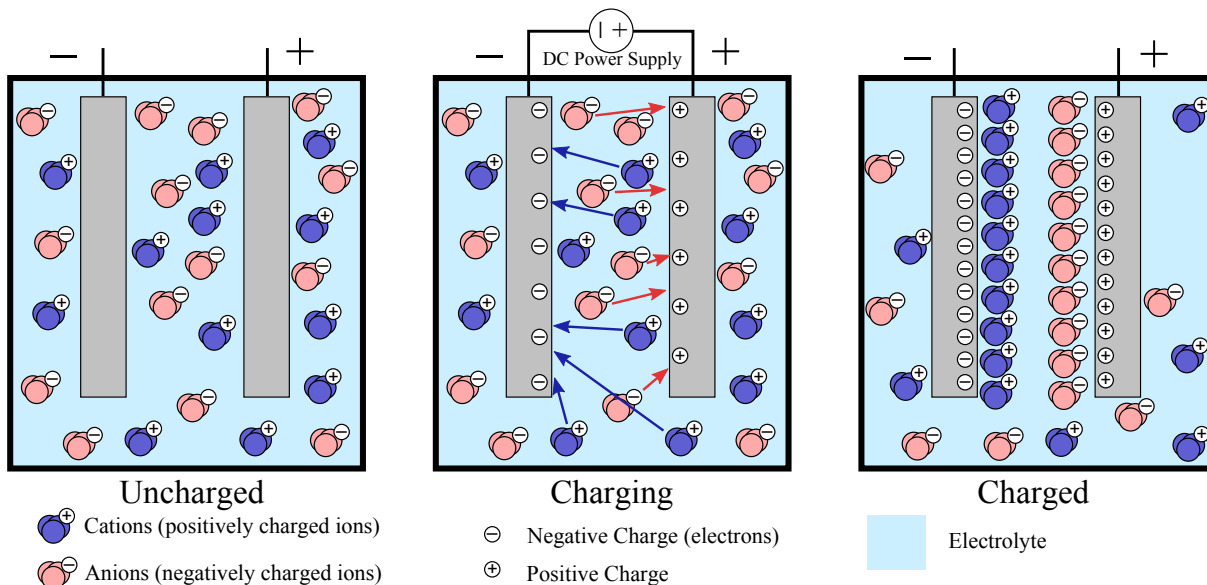


Figure 3.3: Stages of charge in an electrochemical capacitor

Variations There are symmetric and asymmetric designs, referring to the similarity of the two electrodes, and aqueous and organic electrodes [2]. These lead to four potential configurations, the where the differences between the performance of each is nuanced, so this is just mentioned for the interested reader.

System Design Considerations Due lower single-cell voltages of about 6 Volts, hundreds of these cells have to be connected in series to achieve higher voltages. This can be a serious problem for larger system designs, since the typical failure mode for a cell is an open circuit. If a single device fails then the entire system may fail. This presents a reliability risk to be factored into the design of the system.

Another consideration is due to potential damage due to placing a higher-than-rated voltage across a cell, since, unlike batteries, electrochemical capacitors cannot deal with gassing or the drying-up of electrolyte from electrolysis. To keep the voltages within safe operating limitations, resistors or Zener diodes may be connected in parallel and/or the voltage and state-of-charge of each device can be monitored and charged or discharged individually [2].

Operation & Maintenance One of the biggest advantages of electrochemical capacitors over batteries is the ability to charge and discharge more quickly (since there is no waiting for a chemical reaction to occur). And can practically be charged at any rate as long as the system stays within its designed temperature range, which is -55°C to 85°C.

Environmental Impact There are little to no negative environmental impacts of these devices.

Other Resources Overviews of electrochemical capacitors include [2, 9, 14], and in more detail [16].

Summary of Device Parameters The following table summarizes the available technoeconomic parameters for electrochemical capacitors (EDLC parameters presented here) from a number of studies from 2000-2010. All monetary values have been adjusted to 2010 dollars.

Electrochemical Capacitors						
	Source:	Schoenung 2003 [5]	EPRI 2003 [2]	Gonzalez 2004 [3]	Schoenung 2008 [6]	Chen 2009 [7]
Techno. Params.	Roundtrip Efficiency [%]	95	-	90	-	90-98
	Self-discharge [%Energy per day]	-	-	-	-	20-40
	Cycle Lifetime [cycles]	-	-	10k	-	100k+
	Expected Lifetime [Years]	n/a	-	-	-	20+
	Specific Energy [Wh/kg]	-	-	-	-	2.5-15
	Specific Power [W/kg]	-	-	-	-	500-5k
	Energy Density [Wh/L]	-	-	-	-	-
	Power Density [W/L]	-	-	-	-	100k+
Costs	Power Cost [\$/kW]	360	-	350	350	100-300
	Energy Cost [\$/kWh]	36k	-	94k	500	300-2k
	PCS Cost [\$/kW]	-	180	270-580	-	-
	BOP Cost [\$/kW]	-	120	12k	50	-
	O&M Fixed Cost [\$/kW-y]	6.0	14-16	6.4	-	-

Electrostatic or Electrolytic Capacitors		
	Source:	Chen 2009 [7]
Techno. Params.	Roundtrip Efficiency [%]	60-70
	Self-discharge [%Energy per day]	40
	Cycle Lifetime [cycles]	50k+
	Expected Lifetime [Years]	5
	Specific Energy [Wh/kg]	0.05-5
	Specific Power [W/kg]	100k
	Energy Density [Wh/L]	2-10
	Power Density [W/L]	100k
Costs	Power Cost [\$/kW]	200-400
	Energy Cost [\$/kWh]	500-1000
	PCS Cost [\$/kW]	180-580*
	BOP Cost [\$/kW]	50-12k*
	O&M Fixed Cost [\$/kW-y]	6-16*

* Since there are were no PCS, BOP, or O&M costs given for capacitors, these values were assumed based on the corresponding value ranges for electrochemical capacitors from [2, 3, 5, 6].

3.5 Superconducting Magnetic Energy Storage (SMES)

As one of the most futuristic storage devices, this is the only energy storage technology that stores flowing electric current, this flowing current generates a magnetic field in which the energy is stored. These devices are extremely efficient, fast-responding, scalable to large sizes, and environmentally benign, however, costly. They store electrical energy directly in a magnetic field with essentially no losses due to superconducting coils, aside from parasitic losses to keep the coil cool.

How it Works Direct current that is carries through superconducting material experience no resistive loss. The electric current that flows in the coil induces a magnetic field in which the energy is stored. The current continues to loop around the coil indefinitely until it is needed and is discharged. However, there is a price for the superconducting property, and it is that the superconducting coil must be super-cooled to very low temperatures, some in the range of 50-77K [9], others such as alloys of niobium and titanium around 4.5K [2]. These devices requires a cryogenic cooling system using liquid nitrogen or helium, and this system presents, in itself, a parasitic energy loss.

The amount of energy these devices store depends on both the size of the coil and its geometry (which determines the inductance, L , of the coil). Since a coil is an inductor, it follows physical principles that it stores energy based on the square of the current, I , so $E = \frac{1}{2}LI^2$. The amount of current flowing in the coil can be incredibly large. At a magnetic flux density (measure of the strength of the magnetic field) of 5 Tesla, practical superconductors can carry currents of 300,000A/cm² [2].

Variations The major design variations are in the power and energy capacity of the unit and the geometry of the superconducting coil, none of which deviate by much from the functionality described above. Sometimes smaller capacity SMES systems (less than 0.1 MWh [14]) are referred to as micro-SMES.

System Design Considerations These systems are primarily stand-alone units, and the biggest considerations are the PCS systems, which need to convert the incoming AC to DC for storage in the device then back to AC on discharge. The PCS efficiency is often one of the greatest sources of loss in these systems because of how efficient the superconducting coils are. There are also losses due to the cooling system for the coil, which leads to a potentially significant rate of self-discharge even though the overall efficiency of the coil is almost 100%.

Operation & Maintenance The primary focus of O&M would be on ensuring that the cryogenic cooling system is functioning properly and that the PCS is in operating order.

Environmental Impact The one concern with these systems is the potential effects of large magnetic fields, as there is some uncertainty as to the effects of non-ionizing radiation on human physiology. Aside from that, there are little to no negative environmental impacts of these devices, since the components are nontoxic, and there are no chemical reactions. Also the footprint of this device is rather small, so the ecological impact is negligible.

Other Resources Other resources for SMES include [17] and [18], with higher-level system overviews presented in [2, 9, 14].

Summary of Device Parameters The following table summarizes the available technoeconomic parameters for SMES systems from a number of studies from 2000-2010. All monetary values have been adjusted to 2010 dollars. If a value is marked with “-” either the quantity was not found in the corresponding report or the way it was presented was inconsistent with the format used here. For example, the EPRI-DOE report gives total cost in \$/kW or \$/kWh, not a formulation that takes into account both, simultaneously.

	Source:	Schoenung 2003 [5]	EPRI 2003 [2]	Gonzalez 2004 [3]	Schoenung 2008 [6]	Chen 2009 [7]
Techno. Params.	Roundtrip Efficiency [%]	90-95	90-95	90	-	95-98
	Self-discharge [%Energy per day]	-	n/a	-	-	10-15
	Cycle Lifetime [cycles]	-	-	-	-	100k+
	Expected Lifetime [Years]	n/a	-	30	-	20+
	Specific Energy [Wh/kg]	-	-	-	-	0.5-5
	Specific Power [W/kg]	-	-	-	-	500-2k
	Energy Density [Wh/L]	-	-	-	-	0.2-2.5
	Power Density [W/L]	-	-	-	-	1k-4k
Costs	Power Cost [\$/kW]	240	-	350	-	200-300
	Energy Cost [\$/kWh]	60,000	-	2.3k-83k	-	1k-10k
	PCS Cost [\$/kW]	140-650	140-180	270-580	-	-
	BOP Cost [\$/kW]	-	60	1.7k-12k	-	-
	O&M Fixed Cost [\$/kW-y]	12	17-26	9.2-30	-	-

3.6 Lead Acid Batteries

With a history stretching back to Raymond Planté in 1860, lead acid batteries, are one of the oldest and most recognized forms of electrical energy storage, and today come in a number of designs, each with with unique characteristics and preferred applications. Its popularity is due in part to its low cost and relatively high efficiency, tempered, however, by its low cycle lifetime and poor performance at extreme temperatures [7].

How it Works This device operates based on the principles of redox reactions in electrochemical cells described in Section 2.1. Each cell has a negative electrode assembly composed of a lead alloy grid and pure lead active material. The positive electrode is made of a lead alloy grid with lead oxide active material [2]. The electrolyte is a solution of sulfuric acid in water at a concentration of around 37% [7].

Variations There are a number of types of lead acid batteries available, each with different characteristics:

- **FLOODED OR VENTED (VLA):** Electrodes immersed in reservoirs of excess liquid electrolyte, which may require periodic watering to prevent electrolyte depletion.
 - *Starting, Lighting, and Ignition (SLI):* This design is the cheapest, most common type of lead-acid battery, which has very low cycle life at deep cycles. At expected usage conditions, lifetime is 5-7 years [2].
 - *Deep Cycle:* This design has electrode plates that are thicker and sturdier than SLI designs which makes them capable of more frequent deep discharges. At rated usage conditions this design's lifetime is estimated at 3-5 years [2].
 - *Stationary:* Stationary lead acid batteries are designed to experience only occasional discharges while remaining under float-charge for long periods of time. These units, at rated usage conditions, have lifetimes ranging from 15 to 30 years, and some units may have lifetimes of 30 to 40 years [2].
- **SEALED (SLA) AND VALVE-REGULATED (VRLA):** These designs contain the minimal amount of electrolyte required for proper operation, which is why they are often referred to as "starved-electrolyte". These designs also have more negative electrode active material than positive electrode active material, which helps to promote the recombination of oxygen gas produced during overcharge or float charging. Because of this feature, there is no need to replace the electrolyte (add distilled water), so these designs are essentially maintenance-free. The difference between whether a design is SLA or VRLA is based on the assembly of the electrode plates. The SLA design has plates spirally wound in a cylindrical container, while VRLA has flat plates with a prismatic container. VRLA designs are designed to vent at lower temperatures than SLA designs [1]. This type of battery has a potential lifetime of 10 to 20 years [2].
 - *Absorbed Glass Mat (AGM):* The electrolyte is prevented from moving by being absorbed into a porous microfiber glass mat. Since the electrolyte is immobilized, it can be used in applications where it will be jostled and/or placed in non-upright positions without spilling [1].
 - *Gelled electrolyte:* A chemical is added to the electrolyte to cause it to form a gel, which acts to immobilize it, with similar benefits as the AGM design [1].

System Design Considerations Since lead acid batteries are typically available in predetermined sizes, in larger energy storage systems they are typically connected in series/parallel combinations to get the desired power and energy capacity. In theory, they could be interconnected up to any size, but because interconnecting so many units leads to additional points of potential failure, experience suggest the unit should have a voltage no higher than 2000V. The batteries are typically placed on racks with bus interconnections, and require an HVAC system to maintain the temperature in the proper regime [2]. Additionally hydrogen sensors are installed due to the potential for electrolysis in the battery that can lead to the presence of hydrogen gas.

Operation There are a number of important operational considerations for this battery type.

- **THERMAL CONSIDERATIONS:** This battery type performs optimally around 77°F (25°C). Power capacity falls with decreased temperature since the resistance of the electrolyte is increased. Overheating the battery leads to decreased resistance of the electrolyte, causing increased current and further heating, which can cause a thermal runaway, and can result in the failure of the battery [2].
- **FLOAT CHARGING:** When a battery is fully charged, but not in use, it slowly loses energy due to self-discharge. This can be resolved through applying a constant voltage potential to the battery, which produces small current, counteracting the self-discharge, and sulfation. Although most of the energy used for the float charge is dissipated as heat, some of this energy leads to the production of hydrogen through electrolysis of water in the cell [2].
- **EQUALIZATION CHARGING:** Over time cells within a battery can begin to experience different states-of-charge, which can damage a battery. The process of equalization charging overcharges the battery so that all cells once again reach full charge. This will lead to electrolysis, precautions for the production of hydrogen must be considered. This process is not recommended for VRLA batteries since water cannot be added when electrolysis occurs [2].

- **CELL-POST MAINTENANCE:** The metals in cell posts can corrode due to battery fumes and humidity, so they should be regularly inspected and greased [2].
- **WATERING:** Since overcharging (by even small amounts) leads to hydrolysis (water is lost as hydrogen gas is produced from it), most lead acid batteries (with the exceptions of VRLA) must be refilled with distilled water 3 to 4 times a year [2].

Maintenance Due to the chemistry of these devices there are a number of maintenance considerations.

- **GASSING:** These batteries produce both hydrogen and oxygen gasses during normal charging (minimal amounts typically quickly dissipated into the atmosphere), and especially when the battery is overcharged (significant amounts), and this mixture can be dangerously explosive. SLA and VRLA designs typically have mechanisms to recombine the gasses generated during hydrolysis into water, however most other designs do not [1].
- **SULFATION:** When cells are undercharged and during regular discharge lead sulfate (PbSO_4) precipitates on the electrode surfaces and by building up this can lead to decreases in capacity and may damage the cell. This effect is mitigated through maintaining a float charge [2].
- **HYDRATION:** This effect occurs when the battery remains in a low state-of-charge for extended periods the lead components can begin to dissolve into lead hydrates. Once the cell is charged again, the hydrates are converted back into solid lead, and may form short circuits, which in turn leads to higher current during float charging as well as increases self-discharge. As this effect can potentially render a battery unusable within a few hours of hydration, it is imperative that these batteries not be left in a discharged state [2].
- **GRID CORROSION:** Especially for infrequently-cycled units, this is the most prevalent degradation and failure mode. The lead in the positive electrode corrodes to lead oxide, and over time paths for electrical conduction are reduced [2].
- **ELECTROLYTE STRATIFICATION:** A problem common to deep-cycle batteries, due to its association with cells that are cycled repeatedly, this condition involves acid concentrations becoming unequally distributed throughout the cell. The higher-density solution sinks, while the lower-density solution rises, stratifying the electrolyte, and decreasing capacity and performance. Typically this is remediated with an equalization charge, but sometimes requires the electrolyte to be mixed using compressed air [2].

Environmental Impact Clearly, these devices contain large quantities of toxic lead and dangerous sulfuric acid. However, the Battery Council International cites that over 96% of the lead from lead acid batteries is recycled in the United States (compare that with 26% for glass bottles and 45% for aluminum cans). The sulfuric acid can be neutralized then safely disposed of.

Other Resources There are many resources available on lead acid batteries. For technical information on lead acid cell chemistry, operation, and applications, refer to [1], which is an industry standard reference in the that field. For higher-level introductions, refer to [2,3], and the brief multi-part series on basic battery battery concepts related to operation and charging [19–21]. The Chino, California 10MW, 40MWh lead acid battery storage facility is an excellent case study, is discussed in [22]. And for an extensive list of lead acid battery installations, sizes, costs, and applications, refer to [23].

Summary of Device Parameters The following table summarizes the available technoeconomic parameters for lead acid batteries from a number of studies from 2000-2010. All monetary values have been adjusted to 2010 dollars. If a value is marked with “-” either the quantity was not found in the corresponding report or the way it was presented was inconsistent with the format used here. For example, the EPRI-DOE report gives total cost in \$/kW or \$/kWh, not a formulation that takes into account both, simultaneously. It should also be noted that the BOP costs from [3] were given in \$/kWh not \$/kW.

	Source:	Schoenung 2003 [5]	EPRI 2003 [2]	Gonzalez 2004 [3]	Schoenung 2008 [6]	Chen 2009 [7]
Techno. Params.	Roundtrip Efficiency [%]	75	70-82	81	-	70-80
	Self-discharge [%Energy per day]	0.1	0.033	-	-	0.1-0.3
	Cycle Lifetime [cycles]	-	100-2k	-	-	500-1000
	Expected Lifetime [Years]	5-6	3-20	5-10	-	5-15
	Specific Energy [Wh/kg]	-	-	-	-	30-50
	Specific Power [W/kg]	-	-	-	-	75-300
	Energy Density [Wh/L]	-	-	-	-	50-80
	Power Density [W/L]	-	-	-	-	10-400
Costs	Power Cost [\$/kW]	150-300	-	230-350	175	300-600
	Energy Cost [\$/kWh]	180-360	-	200-290	150-200	200-400
	PCS Cost [\$/kW]	120-600	180-260	270-580	-	-
	BOP Cost [\$/kW]	60-180	60-120	58	50	-
	O&M Fixed Cost [\$/kW-y]	6-18	9-52	1.8	-	-

3.7 Nickel-electrode Batteries

With almost as long of a history and market penetration as lead acid batteries are nickel-electrode cells, in particular, nickel cadmium. These devices have a high specific energy and require little maintenance, but have high costs and a somewhat low cycle life. In general, these devices can better-endure more extreme conditions and full discharges without sacrificing loss of capacity, lifetime, or efficiency than lead acid batteries [3]. As of 2009, the largest battery installation in the world was a NiCd array providing 40 MW for 7 minutes, in Fairbanks, Alaska [7].

How it Works This device operates based on the principles of simple electrochemical cells, described in Section 2.1. Each cell has a positive electrode assembly composed of nickel hydroxide Ni(OH)_2 , and the negative electrode is the distinguishing feature in each of the designs described below. The electrolyte is typically potassium hydroxide $\text{KOH(H}_2\text{O)}$ [1].

Variations There are a wide variety of chemistries within this category, the most prevalent of which is nickel-cadmium.

- **NICKEL-CADMIUM (NiCd)** As the most common nickel-electrode system in utility-use today, this chemistry is fairly tolerant of abuse and compared with lead acid batteries these systems have higher energy density, longer cycle life, and require less maintenance [2]. This basic chemistry comes in a number of designs including vented industrial nickel-cadmium, vented sintered-plate nickel-cadmium, and sealed nickel-cadmium [1].
- **NICKEL-IRON (NiFe)** This is the oldest type of this genre of battery, and is quite durable, able to deal with physical and operation abuse (including overcharging, over-discharging, being open-circuited for long periods of time, and being short circuited) without shortening its lifetime significantly. The downside of these systems is that their performance is significantly affected by changes in temperature, they are unable to retain charge, have low power density and produce significant levels of gas while operating [2].
- **NICKEL-HYDROGEN (NiH₂)** A hybrid system with features similar to both batteries and fuel cells and in this design the negative electrode is gaseous hydrogen, and the positive electrode is nickel oxyhydroxide [2]. Although this design is highly reliable, with very long expected lifetime, and requiring little maintenance, this device is the most costly of this genre [2].
- **NICKEL-METAL HYDRIDE (NiMH)** In this configuration, the negative electrode is hydrogen, but the hydrogen is absorbed into a metal alloy [2]. This technology has longer cycle lifetime and does not lose capacity as easily as NiCd, but it is sensitive to overcharge and high-rate discharge [2].
- **NICKEL-ZINC (NiZn)** A relatively new technology that has not shown itself to be outshine other chemistries, however advances in this design could be commercially promising due to its high specific energy [1].

Due to its commercial prevalence, the rest of this review will focus on NiCd chemistries.

System Design Considerations Similar to lead acid batteries, NiCd batteries are typically available in predetermined sizes, and in larger energy storage systems they are typically connected in series/parallel combinations to get the desired power and energy capacity. These systems typically require an HVAC system to maintain the temperature, as well as sensors for monitoring for hydrogen gas [2].

Operation Overview of operations

- **SELF-DISCHARGE** Since the electrolyte is somewhat conductive, a small amount of self-discharge occurs (and is typically mitigated through the application of a float charge). It should also be noted that the rate of self-discharge significantly increases with temperature for this chemistry [2].
- **LIFETIME** Pocket-plate NiCd at 80% depth-of-discharge can last 800-1000 cycles, while at 10% depth-of-discharge it can last around 50,000 cycles. Sintered-plate NiCd at 80% depth-of-discharge may survive 3500 cycles. Nickel-metal hydride and nickel-hydrogen are on par with vented NiCd. Nickel-zinc last about 1000 cycles. For low numbers of cycles, flooded NiCd are rated for 10-15 years, NiFe may last 25 years [2].
- **THERMAL CONSIDERATIONS** These batteries must be kept at room temperature, because the internal resistance of the system is inversely proportional to temperature, so a higher temperature means lower internal resistance. So, as the temperature rises the internal resistance decreases, which leads to increased self-discharge, and decreased the overall lifetime of the device. Since operation at cooler temperatures result in higher charge capacity (in Amp-hours), it is considered optimal to store the battery cold when charged and warm it just prior to discharge [2]. Rule of thumb: calendar-life of NiCd batteries falls by 20% with every 10°C in operating temperature [2].
- **FLOAT CHARGING** Refer to Lead Acid Batteries in Section 3.6.

Maintenance Issues Overview of maintenance issues

- **MEMORY EFFECT** Caused by repeated cycling at shallow depths-of-discharge, leading to a gradual reduction in both voltage and capacity at the end of the shallow cycle (remediated through a full discharge and recharge) [2].
- **FLOAT EFFECT** Causes Watt-hour capacity to decrease after too long on float-charge. This is remediated by 1-3 full charge/discharge cycles [2].

- **IRREVERSIBLE DEGRADATION** Decomposition of organic materials in cell into carbonates, resulting in increased resistance in the electrolyte. Formation of dendrites on the negative electrode (which can penetrate the separator). Gas barrier failure which allows gases to recombine with the cell itself leading to heating, larger self-discharge rates, and eventually short-circuiting. Electrode poisoning (especially poisoning of the positive electrode with iron migrating from the negative electrode) [2].

Environmental Impact A major problem with this battery is the presence of cadmium, an extremely toxic metal, however, most industrial nickel-cadmium batteries are recycled today [2].

Other Resources A detailed source on NiCd batteries and their varying chemistries is [1], and a more concise approach it [2].

Summary of Device Parameters The following table summarizes the available technoeconomic parameters for nickel-electrode batteries (mainly for NiCd chemistries) from a number of studies from 2000-2010. All monetary values have been adjusted to 2010 dollars. If a value is marked with “-” either the quantity was not found in the corresponding report or the way it was presented was inconsistent with the format used here. For example, the EPRI-DOE report gives total cost in \$/kW or \$/kWh, not a formulation that takes into account both, simultaneously.

	Source:	Schoenung 2003 [5]	EPRI 2003 [2]	Gonzalez 2004 [3]	Schoenung 2008 [6]	Chen 2009 [7]
Techno. Params.	Roundtrip Efficiency [%]	65	60-70	-	-	60-70
	Self-discharge [%Energy per day]	-	0.067-0.17	-	-	0.2-0.6
	Cycle Lifetime [cycles]	-	800-3500	-	-	2000-2500
	Expected Lifetime [Years]	10	5-15	-	-	10-20
	Specific Energy [Wh/kg]	-	-	-	-	50-75
	Specific Power [W/kg]	-	-	-	-	150-300
	Energy Density [Wh/L]	-	-	-	-	60-150
	Power Density [W/L]	-	-	-	-	-
Costs	Power Cost [\$/kW]	150-210	-	-	175	500-1500
	Energy Cost [\$/kWh]	710	-	-	600	800-1500
	PCS Cost [\$/kW]	120-600	170-180	-	-	-
	BOP Cost [\$/kW]	60-180	120	-	50	-
	O&M Fixed Cost [\$/kW-y]	6-30	18-32	-	-	-

3.8 Lithium-ion Batteries

Lithium-ion batteries have become popular in recent years due to their extremely high efficiency (compared with other batteries) as well as their high energy density, power density, and cell voltage, as compared to other battery systems. Their high capital cost, however, has prevented many large-scale systems from being developed.

How it Works The positive electrode in this design is made of a lithiated (treated with lithium) metal oxide, and the negative electrode is composed of layered graphitic carbon. The electrolyte is made of salts of lithium that have been dissolved in organic carbonates [7]. Given those electrodes and electrolyte, the principle for electrochemical storage in this device is the redox reaction, described in Section 2.1.

Variations Other designs involving lithium typically use metallic lithium, which is extremely toxic, lithium-ion designs, therefore are less chemically reactive and therefore more stable and will last longer [1].

System Design Considerations Similar to lead acid batteries, Lithium-ion batteries are typically available in predetermined sizes, and in larger energy storage systems they are typically connected in series/parallel combinations to get the desired power and energy capacity.

Environmental Impact Lithium is caustic and may cause fires when exposed to moisture. The electrolyte used in some lithium batteries is toxic, so care should be taken in recycling these units. Recycling programs are available for these battery designs.

Other Resources For details on the electrochemistry of the devices refer to [1], and for a more general discussion see [7].

Summary of Device Parameters The following table summarizes the available technoeconomic parameters for lithium-ion from a number of studies from 2000-2010. All monetary values have been adjusted to 2010 dollars. If a value is marked with “-” either the quantity was not found in the corresponding report or the way it was presented was inconsistent with the format used here. For example, the EPRI-DOE report gives total cost in \$/kW or \$/kWh, not a formulation that takes into account both, simultaneously.

	Source:	Schoenung 2003 [5]	EPRI 2003 [2]	Gonzalez 2004 [3]	Schoenung 2008 [6]	Chen 2009 [7]
Techno. Params.	Roundtrip Efficiency [%]	85	-	-	-	90-98
	Self-discharge [%Energy per day]	0.24	-	-	-	0.1-0.3
	Cycle Lifetime [cycles]	-	-	-	-	1k-10k
	Expected Lifetime [Years]	10	-	-	-	5-15
	Specific Energy [Wh/kg]	-	-	-	-	75-200
	Specific Power [W/kg]	-	-	-	-	150-315
	Energy Density [Wh/L]	-	-	-	-	200-500
	Power Density [W/L]	-	-	-	-	-
Costs	Power Cost [\$/kW]	210-240	-	-	175	1.2k-4k
	Energy Cost [\$/kWh]	600	-	-	500	600-2500
	PCS Cost [\$/kW]	120-600	-	-	-	-
	BOP Cost [\$/kW]	0	-	-	0	-
	O&M Fixed Cost [\$/kW-y]	12-30	-	-	-	-

3.9 Sodium-sulfur Batteries (NaS)

Sodium-sulfur systems are part of a unique category of batteries sometimes referred to as “molten salt” devices (in that their electrodes are both molten) and operate at temperatures around 300°C. They are known for their strong cycle life, decent energy efficiency, and specific energy 3 to 4 times that of lead acid batteries. These devices are able to provide short bursts (30 seconds) of power that is six times their continuous power rating, making them particularly applicable in power quality applications [3]. A significant number of these installations have been built in Japan as part of the Tokyo Electric Power Company (TEPCO), and have been operating for well-over a decade [24].

How it Works This device is made up of a molten elemental sodium negative electrode, a molten sulfur positive electrode, and a solid beta alumina ceramic electrolyte. In order to maintain the electrodes in a molten state the temperature of the device is maintained between 300-350°C [7]. Although the electrodes are molten, the underlying principle of electrochemical storage for this device is the redox reaction, described in Section 2.1.

System Design Considerations These systems typically come in modules with higher power and energy capacity than most secondary batteries, and are generally assembled into series/parallel connections of those modules.

Operation These systems are low maintenance, but there are a few considerations to be made during their operation:

- **SELF-DISCHARGE** Since this device must maintain a temperature of 300°C to keep the electrodes molten, if this device remains unused for a long duration, some of its energy has to be used to keep up the temperature, so this leads to a parasitic loss.
- **LIFETIME** System lifetime ranges from 5,000 cycles at 90% depth-of-discharge, to 43,000 cycles at 10% depth-of-discharge [2]. This is to say that the cycle life is dependent of the average depth-of-discharge of the device.
- **RESPONSE TIME** All NaS modules can reach full power within one millisecond, although it is more efficient (in terms of duty cycle) to have gradual load changes [2]
- **THERMAL CONSIDERATIONS** Resistance heaters maintain the temperature of the module above 290°C during standby [2], and lead to parasitic losses between cycling.

Environmental Impact Minimal since sodium and sulphur can both be safely disposed of.

Other Resources For an exhaustive treatment of sodium sulfur batteries, refer to [25], and for less exhaustive but still informative treatments of the topic, see [2, 3, 7]. Discussions of existing projects and NaS installations are also available [24, 26].

Summary of Device Parameters The following table summarizes the available technoeconomic parameters for sodium-sulfur batteries from a number of studies from 2000-2010. All monetary values have been adjusted to 2010 dollars. If a value is marked with “-” either the quantity was not found in the corresponding report or the way it was presented was inconsistent with the format used here. For example, the EPRI-DOE report gives total cost in \$/kW or \$/kWh, not a formulation that takes into account both, simultaneously.

	Source:	Schoenung 2003 [5]	EPRI 2003 [2]	Gonzalez 2004 [3]	Schoenung 2008 [6]	Chen 2009 [7]
Techno. Params.	Roundtrip Efficiency [%]	70	80-86	71-82	-	75-90
	Self-discharge [%Energy per day]	0.05	-	-	-	20
	Cycle Lifetime [cycles]	-	2500-4500	-	-	2500
	Expected Lifetime [Years]	10-15	15	5	-	10-15
	Specific Energy [Wh/kg]	-	-	-	-	150-240
	Specific Power [W/kg]	-	-	-	-	150-230
	Energy Density [Wh/L]	-	-	-	-	150-250
	Power Density [W/L]	-	-	-	-	-
Costs	Power Cost [\$/kW]	180	-	300	150	1k-3k
	Energy Cost [\$/kWh]	300	-	280	250	300-500
	PCS Cost [\$/kW]	120-600	180-530	270-580	-	-
	BOP Cost [\$/kW]	0-60	120	46	0	-
	O&M Fixed Cost [\$/kW-y]	24	23-61	-	-	-

3.10 Sodium nickel chloride Batteries (ZEBRA)

The sodium nickel chloride battery, like the sodium sulfur battery, is a type of “molten salt” device. (The Sodium nickel chloride battery is also known as the ZEBRA® battery). As compared with its parent device, the NaS battery, it is less sensitive to overcharging and deep discharging, and potentially a safer device. However, it also has a lower energy and power density than NaS devices [7].

How it Works This device is similar to the sodium sulfur battery in that the negative electrode is made of liquid sodium, and is separated from the positive electrode by a solid beta alumina electrolyte. The difference is that this device has a positive electrode of solid nickel chloride, and also uses a second liquid electrolyte of sodium chloroaluminate to allow for fast transport of sodium ions from the nickel chloride electrode back and forth from the ceramic electrolyte [27].

System Design Considerations Much like NaS devices, these systems typically come in modules with higher power and energy capacity than most secondary batteries, and are generally assembled into series/parallel connections of those modules.

- **SELF-DISCHARGE** The system may lose 10% or more of its energy per day if the system is not cycling (due to parasitic heating requirements to maintain the device’s temperature), while it may have zero losses if the system is operational [27].
- **LIFETIME** The major factors affecting the lifetime of these devices are corrosion and a rise in internal resistance [27].

Operation The primary operation consideration is thermal in nature. The melting point for the salt used in this device is 157°C, hence this is the theoretical minimum operating temperature, but the typical range is 270-350°C. Operation is independent of changes in the ambient temperature. The battery management interface restrict the upper temperature limit to 70°C, and there is effectively no lower temperature limit [27].

Maintenance One excellent feature of this device’s failure mode is that cells typically fail to a resistance that is comparable to that of an intact cell, so a series chain of these cells may remain operational even with a number of cell failure, making systems composed of these batteries quite robust, and requiring little maintenance. In fact, there can be a failure of 5-10% of the cells in a system, and the unit could still function properly [27].

Environmental Impact All of the components in a sodium nickel chloride battery system can be recycled into new batteries, and this has been demonstrated successfully through the recycling ZEBRA battery systems [28].

Other Resources A good technical overview of these systems and some applications are given in [27] and a couple of overviews of this system can be found in [7, 28].

Summary of Device Parameters The following table summarizes the available technoeconomic parameters for sodium nickel chloride batteries from a number of studies from 2000-2010. All monetary values have been adjusted to 2010 dollars. If a value is marked with “-” either the quantity was not found in the corresponding report or the way it was presented was inconsistent with the format used here. For example, the EPRI-DOE report gives total cost in \$/kW or \$/kWh, not a formulation that takes into account both, simultaneously.

	Source:	Schoenung 2003 [5]	EPRI 2003 [2]	Gonzalez 2004 [3]	Schoenung 2008 [6]	Chen 2009 [7]
Techno. Params.	Roundtrip Efficiency [%]	-	-	-	-	85-90
	Self-discharge [%Energy per day]	-	-	-	-	15
	Cycle Lifetime [cycles]	-	-	-	-	2500+
	Expected Lifetime [Years]	-	-	-	-	10-14
	Specific Energy [Wh/kg]	-	-	-	-	100-120
	Specific Power [W/kg]	-	-	-	-	150-200
	Energy Density [Wh/L]	-	-	-	-	150-180
	Power Density [W/L]	-	-	-	-	220-300
Costs	Power Cost [\$/kW]	-	-	-	-	150-300
	Energy Cost [\$/kWh]	-	-	-	-	100-200
	PCS Cost [\$/kW]	120-600*	-	-	-	-
	BOP Cost [\$/kW]	0-120*	-	-	-	-
	O&M Fixed Cost [\$/kW-y]	23-61*	-	-	-	-

* indicates assumptions from NaS systems.

3.11 Zinc-bromine Batteries (ZnBr)

The idea for this flow battery (see Section 2.1) was patented in 1885, but not until recently was it feasible to use, since they are very difficult to charge due to the fact that zinc forms dendrites on the electrode, and these dendrites can form short circuiting pathways. This is still a maintenance issue, but for the most part the problem has been resolved by design improvements. As a flow battery the energy capacity and power capacity are scaled up independently and this is a considerable system design advantage over traditional battery systems. Also another benefit of this system design is that complete discharges of the battery (100% depth-of-discharge) not only does not hurt the battery, but improves it [1].

How it Works As this is a type of flow battery, or flowing electrolyte battery, (see Section 2.1 for more information on the operation of flow batteries) the design consists of two electrodes, two electrolytes, and an electrolyte separator. Both electrolytes are aqueous solutions of zinc bromide (ZnBr_2). The negative electrode begins with minimal zinc attached, and during charge, zinc is plated onto this electrode. During charge at the positive, bromine, electrode elemental bromine is formed. There is a microporous separator which serves to isolate each electrode and electrolyte from the other and at the same time allowing zinc and bromine ions to migrate to the opposite flow stream, while at the same time inhibiting the bromine of the positive electrode from crossing over to the negative electrolyte (as this would allow for the chemical interaction of bromine and zinc, resulting in self-discharge [2]). During discharge the zinc plating dissolves back into its aqueous state, and the reactions reverse themselves. These devices differ from other flow batteries in that the electrodes act as substrates for the chemical reactions (similar to conventional batteries) and so these systems must be regularly discharged completely in order to prevent capacity loss [3].

System Design Considerations There are a few design considerations for this battery chemistry:

- **SELF-DISCHARGE** During standby operation, the unit will have losses due to the energy for the pumps required to circulate the electrolyte. The system will also have losses due to bromine crossing over to the negative electrode side of the unit
- **LIFETIME** Most of the system failures of these devices are associated with the corrosivity of bromine, so the lifetime is more dependent on the time in operation rather than the number of cycles and depth-of-discharge. These systems often last 2000 cycles or for 6000 hours of continuous operation [2].
- **PCS/BOP/CONTROLS** During normal operation there is typically little-to-no gas release from this type of system but precautions must be taken in case of bromine leakage, as bromine vapors are highly corrosive and toxic [2].
- **CAPACITY** These systems have decoupled energy and power capacity, and therefore, these two factors can be scaled up independently. By increasing the amount of electrolyte (and if required tank size) the energy capacity can be increased, and increasing the surface area of the electrodes (by adding more electrode cells) the power capacity can be increased. Although specifically-sized units can be created, often a series/parallel combination of these modules are connected to create facilities with high power and energy capacity.

Operation There are a number of operational considerations for zinc-bromine batteries:

- **CHARGING REQUIREMENTS / LIMITATIONS:** This battery can be completely discharged, and at that point the negative plate is free of zinc. This procedure, known as “stripping” is recommended every 5-10 cycles to ensure the highest system efficiency [2].
- **THERMAL CONSIDERATIONS:** These systems are designed for operation between 20-50°C, and performance is weakly dependent on temperature [2].
- **PUMP AND ELECTROLYTE CIRCULATION:** Since zinc dendrites form easily in these systems, circulating the electrolyte can help to remediate this problem, as well as act as thermal management, and remove and polybromide that has formed on the positive electrode (freeing up space on the electrode means more surface area for further reactions). Since running the pump is itself a parasitic loss, during standby the pumps will typically be intermittently activated [2].
- **GASSING CONCERNS:** during normal operation there is typically little-to-no gas release from this type of system (possibly small amount of hydrogen) but precautions must be taken in case of bromine leakage, as bromine vapors are highly corrosive and toxic [2].

Maintenance The routine maintenance on these systems typically consists of monitoring for pump failures, electrolyte leaks, and cell voltage imbalances as well as completing a stripping cycle every 5 cycles.

Environmental Impact The highly corrosive bromine must be managed properly, but these systems can typically be recycled or reused [1].

Other Resources An extensive source on the electrochemistry of this device is [1], and a more accessible treatment of the subject is [2].

Summary of Device Parameters The following table summarizes the available technoeconomic parameters for zinc-bromine batteries from a number of studies from 2000-2010. All monetary values have been adjusted to 2010 dollars. If a value is marked with “-” either the quantity was not found in the corresponding report or the way it was presented was inconsistent with the format used here. For example, the EPRI-DOE report gives total cost in \$/kW or \$/kWh, not a formulation that takes into account both, simultaneously.

	Source:	Schoenung 2003 [5]	EPRI 2003 [2]	Gonzalez 2004 [3]	Schoenung 2008 [6]	Chen 2009 [7]
Techno. Params.	Roundtrip Efficiency [%]	60	66-76	71	-	65-75
	Self-discharge [%Energy per day]	0.24	0.24	-	-	small
	Cycle Lifetime [cycles]	-	2000	2000	-	2000+
	Expected Lifetime [Years]	8	7	-	-	5-10
	Specific Energy [Wh/kg]	-	-	-	-	30-50
	Specific Power [W/kg]	-	-	-	-	-
	Energy Density [Wh/L]	-	-	-	-	30-60
	Power Density [W/L]	-	-	-	-	-
Costs	Power Cost [\$/kW]	210	-	1700	175	700-2500
	Energy Cost [\$/kWh]	480	-	230	400	150-1000
	PCS Cost [\$/kW]	120-600	210-570	270-580	-	-
	BOP Cost [\$/kW]	0	120	included	0	-
	O&M Fixed Cost [\$/kW-y]	24	15-47	-	-	-

3.12 Polysulfide-bromide Batteries (PSB)

This technology is flow battery design that has been commercially produced as the Regenesys system. As with other flow battery systems, the power and energy capacity of the device are essentially independent, so the system is highly scalable. Also, these systems can be overcharged and over-discharged without seriously impacting the lifetime of the unit, making it highly flexible for a number of applications. However, the efficiency of the system is quite low due to the pumping requirements.

How it Works For the background on the operation of flow batteries, see Section 2.1. The concept is the same—the two electrolytes for this system are stored in separate tanks and are pumped through electrochemical cells, where the chemical reactions occur. The electrolytes remain separate by a cation (positively charged ion) exchange membrane. This system uses sodium bromide for the positive electrode and sodium polysulfide for the negative electrode. The system branded as Regenesys uses single large tanks of positive and negative electrolytes rather than a number of smaller modular tanks as well as using larger larger electrodes (about a square meter) [2].

System Design Considerations Like other flow batteries the power and energy capacity are controlled separately by the number of electrochemical cells and the size of the electrolyte tanks, respectively. The design will also have to take into the fact that the efficiency of the system will be reduced due to the parasitic loss caused by the circulation of the electrolyte that requires the use of pumps.

Operation One fortunate part of this design is that overcharging this system or over-discharging does not have seriously negative effects on the lifetime of the device. Also, the response time for this system is relatively low, 20-100ms [2].

Maintenance For this system the plumbing is the number one concern so that the pumps, pipes, and valves are working properly to prevent system failure. Also crystalline sodium sulfate develops due to imperfections in the separating membrane, and this substance needs to be removed to prevent a decrease in overall capacity.

Environmental Impact As with most systems that involve plumbing, these devices are prone to leakage, and because of the dangerous nature of the electrolytes, this presents an environmental concern.

Other Resources Other sources include [2], [3], and [7].

Summary of Device Parameters The following table summarizes the available technoeconomic parameters for PSB systems from a number of studies from 2000-2010. All monetary values have been adjusted to 2010 dollars. If a value is marked with “-” either the quantity was not found in the corresponding report or the way it was presented was inconsistent with the format used here. For example, the EPRI-DOE report gives total cost in \$/kW or \$/kWh, not a formulation that takes into account both, simultaneously.

	Source:	Schoenung 2003 [5]	EPRI 2003 [2]	Gonzalez 2004 [3]	Schoenung 2008 [6]	Chen 2009 [7]
Techno. Params.	Roundtrip Efficiency [%]	65	60-65	57-71	-	60-75
	Self-discharge [%Energy per day]	-	-	-	-	small
	Cycle Lifetime [cycles]	-	n/a	2000	-	-
	Expected Lifetime [Years]	10	15	-	-	10-15
	Specific Energy [Wh/kg]	-	-	-	-	10-50*
	Specific Power [W/kg]	-	-	-	-	-
	Energy Density [Wh/L]	-	-	-	-	16-60*
	Power Density [W/L]	-	-	-	-	-
Costs	Power Cost [\$/kW]	330	-	1400	-	700-2500
	Energy Cost [\$/kWh]	120	-	200-220	-	150-1000
	PCS Cost [\$/kW]	120-600	120-200	270-580	-	-
	BOP Cost [\$/kW]	60	120	-	-	-
	O&M Fixed Cost [\$/kW-y]	18	65-96	-	-	-

* indicates that since there were no values given for this technology, it was assumed that the range was similar to ZnBr and/or VRB so a union of their ranges was used to determine the values shown.

3.13 Vanadium Redox Batteries (VRB)

The Vanadium Redox Battery is a type of flow battery system in which the electrolytes are stored separately from the electrodes and are pumped through sets of electrochemical cells (known as the stack) which contain the electrodes to bring about the necessary chemical reactions. As with other flow battery systems the power and energy capacity are independent and controlled by the number of electrochemical cells and volume of available electrolyte, respectively. These systems have a long lifetime and typically only individual components need to be replaced, such as the stacks, while the electrolyte can be used indefinitely.

How it Works For the background on the operation of flow batteries, see Section 2.1. This concept is unique in that all of the chemical reactions are based on the transfer of electrons between different vanadium ions. “At the negative electrode V^{3+} is converted to V^{2+} , during battery charging by accepting an electron. During discharge the V^{2+} ions are reconverted back to V^{3+} and the electron is released. At the positive terminal a similar reaction takes place between ionic forms of V^{5+} and V^{6+} . The electrolyte is made up of a vanadium and sulfuric acid mixture and is stored in external tanks and pumped as needed to the cells. The cells are divided into two half-cells by a proton exchange membrane (PEM), and separates the two different vanadium-based electrolyte solutions (the anolyte and the catholyte), and allows for the flow of ionic charge (protons or H^+ ions) to complete the electric circuit” [2].

System Design Considerations Like other flow batteries the power and energy capacity are controlled separately by the number of electrochemical cells and the size of the electrolyte tanks, respectively. The design will also have to take into the fact that the efficiency of the system will be reduced due to the parasitic loss caused by the circulation of the electrolyte that requires the use of pumps.

Operation This system has an extremely fast response time and be on the order of a few milliseconds if the pumps are in continuous operation. This however creates a large parasitic loss, so, if the required response time is on the order of a few minutes, the pumps can be powered down and the stacks drained during periods of inactivity.

Maintenance For this system the plumbing is the number one concern so that the pumps, pipes, and valves are working properly to prevent system failure.

Environmental Impact As with most systems that involve plumbing, these devices are prone to leakage, and because of the dangerous nature of the electrolytes, this presents an environmental concern.

Other Resources Other sources include [2], [3], and [7].

Summary of Device Parameters The following table summarizes the available technoeconomic parameters for VRB batteries from a number of studies from 2000-2010. All monetary values have been adjusted to 2010 dollars. If a value is marked with “-” either the quantity was not found in the corresponding report or the way it was presented was inconsistent with the format used here. For example, the EPRI-DOE report gives total cost in \$/kW or \$/kWh, not a formulation that takes into account both, simultaneously.

	Source:	Schoenung 2003 [5]	EPRI 2003 [2]	Gonzalez 2004 [3]	Schoenung 2008 [6]	Chen 2009 [7]
Techno. Params.	Roundtrip Efficiency [%]	70	60-75	67-81	-	75-85
	Self-discharge [%Energy per day]	0.2	-	-	-	small
	Cycle Lifetime [cycles]	-	14000	-	-	12k+
	Expected Lifetime [Years]	10	10-15	10	-	5-10
	Specific Energy [Wh/kg]	-	-	-	-	10-30
	Specific Power [W/kg]	-	-	-	-	-
	Energy Density [Wh/L]	-	-	-	-	16-33
	Power Density [W/L]	-	-	-	-	-
Costs	Power Cost [\$/kW]	210	-	-	175	600-1500
	Energy Cost [\$/kWh]	710	-	200-220	350	150-1000
	PCS Cost [\$/kW]	120-600	370-610	270-580	-	-
	BOP Cost [\$/kW]	36	120	-	30	-
	O&M Fixed Cost [\$/kW-y]	24	33-65	-	-	-

Chapter 4

Storage Technology Summary

This final section is meant to consolidate the parameters of each of the devices into one page for side-by-side comparisons and for use in modeling. What follows in the last section is a summary of the parameters found for each technology discussed, using the referenced sources, most importantly [2,3,5–7]. The ranges of each parameter in this summary correspond to the minimum and maximum values found for each parameter across all references. This may not be the ideal method for consolidation for every purpose, which is why for each technology the compilation of parameter values were also presented. Any assumptions that were made regarding parameter values can also be found in the individual technology sections.

Summary of Device Parameters

What follows is a summary of the parameters found for each technology discussed, using the referenced sources, most importantly [2, 3, 5–7]. The ranges in this summary correspond to the minimum and maximum values found for each parameter across all references.

		Mechanical Storage				Electrical Storage		
		PHS	CAES	FES-LS	FES-HS	CAP	ECC	SMES
Techno. Params.	Roundtrip Efficiency [%]	70-85	57-85	70-95	70-95	60-70	90-98	90-98
	Self-discharge [%Energy/day]	≈0	≈0	100	1.3-100	40	20-40	10-15
	Cycle Lifetime [cycles]	N/A	N/A	20k-100k	20k-100k	50k	10k-100k	100k
	Expected Lifetime [Years]	30-60	20-40	15-20	15-20	5	20	20-30
	Specific Energy [Wh/kg]	0.5-1.5	30-60	10-30	10-30	0.05-5	2.5-15	0.5-5
	Specific Power [W/kg]	0	0	400-1.5k	400-1.5k	100k	500-5k	500-2k
	Energy Density [Wh/L]	0.5-1.5	3-6	20-80	20-80	2-10	0	0.2-2.5
	Power Density [W/L]	0	0.5-2	1k-2k	1k-2k	100k	100k	1k-4k
Costs	Power Cost [\$/kW]	600-2k	400-800	250-360	250-400	200-400	100-360	200-350
	Energy Cost [\$/kWh]	0-23	2-140	230-60k	580-150k	500-1k	300-94k	1k-83k
	BOP Cost [\$/kW]	270-580	270-580	110-600	110-600	180-580	180-580	140-650
	PCS Cost [\$/kW]	0-4.8	46-190	0-120	0-1200	50-12k	50-12k	60-12k
	O&M Fixed Cost [\$/kW-y]	3-4.4	1.6-29	6-22	6-22	6-16	6-16	9.2-30

		Chemical Storage							
		Conventional Battery			Molten Salt Bat.		Flow Battery		
		LA	NiCd	Li-ion	NaS	ZEBRA	ZnBr	PSB	VRB
Techno. Params.	Roundtrip Efficiency [%]	70-82	60-70	85-98	70-90	85-90	60-75	57-75	60-85
	Self-discharge [%Energy/day]	0.033-0.3	0.067-0.6	0.1-0.3	0.05-20	15	0.24	≈0	0.2
	Cycle Lifetime [cycles]	100-2k	800-3.5k	1k-10k	2.5k-2.5k	2.5k	2k	2k	12k-14k
	Expected Lifetime [Years]	3-20	5-20	5-15	5-15	10-14	5-10	10-15	5-15
	Specific Energy [Wh/kg]	30-50	50-75	75-200	150-240	100-120	30-50	10-50	10-30
	Specific Power [W/kg]	75-300	150-300	150-315	150-230	150-200	0	0	0
	Energy Density [Wh/L]	50-80	60-150	200-500	150-250	150-180	30-60	16-60	16-33
	Power Density [W/L]	10-400	0	0	0	220-300	0	0	0
Costs	Power Cost [\$/kW]	175-600	150-1500	175-4000	150-3000	150-300	175-2500	330-2500	175-1500
	Energy Cost [\$/kWh]	150-400	600-1500	500-2500	250-500	100-200	150-1000	120-1000	150-1000
	BOP Cost [\$/kWh]	120-600	120-600	120-600	120-600	120-600	120-600	120-600	120-610
	PCS Cost [\$/kW]	58-180	50-180	0	0-120	0-120	0-120	60-120	36-120
	O&M Fixed Cost [\$/kW-y]	1.8-52	6-32	12-30	23-61	23-61	15-47	18-96	24-65

Symbol	Technology
PHS	Pumped Hydroelectric Energy Storage
CAES	Compressed Air Energy Storage
FES-LS	Low Speed Flywheel Energy Storage
FES-HS	High Speed Flywheel Energy Storage
CAP	Standard Electrostatic Capacitor
ECC	Electrochemical Capacitors (supercapacitors)
SMES	Superconducting Magnetic Energy Storage
LA	Lead Acid Battery)
NiCd	Nickel-Cadmium Battery
Li-ion	Lithium-ion Battery
NaS	Sodium-Sulfur Battery
ZEBRA	Sodium Nickel Chloride Battery
ZnBr	Zinc-Bromine Flow Battery
PSB	Polysulfide-Bromide Flow Battttery
VRB	Vanadium Redox Flow Battery

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