Americans for a Clean Energy Grid

Grid-Scale Energy Storage

Until the mid-1980s, utility companies perceived grid-scale energy storage as a tool for time-shifting electricity production at coal and nuclear power plants from periods of low demand to periods of high demand [15]. Cheap electricity produced at coal and nuclear power plants during off-peak hours was stored – via pumped hydro reservoirs – to meet increased demand during peak hours. This application of grid-scale energy storage reduced the need for generating electricity from more expensive fuels during peak hours. Recent developments in grid-scale storage technologies, such as batteries and flywheels, have allowed utility companies to begin utilizing storage for other grid services. This paper will discuss many of these technologies in turn. But first, it is important to examine the benefits that grid-scale energy storage can provide to the electricity system:

- **Electricity Time-Shifting:** Grid-scale energy storage can store cheaper electricity generated during off-peak hours and dispatch it to match higher demand during peak hours. Additionally, grid-scale energy storage can store excess energy that would otherwise be cut back by the utility companies to avoid reliability issues, produced from renewable sources such as photovoltaic (PV) solar and wind. [15]
- **Regulation and Frequency Response:** Grid-scale energy storage can be used for regulating voltage to comply with the North American Electric Reliability Corporation's (NERC's) Real Power Balancing Control Performance and Disturbance Control Performance reliability standards. Typically, ready and online generating units are used to increase or decrease voltage as needed. Energy storage can replace these ready and online generating units for regulation purposes. Similarly, energy storage can be used to respond to variations in frequency. Fast-acting battery and flywheel storage systems are

better than ready and online generation units at maintaining frequency because of their faster response time. [15]

- **Spinning, Non-Spinning, and Supplemental Reserves:** Reserve capacity is a requirement for the operation of an electric grid. Reserves are used to supply electricity in case a generation unit goes offline unexpectedly. There are three types of reserves: spinning reserves that respond to frequency fluctuations, generation, or transmission issues within a range of ten seconds to ten minutes; non-spinning reserves that respond within ten minutes for use as uninterruptable and/or curtailable (the right of a transmission provider to interrupt transmission when system reliability is threatened or emergency conditions exist) loads; and supplemental loads that can respond within an hour to act as backups to spinning and non-spinning reserves in case of a disruption. Grid-scale energy storage can provide each of these services. [15]
- **Increased Penetration of Renewable Sources:** Energy storage is crucial for eliminating weather-induced fluctuations in electricity production from wind and PV systems. Energy storage systems can store excess electricity produced from renewable resources during sunny and windy weather conditions, and provide electricity during cloudy and calm weather conditions. This can help make wind and solar systems more reliable, and also makes at least some of their generation dispatchable. Additionally, if electricity production from wind and solar systems is stabilized, utility companies and investors would be more likely to invest in the transmission lines necessary to import electricity from remote locations where wind and solar systems are most economical.
- **Distribution Upgrade Deferral:** Energy storage can delay the replacement of old transformers and save money for the owners of transmission infrastructure. When a transformer is replaced with a new, larger transformer, its size is selected to handle increases in electricity demand over the next 15 to 20 years. This leads to the underutilization of transformers for the majority of their lives. Energy storage systems can offload existing transformers during peak hours, thus effectively avoiding the need for new, larger transformers. Energy storage can prolong the operational lives of existing transformers and reduce the underutilization of new transformers. [15]
- **Transmission Congestion Relief:** Energy storage can improve transmission resiliency by relieving transmission congestion. Energy storage can be installed downstream from

transmission congestion points to reduce congestion and improve transmission reliability. Relieving congestion not only helps utility companies avoid congestion charges, it also eliminates the need for transmission expansion projects. Additionally, energy storage can improve transmission reliability by counteracting voltage dips across transmission lines.

Several technologies for large scale storage of renewable energy exist today with their own advantages, restrictions, potential, and applications. Lithium-ion batteries, sodium-sulfur batteries, vanadium-redox flow batteries, metal-air batteries, pumped hydro storage, flywheels and compressed air energy storage are the most prominent technologies that are either being used or being considered for grid-scale energy storage. To effectively compare and analyze these technologies, it is important to understand the performance metrics that will be used for analysis and comparison [3]:

- *Efficiency*: Ratio of "useful power output" over "total power input."
- *Cycle Lifetime*: Total number of charge and discharge cycles that the storage system can manage in its lifetime.
- *Expected Lifetime*: Number of years the storage system can perform satisfactorily before needing to be replaced.
- *Specific Energy*: Measure of the density of energy stored in Watt-hour/kilogram.
- *Specific Power*: Measure of the density of power stored in Watt/kilogram.
- *Energy Storage System Cost*: Capital cost of building the storage system. It is usually divided into Power Capacity Cost ($/kW) and Energy Capacity Cost ($/kWh).
- *Balance of Plant Cost (BOP)*: Sum of all the costs incurred for land, construction, taxes, permits and other non-system costs in $/kW.
- *Power Conversion System Cost (PCS)*: Cost of all components between the storage system and the utility grid. These usually include transformers, transmission lines, safety sensors, control units and other components – measured in $/kW.
- *Operation and Maintenance Fixed Costs (O&M)*: Annual cost of the maintenance necessary for keeping the storage system operational in $/kW-yr.
- *Maturity*: Extent of a technology's deployment.

For side-by-side comparisons of the technologies discussed, please refer to Appendix A.

Lithium-Ion Batteries

The anode of a lithium-ion battery is made up of a lithiated (treated with lithium) metal oxide, and the cathode is made up of graphitic carbon. Lithium salts dissolved in organic carbonates are used as electrolytes in lithium-ion batteries. Unlike other batteries, lithium-ion batteries have complex control circuits to prevent overcharging and side reactions. This lack of overcharging and side reactions gives lithium-ion batteries their characteristic high efficiencies. However, complex control circuits also drive up the cost of lithium-ion batteries. [3][4]

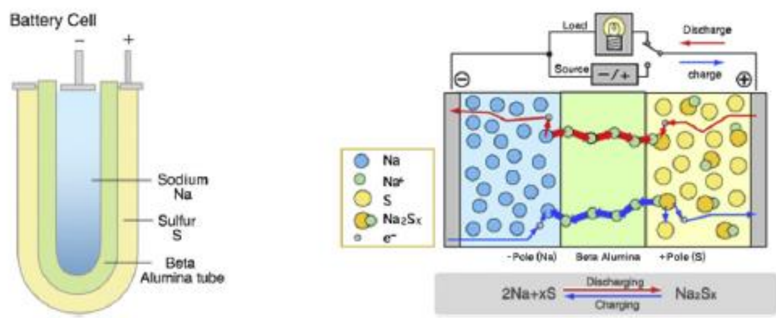
- Advantages: Lithium-ion batteries have high energy and power densities, efficiency and expected life.
- Disadvantages: Lithium-ion batteries have high capital cost and require advanced management for their control circuits [5]. Additionally, the lithium inside these batteries poses a fire threat upon accidental contact with water.
- Example of Existing Installation: Electrovaya agreed to install a 1.2 MWh lithium-ion battery bank in Ontario for renewable energy integration in August of 2011 [4].
- Performance Measures: [3][5]

	Lithium-Ion Batteries
Efficiency (%)	85-98
Cycle Lifetime (cycles)	1,000-10,000
Expected Lifetime (years)	5-15
Specific Energy (Wh/kg)	75-200
Specific Power (W/kg)	150-315
Power Capacity Cost ($/kW)	175-4,000
Energy Capacity Cost ($/kWh)	500-2,500
BOP ($/kWh)	120-600
PCS ($/kW)	0
O&M ($/kW-yr)	12-30
Maturity	Commercial

Sodium-Sulfur Batteries

Sodium-sulfur batteries are part of the molten salt battery family. Both electrodes of a sodium-sulfur battery are in molten form, and the battery operates at high temperatures. The anode is made up of liquid sodium, and the cathode is made up of liquid sulfur. Anode and cathode are separated by a layer of solid beta-alumina electrolyte that only allows positive sodium ions to pass through it. The following chemical reaction produces electricity in a sodium-sulfur battery: [3][4]

$$2Na + 2S = Na_2S_4$$



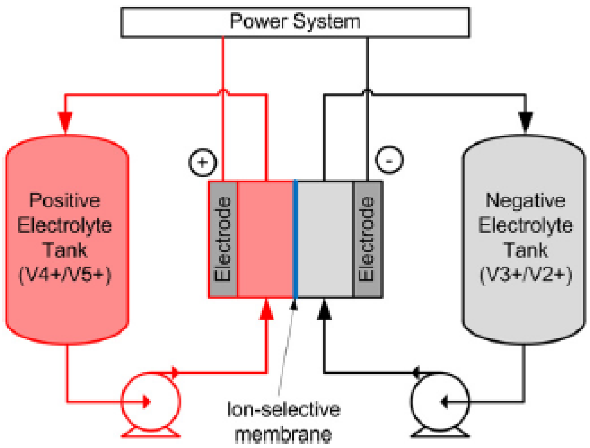
[4]

- Advantages: Sodium-sulfur batteries have high energy density, power density, efficiency and expected life.
- Disadvantages: Sodium-sulfur batteries have high capital cost, and the explosive nature of sodium makes them dangerous to work with [5].
- Example of Existing Installation s: A 34 MW, 245MWh sodium-sulfur battery bank is installed in northern Japan for the stabilization of energy produced by a 51 MW wind farm [5][7].
- Performance Measures: [3][5]

	Sodium Sulfur Batteries
Efficiency (%)	70-90
Cycle Lifetime (cycles)	2,500-25,000
Expected Lifetime (years)	5-15
Specific Energy (Wh/kg)	150-240
Specific Power (W/kg)	150-230
Power Capacity Cost ($/kW)	150-3,000
Energy Capacity Cost ($/kWh)	250-500
BOP ($/kWh)	120-600
PCS ($/kW)	0-120
O&M ($/kW-yr)	23-61
Maturity	Commercializing

Vanadium-Redox Batteries

Vanadium-redox batteries are part of the flow battery family. The two electrolytes used in vanadium-redox batteries are stored in two separate tanks, and each one of them is referred to as a "half-cell." Using pumps, the electrolytes are passed through the electrodes, and electric current is produced as a result of redox reaction. Unlike other batteries, power and energy densities are independent of each other in a vanadium redox flow battery. Power density is directly related to the surface area of electrodes, while the energy density is proportional to the volume of the electrolyte tanks. [3][4]



[4]

- Advantages: Vanadium-redox batteries have high power and energy densities. Additionally, the power and energy densities of these batteries can easily be upgraded without have to replace the whole storage system [5].
- Disadvantages: Vanadium-redox batteries can only operate between 10℃ - 35℃, which significantly restricts the application of these batteries [4].
- Example of Existing Installation: Prudent Energy installed a 4MW, 6MWh vanadium redox battery bank in Japan, which was decommissioned after roughly 270,000 shallow cycles [4][6].
- Performance Measures: [3][5]

	Vanadium-Redox Batteries
Efficiency (%)	60-85
Cycle Lifetime (cycles)	12,000-14,000
Expected Lifetime (years)	5-15
Specific Energy (Wh/kg)	10-30
Specific Power (W/kg)	166

Power Capacity Cost ($/kW)	175-1,500
Energy Capacity Cost ($/kWh)	150-1,000
BOP ($/kWh)	120-610
PCS ($/kW)	36-120
O&M ($/kW-yr)	24-65
Maturity	Developed, but not commercial yet

Nickel-Cadmium Batteries

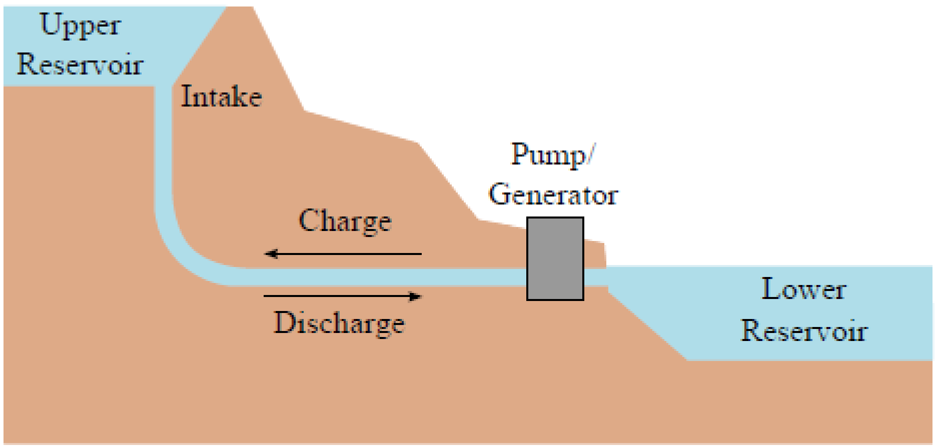
Nickel-cadmium batteries are relatively simple in terms of electrochemistry. The anode is made up of nickel hydroxide, and the cathode is made up of cadmium. The electrolyte usually consists of potassium hydroxide. Similar to lead-acid batteries, nickel-cadmium batteries have been utilized for a long period of time. [3]

- Advantages: Nickel-cadmium batteries have high energy and power densities. Additionally, these batteries can tolerate extreme temperatures [5].
- Disadvantages: Nickel-cadmium batteries have relatively lower efficiency and contain toxic cadmium [5].
- Example of Existing Installation: A 40 MW, 28MWh nickel-cadmium battery bank is installed in Fairbanks, Alaska [3].
- Performance Measures: [3][5]

	Nickel Cadmium Batteries
Efficiency (%)	60-70
Cycle Lifetime (cycles)	800-3,500
Expected Lifetime (years)	5-20
Specific Energy (Wh/kg)	50-75
Specific Power (W/kg)	150-300
Power Capacity Cost ($/kW)	150-1,500
Energy Capacity Cost ($/kWh)	600-1,500
BOP ($/kWh)	120-600
PCS ($/kW)	50-180
O&M ($/kW-yr)	6-32
Maturity	Commercial

Pumped Hydroelectric Storage (PHS)

Pumped hydroelectric storage requires two water reservoirs with differential elevation connected by a pipeline. To store energy, electricity is used to run a motor that pumps water up to the upper reservoir. When electricity is needed, the water from the upper reservoir is allowed to run through a turbine, which rotates the connected generator, and electricity is produced. Some pumped hydroelectric storage facilities have the motor and generator combined in one because motors can act like generators. Motors can be turned to produce electricity, or electricity can be used to turn the motor. [3]



[3]

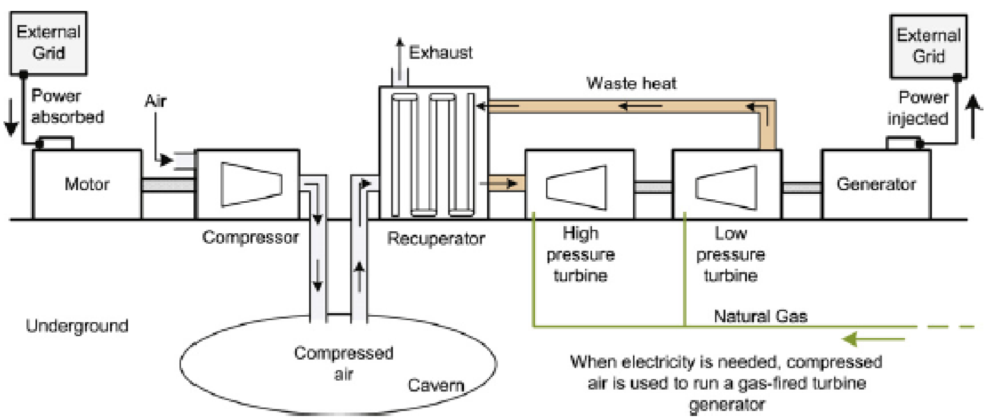
- Advantages: PHS has high power and energy densities. Additionally, this method has the least cost for a large-scale storage project and relatively long expected lifetime.
- Disadvantages: PHS has very specific considerations for site construction, and its construction requires multiple years and large capital investment. PHS can also have a negative impact on marine life in the reservoir.
- Example of Existing Installation: United States has 20.36 GW of pumped hydroelectric storage capacity installed [3].
- Performance Measures: [3][5]

	Pumped Hydro Storage
Efficiency (%)	70-85
Cycle Lifetime (cycles)	N/A
Expected Lifetime (years)	30-60
Specific Energy (Wh/kg)	0.5-1.5
Specific Power (W/kg)	---
Power Capacity Cost ($/kW)	600-2,000
Energy Capacity Cost ($/kWh)	0-23

BOP ($/kWh)	270-580
PCS ($/kW)	0-4.8
O&M ($/kW-yr)	3-4.4
Maturity	Commercial

Compressed Air Energy Storage (CAES)

In compressed air energy storage, excess electricity is used to pump air into underground geological formations until the air is at high pressure. When electricity is needed, the air is released from these underground formations and used to run gas-fired turbine generators. CAES systems are attached to natural gas power plants, where the compressed air is mixed with natural gas for combustion. [3][8]



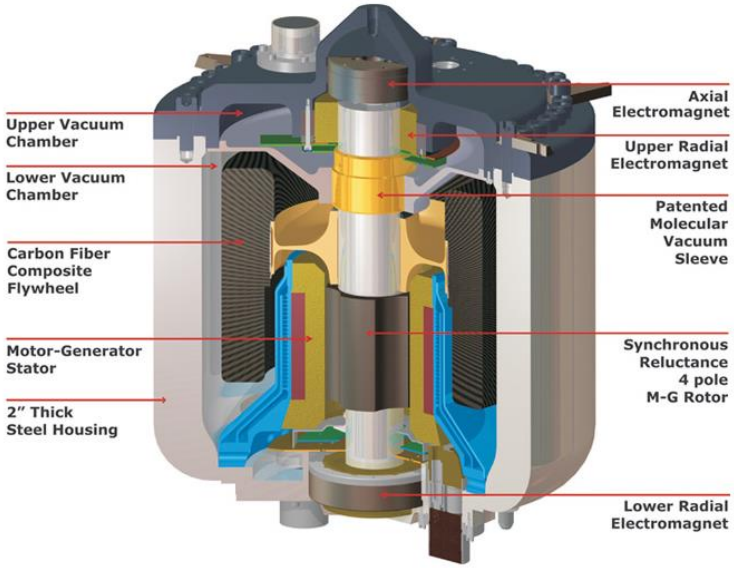
[8]

- Advantages: The similarity of CAES systems to a conventional gas combustion system makes them easy to integrate in the existing grid. CAES systems also have relatively long expected lifetime.
- Disadvantages: CAES systems require specific geographic locations for installations, along with a supply of natural gas. Some CAES installations have relatively low efficiency.
- Example of Existing Installations: Germany has 290 MW and the United Stated has 110 MW of CAES systems installed and functioning [5].
- Performance Measures: [3][5]

	Compressed Air Storage
Efficiency (%)	57-85
Cycle Lifetime (cycles)	N/A
Expected Lifetime (years)	20-40
Specific Energy (Wh/kg)	30-6
Specific Power (W/kg)	---
Power Capacity Cost ($/kW)	400-800
Energy Capacity Cost ($/kWh)	2-140
BOP ($/kWh)	270-580
PCS ($/kW)	46-190
O&M ($/kW-yr)	1.6-29
Maturity	Commercial

Flywheel Energy Storage

Flywheel energy storage systems store kinetic energy as angular momentum. Off-peak electricity is used to power motors that spin large discs, and these discs keep spinning until electricity is required. Once the electricity is required, the spinning discs are connected to generators, and electricity is produced. During electricity generation, the discs slowly lose their momentum and require spinning again. The conventional mechanical bearings of the discs are being replaced by magnetic bearings that significantly reduce friction and increase the efficiency of flywheel energy storage systems. Flywheels that spin under 10,000 RPM are considered low-speed flywheels, and the ones that spin over 10,000 RPM are called high-speed flywheels. [3]



[9]

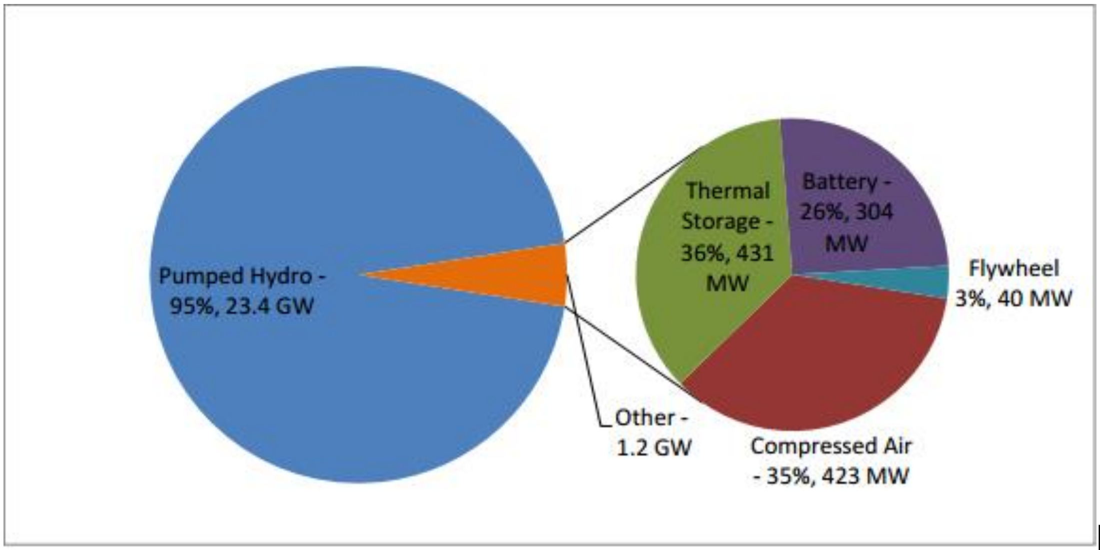
- Advantages: Flywheels have power densities and better cycle lifetime than battery storage technologies.
- Disadvantages: Flywheels have relatively low energy densities and large standby losses due to friction [5].
- Example of Existing Installation: A 20 MW flywheel storage system is installed in Stephentown, New York [10].
- Performance Measures: [3]

	Fly Wheel (Low Speed)	**Fly Wheel (High Speed)**
Efficiency (%)	70-95	70-95
Cycle Lifetime (cycles)	20,000-100,000	20,000-100,000
Expected Lifetime (years)	15-20	15-20
Specific Energy (Wh/kg)	10-30	10-30
Specific Power (W/kg)	400-1,500	400-1,500
Power Capacity Cost ($/kW)	250-360	250-400
Energy Capacity Cost ($/kWh)	230-60,000	580-150,000
BOP ($/kWh)	110-600	110-600
PCS ($/kW)	0-120	0-1,200
O&M ($/kW-yr)	6-22	6-22
Maturity	Developed, but not commercial yet	Developed, but not commercial yet

As of August 2013, there were 202 energy storage system deployments with a combined operational capacity of 24.6 GW in the United States [15]. Of the 202 energy storage systems deployed, 96 energy storage systems are grid-scale with a storage capacity of at least 1 MW [15].

Operational Capacity	**Number of Installations**
1 MW – 10 MW	43
10 MW – 100 MW	19
100 MW – 1 GW	23
Greater than 1 GW	11
	Total = **96**

The pie charts below shows the penetrations of various energy storage technologies in terms of the total energy storage capacity in the United States.



[15]

Pumped hydro storage is by far the most dominant storage technology because of its cost competitiveness and technological feasibility. However, as more resources are being invested in research related to other storage technologies, batteries and flywheels are on track towards playing a bigger role in grid-scale energy storage in the future.

Federal and state governments realize the importance of grid-scale energy storage for electric grid resiliency and are taking steps to promote the development and deployment of these systems. California passed the bill AB 2514 in 2011 to make energy storage more cost effective and easy to regulate [15]. California state law also gives power to the California Public Utilities Commission (CPUC) to mandate certain regional penetration levels for energy storage [15]. In 2010, the State of New York established the NY Battery and Energy Storage Technology Consortium (NY-BEST), a public-private partnership that researches energy storage technology and manufacturing, provides help to energy storage organizations, and advocates for policies that can promote the deployment of energy storage [15]. In 2013, the State of Washington passed laws, HB 1289 and HB 1296, that allow qualifying utilities to credit energy storage output from renewable sources at 2.5 times the normal value, and requires utilities to include energy storage in all integrated resource plans [15]. In addition, the federal government has funded various energy storage projects under the American Recovery and Reinvestment Act of 2009 (ARRA) through the Smart Grid Demonstration Grant program. The results from these demonstration energy storage projects are being used to guide future investment decisions and policy initiatives [15]. Also, the Department of Energy's 2011 Strategic Plan includes a goal of reducing the cost of energy storage by 30% by 2015 [15].

In summary, grid-scale energy storage offers numerous benefits including grid reliability and resiliency. A Cambridge Energy Research Associates (IHS CERA) report states that the energy storage business could grow from $200 million in 2012 to a $19 billion industry by 2017 [15]. This sort of growth in the grid-scale energy storage industry is demonstrative of the crucial role energy storage may come to play in a modernized U.S. electric grid.

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Appendix A

	Lithium-Ion Batteries	Sodium Sulfur Batteries	Vanadium-Redox Batteries	Nickel Cadmium Batteries	Pumped Hydro Storage	Compressed Air Storage	Fly Wheel (Low Speed)	Fly Wheel (High Speed)
Efficiency (%)	85-98	70-90	60-85	60-70	70-85	57-85	70-95	70-95
Cycle Lifetime (cycles)	1,000-10,000	2,500-25,000	12,000-14,000	800-3,500	N/A	N/A	20,000-100,000	20,000-100,000
Expected Lifetime (years)	5-15	5-15	5-15	5-20	30-60	20-40	15-20	15-20
Specific Energy (Wh/kg)	75-200	150-240	10-30	50-75	0.5-1.5	30-6	10-30	10-30
Specific Power (W/kg)	150-315	150-230	166	150-300	---	---	400-1,500	400-1,500
Power Capacity Cost ($/kW)	175-4,000	150-3,000	175-1,500	150-1,500	600-2,000	400-800	250-360	250-400
Energy Capacity Cost ($/kWh)	500-2,500	250-500	150-1,000	600-1,500	0-23	2-140	230-60,000	580-150,000
BOP ($/kWh)	120-600	120-600	120-610	120-600	270-580	270-580	110-600	110-600
PCS ($/kW)	0	0-120	36-120	50-180	0-4.8	46-190	0-120	0-1,200
O&M ($/kW-yr)	12-30	23-61	24-65	6-32	3-4.4	1.6-29	6-22	6-22
Maturity	Commercial	Commercializing	Developed, but not commercial yet	Commercial	Commercial	Commercial	Developed, but not commercial yet	Developed, but not commercial yet