ELECTRIC ENERGY STORAGE

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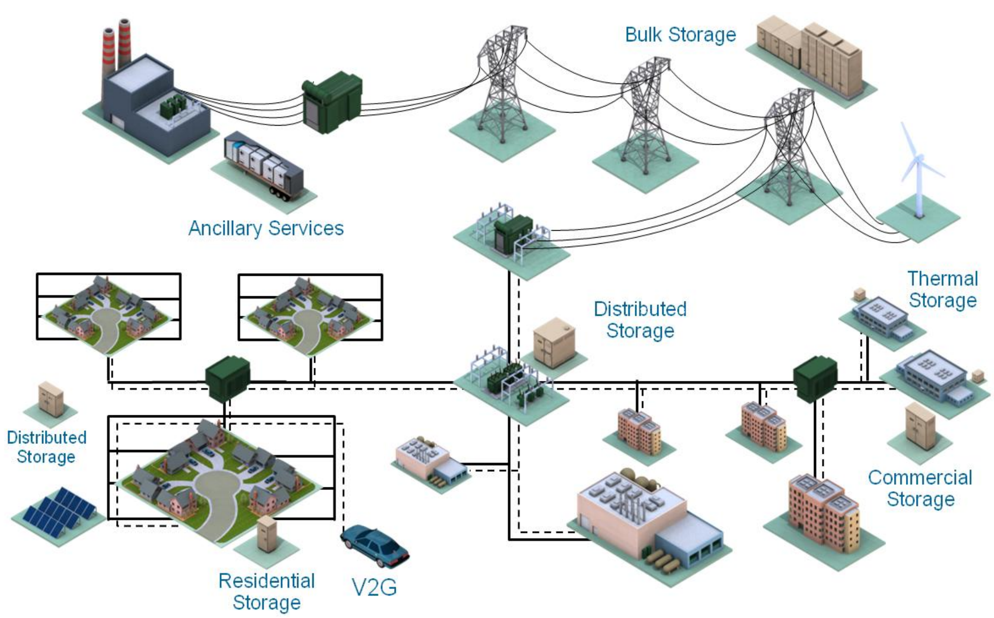
The electric energy storage industry has made significant progress in recent years. This year, for the first time, PSE models two types of storage technology in the IRP analysis: lithium-ion batteries and pumped hydro. In addition, the company is developing a pilot project to test the benefits of battery storage to both the generation and the transmission and distribution functions of the company. This appendix delivers an overview of energy storage technologies, the services they can provide and key development considerations. It presents the assumptions and methodology of our energy storage flexibility analysis, and it describes PSE's pilot project.

OVERVIEW

Electric energy storage (also simply called "energy storage") encompasses a wide range of technologies that are capable of shifting energy usage from one time period to another. These technologies could deliver important benefits to electric utilities and their customers, since the electric system currently operates on "just-in-time" delivery. Generation and load must be perfectly balanced at all times to ensure power quality and reliability. Strategically placed energy storage resources have the potential to increase efficiency and reliability, to balance supply and demand, to provide backup power when primary sources are interrupted and to assist with the integration of intermittent renewable generation. Energy storage is capable of benefiting all parts of the system – generation, transmission and distribution – as well as customers (see Figure L-1).

Throughout this appendix, energy storage resources will be described in terms of their nameplate power rating and their energy storage capacity. For example, a 10 MW/20 MWh storage system is capable of delivering 10 megawatts of AC power for two hours, for a total of 20 megawatt-hours of energy delivered to the grid (10MW x 2 hours = 20 MWhs). Systems can be as large as pumped hydropower facilities that provide hundreds of megawatts of power for many hours or as small as off-grid battery systems that support electric service for small, remote residences and facilities. This flexibility is one of its attractive qualities.

Figure L-1: Overview of Energy Storage Roles on the Electric Grid



Source: EPRI

Recent Industry Developments

The energy storage industry has made significant progress since PSE's last IRP. Among the most notable developments are the following.

- The U.S. installed 61.9 MW of battery energy storage resources in 2014, up 40 percent from 2013, and 180 individual installations were completed. 2015 is expected to be the biggest year in the market's history with 220 MW of deployments, twice the capacity installed in 2013 and 2014 combined.[1]
- Southern California Edison (SCE) procured 250 MW of storage, more than 5 times the requirement mandated by the California Public Utilities Commission (CPUC) Storage Decision.[2] SCE's technology picks ranged from distributed batteries and ice-making air conditioners to the world's largest proposed lithium-ion battery (100 MW/400 MWh). Many of these systems won't be built for several years, but SCE expects that they "will contribute towards grid optimization, greenhouse gas reduction or renewable integration," according to testimony before CPUC.[3]
- Hawaiian Electric Co. launched one of the biggest energy storage requests for proposals for "one or more large-scale energy storage systems able to store 60 to 200 megawatts for up to 30 minutes." The utility seeks at least 60 MW, potentially spread among several separate projects, to help integrate renewable resources, improve reliability and provide auxiliary services to help operate the grid, such as sub-second frequency response and minute-to-minute load following.[4]

1 / GTM Research, U.S. Energy Storage Monitor, 2014 Year in Review. The estimated 220 MW of deployments represents residential, non-residential and utility solar installations in 2015.
2 / California D. 13-10-040 ("the Storage Decision"). In October 2013, the CPUC adopted an energy storage procurement framework and established an energy storage target of 1,325 megawatts for PG&E, Southern California Edison and SDG&E by 2020, with installations required no later than the end of 2024.
3 / Southern California Edison testimony filed with California Public Utilities Commission in support of 2014 Energy Storage Application, 2/28/2014. Retrieved from https://scees.accionpower.com/_scees_1401/documents.asp?strFolder=d. SCE Regulatory Filings/&filedown=&HideFiles=True.
4 / Hawaiian Electric Company web site. "Hawaiian electric close to selecting energy storage providers for Oahu," 9/29/2014. Retrieved from http://www.hawaiianelectric.com/heco/_hidden_Hidden/CorpComm/Hawaiian-Electric-close-to-selecting-energy-storage-providers-for-Oahu?cpsextcurrchannel=1.

- Pacific Gas & Electric (PG&E) issued a request for offers (RFO) in December 2014, pursuant to the CPUC Storage Decision, for up to 74 MW of energy storage resources. Up to 50 MW would be transmission-connected and 24 MW would be distribution-connected. Expected benefits include grid optimization, renewable resource integration and/or a reduction in greenhouse gas emissions. Optimization benefits could include peak reduction, contribution to reliability needs, or deferral of transmission and distribution investments.[5] In its RFO, PG&E stated that the company is soliciting new energy storage systems that would enable it "to defer otherwise necessary investments at up to 5 distribution substations."[6]
- New York regulators approved Con Edison's proposed plan to defer $1 billion in substation upgrades with 52 MW of nontraditional customer- and utility-side solutions by 2018. The program allows Con Edison (ConEd) to procure market-based distributed energy resource solutions like energy efficiency, energy storage, distributed generation and demand-response to reduce load on specific feeders. In February 2014, ConEd introduced a demand management program that includes incentives of $2,100 per kW for battery storage systems sited on customer premises that charge during off-peak hours and discharge during peak periods.
- Oncor released a report concluding that the Electric Reliability Council of Texas (ERCOT) would see net benefits of up to 5 gigawatts from "grid-integrated, distributed electricity storage" if battery prices fall to $350 per kWh. The analysis assumes the capture of as much benefit as possible by integrating the value from increased customer reliability, improved T&D systems and wholesale power market transactions. As a transmission and distribution utility, Oncor is not allowed to put generation assets into its rate base. This report and the legislative efforts it provokes may challenge the conventional separation of transmission and distribution (T&D) from generation.
- Tesla broke ground on its $5 billion "gigafactory" setting the stage to potentially double global production of lithium-ion batteries by approximately 2020. Most of the output will go to electric vehicles (EVs), but about 15 GWh per year is expected to reach the power grid market. Asian competitors (or partners) like Panasonic, LG Chem, NEC/A123 and a host of Chinese contenders continue pushing the volume of lithium-ion battery manufacturing up and costs down.

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5 / PG&E web site, 2014 Energy Storage RFO, "Protocol," page 12, 1/27/15. Retrieved from http://www.pge.com/en/b2b/energysupply/wholesaleelectricsuppliersolicitation/RFO/ES_RFO2014/index.page.
6 / PG&E web site, 2014 Energy Storage RFO, "Appendix E1 - Information for PSA, Distribution Deferral ES," page 1. Retrieved from http://www.pge.com/en/b2b/energysupply/wholesaleelectricsuppliersolicitation/RFO/ES_RFO2014/index.page (1/27/15).

- Snohomish PUD energized the first grid-scale battery system in Washington in late 2014. The 0.5 MW lithium-ion system is located in the Hardeson Substation in Everett. It will serve as a testing ground for developing the Modular Energy Storage Architecture (MESA) standards, as well as for improving reliability and integrating renewable energy. Performance testing and use case analysis began in early 2015.
- Avista deployed a 1 MW battery system at the Schweitzer Engineering Labs (SEL) factory site. Commissioning was completed in June 2015. The goal is to demonstrate providing backup power (outage mitigation), microgrid operation, peaking capacity, grid flexibility, volt/VAR control, and to demonstrate voltage regulation as part of a conservation voltage reduction scheme.[7]
- Some notable failures also took place. Several battery storage companies and integrators went into bankruptcy; however, many reemerged after being purchased by other companies or reorganized. The industry is still young, and it has many nascent players with technologies and business models that are in various stages of development.
- MESA, the Modular Energy Storage Architecture standards group of which PSE is a founding member, launched in October 2014. MESA has proposed a draft specification for communication protocols between energy storage components. Underwriters Laboratories (UL) has also proposed a set of standards for grid electric storage, and work continues on integrating storage with smart inverters for grid management.

7 / *Avista 2015 Electric Integrated Resource Plan Technical Advisory Committee Meeting No. 1 Presentation*

POTENTIAL ELECTRICITY STORAGE SERVICES

Terminology and definitions for the grid services that energy storage may provide are not yet uniform, but the 2013 U.S. Department of Energy DOE/EPRI Electricity Storage Handbook provides the following list (Figure L-2).

Figure L-2: Energy Storage Grid Services

Bulk Energy Services		**Transmission Infrastructure Services**
Electric Energy Time-shift (Arbitrage)		Transmission Upgrade Deferral
Electric Supply Capacity		Transmission Congestion Relief
Avoided Renewable Curtailment		
Ancillary Services		**Distribution Infrastructure Services**
Regulation		Distribution Upgrade Deferral
Spinning, Non-spinning and Supplemental Reserves		Voltage Support
Voltage Support		Outage Mitigation
Black Start		**Customer Energy Management Services**
		Power Quality
		Power Reliability
		Retail Electric Energy Time-shift
		Demand Charge Management

Source: DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA

These applications, how they relate to PSE and some of the potential challenges to adoption are described below. It is important to note that not all of the services described below have been demonstrated in commercial or utility settings. The ability of a single storage resource to provide these services depends on many factors, among them:

1. minimum required energy storage power (MW) and energy (MWh),
2. location requirements,
3. availability requirements (both frequency and duration), and
4. system performance characteristics (response time, ramp rate, etc.).

Moreover, using storage to provide multiple grid services can be complicated, since use for some services can exclude use for other services. For example, an energy storage system that provides transmission reliability service must reserve its storage capacity for contingency needs during certain time periods, rendering it unavailable for other uses during those periods. Detailed modeling is required to evaluate storage resources intended for multiple uses.

Bulk Energy Services. The term "bulk energy services" refers to all of the ways that energy storage is used to avoid the need to generate additional electricity.

ELECTRIC ENERGY TIME-SHIFT (ARBITRAGE). In this application, storage resources stockpile energy for later use, typically charging when the cost of electricity is low and discharging when the cost of electricity is high.

ELECTRIC SUPPLY CAPACITY. In this application, storage resources serve as generation supply capacity resources, similar to peaking plants. Historically, peak load demands – rather than economic conditions – have driven decisions on when to build new power plants. If energy storage can provide reliable peaking capacity, it may enable utilities to postpone or eliminate the need for new peaking power plants. PSE also refers to this service as "Energy Supply Capacity Value."

AVOIDED RENEWABLE CURTAILMENT. When renewable resources like wind continue to produce power even when there is no demand for it, energy storage can store this energy for release when it's needed. In addition to time-shifting, this enables utilities to avoid renewables curtailments that result in the loss of production tax credits (PTCs) and renewable energy credits (RECs).

Ancillary Services. Ancillary services are defined as "those services necessary to support the transmission of electric power from seller to purchaser given the obligations of control areas and transmitting utilities within those control areas to maintain reliable operations of the interconnected transmission system."[8] In other words, these services support the reliable delivery of power and energy over the high voltage transmission system.

REGULATION (OR FREQUENCY REGULATION). Regulation ensures the balance of electricity supply and demand at all times, particularly over short time frames (from seconds to minutes). Because energy storage can both charge and discharge power, it can help manage grid frequency. Many storage technologies can do this faster and more accurately than other regulating resources. Federal Energy Regulatory Commission (FERC) Order 755 requires that ISOs implement mechanisms to pay for regulation resources based on how responsive they are to control signals. Under the new rules, storage resources with high-speed ramping capabilities receive greater financial compensation than slower storage or conventional resources.

8 / U.S. Federal Energy Regulatory Commission 1995, Promoting Wholesale Competition Through Open Access Non-discriminatory Transmission Services by Public Utilities, Docket RM95-8-000, Washington, DC, March 29.

SPINNING RESERVES, NON-SPINNING RESERVES, AND SUPPLEMENTAL RESERVES. Generation capacity over and above customer demand is reserved for use in the event of contingency events like unplanned outages. "Spinning" reserves are generators that are turned on, idling, waiting for the signal to go. Many storage technologies can be synchronized to grid frequency through their power electronics, so they can provide a service equivalent to spinning reserves with minimal to zero standby losses (unlike the idling generators). Energy storage is also capable of providing non-spinning or supplemental reserves, but these services are easier for traditional generators to accomplish cost-effectively.

VOLTAGE SUPPORT. This ancillary service is used to maintain transmission voltage within an acceptable range. Advanced power electronics give storage resources with four-quadrant inverters the capability to inject VARs and correct suboptimal or excessive voltage; however, a number of other devices are capable of providing voltage support at low cost, so the value of this service for energy storage is considered to be low.

BLACK START. This service, typically provided by generators, restores the electric grid following a blackout. While energy storage could theoretically provide this service, black start is of minimal value to PSE, because of its many other low-cost, black start-capable generation resources.

PSE's Open Access Transmission Tariff illustrates the relative cost for PSE to provide ancillary services:

Figure L-3: PSE Open Access Transmission Tariff

Service	Rate ($/kW-yr)
Reactive Supply and Voltage Control	$0.07533
Regulation and Frequency Response	$126.00
Operating Reserve – Spinning	$111.00
Operating Reserve – Supplemental	$108.00

Transmission Infrastructure Services. These services relate to reliability and economics; they enable the electric transmission system to operate more optimally and efficiently.

TRANSMISSION INVESTMENT DEFERRAL. When a generation resource like energy storage or demand-side resources can cost-effectively defer capital expenditure in the transmission system, it's called "transmission investment deferral." Transmission resources are sized to handle peak capacity during normal operation with all elements in service, but it must be designed to meet capacity requirements even when portions of the network are out of service. It is possible to use energy storage to address capacity constraints created by periods of peak demand or specific contingencies; however, this is difficult due to the networked nature of the transmission system and storage specifications such as location, sizing, regulatory requirements and system controls. Also, deferring investment in transmission capacity projects is not always the best solution, since these projects usually increase system reliability and this is a valuable benefit. Radial transmission lines, where the battery could provide backup power, are a major exception.

TRANSMISSION CONGESTION RELIEF. This refers to using storage resources in a geographic area where locational marginal price *(LMP)* is jointly defined by the wholesale market price of energy and the amount of location-specific congestion in the electric system. The storage resource would optimize its dispatch based on an hourly LMP price signal. Since the Pacific Northwest does not use locational marginal pricing, it was not modeled in this analysis.

Distribution Infrastructure Services. These services support the physical infrastructure of the distribution system that connects distribution substations to customer meters.

DISTRIBUTION INVESTMENT DEFERRAL. This is similar to transmission investment deferral, but specific to the distribution system. To relieve overloaded distribution transformers, particularly high-cost substation transformers, energy storage can charge during low load periods and "peak shave" the highest load periods. This may postpone the need for a distribution investment. However, an energy storage system may be limited in its ability to deliver the operational flexibility and reliability improvements that traditional distribution infrastructure provides. For example, using storage to defer a new substation may make it harder to take existing substations offline for maintenance or in response to unplanned outages. For each candidate system, the tradeoffs between reliability, operational flexibility, capacity and cost need to be studied.

DISTRIBUTION VOLTAGE SUPPORT. This service maintains power voltage within acceptable bounds, as defined by ANSI standards (+/- 5 percent of nominal). A storage system could provide voltage support on distribution lines and support a conservation voltage reduction scheme, but the value of this service for energy storage is considered low, because other devices are capable of providing low-cost voltage support.

OUTAGE MITIGATION. When properly designed for this capability, storage resources can provide backup power to the distribution system for a limited time during some outages. For example, if a distribution line had a planned or unplanned outage and a storage resource on the load side of that outage was available for discharge, customers could continue to have electric service during the first few hours of an outage. Complex technical issues need to be addressed and solved regarding the stability, power flow, protection and operation of the "islanded" system, especially as the storage capacity grows.

Customer Energy Management. Although not a part of this study, storage resources placed on the customer side of the meter can also provide direct benefits to customers, such as increased power quality, reliability, the ability to shift consumption to hours with lower energy rates and demand charges.

ENERGY STORAGE TECHNOLOGIES

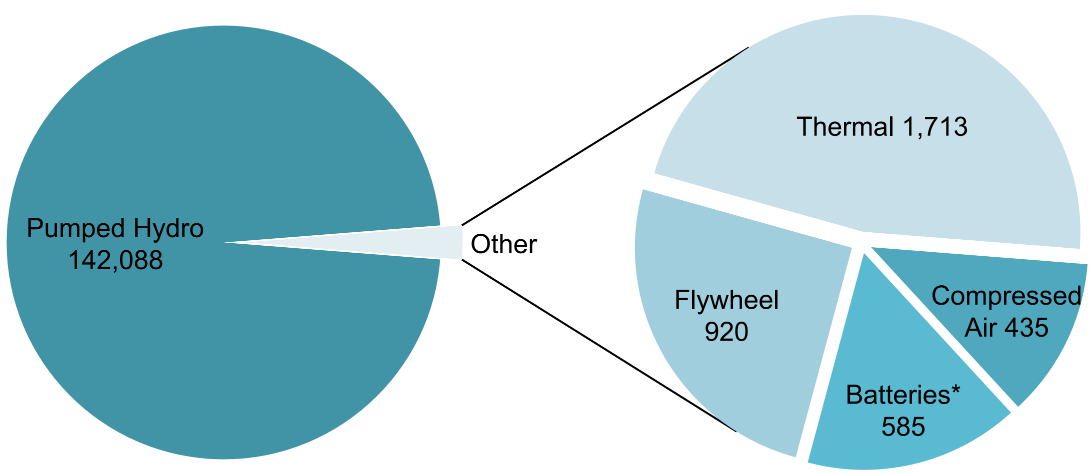
Energy storage encompasses a wide range of technologies and resource capabilities, and these differ in terms of cycle life, system life, efficiency, size and other characteristics.

Figure L-4: Energy Storage Technology Classes

Technology Class	Examples
Chemical Storage	Batteries
Mechanical Storage	Flywheels, Compressed Air
Thermal Storage	Ice, Molten Salt, Hot Water
Bulk Gravitational Storage	Pumped Hydropower, Gravel

Although battery technology has attracted a great deal of industry attention in recent years, pumped hydro technology still supplies the vast majority of grid-connected energy storage (97.5 percent). The remaining categories combined comprise only 2.5 percent of installed capacity, as the chart below illustrates.

Figure L-5: Installed Grid-connected Energy Storage in MW, by Technology, as of 8/2015[9]



*Batteries include Lithium-ion, Flow, Sodium Sulfur, Nickel Cadmium, Lead Acid, Electrochemical Capacitors and Ultracapacitor Batteries

9 / Source: U.S. Department of Energy Global Energy Storage Database (DOE GESDB), August 2015 (http://www.energystorageexchange.org)

Chemical Storage (Batteries)

This class of energy storage includes the following chemistries: advanced lead acid, lithium-ion, sodium-based, nickel-based, flow batteries and electrochemical capacitors. Technologies are further divided into sub-categories based on the specific chemical composition of the main components (anode, cathode, separator, electrolyte, etc.). Each class and sub-category is at a different stage of commercial maturity and has unique power and energy characteristics that make it more or less appropriate for specific grid support applications.

Advanced Lead Acid. Invented in the 19th century, lead acid batteries are the most fully developed and commercially mature type of rechargeable battery. They are widely used in both mobile applications like cars and boats and stationary consumer applications like UPS units and off-grid PV. However, several issues have prevented widespread adoption for utility-scale grid applications. These include short cycle life, slow charging rates and high maintenance requirements.[10] The DOE Energy Storage Database identifies 13 operational projects that have a power rating greater than 1 MW. These perform a variety of services including peak shaving, on-site power, ancillary services, ramping and renewables capacity firming.

Technical Details: Lead acid batteries rely on a positive, lead-dioxide electrode reacting with a negative, metallic lead electrode through a sulfuric acid electrolyte. Ongoing research and development have produced several proprietary technologies in two categories: advanced lead acid and lead acid carbon.

Advanced lead acid batteries incorporate a variety of technological enhancements. Companies such as GS Yuasa and Hitachi are improving system response times with incremental technology enhancements like valve-regulation, solid state electrolyte-electrode configurations and anode electrodes that include capacitors.[11]

While technologically distinct, lead acid carbon is considered a type of advanced lead acid battery.[12] Lead acid carbon batteries add carbon to one or both electrodes. This addresses two major barriers that have limited adoption of lead acid technology: 1) a tendency for sulfate to accumulate on the negative electrode surface which leads to large decreases in capacity and cycle life, and 2) slow charge/discharge rates. Adding carbon reduces sulfate accumulation and allows faster charge and discharge with no apparent detrimental effects.[13]

10 / Navigant (2012)
11 / DOE-EPRI 2013 Energy Storage Handbook
12 / DOE-EPRI 2013 Energy Storage Handbook
13 / DOE-EPRI 2013 Energy Storage Handbook

Research and development by Xtreme Power (now Younicos), Axion Power and Ecoult/East Penn has led to several utility-scale deployments ranging from 1 MW to 36 MW.[14] Improvements in maintenance requirements, cycle life and charging rates are allowing lead acid carbon systems to perform a variety of grid services that were not economic with standard lead acid batteries.

Downsides to lead acid technology include its low power and energy density compared to other batteries, limited life ranges of approximately 6 to 15 years, and toxic lead electrodes and sulfur electrolytes which require special handling and recycling.[15]

Deployments: Deployments total 88 MW/79 MWh in 44 projects. Capacities range from 2 kW/10 kWh to 36 MW/24 MWh. Figure L-6 describes the five largest installations.

Figure L-6: Five Largest Operational Lead Acid Energy Storage Projects[16]

Five Largest Operational Lead Acid Energy Storage Projects, by Energy Rating				
Owner / Project	**Power / Energy (Duration)**	**Technology**	**Location**	**Primary Function**
Duke Energy / Notrees	36 MW / 24 MWh (40 minute)	Advanced lead acid	Goldsmith, TX	Renewables capacity firming
Kuroshio Power / Shiura Wind Park	4.5 MW / 10.5 MWh (2.3 hour)	Valve regulated lead acid	Aomori, Japan	Renewables capacity firming
Shonai Wind Power Generation Co. / Yuza Wind Farm Battery	4.5 MW / 10.5 MWh (2.3 hour)	Valve regulated lead acid	Yamagata, Japan	Renewables capacity firming
First Wind LLC / Kaheawa Wind Project II	10 MW / 7.5 MWh (45 minute)	Advanced lead acid	Maalaea, HI	Renewables capacity firming
GridSolar Boothbay Pilot Project: BESS	0.5 MW / 3 MWh (6 hour)	Valve regulated lead acid	Boothbay, ME	Energy time shift, supply capacity

Lead acid deployments of 11 MW/13 MWh are either planned or under construction. Nine MW of these are from 3 projects.[17]

14 / CELA, Sandia (2012)
15 / IEC (2011)
16 / DOE GESDB (2015)
17 / DOE GESDB (2015)

Lithium-ion. First commercialized in 1991, lithium-ion batteries have experienced tremendous research and development investment and publicity in the last few years due to their high energy density, voltage ratings, cycle life and efficiency. They have been the preferred battery technology for portable electronic devices and electric vehicles, and now they are being scaled up and deployed for utility grid services. Approximately 70 systems with power ratings of 1 MW or greater are currently in operation around the world. Because it can adapt to a range of power and energy ratings, this technology can perform a wide variety of services. Grid-scale units range from small, regulation pilot projects of 1 MW/0.5 MWh (30 minute duration) to large 8 MW/32 MWh (4 hour duration) and 32 MW/8 MWh (15 minute duration) systems that perform ramp control and wind and solar integration.[18]

Technical Details: Lithium-ion is a broad technology class that includes many sub-types. Sub-type classifications generally refer to the cathode material.[19] Some common chemistries are compared in Figure L-7.

Figure L-7: Comparison of Lithium-ion Chemistries[20]

Chemistry (Shorthand)	Safety	Energy	Power	Life	Cost	Summary
	Scale 1-5 with 5 Best					
Lithium Manganese Oxide (LMO)	3	4	3	3	4	Versatile technology with good overall performance & cost
Lithium Iron Phosphate (LFP)	3	3	4	4	3	Similar to LMO, but slightly more power & less energy
Lithium Nickel Cobalt Aluminum (NCA)	1	3	4	4	2	Good for power applications; poor safety & high cost per kWh
Lithium Titanate (LTO)	5	2	5	5	2	Excellent power & cycle life; high cost per kWh
Lithium Nickel Manganese Cobalt (NMC)	3	4	4	4	4	Versatile technology with good overall performance & cost

Lithium-ion technologies are also divided by cell shape: cylindrical, prismatic or laminate. Cylindrical cells have high potential capacity, lower cost and good structural strength. Prismatic cells have a smaller footprint, so they are used when space is limited (as in mobile phones). Laminate cells are flexible and safer than the other shapes.[21]

18 / DOE GESDB (2015)
19 / Yoshio et al. (2009)
20 / Hardin (2014)
21 / Citi (2012)

Lithium-ion battery advantages include high energy density, high power, high efficiency, low self-discharge, lack of cell "memory" and fast response time; challenges include short cycle life, high cost, heat management issues, flammability and narrow operating temperatures.[22]

Deployments: Approximately 312 MW/333 MWh of lithium-ion projects are currently in operation, and - more than 70 projects have power ratings of 1 MW or larger. These utility-scale systems can be separated into two categories: high power, short duration projects that perform frequency regulation and high energy projects that help to integrate intermittent renewable generation.

Figure L-8: Five Largest Operational Lithium-ion Energy Storage Projects[23]

Five Largest Operational Lithium-ion Energy Storage Projects, by Energy Rating				
Owner / Project	**Power / Energy (Duration)**	**Technology**	**Location**	**Primary Function**
State Grid Corporation of China / Zhangbei National Wind and Solar Energy Storage and Transmission Project	6 MW / 36 MWh (6 hour)	Lithium-ion-phosphate	Hebei, China	Renewable generation shifting
Southern California Edison / Tehachapi Wind Energy Storage Project	8 MW / 32 MWh (4 hour)	Lithium-ion	Tehachapi, CA	Renewable generation shifting
State Grid Corporation of China / Zhangbei National Wind and Solar Energy Storage and Transmission Project	4 MW / 16 MWh (4 hour)	Lithium-ion-phosphate	Hebei, China	Renewable generation shifting
Hawaii Renewable Partners / Hawi Wind Farm BESS	1 MW / 15 MWh (15 hour)	Lithium-ion	Hawaii	Renewables capacity firming
Invenergy / Grand Ridge Energy Storage	31.5 MW / 12.08 MWh (23 minute)	Lithium-ion-phosphate	Marseilles, IL	Frequency regulation

There are more than 45 lithium-ion projects with anticipated power ratings greater than 1 MW either planned or under construction, totaling 355 MW.[24]

22 / PNNL (2012)
23 / DOE GESDB (2015)
24 / DOE GESDB (2015)

Sodium Sulfur. Sodium sulfur (NaS) battery technology was invented by Ford Motors in the 1960s, but research, development and deployment by Japanese companies like NGK Insulators and Tokyo Electric Power Company over the past 25 years have established NaS as a commercially viable technology for fixed, grid-connected applications. Commercially deployed systems in the 400 kW to 34 MW power rating range (and system duration of roughly 6 hours) provide numerous high-energy grid support applications.[25]

Technical Details: Sodium sulfur batteries use a positive electrode of molten sulfur, a negative electrode of molten sodium and a solid beta alumina ceramic electrolyte that separates the electrodes. Batteries require charge/discharge operating temperatures between 300-350°C, so each unit has a built in heating element. High operating temperatures and hazardous materials require the systems to include safety features like fused electrical isolation, hermetically-sealed cells, sand surrounding cells to mitigate fire and a battery management system that monitors cell block voltages and temperatures. Typical units are composed of 50 kW modules that are available in multiples of 1 MW/~6 MWh (approximately 6 hour duration). Units are combined in parallel to create large-scale systems, typically between 2 and 10 MW.[26]

The advantages of sodium sulfur are its high power and long duration, extensive deployment history and commercial maturity. Downsides include risk of fire, round-trip efficiencies of 70 percent to 90 percent, and potentially high self-discharge/parasitic load values of 0.05 percent to 20 percent due to the internal heating requirements.[27] NaS is much less efficient for infrequent cycling applications because the internal heating element continually consumes energy.

Deployments: To date about 98.1 MW/640 MWh of sodium sulfur technology is deployed at approximately 26 sites globally, with systems ranging in size from 400 kW to 34 MW. Most installations are in Japan, but 10 systems have been commissioned in the U.S. in the past 10 years. Peak shifting is the most frequent application, but specified services include renewables capacity firming, transmission and distribution upgrade deferral, frequency regulation and electric supply reserve capacity.

25 / DOE-EPRI 2013 *Energy Storage Handbook*
26 / DOE-EPRI 2013 *Energy Storage Handbook*
27 / *SBC Energy Institute (2013)*

Figure L-9: Five Largest Operational Sodium Sulfur Energy Storage Projects[28]

Five Largest Operational Sodium Sulfur Energy Storage Projects				
Owner / Project	**Power / Energy (Duration)**	**Technology**	**Location**	**Primary Function**
Japan Wind Development / Rokkasho Village Wind Farm	34 MW / 238 MWh (7 hour)	Sodium sulfur	Rokkasho Village, Japan	Renewable generation shifting
Tokyo Metropolitan Government / Morigasaki Water Reclamation Center	8 MW / 58 MWh (7.25 hour)	Sodium sulfur	Tokyo, Japan	Load leveling
Hitachi / Automotive Plant ESS	9.6 MW / 57.6 MWh (6 hour)	Sodium sulfur	Ibaraki, Japan	Load leveling
Abu Dhabi Water & Electricity Authority / BESS	8 MW / 48 MWh (6 hour)	Sodium sulfur	Abu Dhabi, United Arab Emirates	Load leveling
American Electric Power / Presidio ESS	4 MW / 32 MWh (8 hour)	Sodium sulfur	Presidio, TX	Ancillary services

The DOE Global Energy Storage Database lists three deployments that are planned or under construction. All three are for Italian utility TERNA and they total 35 MW/278 MWh.

Sodium Nickel Chloride. Sodium nickel chloride batteries ($NaNiCl_2$) are also referred to as ZEBRA (Zero Emissions Battery Research). Their operating characteristics are similar to those of sodium sulfur, but this technology is still in a demonstration and limited deployment stage. GE and FIAMM have currently deployed about 15 installations with power ratings that range from 20 kW/70 kWh (3.5 hour duration) to 1 MW/2 MWh (2 hour duration). These systems are used primarily for integrating renewable generation, providing voltage support, load following and frequency regulation.

Technical Details: In sodium nickel chloride batteries, the cathode is composed of nickel-chloride instead of sulfur. These require operating temperatures between 260°C and 350°C and therefore must have internal thermal management capability. Able to withstand limited overcharging, they are potentially safer than sodium sulfur, and they have a higher cell voltage. Typical cells are 20 kWh, so system power and energy ratings are also easier to customize to a given application than sodium sulfur.[29]

28 / DOE GESDB (2015)
29 / IEC (2011)

Sodium nickel chloride advantages include scalability, the ability to operate in a wide temperature range (-40°C to 60°C),[30] long cycle life, and easy recycling of battery materials.[31] Disadvantages include lack of maturity, commercial deployments, high cost and thermal management.[32]

Deployments: Approximately 3.4 MW/6.4 MWh of sodium nickel chloride installations are operating around the world.[33]

Figure L-10: Five Largest Operational Sodium Nickel Chloride Energy Storage Projects[34]

Five Largest Operational Sodium Nickel Chloride Energy Storage Projects				
Owner / Project	**Power / Energy (Duration)**	**Technology**	**Location**	**Primary Function**
Wind Energy Institute of Canada / Durathon Battery	1 MW / 2 MWh (2 hour)	Sodium nickel chloride	Prince Edward Island, Canada	Renewable generation shifting
General Electric / Wind Durathon Battery Project	0.3 MW / 1.2 MWh (4 hour)	Sodium nickel chloride	Tehachapi, TX	Renewable generation shifting
PDE Inc. / 29 Palms Durathon Battery Project	0.5 MW / 1 MWh (2 hour)	Sodium nickel chloride	Palm Springs, CA	Microgrid
Western Power Distribution / Falcon Project	0.25 MW / 0.5 MWh (2 hour)	Sodium nickel chloride	Milton Keynes, United Kingdom	T&D upgrade deferral
Duke Energy / Rankin Substation ESS	0.4 MW / 0.3 MWh (42 minutes)	Sodium nickel chloride	Mount Holly, NC	Renewable capacity firming

A half dozen deployments are planned or under construction in the United States, Italy and the Maldives.[35] While most of these systems are planned to be rated at 100 kW to 400 kW, two Italian installations are planned to be rated at 1 MW and 4 MW.

30 / GE Website (2014)
31 / EUROBAT Website (2014)
32 / V. Antonucci (2012)
33 / DOE GESDB (2015)
34 / DOE GESDB (2015)
35 / DOE GESDB (2015)

Nickel-based. The two main sub-technologies in the nickel-based family are nickel cadmium (NiCd), which has been in commercial use since 1915, and nickel metal hydride (NiMH), which became available around 1995. Nickel-based batteries are primarily used in portable electronics and electric vehicles due to their high power density, cycle life and round-trip efficiency. Only two operational projects have energy ratings greater than 1 MWh. One of them provides electric supply reserve capacity in Alaska, and the other performs renewable capacity firming on Bonaire Island. Although Sandia states that "Nickel-cadmium and nickel metal hydride batteries are mature and suitable for niche applications,"[36] the fact that so few grid-scale deployments exist suggests that nickel-based technology is not yet competitive with other battery types.

Technical Details: All nickel-based batteries employ a cathode of nickel hydroxide. Sub-categories are classified by anode composition: nickel cadmium, nickel iron, nickel zinc, nickel hydrogen and nickel metal hydride. The first three use a metallic anode; the last two have anodes that store hydrogen.

Nickel cadmium chemistry is a low-cost, mature technology with high energy density, but the toxicity of cadmium necessitated a search for alternatives. Nickel metal hydride was developed in response. The metal hydride chemistry is safer and has a higher specific energy than nickel cadmium, but it charges slower and does not withstand very low operating temperatures.[37] Nickel metal hydride's safety made it the battery of choice for electric and hybrid vehicles, but lithium-ion is challenging this status. Other nickel chemistries are in the research and development phase.

Deployments: Deployments of nickel-based batteries total 30.4 MW/7.9 MWh, of which 27MW/ 6.8MWh is installed in one project. Figure L-11 shows the three largest nickel-based energy storage projects on the DOE Global Energy Storage Database that are not owned by private citizens.

36 / DOE-EPRI 2013 Energy Storage Handbook: p109
37 / Linden (2001)

Figure L-11: Three Largest Nickel-based Energy Storage Projects[38]

Three Largest Operational Nickel-based Energy Storage Projects				
Owner / Project	**Power / Energy (Duration)**	**Technology**	**Location**	**Primary Function**
Golden Valley Electric Association / Battery Energy Storage System	27 MW / 6.75 MWh (15 minutes)	Nickel cadmium	Fairbanks, AK	Electric Supply Reserve - Spinning
EcoPower Bonaire BV / Bonaire Wind-Diesel Hybrid	3 MW / 0.25 MWh (5 minutes)	Nickel cadmium	Bonaire, Netherlands	Renewables capacity firming
Okinawa Electric Power Company / Minami Daito Island	0.3 MW / 0.08 MWh (15 minutes)	Nickel metal hydride	Okinawa, Japan	Frequency regulation

According to the DOE Global Energy Storage Database, there are no megawatt scale nickel-based projects currently planned or under construction.

Flow Batteries. Flow batteries are fundamentally different than other types of electrochemical storage because the systems' power and energy components are separate. This feature allows flow systems to be tailored to specific applications and constraints. A number of megawatt-scale demonstration projects are testing the deep discharge ability, long cycle life and easy scalability that characterize flow batteries. Some chemistries have been more extensively developed and deployed than others; maturity ranges from development stage (for iron-chromium and zinc-bromine) to pre-commercial (for vanadium). Projects in operation range from 5 MW/10 MWh (2 hour duration) to 3 kW/8 kWh (2 hour, 40 minute duration). The larger projects are focused on integrating renewables, while many of the smaller pilots are testing for peak shaving and ancillary services as well.[39]

Technical Details: One or both of a flow battery's active materials is in solution in the electrolyte at any given time. In traditional flow batteries, the electrolyte solution is stored in separate containers and pumped to the cell stack and electrodes where an oxidation-reduction reaction occurs. This allows the electrolyte tanks (energy) and cell stack (power) to be sized separately, which makes these systems very flexible.[40]

38 / *DOE GESDB (2015)*
39 / *DOE-EPRI 2013 Energy Storage Handbook*
40 / *Gyuk/ESTAP (2014)*

Several chemistries have proven technically feasible, including vanadium-vanadium (V^{n+}), iron-chromium (Fe-Cr) and zinc-bromine ($ZnBr_2$). Iron-chromium's advantages are a very safe electrolyte and abundant and low-cost materials.[41] Vanadium uses ions of the same metal on both sides of the reaction, which prevents the crossover degradation that occurs in other flow batteries as ions try to cross the cell membrane.[42] Zinc-bromine combines the features of a conventional battery and flow battery: One electrolyte is stored in an external tank and the other is stored internally in the electrochemical cell. The zinc-bromine chemistry allows higher power and energy densities than other flow batteries but bromine is also corrosive and can lead to component degradation and failure.[43]

Deployments: Vanadium flow batteries are the most mature and commercially deployed systems, as can be seen in Figure L-12. Of the approximately 20 MW/47 MWh of flow battery capacity installed globally, 19 MW/45 MWh are vanadium batteries.

Figure L-12: Five Largest Operational Flow Battery Energy Storage Projects[44]

Five Largest Operational Flow Battery Energy Storage Projects				
Owner / Project	**Power / Energy (Duration)**	**Technology**	**Location**	**Primary Function**
GuoDian LongYuan (Shenyang) Wind Power Co. / GuoDian LongYuan Wind Farm VFB	5 MW / 10 MWh (2 hour)	Vanadium redox	Liaoning, China	Renewable generation shifting
State Grid Corporation of China / Zhangbei National Wind and Solar Energy Storage and Transmission Project	2 MW / 8 MWh (4 hour)	Vanadium redox	Hebei, China	Renewable generation shifting
J-Power / Tomamae Wind Farm	4 MW / 6 MWh (1.5 hour)	Vanadium redox	Hokkaido, Japan	Renewables capacity firming
Sumitomo Electric Industries / Yokohama Works VRB	1 MW / 5 MWh (5 hour)	Vanadium redox	Kanagawa Japan	Renewable generation shifting
Prudent Energy / Gills Onions VRB	0.6 MW / 3.6 MWh (6 hour)	Vanadium redox	Oxnard, CA	Grid-connected commercial (reliability & quality)

41 / Horne/ESTAP (2014)
42 / IEC (2011)
43 / Sandia (2013)
44 / DOE GESDB (2015)

Worldwide, approximately 56 MW/228 MWh of operational flow battery deployments are planned or under construction.[45]

Supercapacitors. Also called electrochemical double-layer capacitors and ultracapacitors, this technology class bridges the gap between batteries and traditional capacitors; it stores energy electrostatically. Supercapacitors are characterized by low internal resistance, which allows rapid charging and discharging, very high power density (but low energy density) and high cycle life.[46] Current deployments are primarily used in voltage support, ramping and regenerative braking in transportation applications. Most are between 300 kW/3 kWh and 1 MW/17 kWh. The technology is still considered to be in demonstration phase.[47]

Technical Details: Supercapacitors use carbon electrodes with very high surface area to create a solid-liquid interface that allows electricity to be stored by the separation of charge, rather than through chemical transformation like traditional batteries.[48] Advantages of supercapacitors include high power density (40-120kW/l), very fast response time (<1 seconds), high efficiency (80 percent to 98 percent), and high cycle life (10k-100k).[49] Disadvantages include low specific energy (30Wh/kg) and corresponding high cost per kWh.

Deployments: Fourteen operational deployments are listed in the DOE Global Energy Storage Database; 11 are rated 1 MW or greater. Total installed capacity is approximately 21.5 MW/0.1 MWh, and the largest projects are summarized in Figure L-13. Supercapacitors installed as standalone energy storage systems focus almost exclusively on providing near-instantaneous voltage ramping and regenerative braking for trains.

45 / DOE GESDB (2015)
46 / IEA-ETSAP/IRENA (2012)
47 / SBC Energy Institute (2013), Sandia ES Handbook (2013)
48 / S. Badwal et al. (2014)
49 / SBC Energy Institute (2013)

Figure L-13: Five Largest Operational Supercapacitor Energy Storage Projects[50]

Five Largest Operational Supercapacitor Energy Storage Projects				
Owner / Project	**Power / Energy (Duration)**	**Technology**	**Location**	**Primary Function**
Electrical Power worX / LIRR Malverne WESS: Ioxus	1 MW / 16 kWh (1 minute)	Ultracapacitor	Malverne, NY	Transportation Services
Electrical Power worX / LIRR Malverne WESS: Maxwell	1 MW / 16 kWh (1 minute)	Ultracapacitor	Malverne, NY	Transportation Services
Incheon Transit Corporation / Incheon Line 1 - Technopark Station	2.3 MW / 13 kWh (33 seconds)	Ultracapacitor	Incheon, South Korea	Transportation Services
Seoul Metro / Seoul Line 2 - Seocho Station	2.3 MW / 13 kWh (33 seconds)	Ultracapacitor	Seoul, South Korea	Transportation Services
Seoul Metro / Seoul Line 4 - Ssangmun Station	2.3 MW / 13 kWh (33 seconds)	Ultracapacitor	Seoul, South Korea	Transportation Services

According to the DOE Global Energy Storage Database, 56 MW/452 kWh of additional deployments are planned or under construction.[51]

50 / DOE GESDB (2015)
51 / DOE GESDB (2015)

Mechanical Storage

Mechanical storage technologies use compressed air and flywheels to store energy.

Compressed Air. Compressed air energy storage (CAES) resources compress air and store it in a reservoir, typically underground caverns or above-ground storage pipes or tanks. Underground facilities are considered less expensive than aboveground and can operate for between 8 and 26 hours; however, siting underground compressed air storage facilities requires finding geologically suitable caverns.[52] Above-ground facilities are more modular and less location-sensitive. According to the DOE, the typical above-ground compressed air storage facility is in the 3 MW to 50 MW power range, with durations of two to six hours;[53] however, the additional incremental cost is significant. DOE cites cost of between $4,900 and $5,000 per MW for a 50 MW/5 hour above-ground system.[54] Figure L-14 shows operational compressed air storage facilities.

Figure L-14: Five Largest Operational Compressed Air Storage Facilities[55]

Owner / Project	Nominal Power / Energy (Duration)	Technology	Location	Primary Function
E. ON / Kraftwerk Huntorf	321 MW / 642 MWh (2 hours)	In-ground natural gas combustion	Elsfleth, Germany	Electric energy time-shift
PowerSouth Utility Cooperative / McIntosh CAES Plant	110 MW / 2,860 MWh (26 hours)	In-ground natural gas combustion	McIntosh, AL	Electric energy time-shift
General Compression, Inc. / Texas Dispatchable Wind	2 MW / 500 MWh (250 hours)	In-ground iso-thermal	Seminole, TX	Renewable generation shifting
SustainX Inc. / Isothermal Compressed Air Energy Storage	1.5 MW / 1.5 MWh (1 hour)	Modular iso-thermal	Seabrook, NH	Renewable generation shifting
Highview Power Storage / Pilot Plant	.35 MW / 2.45 MWh (7 hours)	Modular	Slough, United Kingdom	Renewable generation shifting

52 / *DOE-EPRI 2013 Energy Storage Handbook, p.38.*
53 / *Ibid, p.38.*
54 / *Ibid, p.39-40.*
55 / *DOE GESDB (2015)*

Flywheels. Flywheels are the other mechanical energy storage technology. They accelerate a rotor (flywheel) to a very high speed in a very low-friction environment. The spinning mass stores potential energy to be discharged as necessary. Flywheels are modular and can range from 22 kW in size (Stornetic's EnWheel) to 160 kW (Beacon Power).

Flywheels are best for short-duration, high power, high-cycle applications. They also have a much longer cycle life than other storage alternatives. Flywheels are less heat sensitive than batteries and they last longer (up to 20 years guaranteed performance). Power grid uses include voltage/VAR support and frequency regulation. Primary competitors to flywheels are supercapacitors or ultracapacitors.

Figure L-15: Five Largest Operational Flywheel Facilities[56]

Owner / Project	Nominal Power / Energy (Duration)	Location	Primary Function
European Fusion Development Agreement / EFDA JET Fusion Flywheel	400 MW / 3.3 MWh (50 seconds)	Abingdon, United Kingdom	Onsite power
Max Planck Institute, EURATOM Association / ASDEX-Upgrade Pulsed Power Supply System	387 MW / 0.77 MWh (12 seconds)	Bavaria, Germany	Onsite power
Spindle Grid Regulation, LLC / Beacon Power 20 MW Flywheel Plant	20 MW / 5 MWh (15 minutes)	Stephentown, NY	Frequency regulation
Spindle Grid Regulation, LLC / Beacon Power 20 MW Flywheel Plant	20 MW / 5 MWh (15 minutes)	Hazle Township, PA	Frequency regulation
NRStor Inc. / Minto Flywheel Energy Storage Project	2 MW / 0.5 MWh (15 minutes)	Ontario, Canada	Frequency regulation

56 / DOE GESDB (2015)

Thermal Storage

Thermal storage comes in many forms; the most well-known bulk thermal storage solution is molten salt. Paired with solar thermal generation plants, molten salt thermal storage is used to improve the dispatchability of concentrated solar power (CSP) facilities. The stored energy powers steam turbines to continue generation after the solar day has ended. Because PSE has no thermal solar generating facilities and no plans to acquire such, this technology is not explored further in this assessment.

Figure L-16: Five Largest Operational Bulk Thermal Storage Facilities[57]

Owner / Project	Nominal Power / Energy (Duration)	Technology	Location	Primary Function
Abengoa Solar / Solana Solar Generating Plant	280 MW / 1,680 MWh (6 hours)	Molten salt	Gila Bend, AZ	Renewable generation shifting
Brazos Electric Cooperative / TAS Texas Cooperative	90 MW / 1,080 MWh (12 hours)	Chilled water	Joplin, TX	Electric supply capacity
Abengoa Solar / Kaxu Solar One	100 MW / 250 MWh (2 hours, 30 minutes)	Molten salt	Northern Cape, South Africa	Renewable generation shifting
ACS - Cobra Group / Manchasol 2 Solar Plant	50 MW / 375 MWh (7.5 hours)	Molten salt	Alcazar de San Juan, Spain	Renewable generation shifting
Ortiz – TSK –Magtel / La Africana Solar Plant	50 MW / 375 MWh (7.5 hours)	Molten salt	Posadas, Spain	Renewable generation shifting

Other forms of thermal storage are more distributed in nature. These primarily interact with building heating and cooling systems and support demand-side services such as demand response. Some technologies, such as direct load control of water heaters, have already demonstrated deployment in electrical and heating networks. SCE and PG&E recently awarded contracts to IceEnergy for distributed thermal storage to reduce air conditioning loads. Although promising, many of these technologies are aimed at reducing peak loads during high temperature periods; since PSE is a winter-peaking utility, they are not necessarily a good fit for PSE or our customers' needs.

57 / DOE GESDB (2015)

Bulk Gravitational Storage

Bulk gravitational storage includes technologies such as pumped hydro and gravel in railcars.

Pumped Hydro. Pumped hydro is a mature technology used throughout North America and the world. Off-peak power is used to pump water from a lower reservoir to a higher reservoir; then the water is released to generate electricity during peak periods. Because pumped hydro facilities require above ground reservoirs, specific land configurations are needed. Pumped hydro projects are rarely located close to urban centers, and permitting can take many years due to their large environmental impact.

Figure L-17: Operational Pumped Hydro Storage in Washington State

Owner / Project	Nominal Power / Energy (Duration)	Location	Primary Function
Bonneville Power Administration / John W. Keys III Pump-Generating Plant	314 MW / 25,120 MWh (80 hours)	Grand Coulee, WA	Electric supply capacity

Gravel/Railcar. The gravel/railcar storage method operates in a similar manner to pumped hydro. Off-peak power is used to move rail cars filled with gravel or another heavy material up a slope. When power is needed, the railcar moves down the slope, converting gravitational energy into electricity as it moves down.

Unlike pumped hydro, railcar/gravel energy storage does not require reservoirs to function. Rather, it requires a long slope of existing or new railroad track. This makes it potentially easier to site than pumped hydro, although it is still not suitable for urban areas, nor is it suitable for railroad segments where there is existing traffic.

Figure L-18: Planned Railcar Energy Storage Facility

Owner / Project	Nominal Power / Energy (Duration)	Location	Primary Function	Status
ARES North America / Advanced Rail Energy Storage Nevada	50 MW / 12.5 MWh (15 minutes)	Pahrump, NV	Load following, voltage support	Announced

DEVELOPMENT CONSIDERATIONS

Siting Storage

The siting of an energy storage resource is an important consideration for development feasibility; it affects both costs and benefits. Some resources, like pumped hydro, must be located in areas with specific geology, water access and transmission lines. Natural gas combustion turbines have similar constraints, plus they face air emissions constraints in many locations as well. Many forms of storage, particularly batteries and ice energy, are more flexible when it comes to sizing and siting. Battery resources can be sized from 20 kW to 1000 MW and sited at the customer's location or interconnected to the transmission system. Other factors may also limit where storage can be located, among them space availability, permitting and interconnection upgrade requirements. A few examples of different siting options for battery storage resources follow.

54 kW/54 kWh customer-sited lithium-ion battery.

1 MW/2 MWh customer-sited lithium-ion battery.

4 MW/2 MWh distribution-connected lithium-ion battery

Proposed 100 MW/400 MWh transmission-connected battery.

Development Timelines

Different energy storage resources have significantly different project development timelines. These range from months to years, depending on the technology type, siting, size, permitting and interconnection requirements.

Pumped Hydro and CAES. Pumped hydro and CAES storage facilities, due to their size and environmental impacts, require significantly longer development timelines for analysis, design and extensive permitting activity than many storage resources. It can take 5 to 10 years (or more) to complete one of these projects, depending on public support or opposition for a particular project, the ability to negotiate environmental impact studies and other necessary approvals. Their large size and often remote location also may mean that new transmission is needed; obtaining the necessary permits and regulatory approvals required to start transmission construction can also take years, although this activity may take place concurrently with storage facility planning.

Batteries and Flywheels. Battery or flywheel storage projects can move from concept to commissioning in two to three years. Smaller systems (in the 1 MW to 5 MW) range have been commissioned in less than two years. Timeframes are even shorter for the modular containerized systems that can be installed in the field; these can be brought online within months after they reach the project site.[58] Customer-sited energy storage could be deployed in a matter of months, assuming the systems become standardized and the interconnection process is streamlined, as has happened with distributed solar systems.

Large-scale development projects (20+ MW) are subject to the requirements of the FERC-mandated Large Generator Interconnection Process. PSE would be required to complete interconnection studies before an interconnection agreement could be signed. After the agreement is obtained, it can take anywhere from six months to several years before the project is ready to interconnect to the grid, depending on the complexity of the required interconnection facilities.

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58 / DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA, Sec. 4.3

PSE STORAGE ANALYSIS

Technologies Modeled

PSE chose two categories of storage technologies to evaluate in this IRP analysis. The resources had to be commercially available at large scale and feasible to develop and bring online by 2018. The resources that met these criteria were:

- Electrochemical storage (batteries)
- Pumped hydro

Ultimately, three energy storage/flexibility sensitivities were tested in the Base Scenario for the 2015 IRP.[59]

1. 80 MW of battery storage was added to the portfolio in 2023 instead of the peaker economically chosen by the analysis.
2. 80 MW of pumped hydro storage was added to the portfolio in 2023 instead of the economically chosen peaker.
3. 200 MW of pumped hydro storage was added to the portfolio in 2023 instead of the economically chosen peaker.

In the following pages, we explain the rationale for selection of these alternatives and the cost assumptions used in the analysis. The results of these analyses are presented in Chapter 6, Electric Analysis.

Selecting Battery Technology. Within the battery category, there are many promising chemistries to choose from. To choose a single chemistry to represent the "generic battery," PSE assessed the different chemistries' readiness for large-scale deployment using the DOE Global Energy Storage Database (2014) to review the ten largest electrochemical storage projects in the world (by both power rating and energy rating) and the 10 largest projects announced or under construction.[60] These are described in Figures L-19, L-20 and L-21.

59 / See Chapter 4, Key Analytical Assumptions for a discussion of the portfolio sensitivities reviewed in the 2015 IRP.
60 / http://www.energystorageexchange.org/

Figure L-19: Largest Operational Electrochemical Storage Projects by Power Rating (MW)[61]

Owner / Project	Power / Energy	Technology	Location	Primary Function
Duke Energy / Notrees	36 MW / 24 MWh	Advanced lead acid	Goldsmith, TX	Renewables capacity firming, electric energy time-shift; frequency regulation
Japan Wind Development / Rokkasho Village Wind Farm	34 MW / 238 MWh	Sodium sulfur	Rokkasho Village, Japan	Renewables capacity firming, renewables energy time-shift; capacity spinning reserves
AES / Laurel Mountain	32 MW / 8 MWh	Lithium-ion	Elkins, WV	Frequency regulation and ramping
GVEA / Battery Energy Storage System	27 MW / 6.8 MWh	Nickel cadmium	Fairbanks, AK	Capacity spinning reserves, grid-connected residential (reliability), grid-connected commercial (reliability & quality)
BYD / Shenzen	20MW / 40MWh	Lithium-ion	Shenzen, China	Self-regulation of load, peak shaving
AES / Angamos	20 MW / 6.6 MWh	Lithium-ion	Mejillones, Chile	Frequency regulation and capacity spinning reserves
AES / Tait	20 MW / unknown	Lithium-ion	Moraine, OH	Frequency regulation
NextEra - Frontier	20MW / unknown	Lithium-ion	Illinios	Frequency regulation
AES / Los Andes	12 MW / 4 MWh	Lithium-ion	Atacama, Chile	Frequency regulation and capacity spinning reserves
Sempra / Auwahi Wind Farm	11 MW / 4.4 MWh	Lithium-ion	Kula, HI	Wind ramping

[61] DOE GESDB (2014)

Figure L-20: Largest Operational Electrochemical Storage Projects by Energy Rating (MWh)[62]

Owner / Project	Power / Energy	Technology	Location	Primary Function
Japan Wind Development / Rokkasho Village	34 MW / 238 MWh	Sodium sulfur	Rokkasho Village, Japan	Renewables capacity firming, renewables energy time shift, spinning reserves
Tokyo Metropolitan Government Bureau of Sewage / Morigasaki	8 MW / 58 MWh	Sodium sulfur	Ota-ku, Japan	Electric bill management, electric energy time-shift
Hitachi Ltd., Automotive Systems Group / Hitachi Automotive Plant	9 MW / 54 MWh	Sodium sulfur	Hitachinaka, Japan	Electric bill management, electric energy time-shift
Abu Dhabi Water & Electricity Authority / ADWEA	8 MW / 48 MWh	Sodium sulfur	Abu Dhabi, United Arab Emirates	Electric energy time-shift
BYD / Shenzen	20MW / 40MWh	Lithium-ion	Shenzen, China	Self-regulation of load, peak shaving
State Grid Corporation of China / Zhangbei	6 MW / 36 MWh	Lithium-ion	Zhangbei, China	Renewable generation shifting, renewable capacity firming, frequency regulation
Southern California Edison / Tehachapi	8 MW / 32 MWh	Lithium-ion	Tehachapi, CA	Voltage support, electric capacity, renewables capacity firming, transmission congestion relief
American Electric Power / Presidio	4 MW / 32 MWh	Sodium sulfur	Presidio, TX	Reliability and power quality, electric capacity, non-spinning reserves, voltage support
Okinawa Electric Power Company / Miyako Island	4 MW / 28.8 MWh	Sodium sulfur	Miyakojima Japan	Renewables capacity firming, renewables generation shifting
Pacific Gas & Electric Company / Yerba Buena	4 MW / 28 MWh	Sodium sulfur	San Jose, CA	Grid-connected commercial (reliability and quality), frequency regulation, renewables capacity firming, on-site power

[62] DOE GESDB (2014)

Figure L-21: Largest Electrochemical Storage Projects Announced or Under Construction, by Power Rating (MW)[63]

Owner / Project	Power / Energy (MW/MWh)	Tech	Location	Status	Primary Function
AES / Alamitos	100 MW / 400 MWh	Lithium-ion	Los Alamitos, CA	Announced	Flexible supply capacity
AES / Kilroot	50 MW / unknown	Lithium-ion	Carrickfergus, N. Ireland	Announced	Renewables capacity firming, renewables energy time-shift
Tohoku Electric / Sendai Substation	40 MW/ 20 MWh	Lithium-ion	Sendai, Japan	Under construction	Frequency regulation, voltage support
Invenergy / Grand Ridge	31.5 MW / 12.1 MWh	Lithium-ion	Marseilles, IL	Under construction	Non-spinning capacity reserves
Invenergy / Beech Ridge	31.5 MW / unknown	Lithium-ion	Rupert, WV	Under construction	Frequency regulation, ramping, renewables capacity firming
Alaska Railbelt Cooperative / Anchorage Area ESS	25 MW / 14.1 MWh	Lithium-ion	Anchorage, AK	Announced	Spinning electric supply reserves, transmission/distribution upgrade deferral, electric energy time-shift
AES / Cochrane	20 MW / 6.3 MWh	Lithium-ion	Mejillones, Chile	Announced	Supply capacity, electric energy time-shift
RES Americas / Jake	20 MW / 7.9 MWh	Lithium-ion	Illinois	Under construction (?)	Frequency regulation
RES Americas / Elwood	20 MW / 7.9 MWh	Lithium-ion	Illinois	Under construction (?)	Frequency regulation
Imperial Irrigation District 20 MW BESS	20 MW / unknown	Lithium-ion	Imperial, CA	Announced	Spinning electric capacity reserves, renewable generation shifting, renewables capacity firming

63 DOE GESDB (2014)

Based on this review, PSE chose to model lithium-ion as the large-scale generic battery resource in this IRP for the following reasons:

1. The majority of large projects (especially those announced or under construction) use lithium-ion technology.
2. Cost estimates are more readily available in publically accessible data (though not complete).
3. More data is available on the spectrum of system configurations and sizes, including the on the sizing and timing of systems announced in Southern California Edison's Local Capacity Resources procurement.

For an actual RFP solicitation, PSE will evaluate all proposed technologies based on least-cost and best-fit criteria, including technical and commercial considerations such as warranties, performance guaranties and counterparty credit, etc.

Sizing Assumptions

Unlike conventional generation resources like combustion turbines, battery storage resources are modular, scalable and expandable. It is possible to build the infrastructure for a large storage system and install storage capacity in increments over time as needs grow. This flexibility is a valuable feature of the technology.

Battery Storage Sizing. To simplify the scope of this analysis we modeled 80 MW of generic lithium-ion battery storage resources.

In the next step, we defined energy storage capacity (MWh). To be cost effective, battery systems must have sufficient storage to provide necessary grid services, but without being prohibitively expensive due to extremely long discharge duration. Through prior modeling, PSE determined that a two-hour battery storage system would earn a 100 percent incremental capacity equivalent (ICE) for supply capacity. This should be more than sufficient for system flexibility/ancillary services applications, which require less than one-hour discharge duration.

Pumped Hydro Sizing. Pumped hydro resources are generally large, on the order of 100 MW to 3,000 MW. Most development proposals that PSE has seen have been greater than 400 MW. PSE would not need to purchase the output of an entire plant, as long as others were interested in splitting the output of a particular project. Most likely, any potential pumped hydro resource acquisition would be for a “slice” of the resource, not the entire facility output. This analysis tests two amounts of pumped hydro storage, 80 MW and 200 MW. Both are assumed to be a portion of a larger facility. Based on recent project proposals we have seen, 10 hours of discharge duration is common, so the 80 MW alternative represents 800 MWh and the 200 MW alternative represents 2,000 MWh.

Performance Metrics

Key performance metrics for storage resources include the charge and discharge rates and round-trip efficiency (RTE).

Charge/Discharge Power. Some batteries can discharge at a higher power than they can recharge, others can charge and discharge at equal rates. This affects the overall value of the resource, since ancillary services and flexibility require both the injection and withdrawal of power from the grid.

Round-trip Efficiency. Round-trip efficiency (RTE) refers to the amount of energy that an energy storage system (ESS) can deliver to the grid relative to the amount of energy it withdraws from the grid ESS during its preceding charge cycle. The RTE of energy storage technologies varies substantially. Higher round-trip efficiency is more desirable, all else equal. Differences among technology classes can be significant, but differences due to operational profiles and the environment can be even greater. An average AC-to-AC 85 percent round-trip efficiency for the generic resources system is assumed for this analysis. This does not include standby losses. These are not well known, but they are likely to be an important metric to consider for an actual acquisition.

Degradation. Cycling on the battery system creates wear and tear that eventually causes the system to begin to lose *energy* storage capability over time. Charge and discharge *power* are not affected. The exact amount of degradation that will occur depends on the specific chemistry and the frequency and nature of cycling. For this analysis, we assume a degradation rate of 2 percent per year. At this rate, a 20-year-old system would have about 68 percent of the storage capacity it had when new.

Generic Costs

There is no simple formula for estimating the cost of storage resources at this time. Most systems are custom-designed, built and tailored for very specific, customer-identified applications and sites, so costs vary significantly.

Generic Battery System Costs. PSE reviewed publicly available cost data from existing projects and market research reports that discussed cost trends and estimates for projects recently contracted in California and Hawaii. We also consulted with experienced battery storage project developers regarding recent cost estimates specific to the size of the generic resource being modeled.

PILOT PROJECTS REVIEWED. Few examples are available of detailed costs for large, completed grid-scale systems. We looked closely at two projects: SCE's Tehachapi Wind Energy Storage Project and PSE's Glacier project in Whatcom County.

SCE commissioned the Tehachapi Project, an 8 MW/32 MWh lithium-ion system, in June 2014 with the help of a U.S. Department of Energy grant. When the project was approved for the American Recovery and Reinvestment Act Smart Grid Demonstration Program Funding in 2010, total project cost was estimated at $50,000,000. Actual incurred costs are unknown, but this provides a useful cost data point of $6,250 per kW and $1,562 per kWh. This includes batteries, battery operating systems (BOS), interconnection and every other component.

PSE's 2 MW/4.4 MWh lithium-ion Glacier project in Whatcom County is estimated to cost approximately $11,800,000, which translates to approximately $5,900 per kW and $2,682 per kWh. Economies of scale are important for system costs, which is why the cost per kilowatt-hour for PSE's system is higher than for the SCE Tehachapi system.

Significant non-recurring design, engineering and integration costs are included in both projects, so they may be more costly than future deployments. Many fixed costs don't scale dramatically as the project size increases; permitting and interconnection study costs for a 2 MW project and a 20 MW project are largely the same, for example.

The above pilot projects were priced in 2009 and 2013, respectively. Forward pricing for storage systems delivered in 2018 is significantly lower due to substantial market expansion and increased competition in both the battery and balance-of-systems marketplace. For these reasons, direct cost comparisons between these pilots and the larger-scale 80 MW deployment modeled here have only limited usefulness. They are instructive, however, in terms of showing a cost ceiling.

Battery Cell Costs. The majority of publicly available price research focuses on battery cell costs, especially lithium-ion, because of its widespread use in the electric vehicle market and the transparency of that pricing. Brattle Group, Bloomberg New Energy Finance, Morgan Stanley, CITI Research and Navigant Research all project lithium-ion prices will decrease significantly over the next few years. Price estimates for 2014 ranged from $350 to $700 per kWh. Combining and averaging these sources into one analysis, IBM Research - Australia estimated the current price at approximately $600 per kWh. This is supported by a December 2014 report from UBS. When IBM Research examined future cost projections in the 2015–2020 timeframe, they estimated a range of $200 per kWh to $354 per kWh. Many of the studies averaged were from 2011 and 2012, so they do not reflect the cost reductions experienced in the last few years. In 2014, Tesla estimated its battery cell costs in the $200 to $300 per kWh range.

Based on conversations with an experienced storage resource developer, PSE combined cell cost, battery management system and enclosure costs because these components generally scale with the amount of energy storage (kWh). Estimates ranged from $390 per kWh to $380 per kWh for the 80 MW system, reflecting economies of scale and buying power for the larger system. Given the general trend towards declining prices and the economies of scale that can be obtained with large systems, we believe these cost estimates to be reasonable.

Balance of Systems and Construction Costs. Grid-interconnected batteries require many components in addition to battery cells. Known as balance-of-system (BOS) components, these include power electronics (inverters), control modules, enclosures, interconnection studies and facilities, permitting, installation materials and labor, and contingencies. The Rocky Mountain Institute (RMI) estimates that BOS represents 63 percent of the total installed cost for a 200 kW/200 kWh commercial energy storage system, and 74 percent for a residential system.

The largest BOS costs are associated with power electronics; this includes the inverter/power conditioning system (PCS) and control module/battery management system (BMS). UBS analysts estimate BOS costs to be in the $400 to $500 per kWh range for large-scale systems. Our discussions with vendors suggest that BOS is better evaluated on a cost per power (kW) basis rather than kWh.

For this analysis, PSE assumes $195 per kW for the 80 MW system. In addition to BOS and cell cost, PSE assumes a construction cost of 10 percent to 15 percent of the combined cell and BOS cost.

Land, Permitting and Interconnection. Many project costs, such as interconnection facilities, step-up transformers, transformer installation, switchgear, IT and communications, land and permitting, are utility- and site-specific; in a contracting agreement these constitute “owner’s costs.”

Battery System Cost Assumption Summary

A reasonably good cost comparable to the generic battery peaker storage configurations above is the 100 MW/400 MWh system that Southern California Edison recently contracted for with AES Energy Storage in its LCR procurement. UBS estimates this project to cost roughly $1,500 per kW (implying $375 per kWh). Because the project will be installed at an existing, permitted thermal plant, the land, permitting and interconnection costs likely constitute a relatively small portion the total cost, so we believe the majority of this total system cost comes from batteries and BOS.

PSE assumptions result in a total estimated system cost of $1,498 per kW for the 80 MW unit. This compares reasonably with the estimated cost for the AES-SCE project described in the paragraph above. The cost per kWh is substantially higher for the PSE generic than the SCE project because the SCE project has a 4-hour duration and the PSE generic has a 2-hour duration.

Pumped Hydro Cost Assumptions. Pumped hydro costs are difficult to generalize because they depend so heavily on facility configuration and site-specific costs. For this analysis we use estimates from the March 2014 report "Capital Cost Review of Power Generation Technologies" Prepared by Energy + Environmental Economics (E3) for the Western Electric Coordinating Council, which assumed $2,400 per kW for capex and $15 per kW per year for fixed operations and maintenance for a facility in the West that equals or exceeds 250 MW.

Figure L-22: Summary of Generic Storage Resource Assumptions

2014 $	Units	Battery	Pumped Storage Hydro
Nameplate Capacity	MW	80	200*
Winter Capacity	MW	80	200
Capital Cost	$/kW	$1,498	$2,400
O&M Fixed	$/kW-yr	$7.71	$15.00
O&M Variable	$/MWh	$0.00	$0.00
Capacity Factor	%		
Capacity Credit	%	100%	100%
Total Hours Discharge	Hours	2	10
Location		PSE	WA/OR
Fixed Transmission	$/kW-yr	$0.00	$20.83
Variable Transmission	$/MWh	$0.00	$0.34
First Year Available		2019	2030
Economic Life	Years	20	60
Greenfield Development & Construction Lead time	Years	3	15

** In this analysis, PSE modeled 200 MW and 80 MW of pumped hydro storage using the same cost assumptions.*

Methodology

This analysis evaluates the benefits of storage to the generation system, so its methodology is consistent with that used for traditional generation resources like combustion turbines and reciprocating engines. The generic storage resources are assumed to provide supply capacity, system flexibility and oversupply reduction services to the portfolio.

System Flexibility Methodology. As a Balancing Authority (BA), PSE must retain enough flexibility in the system to keep it in balance at all times, despite moment-to-moment variations in demand and generation. Energy storage may be able to provide valuable system flexibility, though it must be evaluated and compared with other resources that can provide similar flexibility.

The Pacific Northwest does not have a market for ancillary services such as regulation and spinning reserves, so PSE estimated the flexibility benefit provided by storage with a proprietary production cost model that simulates PSE's generation operations with and without energy storage in the generation resource stack. This analysis results in a record of unit deployment for PSE's dispatchable generation, quantifies how each unit contributes to system balancing, and calculates the avoided fuel and operational costs due to using the storage resource instead of traditional resource.

The Resource Integration Team modeled the generic battery system configurations using a subset of the 250 Aurora simulations used in the 2013 IRP, limited to the year 2018. In this analysis, the resulting value of the battery storage was $99.52 per kW per year. This value was considered a benefit to the resource and therefore subtracted from the total fixed operations and maintenance cost in the sensitivity analysis.

This analysis estimates the theoretical potential value of the storage resource, but further work must be done to determine if it can actually provide this value to due to control and operational issues. The operation of storage resource for system flexibility requires a high level of communications and controls and also compliance obligations and would have to meet specific regional reliability coordinator requirements.

See Appendix H, Operational Flexibility, for more information on system flexibility and for a full description of the methodology used to evaluate energy storage in this context.

Energy Supply Capacity Value Methodology. If an energy storage resource can discharge reliably during peak load conditions, it has the potential to defer or avoid the fixed costs of acquiring new generation. Since storage resources' discharge duration is limited, especially batteries, they may not be useful for peak load events and grid contingency events when extended duration is needed. To evaluate this, the IRP team performed and updated Incremental Capacity Equivalent (ICE) analysis for several storage device configurations.

The ratio of the equivalent gas peaker capacity to the alternative resource capacity is the ICE, or the capacity credit, of the alternative resource. The capacity credits for PSE's existing and prospective resources were developed by applying the ICE approach – which is similar to the equivalent load carrying capability (ELCC) approach – with our loss of load probability (LOLP) model. In essence, this identifies the equivalent capacity of a gas-fired peaker plant that would yield the same loss of load probability as the capacity of a different resource such as a wind farm, energy storage facility or even a fixed purchased power contract.

Pilot Project

Glacier Project. In partnership with the Washington State Department of Commerce, PSE is developing a battery storage pilot project in Glacier, a small town east of Bellingham, Wash. The project will involve the installation of a 2 MW/4.4 MWh lithium-ion battery system that will interconnect to the 12.5 kV distribution system near Glacier's existing substation.

Glacier is served by a radial transmission and distribution line that runs along a heavily forested scenic highway and the town experiences frequent and lengthy outages because of how challenging it is for repair crews to reach and repair the lines during storms. The project is funded in part by a $3.8 million Smart Grid Grant from the State Department of Commerce; PSE's investment is estimated at $7.9 million.

The Glacier project tests three primary use cases:

- Outage mitigation
- System-wide peaking (supply capacity)
- System flexibility

The project is currently in the design stage. After the battery system is commissioned, Pacific Northwest National Laboratories (PNNL) will conduct four to six months of testing and evaluation. Identifying the performance and economic benefits of the project will help PSE determine the feasibility of future applications for this technology.

For more information on the Glacier project, go to:
http://pse.com/inyourcommunity/pse-projects/system-improvements/Pages/Glacier-battery-storage-project.aspx