Energy Storage Technology Assessment

Prepared for Public Service Company of New Mexico

HDR Report No. 10060535-0ZP-C1001

Revision B - Draft

October 30, 2017

Principal Investigators
Todd Aquino, PE
Chris Zuelch, PE
Cristina Koss

Table of Contents

ACRONYMS:

AC	Alternating Current
BMS	Battery Management System
BOP	Balance of Plant
CAES	Compressed Air Energy Storage
CAISO	California Independent System Operator
DC	Direct Current
DOD	Depth of Discharge
DOE	US Department of Energy
EMS	Energy Management System
EPC	Engineer Procure Construct
EPRI	Electric Research Power Institute
ERCOT	Electric Reliability Council of Texas
ESS	Energy Storage System
FERC	Federal Energy Regulatory Commission
GE	General Electric
GW	Gigawatt
HMMP	Hazardous Material Management Plan
IESO	Independent Electricity System Operator
IPP	Independent Power Producer
ISO-NE	ISO New England
ISO	Independent System Operator
kW	Kilowatt
kWh	Kilowatt Hour
LAES	Liquid Air Energy Storage
LFP	Lithium Iron Phosphate
Li-ion	Lithium Ion (Battery)
LMO	Lithium Manganese Oxide (Battery)
LTO	Lithium Titanate (Battery)
MISO	Midcontinent Independent System Operator
MW	Megawatt
NaS	Sodium Sulfur (Battery)
NERC	North American Electric Reliability Corporation
NMC	Lithium Nickel Manganese Cobalt Oxide (Battery)
NYISO	New York Independent System Operator
PCS	Power Conversion System
PG&E	Pacific Gas & Electric
PHS	Pumped Hydro Storage
PJM	Pennsylvania Jersey Maryland Interconnection
PNM	Public Service Company of New Mexico
PNNL	Pacific Northwest National Laboratory
POI	Point of Interconnection
PREPA	Puerto Rico Electric Power Authority
RTO	Regional Transmission Organization
SCE	Southern California Edison
SPP	Southwest Power Pool
T&D	Transmission and Distribution
TEPCO	Tokyo Power Electric Company

TMEIC	Toshiba Mitsubishi-Electric Industrial Systems Corporation
UET	UniEnergy Technologies
UPS	Uninterruptible Power Supply
VrB	Vanadium Redox Flow Battery
WECC	Western Electricity Coordinating Council

I. Scope

Public Service Company of New Mexico (PNM) is investigating generation and energy storage technologies in support of its 2017 – 2036 Integrated Resource Plan. As part of these efforts, this Energy Storage Technology Assessment report is intended to provide technology characteristics and estimated cost information for some of the currently available energy storage technologies. Technologies evaluated include:

- Battery Storage
- Compressed Air Energy Storage
- Liquid Air Energy Storage
- Hybrid Battery / Turbine Technologies (combined turbine generation with battery storage)
- Pumped Hydro Storage

As there are many energy storage technologies and alternatives available in the marketplace, this report is not intended to be all encompassing, but inclusive of some of the more widely considered alternatives in the industry. This report includes current technology updates and cost trends and in no way limits the energy storage technologies that PNM will consider or evaluate through its planning processes. The technology updates are broken down by current stage of commercialization, utility applications with associated value streams, and a detailed list of technology performance metrics.

It is not the intention of this report to endorse or promote any specific technology or vendor, but strives to incorporate a wider picture of the energy storage industry as it applies to utilities.

II. Introduction / Purpose

The grid scale energy storage industry is growing quickly towards maturity in terms of technology and ability to serve multiple purposes. While much of the most recent press and excitement has been associated with batteries, pumped hydropower storage (PHS) generating plants initiated the application of utility energy storage technology with the first plant in the U.S. commissioned in 1929. With PHS, the ability to use stored water to generate on-demand electricity has been useful in balancing and following transmission grid demands. Energy storage has evolved to include multiple types of technologies supporting both regional and islanded electrical transmission and distribution (T&D) grids worldwide.

The energy storage industry is challenging from a new entrant perspective given a lack of regulatory mandate for such and difficulties in monetizing the value of energy storage. Reduced project development and construction timelines are needed to support investments in energy storage to address critical grid reliability issues. In addition, production cost models are not granular enough to quantify the revenue streams that can be translated into a straightforward power purchase contract or an understanding of actual market exposure. It is very important that all participants, including regulators, market operators, transmission providers, and end users clearly understand the benefits, risks, and costs of energy storage in the power market.

Storage systems offer the following recognized benefits to the transmission grid, and in some locations many of these benefits are being monetized to a limited degree in local markets.

- Arbitrage;
- Capacity (Resource Adequacy);
- Demand Response/Demand Charge Reduction;
- Frequency Regulation and Automatic Generation Control (AGC);
- Resilience;
- Variable Renewables Integration;
- T&D System Upgrade Deferral; and
- Other Ancillary Services:
  - Voltage Support;
  - Spinning Reserve.

Table 1 below compares the technologies studied in this report with the applications above. One of the challenges related to storage is understanding the right application for the right technology. Details of the suitability of each technology for short duration (power) applications and long duration applications (energy) as represented by frequency regulation and resource adequacy are discussed in this report. Regardless of technical suitability, commercial maturity, project lifetime, and cost typically drive the technology selection. For example, Li-ion batteries are well suited to short duration (power) applications, but they are also used for long duration (energy) applications due to the state of commercial development compared to flow batteries. Some applications, such as transmission upgrade deferral, may require multiple types of technologies to meet the individual needs of the transmission owner.

Table 1 examines the suitability of these technologies when implemented solely for the identified application or use case. When combining multiple use cases, alternate technologies may be considered suitable. For instance, NaS batteries are not suitable for stand-alone frequency regulation. However, they are suitable to provide frequency regulation if also installed for T&D System Upgrade Deferral.

Table 1. Storage Technology vs. Application

	Batteries				Other			
	Li-ion	Lead Acid	NaS	Flow Batteries	Flywheel	Compressed Air Energy Storage	Liquid Air Energy Storage	Pumped Hydro Storage
Frequency Regulation and Response (FRR)	S	US	US	US	S	PS	PS	S
Capacity (Resource Adequacy)	S	S	S	S	US	S	S	S
Combined FRR and Resource Adequacy	S	US	S	PS	US	PS	PS	S
Arbitrage	S	PS	PS	PS	US	S	S	S
Demand Response/Demand Charge Reduction	S	S	PS	PS	US	S	S	S
Grid Asset Optimization and Resilience	S	PS	PS	PS	PS	S	S	S
Variable Renewables Integration	S	S	S	PS	PS	PS	PS	S
T & D System Upgrade Deferral	S	S	S	PS	US	PS	PS	S
Other Ancillary Services								
Voltage Support	PS	US	US	US	US	PS	PS	S
Spinning Reserve	PS	S	PS	PS	US	PS	PS	S

Key

S - Suitable: Has been used for this application at the pilot or commercial level

PS - Potentially Suitable: Has the potential to be used for this application, but few or no installations exist

US- Unsuitable: Unlikely to be suitable for this application

III. The Need for Energy Storage

Why is there a need for energy storage? The answer is that energy storage can profoundly improve on how we generate, deliver, consume and pay for electricity. Energy storage systems (ESS) have the ability to integrate variable energy resources, to mitigate net load challenges, and to provide electricity during emergency outages caused by storms, unscheduled equipment outages, power supply transients, accidents or even unwelcome intentional disruption. Energy storage has an inherent ability to balance power supply and demand instantaneously, within milliseconds, providing a more resilient, efficient, and sustainable solution than ever before.

Peaking generation is one of the most costly aspects of grid power supply. ESS's can facilitate the delay of new capital investment in generating and resource-intensive peaking generation facilities. Over large territory networks such as PJM's (the power transmission operator in the mid-Atlantic region), energy storage systems are providing cost effective frequency regulation while helping cut emissions as it takes more of the load off fossil-fuel generation. PJM has projected that a 10-20% reduction in its frequency regulation capacity procurement could result in $25 million to $50 million savings to consumers. ESS's also allow distribution utilities and commercial customers to lower costs through avoiding premium pricing that they are charged during times of peak demand.

ESS usage can be categorized into three main areas, bridging supply, balancing load, and maintaining power quality. The first category, bridging supply, ensures there is no break in service during the seconds-to-minutes requirement needed to change from one generation asset to another.. The second, balancing load, allows for the shift of energy consumption forward, often by several hours, so that a portfolio of existing generating assets can be used efficiently. Storage also helps to mitigate the significant ramping effects during the late afternoon of increasing air conditioning load and decreasing output that result from extensive solar development. Lastly, ESS's have the ability to support power quality through voltage and frequency control modes on the grid. Power quality is an area of increasing usage for utility and IPP owned storage as developing markets provide for the payment of these type services.

ESS usage is also extremely valuable for integrating variable energy resources. Variable energy resources provide a sustainable source of energy that uses no fossil fuel and produces zero carbon emissions. One of the constraints of variable generation is that the energy available is non-dispatchable; it tends to vary and is somewhat unpredictable and therefore cannot be dispatched specifically when energy is needed to meet load demand. As more variable energy is added to the power system, additional reserves are required. Flexible and dispatchable generators, such as hydro, CAES, or batteries, are required to provide system capacity and balancing reserves to balance load in the hour-to-hour and sub-hour time-frame.

It should be mentioned that variability is not a new phenomenon in power system operation. Demand has fluctuated since the first consumer was connected to the first power plant. The resulting energy imbalances have always had to be managed, mainly by dispatchable power plants. The evolution of variable energy resources in the system is an additional, rather than a new, challenge that presents two elements: variability (now on the supply-side as well), and uncertainty.

IV. Energy Storage Technologies

Multiple energy storage technologies with proven commercial performance are currently available, such as pumped hydro storage (PHS), compressed air energy storage (CAES), various battery technologies, and flywheels. Each type of system offers benefits and challenges when deployed to provide solutions for utilities or commercial users.

PHS does offer tremendous ramping capabilities and reserve capacity to the grid; EPRI indicated that PHS accounts for over 99% of global energy storage system (ESS) installations. In the United States, there are approximately 40 PHS projects totaling over 20 GW of installed capacity. There are also two operating geologic CAES systems worldwide, but CAES has not been widely constructed. Isothermal CAES is gaining commercial maturity at much smaller scales and may be suited for behind-the-meter demand side management applications.

There is not a “one type fits all” energy storage solution available. Each technology offers performance characteristics, capital or life cycle cost advantages, or proven commercial traits which can be utilized to achieve certain end needs. In addition, system characteristics define whether such energy storage technologies could be better suited for “behind the meter” applications for benefits to a single user or “in front of the meter” with intrinsic benefits to the transmission or distribution system. Behind the meter systems are typically installed for reducing peak demand, to offer back-up power supply, or to stabilize the local power supply system; said installations also include “islanded” systems where grid connection may or may not exist. In front of the meter systems target benefits identified in Section II and such systems are the primary focus of this report.

V. Battery Storage Technologies

The most significant growth in energy storage installations has been in the area of battery technologies. In 2016, it has been reported that over 300 MWH of battery capacity was been installed in the U.S. with over 95 percent of this capacity being lithium ion battery technology.

The following charts summarize the rated capacities of battery storage systems that have been operating and have been contracted to complete installation in the US as provided by the DoE’s Energy Storage Database.

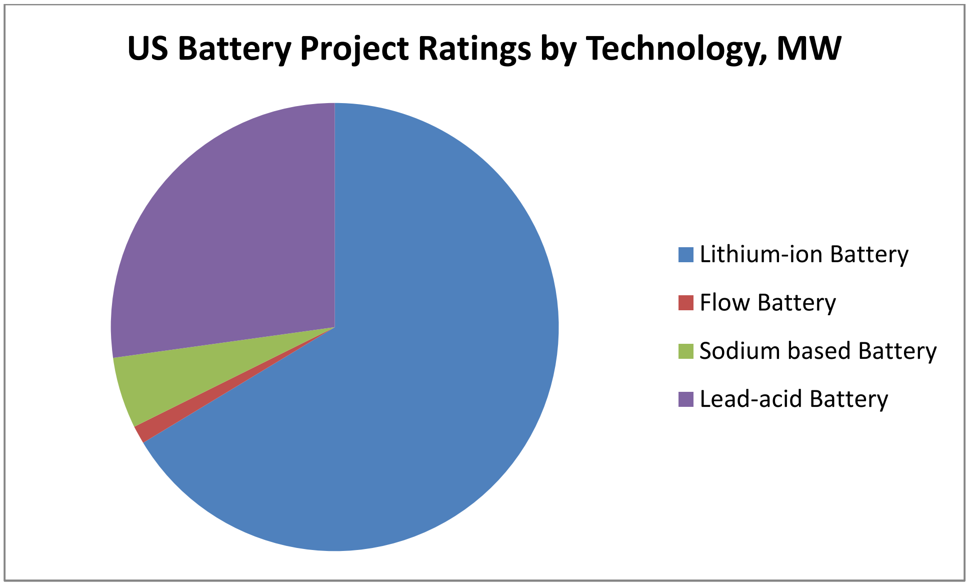


Figure 1 - Rated MW Capacity of US Battery Energy Storage Projects (Existing)

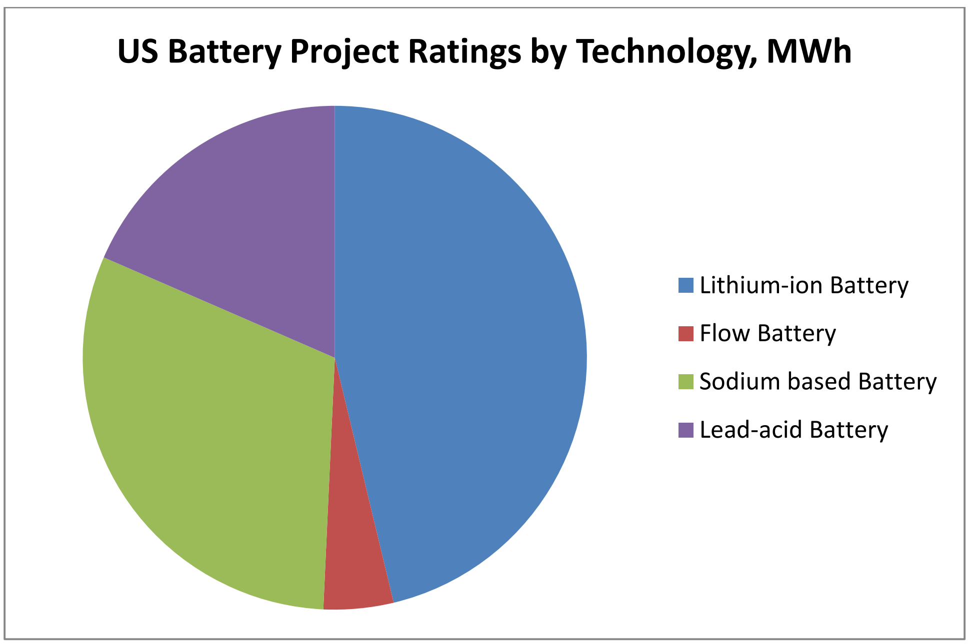


Figure 2 - Rated MWh Capacity of US Battery Energy Storage Projects (Existing)

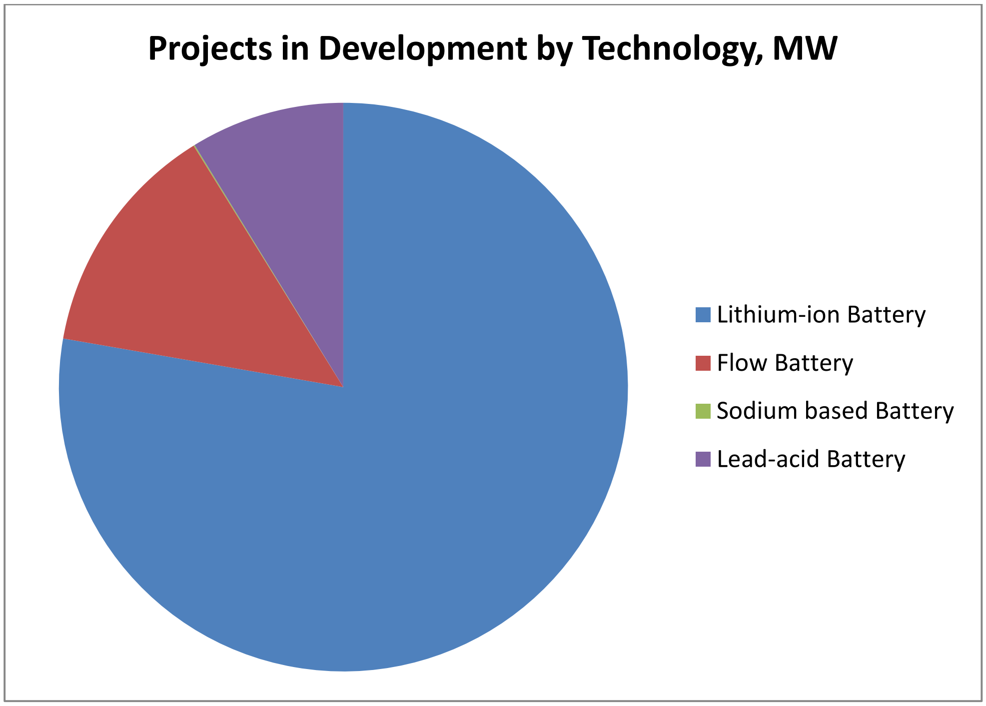


Figure 3 - Capacity of US Battery Energy Storage Projects (Under Development)

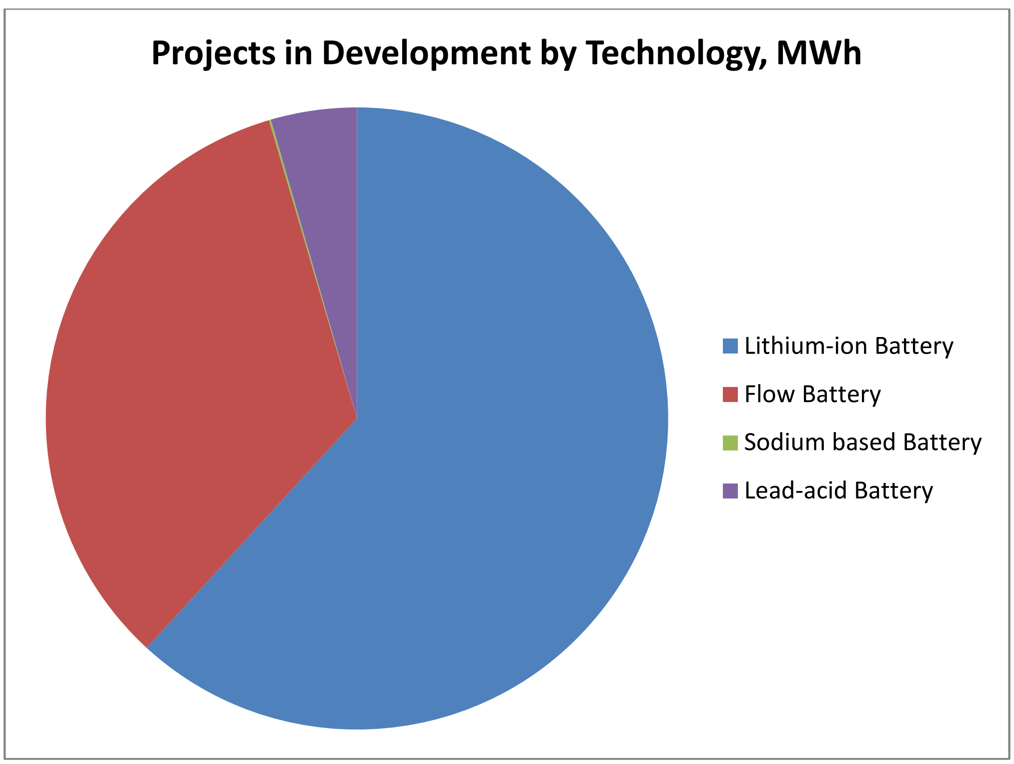


Figure 4 - Rated MWh Capacity of US Battery Energy Storage Projects (Under Development)

The data in the Energy Storage Database shows the significant momentum of Li-ion systems in the market today. Over 75% of planned power capacity additions are using this technology. A single large (25 MW / 75 MWh) flow battery project accounts for the majority of the remaining capacity.

Data from the Energy Storage Database provides an approximate indication of the battery industry and should not be construed as an accurate predictor of industry / market behavior. The data collected is not all inclusive of all commercialized manufacturers, does not include all of the projects a given manufacturer has completed, and does not include any emerging technologies that are under final stages of research and development (e.g. American Recovery and Reinvestment Act (ARRA), Advanced Research Projects Agency-Energy (ARPA-E) funding or stealth companies backed by venture capital (VC)).

This section provides an overview and summary of the battery technologies currently available in the marketplace. To put battery technologies in context, the following provides some definition of key battery terminology and system characteristics.

For a battery application, the battery is typically paired with a Battery Management System (BMS). The primary purpose of the BMS is to protect the battery and prevent uses that would damage or destroy the system. In some cases, such as with a flow battery, the BMS may also act as the Energy Management System (EMS). The EMS acts as a site controller implementing the charge and discharge algorithms. For a single ESS, the BMS and EMS could be combined, but for Li-ion batteries or for a site with multiple ESSs, these are typically in separate devices.

For direct current (DC) systems such as batteries and ultracapacitors, the EMS will also control a power conversion system (PCS). The PCS is similar to a wind or solar inverter, allowing power conversion from DC to alternating current (AC) or vice versa. The PCS will generally be selected based on the voltage of the ESS, required output, and grid interconnection requirements. The PCS will typically produce a 3-phase output voltage of 300VAC – 700VAC from a DC input voltage of 400 VDC – 1000 VDC. It should be noted that the solar market has recently started developing and using 1500VDC PCS's which the battery market has not adopted as of yet.

Finally, a fully integrated system will require Balance of Plant (BOP) equipment. The BOP includes infrastructure like site work, foundations, and fencing. It also includes on-site electrical systems such as medium voltage step-up transformers, switchgear, protective relaying, metering, and any equipment required to interconnect the ESS to the electric utility transmission or distribution grid. Depending on the size of the system, the Point of Interconnection (POI) to the electric utility may be a new transmission substation, a distribution line, or a spare terminal at an existing substation. Systems under 10MW will likely connect to the distribution system, while systems greater than 20MW will connect to the transmission system. Systems from 10MW – 20MW could connect to either depending local conditions on the electric utility grid.

Storage technologies have a few key characteristics which can be useful for comparison. Some of the key battery characteristics typically used by the industry are summarized below. These characteristics are further defined and outlined for each of the reviewed technologies in the following technology-specific discussions.

State Of Charge (SOC)

Different battery technologies have an inherent state of charge range that when operated within avoids accelerated cell degradation. Typically, manufacturers provide systems with a rated nameplate capacity lower than the actual capacity to account for their product's charging characteristics. In this manner, useable system capacities can more readily operate over the end-user's specified 0-100% SOC range. The achievable high and low SOC values are specific to the identified battery chemistry and type.

Charging Rate (C-Rate)

The C rate is the acceptable safe rate of charge and discharge of a battery. A charge or discharge rate equivalent to the battery's capacity over one hour would be 1C. For example, a 1C discharge from a 100 Ah battery is 100 amperes for one hour. On the manufacturer specification sheets that accompany batteries, C-rates that are less than 1 are typically conservative, and may be recommended by the manufacturer to attain longer cycle lifetimes. Typically, discharge rates are higher than charge rates.

Round Trip Efficiency (RTE)

Round Trip Efficiency is the ratio of energy available to be discharged from a battery relative to the amount of energy required to charge the battery to that state of charge. The higher the round trip efficiency, the less energy loss in the energy storage system reducing wasted energy. For example, if it takes 100kWh to charge the battery and the available energy to discharge is 80kWh, the battery has a Round Trip Efficiency of 80%. RTE typically includes the losses from the PCS, heating and ventilation (HVAC), control system losses, and auxiliary loads. Auxiliary losses like air conditioning or heating vary considerably according to the technology and the specific application it must perform.

Availability

An equipment's availability is considered the percent to which a system is operable and dispatchable when called upon for operation. Manufacturers will typically provide availability numbers and at times will offer associated guarantees. The percentages provided within this report are gathered from industry published information. Regularly scheduled annual maintenance expectations are normally not included in the system's availability figure but should be identified by the manufacturer on request.

Degradation

Battery degradation happens each time a cell is cycled and is accounted for by the manufacturer when they size the battery to your intended application. While systems are sized, environmental conditions addressed, and control systems are designed to protect a battery installation, unexpected events resulting from equipment failure or incorrect dispatch control can lead to degradation of the system. Battery degradation is truly dependent on how an end user operates their system. Battery applications are typically broken up into two categories; energy and power. Energy applications can include time shift, supply capacity, and spinning reserves. Power applications are typically load ramping and / or following, voltage support, and frequency response. Because energy response typically has a deeper depth of discharge on a consistent basis, these applications have a steeper degradation curve for some chemistries.

Life Expectancy

Currently in the battery industry, life expectancy is based upon a set number of charging and discharging cycles typically using a 10 year duration. The number of achievable cycles will vary by the specific technology and based on the application's intended use. Suppliers will claim cycle life in excess of 3,000 cycles with the caveat of operation within nominal conditions and provided required maintenance is performed including cell refreshes (cell additions) or replacement of electrolyte depending on the type of system.

Lithium Ion Battery

STORAGE TYPE
Battery

PRICE RANGE
Medium

MATURITY
Commercially mature

DURATION
0.25 - 4 hours

Background

Li-ion batteries have rapidly become the workhorse of the battery storage industry. Large scale manufacturing and production of multiple chemistries (Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$ or NMC), Lithium Iron Phosphate ($LiFePO_4$ or LFP), and Lithium Titanate ($Li_4Ti_5O_{12}$ or LTO),) have given it a significant portion of the commercially viable energy storage market. Li-ion's competitive energy density and power density has made it the standard for portable applications. The global demand for portable technologies has played a direct part in Li-ion investment that in turn carries over into large scale Li-ion production.

Maturity

Li-ion is the second-most mature technology in the stationary battery energy storage market, after lead acid. The technology was first proposed in 1970, released commercially in 1991, and is now the standard technology for portable electronics and electric vehicles. The same technology used for electric vehicles forms the core technology for stationary energy storage.

Since 2009, over 100 Li-ion projects have been installed in the US with capacity of about 300 MW. Over 200 MW was completed in 2015 alone. The largest projects include 32 MW / 8 MWh in Laurel Mountain, West Virginia and 8 MW / 32 MWh in Tehachapi, CA. An additional 6.6 GW is estimated to be under development at this time (GTM Research, 2016).

A large number of vendors produce the technology including Bosch, Panasonic, Johnson Controls, LG Chem, NEC, Samsung, Saft, BYD, Hitachi, and GS Yuasa (Mitsubishi). A number of startups with newer lithium technologies went bankrupt in the 2000's and were acquired by larger vendors. Newer startups like Tesla are primarily engaged in the marketing and product development side of the business. Tesla, for example, utilizes batteries manufactured by Panasonic and will continue to do so in its new US-based factory.

Due to consolidation into large vendors, much of the risk related to the systems is being transferred to the vendors. A survey of vendors shows that they are willing to provide warranties and performance guarantees on system life up to 10 years. With replacements of components, some vendors will offer a 20 year warranty. Both the warranty and performance guarantee are based on the planned use of the system and are negotiated between the owner and the vendor.

Vendors supply systems sized for up to 10 years of life under two main contracting mechanisms. The standard mechanism is to oversize the system at the commercial operation date. If the owner operates within certain parameters, the system will last for the required life. The alternate is a replenishment or "evergreen" option. Under this contracting mechanism, the owner pre-buys battery modules to augment or replace the existing battery modules. Modules may be pre-purchased at the commercial operation date based on a forward cost curve. Modules may instead be pre-contracted at a not-to-exceed price. In that case, the owner purchases the modules as needed over the life but has a guarantee of the maximum price.

Technological Characteristics

Li-Ion batteries consist of a range of technologies varying in size, shape, and chemistry. The primary chemistries in use today are lithium nickel manganese cobalt oxide (NMC), lithium manganese oxide (LMO), lithium iron phosphate (LFP), and lithium titanate (LTO). For stationary applications, the battery industry is moving towards more heavily utilizing NMC.

NMC are the most typical chemistries in grid-scale ESS. These chemistries demonstrate balanced performance characteristics in terms of energy, power, cost, and cycle life.

In contrast to the NMC battery, the LFP technology is a lower cost battery for its high power density. The LFP has a constant discharge voltage, the cell can produce full power to 100% depth of discharge (DOD) and its chemistry is seen as to be highly safe when compared to other Li-ion chemistries. The drawback to the LFP technology is the relatively low demand for applications suited to its low energy capacity and higher degree of self-discharge.

Unlike NMC and LFP, the LTO technology has a lower energy density with a higher cost compared to the others. To its advantage, however, LTO technology does have fast charging characteristics and is considered a stable Li-ion chemistry with higher than average cycle lifetime and a high power density.

Lithium ion battery cells typically consist of a graphite anode, metal-oxide cathode, and a lithium salt electrolyte gel. For stationary applications these are typically packaged in a flat pouch or rolled up like a jelly-roll (prismatic). As shown in Figure 5, battery cells are integrated into battery modules. These battery modules are installed in standard 19" racks similar to those used for telecom equipment. The racks are then installed in a building or specially prepared shipping container to function as an integrated battery system.

Figure 5. Structure of a Li-ion System

Li-ion batteries are highly sensitive to temperature. The building or container is typically provided with an active cooling system to maintain the batteries within an optimal temperature range. The system will be de-rated if operated or stored for any significant length of time outside of these optimal temperature ranges. Li-ion batteries are typically designed for operation in an ambient temperature of 70°F, though the optimal point will vary by vendor and intended use.

Due to the temperature sensitivity, fire hazard, and special shipping requirements, many states classify stationary Li-ion systems as hazardous materials. Facilities in Washington State have required hazardous material management plans (HMMPs). Careful consideration should be given to fire suppression consisting of either gaseous (dry) systems which may require air permitting or liquid systems which may cause concerns with the Clean Water Act.

Characteristics Data

A summary of Li-ion battery key characteristics are presented in Table 2 below.

Table 2. Lithium Ion Battery Technology Characteristics

Characteristics Data Comparison									
Storage Type	Energy		Charge Rate	Round Trip Efficiency	Availability	Capacity Degradation		Life	
	SOC High Limit	SOC Low Limit				Energy	Power	Years	Cycles
Li-Ion NCM	90%	10%	1C	77 - 85%	97%	30-40%	10-20%	10	3,500
Li-Ion LiFePO4	85%	15%	2C-1C	78 - 91%	97%	20-40%	15-25%	10	2,000
Li-Ion LTO	98%	10%	3C-1C	77 - 85%	96%	15-25%	5-15%	10	15,000

Installed Costs

Estimated lithium ion battery system costs for a 4 MW, 16 MWH installation in 2017 dollars are as follows:

Table 3. Summary of Li-ion Costs

Item	Li-Ion NMC	Li-Ion LFP	Li-Ion LTO
BATTERY ($/kWh)	$340-$450	$340-$590	$500-$850
PCS ($/kW)	$150-$350	$150-$350	$150-$350
Power control system cost ($/kW)	$80-$120	$80-$120	$80-$120
Balance of Plant ($/kW)	$90-$120	$90-$120	$90-$120
EPC ($/kWh)	$150-$180	$140-$180	$140-$180
Fixed O&M cost ($/kW yr)	$6-$14	$6-$14	$6-$14
Installed Low	$9,120,000	$9,120,000	$11,680,000
Installed High	$12,840,000	$13,384,000	$18,840,000

Based on a 4MW/16MWh system

Assumptions utilized for the development of the above pricing include:

- Warranty: 1.5% of contract price per year, years 3 – 10
- Performance Guarantee: 2% of contract price per year, years 0 – 10
- Oversized to account for 85% degradation over the 10 year life
- Variable O&M: $0.0003/kWh

Applications

Li-ion batteries are generally cost-effective for up to 4-hours of storage designed for peaking, arbitrage, renewable integration, or resource adequacy. Li-ion is a more mature technology with more established vendors as compared to potentially less expensive flow battery technologies. To optimize the battery economics, Owners should strive to combine resource adequacy/frequency regulation or any other use cases able to be monetized. Research clearly shows the best value for storage occurs when multiple value streams can be monetized. This is particularly the case for longer duration systems with the flexibility to perform multiple functions.

STORAGE TYPE
Battery

PRICE RANGE
Low to Medium

MATURITY
Commercially Mature

DURATION
0.25 - 4 hour

Lead Acid Battery

Background

Lead acid is one of the oldest available battery energy storage technologies. For many years it has been the battery standard for stationary and mobile applications until supplanted by Li-ion for many applications. It is still in use for applications where low energy density, heavy weight, and short life are acceptable, such as conventional car batteries and disposable batteries. Due to lower costs, lead acid systems are still common for large industrial uninterruptable power supply (UPS) systems, because these systems see fewer operational cycles during the project lifetime.

Many of the early grid tied systems were lead acid. As an example, Southern California Edison (SCE) installed a 10MW/40MWh system that operated from 1988 to 1996. Puerto Rico Electric Power Authority (PREPA) installed a 20MW/14MWh system which operated from 1994 to 1999 and was repowered in 2004. In the late 2000's, a number of advanced lead acid systems from Xtreme Power were installed for renewable integration in Alaska, Hawaii, and Texas. Some of these newer systems are reportedly being replaced as they have reached the end of their useful life.

Maturity

While traditional lead acid is one of the most mature battery technologies available, a number of drawbacks have fostered interest in improving the technology. Traditional lead acid systems have a low cost, high tolerance for temperature changes, and limited degradation due to age. Their competition with other technologies is hampered by a low energy density, high weight, and short cycle life. This has lead to research into a new class of batteries referred to as advanced lead acid.

Advanced lead acid technology is far less mature than the traditional lead acid technology. Two companies have been dominant in that field in the 2000s; Xtreme Power and Ecoult. Xtreme Power has discontinued manufacturing its product for a number of reasons including a major fire at a facility in Hawaii and competitiveness with Li-ion. HDR is aware of two Xtreme Power systems used for wind integration which are reaching end of life earlier than expected. Both companies have sought to replace the system with Li-ion, which is a better understood technology. Xtreme Power was purchased by Younicos which only focuses on system integration and controls.

Ecoult is a newer company and is a subsidiary of East Penn Manufacturing, an established vendor of traditional lead acid batteries. While the technology is still largely unproven with only a few installations, East Penn has multiple product lines, suggesting that they will be long term participants in the market. Ecoult systems are sized based on throughput over its life rather than number of charge/discharge cycles over its life. The company provides a guarantee of total MWh charged and discharged by the battery. This makes evaluation of the system life simpler for the customer as they do not need to evaluate the detailed chemistry of the system to analyze and forecast system ratings and lifetimes.

Technical Characteristics

Advanced lead acid batteries generally cover two technologies. The first is an enhancement of traditional lead acid batteries by utilizing carbon in the battery to improve battery life. A number of vendors and Sandia National Laboratories are conducting research in this area.

The technology available from Ecoult is a hybrid of a lead acid battery and an ultracapacitor as shown in Figure 6. The system allows for long duration storage with minimal degradation and operates well in a partial state of charge needed for most utility applications.

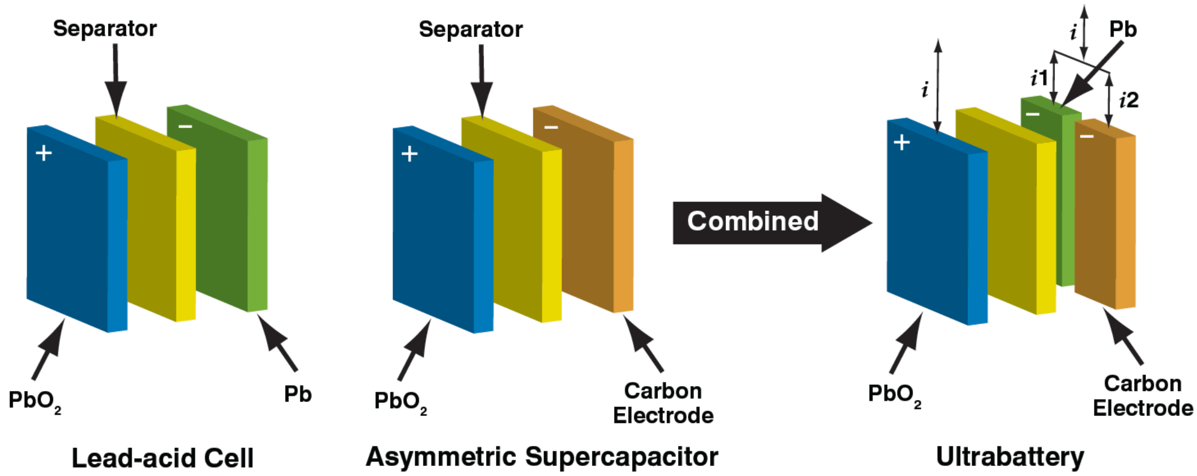


Figure 6. Structure of an Ecoult Battery

The installed system from Ecoult is similar to an installed Li-ion system as shown in Figure 7. Battery cells are combined into battery modules which are rack mounted in a building or container. Due to their temperature tolerance, Ecoult systems may be shipped assembled to the site. Like Li-ion systems advanced lead acid systems should also consider fire suppression as thermal runaway is possible as a result of internal failure mechanisms and associated heat generation.

Figure 7. Installed Ecoult System

Advanced lead acid systems are sized similar to Li-ion systems with typical, cost effective storage durations in the range of 15 minutes to 4 hours. Like Li-ion they can be operated at multiple charging rates.

Installed Costs

Estimated costs for a system from Ecoult based on publicly available data are as follows.

Table 4. Summary of Lead Acid Costs

Item	Lead Acid
BATTERY ($/kWh)	$200-$500
PCS ($/kW)	$150-$350
Power control system cost ($/kW)	$80-$120
Balance of Plant ($/kW)	$120-$250
EPC ($/kWh)	$150-$180
Fixed O&M cost ($/kW yr)	$7-$15
Installed Low	**$ 7,000,000.00**
Installed High	**$ 14,160,000.00**

Assumptions utilized for the development of these costs include:

- Warranty: Included
- Performance Guarantee: Included
- Variable O&M: $0.0003/kWh

Applications

The primary use for advanced lead acid systems is resource adequacy. This is due to a number of factors:

- Short cycle life (reduced number of cycles over the project lifetime)
- Limited degradation due to time

Advanced lead acid systems could also be used for frequency regulation. The higher use rate of the system may cause it to degrade faster than other technologies, but operating experience and maintenance needs are predictable.

Sodium Sulfur Battery

STORAGE TYPE
Battery

PRICE RANGE
Moderate to High

MATURITY
Commercially mature

DURATION
5 hours

Background

NaS batteries were originally developed by Ford Motor Company in 1967 for electric vehicles. It was not until 2002 that the NaS battery was first commercially installed due to an initiative by Tokyo Electric Power Company (TEPCO). Currently, there are approximately 450MW of NaS batteries in commercial operation internationally. A number of US-based NaS system demonstration projects were installed in the early 2000s.

Maturity

There is one primary vendor of sodium-based batteries, NGK Insulators. NGK is primarily a ceramics vendor with products for the electric utility, emissions reductions, and electronics sectors. As noted, NGK has 450MW of installed systems worldwide, half of which are in Japan.

All NGK systems in the USA to date have been in partnership with S&C Electric. S&C provided the PCS control system. S&C also performs the day-to-day monitoring of the system. Systems outside the USA have utilized PCSs from Toshiba and TMEIC.

NGK offers a standard 2-year warranty extendable to 15 years. Warranties include a long term service agreement and performance guarantees. Maintenance is expected to be minimal, though battery module replacement may be needed at end of life. Existing systems from NGK in the United States have not yet reached end of life and have not required replacements during the operating life. NGK lists the lifetime of the system at 4500 cycles. Similar to Li-ion, the life of the battery will vary with its intended use. One other vendor also produces sodium-based batteries. General Electric (GE) produces a sodium nickel battery under the brand Durathon. GE generally doesn't offer these for stationary applications as they are generally not cost competitive with Li-ion batteries.

Technological Characteristics

Among the prevalent technologies, NaS batteries have high energy densities that are only lower than that of Li-ion. The efficiency of NaS varies somewhat dependent on the duty cycle due to the parasitic load of maintaining the batteries at the higher required operating temperature of 330°C. NaS battery cells are a combination of molten liquid sodium and sulfur with an operational temperature of 300-350°C within porcelain containers. The sodium and sulfur are separated by a high temperature ceramic. The system operates at a high temperature and is generally insensitive to environmental conditions. The system will remain at temperature when operating, but will need to be heated if left in standby for long periods of time. The ancillary components (BMS, switches, etc.) are subject to standard equipment operating temperatures of -20°C to 45°C.

As shown in Figure 8, newer systems are structured like other batteries. Individual cells are packaged into modules, modules are packaged into containers, and containers are packaged into complete systems. Each containerized system consists of six (6) battery modules and a BMS. Each container has a nameplate of 220kW/1170kWh for approximately 5 hours of storage.

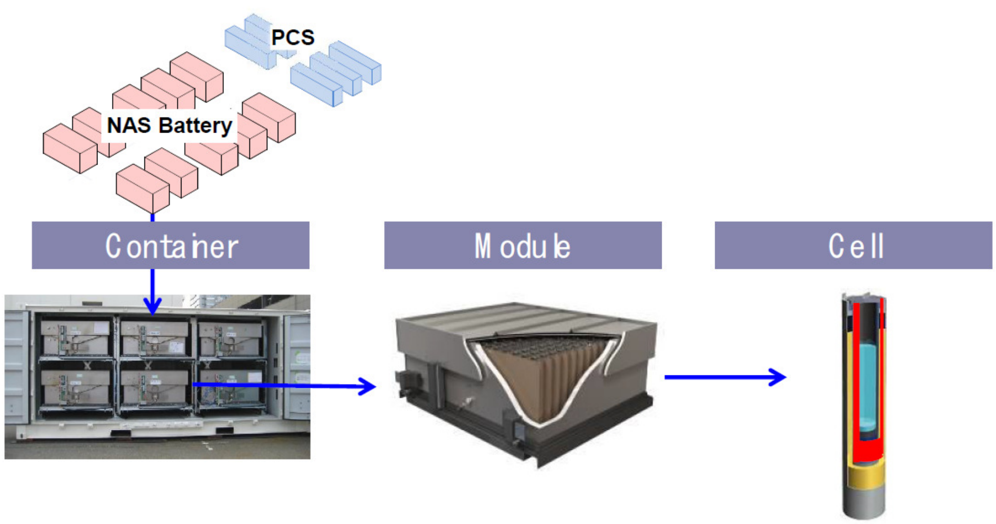


Figure 8. Structure of a NaS Battery

The batteries sit in fireproof compartments to limit the spread of fire from one module to the next. No fire suppression is included. A faulted battery module will burn out without damaging the adjacent equipment. It is unclear if the container will act as secondary containment in the event of a battery leak. Additional containment may be required.

Containers will be installed in series (based on PCS voltage) and parallel to achieve the desired nameplate rating. With a PCS by S&C, the maximum is three containers in series. Alternate configurations can be used with different PCS sizes.

Containers are shipped completely assembled and do not have special handling requirements. The vendor will typically supply the batteries, container, and BMS. The PCS and EMS are by the owner. The systems are designed for 4500 cycles, which allows for 300 full cycles each year over a 15 year lifetime.

Critical to the design of these systems is that the system has differing charge and discharge rates. The maximum charging current is approximately 92% of the maximum discharge current.

Characteristics Data

A summary of NaS battery key characteristics are presented in Table 5 below.

Table 5. NaS Battery Technology Characteristics

Characteristics Data Comparison									
Storage Type	Energy		Charge Rate	Round Trip Efficiency	Availability	Capacity Degradation		Life	
	SOC High Limit	SOC Low Limit				Energy	Power	Years	Cycles
NaS	90%	10%	1C-0.5C	77 - 83%	95%	15-30%	5-15%	15	4,500

Installed Costs

System costs are higher than other comparable systems, though initiatives like containerization should reduce the cost. The system utilizes less land than a comparable Li-ion system which makes them better suited to areas with land constraints. Estimated NaS battery system costs for a 4 MW, 16 MWH installation in 2017 dollars are as follows:

Table 6. Summary of NaS Costs

Item	NaS
BATTERY ($/kWh)	$500-$1000
PCS ($/kW)	$500-$750
Power control system cost ($/kW)	$80-$120
Balance of Plant ($/kW)	$100-$125
EPC ($/kWh)	$140-$200
Fixed O&M cost ($/kW yr)	$7-$15
Installed Low	**$12,960,000.00**
Installed High	**$23,180,000.00**

Assumptions utilized for the development of these costs include:

- Warranty: Included
- Performance Guarantee: Included

Applications

The primary use for NaS systems would most likely be resource adequacy combined with frequency regulation. This is due to a number of factors:

- Fixed system size of 5-hours
- High cost

Due to the high cost of these systems, a combination of use cases will be required to make the system commercially viable. There may be opportunities for colocation with renewable projects to prevent curtailment.

STORAGE TYPE
Flow Battery

PRICE RANGE
Moderate to High

MATURITY
Commercially New

DURATION
2 – 8 Hours

Vanadium Redox Flow Battery

Background

Vanadium Redox Batteries (VrBs) are a fundamentally different type of battery energy storage to the forms previously discussed. A VrB system, similar to a NaS system, uses a liquid anode and cathode rather than a single liquid electrolyte. Unlike the NaS system, the anode and cathode fluids are circulated through the battery cell into holding tanks.

The systems are relatively new and early versions were complex custom engineered systems. The VrB industry is moving more towards pre-packaged systems in containers to compete with Li-ion systems.

There is much interest in these systems as they have a high cycle life, have large allowable temperature range, operate at low temperature, and have long storage durations.

Maturity

While the first operational system was demonstrated in Australia in the 1980's, there are only a few systems in operation worldwide. A number of vendors make these systems including UniEnergy Technologies (UET), Gildemeister (American Vanadium), Rongke Power, Prudent Energy, ViZn Energy, Vionx Energy, and Sumitomo. The industry is currently in a phase of continuous improvement, with three generations of technology available. Only a few systems commercially operate from a worldwide perspective.

VrB systems use electrodes to generate currents through flowing electrolytes. The size and shape of the electrodes govern power density, whereas the amount of electrolyte governs the energy capacity of the system. The cell stacks are comprised of two compartments separated by an ion exchange membrane. Two separate streams of electrolyte flow in and out of each cell with ion or proton exchange through the membrane and electron exchange through the external circuit. Ionic equations at the electrodes can be characterized as follows:

$$\text{Anode: } V^{5+} + e^- \leftrightarrow V^{4+}$$

$$\text{Cathode: } V^{2+} \leftrightarrow V^{3+} + e^-$$

VrB systems are recognized for their long service life as well as their ability to provide system sizing flexibility in terms of power and energy. VrB round trip efficiency tends to be in the range of 70-75%. The separation membrane prevents the mix of electrolyte flow, making recycling possible.

The industry, marked by UET and Gildemeister, is moving away from custom systems to prepackaged systems to compete with Li-ion. UET is also offering 2 to 20 year warranties with performance guarantees and long term service agreements. The industry is currently hampered by the infancy of the companies providing the technology. Many of the vendors are venture-capital backed companies with only a single product line. Also, the systems tend to be uneconomic for storage durations less than 3 hours and better suited for longer duration applications. While this technology holds promise, it is still in its early phases of commercialization.

Technological Characteristics

All flow batteries share the common topology of a battery cell with flowable electrolyte pumped between storage tanks. Electrolyte is pumped through the cell for charging or discharging, and is stored in separate tanks for longer duration storage. The volume of the storage tank determines the duration of energy storage. Early systems, and those provided by Prudent Energy and Sumitomo, are still custom engineered with varying durations of storage.

As noted previously, the industry is moving towards containerized systems with pre-determined storage durations of 3 – 5 hours. The prepackaged systems utilized one or more containers per battery. In the case of UET a 4 MW / 16 MWh system utilizes five (5) 20-foot ISO containers, four (4) for the battery and one (1) for the PCS. The containers typically have both secondary and tertiary containment for the electrolyte fluid.

VrB batteries are characterized by a high cycle life and insensitivity to temperature. They operate at a low temperature and are only limited by the temperature rating of the auxiliary components (pumps, sensors, etc…). The electrolyte degrades very slowly over time, allowing for a very high cycle life. Due to the pumps, they have a high station service load yielding a lower round trip efficiency than other technologies.

Critical to the design of these systems is that the energy available from the battery depends on the discharge rate. For a continuous discharge at a specified rate (resource adequacy), the storage duration could vary from 2 to 8 hours.

Characteristics Data

A summary of VrB battery key characteristics are presented in Table 7 below.

Table 7. VrB Battery Technology Characteristics

Characteristics Data Comparison									
Storage Type	Energy		Charge Rate	Round Trip Efficiency	Availability	Capacity Degradation		Life	
	SOC High Limit	SOC Low Limit				Energy	Power	Years	Cycles
VRB	95%	5%	1C-0.25C	65 - 78%	95%	5-10%	5-10%	15	5,000

Installed Costs

Estimated VrB battery system costs for a 4 MW, 16 MWH installation in 2017 dollars are as follows:

Table 8. Summary of VrB Costs

Item	VrB
BATTERY/PCS/power control systems ($/kWh)	$730-1200
Balance of Plant ($/kW)	$100-$125
EPC ($/kWh)	$140-$200
Fixed O&M cost ($/kW yr)	$7-$16
Installed Low	**$14,320,000.00**
Installed High	**$22,900,000.00**

Assumptions utilized for the development of these costs include:

- Warranty: Included with ESS
- Performance Guarantee: $261,720 per 0.5MW/4hr system
- Variable O&M: $0.0003/kWh

HDR based the per-kWh and per-kW price on operating the system at a 4 hour discharge. Note the kWh available from the system varies with the rate of discharge.

Applications

The primary use for VrB systems would typically be resource adequacy combined with frequency regulation. This is due to a number of factors:

- Fixed system size
- High fixed costs for each system
- Low variable cost of adding hours (for custom systems)

VrB battery systems have a higher fixed cost than Li-ion or lead acid due to the need for pumps, motors, the battery cell, and containment. Due to these fixed costs and the containerization into 3-5 hours systems, VrB systems are best utilized for long duration storage. As it may be more difficult to monetize long-duration applications, there may be opportunities for colocation with renewable projects to prevent curtailment.

STORAGE TYPE
Flow Battery

PRICE RANGE
Moderate to High

MATURITY
Commercially New

DURATION
2 – 8 Hours

Zinc Bromine Flow Battery

Background

A ZnBr system, similar to a VrB system, uses a liquid anode and cathode rather than a single liquid electrolyte. The systems are relatively new and early versions were complex custom engineered systems. The industry is moving more towards pre-packaged systems in containers to compete with Li-ion systems.

These systems have a high cycle life, have large allowable temperature ranges, operate at low temperature, and have long storage durations.

All flow batteries share the common topology of a battery cell with flowable electrolyte pumped between storage tanks. Electrolyte is pumped through the cell for charging or discharging, and is stored in separate tanks for longer duration storage. The volume of the storage tank determines the duration of energy storage.

Maturity

Similar to VrB, ZnBr have only a few systems in operation worldwide. A number of vendors make systems including Enphase (Previously ZBB), Primus Power Flow, and RedFlow. The ZnBr industry is currently in a phase of continuous improvement, with varying generations of technology available. Only a few systems commercially operate from a worldwide perspective.

Technological Characteristics

The fundamentals of energy conversion for ZnBr batteries are the same as that of VrBs. Two separate streams of electrolyte flow in and out of each cell compartment separated by an ion exchange membrane. Ionic equations at the electrodes can be characterized as follows:

$$\text{Anode: } Br_2 + 2e^- \leftrightarrow 2Br$$

$$\text{Cathode: } Zn \leftrightarrow Zn^{2+} + 2e^-$$

Like VrBs, ZnBr batteries are also recognized for their long service life and flexible system sizing based on power and energy needs. The separation membrane prevents the mix of electrolyte flow, making recycling possible. ZnBr round trip efficiency is in the 60% range. Premium Power (currently Vionx Energy) was previously focused on power quality, island / UPS applications, and on peak shaving / load leveling projects with its ZnBr battery technology. Projects in their portfolio included multiple-hour systems including 6.9 MW / 17.2 MWh installed in the US. Like the VrB systems, ZnBr battery technology is considered in its early stages of commercialization. At the time of writing, there was no publicly available information on any of its electricity storage plants; the number and size of projects installed to date were previously provided by Premium. Figure 9 illustrates Premium's standard cell stack. Figure 10 shows Premium's TransFlow2000, a complete ZnBr battery system, complete with cell stacks, electrolyte circulation pumps, inverters and thermal management system configured into a standard trailer. Premium (now Vionx Energy) is currently focused on the development and marketing of its VrB battery technology in lieu of this ZnBr technology for future opportunities.

Figure 9. Structure of a ZnBr Battery

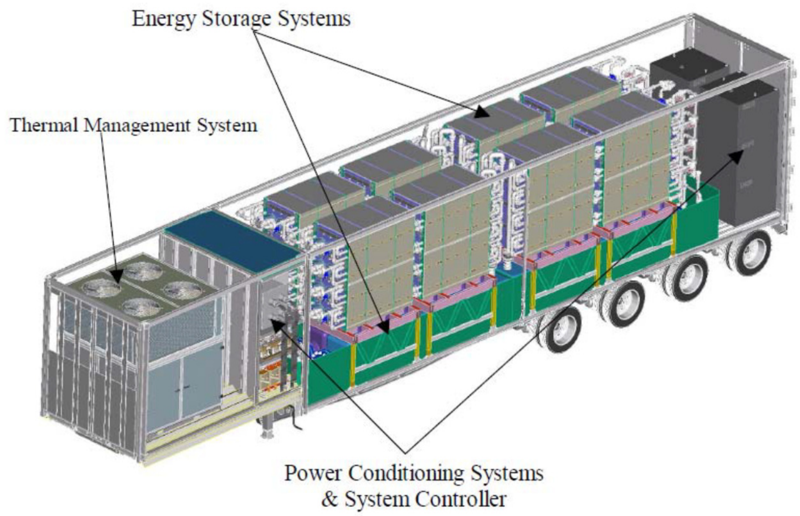


Figure 10 - Premium's TransFlow2000 Section (ZnBr battery)

Critical to the design of these systems is that the energy available from the battery depends on the discharge rate. For a continuous discharge at a specified rate (resource adequacy), the storage duration could vary from 2 to 8 hours.

Characteristics Data

A summary of ZnBr battery key characteristics are presented in Table 9 below.

Table 9. ZnBr Battery Technology Characteristics

Characteristics Data Comparison									
Storage Type	Energy		Charge Rate	Round Trip Efficiency	Availability	Capacity Degradation		Life	
	SOC High Limit	SOC Low Limit				Energy	Power	Years	Cycles
ZnBr	98%	5%	1C-0.25C	65 - 80%	95%	5-10%	5-10%	15	3,000

Installed Costs

Estimated ZnBr battery system costs for a 4 MW, 16 MWH installation in 2017 dollars are as follows:

Table 10. Summary of ZnBr Costs

Item	ZnBr
BATTERY ($/kWh)	$525-$725
PCS ($/kW)	$500-$750
Power control system cost ($/kW)	$100-$140
Balance of Plant ($/kW)	$100-$125
EPC ($/kWh)	$140-$200
Fixed O&M cost ($/kW yr)	$7-$17
Installed Low	**$ 13,440,000.00**
Installed High	**$ 18,860,000.00**

Assumptions utilized for the development of these costs include:

- Warranty: Included with ESS
- Variable O&M: $0.0003/kWh

Applications

The primary use for ZnBr systems would typically be resource adequacy combined with frequency regulation. This is due to a number of factors:

- Fixed system size
- High fixed costs for each system
- Low variable cost of adding hours (for custom systems)

ZnBr battery systems have a higher fixed cost than Li-ion or lead acid due to the need for pumps, motors, the battery cell, and containment. Due to these fixed costs and the containerization into 3-8 hours systems, ZnBr systems are best utilized for long duration storage. As it may be difficult to monetize long-duration applications, there may be opportunities for colocation with renewable projects to prevent curtailment.

STORAGE TYPE
Battery

PRICE RANGE
Low to Medium

MATURITY
Commercially New

DURATION
1-4 Hours

Zinc - Air Battery

Background

The first rechargeable zinc air batteries were manufactured in 1996 by a Slovenian innovator Miro Zoric. They were developed to power vehicles using the first AC-based drive trains, also developed by Mr. Zoric. The first vehicles on roads to use zinc air batteries were small and mid-sized buses in Singapore, where Mr. Zoric led the national electrification program at Singapore Polytechnic, during his technology transfer post. The mass production assembly line for his zinc air batteries was put in place in 1997. The cells offered much higher energy density and specific energy (and weight) ratio, compared to then standard lead acid batteries.

Zinc-air battery systems look as if they would be a fit for utility applications if improvements can be made in their size/scale as well as charge and recharge cycles. The challenge for researchers has been to devise a method where the air electrolyte is not deactivated, causing a slowed oxidation reaction, in the recharging damaging the battery's ability to be used. EOS, founded in 2008 after the issuance of the patent for its core technology, started research and development to develop a hybrid Zinc battery technology. The Eos Energy System is a containerized battery system which provides 1 MWh of storage

Maturity

These systems are in the early stages of commercialization and with limited production throughput. Although being researched by more than one company, most installations are demonstration projects including; Con Edison, National Grid, Enel and GDF SUEZ who have started testing the battery for grid storage. Con Edison and City University of New York are testing a zinc-based battery from Urban Electric Power as part of a New York State Energy Research and Development Authority program.

Technological Characteristics

Zinc hybrid cathode (Zinc-air) batteries are a type of metal-air battery which uses an electropositive metal in an electrochemical couple with oxygen from the air to generate electricity. Zinc-air batteries take oxygen from the surrounding air to generate current. The oxygen serves as an electrode while the battery construction includes an electrolyte and a zinc electrode that channels air inside the battery.

To function, rechargeable zinc–air cells need precisely controlled zinc precipitation from the aqueous electrolyte. There are issues to consider during this process such as dendrite formation, non-uniform zinc dissolution and limited solubility in electrolytes. Electrically reversing the reaction at a bi-functional air cathode can be difficult with the current medium having lower efficacies.

The power densities of zinc-air batteries are similar to Li-ion batteries, however they have lower energy density. An advantage to Zinc-air batteries when compared to Li-ion, is that their manufacturers typically claim them to be benign. It should be noted that like many batteries, they contain acidic or an alkaline compound and could produce SO2 during combustion.

Zinc-air systems appear attractive for utility applications if their ability to charge and recharge can be improved. The challenge for researchers has been to devise a method where the air electrolyte is not deactivated in the recharging cycle to the point where the oxidation reaction is slowed or stopped. Newer technology, developed by Eos, claims to have addressed these issues by implementing a near-neutral, non-dendritic, and self-healing electrolyte solution. This, Eos claims, prevents air electrode clogging, rupture of the membrane due to dendrites, and the drying out of the electrolyte, along with other innovations that have prepared the system for commercial launch.

Characteristics Data

A summary of Zinc Air battery key characteristics are presented in Table 11 below.

Table 11. Zinc Air Battery Technology Characteristics

Characteristics Data Comparison									
Storage Type	Energy		Charge Rate	Round Trip Efficiency	Availability	Capacity Degradation		Life	
	SOC High Limit	SOC Low Limit				Energy	Power	Years	Cycles
Zinc-air	98%	10%	2C-1C	72 - 75%	96%	15-25%	5-15%	10	5,000

Installed Costs

Estimated Zinc Air battery system costs for a 4 MW, 16 MWH installation in 2017 dollars are as follows:

Table 12. Summary of Zinc-Air Costs

Item	Zinc-air
BATTERY ($/kWh)	$200-$400
PCS ($/kW)	$350-$500
Power control system cost ($/kW)	$100-$140
Balance of Plant ($/kW)	$80-$100
EPC ($/kWh)	$120-$180
Fixed O&M cost ($/kW yr)	$6 - $13
Installed Low	**$ 7,240,000.00**
Installed High	**$ 12,240,000.00**

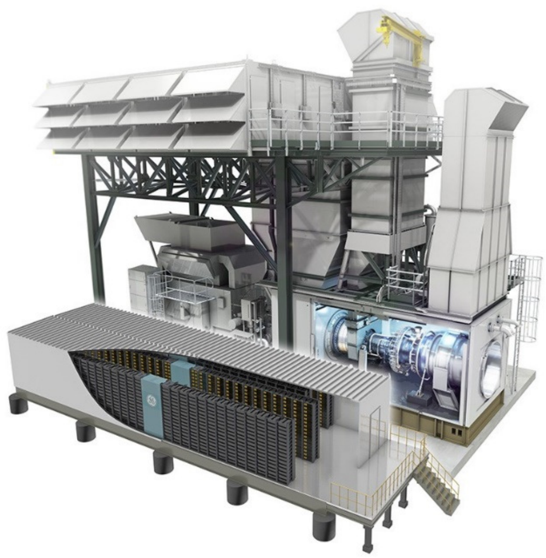
Assumptions utilized for the development of these costs include:

- Warranty: Included with ESS
- Variable O&M: $0.0003/kWh

Applications

The primary use of Zinc Air batteries would include resource adequacy combined with frequency regulation. Zinc-Air batteries, however, are still in the very early stages of development and deployment.

VI. Hybrid Battery/Turbine Technologies



STORAGE TYPE
Battery

PRICE RANGE
Medium to High

MATURITY
Commercially New

DURATION
<1-4 Hours

Hybrid Battery/Turbine Technologies

Recently, certain gas turbine manufacturers including GE and Siemens have begun promoting and offering hybrid generation packages for new turbine and combined cycle installations. The first installation of this type has been installed by Southern California Edison by a team of GE and Wellhead Power Solutions involving GE's LM6000 Hybrid EGT technology. These hybrid technology packages consist of a standard generating facility paired with a bank of batteries and coupled with an inverter. These hybrid options are currently being promoted for peaker and small combined cycle plants where rapid response time and quick regulation of output power are a necessity.

The battery packs included with these turbine-based solutions work as a supplement to the operation of the generating units. The major benefit associated with the inclusion of the battery packs in these hybrid systems is the response time to the grid. The effective start time of the hybrid system can be drastically reduced since the batteries can essentially supply immediate power to the grid during the facility start and the associated ramp up time of the generating unit(s). In this manner, the hybrid system can be counted as a spinning reserve resource eliminating the need for additional units to be spinning at minimum load and burning fuel. In a combined cycle installation, a battery system can also be applied to expedite the steam turbine start-up and obtain full steam turbine capacity in a shorter period of time.

Maturity

While the idea of these hybrid configurations is a relatively new concept, the individual technologies involved, i.e. the batteries, gas turbines, and steam turbines are well tested and proven. The main barrier to market penetration for this technology is not so much the development of each individual technology as the successful integration of the two via system controls into a harmonious working system. The Southern California Edison GE/Wellhead Hybrid EGT system is the first of these installations that has been successfully placed into service in 2017.

Technological Characteristics

As a representative hybrid installation, the LM6000 Hybrid EGT consists of one GE LM6000 gas turbine unit rated from 45 to 58MW depending upon the specific model and associated site conditions. This LM6000 generating unit is paired with a Li-ion battery energy storage system. The battery system proposed by GE for the base EGT package is a 10MW-4.3MWh system. These are paired with eight 1.25 MVA inverters with the combination allowing for an overall start time of 5 minutes or less for full turbine unit capacity. It can also provide black start capability to the gas turbine.

Installed Costs

Estimated costs for a hybrid 45 MW turbine unit with a 10MW battery pack in 2017 dollars are as follows:

Table 13. Summary of Estimated Hybrid Turbine/Battery Costs

Item	Hybrid Turbine / Battery System
GT & supporting equipment ($/kW)	$800-$1000
BATTERY ($/kWh)	$340-$450
PCS ($/kW)	$150-$350
Power control system cost ($/kW)	$80-$120
Balance of Plant ($/kW)	$90-$120
EPC ($/kWh)	$150-$180
Fixed O&M cost ($/kW yr)	$6-$14
Installed Low	$51,147,000
Installed High	$65,800,000

Based on a 45MW turbine with 10MW-4.3MWh battery

Assumptions utilized for the development of the above pricing include:

- GE LM6000 price of $19M
- Battery system oversized to account for 85% degradation over the 10 year life
- Battery Variable O&M: $0.0003/kWh

Applications

The primary application of a hybrid unit would be its availability as a spinning reserve asset. Since a hybrid unit like the LM6000 EGT can provide nominally 50 MW of spinning reserve, other fuel burning assets can be run at full capacity and maximum efficiency thereby reducing the overall cost of generation and the emissions produced per unit of generation. The leveling effect of the hybrid unit's power output can be further extrapolated from the quick start capability suggested above to include a leveling of the start time between gas and steam cycles in a combined cycle plant preventing the plants start time form being limited by the steam cycle start up time.

VII. Flywheel Technology

STORAGE TYPE
Flywheel

PRICE RANGE
TBD

MATURITY
Early to Medium

DURATION
4 - 15 Minutes

Flywheel

Background

Flywheel energy storage is a form of mechanical energy storage predominantly used for industrial UPS systems. While the general technology is fairly mature, its use for energy storage in utility applications has been limited to demonstration projects.

Maturity

A number of commercially available systems exist in the market today. For utility applications the primary vendors are Beacon Power (US), Temporal (Canada), ABB, and Stornetics (Germany). Beacon Power was one of the original energy storage companies participating in frequency regulation markets. They operate three projects in ISO-NE, NYISO, and PJM which were partially funded through DOE grants. Due to lack of demand, the company went through a bankruptcy and was acquired by a venture capital company. The other two primary vendors are also single-purpose companies backed by venture capital. ABB acquired a venture firm named Powerstore and is selling a flywheel-based generator as a voltage and frequency regulator for microgrids (smaller scale).

The products offered by these vendors are high speed DC flywheels. This is a newer application of the technology and significantly different than versions utilized for UPS systems. Due to the limited number of installations, venture-capital backing, and newness of the technology, this should be considered a relatively immature technology but one which could have niche applications. Most of the deployments to date have been technology launches and test installations as opposed to being long-term commercial installations. They have demonstrated suitable durability to frequent cycling but most systems have been installed and operational for less than four years.

Technological Characteristics

Flywheels are electromechanical energy storage devices that operate on the principle of converting energy between kinetic and electrical states. A massive rotating cylinder, usually spinning at high speeds, connected to a motor stores usable energy in the form of kinetic energy. The energy conversion from kinetic to electric and vice versa is achieved through a variable frequency motor or drive. The motor accelerates the flywheel to higher velocities to store energy, and subsequently slows the flywheel down while drawing electrical energy. Flywheels also typically operate in a low friction environment to reduce inefficiencies. Superconductive magnetic bearings may also be used to further reduce inefficiencies.

Generally, flywheels are used for short durations to supply backup power in a power outage event, for regulating voltage and frequency, and for bridging from grid power to backup power sources.

Flywheels are recognized for potentially long service life, fast power response and short recharge times. Mechanical efficiencies are typically over 97%, and they also tend to have relatively high round-trip (charge/discharge) efficiencies on the order of 85%. This energy storage technology is classified as commercial in regards to utility applications.

A survey of installed energy storage systems reveals that there are two primary markets for flywheel companies, namely bulk power (grid scale) control and uninterruptible power supply applications. Companies in the bulk power market, including Beacon Power Corporation, target voltage and frequency regulation. These installations are large in scale and are often designed for discharge operation times of up to 15 minutes. One such installation by Beacon Power, in Stephentown, NY, is sized at 20MW and provides over 30% of the area control error correction to the NYISO market.

The other key market for flywheels is for uninterruptible power supply (UPS) applications, which focus on power quality and providing a bridge between grid power and backup power supplies. These UPS applications are shorter in duration and are used for "mission critical" loads such as hospitals and data centers. Companies in this market include Piller, Vycon and Active Power. Flywheels can be parallel with batteries coupled with a reactor so that the flywheel will isolate the batteries for short term outages, such as a utility reclose. This limits the number of cycles to batteries, significantly extending the battery end of life.

The individual flywheel modules are typically installed below grade due to the risk of detonation from mechanical failure (carbon dust detonation). A flywheel system installed and operated by Beacon in New York suffered such a failure.

Characteristics Data

A few performance characteristics of flywheels include: low lifetime maintenance, operation can typically be of high number of cycles, 20+-year effective useful life and since kinetic energy is used as the storage medium, there are no exotic or hazardous chemicals present.

Roundtrip AC-to-AC efficiency of the system is on the order of 85% with primary parasitic loads being the Power Conversion System (PCS) and internal cooling system, among the mechanical and friction losses of the system. Primary losses are intrinsic, and include friction (between rotor and environment) and energy conversion losses (generator losses including windings, copper, induction).

Energy footprint for bulk power flywheel installations is generally large and comparable to that of pumped hydropower. UPS-type flywheel installations are more compact and can be scaled to fit the requirements of the critical load. Plant life is expected to be over 25 years with no change in energy storage capacity resulting in a high amount of energy throughput throughout its effective useful life.

Flywheel's largest limitations are its footprint and its relatively short energy storage duration of 15 minutes or less per system. System response times for bulk power applications are less than 4 seconds and ramp up/down rates can be 5 MW per second. This makes it an ideal candidate to serve in the frequency regulation services to the grid operator while maintaining reliability. According to Beacon, one technology risk associated with flywheel systems lie in its power electronics modules which have statistically failed once every 150,000 hours of operations. There is also risk associated with catastrophic flywheel failure.

Response times for UPS applications are immediate and there are no limits on ramp rates, which is appropriate for serving critical loads. According to Piller, the mean time between failures for their installations is 1.4 million hours, indicating high reliability for UPS applications.

A summary of flywheel key characteristics are presented in Table 14 below.

Table 14. Flywheel Technology Characteristics

Characteristics Data Comparison									
Storage Type	Energy		Charge Rate	Round Trip Efficiency	Availability	Capacity Degradation		Life	
	SOC High Limit	SOC Low Limit				Energy	Power	Years	Cycles
Flywheel	100%	0%	Varies	70 - 80%	94%	0%	0%	20	unlimited

Installed Costs

Capital and operating cost data points from Beacon Power Corporation remain proprietary and cannot be disclosed unless a Non-Disclosure Agreement (NDA) has been signed and executed. However, data points from publicly-available documents suggest that the 20 MW Beacon flywheel plant is estimated to cost $50 million. This yields $2,400 per installed kW.

According to Piller, capital costs for a 2.7MW unit are approximately $600/kW, operating costs are approximately $15k/year, plus $45k once every 10 years for bearing changes.

Throughout its service life, it is anticipated that the flywheel system will require standard and routine maintenance including general housekeeping and preventive maintenance on its electrical equipment. The flywheel plant will require telecommunications infrastructure (e.g. radio, telephone or local area network (LAN) to allow for remote monitoring.

Applications

Due to the short duration of storage and capability of handling repeated cycling, flywheels are best suitable for grid frequency regulation applications (say 10 to 20 MW of storage available for 7 to 20 minutes of services) or ramp rate control on select solar energy projects.

VIII. Compressed/Liquid Air Energy Storage

STORAGE TYPE
Compressed Air Energy Storage

PRICE RANGE
TBD

MATURITY
Commercial

DURATION
Hours

Compressed Air Energy Storage

Background

Compressed Air Energy Storage consists of a series of motor driven compressors capable of filling a storage cavern with air during periods of low cost electricity (e.g. off peak, low load hours). Subsequently, during periods of high value electricity (e.g high load, on peak hours), the stored compressed air is delivered to a series of combustion turbines which are fired with natural gas for power generation. Utilizing pre-compressed air removes the need for a compressor on the combustion turbine, allowing the turbine to operate at high efficiency during peak load periods.

Maturity

Compressed air energy storage is the least implemented and developed of the stored energy technologies. Only two plants are currently in operation, including Alabama Electric Cooperative's (AEC) McIntosh plant (rated at 110 MW) which began operation in 1991. The McIntosh plant was mostly funded by AEC, but the project was partially subsidized by EPRI and other organizations. Dresser Rand supplied the compressors and recuperators. The other plant in operation, the Huntorf facility, is located in Huntorf, Germany which utilizes an Alstom combustion turbine turbine. Some CAES plants have been proposed but, as of yet, have not moved forward beyond conceptual design. Some of these proposed projects include the Western Energy Hub Project, the Norton Energy Storage (NES) project, the Iowa Stored Energy Park, the PG&E Kern County CAES plant, the ADELE CAES plant in Stassfut, Germany, the APEX Bethel Energy Center, Chamisa Energy Project, Gaelectric CAES plant in Lame, UK, and the Toronto Hydro UCAES Project.

The Western Energy Hub project, promoted by Magnum Energy, LLC (Magnum), is probably the most advanced CAES project under development in the U.S. The salt dome geology has been well characterized, as well as land acquisition and local and state permitting underway.

The first phase of the Magnum project is for natural gas liquids (propane and butane) storage which broke ground in April 2013. The second phase of the project under development is construction of four additional solution-mined underground storage caverns capable of storing 54 billion cubic feet of natural gas. Magnum has been granted all the necessary permits for construction and operation of the gas storage facility from the State of Utah.

The final phase of the Western Energy Hub project is CAES, in conjunction with a combined-cycle power generation project. The CAES will utilize additional solution-mined caverns to store compressed air. Off-peak renewable generation will be used to inject air into the caverns which will be released during periods of peak power demand. The compressed air will be delivered to a combustion turbine, eliminating the need for a compressor on the combustion turbine, allowing the turbine to operate at high output and efficiency during peak load periods. Magnum plans up to 1,200 MW of capacity spread across four 300 MW modules, with two days of compressed air at full load. Magnum anticipates an in-service date of around 2021 for the first module.

In addition, Pacific Gas & Electric (PG&E) has been awarded a $25M grant from the Department of Energy (DOE) to research and develop a CAES plant. The California Public Utility Commission (CPUC) has matched the grant and supplied an additional $25M; the California Energy Commission has supplied an additional $1M of support. The proposed project is a 300 MW plant in Kern County, CA with minimum storage duration of 4 hours. The first phase of development involved a reservoir feasibility study that completed in Q4 2015. If the project proceeds, the plant is estimated to be operational in 2020. It has not been stated whether the proposed plant will be diabatic or adiabatic and is likely subject to the outcome of the feasibility study. PG&E issued a Request for Offers on October 9, 2015 to procure products and services related to the CAES project. Potential negotiations with shortlisted bidders commenced in August 2016. A nearly depleted natural gas field in San Joaquin County has been selected for the project site.

The ADELE project is an adiabatic (heat generated during compression is stored, then returned to the air when decompressed) CAES plant in Stassfort, Germany. The project is planned to have a storage capacity of 360 MWh, with a total output of 90 MW and projected efficiency of 70%. The project is part of the Federal Government's Energy Storage Initiative and is funded by the German Federal Ministry of Economics and Technology. The initial development phase is funded with $17M (12M Euro) and was expected to be completed by 2013. The total project was expected to have a duration of 3.5 years and a cost of $56M (40M Euro). The project development was revised for completion in 2016 and according to the Department of Energy Global Energy Storage Database the project is now operational, although little additional information is available regarding the project.

Another CAES project, the Iowa Stored Energy Park, was a planned 270 MW project planned to be in-service near Des Moines, Iowa in 2015. However, after 8 years in development, the project was terminated. While there were a number of legislative, market, and contract challenges associated with the project development, the project was ultimately terminated as a result of site geological limitations. In this case, there was no existing data or prior use of the reservoir to establish geologic feasibility.

The equipment utilized in CAES plants, which includes compressors and gas turbines, is well proven technology used in other mature systems and applications. Thus, the technology is considered commercially available, but the complete CAES system lacks the maturity of some of the other energy storage options as a result of the very limited number of installations in operation.

Technological Characteristics

Two primary types of CAES plants have been implemented or are being reviewed for commercial operation: (a) diabatic and (b) adiabatic. In diabatic CAES, the heat resulting from compressing the air is wasted in the process. The air leaving the storage cavern must be reheated prior to expansion in the combustion turbine. Adiabatic CAES stores the heat of compression in a solid (concrete, stone) or a liquid (oil, molten salt) form that is reused when the air is expanded. Due to the conservation of heat, adiabatic storage is expected to achieve round trip efficiencies of 70%. Both the McIntosh and Huntorf are diabatic CAES plants with efficiencies in the range of 50%. One adiabatic plant (ADELE) is currently under development in Germany.

During discharge of the compressed air, the AEC McIntosh plant achieves a fuel heat rate of roughly 4,550 Btu/kWh (HHV). Dresser Rand has made improvements to their CAES equipment offering since the commissioning of the McIntosh plant. These improvements could result in a heat rate of 4,300 Btu/kWh (HHV) but have not been proven on a commercial scale application that is in operation. The primary function of the McIntosh plant is for peak shaving.

The ADELE plant will have similar operating characteristics to McIntosh and Huntorf. The compressors are being designed for compression of up to 1,450 psia; however, the planned storage pressure is 1,015 psia. The total storage capacity is expected to be 360 MWh with an electrical output of 90MW; equivalent to 4 hours of energy storage at full utilization. The big improvement in the adiabatic plant is the round-trip efficiency. The ADELE plant is projected to have a total efficiency in excess of 70%; compared to AEC McIntosh (54%) and Huntorf (42%). The efficiency gains are a result of capturing the heat in the adiabatic process.

Varying sources over varying time periods report that the AEC McIntosh plant offers availability from 86 to 95 percent. At this facility, every air compressor is mounted to a single shaft that is coupled to a combined motor/generator unit via a clutch. Likewise, every turbine is also mounted to a single shaft that is coupled to a combined motor/generator unit via a clutch. Depending on the operational mode, compression or power generation, the motor/generator unit is either coupled to the air compressors or turbines but not both. AEC not only recommends separating the motor for compression and generator for electrical production, but also recommends separating each air compressor and turbine to alleviate maintenance complexities and to increase reliability.

Compressed air energy storage requires initial electrical energy input for air compression and utilizes natural gas for combustion in the turbine. The McIntosh plant offers fast startup times of approximately 9 minutes for an emergency startup and 12 minutes under normal conditions. As a comparison, simple cycle peaking plants consisting of gas turbines also typically require 10 minutes for normal startup. The Huntorf CAES plant has been designed as a fast-start and stand-by plant; it can be started and run at full-load in 6 minutes.

Technological Risks

CAES has performed very well at the AEC McIntosh plant and therefore little risk is perceived from a technical standpoint provided the proper equipment suppliers are utilized and design factors are considered. Dresser Rand provided the majority of the equipment for the AEC McIntosh plant. The construction of the Huntorf facility in Germany began construction in 1976, a time when gas turbines were not commercially implemented so the Huntorf turbine is a modified steam turbine. Prior to their acquisition by GE, Alstom did offer a gas turbine for compressed air applications, but none are currently in operation. As such, there is limited potential to competitively bid the major equipment without exposing risk for utilizing first-of-a-kind equipment from an unproven supplier. Another significant risk involves the ability to identify an energy storage geological formation with integrity and accessibility.

Adiabatic designs are under development and introduce new risks into the design of a CAES plant. There are additional heat-storage devices and components in the system that will increase the design complexity of the system. The compressed air is expected to have temperatures in excess of 1,100°F, which will require alloyed and/or ceramic materials. There is still uncertainty regarding materials of construction for the compressors and heat storage that would optimize the design. GE Oil & Gas is currently developing an air compressor and air-turbine for use in the ADELE project. A partnership between German companies Zublin and Ooms-Ittner-Hof are developing the heat storage capabilities.

As previously noted with the Iowa Stored Energy Park, while technological risks are reasonably well understood, one of the most significant challenges associated with CAES is the geologic risk associated with the integrity of the associated compressed air storage caverns.

Applications

CAES units can swing quickly from generation to compression modes. Compression and generation functions are independent, so ancillary services are available from both. They are very well suited for markets in which the loads and electricity prices vary significantly throughout the day.

Installed Costs

CAES options can vary considerably depending upon the specific project. The power island for a CAES option is typically small and similar in size to that of a combined cycle plant. Construction of the underground storage reservoir is a significant contributor to the cost of CAES. Aquifers and depleted gas reservoirs are the least expensive storage formations since mining is not necessary. Salt caverns are the most expensive storage formations since solution mining is necessary before storage. Storage formations vary in depth but most formations that can currently be utilized range between 2,500 ft to 6,000 ft below the earth’s surface. Storage formations vary naturally in size but storage caverns can be appropriately mined to achieve a specific storage capacity

The McIntosh project was commissioned in 1991 and at that time cost $65 million. Since the McIntosh plant offers 110 MW of net power, the plant cost was $590/kW. Due to the limited number of CAES projects completed and vague task descriptions often associated with project costs as well as external funding that was provided for McIntosh, HDR estimates that CAES project capital costs would be in the range of $1,600/kW to $2,300/kW for a 300 to 500 MW diabatic CAES plant, including 12 to 48 hours of solution-mined storage capacity. The technology for an adiabatic plant has not been made public and a capital cost cannot be accurately projected at this time; the total capital cost will be greater than a diabatic plant. HDR assumes project capital costs to include project direct costs associated with equipment procurement, installation labor, and commodity procurement as well as construction management, project management, engineering, and other project and owner indirect costs. This estimate does not include storage cavern cost. Values are presented in 2017 dollars.

Fixed operations and maintenance costs take into account plant operating and maintenance staff as well as costs associated with facility operations such as building and site maintenance, insurances, and property taxes. Also included are the fixed portion of major parts and maintenance costs, spare parts and outsourced labor to perform major maintenance on the installed equipment. The estimated fixed O&M costs for a nominal 100 MW CAES plant would be $19.0/kW in 2017 USD. Fixed O&M costs are expected to be similar for a diabatic CAES facility. An adiabatic plant would have greater fixed O&M costs due to increased complexity in the system design.

The non-fuel related variable O&M costs for a nominal 100 MW CAES plant is estimated to be $2.3/MWh in 2017 USD. Variable O&M costs are expected to be similar for a diabatic CAES facility. Additional variable O&M for fuel and electric costs should be considered when evaluating a diabatic plant. Fuel and electric costs should be considered based on existing gas and power purchase agreements or local market pricing.

STORAGE TYPE
Liquid Air Energy Storage

PRICE RANGE
TBD

MATURITY
Early

DURATION
Hours

Liquid Air Energy Storage

Background

LAES uses off-peak electricity to cool air from the atmosphere to minus 195 °C, the point at which air liquefies. The liquid air, which takes up one-thousandth of the volume of the gas, can be kept for a long time in a large vacuum flask at atmospheric pressure. At times of high demand for electricity, the liquid air is pumped at high pressure into a heat exchanger, which acts as a boiler. Either ambient air or low grade waste heat is used to heat the liquid and turn it back into a gas. The massive increase in volume and pressure from this is used to drive a turbine to generate electricity.

Maturity

The system's existing components are mature technology (liquefier, liquid air storage, power turbine) and the process integrates well with other industrial process plant (utilizing waste heat/cold) to enhance performance, but the system lacks the maturity that other energy storage alternatives have.

Technological Characteristics

In isolation, the LAES process is only 25% efficient, but this is expected to be able to be increased (to around 50%) when used with a low-grade cold store, such as a large gravel bed, to capture the cold generated by evaporating the cryogen. The cold is re-used during the next refrigeration cycle. Efficiency is further increased when used in conjunction with a power plant or other source of low-grade heat that would otherwise be lost to the atmosphere.

There is currently only one LAES facility worldwide. A 350 kW, 2.5MWh storage capacity pilot cryogenic energy system developed by researchers at the University of Leeds and Highview Power Storage, uses liquid air (with the CO2 and water removed as they would turn solid at the storage temperature) as the energy store, and low-grade waste heat to boost the thermal re-expansion of the air. This facility was operating at a biomass power station in Slough, UK, since 2010 until relocating to the University of Birmingham in 2014. The efficiency is less than 15% for this pilot plant. The company can design plants ranging from around 5 MW output to 15 MWh of storage capacity to 50 MW output and 200 MWh of capacity. In addition to storage, Highview systems can use industrial waste heat/cold from applications such as thermal generation plants, steel mills, and LNG terminals to improve system efficiency.

Round trip efficiency for a standalone LAES plant is projected to be around 60 percent once the technology matures, which is slightly below that of a conventional CAES plant. Integrating the LAES plant with a waste heat source such as that from a peaking plant is projected to increase round trip efficiency to 70 percent. These efficiencies have not been demonstrated to date in a pilot or pre-commercial plant.

The Highview pilot facility can respond quickly to surges in demand with a start time between 2 and 5 minutes.

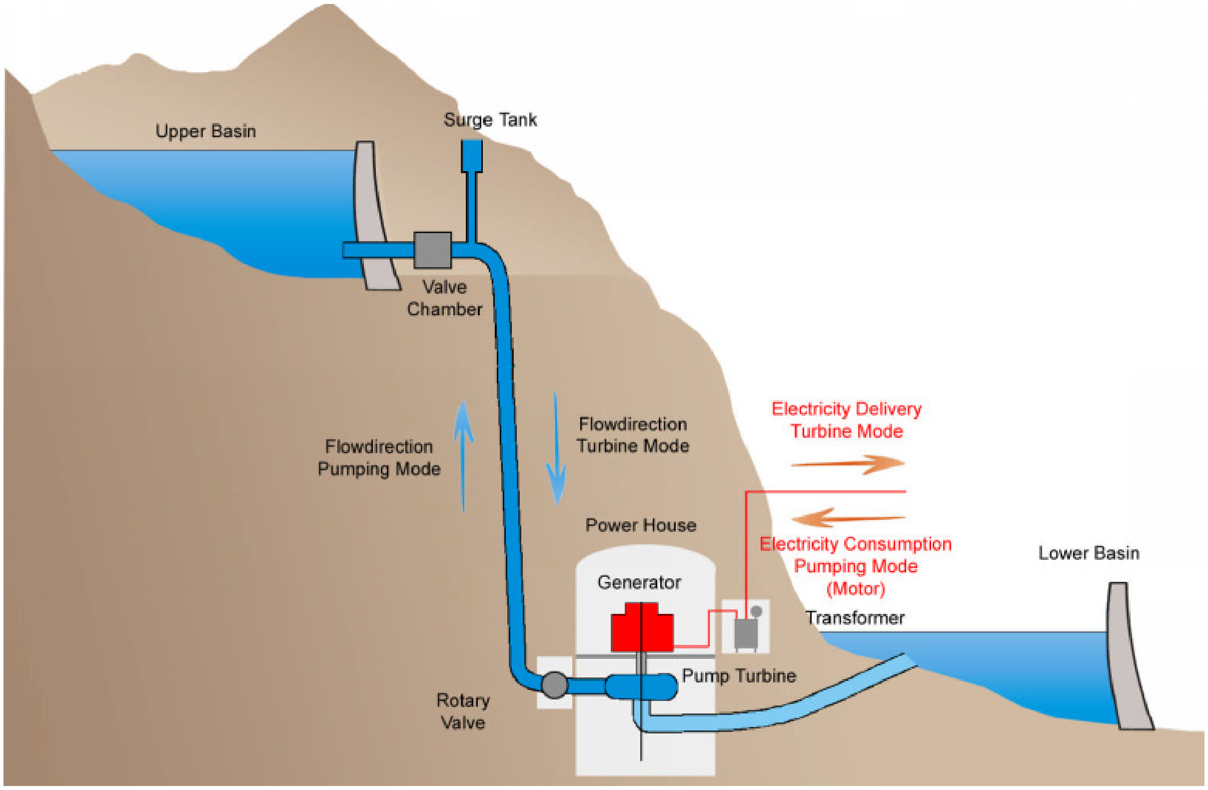
Applications

Similar to CAES units, LAES can swing quickly from generation to compression modes. Compression and generation functions are independent, so ancillary services are available simultaneously from both. They are very well suited for markets in which the loads and electricity prices vary significantly throughout the day. The intent of the Highview project was to demonstrate LAES servicing a number of balancing services, including Short Term Operating Reserve (STOR), Triad avoidance (supporting the grid during the winter peaks) and testing for the PJM regulation market.

Installed Costs

Limited capital, operating, and maintenance cost data is available for LAES, but some data has been made available from the Highview Power Storage Facility. Capital costs for the pilot and future pre-commercial projects are indicated to be $2,000-$4,000 per kW. These costs are projected to fall to less than $2,000 per kW in the future as the technology matures, although this has not been demonstrated on a commercial plant. The storage capacity of these facilities is limited by the number of storage vessels installed, which can affect project costs. Typical storage volumes of pilot and pre-commercial projects are indicated to be 4 hours. The plant life is expected to be 30 years (assuming no electrochemical degradation).

Since this technology is not commercial, little information is available regarding operating and maintenance costs. Turbine maintenance is expected to be lower then that of a conventional CAES plant since there is no combustion system or hot gas path to maintain. This cost savings would be offset to some extent by the additional liquefier equipment. O&M is therefore expected to be comparable to a conventional CAES plant.



IX. Pumped Hydro Storage

STORAGE TYPE
Pumped Hydro

PRICE RANGE
$1,500-$3,000/kW

MATURITY
Commercially Proven

STORAGE DURATION
6 to 20 hrs

Pumped Hydro Storage

Background

Pumped storage hydroelectric projects have been providing energy storage capacity and transmission grid ancillary benefits in the U.S. and Europe since the 1920s. Today, there are approximately 40 pumped storage projects operating in the U.S. that provide more than 20 GW, or nearly 2 percent, of the capacity for our nation's energy supply system (Energy Information Admin, 2007). Pumped storage facilities store potential energy in the form of water in an upper reservoir, pumped from another reservoir at a lower elevation. During periods of high electricity demand, electricity is generated by releasing the stored water through pump-turbines in the same manner as a conventional hydro station. In periods of low energy demand or low cost, usually during the night or weekends, energy is used to reverse the flow and pump the water back up hill into the upper reservoir.

Reversible pump-turbine/generator-motor assemblies can act as both pumps and turbines. Pumped storage stations are a net consumer of electricity, due to hydraulic and electrical losses incurred in the cycle of pumping back from a lower reservoir to the upper reservoir. However, these plants typically perform well economically, capturing peak to off-peak energy price differentials, and providing ancillary services to support the overall electric grid.

Maturity

Pumped storage is the most mature energy storage technology in today's market. The first U.S. pumped-storage plant was developed in the 1920s to balance loads from fossil fuel plants within a very nascent grid. A typical pumped storage plant is designed for more than 50 years of service life, but many projects that were constructed in the 1920's and 1930's are still operational today which is comparable to a conventional hydropower unit. Similar to other rotating power technologies, a generator-motor rewind or upgrade can be expected after approximately 20 years of service, with the pump-turbine equipment lasting for a longer period of time with routine maintenance. Advances in hydraulic computational fluid dynamics are the primary driver for pump-turbine upgrades when thos efficiency and capacity gains of modern equipment justify the expenditure.

Technological Characteristics

Fixed Speed Pump-turbines

The generating equipment for the majority of the existing pumped storage plants in the U.S. is the reversible, single-stage Francis pump-turbine. See Figure 11 for a cross section of a reversible, single-stage Francis pump-turbine. The runner-impeller changes the direction of its rotation to operate in either the pumping or generating mode. The generator-motor changes direction with the runner-impeller to either provide power in the pumping direction or generate when the unit is in the turbine mode. Most of the major equipment vendors have significant experience with this type of unit, and can apply modern designs to runner-impellers, wicket gates, and water passageway shape modifications to older machines during rehabilitation programs, resulting in significant efficiency and capacity improvements. The technology for single-stage units continues to advance, and a broader range of equipment configurations are available depending upon the available head, reservoir volume, and desired operation.

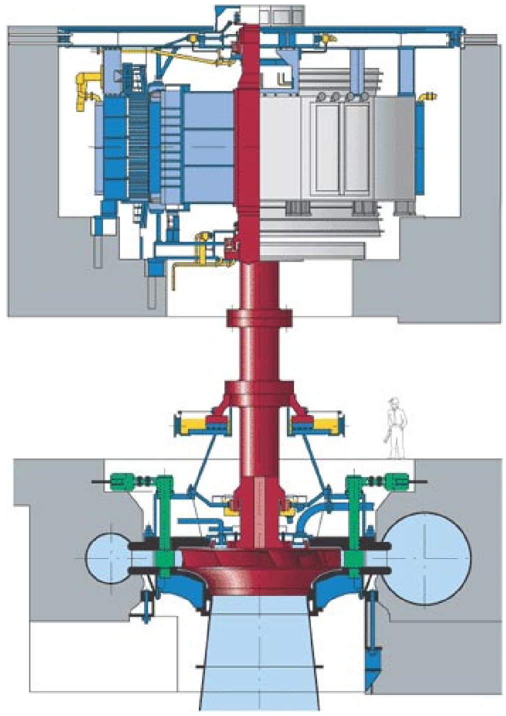


Figure 11- Reversible Francis Type Pump-turbine (Voith)

Variable Speed Pump-turbines

Variable speed pump-turbines have been used since the early to mid-1990's in Japan and late 1990s in Europe. They are being increasing considered during project development in Europe and Asia due to a high percentage of renewable energy penetration. In California, three large pumped storage projects in development are considering variable speed technology almost exclusively due to the growing need for detrimental reserves at night, enabling greater penetration of variable renewable energy resources. Although the technology has been in place since the 1990's, major equipment vendors are continuously redesigning the equipment to improve performance.

In a conventional, single speed pump-turbine, the magnetic field of the stator and the magnetic field of the rotor always rotate with the same speed and the two are coupled. In a variable speed machine, those magnetic fields are decoupled. Either the stator field is be decoupled from the grid frequency using a frequency converter between the grid and the stator winding, or the rotor field is decoupled from the rotor body by a multi-phase rotor winding fed from a frequency converter which is connected to the rotor.

Table 15 provides a summary comparing the operational characteristics and advantages/disadvantages of single and variable-speed turbine units for an example project. Actual benefits will vary depending on specific site characteristics. Because of the multiple advantages, variable-speed units have been discussed in this report.

Table 15 - Example Comparison of Primary Characteristics

Characteristic	Single-speed	Variable-speed
Proven Technology	45+ years - Worldwide	10+ years - Europe and Japan
Equipment Costs	-	Approximately 10% to 30% Greater
Powerhouse Size	-	Approximately 25% to 30% Greater
Powerhouse Civil Costs	-	Approximately 20% Greater
Project Schedule	-	Longer - Site Specific
O&M Costs	-	Greater for the Power Electronics
Operating Head Range	80% to 100% of Max. Head	70% to 100% of Max. Head
Generating Efficiency		Approximately 0.5% to 2% Greater
Power Adjustment Generation Mode*	Approximately 60% to 100%	Approximately 50% to 100%
Power Adjustment Pump Mode*	None	+/- 20%
Operating Characteristics		
Idle to Full Generation	Generally Less than 3 Minutes	Generally Less than 3 Minutes
100 Percent Pumping to 100 Percent Generation	Generally Less than 6 to 10 Minutes	Generally Less than 6 to 10 Minutes
100 Percent Generation to 100 Percent Pumping	Generally Less than 6 to 10 Minutes	Generally Less than 6 to 10 Minutes
Load Following	Seconds (i.e., 10 MW per Second)	Seconds (i.e., 10 MW per Second)
Reactive Power Changes	Instantaneously	Instantaneously
Automatic Frequency Control	Yes in generate mode	Yes in both pump and generate modes

***Power Adjustment:** The ability of a pump-turbine generator-motor to operate away from its best operating point based on rated head and flow. Single-speed units can operate over a range of flow in the generating mode which is identical to a conventional hydropower turbine, but not in the pumping mode (in pumping mode a single speed machine cannot vary flow or wicket gate settings at all). Variable-speed units have the ability to operate the turbine's off-peak efficiency point in the pumping mode via the power electronics (no substantive change in flow), and typically have greater flexibility in the generating mode than single-speed units.

Open-Loop and Closed-Loop Systems

Both open-loop and closed-loop pumped storage projects are currently operating in the U.S. The distinction between closed-loop and open-loop pumped storage projects is often subject to interpretation. The Federal Energy Regulatory Commission (FERC) offers the formal definitions for these projects: Closed-loop pumped storage are projects that are not continuously connected to a naturally-flowing water feature; and open-loop pumped storage are projects that are continuously connected to a naturally-flowing water feature.

Closed-loop systems are preferred for new developments, or Greenfield projects, as there are often significantly less environmental issues, primarily due to the lack of aquatic resource impacts. Projects that are not strictly closed-loop systems can also be desirable, depending upon the project configuration, and whether the project uses existing reservoirs.

Repurposing Mines as Alternative Storage Reservoirs

Recently, the concept of using repurposing abandoned mines as alternative locations for one or both storage reservoirs has been considered. The use of an open pit mine, such as the abandoned iron ore mine pits in Southern California proposed for the Eagle Mountain Pumped project, in concept is a viable alternative, and is similar to using a manmade reservoir. There is no incremental environmental impact and the upper and lower reservoirs (the abandoned open pit quarries) are existing and simply hydraulically connected.

Locating one or both of the reservoirs in underground mines, however, has significant concerns and challenges. Typical underground mining results in small passages looking like an ant farm in cross section and are not suitable as is for a lower reservoir configuration. Quite simply, the pump-turbines would be starved of water in the pump mode. The underground excavation and material costs, construction risk, and time required for underground excavation and construction necessary for the volume of water and elevation difference make the economics of such a project questionable. These underground sites have been evaluated due to the perceived lack of availability of potential surface reservoirs and the potential for reduced environmental impacts. There are no operating pumped storage projects worldwide that utilize an underground reservoir.

Performance Characteristics

Pumped storage hydro plants can provide load balancing and shifting (energy arbitrage) and historically have done so by pumping during night time hours and on weekends, and then generating during periods of higher demand. A pumped storage project would typically be designed to have between 6 to 20 hours of hydraulic reservoir storage for operation at full generating capacity. By increasing plant capacity in terms of size and number of units, hydroelectric pumped storage generation can be concentrated and shaped to match periods of highest demand, when it has the greatest value. Existing pumped storage projects range in capacity from 9 to 2700 MW, and in available energy storage from 87 MWh to 370,000 MWh of storage.

Water-to-wire efficiencies vary based on individual equipment designs, age of the project, and site hydraulics, and include the pump-turbine, generator-motor and transformer efficiencies. Water-to-wire efficiency is typically near 85 - 90% for pumping mode and approximately 88% generating mode for fixed speed Francis pump-turbines, resulting in a turnaround or cycle efficiency of approaching 82%.

Installed Costs

The direct cost to construct a pumped storage facility is highly dependent on a number of physical site factors, including but not limited to topography, geology, regulatory constraints, environmental resources, project size, existing infrastructure, technology and equipment selection, capacity, active storage, operational objectives, etc. The direct cost of a pumped storage facility utilizing single speed unit technology is expected to be in the order of $1,500 to $3,000 per kW. The direct cost for a facility utilizing variable speed unit technology is expected to be approximately 10 to 20 percent greater than that of a facility utilizing single speed technology. Indirect costs, such as project engineering, licensing, and construction management, generally run between 15 and 30 percent of direct costs and are largely dependent on configuration, environmental/regulatory, and ownership complexities.

Operation, maintenance, and outage costs vary from site to site dependent on specific site conditions, the number of units, and overall operation of the project. Previous Electric Power Research Institute (EPRI) studies provide the following equation for estimating the annual operations and maintenance (O&M) costs for a pumped storage project in 1987 dollars:

$$\text{O\&M Costs (\$/yr)} = 34{,}730 \times C^{0.32} \times E^{0.33}$$

Where: C = Plant Capacity, MW

E = Annual Energy, GWh

An escalation factor of 2.2 is recommended going from 1987 to 2017 based on the US Bureau of Labor Statistics. For a 1,000 MW pumped storage project generating 6 hours per day 365 days per year, and annual energy production of 2,190 GWh. The calculated annual O&M costs are approximately $8.8 million in 2017 USD.

Bi-Annual Outage Costs

In addition to annual O&M costs, it is recommended within the industry that bi-annual outages be conducted. Again, the frequency of the inspections and the subsequent repairs following inspections can vary depending upon how the units are operated, how many hours per year the units will be on-line, how much time has elapsed since the last inspection/repair cycle, the technical correctness of the hydraulic design for site specific parameters, and water quality issues.

Conservatively, in a four unit, 1,000 MW powerhouse, two units would be taken out of service for approximately a three week outage every two years. For units of this size, $280,000 for two units should be budgeted.

Major Maintenance Costs

It is recommended within the industry that a pump-turbine overhaul accompanied by a generator rewind be scheduled at year 20. The typical outage duration is approximately six to eight months. Pumped storage units are typically operated twice as many hours or more per year than conventional generating units if utilized to full potential. This increased cycling duty also dramatically increases the degradation of the generator components. This increased duty results in the requirement to perform major maintenance on a more frequent basis.

The work included and the frequency of this outage can vary based on project head, project operation, and regular maintenance cycles. Overhauls typically include restorations of all bushings and bearings in the wicket gate operating mechanism, replacement of wicket gate end seals, rehabilitation of the wicket gates including non destructive examination (NDE) of high-stress areas, rehabilitation of the servomotors, replacement of the runner seals, NDE of the head cover, restoration of the shaft sleeves and seals, and rehabilitation of the pump-turbine bearing. The end result is restoring the pump-turbine to like-new running condition. Pump-turbine inlet isolation valves will likely require refurbishment of the valve seats and seals. The service life of a generator-motor is generally dependent upon the condition of the insulation in the stator and rotor. The need for re-insulation of the stator and rotor, typical of a salient pole design, can vary from 20 to 40 years depending upon the duty cycle and insulating materials utilized.

The costs for these modifications depend on many factors. Due to the complexity of the scope, an estimate must be developed for each installation. For the purposes of this study, approximately $6.7 million was estimated for reversible Francis units at year 20.

Applications

The contributions of pumped storage hydro to our nation's transmission grid are considerable, providing stability services, energy-balancing, and storage capacity. Pumped storage can store energy when surplus energy is being produced, typically at night when overall energy demand is low. Pumped storage projects also provide ancillary services such as network frequency control, firming capacity, both incremental and decrimental reserves, reactive power, black start capability, voltage stability and frequency support.

The incorporation of variable speed technology would increase the flexibility of a pumped storage project in the pumping mode. When pumping, a fixed speed pump-turbine has a set relationship of power input required to net head; therefore, the power input to the pump-turbine cannot change while it is on line. Existing pumped storage projects therefore utilize "blocks" of excess energy from the grid for pumping operations. With the advent of variable speed pump-turbines, load balancing in the pump mode can provide critical decrimental and frequency regulation reserves, thus smoothing the supply curve.

In the generation mode, the capabilities of both single and variable speed machines are identical to conventional hydropower units. By varying the wicket gate position to be between 60 to 100 percent, the units can provide incremental and detrimental reserves via load-balancing at partial load and provide Automatic Generation Control (AGC) services.

As more variable energy is added to the power system, additional reserves are required, and flexible and dispatchable generators, such as pumped storage, are required.

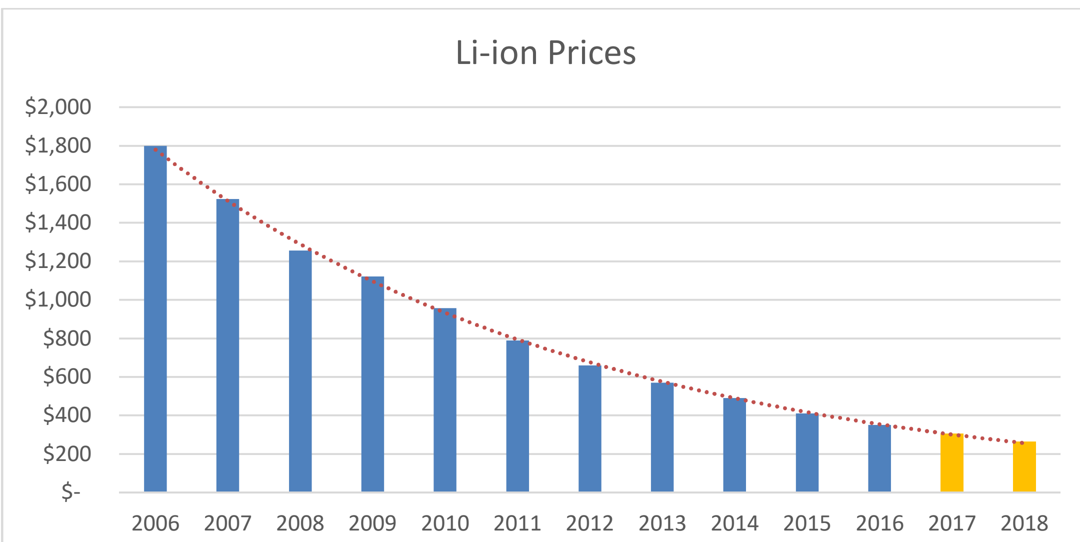
.

X. Conclusions

As both a generation asset owner and electric market participant, Public Service of New Mexico (PNM) is considering investment in energy storage systems. To best assess the characteristics of energy storage systems, this assessment defines applications where various ESSs can provide value, characterizes the ESS technologies available, and evaluates commercially proven technologies that may provide benefit.

At the present time, Li-ion and NaS battery-based systems are the leading technologies in the battery industry with some growth in flow battery technology. Furthermore, flywheels, lead acid batteries, and compressed air energy storage systems have proven technically capable and are approaching commercial viability, but for more limited applications. Liquid air energy storage is technically feasible, but hasn't reached a viable maturity level yet as there is only one pilot plant worldwide in operation. For large scale grid storage applications, pumped storage remains the most proven technology, with closed loop site applications being environmentally benign and permittable.

The costs for battery storage technologies are expected to continue to fall as maturity is gained and the economies of market orders are secured. The cost of Li-ion batteries have continued to drop and are trending down at a rate of approximately 14% a year over the past 5 years having dropped nearly 90% from their commercialization in early 1990. Most indications show that the downward trend will continue as suppliers continue to improve manufacturing processes and production capacity but may begin to flatten. The graph below shows the approximate battery price trend out to 2018.



* collected from industry data

Figure 12. Li-ion Battery Costs

Tables 16 through 20 provide a comparison of the technical parameters and estimated costs for each of the previously identified storage technologies. The included characteristics are by no means an exhaustive list but are intended to show a comparison of the technologies reviewed.

Table 16. Battery Characteristics Data Comparison

Characteristics Data Comparison									
Storage Type	Energy		Charge Rate	Round Trip Efficiency	Availability	Capacity Degradation		Life	
	SOC High Limit	SOC Low Limit				Energy	Power	Years	Cycles
Li-Ion NCM	90%	10%	1C	77 - 85%	97%	30-40%	10-20%	10	3,500
Li-Ion LiFePO4	85%	15%	2C-1C	78 - 91%	97%	20-40%	15-25%	10	2,000
Li-Ion LTO	98%	10%	3C-1C	77 - 85%	96%	15-25%	5-15%	10	15,000
NaS	90%	10%	1C-0.5C	77 - 83%	95%	15-30%	5-15%	15	4,500
VRB	95%	5%	1C-0.25C	65 - 78%	95%	5-10%	5-10%	15	5,000
ZnBr	98%	5%	1C-0.25C	65 - 80%	95%	5-10%	5-10%	15	3,000
Zinc-air	98%	10%	2C-1C	72 - 75%	96%	15-25%	5-15%	10	5,000
Flywheel	100%	0%	Varies	70 - 80%	94%	0%	0%	20	unlimited

Table 17. BESS Opinion of Costs

BESS SYSTEM OPINION OF PROBABLE COST				
System Size Year Use Case	4MW/16MWh 2016 Resource Adequacy	10MW/20MWh 2016 Freq Response/RA	4MW/16MWh4 2017 Resource Adequacy	4MW/16MWh6 2018 Resource Adequacy
BESS Warranty	10 YEAR	10 YEAR	10 YEAR	10 YEAR
BOP Major Equipment	$ 350,000.00	$ 380,000.00	$ 354,550.000	$ 359,159.15
BESS Equipment	$ 8,857,000.00	$ 13,558,000.00	$ 8,170,008.526	$ 7,578,363.384
EPC	$ 2,400,000.00	$ 2,600,000.00	$ 2,431,200.000	$ 2,633,800.000
Interconnection	$ 390,000.00	$ 460,000.00	$ 395,070.000	$ 400,205.91
Total	$ 11,997,000.00	$ 16,998,000.00	$ 11,350,828.53	$ 10,971,528.44
$/kWh Installed	$ 749.81	$ 849.90	$ 709.43	$ 685.72
$/kWh battery	$ 350.58	$ 395.47	$ 305.01	$ 265.36

Table 18. Battery Cost Comparison

Item	Lead Acid	Li-Ion NCM	Li-Ion LiFePO4	Li-Ion LTO	NaS	VRB	ZnBr	Zinc-air
BATTERY ($/kWh)	$200-$500	$340-$450	$340-$590	$500-$850	$500-$1000		$525-$725	$200-$400
PCS ($/kW)	$150-$350	$150-$350	$150-$350	$150-$350	$500-$750	$730-1200	$500-$750	$350-$500
Power control system cost ($/kW)	$80-$120	$80-$120	$80-$120	$80-$120	$80-$120		$100-$140	$100-$140
Balance of Plant ($/kW)	$120-$250	$90-$120	$90-$120	$90-$120	$100-$125	$100-$125	$100-$125	$80-$100
EPC ($/kWh)	$150-$180	$150-$180	$140-$180	$140-$180	$140-$200	$140-$200	$140-$200	$120-$180
Fixed O&M cost ($/kW yr)	$7-$15	$6-$14	$6-$14	$6-$14	$7-$15	$7-$16	$7-$17	$6 - $13
Installed Low	**$ 7,000,000**	**$ 9,120,000**	**$ 9,120,000**	**$ 11,680,000**	**$ 12,960,000**	**$ 14,320,000**	**$ 13,440,000**	**$ 7,240,000**
Installed High	**$ 14,160,000**	**$ 12,840,000**	**$ 13,384,000**	**$ 18,840,000**	**$ 23,180,000**	**$ 22,900,000**	**$ 18,860,000**	**$ 12,240,000**

* Collected from industry data
* Cost comparisons are based on 4MW/16MWh systems
* Costs in 2017$

Table 19. CAES and LAES Comparison

Item	Compressed Air Energy Storage	Liquid Air Energy Storage
General Criteria		
Commercial status (developmental, commercial, mature)	Commercial	No Commercial Operation
Number of plants to date	2 to 3 commercial plants currently operational	1 pilot plant worldwide
Year of first operation	1978	2010
Typical project lead times (months)	24 to 28 months	Not enough data available
Footprint or energy density (ft^2 per MW)	20 acres for 135 MW Block	Not enough data available
Applicability for long-term operation- multiple hour operation (e.g., peak shaving, sustained outages)	Peak shaving and Intermediate Service (8 hours of daytime operation w/ 8 hours of compression at night typical)	Peak shaving and Intermediate Service (8 hours of daytime operation w/ 8 hours of compression at night typical)
Applicability for short-term operation- subhourly operation (e.g., power quality applications)	Similar characterstics to a simple cycle gas turbine, provided compressed air is available.	Similar characterstics to a simple cycle gas turbine, provided compressed air is available.
Potential environmental/regulatory factors	Plant emissons similar to simple cycle gas turbine application. Compressors require cooling water supply (mechanical draft cooling tower required).	Plant emissons similar to simple cycle gas turbine application. Compressors require cooling water supply (mechanical draft cooling tower required).
Electrical transmission considerations	Same as a simple cycle gas turbine.	Same as a simple cycle gas turbine.
Vehicular access and local infrastructure considerations	Same as a simple cycle gas turbine. Natural gas pipeline required.	Same as a simple cycle gas turbine. Natural gas pipeline required.
Geological or topographic factors	Solution mined salt cavern, aquifer, or mined hard rock cavity (limestone mines) required.	No major geological requirements
Required size of interconnection (kV)	230 kV or higher	230 kV or higher
Technology risks	Limited suppliers available, integrity of cavern used for storage of compressed air.	Existing components are mature technology, but the overall system lacks maturity that other energy storage systems have.
Potential fatal flaws to commercial viability	Satisfactory Geology	System lacks maturity that other energy storage processes have
Staffing requirements (# full time staff members for 100 MW Facility)	2 hourly, 6 salaried	2 hourly, 6 salaried
Performance Characteristics		
Range of power capacity (MW)	100 MW +	100 MW +
Range of discharge time (hrs)	8 hours typical	4 hours typical
Range of energy capacity (MWh)	800 MWh +	400 MWh +
Average Annual Availability (% of time)	93%	Not enough data available
Typical Plant Capacity Factor	23.7%	12%
Expected life of equipment (years)	30	30
Gross Plant Output (MW), Average Ambient Day	101.0	100.0
Aux Power (MW), Average Ambient Day	1.01	-
	1.0%	-
Net Plant Output (MW), Average Ambient Day	100.0	-
Net Plant Heat Rate (btu/kWhr), Average Ambient Day	4436	4436
% of Energy Recovered From Compression	83.4%	-
Net Plant On Peak Efficiency (Gas Turbine Efficiency)	76.92%	-
Complete Plant Turn around efficiency (AC-AC efficiency) (%)	64.11%	60%
Basis for Cost Estimates (costs are expressed in 2017 US dollars)		
EPC Cost ($/kW)	$1,200 - $1,400 per kW	-
Total Project Cost including Caverns ($/kW)	$2,000 - $2,300 per kW	$2,000 - $4,000 per kW
Cost to Solution Mine Salt Caverns	$68 MM	Not Applicable
Estimated fixed operations and maintenance cost ($ per kW)	$18.90	-
Estimated variable O&M cost (excluding fuel & electric costs) ($ per MWH)	$2.30	$2.0-$2.50

Table 20. Pumped Hydro Storage Overview

	Item	General Pumped Hydro Projects				
		General	Single Speed	Variable Speed	Closed Loop(1)	Open Loop(2)
	General Criteria					
1	Commercial status (developmental, commercial, mature)	mature	mature	commercial	mature	mature
2	Number of plants to date (United States)	40	40	0 (10 worldwide)	18	22
3	Year of first operation (United States)	1929	1929	1990 (Japan)	1963	1929
4	Typical project lead times (years)	5 licensing 5 construction	5 licensing 5 construction	5 licensing 5 construction	< 5 licensing 5 construction	> 5 licensing 5 construction
5	Footprint or energy density (MWh/ft^2)	Varies depending upon head and reservoir size, for example, Bath County has 700 acres for 2700 MW				
6	Applicability for long-term operation- multiple hour operation (e.g., peak shaving, sustained outages)	Load shifting and peak shaving (8 hours of daytime operation w/ 12 hours of pumping), with sufficiently sized reservoirs, weekly and seasonal storage available				
7	Applicability for short-term operation- subhourly operation (e.g., power quality applications)	load following, frequency regulation, spinning reserve, for both single and variable speed. variable speed provides faster response times and finer adjustments				
8	Potential environmental/regulatory factors	vary widely from site to site. may include land use, recreation and fisheries issues	vary widely from site to site. may include land use, recreation and fisheries issues	vary widely from site to site. may include land use, recreation and fisheries issues	generally fewer impacts and shorter licensing period than open loop	generally more impacts and longer licensing period than closed loop
9	Electrical transmission considerations	proximity to transmission line can affect project economics				
10	Required size of interconnection (kV)	>230 to 500 kV preferred				
11	Vehicular access and local infrastructure considerations	projects may be in remote locations. roads, additional construction material transportation cost, and electrical transmission may be included in total project cost.				
12	Geological or topographic factors	short length of conveyance and high head create better project economics	short length of conveyance and high head create better project economics	short length of conveyance and high head create better project economics	makeup water for the reservoirs must be considered (but generally easy to overcome)	may have more fisheries and environmental considerations than a closed loop system.
13	Technology risks	tunneling, sedimentation, seismology	generating technology is proven	variable speed not implemented in US, but has been proven internationally	tunneling, seismology, makeup water for reservoirs	tunneling, sedimentation, seismology
14	Potential fatal flaws to commercial viability	environmental fatal flaws, seismology, project financing	environmental fatal flaws, seismology, project financing	environmental fatal flaws, seismology, project financing	environmental fatal flaws, seismology, project financing	environmental fatal flaws, seismology, project financing
15	Staffing requirements (# full time staff members for 1000 MW facility)	15 to 25 depending on asset portfolio in region				
	Performance Characteristics					
1	Range of power capacity of plant (MW)	9 - 2800	9 - 2800	85 - 600 (internationally)	28 - 2700	9 - 2000
2	Range of discharge time (hrs)	5 - 100+	5 - 100+	same capacity as single speed (NA in US)	5 - 100+	9 - 100+
3	Range of energy capacity (MWhr)	87-370,000	87-370,000	same capacity as single speed (NA in US)	247-190,000	87-370,000
4	Annual forced outage rate (% of time)	0-3%				
5	Expected life of generating equipment (years)	20+				
6	Expected life of project (years)	50+				
7	Expected life of project (number of cycles)	>10 cycles/day/year for 50 years				
8	Parasitic load (for a 1000 MW plant) (MWhr/year)	5 MW				
9	Turn around efficiency (AC-AC efficiency) (%)	75 - 80%	75 - 80%	80 - 82%	75 - 80%	75 - 80%
	Basis for Cost Estimates (costs are expressed in 2017 US dollars)					
1	Range of capital cost ($ per kW)	$1,500-$4,700 per kW				
2	Range of operations and maintenance cost ($ per kW-yr)	$6.2-$43.3				
3	Biannual Outage Costs (for a 1,000 MW project)	$280,000				
4	Major Maintence Costs (for a 1,000 MW project at year 20)	$6,700,000				
5	Replacement frequency (years)	20				

1. Closed loop system- A pumped storage system in which the upper and lower reservoirs are connected by a relatively short water conveyance system and the dams are not on a main-stem river.
2. Open loop system- A pumped storage system in which one or more of the dams are on a main-stem river.
3. O&M Cost/MW based on largest and smallest pumped storage plants in US

XI. References

The following references were cited in the preparation of this report.

- Federal Energy Regulatory Commission, "Market Oversight Glossary", http://www.ferc.gov/market-oversight/guide/glossary.asp.
- ERCOT "Nodal Protocols".
- ERCOT Concept Paper, "Future Ancillary Services In ERCOT", Draft Version 1.1, 2013.
- IESO Website.
- Midcontinent ISO, "Business Practices Manual 002" and "Business Practices Manual 015".
- FERC Docket No. ER12-1664-000, Issued September 20, 2012.
- SBC Energy Institute, "Electricity Storage Factbook", September, 2013.
- NYISO, "Market Administration and Control Area Services Tariff, 15.3 MST Rate Schedule 3".
- NYISO, "Ancillary Services Manual", V.4, 2014.
- PJM, "State of the Market Report", 2014.
- PJM, "Manual 11, Energy & Ancillary Services Market Operations", Revision 73, April, 2015.
- Department of Energy, "Grid-Scale Energy Storage Demonstration using Ultrabattery Technology", October, 2012.
- Ecoult Website.
- Beacon Power Website.
- Uni Energy Technologies Website.
- Rocky Mountain Institute, HOMER Energy, and global X, "The Economics of Load Deflection", April, 2015.
- NERC, "Ancillary Services Summary Across North American RTOs and ISOs".
- U.S. DOE, NETL, "Seneca Compressed Air Energy Storage (CAES) Project", September, 2012.
- GTM Research, "U.S. Energy Storage Monitor: 2014 Year in Review: Executive Summary"
- The Brattle Group, "The Value of Distributed Electricity Storage in Texas", Prepared for ONCOR, November, 2014.
- Sandia National Laboratories, "Performance Assessment of the PNM Prosperity Electricity Storage Project", Report SAND2014-2883, May, 2014.
- Sandia National Laboratories, "Market and Policy Barriers to Energy Storage Deployment: A Study for the Energy Storage Systems Program", Report SAND2013-7606, September, 2013.
- Sandia National Laboratories, "Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems", Report SAND2013-7084, August, 2013.
- International Energy Agency, "Technology Roadmap: Energy Storage", 2014.
- U.S. Department of Energy (DOE), "Grid Energy Storage", December, 2013.
- U.S. Department of Energy (DOE), "Energy Storage Safety Strategic Plan", December, 2014.
- CAISO, "Advancing and Maximizing the Value of Energy Storage Technology: A California Roadmap", December, 2014.
- CAISO, "Draft Energy Storage Roadmap for California", October, 2014.
- DOE, "DOE/EPRI 2013 Electricity Storage Handbook", in Collaboration with NRECA, July, 2013.

- Executive Office of the President (White House) and DOE, "Economic Benefits of Increasing Grid Resilience to Weather Outages", August, 2013.
- PNNL and DOE, "National Assessment of Energy Storage for Grid Balancing and Arbitrage", Phases 1 (WECC) and 2 (Cost and Performance Characterization), Volumes 1 and 2, June, 2012 and September, 2013.
- EPRI, "Cost-Effectiveness of Energy Storage in California", June 2013
- Lux Research "Grid Storage under the Microscope:" April, 2012
- Sandia Report, "Estimating the Maximum Potential Revenue for Grid Connected Electricity Storage: Arbitrage and Regulation," Dec. 2012

- Sandia Report, "Estimating the Maximum Potential Revenue for Grid Connected Electricity Storage: Arbitrage and Regulation," Dec. 2012

- Energy Information Admin, "Annual Energy Outlook 2007" Feb. 2007

XII. Glossary

Capacity The number of ampere-hours or amp-hours (Ah) a fully charged ESS can deliver.

Charge Cycle (cycle) Refers to the battery discharge, charge then discharge again process. A charge cycle does not have to be to full discharge/charge to be considered a cycle. Batteries are typically rated for a number of cycles to a specific depth of discharge and a specific discharge rate. For example, an ESS may be rated for 10,000 cycles to a 40% DOD at a 2C rate. The same ESS may be rated for 3,000 cycles to an 80% DOD at a 2C rate. The same ESS may also be rated for 12,000 cycles to 40% DOD at a 1C rate. The life expectancy of a battery is typically specified by the number of expected charge cycles. Cycles may be used as a proxy for comparing technologies, but should not be used solely to determine lifetime. Battery vendors will typically analyze a detailed electrochemical model of their battery to determine the lifetime for a specific use case.

Charge Rate (C-rate) The rate of charge and discharge current of a battery. A charge or discharge equivalent to the batteries' capacity over one hour would be 1C. For example, A 1C discharge from a 100 Ah battery is 100 amperes for one hour.

Depth of Discharge (DOD) A way to quantify the capacity discharged from a battery during any status of the cycle. It can be written as amp-hours used or percentage used. For example, a 100 Ah battery that has discharged 20 Ah would be at a 20% depth of discharge. Depth of discharge is complimentary to State of Charge.

Duty Cycle Expressed as a percentage, the duty cycle is a calculation of both the amount of power discharged from a battery and the amount of time for which it is discharged, relative to the battery's intended discharge cycle. The duty cycle accounts for both continuous and non-continuous loads throughout the battery's discharge cycle. For example if a 200Ah battery discharges at 1C with a DOD of 50% and a load of 75Ah is applied, the duty cycle would be 75%.

Energy	The measurement of power with respect to time. As power is an instantaneous measurement of work, energy is the amount of power over an established time interval. The units for energy are typically Kilowatt-hours (kWh) or Megawatt-hours (MWh). For example, a load of 2MW (power) operating for 5 hours would be 10MWh (energy).
Energy Application	A use of the ESS where the duration of response is greater than the magnitude of response. Peak shifting is an Energy Application as it provides MW for a longer duration (1MW/4MWh or 4-hours).
Power	The amount of work being transferred through the electrical system. The unit for power in an electrical circuit is the Watts (W), Kilowatts (kW) or Megawatts (MW). Power is determined by the voltage, current and resistance of the circuit.
Power Application	A use of the ESS where the magnitude of response is greater than the duration of response. Frequency Regulation and Spinning Reserve are Power Applications as they provide MW for a short duration (4MW/1MWh or 15-minutes)
Round Trip Efficiency	The ratio of energy available to be discharged from a battery relative to the amount of energy required to charge the battery to that state of charge. The higher the round trip efficiency, the less energy loss in the energy storage system reducing wasted energy. For example, if it takes 100kWh to charge the battery and the available energy to discharge is 80kWh, the battery has a Round trip efficiency of 80%.
State of Charge (SOC)	A way to quantify the capacity left in a battery during an instantaneous part of the cycle. It is a percentage of the batteries' present level to the batteries' full capacity. For example, a 100 Ah battery that has discharged 20 Ah would be at an 80% state of charge. State of charge is complimentary to Depth of Discharge.
State of Health (SOH)	Compares the batteries actual condition to its ideal in the form of a percentage. If a battery is functioning at 70% of the battery's specifications, the SOH would be 70%. SOH decreased over the life of the battery. Energy Storage parameters typically used to derive the

SOH are internal impedance, self-discharge, ability to accept a charge, and number of charge-discharge cycles.

Thermal Runaway A condition where a cell charging or discharging will destroy itself through internal heat generation. Thermal Runaway can be caused by high overcharge or high rate of discharge or other abusive conditions as well as internal failures. In multi-battery cell applications, neighboring cells can heat up adjoining cells causing a further increase in temperature of the whole system causing additional failure.

750 Old Hickory Blvd
Suite 200
Brentwood, TN 37027-4528
(615) 983-4159

hdrinc.com