



2020 Energy Storage Assessment Study

Black Hills Energy

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Contents

1	Introduction	3
2	Energy Storage Technology Overview.....	3
	2.1 Battery Technology.....	4
	2.1.1 Lithium-ion	4
	2.1.2 Vanadium Redox Flow	7
	2.2 Other Emerging Technologies	8
3	Energy Storage as a Non-Wires Alternative.....	10
	3.1 Definition	10
	3.2 Examples	11
4	Cost Assessment	12
	4.1 Trends.....	12
	4.2 BESS Cost Estimation	13
5	Upgrade Deferral Valuation	18
6	References	20
7	Appendix.....	22
	7.1 Project Team.....	22

Tables

Table 1: Summary of compiled 2018 findings and 2025 predictions of cost and parameter ranges by technology type - BESS (PNNL, 2019).....	14
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Figures

Figure 1. Cost Projections for 4-hour Battery Energy Storage Systems	13
Figure 2: BESS CapEx vs Duration.....	15
Figure 3: Li-ion vs Flow BESS Installed Cost	16
Figure 4: Specific Capital Cost vs BESS Size	17
Figure 5: Flow Chart for Deferral Cost-Benefit Analysis.....	19
Figure 6: Deferral Benefit vs Deferral Years (IEEE Example).....	20

Acronyms and Abbreviations

AHJ	Authority Having Jurisdiction
BESS	Battery Energy Storage Systems
BHE	Black Hills Energy
CAES	Compressed Air Energy Storage
CapEx	Capital Expenditure
CPUC	Colorado Public Utilities Commission
DOD	Depth of Discharge
ESS	Energy Storage System

HMMP	Hazardous Material Management Plan
HMA	Hazard Mitigation Analysis
LFP	Lithium-Iron-Phosphate
Li-ion	Lithium-ion
LTO	Lithium-Titanate
MW	Megawatt
MWh	Megawatt-hour
NMC	Nickel-Manganese-Cobalt
NPV	Net Present Value
NWA	Non-Wires Alternative
PHES	Pumped Hydropower Energy Storage
PCS	Power Conversion System
PNNL	Pacific Northwest National Laboratory
RTE	Round Trip Efficiency
T&D	Transmission & Distribution
VrB	Vanadium Redox Battery
VAR	Volt-Ampere Reactive

1 Introduction

Black Hills Energy (BHE) is investigating energy storage as part of its efforts to comply with the Colorado Public Utilities Commission (CPUC) Rules 3206 (Transmission) and 3207 (Distribution). These rules require that BHE consider energy storage in its planning process as an alternative to construction or extension of transmission/distribution facilities. The use of energy storage for this application is an example of what are commonly referred to as “Non-Wires Alternatives” (NWAs). Energy storage technology has advanced considerably in recent years in both technical aptitude and reduced cost, which has led to increasing interest amongst electric utilities in the deployment of energy storage systems, in place of more conventional transmission and distribution solutions.

This report provides a technical overview of the current state of the energy storage industry, including types of commercially available energy storage technology that may be applicable as NWAs in BHE’s transmission and distribution planning processes. Key characteristics that influence the design, cost, and performance of energy storage projects are discussed. An overview of how energy storage systems can be used as NWAs is also presented, including specific examples from real-world projects.

In order to establish a quantifiable basis of comparison between energy storage systems and conventional T&D facilities, an approximation of installed cost for Li-ion battery energy storage systems is included. Li-ion battery technology is chosen for this cost assessment, as it is the most prevalent and widely deployed energy storage technology for systems of this scale and for this purpose.

The final part of this report includes a summary comparison table for the purpose of directly comparing energy storage systems to conventional T&D facilities on the basis of both technical and economic feasibility. This table will compare “typical” energy storage system parameters to specific examples of BHE projects from past planning periods.

2 Energy Storage Technology Overview

Disclaimer: *It is not the intention of this report to endorse or promote any specific vendor, but to incorporate a wider picture of energy storage technology as applied to utilities and specifically to BHE.*

There are a wide assortment of Energy Storage System (ESS) technologies available for utility-scale applications. A few of these options have reached commercial maturity and are being deployed regularly today. Historically, the vast majority of ESS that have been installed to date are pumped hydropower energy storage systems (PHES). This is a very mature and well established technology; however, the specific geotechnical requirements and long installation times for PHES make it unsuitable for consideration as a NWA for most applications. Therefore, PHES will not be discussed further in this report.

Advancements in battery cell technology, largely due to the immense demand for lightweight and energy dense batteries for portable electronics, have opened the door to applying the same technology to very large scale stationary storage applications. The last decade has seen a steady growth in the number and size of utility-scale energy storage systems that are based on electrochemical energy storage technology. These types of systems are referred to as “Battery Energy Storage Systems” (BESS). Many different battery chemistries and form factors have been considered for large BESS applications, each with varying degrees of energy density, cycle life, efficiency, cost, thermal runaway considerations, and many other factors. Some of these chemistries and form factors have already seen widespread deployment and could be considered “commercially mature”, while others are in the research & development or demonstration phase.

Of the currently available BESS chemistries; lithium ion (Li-ion), sodium sulfur, and vanadium redox flow have emerged as commercially viable at this time. These types of storage technologies have characteristics and costs that make them suitable for consideration by BHE and are discussed in depth in this report. Other energy storage technologies such as compressed air energy storage, mechanical storage, hydrogen storage, flywheels, other battery chemistries, and liquid air systems are not considered appropriate technologies for BHE at this time for a variety of reasons including challenges associated with technological maturity, system complexity, storage duration, geographical requirements and commercial availability. Some description of these technologies is provided in this report, but the technologies are not compared on an economic basis.

2.1 Battery Technology

The power input and output of battery energy storage systems are governed by a bidirectional inverter known as a Power Conversion System (PCS). A PCS can respond to a dispatch signal to charge or discharge in milliseconds, allowing a BESS to ramp up from standby mode to full nameplate capacity in less than 2 seconds, including communication latencies. Because there is no rotational inertia, a BESS can change from charging to discharging (and vice versa) nearly instantaneously. This enables the provision of very high performance ancillary services such as frequency regulation. Additionally, battery PCS units have the ability to supply full four-quadrant AC output, which can be utilized to supply voltage and volt-ampere reactive (VAR) support.

2.1.1 Lithium-ion

Background

Li-ion batteries have rapidly become the workhorse of the battery energy storage industry. Large scale manufacturing and production of multiple chemistries (lithium nickel manganese cobalt oxide (LiNiMnCoO₂ or NMC), lithium iron phosphate (LiFePO₄ or LFP), lithium manganese oxide (LMO), and lithium titanate (Li₄Ti₅O₁₂ or LTO)) have given it a significant portion of the commercial energy storage market. Li-ion’s competitive energy density and power density have 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 (conventional lead acid battery systems are not economical for utility energy storage because of their low energy density, short cycle life, and high cost). The Li-ion 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 has become widely accepted for large-scale energy storage applications and also forms the core technology for stationary energy storage.

The vast majority of the BESS systems currently in operation are on the order of 10MW or less. It has not been until recent years that larger systems are being constructed. Currently, the largest BESS in operation worldwide is the 100MW (129MWh) Lithium-ion system for Hornsdale Power Reserve in South Australia. This record will not stand for long, as several Li-ion BESS projects are set to come online in 2020-2022 that will exceed 100 MW by some margin.

A large number of vendors, known as Original Equipment Manufacturers or OEMs, produce the technology, including Bosch, Panasonic, Johnson Controls, LG Chem, NEC, Samsung, Saft, BYD, Hitachi, CATL, and GS Yuasa (Mitsubishi). Other companies, known as integrators, are involved in the purchase and assembly of battery cells from OEMs into large, containerized units for deployment in the field.

All Lithium-ion battery systems will gradually degrade in energy capacity over time. The rate of this degradation is heavily dependent on duty cycle, cell chemistry, charge/discharge rates, and other factors. In order to account for this degradation, Li-ion systems can be over-built at the beginning of a project, have modules replaced or added periodically, or some combination of these approaches can be utilized. The addition of new modules to retain nameplate capacity over time is known as “augmentation.” Li-ion battery suppliers are now offering capacity maintenance agreements to maintain capacity for at least 20 years using periodic augmentation or full module replacement. These augmentation periods typically are planned to occur every 5-10 years.

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 has thus far moved toward more heavily utilizing NMC. NMC is the most typical chemistry in utility-scale BESS due to its balanced performance characteristics in terms of energy, power, cost, and cycle life.

There has been growing interest in LFP batteries for utility-scale BESS in recent years. In contrast to the NMC battery, LFP technology is a lower cost battery with a slightly decreased power density, thus requiring more space than NMC for the installation of a similar energy rating. LFP technology has a constant discharge voltage, the cell can produce full power to 100 percent depth of discharge (DOD) and its chemistry is seen as safer and less of a fire risk when compared to other Li-ion chemistries due to its higher temperature threshold for thermal runaway. LFP batteries are also prone to a higher degree of self-discharge meaning that the batteries will tend to lose charge faster than other technologies when not in use.

Li-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). Battery cells are integrated into battery modules, which are typically installed in standard 19-inch-wide racks similar to those used for telecom or substation equipment. The racks are then installed in a building or specially prepared steel container to function as an integrated battery system. Essential to any BESS installation is a battery management system (BMS), which monitors the electrical and thermal conditions of the cells and controls the charging, discharging, and cell balancing while ensuring the system is operated within its designed limits and protected from damage.

Connecting this DC power system to an AC grid at the point of interconnection requires a bi-directional inverter, generally known as a “power conversion system” (or PCS). A PCS is similar to an inverter used for solar power systems, with the added capability of allowing power to flow in the reverse direction (from AC to DC) to charge the BESS. PCS are typically standalone units installed separately from a battery container, however some suppliers offer containers with integrated PCS.

Li-ion batteries are highly sensitive to temperature. The building or container is typically fitted with an active cooling system to maintain the batteries within an optimal temperature range. The system will quickly degrade 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. Some jurisdictions may require hazardous material management plans (HMMP) and/or a hazard mitigation analysis (HMA). In general, most states, including Colorado, adopt the International Fire Code which leaves it up to the authority having jurisdiction (AHJ) to decide whether HMMPs or HMAs are required. Careful consideration should be given to fire suppression consisting of either gaseous (dry) systems, which may require air permitting, or liquid systems that may cause concerns with the Clean Water Act.

The C-rate of a battery is the ratio of the system’s rated charge/discharge power, to its rated energy capacity. Lithium-ion battery systems are inherently best suited for C-rates between 0.25 and 2. This translates to storage charge/discharge durations between 0.5 and 4 hours. Different use-cases necessitate different storage durations, but most recent lithium-ion installations are 1-4 hour systems, as this duration is typically sufficient to cover the peak load duration of a utility. To achieve longer durations, more racks or containers can be added in parallel while maintaining balance of plant equipment with the same rated power.

Lithium-ion batteries have a round trip efficiency (RTE) generally 85-90 percent at the AC point of interconnection. The auxiliary power required for system HVAC, controls, and other loads varies heavily. This aux power is generally self-supplied and included in the RTE number.

2.1.2 Vanadium Redox Flow

Background

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

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

Maturity

While the first VrB operational system was demonstrated in Australia in the 1980s, there are only a few systems in operation worldwide. A number of vendors manufacture these systems, including, Gildemeister (American Vanadium), Rongke Power, Prudent Energy, ViZn Energy, Vionx Energy, and Sumitomo. The industry is currently in a phase of continuous improvement, with multiple generations of technology available. Only a few systems operate commercially from a worldwide perspective. San Diego Gas & Electric has a demonstration project in coordination with Sumitomo Electric from Japan. The flow battery system provides 2 megawatts (MW) and 8 megawatt hours (MWh) of energy, enough to power the equivalent of about 1,000 homes for up to four hours.

VrB systems use electrodes to generate current through flowing vanadium 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.

VrB systems are recognized for their long service life (up to 20,000 life cycles with routine maintenance) as well as their ability to provide system sizing flexibility in terms of power and energy. The separation membrane prevents the mix of electrolyte flow, making recycling possible. The end of life can be extended by replacing the electrolyte and the membrane.

The industry is moving away from custom systems to more prepackaged systems, to compete with Li-ion. Some vendors are 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. Additionally, 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 toward containerized systems with pre-determined storage durations of 3 to 8 hours. The prepackaged systems utilized one or more containers per battery. The containers typically have both secondary and tertiary containment for the electrolyte fluid. Some containerized flow products can be stacked vertically to reduce their footprint. As with Li-ion systems, a PCS is required to connect the DC battery system to an AC grid.

For larger flow systems on the scale of 50MW or more, it is sometimes advantageous to install the equipment in one large building rather than in modularized containers. This can improve energy density and reduce auxiliary power costs. One such facility is currently under construction in Dalian, China. The 200MW, 800MWh Vanadium redox flow system, provided by Rongke Power, is scheduled to come online in 2020.

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. This allows VrB systems to maintain nameplate capacity for 20+ years without requiring the periodic replacement or “augmentation” that Li-ion systems must undergo. Due to the pumps and other losses, they have a high station service load yielding a lower round trip efficiency than other technologies. With current technology, RTE values for VrB systems are generally quoted to be around 70-75 percent¹.

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.

2.2 Other Emerging Technologies

There are several other ESS technologies listed below, that are not discussed or compared in this report as they are either not technologically applicable to BHE’s NWA planning needs, or are not sufficiently developed to be considered commercially available. Some of these technologies may be available on a commercial scale, but because of duration limitations, capability limitations, limited supplier base, or limited operating experience, they are not considered favorable for BHE and are not compared from an economic perspective. A brief discussion is presented for each technology summarizing reasons for not including them in the economic evaluation.

Advanced Lead-Acid, Zinc-Bromine, Zinc-Air flow, and other battery chemistry

There are numerous electrochemical (battery) energy storage solutions with various chemistries in various stages of development and deployment, in addition to the Li-ion and VrB technologies detailed in this report. Some of these technologies have the potential to be cost competitive with the established chemistries, but none appear to offer significantly

¹ AC-to-AC, including auxiliary power.



better economics. Therefore, the technologies that were evaluated, Li-ion and VrB can act as proxy for these chemistries that were not evaluated in detail. As these battery chemistries become commercially available, they should be compared with established systems for specific applications on the basis of cost effectiveness, reliability, warranty/guarantee protection, and other factors.

Liquid Air

Liquid air storage uses electricity to cool air from the atmosphere to the point at which air liquefies, approximately minus 195 °C. The liquid air, which takes up approximately one-thousandth of the volume of air in the gas phase, can be stored for long periods in a vacuum insulated vessel at atmospheric pressure. At times when electricity is demanded, the liquid air is pumped into a heat exchanger, which acts as a boiler. Either heat from ambient air or low grade waste heat is used to heat the liquid and turn it back into a gas. The increase in volume and pressure from this is used to drive a turbine to generate electricity. In isolation, liquid air storage systems have a round-trip efficiency of approximately 25 percent. This can be increased to 50-60 percent with the addition of a cold store to capture the energy generated by evaporating the liquid air. There is one pilot facility in operation worldwide, a 2.5 MWh system developed by University of Leeds and Highview Power Storage. Because of the relatively low round-trip efficiency and very limited number of deployments, this technology was not considered favorable for BHE.

Hydrogen Storage

Hydrogen energy storage systems use hydrogen as the medium for storage of energy. Hydrogen is generated using electrical energy through electrolysis of water and stored as compressed gas in underground caverns or aboveground tanks. The hydrogen is converted back to electricity through a conventional gas turbine or internal combustion engine or through a fuel cell. Hydrogen systems are capable of storage energy density that is higher than a compressed air energy storage system (CAES), leading to modest costs for the storage portion of the ESS. This technology is characterized by low round-trip efficiency in the 30 to 40 percent range and high power conversion system cost, approximately two to eight times as expensive as PHES. Given the low round-trip efficiency, lack of commercial scale demonstration, and high cost, this technology was not considered favorable for this BHE application.

Flywheels

Flywheel technology is a well-established technology with discharge durations in the scale of seconds to minutes. They are well suited for power related services such as UPS, frequency regulation, and bridging to back-up system. They are not commercially available for bulk-storage applications with discharge durations in the range of multiple hours as may be required by BHE.

Capacitors

Capacitors are a direct method of storing electrical energy, storing energy as electrical charges. They are widely used in power-quality related services such as bridging and ride-through. They have short storage durations on the scale of milliseconds up to a few

minutes. Current capacitor technology has energy density that is orders of magnitude lower than state-of-art battery systems. Because of their low energy density and short discharge times, they are not considered favorable for BHE's bulk-storage needs.

Magnetic and superconducting magnetic systems

Magnetic and superconducting magnetic energy storage system are a direct method of storing electrical energy, storing energy in the form of a magnetic field created by flowing electrical charges. Because of their fast response time, they are suitable for power-quality related services such as bridging and ride-through. They have short storage durations on the scale of milliseconds up to a few minutes. Current magnetic technology has energy density that is higher than the energy density of capacitors, but is still orders of magnitude lower than state-of-art battery systems. Because of their low energy density and short discharge times, these systems are not considered favorable for BHE's bulk-storage needs.

Gravitational Potential Energy

Mechanical gravity energy storage systems convert electrical energy into potential energy by raising heavy solid objects in the earth's gravitational field. The stored potential energy can be converted back to electrical energy by a generator coupled to the object that allows the object fall in a controlled way. PHES is a form of mechanical gravity energy storage that uses water as the working medium. Various arrangements have been proposed including railcar systems, crane-based systems, and in-ground systems. There have been a few demonstration projects completed, but no commercial deployment has been made. Because of the lack of any commercial deployment, this technology is not considered favorable for BHE's applications.

3 Energy Storage as a Non-Wires Alternative

3.1 Definition

Non-Wires Alternatives are defined as "an electricity grid investment or project that uses non-traditional transmission and distribution solutions, such as distributed generation, energy storage, energy efficiency, demand response, and grid software and controls, to defer or replace the need for specific equipment upgrades, such as T&D lines or transformers, by reducing load at a substation or circuit level," (Navigant, 2017). Generally speaking, an energy storage system can be placed "downstream" of a particular asset that is experiencing (or may experience) overloading. By charging during low-load periods and discharging during peak-load periods, a process known as "peak shaving", the peak load on that particular asset can be reduced. This can either postpone the need for replacing or upgrading the asset, or prolong the life of the asset (or both). The value of the deferred upgrade and/or the prolonged asset life can then be compared to the cost of the energy storage system to determine economic feasibility. This process is discussed further in Section 5 below.

Because energy storage systems are time-limited resources, they need to be classified both in terms of power rating and energy capacity. It is important to consider not just the power required for a specific application, but also the amount of energy, or in other terms, the duration for which that power is required. Both power and energy ratings factor into the cost of an energy storage system. For example, a 1 MW, 0.5 MWh BESS is likely to be significantly smaller and less expensive than a 1 MW, 4 MWh BESS. As a result, it is generally more cost effective to use storage for peak shaving when the shapes of the peaks are sharp and narrow, as opposed to more broad and less pronounced.

3.2 Examples

OPALCO - DECATUR ISLAND BESS, WA

Orcas Power & Light Coop. (OPALCO) is currently in the construction stages of a 0.5 MW/2 MWh Lithium-ion BESS located on Decatur Island. OPALCO services 20 islands in San Juan County, Washington. The islands receive power from BPA via a subsea transmission cable connected to the mainland, which first reaches customers on Decatur Island. The primary purpose of the BESS is to defer the replacement of the subsea cable by peak shaving on a daily basis. Pacific Northwest National Laboratory estimates the total value of this upgrade deferment to be \$2.0 Million. The BESS will also be providing volt/var support, demand charge reduction, and outage mitigation, further adding value to the project. The BESS is scheduled to become operational in 2020.

APS – PUNKIN CENTER BESS, AZ

Arizona Public Service (APS) Electric completed the installation of a 2 MW/8 MWh BESS at Punkin Center, Arizona in 2018. The project consists of two 40' x 8' steel containers filled with Lithium-ion battery modules. APS determined that the storage system provided a more affordable solution to address load growth than the option of rebuilding 17 miles of distribution lines over rough terrain. The system provides peak shaving to reduce thermal load on the existing distribution feeder, as well as volt/var support to maintain power quality.

The Punkin Center is considered a critical load facility, so spare equipment is kept on site along with an interconnection point for a diesel generator in case of a contingency event.



“The project proved to be a cost-effective solution for APS to serve the rural community, compared to reconductoring of the line. The success of the project demonstrates the capability of this NWA solution to serve the residents of Punkin Center for a decade and possibly longer depending on the load growth.” –Smart Electric Power Alliance, 2019

The site was developed with provisions for anticipated expansion of the BESS to meet future load growth. APS is planning to install up to 500 MW of energy storage capacity over the next 15 years.

DUKE ENERGY – MOUNT STERLING MICROGRID, NC

In 2017, Duke Energy completed the implementation of a microgrid to service a remote communications tower in Great Smoky Mountains National Park. The microgrid features a 10 kW PV solar installation and a 95 kWh Zinc-air BESS. The system was selected as an alternative to four miles of distribution line, which was decommissioned as a result of the project. Duke Energy elected to utilize the Zinc-air battery technology due to its very low risk of fire, given the sensitive surroundings. When fully charged, the BESS is capable of supporting load continuously for 11 days. The new microgrid offers improved reliability over the previous distribution line for critical communications equipment for the National Park.

DOMINION ENERGY – HANOVER COUNTY BESS, VA

In 2019, Dominion Energy of Virginia announced plans to build three battery energy storage pilot projects, totaling 16 MW. One of these projects, located at Hanover Substation, will utilize a 2 MW/4 MWh Lithium-ion BESS to *“explore the feasibility of using battery energy storage systems instead of traditional grid investments, such as transformer upgrades, necessary to serve customers during times of high energy usage.”* The project is expected to be in service by the end of 2020.

4 Cost Assessment

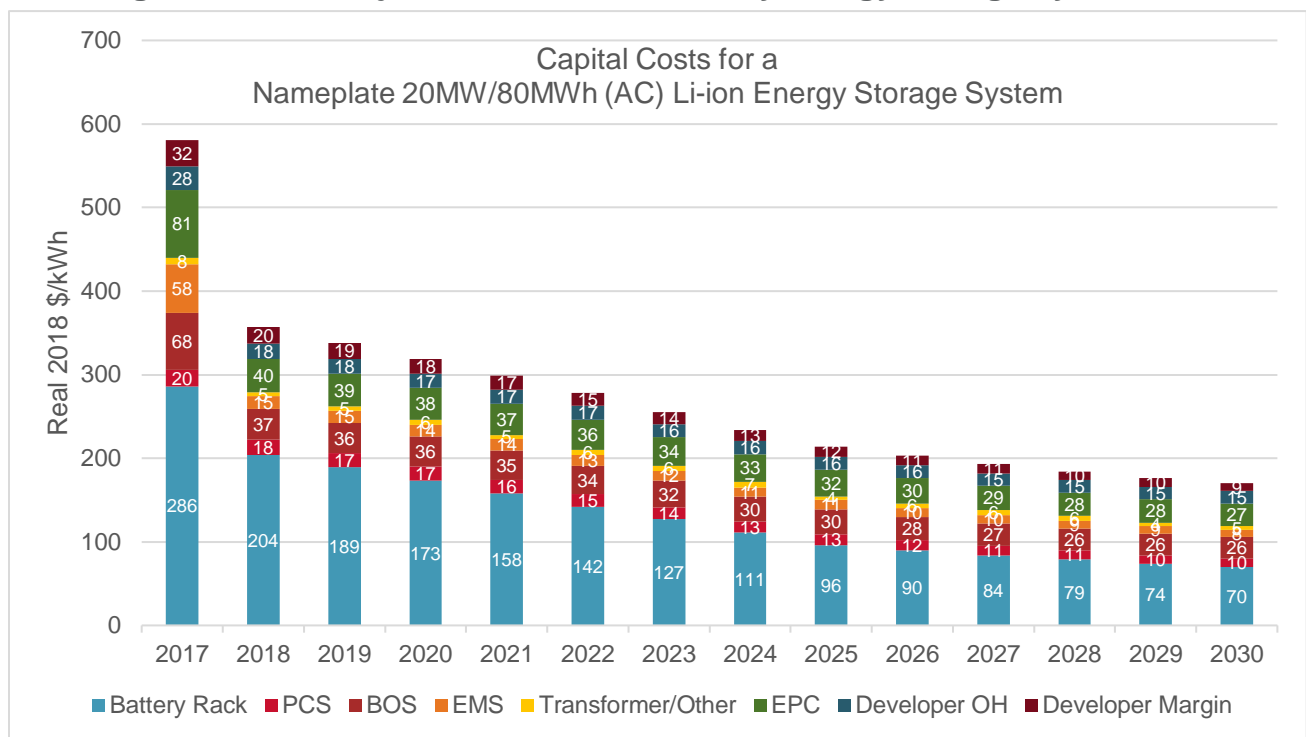
4.1 Trends

The costs for battery storage technologies are expected to continue to fall as maturity is gained and the economies of growing market orders are secured. The cost of Li-ion batteries have dropped nearly 90 percent from their commercialization in 1991 and have been trending down at an annual rate of approximately 14 percent over the past 5 years. Most indications show that the downward trend will continue as suppliers continue to improve manufacturing processes and production capacity. In 2018, increasing demand for mineral resources, especially cobalt, slowed the decline in NMC battery prices and increased lead times. Since then, newer NMC cell designs have been introduced to the market that use significantly less cobalt than their predecessors. Less established technologies such as flow batteries will likely see a substantial decline in installed cost if they are able to reach the level of widespread commercialization that Li-ion batteries are

now experiencing. Many flow technologies also offer the advantage of a very long cycle life as compared to current Li-ion cell technology. This means they do not require the same periodic augmentation or replacement (and the associated costs) that Li-ion batteries do to maintain energy capacity.

Figure 1 below shows the approximate battery installed cost trend out to 2030, based on data assembled by Bloomberg New Energy Finance in 2018. The most significant component of capital expenditure (CapEx) tends to be the cost of the battery modules themselves (shown in light blue below), which is projected to continue to decline due to aggressively scaled manufacturing and technological improvements. Other components of BESS CapEx are comprised of more conventional and commercially mature equipment, therefore cost decline associated with this other equipment is expected to be modest.

Figure 1. Cost Projections for 4-hour Battery Energy Storage Systems



4.2 BESS Cost Estimation

In order to approximate the capital and operating expenses of a Battery Energy Storage System, it is important to understand the many variables that factor into the cost equation. There is still a wide range of installed costs for real-world projects, and it is generally overly simplistic to use a flat dollar-per-kWh value when estimating the cost of a hypothetical BESS. The following factors tend to have a major impact on the resulting capital and operational expenses of a BESS:

TECHNOLOGY SELECTION

In July of 2019, the Pacific Northwest National Laboratory (PNNL) published the “*Energy Storage Technology and Cost Characterization Report*” which aimed to compare various energy storage technologies from an economic and technical standpoint. The table below represents the main findings of the report, showing cost breakdowns by technology with price ranges and averages for 2018, along with predictions for 2025 pricing. All prices are approximated for a 1 MW, 4 MWh energy storage system. As demonstrated by the table, Li-ion remains the most cost effective choice for most applications.

Table 1: Summary of compiled 2018 findings and 2025 predictions of cost and parameter ranges by technology type - BESS (PNNL, 2019)

Parameter	Sodium-Sulfur Battery		Li-Ion Battery		Lead Acid		Sodium Metal Halide		Zinc-Hybrid Cathode		Redox Flow Battery	
	2018	2025	2018	2025	2018	2025	2018	2025	2018	2025	2018	2025
Capital Cost – Energy Capacity (\$/kWh)	400-1,000 661	(300-675) (465)	223-323 271	(156-203) (189)	120-291 260	(102-247) (220)	520-1,000 700	(364-630) (482)	265-265 265	(179-199) (192)	435-952 555	(326-643) (393)
Power Conversion System (PCS) (\$/kW)	230-470 350	(184-329) (211)	230-470 288	(184-329) (211)	230-470 350	(184-329) (211)	230-470 350	(184-329) (211)	230-470 350	(184-329) (211)	230-470 350	(184-329) (211)
Balance of Plant (BOP) (\$/kW)	80-120 100	(75-115) (95)	80-120 100	(75-115) (95)	80-120 100	(75-115) (95)	80-120 100	(75-115) (95)	80-120 100	(75-115) (95)	80-120 100	(75-115) (95)
Construction and Commissioning (\$/kWh)	121-145 133	(115-138) (127)	92-110 101	(87-105) (96)	160-192 176	(152-182) (167)	105-126 115	(100-119) (110)	157-188 173	(149-179) (164)	173-207 190	(164-197) (180)
Total Project Cost (\$/kW)	2,394-5,170 3,626	(1,919-3,696) (2,674)	1,570-2,322 1,876	(1,231-1,676) (1,446)	1,430-2,522 2,194	(1,275-2,160) (1,854)	2,810-5,094 3,710	(2,115-3,440) (2,674)	1,998-2,402 2,202	(1,571-1,956) (1,730)	2,742-5,226 3,430	(2,219-3,804) (2,598)
Total Project Cost (\$/kWh)	599-1,293 907	(480-924) (669)	393-581 469	(308-419) (362)	358-631 549	(319-540) (464)	703-1,274 928	(529-860) (669)	500-601 551	(393-489) (433)	686-1,307 858	(555-951) (650)
O&M Fixed (\$/kW-yr)	10	(8)	10	(8)	10	(8)	10	(8)	10	(8)	10	(8)
O&M Variable (cents/kWh)	0.03		0.03		0.03		0.03		0.03		0.03	
System Round-Trip Efficiency (RTE)	0.75		0.86		0.72		0.83		0.72		0.675	(0.7)
Annual RTE Degradation Factor	0.34%		0.50%		5.40%		0.35%		1.50%		0.40%	
Response Time (limited by PCS)	1 sec		1 sec		1 sec		1 sec		1 sec		1 sec	
Cycles at 80% Depth of Discharge	4,000		3,500		900		3,500		3,500		10,000	
Life (Years)	13.5		10		2.6	(3)	12.5		10		15	
MRL	9	(10)	9	(10)	9	(10)	7	(9)	6	(8)	8	(9)
TRL	8	(9)	8	(9)	8	(9)	6	(8)	5	(7)	7	(8)

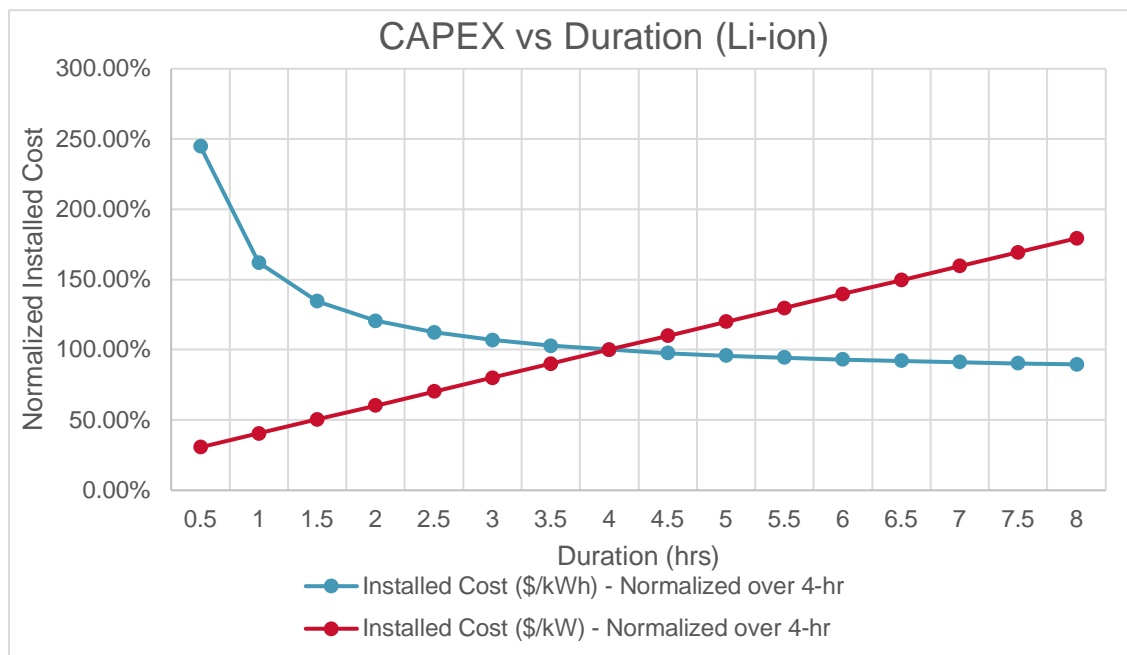
(a) An E/P ratio of 4 hours was used for battery technologies when calculating total costs.
 MRL = manufacturing readiness level; O&M = operations and maintenance; TRL = technology readiness level.

C-RATE

When referring to an energy storage system, “C-rate” is the ratio between the power rating and the energy rating of a system. It is the inverse of the “duration” of the system; in other words, a 4-hour BESS would have a C-rate of 0.25, and a 1-hour BESS would have a C-rate of 1. It is important to consider both power rating and energy rating when evaluating a BESS, as some components (such as the number of battery modules required) depend more heavily on energy rating, while other components (such as the number and size of PCSs required) depend on the power rating.

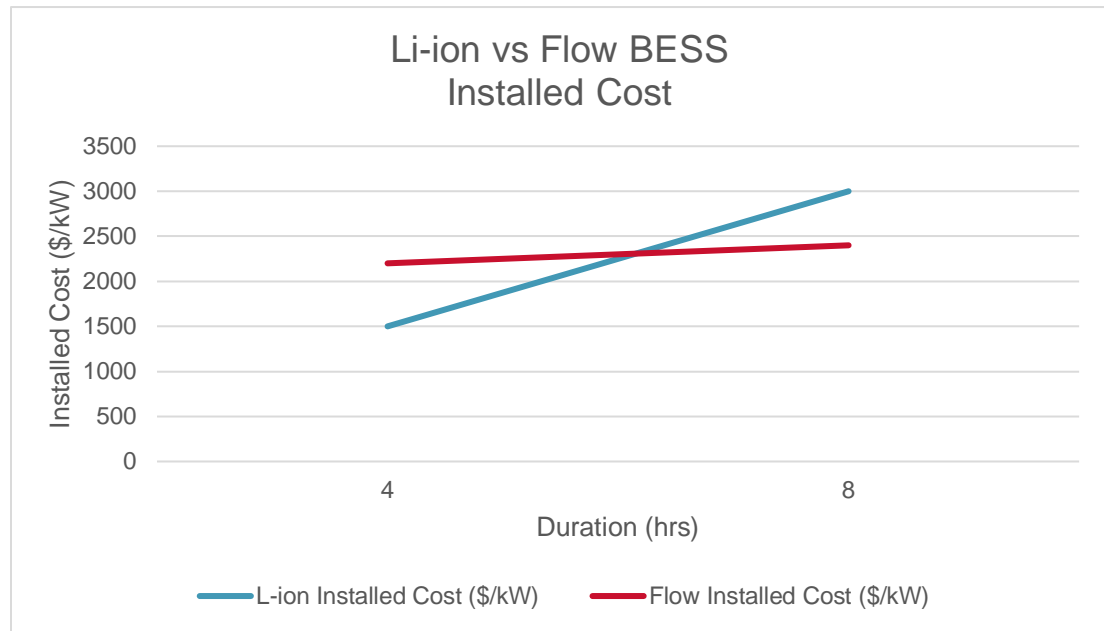
For a multitude of reasons, most BESS installations in recent years have been Li-ion systems with a 4-hour duration. Therefore, many resources that track energy storage pricing, including the PNNL report references above, *assume* a 4-hour duration (or a C-rate of 0.25). Figure 2 below, extrapolated from the PNNL data, illustrates how the \$/kWh price point increases dramatically for shorter duration systems. For example, a 4 MWh BESS with a 2-hour duration (therefore a 2 MW power rating), would cost approximately 20% more than a 4 MWh BESS with a 1 MW power rating.

Figure 2: BESS CapEx vs Duration



However, there are some advantages presented by flow battery solutions that make them potentially more cost-effective than Li-ion for longer durations (i.e. lower C-rates). Because flow battery systems are comprised of a small number of very large, fluid cells rather than thousands of very small pre-fabricated cells, there is more flexibility in de-coupling energy rating from power rating. With a flow system, power modules and energy modules are typically separated, allowing higher energy capacities to be achieved through the use of more or larger electrolyte tanks, without requiring more power modules. Because of this, there is potential for flow systems to offer a lower dollar-per-kWh price than typical Li-ion systems. This concept is illustrated by Figure 3 below.

Figure 3: Li-ion vs Flow BESS Installed Cost

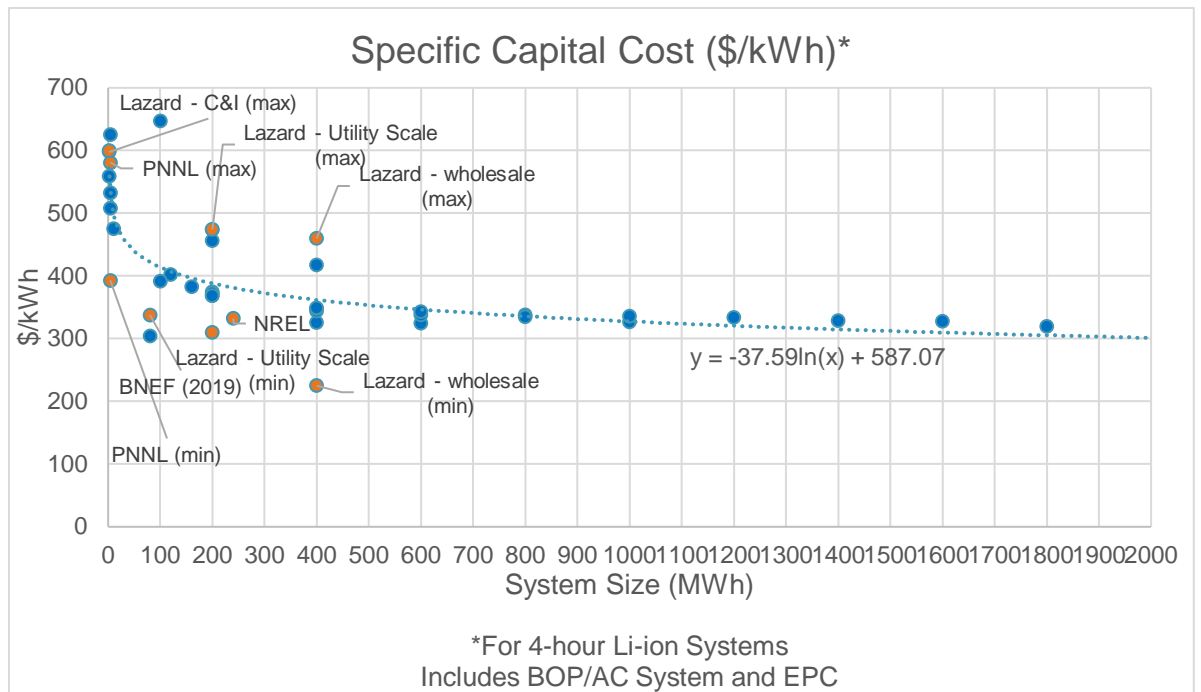




ECONOMIES OF SCALE

The concept of economies-of-scale, or the reduced unit cost of something as the number of units increases, applies well to BESS installations as they are generally very modular and repetitive systems. Equipment cost per unit, along with the associated shipping and installation, generally decreases with increasing order volumes. Additionally, the balance-of-plant costs and overall site footprint tend to be more consolidated with larger installations. The Figure 4 below represents a combination of recent installed cost estimates from publicly available resources (identified in orange) and HDR’s internal database of quotes for real-world projects (in blue) for 4-hour Li-ion systems. The best-fit line illustrates the sharp decline in \$/kWh for system sizes larger than 5-10 MWh.

Figure 4: Specific Capital Cost vs BESS Size



DEGRADATION & CAPACITY MAINTENANCE

It is widely understood that battery capacities tend to fade through time and use. The rate at which capacity degradation occurs varies widely depending on: battery chemistry and manufacturing quality, the depths and frequencies of charge/discharge cycles, battery temperature, years of service, and several other variables. Most battery suppliers can predict with some accuracy the rate at which their product will degrade, and can offer a “Capacity Maintenance Plan” or “Capacity Maintenance Agreement” to maintain the nameplate energy capacity of the BESS throughout the life of the project. This is accomplished by periodically “augmenting” or adding new battery modules to the system, and/or replacing old modules with new ones. The cost associated with these augmentations and replacements can be difficult to accurately predict without knowing the specific cell chemistry and daily dispatch cycle of the proposed BESS. Flow batteries tout their ability to maintain energy capacity for 20+ years without the need for augmentation, however this claim must be evaluated on a case-by-case basis.

For Li-ion projects, degradation rate varies heavily based on how the battery is charged/discharged and the underlying cell chemistry, as such there are many different strategies for capacity maintenance. Augmentations or replacements can be required between every 2 to 10 years, and costs can range from approx. \$2.50/kWh-yr to \$12.00/kWh-yr. Because of this variability, HDR recommends conservatively assuming \$10.00/kWh-yr for small Li-ion systems (10MWh or less). In reality, these costs are not incurred annually but rather every few years. However, for the purpose of a high-level economic analysis it can be advantageous to simplify this to an annualized cost.

5 Upgrade Deferral Valuation

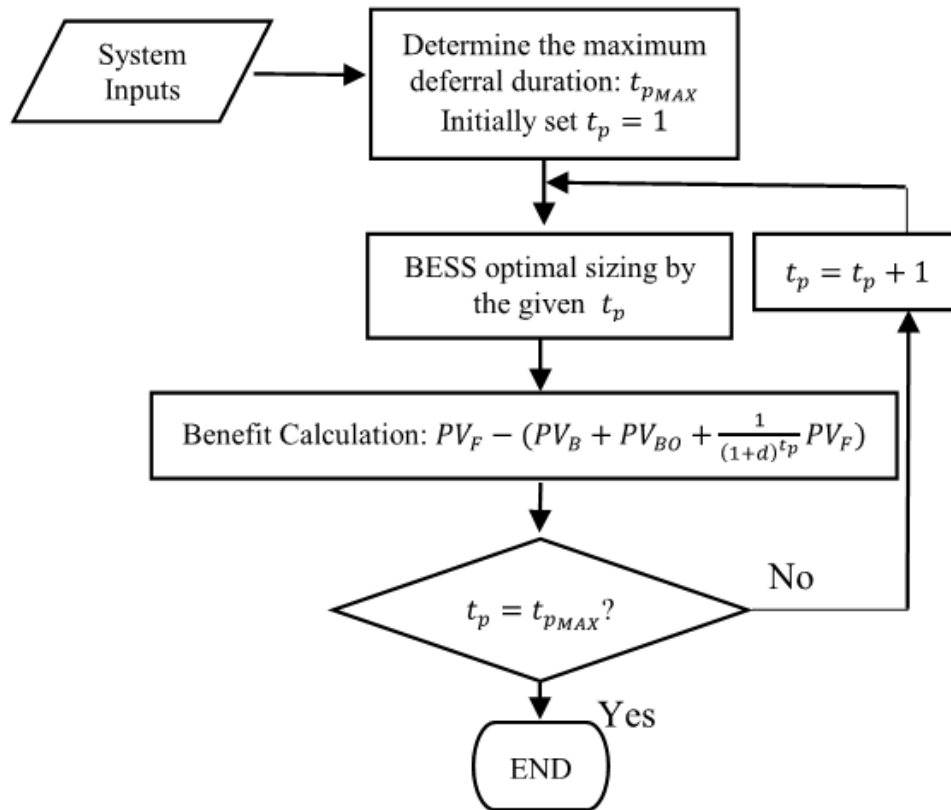
In order to properly consider energy storage as an alternative to conventional T&D infrastructure, the cost of the proposed energy storage system (outlined in the previous section) must be weighed against the economic benefit that it would provide to BHE and its ratepayers. The primary benefit offered by energy storage as a NWA is the deferral of a planned upgrade to a piece of infrastructure to meet thermal constraints due to load growth. The method for estimating the value of a deferred upgrade must coincide with BHE's planning and project finance mechanisms and thus would be best developed by the in-house subject matter experts at BHE. However, it can be prudent to first establish a proof-of-concept by performing a high-level economic evaluation of the deferral benefit using a simplified approach.

One such approach is outlined in the IEEE report titled "*Distribution Feeder Upgrade Deferral Through use of Energy Storage Systems*" by Zhang, Emanuel, and Orr. This report uses a hypothetical distribution feeder upgrade as a basis for demonstrating how an energy storage vs T&D infrastructure cost-benefit analysis might work. In their analysis, the net present value (NPV) of a feeder upgrade, PV_F is compared to the NPV of an optimally-sized storage system including both the CapEx, PV_B , and the OpEx, PV_{BO} , of the BESS. The total benefit is measured by taking the difference between the feeder NPV if installed at present and the sum of the BESS NPV installed at present and the feeder NPV if installed after " t_p " years. This formula is shown as the "Benefit Calculation" equation in the flow chart below. With this scenario, it is assumed that the CapEx of the T&D infrastructure is funded by loan with a specified interest rate and loan period. Discount rate (d) is also taken into account.

The flow chart below depicts the iterative process used for determining the maximum NPV that can be generated by an optimally-sized energy storage system to defer a T&D upgrade.



Figure 5: Flow Chart for Deferral Cost-Benefit Analysis



Parameter	Variable	Definition
Deferral Duration	t_p	The number of years the proposed BESS can defer the proposed T&D project.
Feeder Present Value	PV_F	The present value of the feeder (or other T&D) installation.
BESS CapEx Present Value	PV_B	The present value of the capital/installed cost of the BESS.
BESS OpEx Present Value	PV_{BO}	The present value of the operational costs of the BESS. This includes annual O&M as well as periodic battery augmentations/replacements to maintain capacity.
Discount Rate	d	Discount rate applied to the project finance formula.
Maximum Deferral Duration	t_{pMAX}	The number of years of deferral for which the maximum net benefit is achieved.

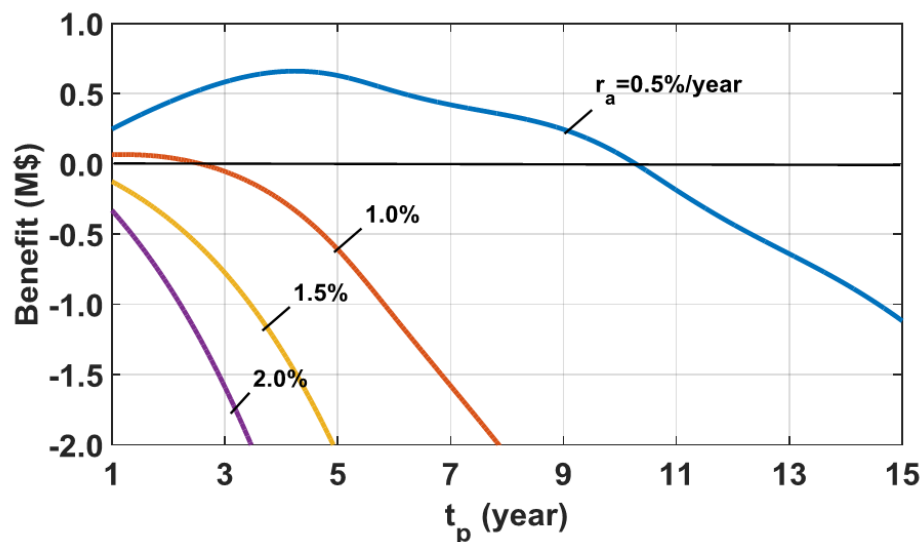
The process outlined in the IEEE report (and the flow chart above) is as follows:

1. Determine system inputs such as discount rate, interest rates, loan durations, cost rates for the proposed BESS and T&D infrastructure, etc.
2. Assume an initial deferral duration of $t_p = 1$ year.
3. Determine the BESS size that will be required to replace the need for the T&D project for t_p years.

4. Run the benefit calculation based on these parameters.
5. If the maximum benefit has been achieved, end the process. If not, proceed to step 6.
6. Increase the deferral duration, t_p , by one year. Proceed to step 3.

As can be expected, the more years of deferral achieved by the energy storage system, the greater the benefit valuation. The length of the deferral period is heavily dependent on the rate at which load is expected to grow at the point of constraint. If load growth is rapid, a BESS of a certain size will be capable of adequate peak shaving services for fewer years. The figure below, taken from the report, shows how the expected annual load growth rate (r_a) has a major influence on the deferral benefit of the energy storage system in the evaluated hypothetical scenario. Faster load growth resulted in a shorter period during which energy storage could defer the upgrade, resulting in diminished and sometimes strictly negative benefit.

Figure 6: Deferral Benefit vs Deferral Years (IEEE Example)



As described in the previous section, the cost of a BESS required to provide adequate peak shaving to defer an upgrade is heavily dependent on both the power and energy rating. The load profile at the point of constraint is thus another critical factor in the assessment. A tall and narrow peak offers a greater value proposition for the use of energy storage than a short and broad peak. Ultimately, BHE's planning group will need to determine optimal BESS size and deferral period on a case-by-case basis based on the load profile and expected load growth rate at the point of constraint.

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7 Appendix

7.1 Project Team

HDR has been a leader in the evaluation, development, implementation and innovation of a wide variety of battery energy storage systems. They understand the many roles that energy storage currently plays in enhancing the performance, reliability and value of the grid and how those roles are expected to expand in the future. HDR's staff has worked with reliability organizations, utilities, transmission and independent system operators, project developers, regulators, investors and other stakeholders on a variety of energy storage projects.

HDR is uniquely positioned to help clients develop electrical systems to suit their specific needs. Whether the task is providing energy security for the Department of Defense, enhancing the value of VER projects, understanding the impact of variable generation on our utility clients, or modernizing infrastructure at existing pumped storage plants, HDR's engineers have the experience to understand the appropriate technologies and evaluate their effectiveness for each application.

Through their knowledge of energy storage technology and their experience with renewable energy, traditional power generation, power delivery and grid operations, HDR provides strategic solutions to battery energy storage systems (BESS) challenges.

A confluence of new technologies, new financing mechanisms, and government regulations is driving fundamental changes in how we generate, deliver and maintain quality power. BESS are a key component in the evolving topic of the grid modernization and are becoming a fundamental part of solving the new and dynamic challenges associated with variable energy resources (VER) and microgrids. Improving resource adequacy and renewable integration as well as providing energy resiliency for critical infrastructure, IEEE 1547A compliance or regulating system frequency are just some of the potential applications of a well-executed BESS.

HDR's engineers have first-hand experience in the following roles:

- **Feasibility Assessment:** Energy planners have addressed integrated resource plans (IRP) including those with high penetration levels of VERs and assessed strategic flexibility solutions for electric utilities across the U.S.
- **Technical Design:** Engineers and designers have extensive experience developing designs for the integration of stationary battery energy storage systems.
- **Owners' Engineering:** The HDR team has worked alongside clients from project conception to construction to energization.
- **Specifications:** Engineers have partnered with clients to develop the project technical specifications and performance guarantees to ensure the BESS meets their use case.
- **Standards and Associations:** The HDR team includes committee members and advisors of government and private associations addressing new and existing energy storage technologies.

HDR's approach for this project has been developed to provide BHE with an exceptional engineering and consulting team to perform the required activities and address project scope. The project team was selected based on technical competence, project understanding, and experience with similar projects.

ENERGY STORAGE TECHNICAL LEAD – LUKAS ROWLAND

Lukas has extensive experience providing owner's engineering and design support on numerous battery energy storage projects ranging from 500 kWh to 400 MWh. This work includes specification writing, bid evaluations, electrical design, construction cost estimates, technical research, and system optimization. He has also lead electrical balance of plant design and performed quality control reviews for multiple battery energy storage projects, including utility-scale facilities (both standalone and co-located with solar or wind plants), and commercial/industrial scale installations located behind-the-meter for customer energy management and resiliency.

QA/QC LEAD – TOMAS VAZQUEZ

Tomas manages engineering efforts and consulting services for utility-scale power generation and industrial projects including desalination plants, transmission lines, highway and railroad bridge design, and construction. His experience encompasses thermal (fossil-fired fueled projects), LNG, and renewable (solar, wind, hydro) power plant development as well as the design of civil/structural systems.

Moreover, Tomas has expertise in the areas of independent engineering management, owner's engineering management, technical and environmental due diligence, project engineering, and business development.