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WHITE PAPER

Comparing the Costs of Long Duration Energy Storage Technologies

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Section 1
INTRODUCTION

This white paper is the second in a three-part series exploring long duration energy storage technologies for the power grid. The first paper examined the factors driving the need for long duration energy storage and the role it plays on the grid. In this second paper, the installation and operating costs of the five competing long duration energy storage technologies are explored in greater detail. The third and final paper in the series will discuss other non-monetary factors that should be considered when evaluating energy storage technologies.

1.1 Utility-Scale Long Duration Energy Storage Technologies

The utility-scale energy storage market encompasses a range of technologies with differing operating characteristics, strengths, and weaknesses. Some technologies are best suited to provide short-duration grid stability services including frequency regulation and voltage support. Such technologies include flywheels, ultracapacitors, and certain lithium ion (Li-ion) chemistries. Other technologies like pumped hydro storage (PHS) or compressed air energy storage (CAES) systems are best designed for large-scale long duration bulk energy storage. The following sections introduce the five most prevalent technologies competing in the long duration energy storage market.

1.1.1 Pumped Hydro Storage

PHS has traditionally been the technology of choice for delivering long duration storage services. It is the most mature and the largest capacity storage technology available, and currently provides approximately 93 percent of global operational electricity storage capacity. PHS facilities pump water from one reservoir into another at a higher elevation, typically using lower priced off-peak or surplus renewable electricity. When energy is required, the water in the higher elevation reservoir is released and runs through hydraulic turbines that generate electricity. PHS plants typically have a round-trip efficiency of 75–80 percent.

*A key feature of any energy storage system is its **discharge duration**, which refers to the ratio between the system's maximum power output capacity in megawatts and its stored energy capacity in megawatt-hours.*

PHS technology has evolved over the years. Variable speed pumps represent the latest generation of the technology and provide significant advantages. A variable speed pump turbine can be regulated to plus or minus 20 percent of capacity during a pumping cycle, which provides the ability to accurately follow changes in both load and the supply of fluctuating renewable generation. In addition, variable speed PHS facilities can be designed to transition rapidly between pumping and generating. This flexibility, combined with large storage capacity, means that PHS facilities offer grid operators capabilities that are critical to managing high penetrations of renewables and aligning variable renewable energy supply with shifts in load.

1.1.2 Compressed Air Energy Storage

CAES systems compress ambient air, store it under high pressure conditions, and then release it to power generator-tied turbines when electricity is needed. The largest barrier to CAES development arises from geographical restrictions because the systems require either natural underground caverns or underground tanks, which are rarely in convenient locations. CAES systems are advantageous for the purposes of large-scale storage because they typically range from 50 MW to 300 MW of power output and can be brought to full output in around 10 minutes. However, CAES systems have relatively low round-trip efficiencies, ranging from only 48 percent for older designs to as high as 75 percent for more modern systems. There are only two large-scale CAES plants in operation—one in the US state of Alabama and one in Germany, with durations of 26 and 4 hours, respectively.

1.1.3 Flow Batteries

Flow batteries are single-celled batteries that transform the electron flow from activated electrolyte into electric current. They achieve charge and discharge by pumping a liquid anolyte and catholyte across a membrane. While there are many different flow battery chemistries, the vanadium redox chemistry has emerged as the market's leading technology. The round-trip efficiency for flow batteries ranges from 65–85 percent.

> ***Round trip efficiency*** *refers to the difference between the amount of energy that is stored, and the amount of energy available for discharge. If a battery is charged with 100 kWh, but provides 75 kWh of energy when discharged, it has a round trip efficiency of 75 percent.*[1]

Flow batteries have several inherent advantages over other battery technologies. Their discharge duration is correlated to the volume of electrolytes stored, so storage can be increased simply by adding additional tanks of electrolyte, with limited marginal costs. The technology is also generally safer than Li-ion or molten salt batteries—the use of nonflammable electrolytes means that most flow battery systems do not present a fire safety hazard. However, the electrolytes used in most flow batteries are corrosive and may be an environmental hazard if spilled. Furthermore, flow batteries experience little to no depletion of active materials over time, giving them greater cycle life expectancies (10,000+ cycles) than other battery types.

[1] Hennessy, Tim, "Calculating the True Cost of Energy Storage," *Renewable Energy World*, January 12, 2015.

1.1.4 Molten Salt Batteries

Molten salt batteries include sodium sulfur (NaS) and sodium-metal halide (NaMx) systems, both of which use a molten sodium anode and a solid beta-alumina electrolyte at high operating temperatures of about 300°C or more. Typical performance characteristics of NaS and NaMx batteries are relatively similar with regard to high energy density, long cycle life, and moderate-to-high round-trip efficiencies of 75–90 percent.

Molten salt batteries gained traction in the market early on, but the battery storage market has shifted heavily toward Li-ion technologies. This is because molten salt batteries' performance characteristics and high price point (which is driven by expensive beta-alumina membranes) make them better suited for long duration applications, while the energy storage industry has recently focused largely on short-duration applications.

1.1.5 Lithium Ion Batteries

Li-ion batteries use the flow of lithium ions between the cathode and anode of the battery to charge and discharge. Li-ion batteries have excelled as the primary chemistry of choice in consumer electronics for the last decade, and are now finding a limited role on the grid.

In general, Li-ion batteries have excellent energy and power densities and round-trip efficiency. However, as discussed in Section 2, their average duration of 4 hours limits their ability to support the integration of high percentages of renewable energy. A more thorough exploration of this issue is presented in the first white paper in this series, *What Is Driving Demand for Long Duration Energy Storage?*[2]

The relatively short cycle life of Li-ion batteries, which can range from 500 to 10,000 cycles depending on usage and the specific Li-ion chemistry that is used, translates into a 3–15-year lifespan. This makes Li-ion batteries an expensive choice for long-term grid applications.

In the context of energy storage systems, one sequence of charging and discharging is referred to as a ***cycle****. A system's* ***cycle life*** *refers to the number of times it can cycle or be charged and discharged before it degrades and becomes inoperable or unusable for a given application.*

[2] Navigant Research and National Grid Ventures, *What Is Driving Demand for Long Duration Energy Storage?* SL Energy Storage, 2Q 2019, https://www.slenergystorage.com/resources.html.

Section 2

LONG DURATION ENERGY STORAGE TECHNOLOGIES: FACTORS TO CONSIDER WHEN EVALUATING COSTS

2.1 Comparing Apples to Oranges: Varying Characteristics and Costs

The five major long duration energy storage technologies discussed in this paper differ widely in terms of their operational benefits, cost structure, typical project scale, and development timelines. This section provides an overview of key points of comparison.

2.1.1 Discharge Duration

Discharge duration refers to the length of time an energy storage system can discharge at full output capacity. While all five major long duration energy storage technologies are capable of long duration discharge, they vary considerably in their range of duration. Table 2-1 lists the average discharge duration for each of these technologies.

Table 2-1. Average Discharge Duration Assumptions, Long Duration Energy Storage Technologies

Technology	Average Duration
CAES	3–24 hours
Flow Battery	2–12 hours
Lithium Ion Battery	0.5–8 hours
Molten Salt Battery	6–7 hours
Pumped Hydro Storage	6–24 hours

(Source: Navigant Research)

Although Li-ion battery projects can be designed to have a duration of up to 8 hours, most operational Li-ion batteries have durations of 4 hours or less. This places them at the low end of the duration range and limits their ability to offer a full suite of grid services. At the other end of the spectrum, PHS projects have average durations that range from 6 to 24 hours, with some plants designed to discharge at full power for longer than 24 hours. This duration enables them to replicate the grid and reliability services provided by conventional power plants.

2.1.2 Project Scale and Development Timelines

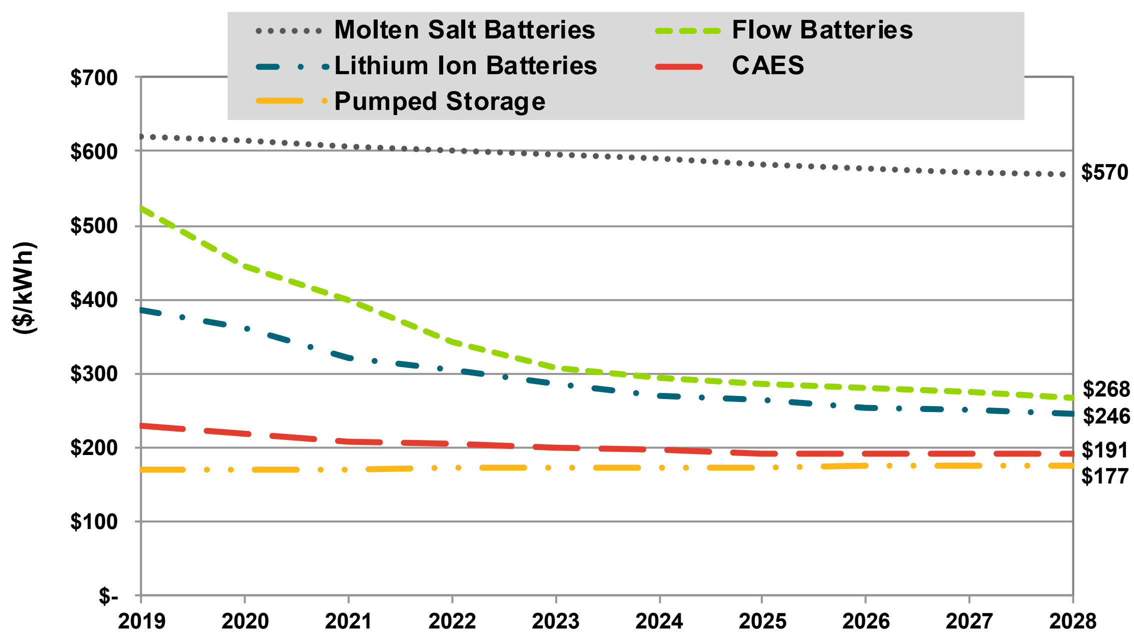
Long duration energy storage technologies can vary greatly in their scale and development timelines, with corresponding impacts on upfront costs. While battery projects can be deployed more quickly at a lower initial cost they are often smaller in scale, averaging 5–50 MW in capacity. In contrast, PHS and CAES facilities are typically large-scale plants that provide 100 MW of capacity or more, requiring significant upfront investment and longer lead times.

The scaling of duration and total project cost also varies considerably between technologies. For Li-ion battery projects, scaling to longer durations requires adding more battery packs, which represent the largest cost component of the project. Increasing duration results in an essentially linear increase in costs. By comparison, larger scale technologies such as PHS have different cost structures. Much of the cost to build a PHS project is fixed, coming from land development and construction. Scaling a PHS plant to longer durations requires only increasing the volume of the reservoirs being used, which has a relatively small impact on total system cost relatively to construction and development expenses.

2.1.3 Upfront Installed Costs versus Lifetime Costs

Long duration energy storage technologies have a wide range of installed costs, which are typically noted in dollars per kilowatt-hour of stored energy capacity. Navigant Research expects total upfront installed cost for each of the major technologies to range from $170.3/kWh for PHS to $619.7/kWh for molten salt batteries, as illustrated by Chart 2-1.

Chart 2-1. Average Utility-Scale Bulk Energy Storage System Installed Cost (CAPEX) by Battery Technology, World Markets: 2019-2028



(Source: Navigant Research)

The falling upfront costs of Li-ion batteries have made them attractive for some grid applications, but they have a short lifespan compared to conventional generation assets and PHS facilities, which are typically designed to last for several decades. The average lifespan of a Li-ion battery storage system ranges from 3–15 years depending on how it is used and how the specific Li-ion chemistry employed. While the inevitable degradation of Li-ion systems can be addressed by replacing depleted battery modules over time, this practice increases lifetime project costs considerably. These and other considerations are explored in Section 3.

Section 3

ACCURATELY COMPARING THE COST OF ENERGY STORAGE TECHNOLOGIES

3.1 Comparing Apples to Apples: Levelized Cost of Storage

When evaluating energy storage technology options, it is critical that grid operators and regulators consider key pieces of the energy storage cost puzzle beyond upfront cost. A levelized cost of storage (LCOS) calculation can be used to more accurately evaluate the lifetime costs of different technologies and yield cost per megawatt-hour figures that support fair and valid comparisons.

Lazard has conducted extensive evaluations of energy storage technologies and applications. The advisory firm has developed a method for calculating LCOS that is perhaps the most robust comparison of the true cost to own and operate different storage technologies.

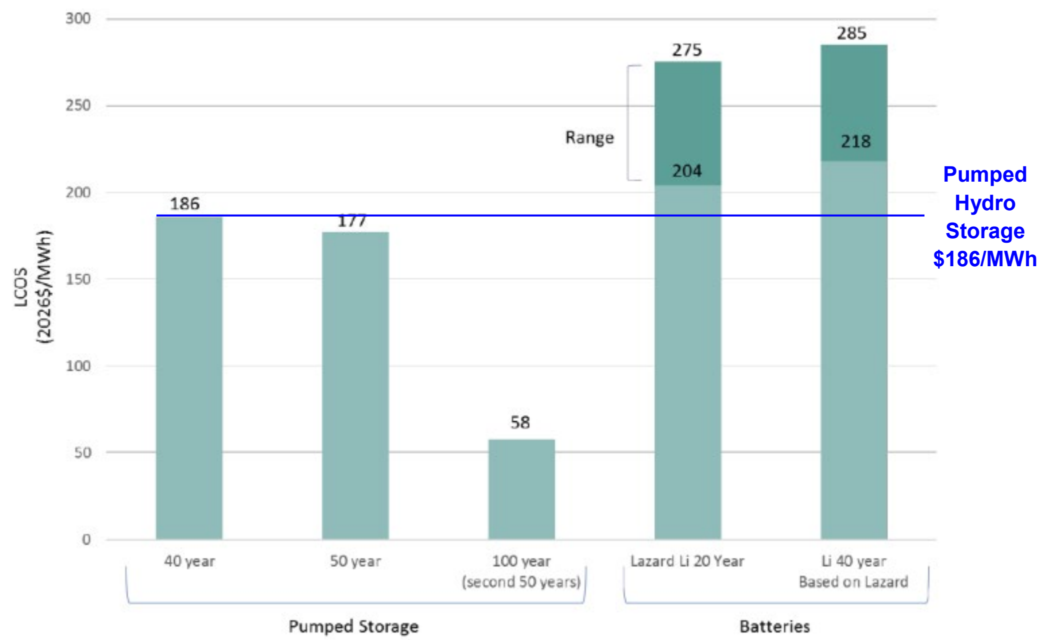
Lazard's LCOS calculation factors in the upfront investment required for a given storage technology. The calculation also incorporates operating patterns (cycles per day/year) for a given application, depth of discharge, round-trip efficiency, annual operations and maintenance costs, equipment replacement costs, system charging costs, and the overall useful life to yield an estimate for the cost per megawatt-hour, thereby enabling an apples-to-apples comparison.

Figure 3-1 illustrates the stark contrast in the LCOS for PHS and Li-ion batteries over similar time periods based on PHS project evaluation conducted by the San Diego County Water Authority.[3] PHS projects are designed for up to 50 years of operation with limited equipment replacement, a lifespan that can be extended to 100 years with proper maintenance and component replacements. By comparison, Li-ion battery projects typically have much shorter lifespans, although it is possible to keep them operating for 20 or even 40 years with proper maintenance and battery replacement.

[3] Victor, David G, et al., *Pumped Energy Storage: Vital to California's Renewable Energy Future*. San Diego County Water Authority, 2019, *Pumped Energy Storage: Vital to California's Renewable Energy Future*, www.sdcwa.org/sites/default/files/White Paper - Pumped Energy Storage V.16.pdf.

As shown, these differences in operating life result in significantly higher levelized costs for Li-ion batteries. Using projected costs for facilities with a commercial operation date of January 1, 2026, over a 40-year operating life, PHS facilities have an LCOS of $186/MWh, compared to $285/MWh for Li-ion battery facilities for the same period.

Figure 3-1. Levelized Cost of Storage Comparison, Pumped Hydro Storage versus Li-ion Batteries



(Source: Lazard and San Diego County Water Authority)

Section 4
CONCLUSION

This report highlights several factors that can affect the true cost of different long duration energy storage technologies. In addition to the upfront costs to build a new project, the required operating costs and expected lifespan of each storage technology must also be considered.

While the falling upfront costs of Li-ion battery storage systems have attracted a lot of attention and increased the competitiveness of small to midsized battery projects, a more holistic view of total project costs shows that PHS and CAES deliver much better economics for ratepayers.

This white paper expands on the topic of long duration energy storage introduced in the first paper in this series. In addition to the financial considerations for each long duration technology presented in this report, there are many non-financial issues surrounding these technologies that must be considered when comparing technologies. These issues, including the safety, sustainability, and long-term reliability of battery energy storage technologies, will be explored in the third white paper in the series.

Section 5
ACRONYM AND ABBREVIATION LIST

CAES.......Compressed Air Energy Storage

kWh.......Kilowatt-hour

LCOS.......Levelized Cost of Storage

Li-ion.......Lithium Ion Battery

MW.......Megawatt

MWh.......Megawatt-hour

NaMx.......Sodium-Metal Halide Battery

NaS.......Sodium Sulfur Battery

PHS.......Pumped Hydro Storage

US.......United States

Section 6
SCOPE OF STUDY

This white paper examines the market for long duration energy storage technologies on the power grid. Specific attention is paid to the differences among technologies in terms of operational characteristics, lifetime, and project cost. Navigant Research prepared this white paper to provide an independent analysis of the opportunities for long duration energy storage. This white paper does not consist of any endorsement of any specific technology, project, or company. Rather, this paper provides readers with an understanding of technologies competing in the market for long duration storage and how they compare to one another.

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