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2020 Energy Storage Pricing Survey

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ABSTRACT

The annual Energy Storage Pricing Survey (ESPS) series is designed to provide a standardized reference system price for various energy storage technologies across a range of different power and energy ratings. This is an essential first step in comparing systems of the different technologies' usage costs and total cost of ownership. The final system prices are developed based on data from an extensive set of interviews with representatives across the manufacturing and project development value chain, plus available published data. This information is incorporated into a consistent methodology structure that will allow pricing information to be incorporated at whatever level it was obtained, ranging from component to fully installed system. The ESPS system pricing methodology breaks down the cost of an energy storage system into the following component categories: the storage module; the balance of system; the power conversion system; the energy management system; and the engineering, procurement, and construction costs. By evaluating each of the different component costs separately, a more accurate system cost can be developed that provides internal pricing consistency between different project sizes using the same technology, as well as between different technologies that utilize similar components.

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
AC	Alternating current
ACAES	Advanced Compressed Air Energy Storage
Ah	Ampere-hour
BESS	Battery energy storage system
BMS	Battery management system
BOM	Bill of materials
BOP	Balance of plant
BOS	Balance of system
CAES	Compressed Air Energy Storage
DC	Direct current
DOD	depth of discharge
DOE	U.S. Department of Energy
EMS	Energy management system
EPC	Engineering, procurement and construction
EPRI	Electric Power Research Institute
ESS	Energy storage system
FBFe	Flow Battery: Iron
FBV	Flow Battery: Vanadium
FBZnBr	Flow Battery: Zinc Bromide
FWLD	Flywheel: Long Duration
FWSD	Flywheel: Short Duration
GES	Gravity Energy Storage
GW	Gigawatts
GWh	Gigawatt Hour
Hr	Hour
HVAC	Heating ventilation and air conditioning
kW	Kilowatt

Abbreviation	Definition
kWh	Kilowatt hour
LAES	Liquid Air Energy Storage
LCOE	levelized cost of energy
LFP	lithium-ion iron phosphate
LiLFP	Lithium Ion: LFP
LiNMC	Lithium Ion: NMC
MW	Megawatt
MWh	Megawatt hour
Na	Sodium
NMC	nickel manganese cobalt
NRE	Non-recurring engineering
O&M	Operation and maintenance
OEM	Original equipment manufacturer
Pb	Lead
PCS	Power conversion system
PHS	Pumped Hydro Storage
PSH	pumped storage hydro
RTE	Round trip efficiency
SM	Storage module
SOC	state of charge
TCO	Total Cost of Ownership
Zn	Zinc

1. SURVEY RESULTS

The Energy Storage Pricing Survey developed a range of unique system price quotes for the year 2020, and a 10-year forecast. Table 1-1 provides a snapshot of the pricing in 2020. The full complement of 2020 survey results and resulting forecasts can be found in Chapter 5.

1.1. Energy Storage Pricing Snapshot

Table 1-1. 2020 Energy Storage Pricing Snapshot

2020 Energy Storage Pricing					
	Size (MW)				
	100	10	1	0.1	0.01
$/kW					
PHS	2634.0				
CAES	1369.1				
ACAES	1727.8				
FWSD		1081.5	1196.6	1470.0	
$/kW (4 Hr)					
GES	358.8				
FWLD		666.8	735.8	814.6	937.5
LiNMC	315.6	382.3	444.9	667.8	947.5
LiLFP	296.6	366.8	427.7	653.2	929.7
Zn	275.3	300.4	343.0	402.4	
Pb			370.1	518.4	687.1
$/kW (6 Hr)					
Na	367.5	393.7	425.6		
FBZnBr	348.8	370.3	384.4	425.5	
$/kW (8 Hr)					
FBV	322.6	374.3	427.6	605.8	
FBFe	344.6	370.5	393.0	435.4	
LAES	267.4				

1.2. Comparative Project Cost Metrics

In an attempt to move the comparison of energy storage technologies from a product cost comparison to a project cost comparison, a section on comparative metrics was added to the Energy Storage Pricing Survey.

The first comparative matric is a lifetime throughput metric base on the initial capital cost of the system, and the total amount of energy cycled through the system over the life of the unit; lower results indicate a lower capital cost per lifetime energy throughput.

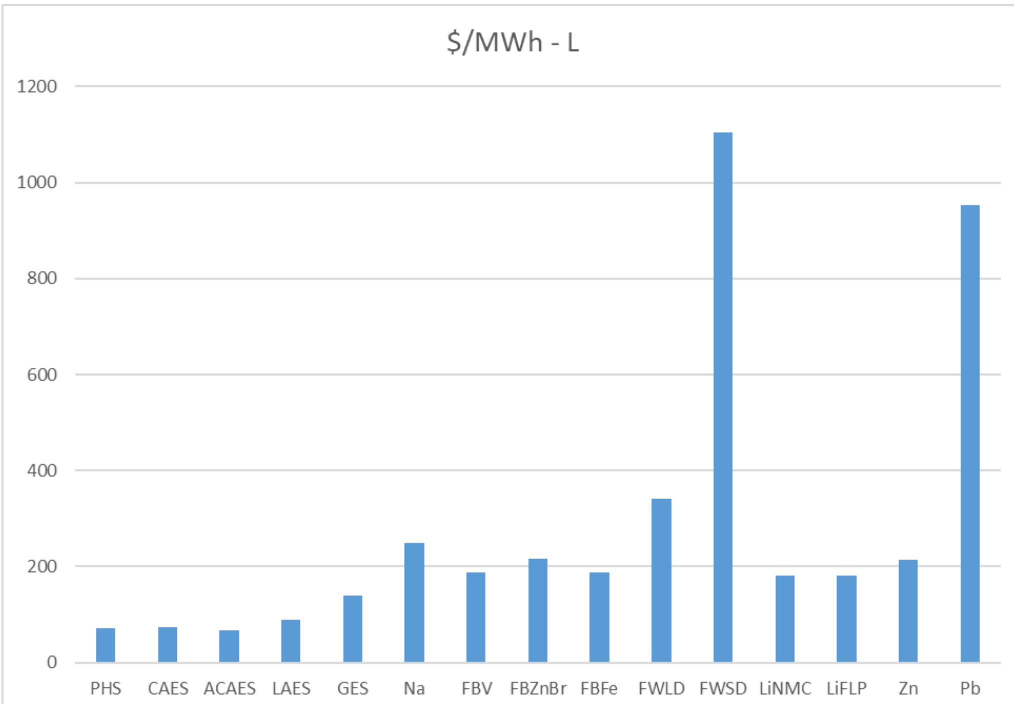


Figure 1-1. Energy Storage Lifetime Throughput Cost Metric

2. ENERGY STORAGE PRICING SURVEY

2.1. Purpose

The annual Energy Storage Pricing Survey (ESPS) is designed to provide a standardized reference system price to market participants, government officials, and financial industry participants for a variety of energy storage technologies at different power and energy ratings. Because of the impact of the myriad of possible design and usage profiles have on the capital equipment requirements, a price of an energy storage system to a customer can vary considerably. In addition, there are competitive market forces that will also impact the potential price, leaving the potential customer sometimes bewildered by the resulting offers even for the same "sized" systems. For this reason, the ESPS is designed to provide a realistic expectation of the price of energy storage systems.

The system price provided is the total expected installed cost (capital plus EPC) of an energy storage system to a customer. Because the capital cost of these system will vary depending on the power (kW) and energy (kWh) rating of the system, a range of system prices has been provided for the reader. In order to ensure that the results are useful for customers as they evaluate systems at different scales, a key part of the Energy Storage Pricing Survey is an internally consistent analysis framework which allows for a reliable comparison of different system power and energy ratings (power / energy). The Energy Storage Pricing Survey accomplishes this by developing the pricing structure and forecast at the component level, and then scaling up to the requisite power & energy rating.

The goal of this Report series is to set expectations for customers of the cost of energy storage systems at different power and energy levels. Estimating the system price of an energy storage can be difficult as there is no "standard" system configuration, and due to the nascent nature of the industry and the ongoing scarcity of equipment, different system sizes. These, and other reasons, make it difficult for customers to use the available published pricing for specific energy storage systems to extrapolate to a system that fits their needs.

This approach benefits the results in a number of ways.

- First, all technologies are broken down into a standard list of components, allowing the different technologies to have a similar cost framework of evaluation wherever possible.
- Secondly, this approach allows a greater amount of precision on the components that are similar across technologies-balance of systems, power electronics, construction—using the same cost structure where appropriate. By being as precise as possible on the individual component portions, the overall system price can focus on the accuracy of the system prices. This includes separate component pricing values at the different energy & power levels for the same components.
- Third, the forecasted prices are thus developed at the component level which supports greater precision for each price estimate as the future costs for the different components will change at different rates.
- Finally, this structure also allows for a systematic evaluation of systems at different power and energy ratings. By have a component level pricing relationship for power electronics (for example), then the overall system price for the same technology will have a more accurate relationship to other systems at different power and energy ratings.

2.2. Coverage

The Energy Storage Pricing Survey provides data on 15 different energy storage technologies based on similar design or operating characteristics.

Table 2-1. Energy Storage Technologies Covered

	Technology	Abbreviation
1	Pumped Hydro Storage	PHS
2	Compressed Air Energy Storage	CAES
3	Advanced Compressed Air Energy Storage	ACAES
4	Liquid Air Energy Storage	LAES
5	Gravity Energy Storage	GES
6	Sodium	Na
7	Flow Battery: Vanadium	FBV
8	Flow Battery: Zinc Bromide	FBZnBr
9	Flow Battery: Iron	FBFe
10	Flywheel: Long Duration	FWLD
11	Flywheel: Short Duration	FWSD
12	Lithium Ion: NMC	LiNMC
13	Lithium Ion: LFP	LiLFP
14	Zinc	Zn
15	Lead	Pb

The list of covered technologies for the ESPS will remain flexible in future editions of the Energy Storage Pricing Survey to address emerging new energy storage technologies with sufficient market representation to justify a separate category. This flexibility will also take into account energy storage technology families that lose currently operating firms, rendering that technology non-viable and hence removal from the Energy Storage Pricing Survey.

The Energy Storage Pricing Survey provides pricing information on possible energy storage systems according to variable power and energy ratings. The ranges of these ratings provide potential customers with a framework for the resulting costs of the different systems.

Table 2-2. System Ratings Indices

Energy Storage Technologies	
Power (kW) Rating	Standardizes Power ratings from 10 kW to 100 MW (and over). Note not all technologies are viable at all scale
Energy (kWh) Rating	Standardized Energy ratings from less than 1 hour to 8 (and over) hours, depending on the technology. Note: not all technologies are viable at all scales

Additional information on the survey detailed methodology can be found in Chapter 3.

2.3. Survey Outreach

A central tenant of the Energy Storage Pricing Survey providing useful results and insights is obtaining relevant pricing information about energy storage system components to provide an internally consistent range of prices for energy storage systems according to the power and energy ratings. Interviews with market participants are drawn from across the industry's supply chain: OEMs, system integrator, project developer, and financial participant to provide a balanced estimate for each of the component layers of the system price build.

Overall, 83 interviews were conducted that yielded over 277 unique energy storage component prices. This information was used to develop the 136vfinal prices provided in Chapter 4.

Table 2-3. ESPS Data Collection

ESPS Data Collection	
Total Interviews	83
Unique Component Price Quotes	277
Final Synthetic Price Quotes	136

3. METHODOLOGY

In order to provide the energy storage industry with a standardized reference system price for energy storage systems, the Energy Storage Pricing Survey (ESPS) has developed a structured methodology that allows for the inclusion of all of available data, weights that data towards the more relevant sources, and creates an internally consistent pricing framework which can be used to develop system costs that span both standardized power and energy ratings.

The Energy Storage Pricing Survey provides a series of internally consistent reference system price to customers for the different energy storage technologies. The resulting price is a realistic expectation of the installed capital cost of an energy storage system. Because the capital cost of these system will vary depending on the power (kW) and energy (kWh) rating of the system, a range of system prices has been provided. The goal of the Energy Storage Pricing Survey is accuracy for all customers, over precision for one customer. This is achieved by providing a consistent estimation for customers for what they should expect for a particular energy storage technology price estimate. Depending on market conditions, the actual price offered to a particular customer will vary from customer to customer.

To bolster the accuracy of the results of the Energy Storage Pricing Survey, the analysis is based first on the interviews with key firms representing groups from across the energy storage industry. These interviews provided component and system level price quotes of different energy storage technologies at these different system ratings. Additional data is collected from secondary sources to enhance the depth and breadth of available insights into the market price of energy storage systems.

The methodology structure is designed to incorporate all available data sources since the available data comes in a variety of types and qualities. If complete AC system prices were provided, these were used fully for that particular power/energy rating. The vast majority of price quotes typically collected were for system components. These data points for a particular component were averaged together to arrive at component price which was then added to different component prices to arrive a full system price.

3.1. System Price

The Energy Storage Pricing Survey is designed to provide a realistic expectation system price of energy storage systems at different power and energy ratings for customers. There is generally a distinction made between cost and price of an energy storage system, and this is understandable. A system cost is generally a derived from bottom-up calculation made from adding the cost of all of the subassemblies and components needed to construct the final version of the product, many times described internally as a Bill of Material (BOM). This will vary most directly based on the variations of an energy storage system's particular power and energy rating. Customers do not pay this amount. They are presented with an all-in total that will include equipment, services, and overhead charges needed to keep the various firms in operation.

Market forces governing profitability assumptions and unit competitiveness from differing vendors can provide additional variability to the price presented to the customers. Pricing drivers above equipment costs internally to a firm would include standard markups on 3rd party equipment incorporated into the system, overhead to operating expenses such as technical services, SG&A, etc. and a target profit margin, if not incorporated into overhead/general expenses. Issues that can cause a variation in prices seen by a customer external to a company include pricing from different vendors, different generations of the same product, and pricing pressure (or advantage) that a particular seller has with a particular customer of a system integrator.

Unless specified, the Energy Storage Pricing Survey will not take into account policy driven price drivers, such as tariffs, etc. unless they are already incorporated into the available pricing quotes used by the survey.

3.1.1. Realistic Expectation Price Quote

In order to provide a consistent pricing framework across the different power and energy scales of energy storage projects, the Energy Storage Pricing Survey develops a standardized pricing structure to produce a realistic expectation price quote for the modeled installed system price. The Energy Storage Pricing Survey is designed to provide customers with what they should expect to see in the market for a particular technology at a specific power and energy rating. Because of the different purchasing power by different customers, the Survey should not be used as what a specific system price is for a particular technology at a designated power and energy rating for a particular customer.

In order to produce the pricing of different energy storage systems at all potential power and energy ratings, the unit component data is used to produce weighted average specific component prices at the different system size levels, and then pulled together at the end to develop a complete system price. Although this might lose some of the system price precision obtained from a particular data point, it more than makes up by ensuring consistency and accuracy across all of the different power and energy system ratings.

Critically, this approach ensures that proprietary pricing from a particular vendor or interview source is not disclosed directly, and that all potential survey participants know that all data published will be put through this process, ensuring anonymity. This has and continues to be a critical aspect of gaining continued support from the different market participants. This concern for individual data sources also supports the goal of the Energy Storage Pricing Survey to focus on the accuracy of the overall forecast over the precision of one particular system estimate.

3.1.2. Overnight Construction Cost

The Energy Storage Pricing Survey utilizes an overnight construction cost pricing structure for the resulting energy storage system prices. This means that the pricing obtained from survey participants for the cost of systems being quoted currently will be used to price a system quoted in the year 2020.

Overnight capital cost or overnight construction cost are standard approaches used in the power generation industry to describe the cost of building a power plant as part of evaluating the economic valuation of a power facility. The main drawback is that this approach does not take into account the time required to build a power facility, and hence any construction financing costs. However, this approach allows a standard means of comparing the different technology costs of power facilities based on currently available quotes.

When utilizing this approach for energy storage system pricing, the drawback exists that systems quoted for 2020 are not built in 2020, not simply because of the construction time, but also because of the backlog stemming from a lack of battery system for deployment. Therefore, many times energy storage projects quoted this year may not be constructed for 1-2 years. Because of the declining cost curve of battery systems, this can lead to a confusing array of quoted system for a particular year actually being deployed across a range of future years. Since different energy storage technologies can take a varying length of time to be deployed, this increases the potential level of confusion when comparing prices quoted.

Therefore, the EPSP utilizes the overnight construction costs framework to normalize the estimated system costs for those systems being quoted today for construction in the next 1-2 years. Price estimates beyond this are not incorporated in the current year estimate but used instead to develop the forecasted system price.

3.1.3. Forecast

The 2020 Energy Storage Pricing Survey provides a 10-year forecast of energy storage system costs. Typically, the first 3 years are guided by insights from the pricing survey interviews. The remainder of the forecast will be driven by the forecast methodology assumptions.

The complete system forecasted price relies on individually component level price forecasts, which are then compiled to provide the system level forecasts. This allows for a more accurate overall system pricing estimate as this allows us to consider the different price trends for the different components and segment margin assumptions.

3.2. Data Acquisition

Acquiring the component and system pricing data is the first goal of the Energy Storage Pricing Survey. The effort here is not to just capture the anecdotal pricing data, but sufficient qualifiers about the relevant system attribute data point to make it useful in the analysis framework. For instance, obtaining the cost of a particular system is not helpful unless the relevant power (kW) and energy (kWh) attributes, etc. are obtained as well (besides determining if installation costs are installed or not, etc.). This is critical in order to build an internally consistent pricing structure across the different power and energy scales for the different technologies.

Data about energy storage systems is available in a bewildering array of specifics, with unfortunately many of the specifics missing. Because of the variations in design scale and operating patterns, data gathered for the Energy Storage Pricing Survey is obtained in as standardized a fashion as possible. Critically important are any and all attributes about the system connected to the price quote in order to incorporate the data into the analysis in a proper manner. Common attributes about energy storage systems will include:

- Power Rating
- Energy Rating
- Capital Cost
- Operating Costs
- Performance Metrics

By capturing as much of these types of attributes about the system, the confidence level of what an expected system price for an energy storage system will increase. To accomplish this goal, the Energy Storage Pricing Survey utilizes both Primary and Secondary data sources in order to obtain as much detailed data as possible.

3.2.1. Primary Data Sources

The first stage of data collection is from primary data sources, typically derived through direct interviews with people and firms active in the energy storage industry. The goal of this effort is to obtain the most relevant & precise data available for each of the different energy storage technologies, hence the emphasis on obtaining data input from across the energy storage industry supply chain.

Participating Groups	2020 ESPS
Energy Storage OEM	26
Gov / NGO / Edu	7
System Integrator	5
Power Electronics	2
Developer / IPP	11
Financial / Insurance	9
Consultant / Engineering	12
Balance of System	1
EPC / ECI	7
Utility	1
Total Interviews	**83**
Published Data Sources	**15**
Total All Data Sources	**98**

Figure 3-1. 2020 Energy Storage Pricing Survey

The overall goal of the ESPS is to obtain the most realistic expected system price for end use customers. Therefore, direct component data is essential, but it must be incorporated into the pricing structure along with data from groups farther down the value chain in order to provide the best and balanced estimate of the general expectation for most customers, not simply the lowest price available. Therefore, a variety of firms representing other component manufacturers and balance of system providers are incorporated, as well as groups representing system integrators, project developers, EPC firms, and capital providers.

In total, data from 83 direct interviews was obtained from these key firms representing groups from across the energy storage industry in one-on-one interviews. These interviews provide different component and complete system level price quotes of different energy storage technologies. These interviews are viewed as essential at this point in the industry's development to obtain the needed data, instead of utilizing an emailed survey.

- First, there is a significantly improved response rate to phone/in-person interview verses the online survey. This is very important for those energy storage technologies where there are only a handful—or even only one—vendor of a particular technology. Missing that interview would mean missing the data update for that technology.
- Secondly, insights from the OEMs themselves to understanding the physical and cost structure of the energy storage system is important as the industry continues to evolve; what

was the "norm" last year may not be commonplace the following year, so if surveys were written with last year's cost structure in mind, the current year survey could miss an important emerging pricing issue.

- Thirdly, all of the different technologies are evolving, so there will be at least a few structurally new cost-related items that will occur each year.
- Finally, again because of the evolving nature of the industry and technology, there are a number of new items that are important to properly pricing an energy storage system that emerge each year outside of the core energy storage technology; EPC costs, system integration, safety, and fire suppression, etc. Only through having a one-on-one conversation can you obtain these insights.

As the industry matures, it is expected that direct survey responses would improve, and that the evolving nature of the energy storage technologies would slow so that obtaining primary data on energy storage technologies would be a viable option.

3.2.2. Secondary Data Sources

Additional data on energy storage system pricing is incorporated from published, secondary sources to supplement the primary sources of data in the Energy Storage Pricing Survey. Over time, this type of data has grown in quantity and quality and is expected to become a larger source of data in the future.

One critical caveat and difference in collecting data in this manner is that the details and specific metrics about the data are presented as is. For instance, a published price quote of "X" $/kWh for a particular technology may or may not have additional details such as the specific power and energy rating of the system that is the basis for the publication. This is important as component costs for energy storage systems vary depending on the scale of the system. For this reason, some available data is not actually usable in the ESPS if only partial system descriptions are provided, which limits the ability of integrating the data on comparative metrics (energy, power, etc.)

These technical specifications that define the price quote are important if the data is to be fully incorporated into a pricing framework. In addition, some system price quotes are for the capital equipment only, while others include the EPC prices to provide a deployed cost for the customer. Finally, care should be taken to ensure that the data source one is using is reliable; although a number is published, its validity can be in question if the underlying sourcing and methodology is in questions.

3.2.3. Data Weighting

Because of the variety of the quality of data sourcing, a weighting for the different price quotes was developed to give higher importance for better quality information sources. Two primary metrics were used to develop the weighting scale.

First, whether it was a direct quote, or an indirect quote. For instance, when concerning a particular energy storage technology, we would many times obtain price quotes directly from OEMs, but would also obtain quotes from project developers, system integrators, etc. representing to be for the same equipment. We would overlay a higher grading metric to the price quote that came directly from the OEM.

Secondly, what is the market position of the firm providing the quote. The Energy Storage Pricing Survey receives price quotes from a number of different market participant, with a number of them being competitors of the same product—for instance different lithium-ion battery manufacturers. Within this sub-market, some firms are clear market leaders, while others are significantly smaller players. In order to obtain the weighted average prices for the battery system that best represents the range of market prices for these battery systems, the market leaders are weighted more heavily than others.

3.2.4. Component vs. System Pricing

The data in the energy storage pricing survey was obtained as provided by participants, and thus came in a variety of forms. This included pricing information ranging from all of the different component pieces, to complete AC systems including the EPC component ("All-in"). The modeling structure was thus designed as to be able to utilize whatever data was available. Therefore, beyond obtaining the specific pricing information ($/kWh of a particular technology) it was vitally important to obtain additional qualifiers such as the specific power and energy rating of the system in to be able to align this data with the existing modeling structure so it could be incorporated at the proper level.

Table 3-1. Energy Storage Pricing Quotes

Energy Storage Price Survey	
Unique Component Price Quotes	277
Final Synthetic Price Quotes	136

3.3. Energy Storage Technologies

There are a number of energy storage technologies utilized in stationary energy storage deployment.

3.3.1. Technology Types

A total of 15 energy storage technology types are included in the 2020 Energy Storage Pricing Survey. This grouping is based on the survey results where differentiation in energy storage pricing is evident. Possible changes to the list are expected to occur in the future as the mix of energy storage technologies actively being develop continues to evolve.

Where possible, continuity of pricing history is preserved. It should also be noted that as vendors enter the market within existing technology groupings, the pricing quotes will change. Substantial changes due to a design difference should be evident in the range of price quotes conforming to different energy ratings.

The 15 energy storage technology types covered in the 2020 Energy Storage Pricing Survey are:

Table 3-2. Energy Storage Technology Types

	Technology	Abbreviation
1	Pumped Hydro Storage	PHS
2	Compressed Air Energy Storage	CAES
3	Advanced Compressed Air Energy Storage	ACAES
4	Liquid Air Energy Storage	LAES
5	Gravity Energy Storage	GES
6	Sodium	Na
7	Flow Battery: Vanadium	FBV
8	Flow Battery: Zinc Bromide	FBZnBr
9	Flow Battery: Iron	FBFe
10	Flywheel: Long Duration	FWLD
11	Flywheel: Short Duration	FWSD
12	Lithium Ion: NMC	LiNMC
13	Lithium Ion: LFP	LiLFP
14	Zinc	Zn
15	Lead	Pb

3.3.2. System Scaling: Power

In order to provide a guide for potential customers, energy storage pricing is divided along two comparative metrics, with the first being the power rating of the system. The ESPS utilizes 5 different power ratings to help differentiate systems for customers. This approach provides some benefits in providing additional characteristic detail:

First, energy storage systems are used at all levels of the electric power system. Therefore, a power scaling rating of from 1 to 5 is used which broadly aligns the size of the unit with a potential usage in the market, although this is of course not a hard and fast rule. The scaling rating cover a variety of market uses, including wholesale (Size 1), utility (Size 2), distribution/microgrid (Size 3), commercial & industrial (Size 4), and residential markets (Size 5). To accommodate additional units outside of these ranges, residential (Size 5) covers 10 kW and less, while wholesale (100 MW) covers 100 MW and above.

Table 3-3. System Power Rating Sizing

System Size	MW	Potential Market Segment
1	100	Wholesale
2	10	Utility
3	1	Distribution & Microgrid
4	0.1	Commercial & Industrial
5	0.01	Residential

Secondly, different energy storage technologies are typically available at different scales typically based on either engineering or economics reasons. A key distinction needs to be made about what energy storage technology system pricing is estimated at these different levels. Essentially, although a technology may be technically capable of supporting a certain market segment for a system scale, the ESPS will endeavor to provide information on different systems based on the likely market usage. For instance, pumped hydro storage systems are generally only available over a power rating of 100MW, while lead acid battery systems are not typically available beyond single digit MW scale systems. The choice in deployment filter for the Energy Storage Pricing Survey is based on actual usage and available real data. However, possible future deployment options are monitored, and if a chance in the analysis coverage is warranted, the analysis methodology will be adjusted accordingly.

Thirdly, the price of a particular energy storage system will generally trend lower with increasing power rating. This is due to a number of factors, including purchasing power of equipment and some fixed capital costs of components can be shared across larger scaled systems.

The following table displays the general availability of energy storage technologies on a power scaling capability. The growing interest in large scale energy storage systems portends to possibility of facilities in the multi-hundreds of MWs, but these will be incorporated into the System Size 1 quote for the filter.

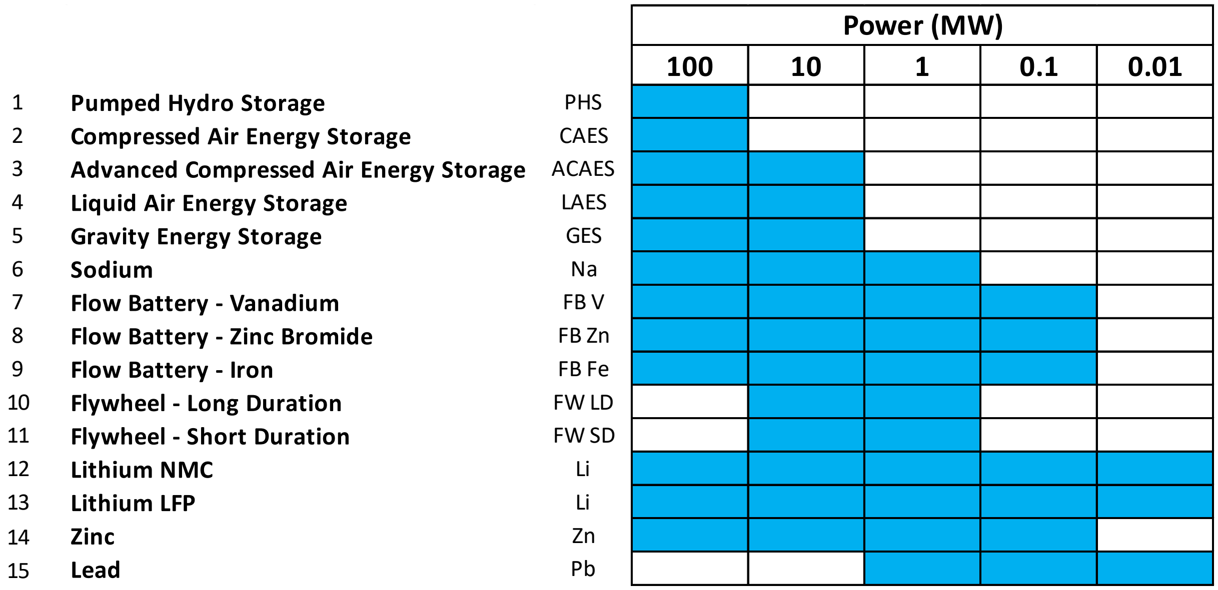


Figure 3-2. Power Rating System Range

These examples should not be taken as limiting the "Size" category to these specific applications but are for survey design purposes. Generally, the scale of an energy storage system impacts the system's pricing, with larger systems typically lower in cost (on a $/kWh basis) than smaller ones—holding other attributes stable.

3.3.3. System Scaling: Energy

Different energy storage technologies are typically available with varying amounts of energy capacity based on design and economic drivers. Specifically, although the energy storage capacity of the most basic unit of energy storage can be scaled into a variety of designs, OEMs and system integrators typically build the energy storage systems into specific building blocks of discharge duration.

This will have a profound impact on the deployment of energy storage technologies, and their potential for market usage. For instance, most flow batteries are not available for short duration (less than 3 hours) due to design issues. Conversely, cell-based technologies are thus able to be designed into a wide range of deployment designs (2 through 8 hours) but are typically only deployed where there is current or near-term expected economically viable uses. Therefore, a particular technology, such as lithium ion can deployed with a wide range of discharge durations, these different possible deployment options would have different cost ratings ($/kWh) and thus a different economic profile.

The growth of long-duration storage has caused an adjustment for some technology energy capacity ratings. Large scale technologies many times can have significant upfront costs no matter how many hours of deployment are included. These technologies would include PHS, CAES, ACAES, etc. Therefore, some of the technologies will be listed as 8-Hr for the energy rating, although the actual price quote will be for even longer duration units.

The following table displays the general availability of energy storage technologies on an energy scaling capability.

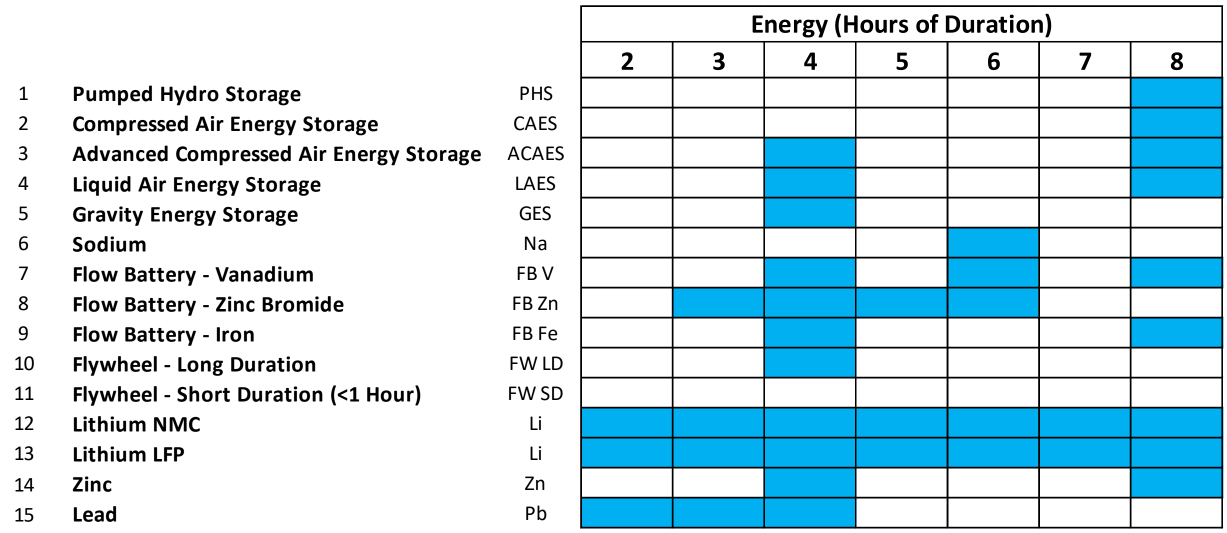


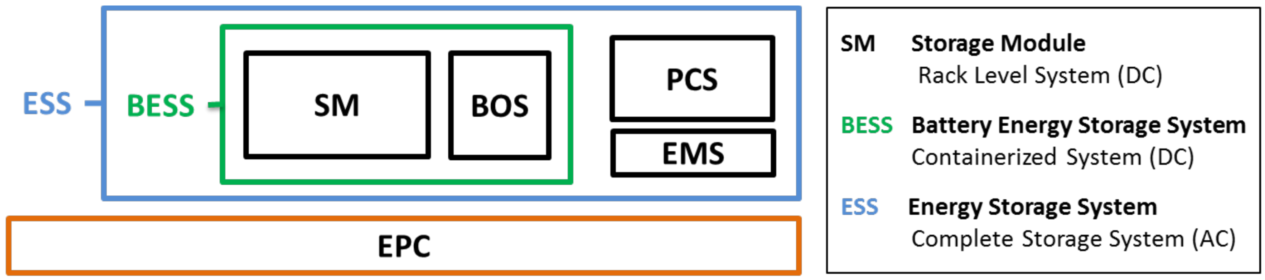
Figure 3-3. Energy Rating System Range

3.4. System Cost Structure

The Energy Storage Pricing Survey utilized a standardized component design cost structure in order to maintain its internal pricing structure consistency. This common system architecture framework is used across all energy storage technology platforms to provide a common frame of pricing reference between the different technologies.

This structure used to ensure the ability to compare technologies so that although pricing data that is available from different energy storage technologies at different architecture level can then be incorporated into systems of compatible power and energy ratings for equitable comparisons. Therefore, the specific values for the same component class may differ based on survey data (cost of Storage module, etc.), but the structure remains similar.

For instance, technology types based on unit cells will have price quotes from the storage module level, battery energy storage system (BESS) and the complete energy storage system (ESS). Conversely, technology types with larger building blocks such as flow batteries will have price quotes from the battery energy storage system (BESS) level and energy storage system (ESS) level.



Storage Module (SM)	Balance of System (BOS)	Power Conversion System (PCS)	Energy Management System (EMS)	Engineering Procurement & Construction (EPC)
Racking Frame / Cabinet	Container	Bi-directional Inverter	Application Library	Project Management
Local Protection (Breakers)	Electrical Distribution & Control	Electrical Protection	Economic Optimization	Engineering Studies / Permitting
Rack Management System	Fire Suppression	Connection to Transformer	Distributed Asset Integration	Equipment Procurement / Shipping
Battery Management System	HVAC / Thermal Management		Data Logging	Site Preparation / Construction / Mounting
Battery Module			Communication	Commissioning

Source: Mustang Prairie Energy

Figure 3-4. Energy Storage System Structure

The calculations for the final system prices are done from a system integrator's point of view, which includes equipment costs plus profit margins / markups that occur at the different stages. This approach is followed as the goal is to provide potential customers with the best realistic expectation for a system price for a particular energy storage technology a specific power and energy rating.

3.4.1. Commonality vs. Specific

The availability of specific component data will dictate the level of precision for any one component price. Early on, components such as the Balance of System, where possible, when a particular component power conversion system is used across many technologies, the pricing of the different stages of the power conversion system is calculated separately for each of the different power ratings. These resulting prices are then used in the calculation of the overall system pricing for the relevant energy storage technology to arrive at comparable full AC systems prices.

3.4.2. System Cost Structure Components

The general cost structure of energy storage systems used across all energy storage technologies include the following components:

Section	Description	Relationship
SM	Storage Module (Rack)	
BOS	Balance of System	
BESS	Battery Energy Storage System (Complete DC System)	**BESS = SM + BOS**
PCS	Power Conversion System	
EMS	Energy Management System	
ESS	Energy Storage System (Complete AC System)	**ESS = BESS + PCS + EMS**
EPC	Engineering Procurement & Construction	
ESS Installed	Installed Complete AC System	**ESS Installed = ESS + EPC**

Figure 3-5. Energy Storage System Component Relationships

3.4.2.1. Storage Module (SM)

The storage module is the most basic component, typically an assembly of energy storage medium components (battery cells) built into a modular unit to construct the energy storage capacity (kWh) of an energy storage system.

For a lithium-ion system, for example, it would be the complete rack (or tower, or cabinet), consisting of the battery modules, battery management system (BMS), and the rack and associated electrical cabling. Most cell-based energy storage technologies will have a similar unit block but may have different costs structures for each sub-component; for instance, lead acid battery systems do not require a BMS system as sophisticated as that of a lithium-ion system.

3.4.2.2. Balance of System (BOS)

The Balance of System is the equipment needed to combine a series of the storage modules into a complete DC level system. This will include electrical cabling, switchgear, thermal management, fire suppression, plus the enclosure, ranging from a special purpose enclosure, container, or a building.

For many non-cell-based systems, this component is incorporated by OEMs into their smallest commonly priced unit. This is commonly done by flow batteries and flywheels. For some cell-based systems with extensive module packaging, such as sodium and zinc-based systems, prices are only available with the balance of system included.

3.4.2.3. Battery Energy Storage System (BESS)

The Battery Energy Storage System is the complete DC level energy storage system and is comprised of one or more storage modules with the accompanying Balance of System equipment so the unit can be electrically connected with other electrical components to provide AC level interconnection of the system.

Increasingly, there is interest for DC level storage equipment to be connected on a DC system distribution system—for instance connecting on a solar array behind the solar field inverter. Although a DC level system does not need a inverter for conversion to AC power, most design contain a DC:DC converter in the design. This pricing structure will be dealt with separately in a future edition of the ESPS once more reliable data is available.

3.4.2.4. Power Conversion System (PCS)

The Power Conversion System is responsible for converting and managing the power (kW) flow between the Battery Energy Storage System's DC power output and connects that to an external AC power circuit—typically a step-up transformer to an AC distribution system. Components within the PCS would include the bi-directional inverter, any protection equipment to help isolate the DC system if needed, and the required cabling or busbar.

Pricing for these systems is standardized along the different system size ranking (1-5) corresponding to the different general pricing levels found at different power ratings.

3.4.2.5. Energy Management Software (EMS)

The Energy Management System is the software system used to control the operations of the energy storage system, especially with regards to the import and export of energy according to predetermined operating strategies. The degree of the sophistication of this system is dictated generally by the range of expected market roles or applications the unit is expected to perform, and at what level in the market.

For instance, a simple residential energy storage system providing only a few support functions will be significantly less robust than the EMS of a large utility levels system interconnected at the transmission level and expected to operate in a multifunctional role. Typically, large scale systems will include the communication equipment to connect to the utility SCADA and DMS systems.

3.4.2.6. Energy Storage System (ESS)

The Energy Storage System is the complete equipment package for an AC level energy storage system. This will include all of the equipment up to, but not including the step-up transformer. For ease of comparison, this will not include some electrical equipment such as metering equipment which can vary from location.

3.4.2.7. Engineering, Procurement, and Construction (EPC)

The Engineering, Procurement, and Construction component of the system costs deals with all components related to project construction. This aspect of the system cost can vary widely due to a number of factors: experience level of the developer and EPC providers, the scale and complexity of the system, and the deployment location of the unit. Aspects of this cost component include any engineering and permitting studies, equipment procurement logistics and shipping, site preparation and construction, and commissioning. This is discussed in greater detail in the Section 3.5.

3.4.2.8. ESS - Installed

The estimated complete system cost for an AC level system installed is comprised of the ESS system price, plus the corresponding EPC costs.

3.4.3. *System Cost Structure: Quote Filter*

The Energy Storage Pricing Survey obtains component pricing quotes from various OEMs, System Integrators, Developers, etc. at either complete system or, preferably, at the component level. The availability of component level pricing varies by energy storage technology.

Typically, larger, more integrated technologies (CAES) provided more complete (ESS) levels quotes, while systems made up of cell-based systems (Lithium, lead, etc.) provided the most discrete (SM) level quotes.

The ESPS attempts to obtain the most discrete level of data about each technology in order to provide for the greatest flexibility in designing possible system pricings results. Available data on the different energy storage technology classes is described in the following table.

		SM	BESS	ESS
		Storage Module (SM)	Battery Energy Storage System (BESS)	Energy Storage System (ESS)
Pumped Hydro Storage	PHS			■
Compressed Air Energy Storage	CAES			■
Advanced Compressed Air Energy Storage	ACAES			■
Liquid Air Energy Storage	LAES			■
Gravity Energy Storage	GES			■
Sodium	Na		■	
Flow Battery - Vanadium	FB V		■	
Flow Battery - Zinc Bromide	FB Zn		■	
Flow Battery - Iron	FB Fe		■	
Flywheel - Long Duration	FW LD		■	
Flywheel - Short Duration	FW SD		■	
Lithium NMC	Li	■		
Lithium LFP	Li	■		
Zinc	Zn		■	
Lead	Pb	■		

Figure 3-6. Pricing Data Available by Technology

3.5. Engineering, Procurement & Construction (EPC)

EPC costs have proven to be the most historically variable component of energy storage project installation costs. Due to the nascent nature of the energy storage industry, there is still a fairly strong learning curve associated with this engineering work needed for the different providers of this service, resulting in sometimes a wide range of bids for a project. Leaders at EPC firms also cited the lack in continuity in partners, (OEMs, System Integrators, Project Developers, etc.) as another driver in cost-overruns. The variability in pricing is driven by a number of issues, including location (rural / urban), site conditions (greenfield / brownfield) and enclosure requirement (indoor / outdoor). Experience, partner continuity, and improved designs are expected to provide the basis for cost reductions for the near future.

Happily, there has been a significant amount of advancement in both the reduction of cost, and, more importantly, the variability surrounding the cost estimates. Much of these reductions are derived from process improvements stemming from a growing body of experience by a wider number of existing EPC. Another important development has been the improvement in system design which allows for easier installation, and hence lower cost.

As the name indicates, EPC costs are derived from three areas, engineering, procurement, and construction.

3.5.1. Components

- Engineering costs relate to the work required to plan the integration of the energy storage asset into the local power system. This would also entail any permitting studies needed for the specific site. The cost of this will generally scale with the complexity of that task.
- Procurement costs are derived from the purchasing and delivery logistics of the needed equipment from the suppliers to the project site for construction. Costs generally scale with size and complexity of system, and accessibility of the site. Procurement costs overruns can be driven by several factors, but those most unique to the energy storage industry would be OEM supplier reliability on delivery or slippage of schedule.
- Construction costs generally decline as a percentage of capital costs as the system size increases as there are several fixed costs that larger facilities can benefit from. As with engineering costs, there is also a large site-specific impact and variability that can drive up costs, especially for smaller systems especially where the energy storage unit is being installed into an existing structure with limited space. After construction of the facility is completed, commissioning of the facility is required for the system to begin operation. Commissioning typically entails running a series of tests to ensure the unit is capable and ready for commercial operation.

3.5.2. Current Estimates

The 2020 Energy Storage Pricing Survey applies a different EPC cost estimate based on a percentage of total capital costs for each of the different system sizes. These cost estimates are based on survey input to account for differences in EPC costs as systems scale in size and complexity.

Because of the preponderance of lithium-ion battery systems, these systems are the basis for the cost estimates for energy storage system EPC costs in general. Where possible, differing EPC costs have been collected applied to different energy storage technologies where survey results point to a different cost structure. As greater detailed information is available on different energy storage technologies, the Energy Storage Pricing Survey will be able to break out different global component estimates by technology when the confidence is sufficient.

Table 3-4. Baseline Energy Storage EPC Cost Estimates

System Size	Potential Market Use	EPC Cost Estimate		
		Low	Avg	High
1	Wholesale	15.0%	17.5%	20.0%
2	Utility	17.5%	20.0%	22.5%
3	Distribution & Microgrid	20.0%	22.5%	25.0%
4	Commercial & Industrial	22.5%	25.0%	27.5%
5	Residential	25.0%	30.0%	35.0%

These average EPC cost estimates are only to represent the generally expected EPC costs of a plain vanilla deployment for each of the different system sizes. Because of the complexity of the EPC component for energy storage systems generally, a wide range of possible EPC costs exists, and is expected to continue with a large variance until significant experience is reached across the industry. For this reason, additional low and high estimates are given to provide a confidence interval for where the expected EPC costs will range. With increasing experience and scale, these costs are expected to decline over time.

These variations are driven by many factors, chief among them the scale of the facility, and the type of deployment location, such as in a greenfield site, inside or outside of an industrial/commercial building, etc. For this reason, the average EPC cost estimates used in the survey results should be viewed as general estimates of expected costs, with actual costs ranging higher if complexity is encountered.

3.5.3. Recent Activity

Efforts derived from the automotive market are benefitting the stationary market in surprising ways. The recent emphasis by major cell providers is toward a “Cell-to-Pack” The first effort will be to reduce the manufacturing complexity and equipment requirement, resulting in lower costs. Historically, individual batteries were developed into modules, which were then collected into packs which incorporate greater cell protection and management. The newer design allows for the direct manufacture of packs.

Although this is still an emerging area of design by OEMs, the results can be seen in the increasing deployment of enclosures by leading providers instead of 20’ or 40’ containers. These enclosures allow for complete construction at the factory, with minimal installation and commissioning required in the field.

Estimates vary, but many claims of an improvement in pack manufacturing costs by more than 10% and a reduction of the number of individual parts allows for a greater cost reliability. These design changes have also lead to a reduction in EPC costs for some Lithium-ion projects utilizing purpose built enclosures for 500 kWh or 1 MWh.

3.6. Operating Costs

Because of the need to maintain the quick and reliable response capability of energy storage assets to derive their value, the operations costs of energy storage assets are gaining in importance. Operating costs include fixed and variable cost components. Fixed costs are made up predominately of operation & maintenance contracts, while variable costs are driven by the efficiency losses stemming from operation.

3.6.1. Fixed Costs

Operation & Maintenance costs are structured as the largest fixed cost price for energy storage system. Additional station load electrical costs for relatively fixed electrical loads such as the energy management system would also be included here, but all of these are negligible compared to the O&M contract charge.

Operation and Maintenance (O&M) costs are becoming of greater concern to estimate the total cost of ownership of the system. O&M costs will cover monitoring and scheduled maintenance of both the battery system, HVAC, and power electronics. Chemical batteries such as Lithium-ion systems are typically a low-maintenance cost technology as compared to others with moving parts that require more frequent maintenance. On average, higher usage of the system will require more maintenance for all technologies. Because of the lack of significant experience with any storage system over the long-term, there remains open questions as the O&M needs to maintain expected performance levels for a wide variety of applications—especially when operating in multiple modes simultaneously.

Typical maintenance costs are contracted for a specific annual dollar value per year, although the range can vary widely depending on the level of reliability desired. These costs correspond to a range of anywhere from 1% of the capital cost, to 5% per year. This has generally cover one or two visits per year to visually inspect the system and change out consumables such as air filters for the cooling systems; some contracts also provide for one or two unscheduled visits. Increasingly, remote monitoring is being included to reduce these visit requirements. Remote monitoring in particular helps lower the cost to inspect the units. It also provides an opportunity to gather data for predictive maintenance, as the body of operating experience grows. Operation and maintenance concerns have grown with the push toward longer-lived systems, driving a focus on the operation of the facility over time, rather than maintenance of the initially installed equipment and hopes that it will operate whole life without incident.

3.6.2. Variable Costs

The second component of Operating Costs represent those costs that vary based on the level of activity of the system. The predominate variable components are represented by round trip efficiency losses, and Replenishment Costs.

3.6.2.1. Efficiency Loss

Efficiency loss represents an important variable operating cost for energy storage facilities and can lead to significant negative economic impact—especially for more actively usage profiles. As one would imagine, different energy storage technologies have different round trip efficiencies (RTE) based on the method needed to convert the electrical energy into a form for storage, and back again. Since RTE can impact total operating costs, it is an important input into economic modeling calculations. These charging costs will also vary between technologies as the round-trip efficiencies vary widely—flow batteries can achieve into the 80% range for round-trip-efficiency (DC:DC), whereas lithium-ion modules routinely state 95%+ round trip efficiency (DC:DC). In reality, average AC level RTE values based on real-world experience are lower than the optimal values provided by manufacturers.

Typically, the cell (or module) efficiency is highlighted, but it is important to use the complete round trip efficiency (RTE) of a system, which (for cell-based systems like lithium-ion) includes the DC battery modules, the power conversion system (primarily inverter), the parasitic load from the HVAC (Heating, Ventilation and Air Conditioning) equipment, and the station power needed to power the electrical controls of the facility (not significant but should be considered). Because the HVAC load can vary significantly based on the geographical location of the system, and to the degree of how actively used is the energy storage system, this location specific variance is not typically added to the station power load estimate. The impact of HVAC is becoming more important as operating data becomes more widely published. This HVAC loads will always vary as different seasons and regions of the country require different cooling loads, and different applications require different usage levels, requiring different cooling loads.

3.6.2.2. Replenishment

Project developers must incorporate a replenishment plan into the design of the project to ensure that the facility will be able to maintain sufficient capacity (kWh) over its lifetime sufficient to meet any contract obligations or market strategy requirements. This plan is dependent upon several factors that will affect the degradation of the storage technology's capability, including the type of energy storage technology, the expected usage profile, and the environmental conditions where it will operate. It should be noted that a number of technologies do not have significant degradation in the energy capacity of the system, and thus do not require this added cost to support the project.

Replenishment strategies attempt to find the least-cost approach to obtain the required capability of the system over its lifespan. The challenge is to map the declining capability of the batteries with the expected usage profile over time to determine how much additional storage capacity must be added. Since energy storage technologies are expected to decline over time, installing only that which is needed now incurs the least cost for the batteries, but incurs other balance of system costs.

A key point underlying this effort is the technical operating lifespan of the storage asset. Most chemical batteries have a gradual and roughly linear decline in capacity over its lifespan until it reaches a point where the degradation per cycle accelerates. This point has typically been the "technical lifespan" of the cell, historically when the cell has 80% of its capacity remaining. Advances in battery technology and significantly greater operating experience has extended the linear declining lifespan of cells until the 70% or even 60% remaining capacity remains.

Three strategies are prominent in most replenishment plans, initial oversizing of the facility, and augmentation later in the life of the unit. Due to the declining cost of the equipment, the typical cost minimization strategy is to push off into the future as much of the augmentation as possible as future batteries are expected to cost less. Determining the least-cost augmentation schedule will continue to vex many project developers who desire to use the energy storage facility for a number of applications. Thus, the result is typically some mixture of initial oversizing—with augmentation occurring a few years into the future, but as infrequently as possible in order to minimize the labor component.

3.6.2.2.1. Oversize

Initially oversizing the energy storage system is a common strategy for many project developers. This produces a system that has additional capacity in the event of a problem early in the operating life of the unit and allows the operator to understand the exact degradation of the equipment. For many systems with a 10 year or less lifespan, it is sometimes easier to incorporate sufficient battery capacity initially so there is no requirement to later add battery modules to the unit.

3.6.2.2.2. Augmentation

Augmentation represents the periodic addition of energy storage equipment over its operating lifespan needed for the system to maintain the capability agreed to under the performance guarantee or support a specific usage profile. The augmentation strategy benefits from the expected lower cost of energy storage systems in the future. A key component of the forward cost is the planning for ancillary costs such as additional balance of systems and EPC costs that should be taken into account or at least planned for at the beginning of the project.

Augmenting the energy storage capacity of a facility often means adding more than just additional battery modules. Historically, for lithium-ion batteries this question manifests as to whether the project is only required to added DC battery modules, or complete AC level systems. The issue is based on the ability to add new battery modules in line with existing, older battery modules tied to a common inverter—which had been the practice for many cost-conscious developers. As the modules will have different electrical properties (due to age), balancing them becomes more difficult, thus the earlier strategy of simply adding new modules to strings with older battery modules has been proven not to work well. However, if the modules are instead added to the overall system with a new inverter (at the AC level), or with a DC-DC converter, then the new modules can be electrically isolated from the older ones and run with more reliable performance over time, albeit at a slightly higher capital cost.

3.6.2.2.3. Replacement

The third strategy is replacement of the existing storage modules if their technical operating life does not last as long as the project's operating lifespan. Like the augmentation strategy, this strategy will benefit from a lower future cost of batteries, lowering the effective replenishment cost. A critical deciding point for this strategy is the warranty coverage of the battery system. Since many lenders require all of the equipment to stay under warranty during the loan period, modules that reach the end of warranty coverage will be replaced for contractual, rather than a purely technical choice.

3.7. Project Costs

In addition to the capital and operating costs, there are a number of project related costs that are needed to be considered when calculating a total cost of ownership. These include warranty costs for the capital equipment, insurance to support a viable risk management strategy for the facility, and the End-of-Life strategy to close out the facility.

3.7.1. Warranty

Warranty coverage ensures asset owners that there is recourse from the OEM in the event that the product does not perform as stated. Warranty coverage is very important to project developers, insurance firms, and capital providers to reduce downside risk of the equipment not being available to support revenue generation. The warranty period can vary depending upon the market and/or usage profile under which the battery is intended to operate; residential and commercial units are typically focused on 10-year lifespans, while utility and front of the meter systems are focused on 20-year project lifespans. Some aspects related to warranty coverage, however, are not expected to ever be covered freely by the OEM, however. For instance, warranties cover the cost of the equipment, and not the labor to replace the unit, or shipping it back for repair or replacement. This is an important issue with price conscious customer—such as residential—who are primarily concerned with up front capital costs and not total life operating expenses. Warranty coverage is typically focused on three areas: manufacturing defect, performance, and availability.

The limited warranty covering manufacturing defect guarantees the energy storage system to be free from defects in material and workmanship and provides relief in the event only that there were defects in the manufacturing of the product with the vendor required to repair or replace the defective components. This warranty does not extend to any design issues of the product and does not reimburse for economic loss resulting from downtime. These warranties are included in the purchase price of the unit and can have a lifespan of between 15-20 years. These warranties have grown in duration as experience proves out the products.

Performance warranty coverage ensures that the system will perform according to the specification details provided at purchase. These are typically not a simple blanket coverage (x number of cycles, etc.) but provide conditional coverage depending on the usage (cycle life, Depth of Discharge, C-Rate, etc.) and operating conditions (temperature, elevation, etc.). The cost of these warranties is dependent upon the energy storage technology. Most lithium NMC manufacturers provide the first 1-3 years of coverage with the purchase price, and then allow an annual subscription for the remainder of the project life. Many non-lithium energy storage technologies follow this strategy. Conversely, many Lithium LFP manufacturers include the full lifespan coverage in the purchase price. Current offerings are typically up to 10–20-year range (depending on the market & operating conditions) but have specific attribute limitations. As with manufacturing warranties, the length of coverage for performance warranties have also expanded as the experience level grows.

The most recent area for warranty coverage deals with the availability of the unit. Whereas manufacturing warranties are targeted at ensuring the unit can operate, and performance warranties are targeted at ensuring the unit can operate over the intended life of the unit, availability warranty coverage is designed to ensure that the unit is available to operate when the unit can operate. This area is of growing importance for systems targeted at providing capacity services into the market. The coverage is usually linked to the number of operations per month or year required, and have a lifespan typically linked to the same as the performance warranty lifespan.

3.7.2. Insurance

Insurance is an important consideration for capital providers of any power system project and are a standard component of a project development effort. Typical standard insurance coverage for energy storage systems include property, liability, business interruption, etc. These costs run typical to other property costs but remain higher than for other technologies.

Of growing interest is a performance warranty coverage. This coverage is in addition to the OEMs warranty coverage, to provide developers and operators with confidence there is a cap on any potential overruns of maintenance costs than expected. These costs are typically important for less common technologies such as flow-batteries but have been found with different customers wanting to cap any potential overage cost exposure.

3.7.3. *End of Life*

To fully account for the total system cost of an energy storage asset, an end-of-life cost must be included for the end of life of the asset. This end-of-life cost estimate will contain three parts: Decommissioning, Transportation, and Disposal.

Table 3-5. Energy Storage End of Life Cost Estimates

EOL Component	EOL Cost Percentage
Decommissioning	30.0%
Transportation	20.0%
Disposal	50.0%

The actual cost of the EOL charges is represented as a percentage of capital costs, with initial estimates accounting for 10% to 15% of the initial capital cost of the system for most cell-based technologies currently in use. These costs will vary by technology and can rise for large scale energy storage systems that have a large portion of civil work.

3.7.3.1. Decommissioning

Decommissioning of the energy storage facility is the act of dismantling of the equipment and returning the site/location back to a brownfield state. This can roughly be described as the construction/commissioning process in reverse, including the removal of the battery systems and then the housing and balance of systems.

3.7.3.2. Transportation

After decommissioning the site, the components of the energy storage system will be transported to a facility for disposal. The transportation of the various components will need to be done in accordance with the controls and regulations of these systems, and with the understanding that regulations in the future will probably be more stringent for the transportation of caustic chemicals, along with partially energetic chemical devices. The transportation of energy storage system components will generally conform to a reversal of the original equipment's initial transportation to the site.

3.7.3.3. Disposal

Disposal of the energy storage system's equipment is the final end-of-life decision. There are essentially three areas of focus here: second life (re-use) issues, recycling, and the disposal of waste to an appropriate final location.

4. CHANGES IN THE ENERGY STORAGE PRICING SURVEY

To provide an accurate benchmark system price, the Energy Storage Pricing Survey relevant, various components are either updated or augmented on an annual basis. Between the 2019 and the 2020 edition of the ESPS, the follow changes were made.

4.1. Data Acquisition

The amount of available data on the pricing and performance of energy storage system continues to increase year over year, allowing for a higher confidence level of the reported estimates. This also allows for eventual expansion of component price analysis precision, supporting a greater overall accuracy of a standardized reference system price.

4.1.1. Primary Data

Interviews with industry participants continue to be basis for the primary data sources Ongoing effort continue to maintain a good level of contact at the different OEMs as individuals move around the industry. Some effort was made toward standardizing the data input with a template of information requested. This will continue to be used to provide OEMs a clearer description of the data requested, but most interviews continue to be done in-person or over the phone for both clarity and to ensure anonymity.

4.1.2. Secondary Data

The number and quality of published data sources continue to expand as the interest in the energy storage market grows. Along with the increased frequency of published instances, the level of detail for price quotes continues to increase, qualifying these published data points as usable.

In the near future, the growing number of structured pricing survey on energy storage installations (state level, etc.) is promising to provide a number of easily verifiable data source.

4.2. Energy Storage Technologies

The number of technologies covered in the ESPS is moving from 14 to 15 energy storage technologies.

New unique energy storage technologies:

- Advanced Compressed Air Energy Storage (ACAES)
- Liquid Air Energy Storage (LAES)
- Gravity Energy Storage (GES)
- Lithium Ion: NMC (LiNMC)
- Lithium Ion: LFP (LiLFP)

Changes in Definitions

- Compressed Air Energy Storage (CAES) was split into three categories. Existing CAES facilities remain in CAES. Advanced Compressed Air Energy Storage (ACAES) and LAES prices are now their own technology type category.

- Lithium-Ion Energy and Lithium-Ion Power have been reworked to be Lithium Ion: NMC and Lithium Ion: LFP.
- Lead (Pb) and Lead Carbon (Pb) have been combined into Lead.

The energy storage technologies removed were:

- Nickel (Ni)

4.3. System Cost Structure

A variety of changes occurred under the system cost structure area in the 2020 Energy Storage Pricing Survey. However, there was no change to the capital cost structure. With the expansion

Some system cost structure components did gain some improved precision. These included:

4.3.1. Long Duration

The growth of long-duration storage has caused an adjustment for some technology energy capacity ratings. Large scale technologies many times can have significant upfront costs no matter how many hours of deployment are included. These technologies would include PHS, CAES, ACAES, etc. Therefore, some of the technologies will be listed as 8-Hr for the energy rating, although the actual price quote will be for even longer duration units.

4.3.2. High / Low Pricing Band

To further the goal of providing a realistic expectation for energy storage pricing, a high and low pricing band was included in the methodology. The high and low pricing is built from the bottom up, utilizing the lowest realistic price for each component.

This increased range of pricing expectations will allow the energy storage pricing survey to give additional insights into what pricing is possible by the different technologies each year. These additional pricing estimates should not be taken as the highest and/or lowest price quote for each technology each year, but a range where realistic expectations for prices will fall.

4.3.3. Engineering, Procurement & Construction (EPC)

With growing experience, the EPC cost component of energy storage systems continues to decline, with expectation for sustained reductions for the foreseeable future. Drivers for this decline include experience by the project developer, EPC firm, and design improvements by the OEM and System integrator making the installation of the unit easier.

The 2020 Energy Storage Pricing Survey began the process of developing individual EPC cost estimates for each technology and provides a high and low band for the realistic expectations.

4.4. Operating Costs

Operating costs represent the cost components to successfully operate the facility. As the experience of operating these facilities have grown, it has become more evident as to how to structure these costs into their fixed and variable elements.

Fixed operating costs are comprised primarily of Operation and Maintenance (O&M) services. Contracts for these support services are typically a flat fee per year, based on the scale and complexity of the services. The level of O&M service can vary, leading to sometimes “Tiers” of services for premium support, but typically are a base cost for a standard level of service to ensure successful operation.

Variable operating costs are comprised of energy loses from operation, and the replenishment costs associated with battery replacement. The round-trip efficiency losses vary by technology, and then by usage profile, with faster operation typically operating under a lower efficiency rate. Replenishment represents the cost needed to maintain the nameplate energy storage capacity of the system. This varies by technology, with some not losing any energy capacity from degradation (for example, flywheels) whereas chemical cells (for example lithium ion). Replenishment costs are derived from initial oversize requirements, periodic augmentation, and full system replacement. Since these costs are highly variable, they are many times converted to an annual charge for budgeting purposes.

4.5. Project Costs

Project costs are structured for total cost of ownership calculations. Three areas of these project costs are defined, including warranty costs, insurance costs, and end-of-life costs. These project cost structures are similar across all technology classes, and detailed cost estimates are expected to gain in precision as experience is gained over time.

The methodology to calculate the end-of-life value is systematically similar across all technologies, but the actual value is intended to be specific to each technology. To fully account for the total system cost of an energy storage asset, an end-of-life cost must be included for the end of life of the asset. This end-of-life cost estimate will contain three parts: Decommissioning, Transportation, and Disposal.

4.6. Comparative Metrics

In an attempt to move the comparison from a product cost comparison to a project cost comparison, a section on comparative metrics was added to the Energy Storage Pricing Survey. The first comparative matric is a simple throughput metric base on the initial capital cost of the system, and the total amount of energy cycled through the system over the life of the unit. Additional comparative metrics will be developed in future surveys.

5. ENERGY STORAGE TECHNOLOGY DETAIL

This chapter includes more detailed pricing survey information on the different technologies. This chapter is divided into fifteen sections, each one representing a different technology type. The sections included in the 2020 Energy Storage Pricing are listed in the following table:

Table 5-1. Energy Storage Technologies Covered

	Technology	Abbreviation
1	Pumped Hydro Storage	PHS
2	Compressed Air Energy Storage	CAES
3	Advanced Compressed Air Energy Storage	ACAES
4	Liquid Air Energy Storage	LAES
5	Gravity Energy Storage	GES
6	Sodium	Na
7	Flow Battery: Vanadium	FBV
8	Flow Battery: Zinc Bromide	FBZnBr
9	Flow Battery: Iron	FBFe
10	Flywheel: Long Duration	FWLD
11	Flywheel: Short Duration	FWSD
12	Lithium Ion: NMC	LiNMC
13	Lithium Ion: LFP	LiLFP
14	Zinc	Zn
15	Lead	Pb

Each section of the chapter has a short description of the technology, issues governing deployment concerns, important operating characteristics, and how these impact the typical market applications. This is to provide some context for the reader.

The pricing section provides the calculated realistic expectation system prices at the specified power and energy ratings for installed system cost. Because of the multiple system ratings, the final calculation is provided in graphic form to aid in understand the patterns of the system pricing as the power or energy rating is changed. An accompanying data table is also provided to provide readers with the specific results used for the graphical presentation.

The Energy Storage Pricing Survey is focused on grid energy storage technologies, which dictates the type and scale of energy storage technologies evaluated. The energy storage technologies covered are those with OEMs commercially active, in order to obtain pricing information. This means that those energy storage technologies that had been commercially active in the past but are no longer available are not included in the survey. This includes such technologies as Superconducting Magnetic Energy Storage (SMES), and Zinc Chromium (FB ZnCr) Flow Batteries. Other technologies that support some specialized market roles besides grid storage are not currently support either. For instance, certain lead acid (Pb), Nickel Zinc (NZ), and Supercapacitors (SCap) systems targeted at supported the UPS are not yet included as the UPS market is not currently covered.

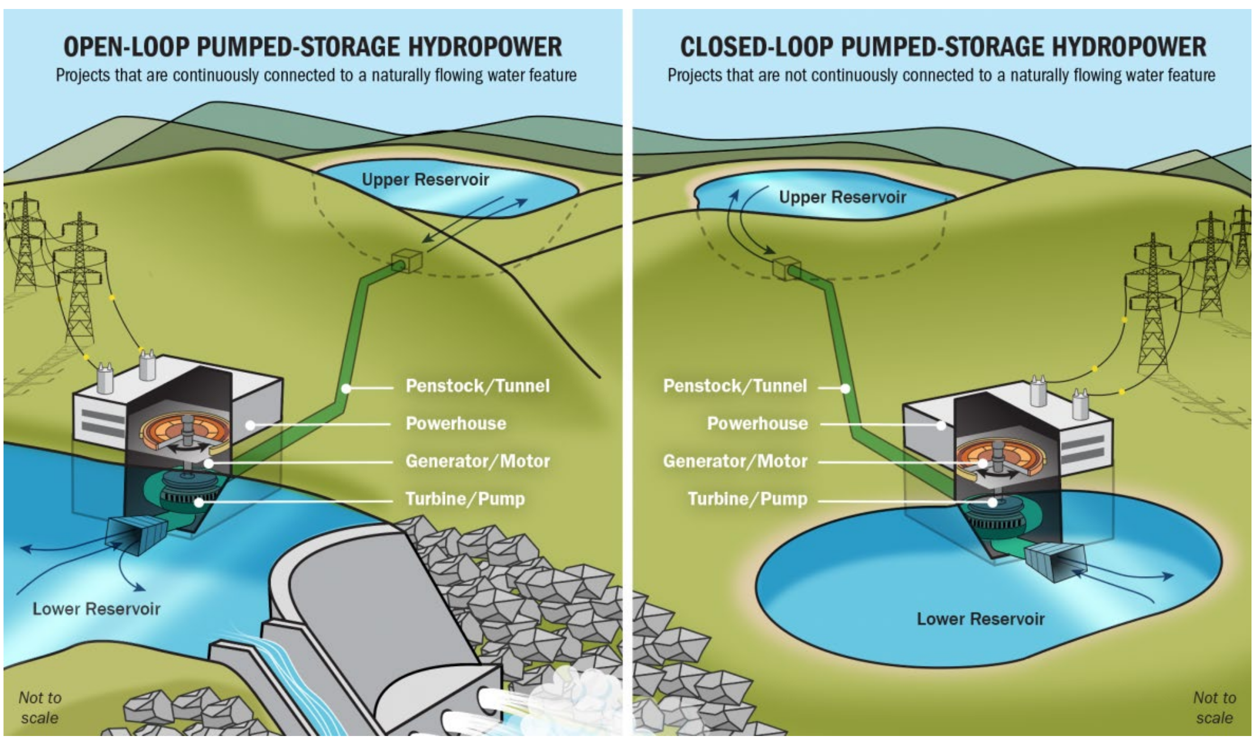
5.1. Pumped Hydro Storage (PHS)

Capital costs for pumped hydro storage (PHS) energy storage systems are provided in $/kW in the energy storage pricing survey because the majority of the costs are associated with the power train and physical installation separate from the energy storage capacity of the facility. Depending on the market use of the facility, a range of reservoir size could be used for the same powerhouse equipment, skewing the more common $/kWh pricing metric for energy storage technologies.

5.1.1. Technology Description & System Design

A typical PHS facility consists of three key components: the reservoirs (upper and lower), the penstock (tunnel) connecting the two reservoirs, and the powerhouse equipment. The upper reservoir can be located anywhere from 30 m to 650 m above the lower reservoir, with 300 m of hydraulic head (the difference between the two reservoirs) generally considered the preferred height for new development. The powerhouse equipment is dominated by the reversible turbine, which can be either of a fixed, or variable speed design.

Typically, pumped hydro storage facilities can be sized anywhere from the 10's to 100's of MWs (although above 100MW is typical due to the high fixed costs of the power train, penstocks and storage facility). The discharge duration can also range from a few to more than 10 hours, depending on need. For pumped hydro storage systems, the size and the elevation difference of the reservoirs are aspects of the system that most impacts the storage costs of the facility.



Source: U.S. Department of Energy

Figure 5-1. Pumped Hydro Storage System Design

5.1.2. Deployment Options

Location of these facilities is dictated by geography. Although the upper reservoir is typically constructed near a strong vertical area or relief, designers typically try and utilize an existing large body of water for the lower reservoir. A conventional hydropower lake is many times preferred, so that the lake level is controlled. Closed loop options have been devised where the upper and lower reservoirs are not connected to other bodies of water, allowing for a freer deployment option, although periodic addition of water is required to balance evaporation.

Pumped hydro storage facilities are also gaining interest as a base for hybrid storage designed, coupled with lithium-ion systems to provide a wider and more responsive range of market services.

5.1.3. Operating Characteristics

The round-trip efficiency of pumped hydro facilities is determined by the efficiency of the pump/generator, and friction losses stemming from the physical design and layout of the facility. These friction losses are incurred as the water travels through the pump/generators and from the friction and turbulence of the water in the penstock connecting the upper and lower reservoir. It was not uncommon for older designs (prior to the 1980's) to have round-trip efficiencies of little more than 60% but repowering of plants with new turbines and impellers have achieved round trip efficiencies of upwards of 70% -80% (AC).

Pumped hydro storage systems do not experience significant degradation in either their power or energy rating over time during operation. Their ability to store and retrieve energy is based on the reversible pump turbines, and the storage capability of reservoirs also does not experience significant reduction over time. This allows pumped hydro power to operate repeatedly, cycling energy through the system without worry of degradation that occurs from cell-based energy storage. As with many rotating machines, efficiency can decline slightly over time, but not significantly if operated and maintained in good working order.

Table 5-2. Pumped Hydro Storage (PHS) System Performance Characteristics

Pumped Hydro Storage (PHS) Performance Characteristics	
Lifespan:	40+ Yrs.
Round-Trip Efficiency (AC):	70-80%
Operating Range (Depth of Discharge %):	100%
Capacity at End of Life (% of Original):	100%
Operation & Maintenance (O&M):	1%

5.1.4. Applications

Due to their physical size, pumped hydro storage facilities are active primarily in the wholesale power market, providing both energy and power products and services.

Pumped hydro storage systems are designed for long duration storage, with reliable, long-calendar year lifespan measured in multiple decades. Traditionally, fixed speed turbines provided the power for pumping water up / generating power when released. Newer, variable speed turbines have increased the range and responsiveness of the facility output, makes these pumped hydro systems valuable for load following and ancillary services. Moderate round trip efficiency is balanced by the scale of the units in wholesale market operation.

Increasingly, pumped hydro storage systems are receiving renewed interest by utilities and other power asset owners wanting large scale energy storage facilities (300MW+) with the greatest interest coming in the 8, 10, and even 12+ hour capacity to support a wider range of zero-carbon power output.

5.1.5. System Capital Costs

Key drivers for pumped hydro storage equipment costs are the amount of land required, and the scale of construction and cement required. Construction costs include the required holding reservoirs, the penstocks (tunneling and construction), and the powerhouse building. The powerhouse equipment can also be substantial, increasing the relative costs of smaller facilities.

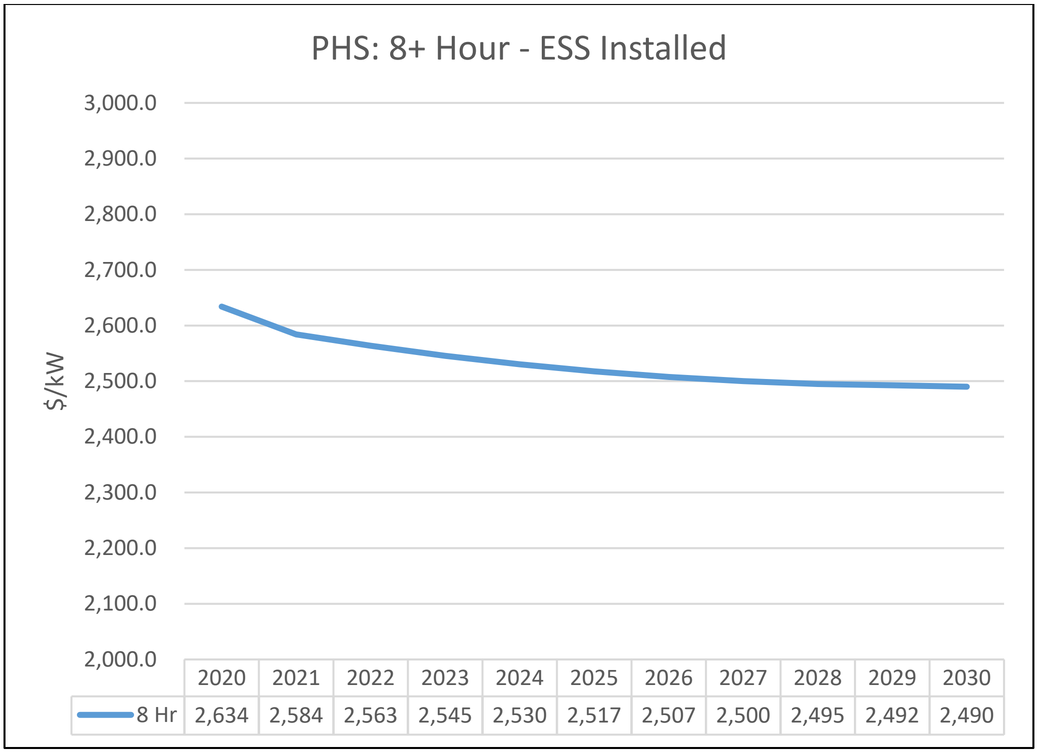
The equipment cost for traditional pumped hydro storage systems is not expected to change dramatically over the forecast due to the more mature nature of the technology. The introduction of variable speed generators has increased the capital cost of that system component, but with a corresponding increase in the capability of the unit.

Potential significant improvements in future capital cost reductions of pumped hydro storage are limited due to the level of maturity of the technology. Any future improvements are expected to be in regard to improvement in power train technology.

Note: There has been a change in the system description of the pumped hydro storage to take into account the trend toward larger and longer duration capability. Earlier survey data was limited to only a few, older results. By expanding the survey into including multi-hundred, 8 hour and greater systems using more advanced variable speed drive designs, the 2020 ESPS can provide a better realistic expectation prices for this technology type.

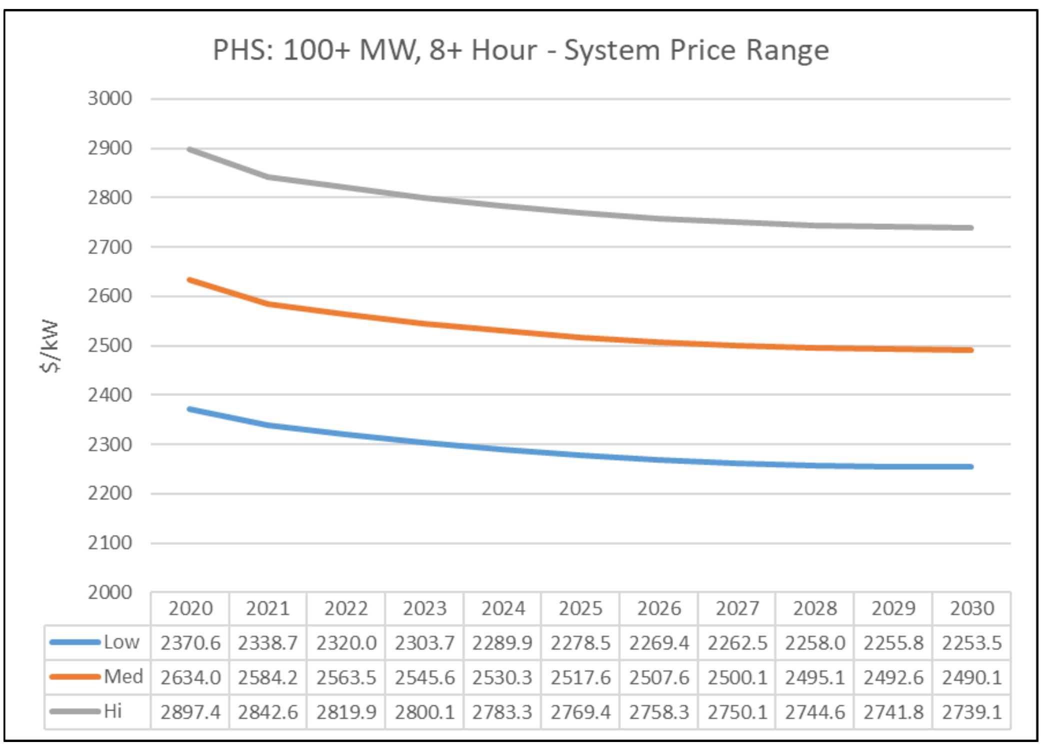
Table 5-3. Pumped Hydro Storage (PHS) 2020 Installed System Costs

Pumped Hydro Storage (PHS) - 2020					
$/kW	Size (MW)				
	100	**10**	**1**	**0.1**	**0.01**
PHS: 8+ Hr	2634.0				



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
8 Hr	2,634	2,584	2,563	2,545	2,530	2,517	2,507	2,500	2,495	2,492	2,490

Figure 5-2. Pumped Hydro Storage (PHS) System Price Forecast



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low	2370.6	2338.7	2320.0	2303.7	2289.9	2278.5	2269.4	2262.5	2258.0	2255.8	2253.5
Med	2634.0	2584.2	2563.5	2545.6	2530.3	2517.6	2507.6	2500.1	2495.1	2492.6	2490.1
Hi	2897.4	2842.6	2819.9	2800.1	2783.3	2769.4	2758.3	2750.1	2744.6	2741.8	2739.1

Figure 5-3. Pumped Hydro Storage (PHS) System Price Range

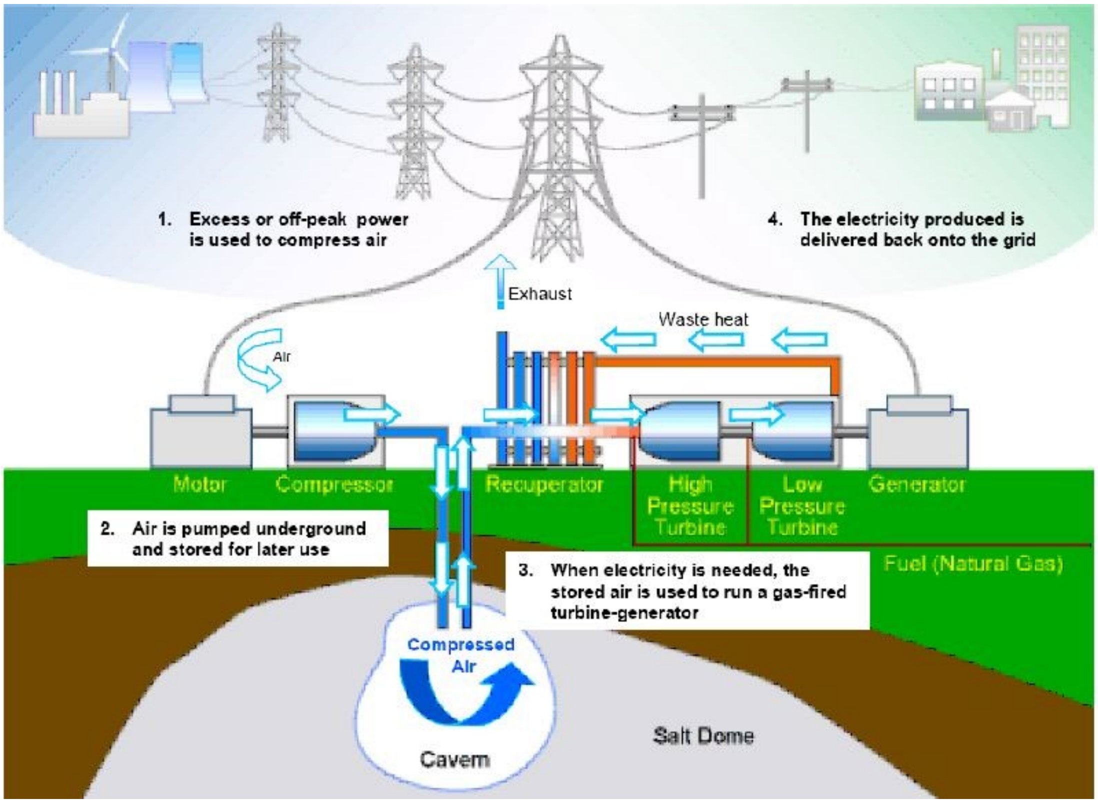
5.2. Compressed Air Energy Storage (CAES)

Capital costs for compressed air energy storage (CAES) systems are provided in $/kW for the energy storage pricing survey because the majority of the costs are associated with the power rating of the facility. Depending on the market use of the facility, a set of small or large air reservoirs could be used for the same powertrain equipment, skewing the more common $/kWh pricing metric for energy storage technologies.

5.2.1. *Technology Description & System Design*

Traditional CAES facilities can be most easily thought of as a gas turbine with the compressor and combustion chamber on separate drive shafts instead of a single one. CAES systems use off-peak power to pressurize air into a reservoir, which is then released during peak hours to power an air expander/gas turbine for power production.

Potentially, compressed air energy storage facilities could be sized anywhere from the 10's to 100's of MWs, depending on the gas turbine power train used. Typically, each power train is sized over 100 MW. The discharge duration can also range from a few to more than 10 hours, depending on the reservoir. Reservoirs can either be salt caverns, aquifers, dedicated hard rock mines or above ground storage tank.



Source: Ridge Energy Storage & Grid Services, LP

Figure 5-4. Compressed Air Energy Storage (CAES) System Design

5.2.2. *Deployment Options*

CAES system deployment is determined by the available location of the particular storage reservoir option. Many traditional CAES facilities utilize natural geological features like aquifers, hard rock mines, salt caverns, or conversely, man-made surface tank storage.

5.2.3. *Operating Characteristics*

The round-trip efficiency of compressed air energy storage facilities is determined by the efficiency of the compressor/generator, and friction losses stemming from driving the air into the typically underground cavern. The average round-trip efficiency for existing traditional CAES facilities ranges between 55% and 75%; with newer designs claiming RTE's higher still.

Compressed air energy storage systems do not experience significant degradation in either their power or energy rating over time during operation. Their ability to store and retrieve energy is based on the compressors and power generators in the power train and the storage capability of air chamber does not experience significant reduction over time. This allows compressed air energy storage systems to operate repeatedly, cycling energy through the system without worry of degradation that occurs from cell-based energy storage. As with many rotating machines, efficiency can decline slightly over time, but not significantly if operated and maintained in good working order.

The cycle life of these units is based on the mature mechanical powertrains developed in the gas turbine and compressor markets, providing these systems with a very mature technology base from which to operate. Generally, the lifespan is counted like a power facility of many decades,

Table 5-4. Compressed Air Energy Storage (CAES) System Performance Characteristics

Compressed Air Energy Storage (CAES) System Performance Characteristics	
Lifespan:	30+ Yrs.
Round-Trip Efficiency (AC):	55-75%
Operating Range (Depth of Discharge %):	100%
Capacity at End of Life (% of Original):	100%
Operation & Maintenance (O&M):	1%
Heat Rate (DT/MWh):	4.1%

5.2.4. *Applications*

Due to their physical size, compressed air energy storage facilities are active primarily in the wholesale power market, providing both energy and ancillary services. In the traditional CAES design, off-peak electricity can be used to power an electric motor during the compression phase to charge the reservoir chamber. Since the drive saft between the compressor and combustion chamber are separate, it is possible for a CAES system to both be charging the reservoir while discharging, or the two activities can be done separately.

Compressed air energy storage systems are designed for long duration storage, with reliable, long-calendar year lifespan. Variable output makes these systems valuable for load following and ancillary services. Moderate round trip efficiency is balanced by the scale of the units in wholesale market operation.

5.2.5. System Capital Costs

Key drivers for CAES equipment costs are the compressor/expander, and the storage reservoir. Most designs look to leverage existing geological / man-made facilities, so their mostly fixed costs can be leveraged with larger sizes.

The equipment cost for traditional CAES systems is not expected to change dramatically over the forecast due to the more mature nature of the technology.

Potentially significant improvements in future capital cost reductions of traditional compressed air energy storage systems are limited, but external forces will impact the design. The technology will continue to benefit from the advancing technology level of gas turbine technology, so there are expectations for a consistent level of cost reduction and capability improvement over the forecast.

Table 5-5. Compressed Air Energy Storage (CAES) 2020 Installed System Costs

Compressed Air Energy Storage (CAES) - 2020					
$/kW	Size (MW)				
	100	10	1	0.1	0.01
CAES: 8+ Hr	1369.1				

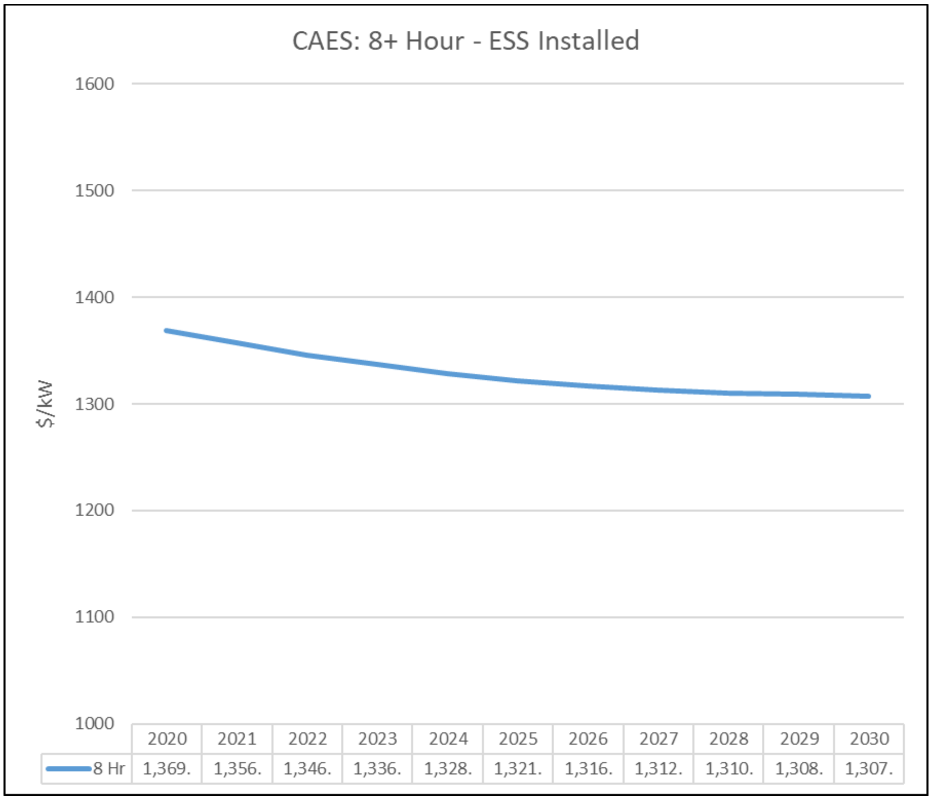


Figure 5-5. Compressed Air Energy Storage (CAES) System Price Forecast

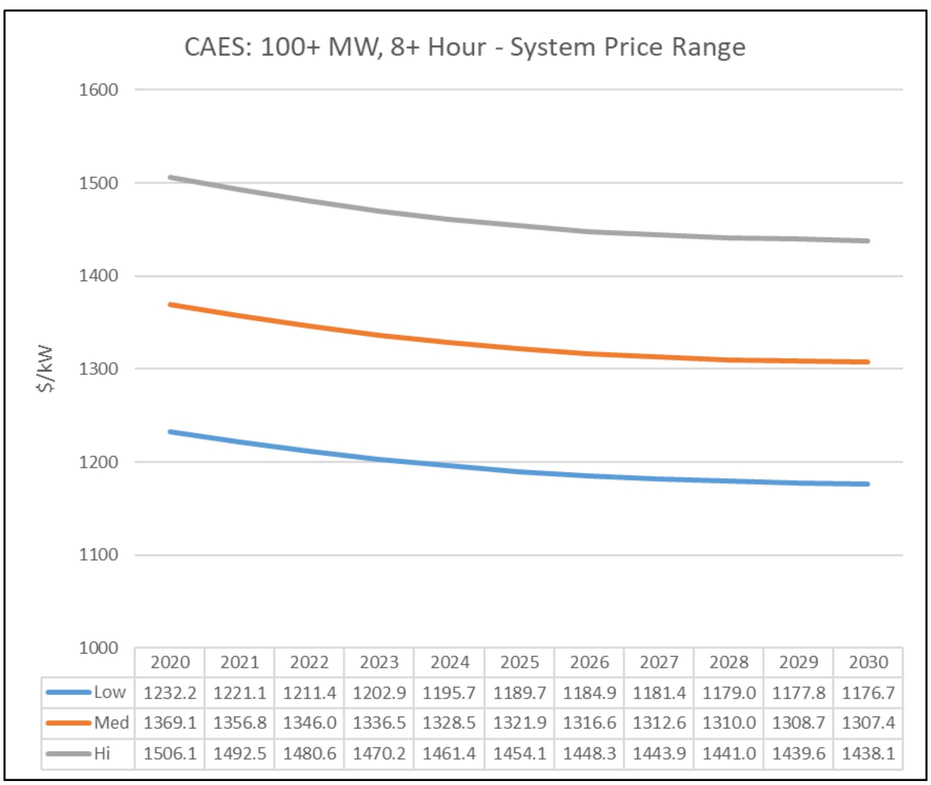


Figure 5-6. Compressed Air Energy Storage (CAES) System Price Range

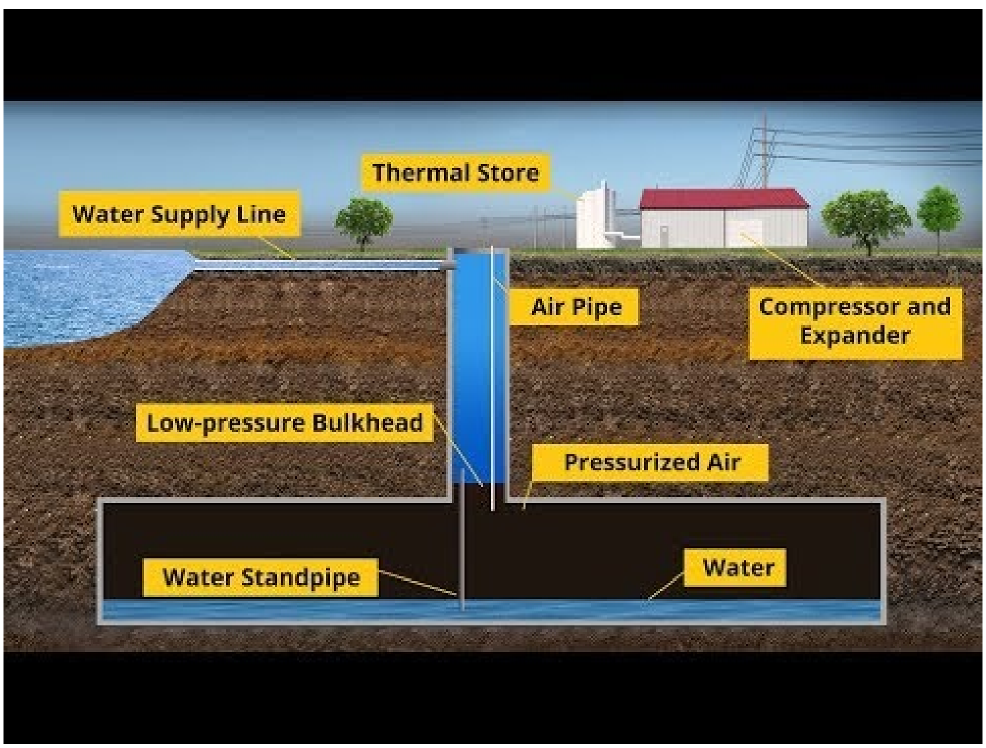
5.3. Advanced Compressed Air Energy Storage (ACAES)

Capital costs for advanced compressed air energy storage (ACAES) systems are provided in $/kW for the energy storage pricing survey because the majority of the costs are associated with the power rating of the facility. Depending on the market use of the facility, a set of small or large air reservoirs could be used for the same powertrain equipment, skewing the more common $/kWh pricing metric for energy storage technologies. The ACAES technology is similar to the CAES technology, but does not use natural gas, eliminating that cost component.

5.3.1. Technology Description & System Design

ACAES facilities use off-peak power to drive a compressor to pressurize air into a reservoir, which can then be released through an expander during peak hours to drive a generator to produce power. A key difference with CAES systems is that the ACAES does not use natural gas in a combustor stage, allowing the ACAES to operate fuel free.

Potentially, advanced compressed air energy storage facilities could be sized anywhere from the 10's to 100's of MWs, depending on the compressor / expander power train used. The discharge duration can also range from a few to more than 10 hours, depending on the reservoir. Reservoirs can either be salt caverns, aquifers, dedicated hard rock mines or above ground storage tank.



Source: Hydrostor, Inc.

Figure 5-7. Advanced Compressed Air Energy Storage (CAES) System Design

5.3.2. Deployment Options

ACAES system deployment is determined by the available location of the particular storage reservoir option. Lower cost options utilize natural geological features like aquifers, hard rock mines, salt caverns, or conversely, man-made surface tank storage.

5.3.3. Operating Characteristics

The round-trip efficiency of advanced compressed air energy storage facilities is determined by the efficiency of the compressor/generator, and friction losses stemming from driving the air into the typically underground cavern. Although there is not additional natural gas input during power generation, RTE levels are comparable to CAES technologies, with estimates ranging around 70%, with expectation for slight improvements as the technology matures.

Advanced compressed air energy storage systems do not experience significant degradation in either their power or energy rating over time during operation. Their ability to store and retrieve energy is based on the motor generators in the power train and the storage capability of air chamber does not experience significant reduction over time. This allows compressed air energy storage systems to operate repeatedly, cycling energy through the system without worry of degradation that occurs from cell-based energy storage. As with many rotating machines, efficiency can decline over time, but not significantly if operated and maintained in good working order.

The cycle life of these units is based on mature compressor and expanders industrial machinery industry, providing these systems with a very mature technology base from which to operate. Generally, the lifespan is counted along the lines of a similarly sized a power generating facility of a number of decades.

Table 5-6. Advanced Compressed Air Energy Storage (ACAES) System Performance Characteristics

Advanced Compressed Air Energy Storage (ACAES) System Performance Characteristics	
Lifespan:	30 Yrs.
Round-Trip Efficiency (AC):	70%
Operating Range (Depth of Discharge %):	100%
Capacity at End of Life (% of Original):	100%
Operation & Maintenance (O&M):	1-2%

5.3.4. Applications

Due to their physical size, advanced compressed air energy storage facilities would be active primarily in the wholesale power market, providing both energy and ancillary services. Depending on the design, it is possible to have a separate compressor and expander, or a combined one. If separate, the unit could operate akin to the CAES system, allowing both charging and discharging from the facility if market roles promote this.

Advanced compressed air energy storage systems are designed for long duration storage, with reliable, long-calendar year lifespan. Variable output makes these systems valuable for load following and ancillary services. Moderate round trip efficiency is balanced by the scale of the units in wholesale market operation.

5.3.5. System Capital Costs

Key drivers for ACAES equipment costs are the compressor/expander, and the storage reservoir. Most designs look to leverage existing geological or man-made facilities, so their mostly fixed costs can be leveraged with larger sizes.

The equipment cost for ACAES systems are expected to experience some sustained price reduction as although the base technology comes from mature industrial markets, the integration in the ACAES is still early. Therefore, there are cost reduction opportunities in the integration arena.

Potentially significant improvements in future capital cost reductions of traditional compressed air energy storage systems are limited, but external forces will impact the design. The technology will continue to benefit from the advancing technology level of compressor / expander technology, so there are expectations for a consistent level of cost reduction and capability improvement over the forecast.

Table 5-7. Advanced Compressed Air Energy Storage (CAES) 2020 Installed System Costs

Advanced Compressed Air Energy Storage (ACAES) - 2020					
$/kW	Size (MW)				
	100	10	1	0.1	0.01
ACAES: 8+ Hr	1727.8				

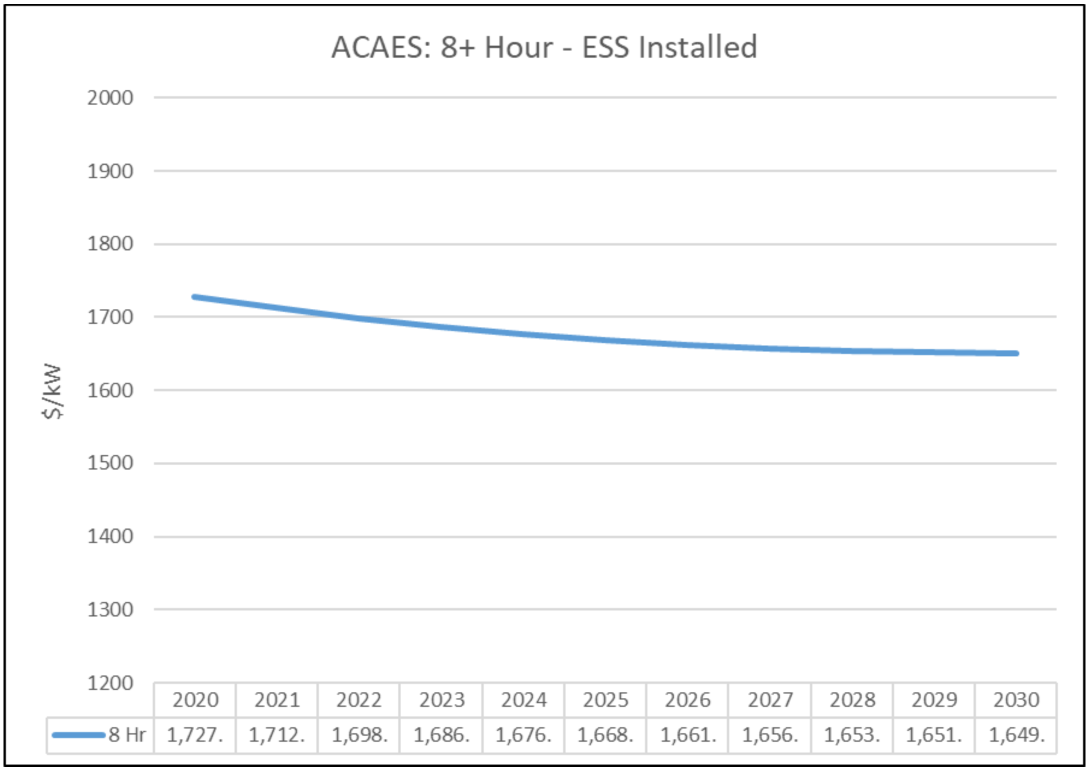


Figure 5-8. Advanced Compressed Air Energy Storage (ACAES) System Price Forecast

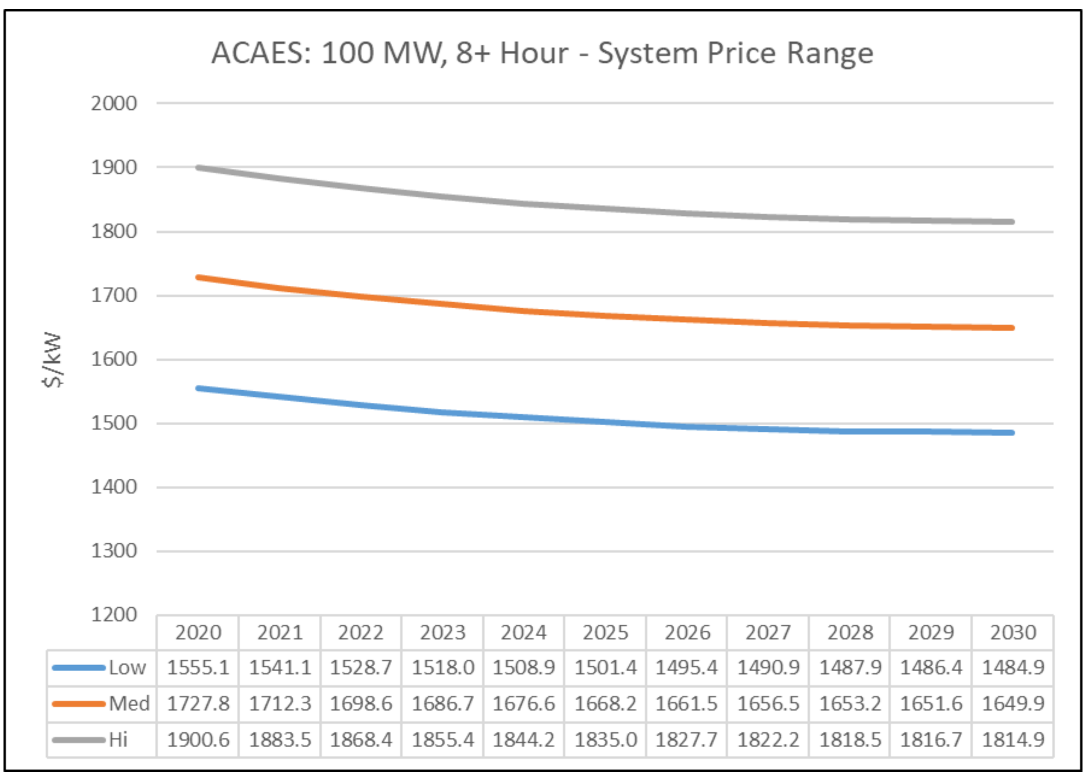


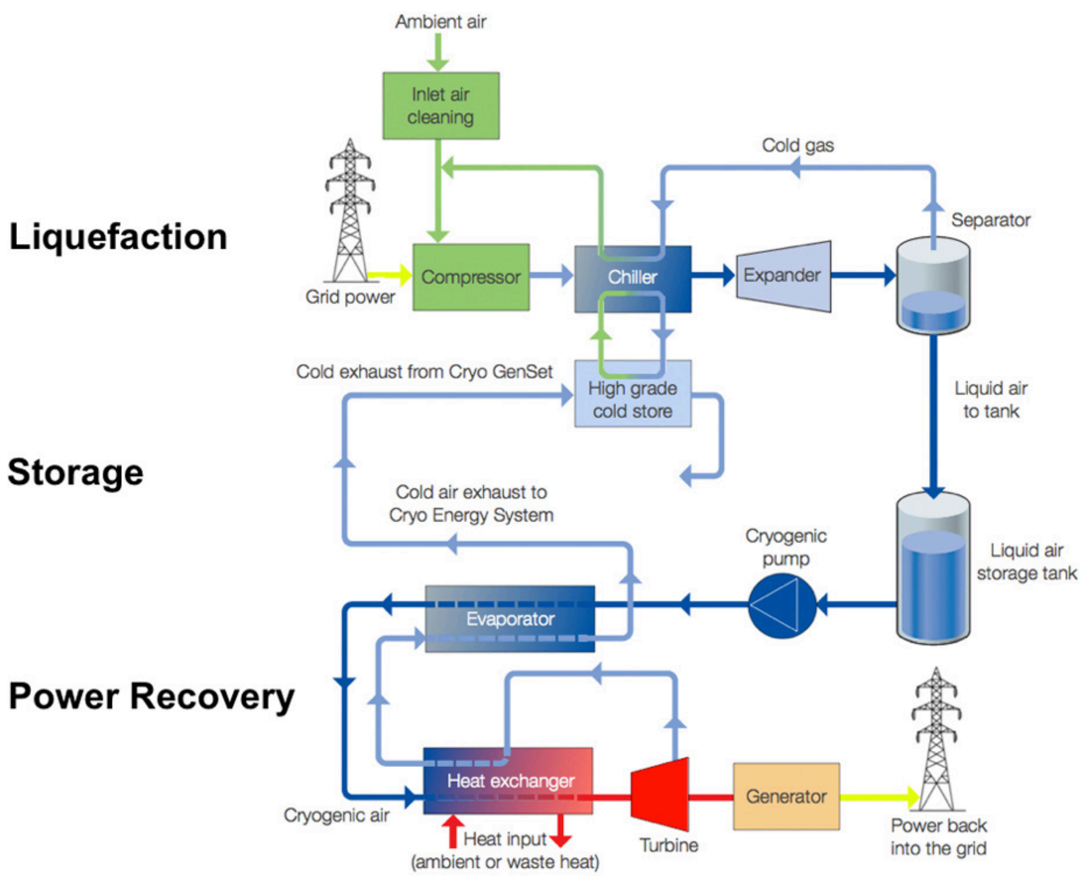
Figure 5-9. Compressed Air Energy Storage (CAES) System Price Range

5.4. Liquid Air Energy Storage (LAES)

Capital costs for liquid air energy storage (LAES) systems are provided in $/kWh as the system is specifically designed to allow for long duration operation. Even though the central charging/discharging equipment can be expensive on a $/kW basis, the technology is specifically designed for storage and cycling of large amounts of energy. Depending on the market use of the facility, a set of small or large air reservoirs could be used for the same powertrain equipment, skewing the more common $/kWh pricing metric for energy storage technologies.

5.4.1. Technology Description & System Design

LAES facilities utilize the advancements in cryogenics to store energy through converting air from a gas to a liquid state. These systems lean heavily on the advancements made in large scale chemical processes and turbomachinery--both mature technologies. Typically, liquid air energy storage facilities can be sized anywhere from the 10's to 100's of MWs. The discharge duration can also range from a few to more than 10 hours, depending on need. For LAES systems, the size of the cryogenic tanks is the aspect of the system that most impacts the storage costs of the facility for the $/kWh metric.



Source: Highview Power Storage

Figure 5-10. Liquid Air Energy Storage (LAES) System Design

5.4.2. Deployment Options

LAES system can be deployed at the developer's discretion as the storage medium is hosted in the cryogenic tanks onsite. Due to their physical size, liquid air energy storage facilities can be active in markets ranging from very large industrial facilities to the wholesale power market and can provide both energy and ancillary services support. The system's modular nature supports their ability to support the wide range of possible deployment options.

5.4.3. Operation

The round-trip efficiency of liquid air energy storage facilities is determined by the efficiency of the charging/discharging equipment.

Liquid air energy storage systems do not experience significant degradation in either their power or energy rating over time during operation. Their ability to store and retrieve energy is based on the motor generators in the power train and the storage capability of liquified air tanks does not experience significant reduction over time. This allows liquified air energy storage systems to operate repeatedly, cycling energy through the system without worry of degradation that occurs from cell-based energy storage. As with many rotating machines, efficiency can decline over time, but not significantly if operated and maintained in good working order.

The technology can have a wide operating efficiency range, depending on the amount of operation. Liquid air energy storage systems are designed for long duration storage, with reliable, long-calendar year lifespan. Variable output makes these systems valuable for load following and ancillary services. Moderate round trip efficiency is balanced by the scale of the units in wholesale market operation.

Table 5-8. Liquid Air Energy Storage (LAES) System Performance Characteristics

Liquid Air Energy Storage Performance Characteristics	
Lifespan:	30+ Yrs.
Round-Trip Efficiency (AC):	60-75%
Operating Range (Depth of Discharge %):	100%
Capacity at End of Life (% of Original):	100%
Operation & Maintenance (O&M):	1-2%

5.4.4. Applications

Due to their power and energy ratings, liquified energy storage facilities would be active primarily in the wholesale power market, providing both energy and ancillary services. Because the evaporator and condenser are on separate loops, it is possible for the unit to both charge and discharge at the same time if market roles promote this.

Liquid air energy storage systems are based on modular design that can allow for long duration storage, with reliable, long-calendar year lifespan. Variable output makes these systems valuable for load following and ancillary services. With the ability to scale the energy reservoir with a limit scale expansion of the tankage, this unit can provide significant amounts of power and energy storage in a condensed industrial site.

5.4.5. System Capital Costs

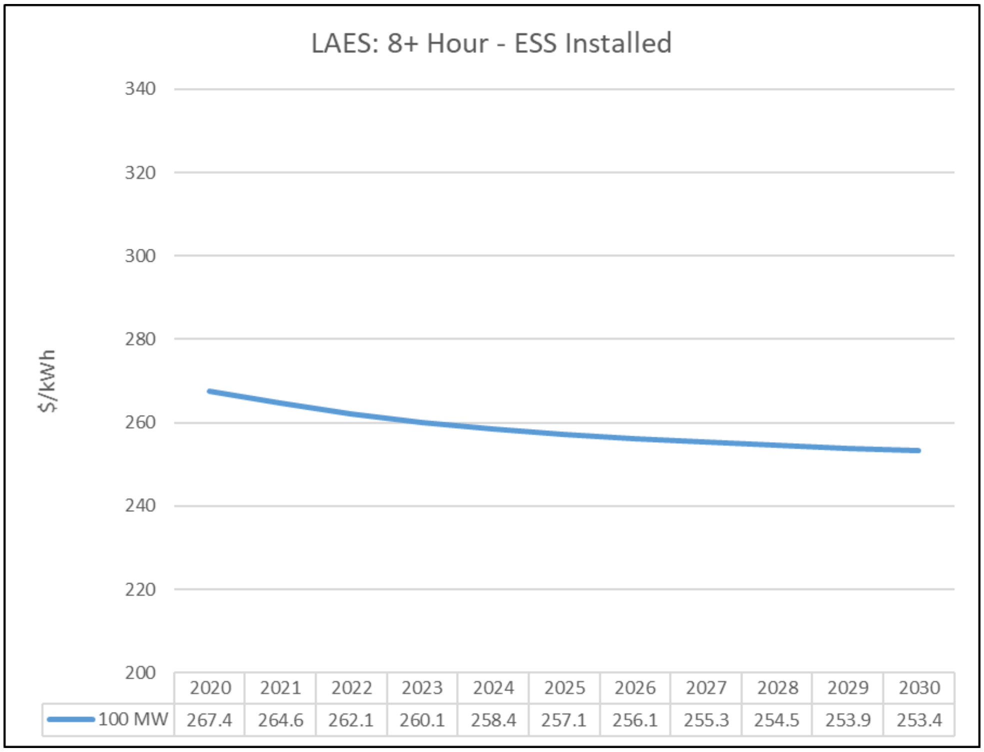
Key drivers for LAES equipment costs are the integrated storage facility and cryogenic storage technology. Most designs have a modular condenser / evaporator powertrain, so larger energy storage capacity can lower energy storage costs (on a $/kWh ratio) through additional tankage deployment.

The equipment cost for liquid air energy storage systems has the opportunity to experience some sustained cost reductions as the technology gains experience from deployment and operation.

Potential significant improvements in future capital cost reductions of Liquid Air Energy Storage systems are expected to only be moderate as the components of the systems are mature, but the integration promotes some areas for cost and design reduction.

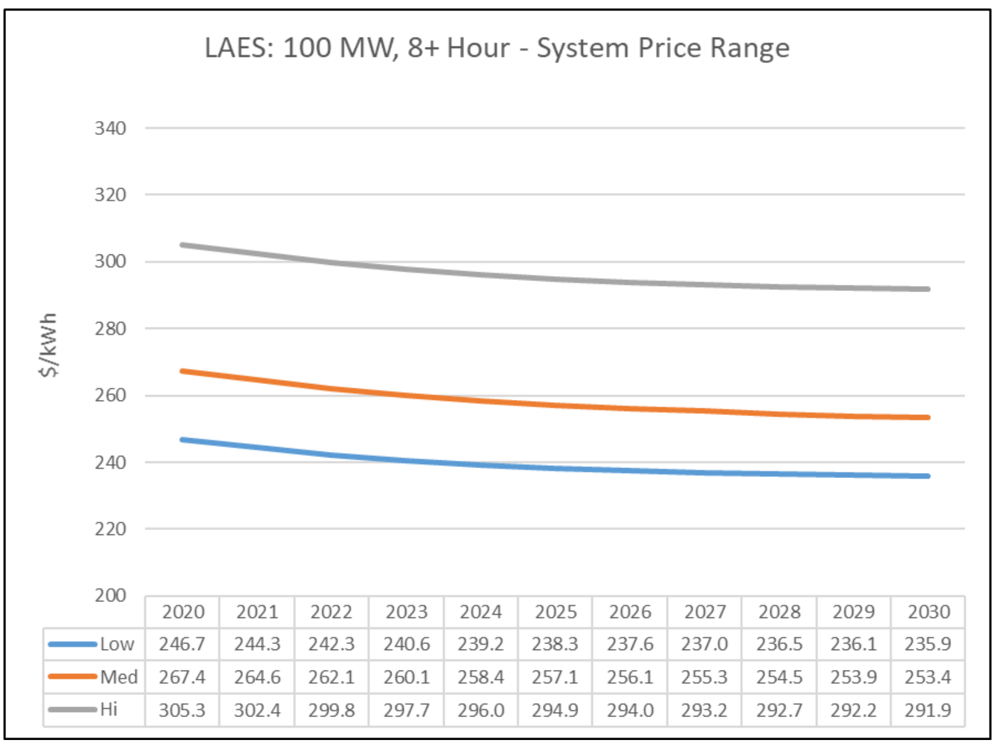
Table 5-9. Advanced Compressed Air Energy Storage (CAES) 2020 Installed System Costs

Liquid Air Energy Storage (LAES) - 2020					
$/kWh	Size (MW)				
	100	10	1	0.1	0.01
LAES: 8+ Hr	267.4				



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
100 MW	267.4	264.6	262.1	260.1	258.4	257.1	256.1	255.3	254.5	253.9	253.4

Figure 5-11. Liquid Air Energy Storage (LAES) System Price Forecast



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low	246.7	244.3	242.3	240.6	239.2	238.3	237.6	237.0	236.5	236.1	235.9
Med	267.4	264.6	262.1	260.1	258.4	257.1	256.1	255.3	254.5	253.9	253.4
Hi	305.3	302.4	299.8	297.7	296.0	294.9	294.0	293.2	292.7	292.2	291.9

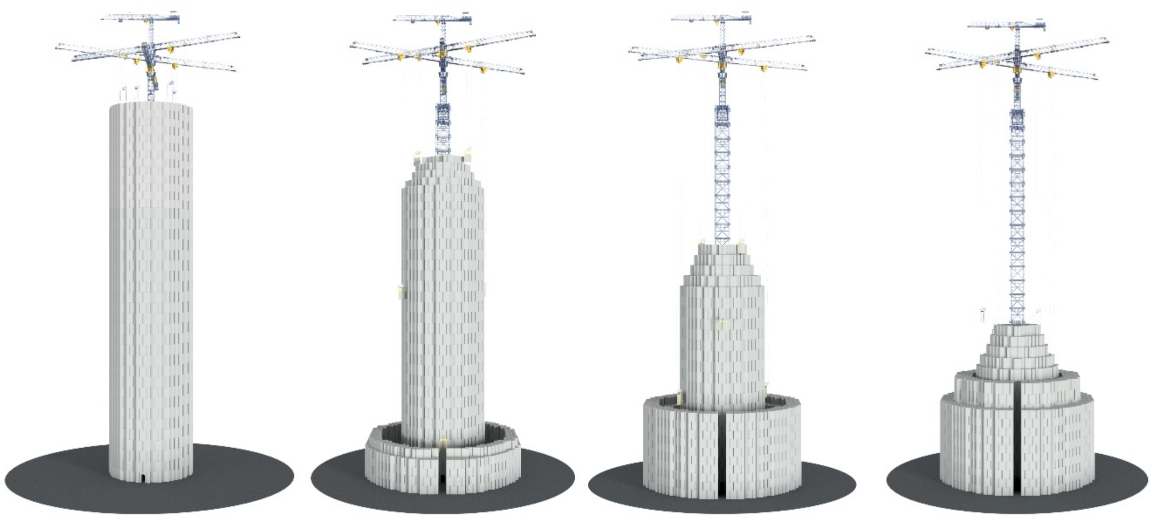
Figure 5-12. Liquid Air Energy Storage (LAES) System Price Range

5.5. Gravity Energy Storage (GES)

Capital costs for gravity energy storage (GES) systems are provided in $/kWh for the energy storage pricing survey as although the majority of the costs are associated with the power aspect of the technology, the ability to shift the mass from different states gives the technology. Depending on the market use of the facility, a standardized set of motor/generators could be used to provide a wide range of storage capacity, depending on the distance moved lending to the use of the $/kWh pricing metric.

5.5.1. Technology Description & System Design

GES system store energy through the movement of a mass from a lower to a higher position. The conversion of the electrical power into potential power allows these systems to either be focused on long duration energy storage, or ancillary services for the wholesale power market, depending on the rate of power charging in the system. Gravity energy storage systems can be sized anywhere from the 10’s to 100's of MWs. The discharge duration can also range from less than an hour to more than 10 hours, based on the technology used, and the response time required depending on need.



Source: Energy Vault

Figure 5-13. Gravity Energy Storage (GES) System Design

5.5.2. Deployment Options

For GES systems, the size and the elevation difference of the difference where the mass travels are aspect of the system that most impacts the storage costs of the facility. GES deployment options are typically defined by the type of storage approach. If utilizing natural height variability, then a sloping ground is typically required. If utilizing artificial height differentials, then the GES facility has a wider latitude of deployment options. Due to their physical size, gravity energy storage facilities are active primarily in the wholesale power market, providing both energy and power products and services.

5.5.3. Operation

The round-trip efficiency of gravity energy storage facilities is significantly impacted by the method of energy conversion, and the friction losses stemming from the physical design and layout of the facility.

Gravity energy storage systems do not experience significant degradation in either their power or energy rating over time during operation. Their ability to store and retrieve energy is based on the motor generators in the power train and the storage capability of moving mass does not experience any reduction over time. This allows gravity energy storage systems to operate repeatedly, cycling energy through the system without worry of degradation that occurs from cell-based energy storage. As with many rotating machines, efficiency can decline over time, but not significantly if operated and maintained in good working order.

Table 5-10. Gravity Energy Storage (GES) System Performance Characteristics

Gravity Energy Storage Characteristics	
Lifespan:	30+ Yrs.
Round-Trip Efficiency (AC):	80-85%
Operating Range (Depth of Discharge %):	100%
Capacity at End of Life (% of Original):	100%
Operation & Maintenance (O&M):	1-2%

5.5.4. Applications

Gravity energy storage systems can be designed for short to long duration storage, with reliable, long-calendar year lifespan. Variable output makes these systems valuable for load following and ancillary services. Moderate round trip efficiency is balanced by the scale of the units in wholesale market operation.

5.5.5. System Capital Costs

Key drivers for GES equipment cost are typically the mechanical moving components. Generally, the energy storage medium itself is deigned to be as low cost as possible, hence very saleable.

The equipment cost for gravity energy storage systems has the opportunity to experience some sustained cost reductions as the technology gains experience from deployment and operation.

Potential significant improvements in future capital cost reductions of gravity energy storage systems are expected to only be moderate as the components of the system are mature, but the integration promotes some areas for cost and design reduction.

Table 5-11. Gravity Energy Storage (GES) 2020 Installed System Costs

Gravity Energy Storage (GES) - 2020					
$/kWh	Size (MW)				
	100	10	1	0.1	0.01
GES: 8+ Hr	358.8				

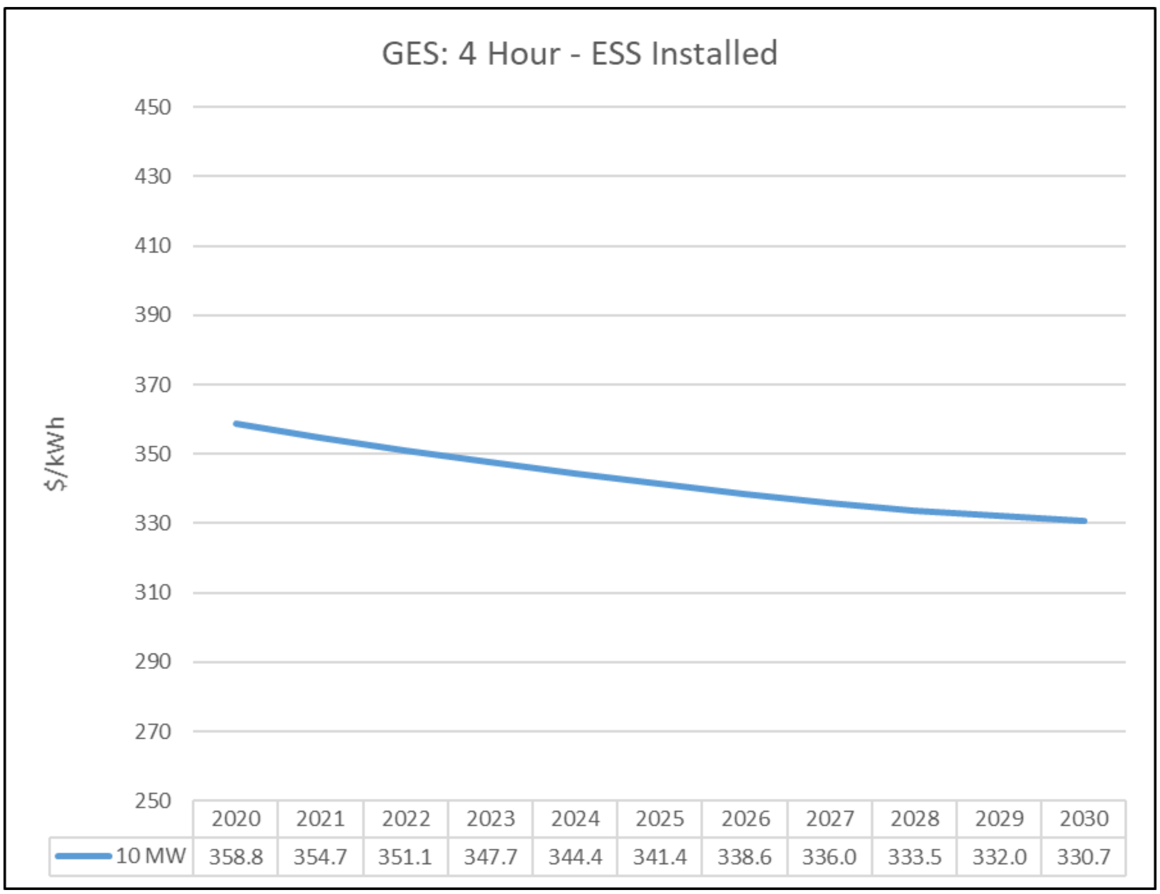
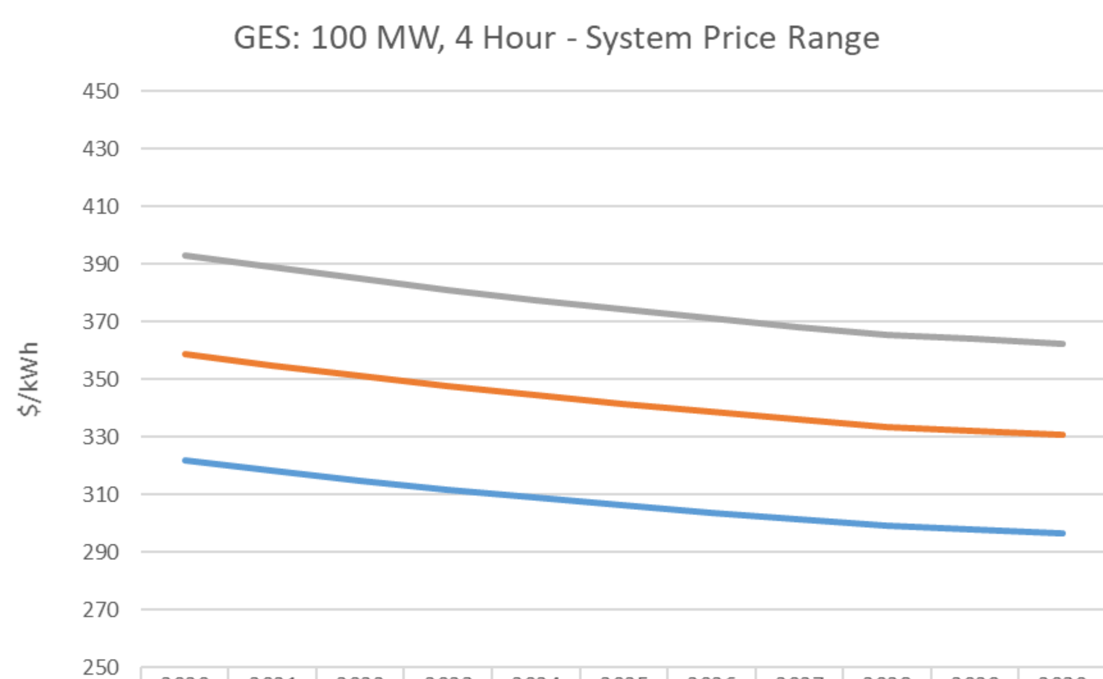


Figure 5-14. Gravity Energy Storage (GES) System Price Forecast



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low	321.8	318.1	314.9	311.8	308.9	306.2	303.7	301.3	299.1	297.7	296.5
Med	358.8	354.7	351.1	347.7	344.4	341.4	338.6	336.0	333.5	332.0	330.7
Hi	393.3	388.8	384.8	381.1	377.5	374.2	371.1	368.2	365.6	363.9	362.4

Figure 5-15. Gravity Energy Storage (GES) System Price Range

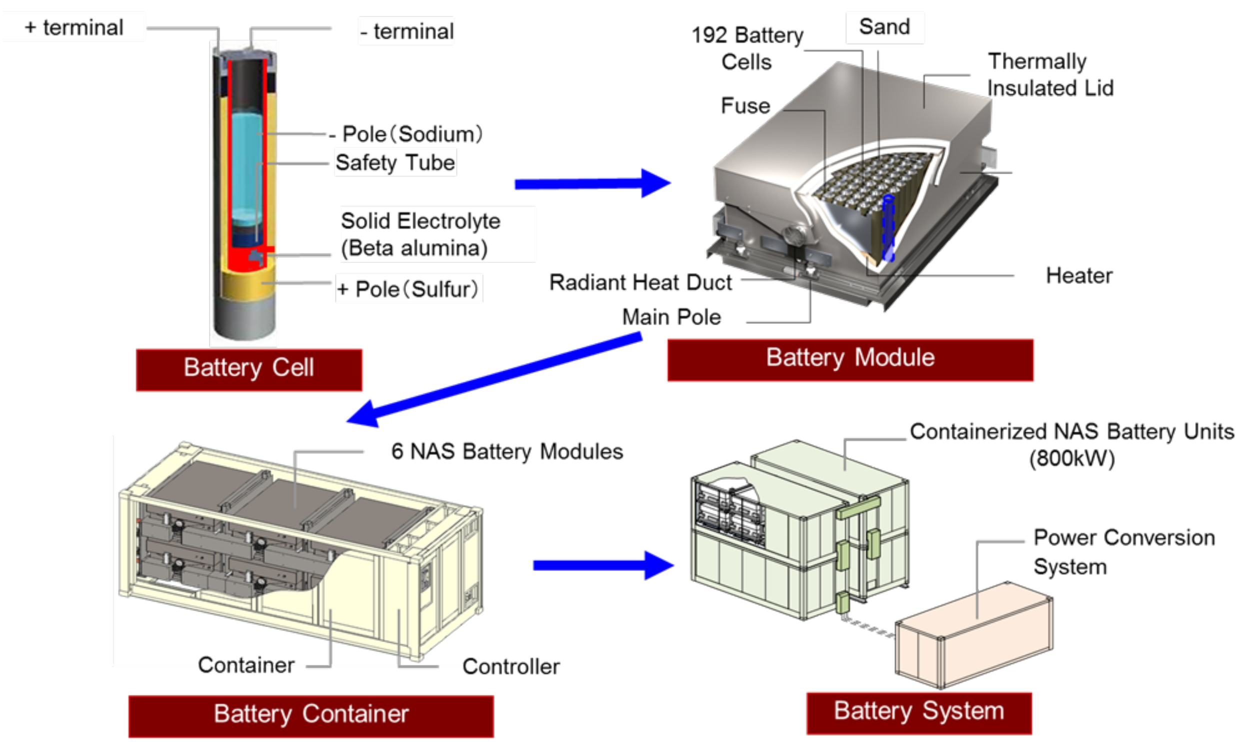
5.6. Sodium (Na)

Capital costs for sodium (Na) energy storage systems are provided in $/kWh for the energy storage pricing survey as the value of the technology is tied to the amount of energy the system is able to store and discharge as other cell-based technologies. In addition, the majority of the active ingredients in the cell chemistry are designed to maximize the storage of energy.

5.6.1. Technology Description & System Design

The sodium technology with the most deployment is the sodium sulfur (NAS) which operates in a molten liquid state. The NAS battery cell is a cylindrical electrochemical cell with a molten sodium negative electrode in the center and a molten-sulfur positive electrode on the outside, separated from the negative electrode by the β-alumina solid electrolyte. As a cell-based system, the power and energy of each sodium battery is fixed.

Sodium system can be optimized for power or energy. Energy applications are more common, utilizing the chemistry's 6-hour discharge duration.



Source: NGK Insulators. LTD.

Figure 5-16. Sodium (Na) System Design

5.6.2. Deployment Options

Sodium battery systems are designed for outdoor deployment. Because of their molten nature, these battery systems are able to tolerate far higher ambient temperatures than other batteries. To ensure that the molten sodium electrode remains a liquid during stand-by periods, an accompanying heating system is coupled with the unit. This allows the system to operate in colder environments, but with some efficiency penalty.

5.6.3. Operation

The round-trip efficiency of the sodium sulfur battery is determined by the ability of the sodium-ion to transport through the separator, assisted by the molten temperature, which also produces significant parasitic losses. Sodium sulfur batteries provide a longer duration operation than some competing technologies, with the added ability to operate in higher temperature environments.

Sodium based energy storage systems experience some degradation in their energy storage capacity over time during operation. As a chemical cell-based energy storage system, sodium-based battery systems slowly degrade over time due to an accumulation of small but irreversible changes in the structure of the battery as the ions migrate back and for the from the cathode to the anode.

With lower than comparable cyclical cell degradation, the cycle life is higher than some other chemical batteries, generally using 15 years as an average operating lifespan. As with other chemical batteries, shallower discharges provide for a longer cycle life. Through an expected 15-year operational life, the degree of degradation for the NAS battery cell is highly related to the corrosion of the sulfur electrode.

Table 5-12. Sodium (Na) System Performance Characteristics

Sodium (Na) Performance Characteristics	
Lifespan:	15 Yrs.
Round-Trip Efficiency (AC):	75%
Operating Range (Depth of Discharge %):	100%
Capacity at End of Life (% of Original):	100%
Operation & Maintenance (O&M):	1-2%

5.6.4. Applications

NAS energy storage system can support a number of applications ranging from large commercial, to utility, and wholesale applications. Because of their longer duration of 6 hours, the market applications are geared more towards energy applications.

5.6.5. System Capital Costs

Key drivers for NAS equipment costs are the manufacture of the specialty cells, both process and materials. Without significant changes in design of the cells, manufacturing scale and lower cost material acquisition will be the key to continue lowering the cost of the equipment.

The equipment cost for existing NAS battery systems is not expected to change dramatically over the forecast due to the more mature nature of the technology.

Potential significant improvements in future capital cost reductions of sodium battery are only expected to be modest in the potential development of improved chemistry of the cell.

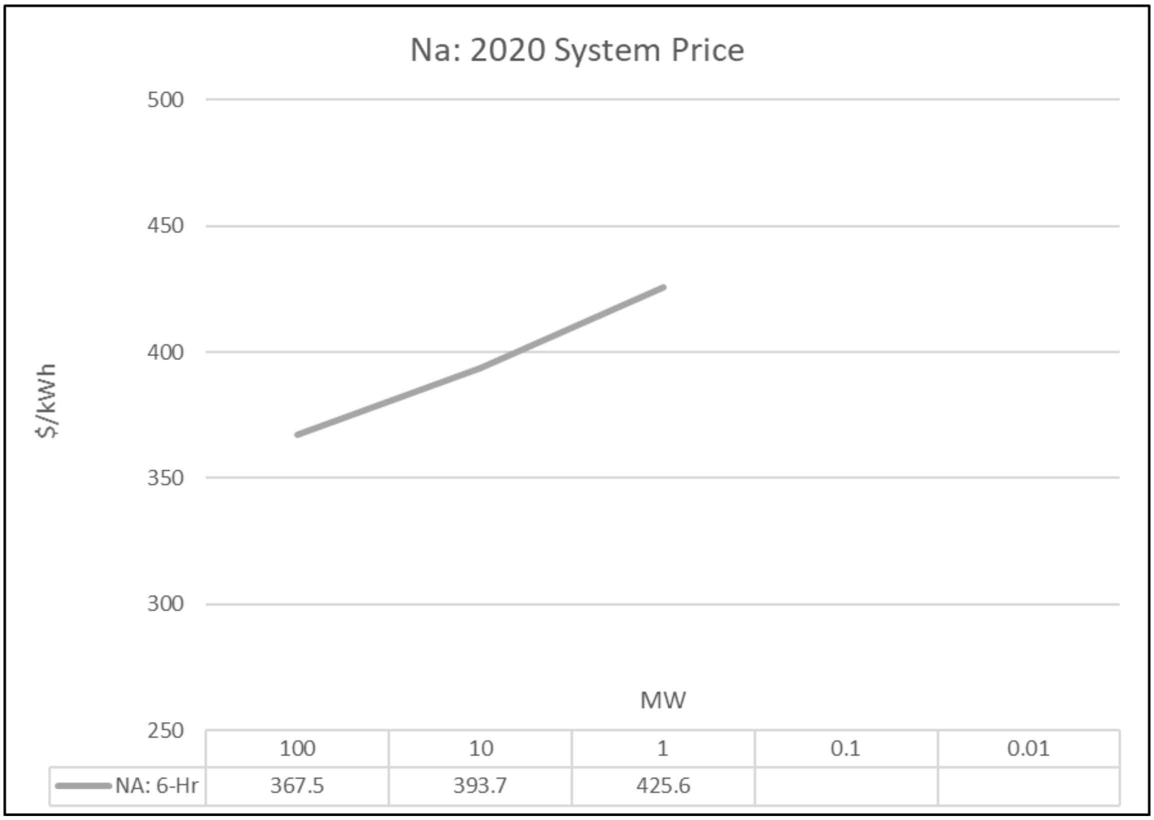
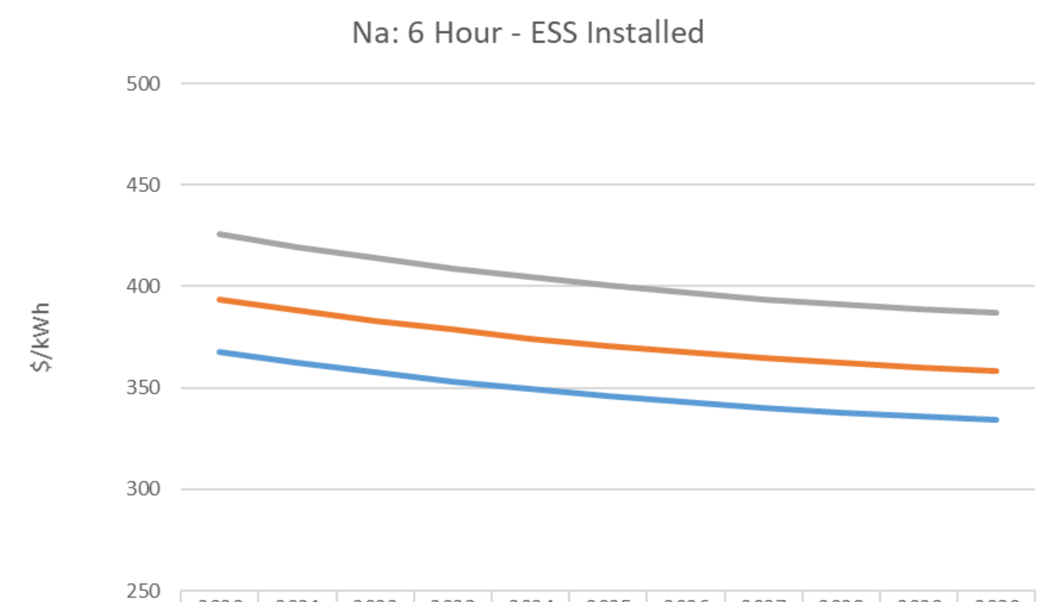
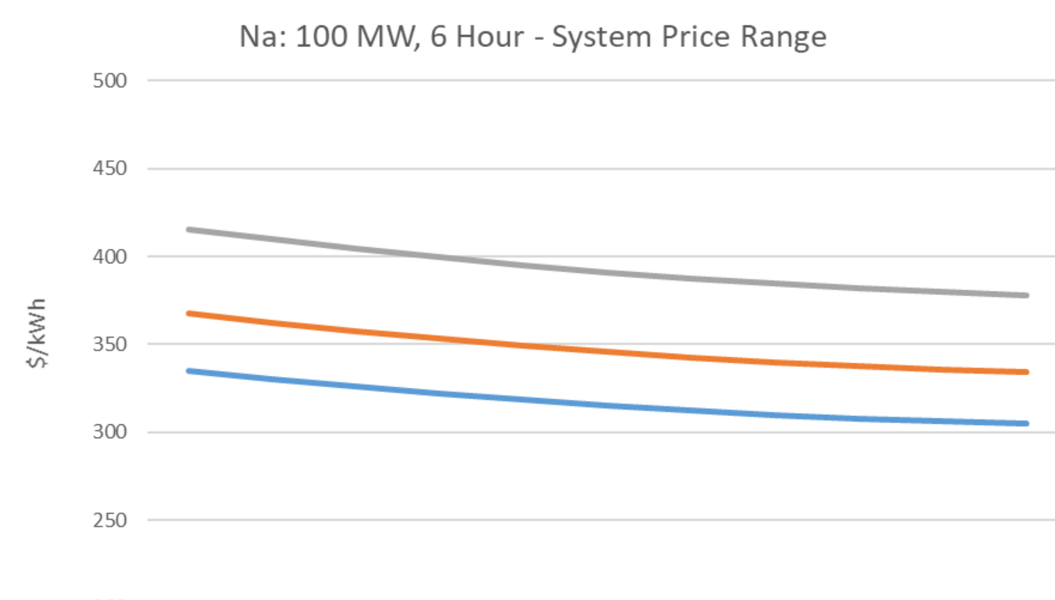


Figure 5-17. Sodium (Na) 2020 Installed System Costs



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
100 MW	367.5	362.3	357.6	353.2	349.3	345.9	342.8	340.1	337.8	335.9	334.3
10 MW	393.7	388.2	383.2	378.6	374.4	370.7	367.5	364.6	362.2	360.2	358.5
1 MW	425.6	419.6	414.1	409.0	404.4	400.4	396.9	393.7	391.1	388.9	387.0

Figure 5-18. Sodium (Na) System Price Forecast



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low	335.2	330.5	326.1	322.1	318.5	315.4	312.5	310.0	308.0	306.2	304.7
Med	367.5	362.3	357.6	353.2	349.3	345.9	342.8	340.1	337.8	335.9	334.3
Hi	415.4	409.6	404.3	399.4	395.0	391.1	387.7	384.6	382.1	379.9	378.1

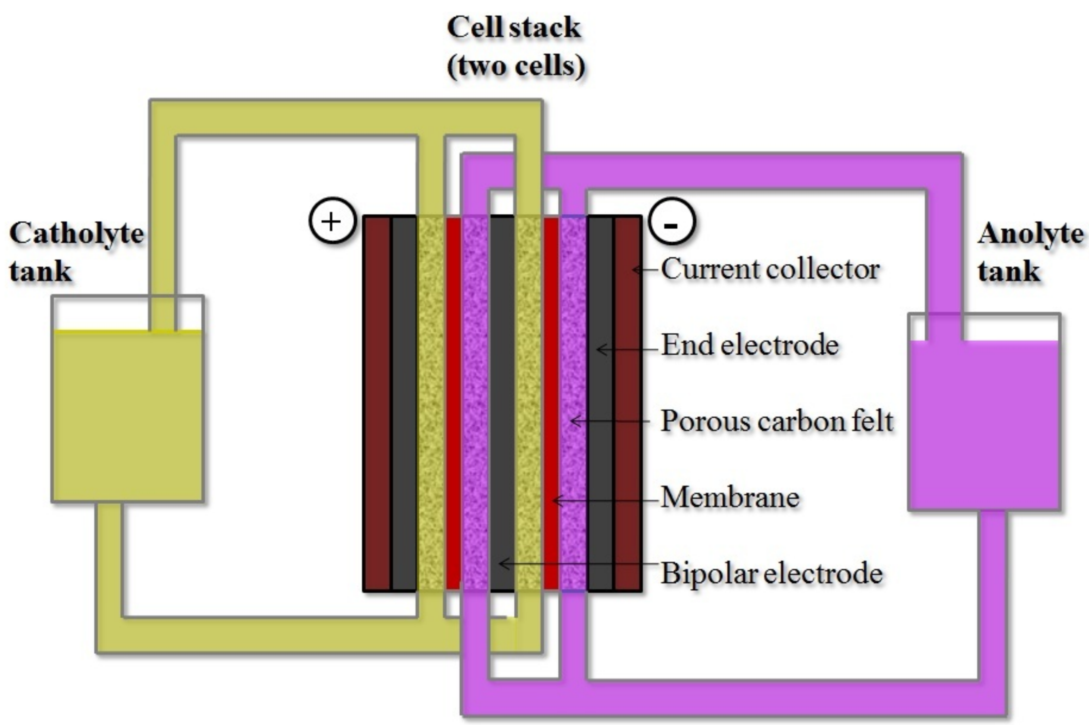
Figure 5-19. Sodium (Na) System Price Range

5.7. Flow Battery: Vanadium (FBV)

Capital costs for vanadium flow battery (FBV) systems are provided in $/kWh as the system is specifically designed to allow for longer duration operation. Even though the central charging/discharging equipment can be expensive on a $/kW basis, the technology is specifically designed for storage and cycling of large amounts of energy over the unit's long lifespan.

5.7.1. Technology Description $ System Design

Vanadium flow batteries are a liquid based energy storage system where the energy is storage in 2 closed loop systems with differently charged species of vanadium electrolytes. Vanadium flow batteries have the power and energy component separate, meaning that each can be scaled independently. For vanadium flow battery systems, the design allows for longer duration operation, significantly lowering the per kWh capital equipment costs.



Source: University New South Wales

Figure 5-20. Flow Battery: Vanadium (FBV) System Design

5.7.2. Deployment Options

Vanadium flow batteries are typically designed for outdoor deployment due to their size but can also be housed in purpose-built buildings as the system scales to multi-MW units. These systems are generally able to tolerate a wider range of ambient temperatures without suffering degradation. Vanadium flow batteries can operate across a number of applications, ranging from large commercial, to utility, and wholesale applications.

5.7.3. Operation

The round-trip efficiency of vanadium flow battery facilities is determined by the efficiency of the charging/discharging equipment, with a noticeable load from the pumps required to move the electrotypes through the system.

Vanadium flow batteries do not experience degradation in their energy storage capacity over time during operation. The energy storage capacity is based on the volume of anolyte and catholyte in the system. With regular maintenance to replace any lost material, the full energy storage capacity of the system can be maintained for the life of the system. Their ability to store and retrieve energy is based on the speed of the ion transfer across the separator membrane in the reaction chamber. The lifespan of the membrane material is designed for the life of the system. Combined, these attributes allow vanadium flow batteries to operate repeatedly, cycling significantly more energy through the system than for chemical cell-based storage systems.

The technology can have a wide operating efficiency range, depending on the usage profile.

Table 5-13. Flow Battery: Vanadium (FBV) System Performance Characteristics

Flow Battery: Vanadium Performance Characteristics	
Lifespan:	20 Yrs.
Round-Trip Efficiency (AC):	70-75%
Operating Range (Depth of Discharge %):	100%
Capacity at End of Life (% of Original):	100%
Operation & Maintenance (O&M):	2-3%

5.7.4. Applications

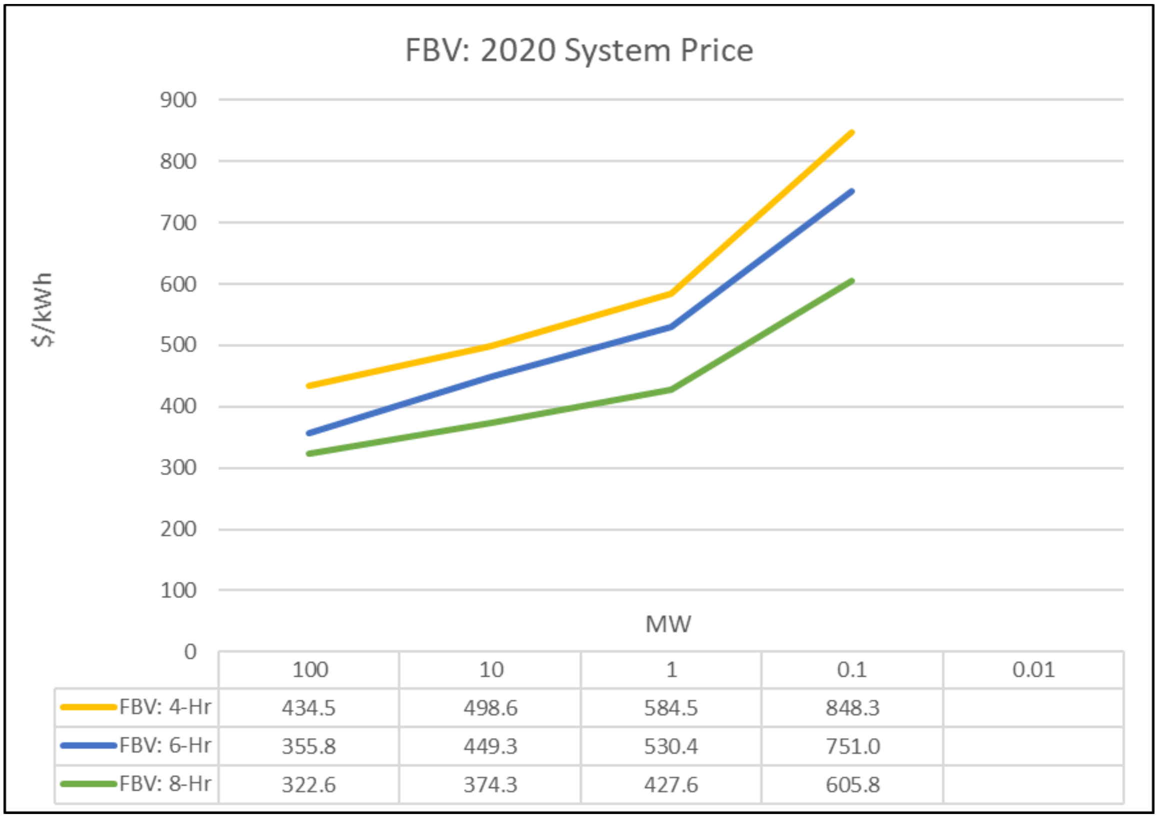
Vanadium flow batteries are designed for long duration storage, with reliable, long-calendar year lifespan. Variable output makes these systems valuable for load following and ancillary services. Moderate round trip efficiency is balanced by the scale of the units in wholesale market operation. Because of their ability to cycle large amounts of energy through the system, these systems are being extensively evaluated for utility reliability and renewable energy time shifting applications.

5.7.5. System Capital Costs

Key drivers for vanadium flow battery equipment costs are the cost of the stacks, and plumbing/piping for the electrolyte. Because vanadium can be expensive, some vanadium OEMs provide a means to lease the vanadium in the flow battery instead of buying it. This helps reduce the capital cost, by adding a relatively smaller leasing payment in the operating costs.

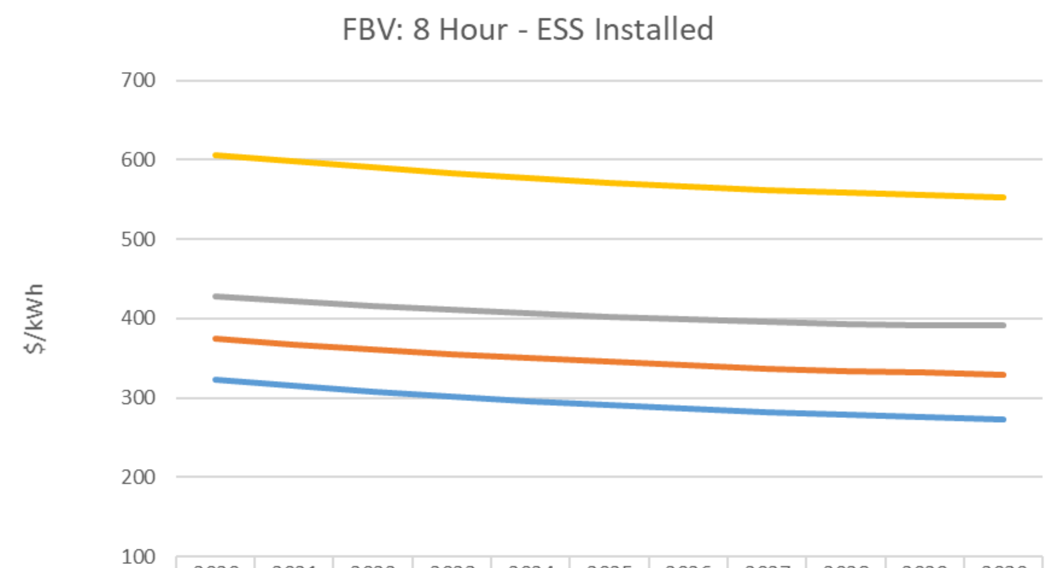
The equipment cost for vanadium flow battery technology has the potential for modest cost reductions over the forecast period.

Potential significant improvements in future capital cost reductions for vanadium flow batteries are possible through improved chemistry.



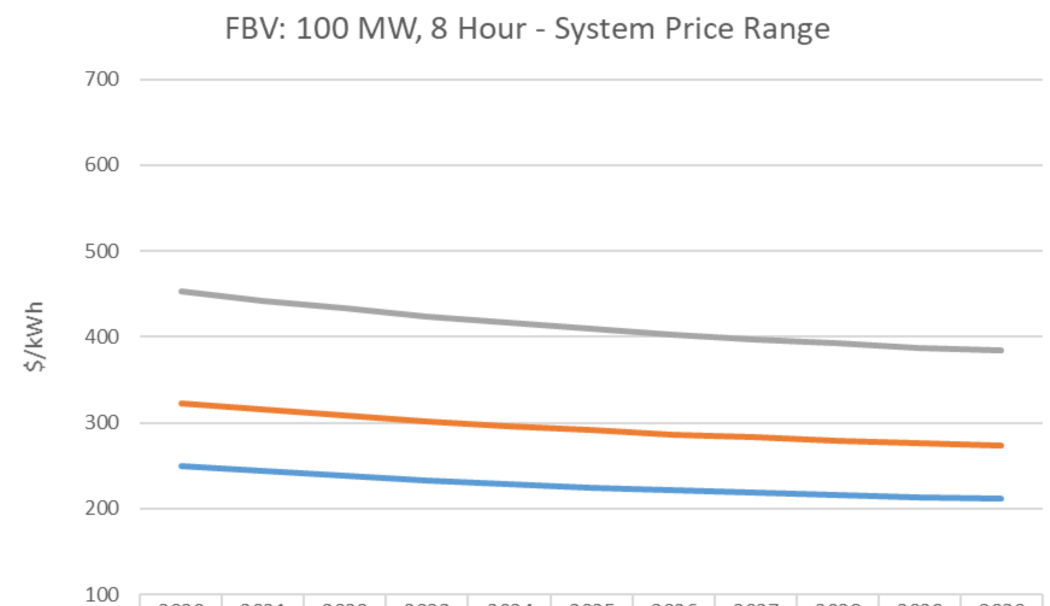
	100	10	1	0.1	0.01
FBV: 4-Hr	434.5	498.6	584.5	848.3	
FBV: 6-Hr	355.8	449.3	530.4	751.0	
FBV: 8-Hr	322.6	374.3	427.6	605.8	

Figure 5-21. Flow Battery: Vanadium (FBV) 2020 Installed System Prices



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
100 MW	322.6	315.1	308.3	302.0	296.3	291.3	286.7	282.7	279.2	276.1	273.4
10 MW	374.3	367.4	361.1	355.3	350.0	345.3	341.1	337.4	334.2	331.5	329.1
1 MW	427.6	421.6	416.1	411.0	406.5	402.5	398.9	395.8	393.1	390.9	390.8
0.1 MW	605.8	597.5	589.9	583.0	576.7	571.1	566.2	561.9	558.3	555.2	552.7

Figure 5-22. Flow Battery: Vanadium (FBV) System Price Forecast



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low	249.4	243.6	238.3	233.4	229.0	225.1	221.5	218.4	215.7	213.3	211.2
Med	322.6	315.1	308.3	302.0	296.3	291.3	286.7	282.7	279.2	276.1	273.4
Hi	452.8	442.4	432.8	424.1	416.1	409.1	402.7	397.0	392.1	387.8	384.1

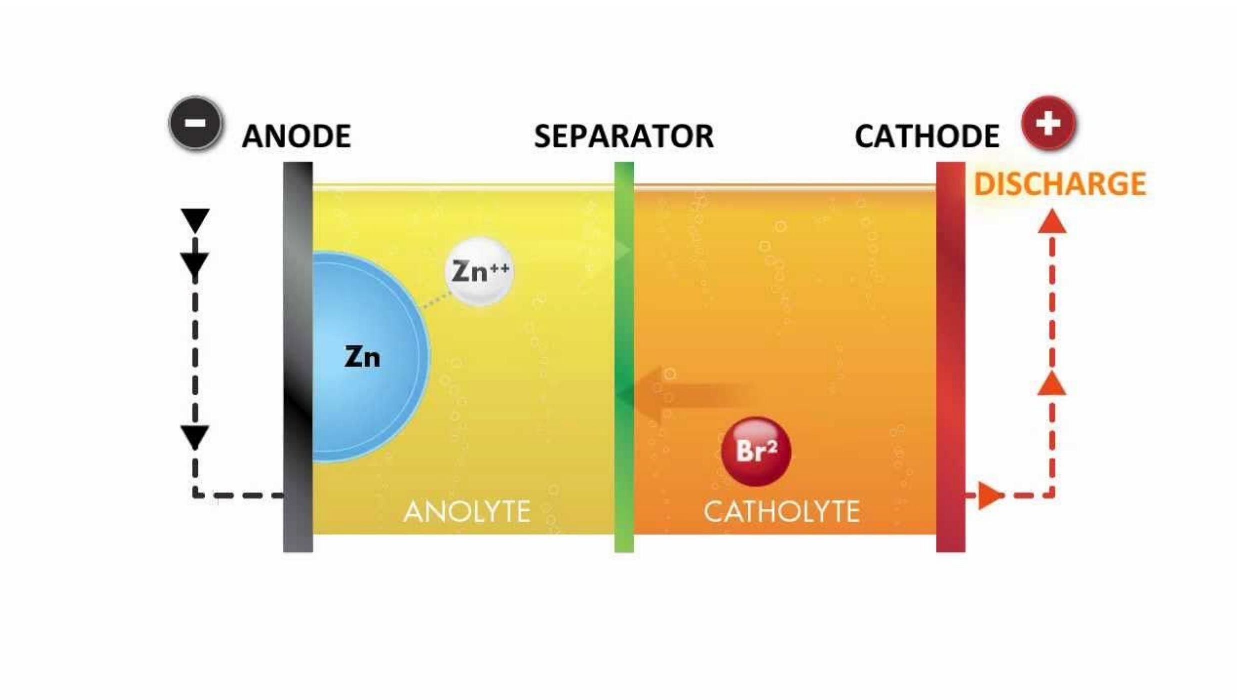
Figure 5-23. Flow Battery: Vanadium (FBV) System Price Range

5.8. Flow Battery: Zinc Bromide (FBZnBr)

Capital costs for zinc bromide (FBZnBr) flow batteries systems are provided in $/kWh as the system is specifically designed to allow for longer duration operation. Even though the central charging/discharging equipment can be expensive on a $/kW basis, the technology is specifically designed for storage and cycling of large amounts of energy over a long lifespan.

5.8.1. Technology Description & System Design

Zinc Bromide flow batteries store energy through the plating of zinc onto the anode. The zinc is held in solution and pumped through a reaction chamber. Since the operation of the flow battery pulls zinc out of solution, there is a finite amount of zinc that can be plated due to the dropping concentration of zinc in solution, and growing thickness of zinc while plating. For zinc bromide flow battery systems, the material selection and manufacturing process have the largest impact on the capital equipment costs.



Source: ZBB Energy

Figure 5-24. Flow Battery: Zinc Bromide (FBZnBr) System Design

5.8.2. Deployment Options

Zinc bromide flow batteries are designed for outdoor deployment. These systems are generally able to tolerate a wider range of ambient temperatures without suffering degradation. Zinc Bromide flow batteries can operate across a number of applications, ranging from large commercial, to utility, and off grid solar applications.

5.8.3. Operation

The round-trip efficiency of zinc bromide flow battery facilities is determined by the efficiency of the charging/discharging equipment, with a noticeable load from the pumps required to move the electrotypes through the system.

Zinc bromide flow batteries do not experience degradation in their energy storage capacity over time during operation. The energy storage capacity is based on the volume of anolyte and catholyte in the system. With regular maintenance to replace any lost material, the full energy storage capacity of the system can be maintained for the life of the system. The unit's ability to store and retrieve energy is based on the speed of the zinc to be deposited on the anode. The lifespan of the separator membrane material is designed for the life of the system. Combined, these attributes allow zinc bromide batteries to operate repeatedly, cycling significantly more energy through the system than for chemical cell-based storage systems.

The technology can have a wide operating efficiency range, depending on the amount of operation. Zinc bromide flow battery systems are designed for long duration storage, with reliable, long-calendar year lifespan. Variable output makes these systems valuable for load following and ancillary services. Moderate round trip efficiency is balanced by the scale of the units in wholesale market operation.

Table 5-14. Flow Battery: Zinc Bromide (FBZnBr) System Performance Characteristics

Flow Battery: Zinc Bromide Performance Characteristics	
Lifespan:	20 Yrs.
Round-Trip Efficiency (AC):	70%
Operating Range (Depth of Discharge %):	100%
Capacity at End of Life (% of Original):	100%
Operation & Maintenance (O&M):	2-3%

5.8.4. Applications

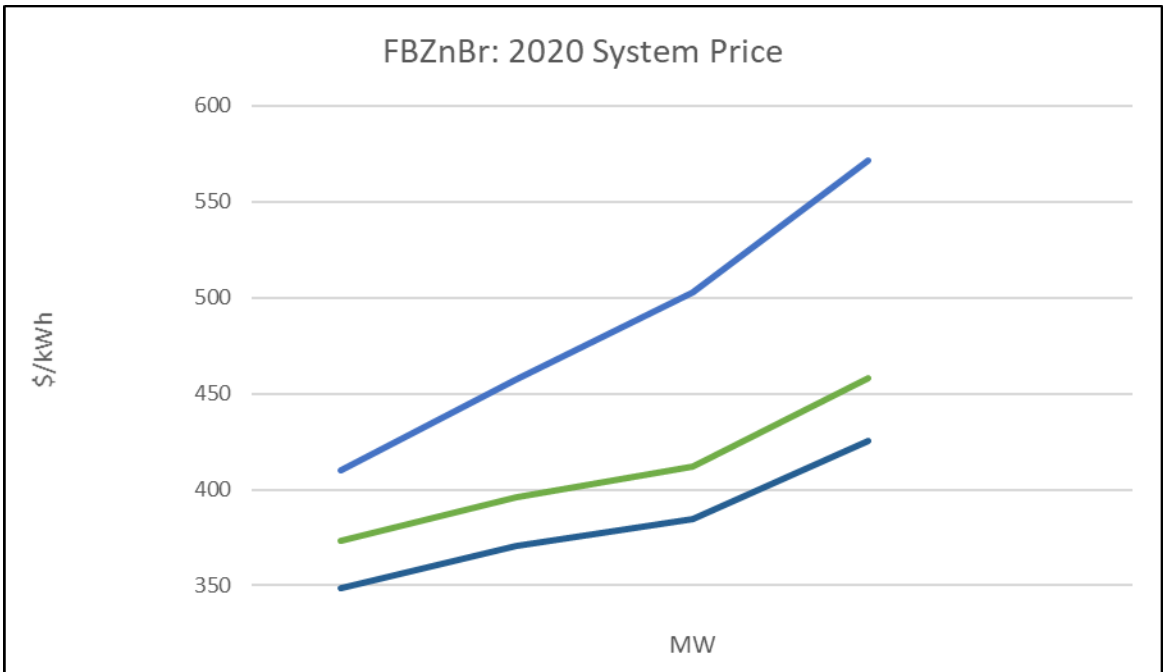
Zinc Bromide flow batteries are designed for long duration storage, with reliable, long-calendar year lifespan. Variable output makes these systems valuable for load following and ancillary services. Moderate round trip efficiency is balanced by the scale of the units in wholesale market operation. Because of their ability to cycle large amounts of energy through the system, these systems are being extensively evaluated for utility reliability and renewable energy time shifting applications.

5.8.5. System Capital Costs

Key drivers for zinc bromide flow battery equipment costs are the cost of the reaction stacks, and plumbing/piping for the electrolyte. Overall manufacturing cost reduction, scale, and material sourcing advances are the key avenues for continued cost reductions.

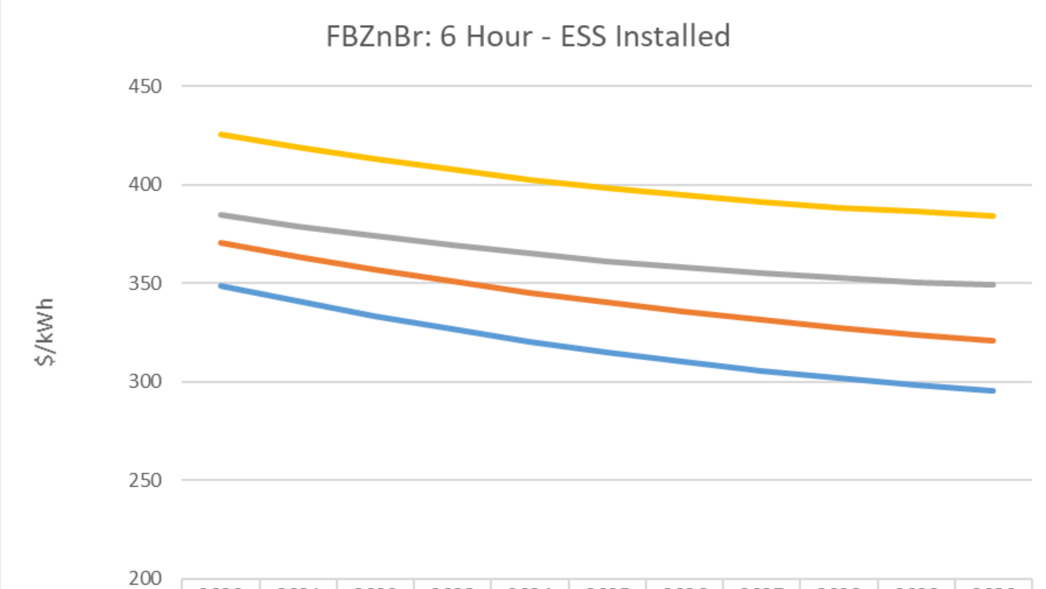
The equipment cost for zinc bromide flow battery technology has the potential for modest cost reductions over the forecast period.

Potential significant improvements in future capital cost reductions for zinc bromide flow batteries are possible through improved chemistry.



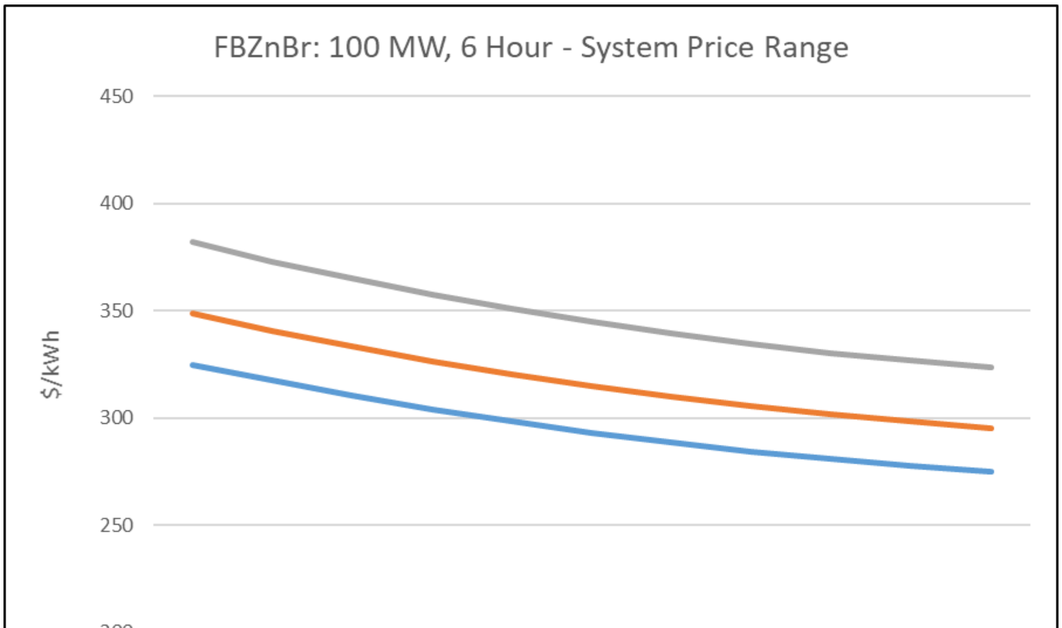
	100	10	1	0.1	0.01
FBZnBr: 4-Hr	410.3	457.3	502.8	571.6	
FBZnBr: 5-Hr	373.4	396.3	411.9	457.9	
FBZnBr: 6-Hr	348.8	370.3	384.4	425.5	

Figure 5-25. Flow Battery: Zinc Bromide (FBZnBr) 2020 Installed System Price



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
100 MW	348.8	340.7	333.3	326.5	320.3	314.8	309.8	305.4	301.6	298.3	295.4
10 MW	370.3	363.3	356.8	350.8	345.1	340.1	335.4	331.1	327.4	323.9	320.9
1 MW	384.4	378.9	373.8	369.2	364.9	361.2	358.0	355.0	352.7	350.6	348.9
100 kW	425.5	419.1	413.1	407.6	402.6	398.4	394.6	391.2	388.5	386.1	384.2

Figure 5-26. Flow Battery: Zinc Bromide (FBZnBr) System Price Forecast



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low	325.0	317.5	310.5	304.2	298.4	293.3	288.7	284.6	281.0	277.9	275.2
Med	348.8	340.7	333.3	326.5	320.3	314.8	309.8	305.4	301.6	298.3	295.4
Hi	382.0	373.1	365.0	357.6	350.8	344.8	339.4	334.6	330.4	326.8	323.6

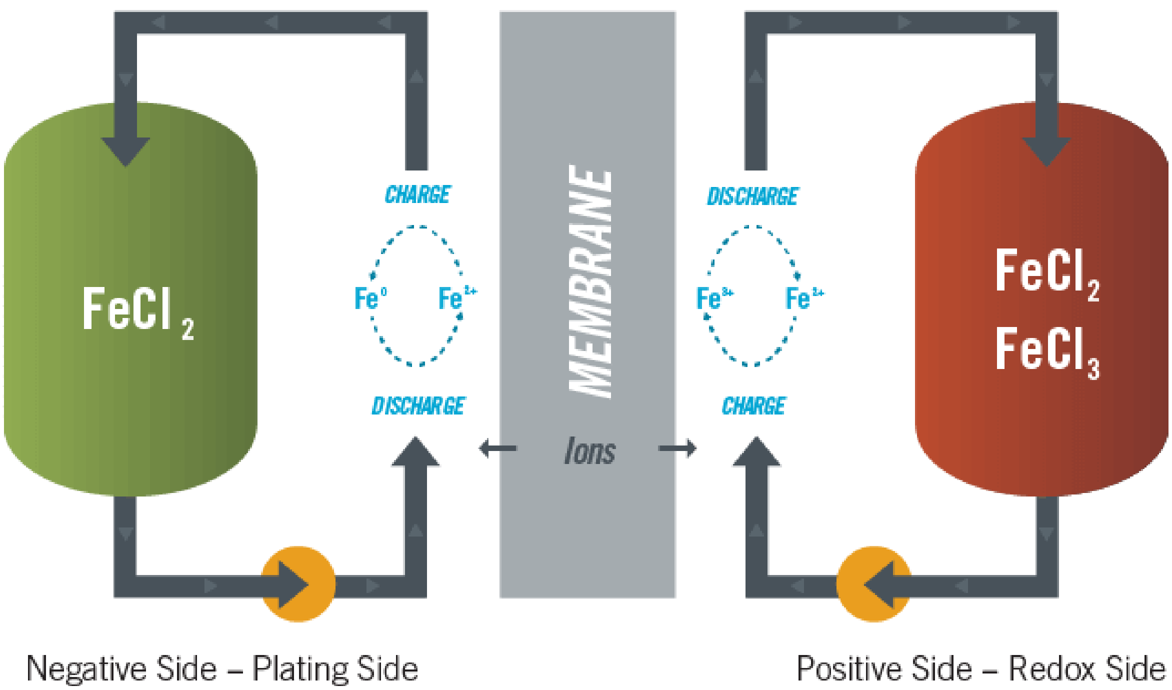
Figure 5-27. Flow Battery: Zinc Bromide (FBZnBr) System Price Range

5.9. Flow Battery: Iron (FBFe)

Capital costs for iron flow battery (FBFe) systems are provided in $/kWh as the system is specifically designed to allow for longer duration operation. Even though the central charging/discharging equipment can be expensive on a $/kW basis, the technology is specifically designed for storage and cycling of large amounts of energy across the unit's long operating life.

5.9.1. Technology Description & System Design

Iron flow batteries are a liquid based energy storage system where the energy is storage in 2 closed loop systems utilizing iron chloride for charge storage. Iron flow batteries have the power and energy component separate, meaning that each can be scaled independently. For iron flow battery systems, the design allows for longer duration operation, significantly lowering the per kWh capital equipment costs.



Source: ESS, Inc.

Figure 5-28. Flow Battery: Iron (FBFe) System Design

5.9.2. Deployment Options

Iron flow batteries are designed for outdoor deployment. These systems are generally able to tolerate a wider range of ambient temperatures without suffering degradation. Iron flow batteries can operate across a number of applications, ranging from large commercial, to utility, and wholesale applications.

5.9.3. Operation

The round-trip efficiency of iron flow battery facilities is determined by the efficiency of the charging/discharging equipment, with a noticeable load from the pumps required to move the electrotypes through the system.

Iron flow batteries do not experience degradation in their energy storage capacity over time during operation. The energy storage capacity is based on the volume of anolyte and catholyte in the system. With regular maintenance to replace any lost material, the full energy storage capacity of the system can be maintained for the life of the system. Their ability to store and retrieve energy is based on the speed of the ion transfer across the separator membrane in the reaction chamber. The lifespan of the membrane material is designed for the life of the system. Combined, these attributes allow iron flow batteries to operate repeatedly, cycling significantly more energy through the system than for chemical cell-based storage systems.

Table 5-15. Flow Battery: Iron (FBFe) System Performance Characteristics

Flow Battery: Iron Performance Characteristics	
Lifespan:	20 Yrs.
Round-Trip Efficiency (AC):	70%
Operating Range (Depth of Discharge %):	100%
Capacity at End of Life (% of Original):	100%
Operation & Maintenance (O&M):	2-3%

5.9.4. Applications

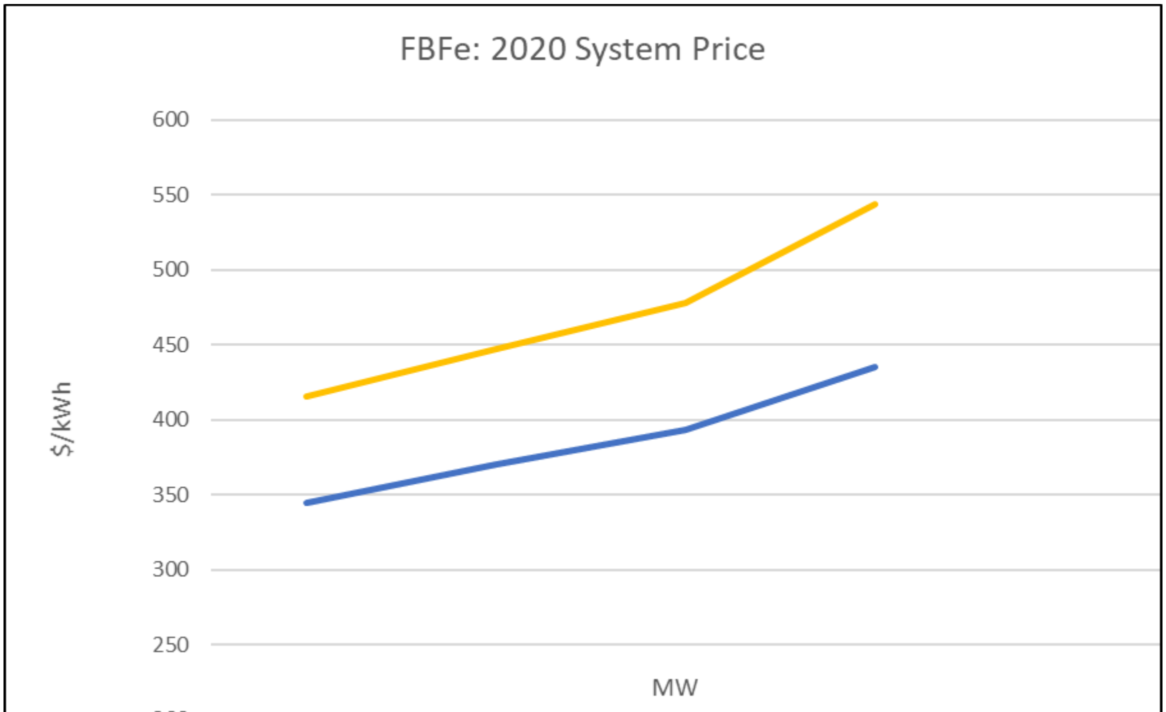
Iron flow battery systems are designed for long duration storage, with reliable, long-calendar year lifespan. Variable output makes these systems valuable for load following and ancillary services. Moderate round trip efficiency is balanced by the scale of the units in wholesale market operation. Because of their ability to cycle large amounts of energy through the system, these systems are being extensively evaluated for utility reliability and renewable energy time shifting applications.

5.9.5. System Capital Costs

Key drivers for iron flow battery equipment costs are the cost of the stacks, and plumbing/piping for the electrolyte. Manufacturing cost reduction, scale, and material sourcing advances are the key avenues for continued cost reductions.

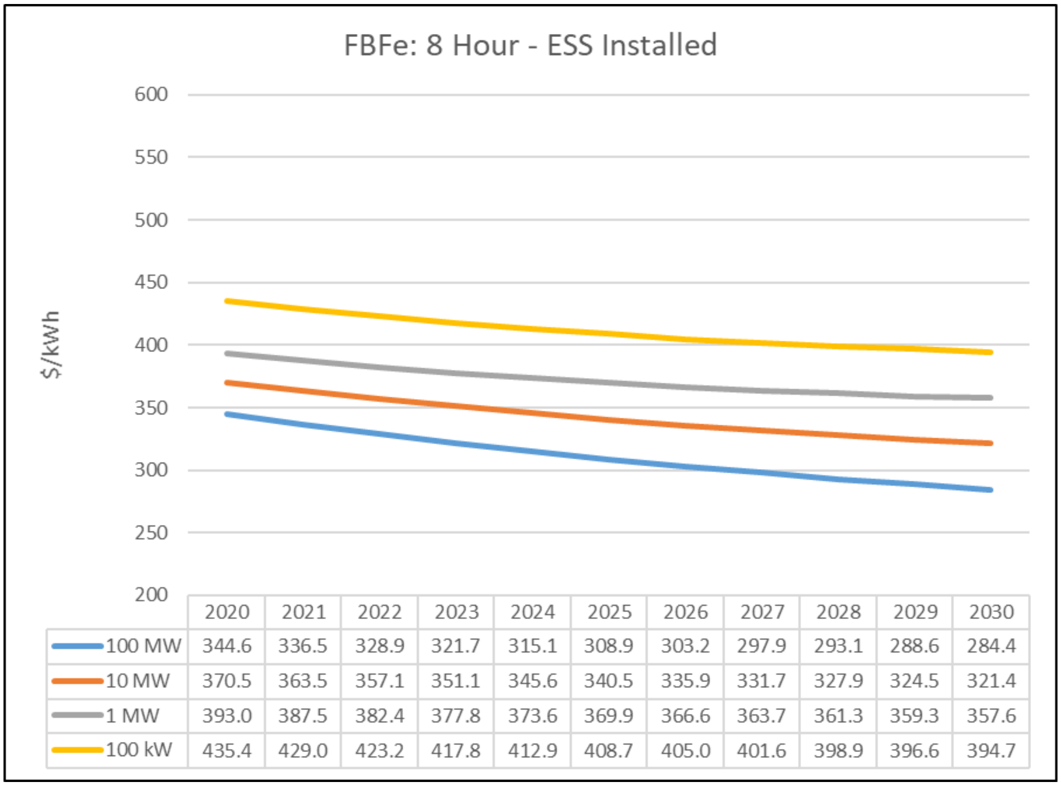
The equipment cost for iron flow battery technology has the potential for modest cost reductions over the forecast period.

Potential significant improvements in future capital cost reductions for iron flow batteries are possible through improved chemistry.



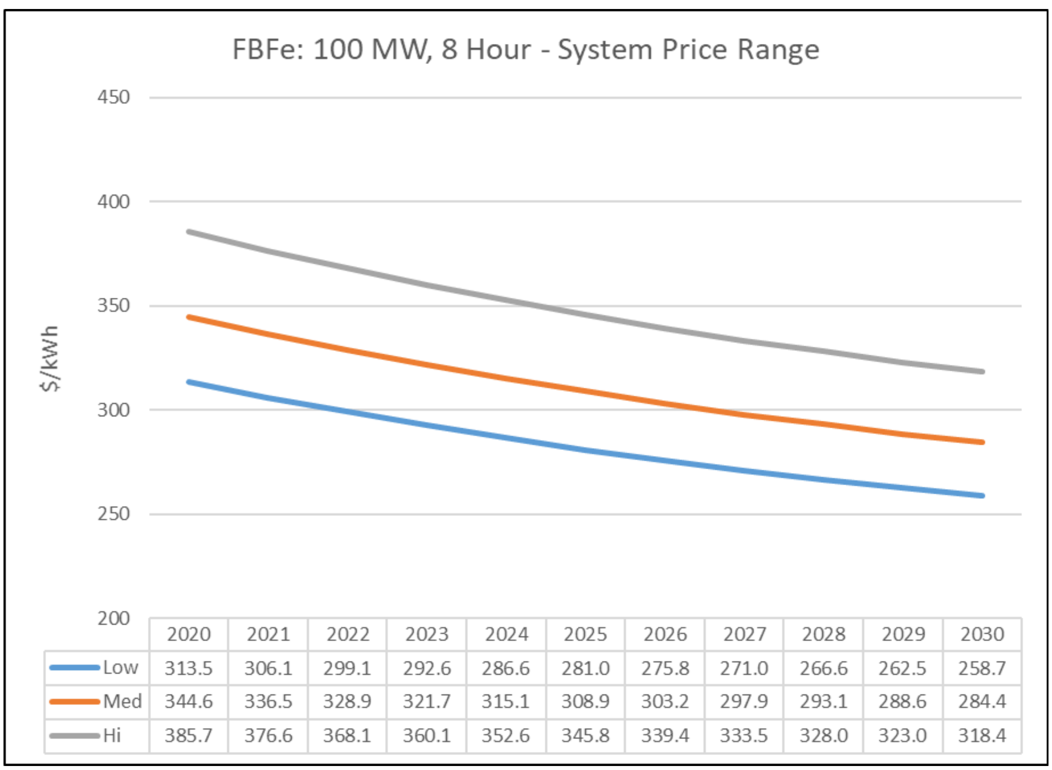
	100	10	1	0.1	0.01
FBFe: 4-Hr	415.7	446.9	478.0	543.6	
FBFe: 8-Hr	344.6	370.5	393.0	435.4	

Figure 5-29. Flow Battery: Iron (FBFe) 2020 System Price Forecast



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
100 MW	344.6	336.5	328.9	321.7	315.1	308.9	303.2	297.9	293.1	288.6	284.4
10 MW	370.5	363.5	357.1	351.1	345.6	340.5	335.9	331.7	327.9	324.5	321.4
1 MW	393.0	387.5	382.4	377.8	373.6	369.9	366.6	363.7	361.3	359.3	357.6
100 kW	435.4	429.0	423.2	417.8	412.9	408.7	405.0	401.6	398.9	396.6	394.7

Figure 5-30. Flow Battery: Iron (FBFe) System Price Forecast



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low	313.5	306.1	299.1	292.6	286.6	281.0	275.8	271.0	266.6	262.5	258.7
Med	344.6	336.5	328.9	321.7	315.1	308.9	303.2	297.9	293.1	288.6	284.4
Hi	385.7	376.6	368.1	360.1	352.6	345.8	339.4	333.5	328.0	323.0	318.4

Figure 5-31. Flow Battery: Iron (FBFe) System Price Range

5.10. Flywheel: Long Duration (FWLD)

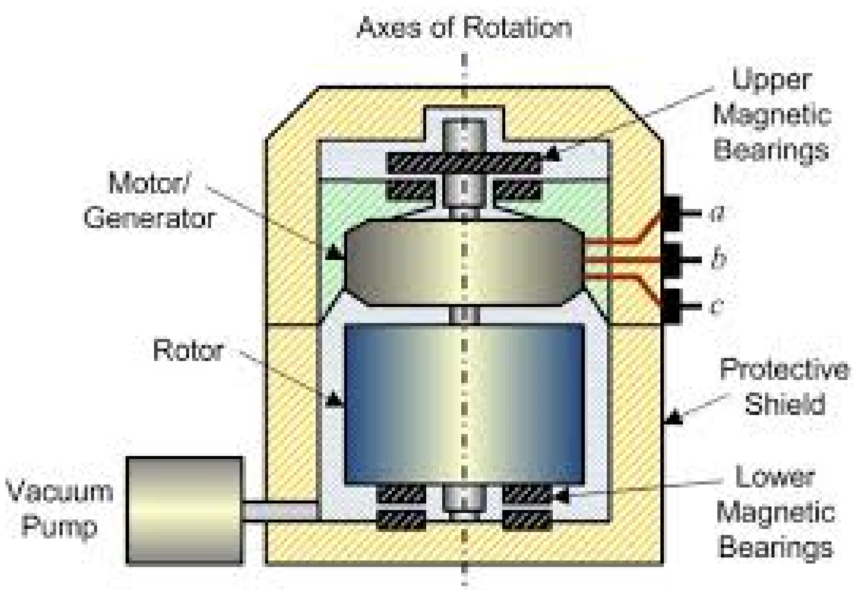
Capital costs for long duration flywheel (FWLD) energy storage systems are provided in $/kWh because their primary application is as a battery replacement, and thus using the same pricing metric is critical.

5.10.1. Technology Description & System Design

Flywheels store energy through rotational energy—spinning a mass to high speed and using a motor generator to inject and withdraw power. The energy stored is linear with the mass of the spinning rotor, and the square of the surface speed. Long duration flywheels are designed to operate with the focus on storing energy sufficient to discharge over a number of hours. Long duration flywheels are typically designed with multiple hours of duration to replicate battery systems. For long duration flywheel energy storage systems, the hub/rotor system able to support the maximum energy storage of the unit has the largest impact on the capital equipment costs.

Typical long duration flywheel systems utilize a magnetically levitated rotor spinning in a vacuum, so there is little loss from the system during rest. Because energy is stored mechanically and not chemically, flywheels are able to charge and discharge at very high rates or power without damaging unit.

Even though the central charging/discharging equipment can be expensive on a $/kW basis, the technology is specifically designed for storage and cycling of large amounts of energy over a long lifespan.



Source: Amber Kinetics, Inc.

Figure 5-32. Flywheel: Long Duration (FWLD) System Design

5.10.2. Deployment Options

Long duration flywheel systems can support either indoor or outdoor deployment depending on scale of the individual units. These systems are generally able to tolerate a wider range of ambient temperatures without suffering degradation.

Because of the safety factor dealing with high-speed rotating machines, each individual flywheel has a containment vessel in the event of failure. When the flywheels scale to a larger size, many developers have installed the units underground for additional safety precautions.

5.10.3. Operation

The round-trip efficiency of long duration flywheel systems is predominately determined by the efficiency of the motor/generator. Roundtrip efficiencies of many current production models are in the 70% to 80% range, with some newer designs promise continued improvement.

Long duration flywheel systems do not experience degradation in their energy storage capacity over time during operation. Their ability to store and retrieve energy is based on the motor/generator's ability to accelerate the rotational speed of the rotor repeatedly, thus experiencing no physical reduction in the energy storage capacity of the unit. This allows long-duration flywheel systems to support high cycle operation, cycling significantly more energy through the system than for chemical cell-based storage systems. Possible harm can come from the charging or discharging the unit more rapidly than the system is able to dissipate heat, which would harm the motor/generator. This can be avoided through limitations on operating patterns. Flywheels are capable of reacting very quickly and alter their charging or discharging without meaningful degradation to the system as can occur in a battery.

Table 5-16. Flywheel: Long Duration (FWLD) System Performance Characteristics

Flywheel: Long Duration Performance Characteristics	
Lifespan:	20 Yrs.
Round-Trip Efficiency (AC):	70-80%
Operating Range (Depth of Discharge %):	100%
Capacity at End of Life (% of Original):	100%
Operation & Maintenance (O&M):	1-2%

5.10.4. Applications

Long duration flywheel systems can operate across a number of market roles, ranging from large commercial, to utility, and off grid solar applications.

5.10.5. System Capital Costs

Key drivers for flywheel equipment costs are the cost of the motor generator, rotor, and hub that need to be both low cost and able to handle high speed operation.

The equipment cost for existing long duration flywheel technology has the potential for some cost reductions over the forecast period.

Potential significant improvements in future capital cost reductions in flywheels are possible through improved motor/generator design or use of different materials.

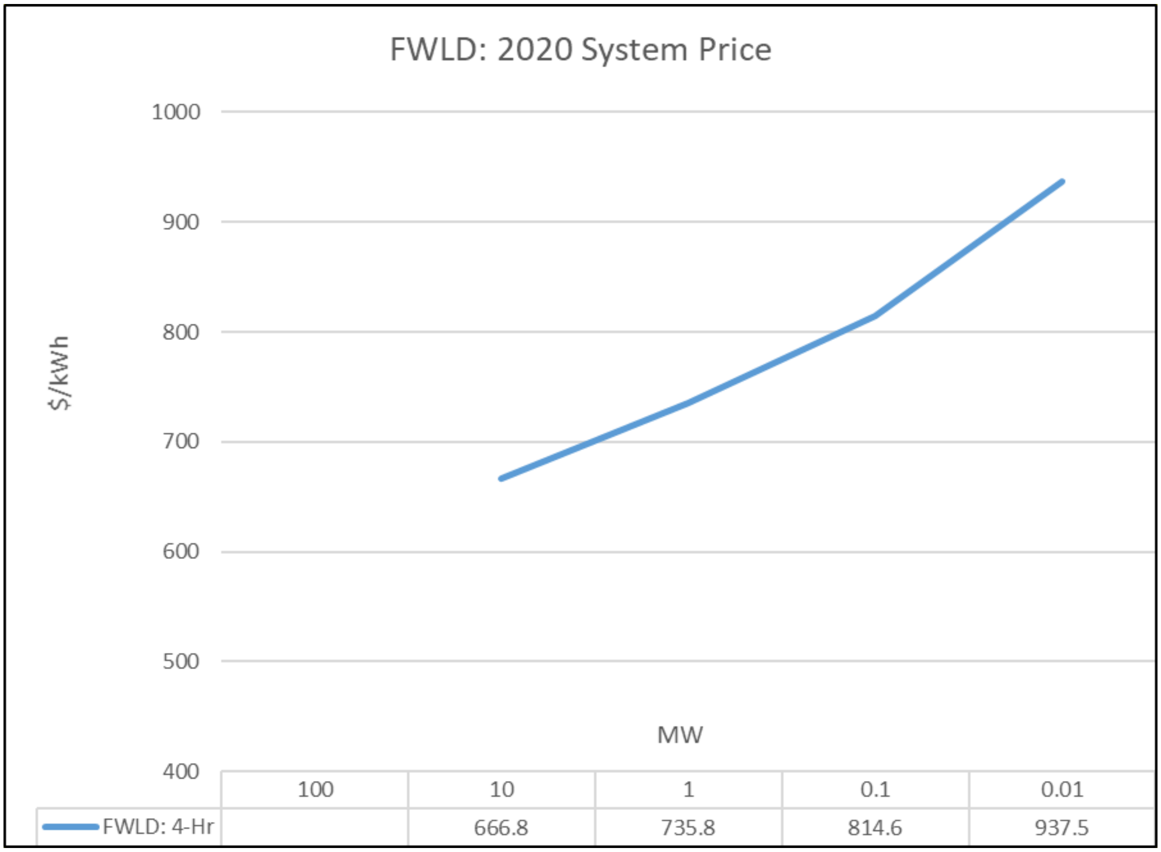
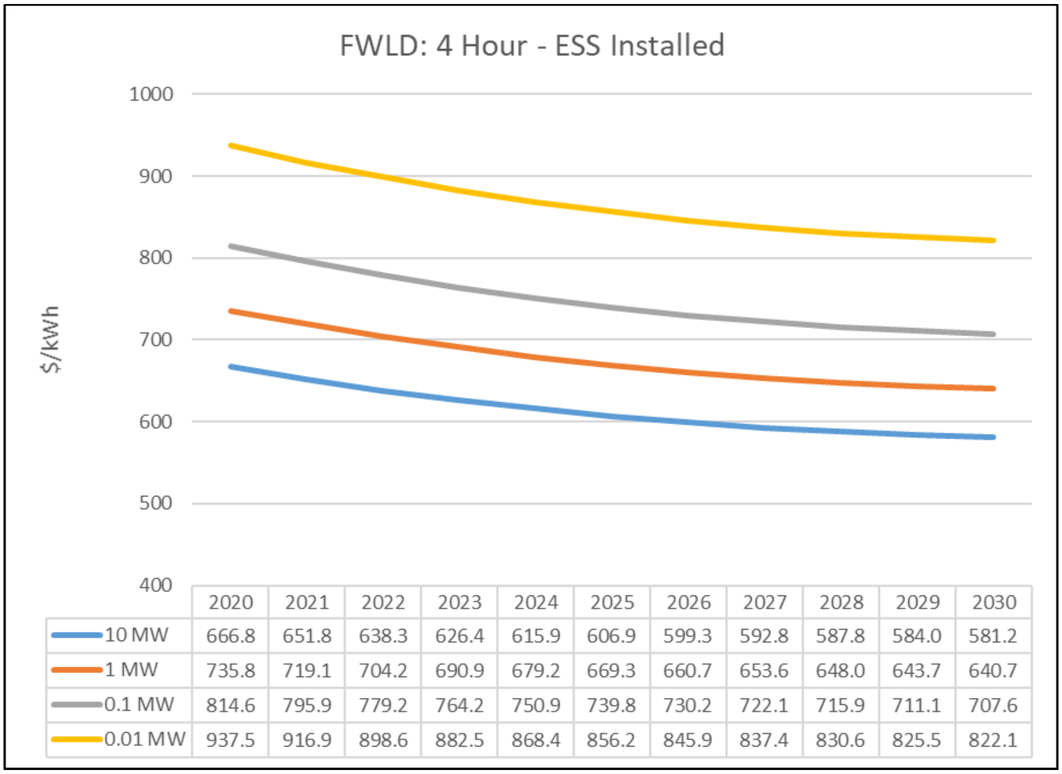
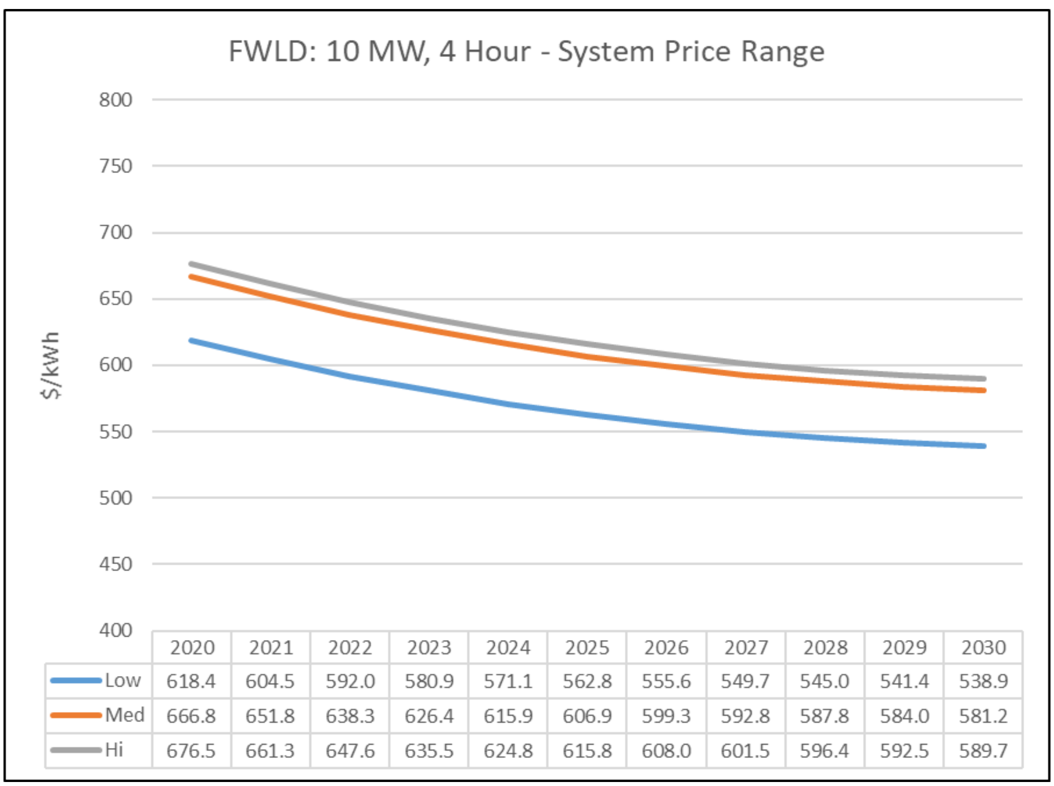


Figure 5-33. Flywheel: Long Duration (FWLD) 2020 Installed System Costs



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
10 MW	666.8	651.8	638.3	626.4	615.9	606.9	599.3	592.8	587.8	584.0	581.2
1 MW	735.8	719.1	704.2	690.9	679.2	669.3	660.7	653.6	648.0	643.7	640.7
0.1 MW	814.6	795.9	779.2	764.2	750.9	739.8	730.2	722.1	715.9	711.1	707.6
0.01 MW	937.5	916.9	898.6	882.5	868.4	856.2	845.9	837.4	830.6	825.5	822.1

Figure 5-34. Flywheel: Long Duration (FWLD) System Price Forecast



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low	618.4	604.5	592.0	580.9	571.1	562.8	555.6	549.7	545.0	541.4	538.9
Med	666.8	651.8	638.3	626.4	615.9	606.9	599.3	592.8	587.8	584.0	581.2
Hi	676.5	661.3	647.6	635.5	624.8	615.8	608.0	601.5	596.4	592.5	589.7

Figure 5-35. Flywheel: Long Duration (FWLD) System Price Range

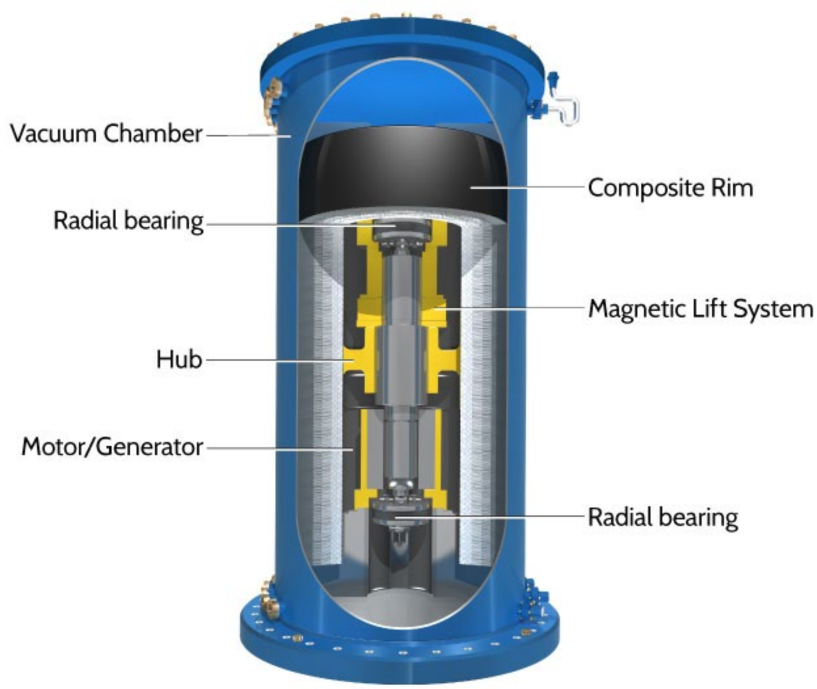
5.11. Flywheel: Short Duration (FWSD)

Capital costs for short duration flywheel (FWSD) systems are provided in $/kW for the energy storage pricing survey as the majority of the costs are associated with the power aspect of the technology. Because the primary usage of short duration flywheels is for such applications such as frequency regulation that is measured in $/kW, this pricing metric allows the system to be compared with its other, power centric energy storage technologies more easily. In addition, since short duration flywheels have such a small energy storage capacity, the resulting $/kWh price would not provide to be a useful comparison.

5.11.1. Technology Description & System Design

Flywheels store energy through rotational energy—spinning a mass to high speed and using a motor generator to inject and withdrawal power. The energy stored is linear with the mass of the spinning rotor, and the square of the surface speed. Short duration flywheels are designed to operate with the focus on moving energy rapidly in and out of the flywheel, with typical charge and discharge cycles measured in minutes.

Typical short duration flywheel systems utilize a magnetically levitated rotor spinning in a vacuum, so there is little loss from the system during rest.



Source: Beacon Power Corporation

Figure 5-36. Flywheel: Short Duration (FW SD) System Design

Short duration flywheels are typically designed with only a few minutes of duration, but high-power capacity. For short duration flywheel energy storage systems, the motor/generator and material selection able to support rapid charging and discharging of the unit (and manufacturing scale) has the largest impact on the capital equipment costs.

5.11.2. Deployment Options

Short duration flywheel systems can support either indoor or outdoor deployment. These systems are generally able to tolerate a wider range of ambient temperatures without suffering degradation.

Because of the safety factor dealing with high-speed rotating machines, each individual flywheel has a containment vessel in the event of failure. When the flywheels scale to a larger size, many developers have installed the units underground for additional safety precautions.

5.11.3. Operation

Roundtrip efficiencies of many current production models are in the 70% to 80% range, with some newer designs even higher. The round-trip efficiency of short duration flywheel systems is determined by the efficiency of the motor/generator. With their design focus on fast power delivery, the round-trip efficiency of short duration flywheel systems is lower than those of the long duration systems that focus on energy storage.

Short duration flywheel systems do not experience degradation in their energy storage capacity over time during operation. Their ability to store and retrieve energy is based on the motor/generator's ability to accelerate the rotational speed of the rotor repeatedly, thus experiencing no physical reduction in the energy storage capacity of the unit. This allows short-duration flywheel systems to operate repeatedly, cycling significantly more energy through the system than for chemical cell-based storage systems. Possible harm can come from the charging or discharging the unit more rapidly than the system is able to dissipate heat, which would harm the motor/generator. This can be avoided through limitations on operating patterns.

Flywheel energy storage systems remain highly suitable for applications requiring deep, fast charge/discharges; using battery terminology, they are able to handle repeated discharges ranging from 4C to 15C or more without negative effect. Because energy is stored mechanically and not chemically, flywheels are able to charge and discharge at very high rates or power without damaging unit.

Table 5-17. Flywheel: Short Duration (FWSD) System Performance Characteristics

Flywheel: Short Duration Performance Characteristics	
Lifespan:	20 Yrs.
Round-Trip Efficiency (AC):	70-80%
Operating Range (Depth of Discharge %):	100%
Capacity at End of Life (% of Original):	100%
Operation & Maintenance (O&M):	2%

5.11.4. Applications

Short duration flywheel systems are designed to operate in the ancillary services market where power delivery and fast ramping is of greater value. Although these systems can provide UPS backup, the 2020 Energy Storage Pricing Survey is not explicitly covering that application.

5.11.5. System Capital Costs

Key drivers for flywheel equipment costs are the cost of the motor generator, rotor, and hub that need to be both low cost and able to handle high speed operation.

The equipment cost for existing short duration flywheel technology has the potential for some cost reductions over the forecast period.

Potential significant improvements in future capital cost reductions in flywheels are possible through improved motor/generator design or use of different materials.

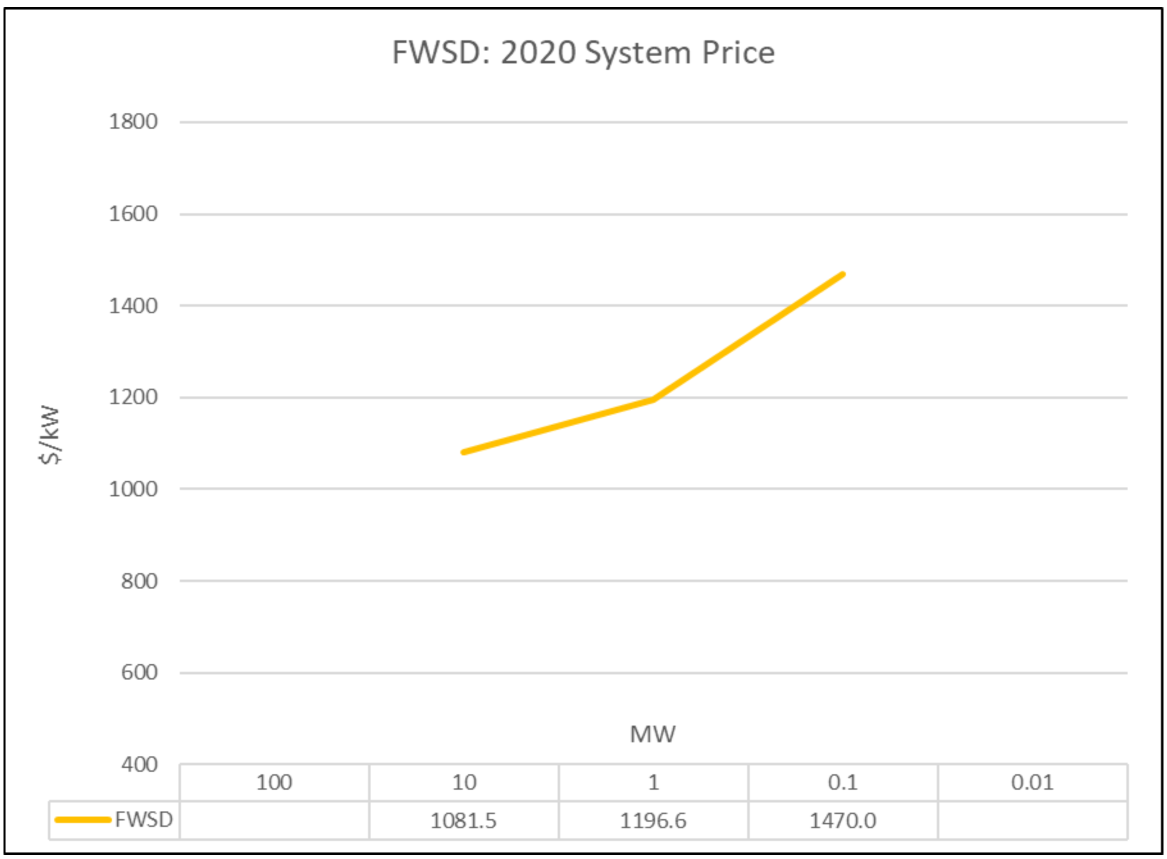
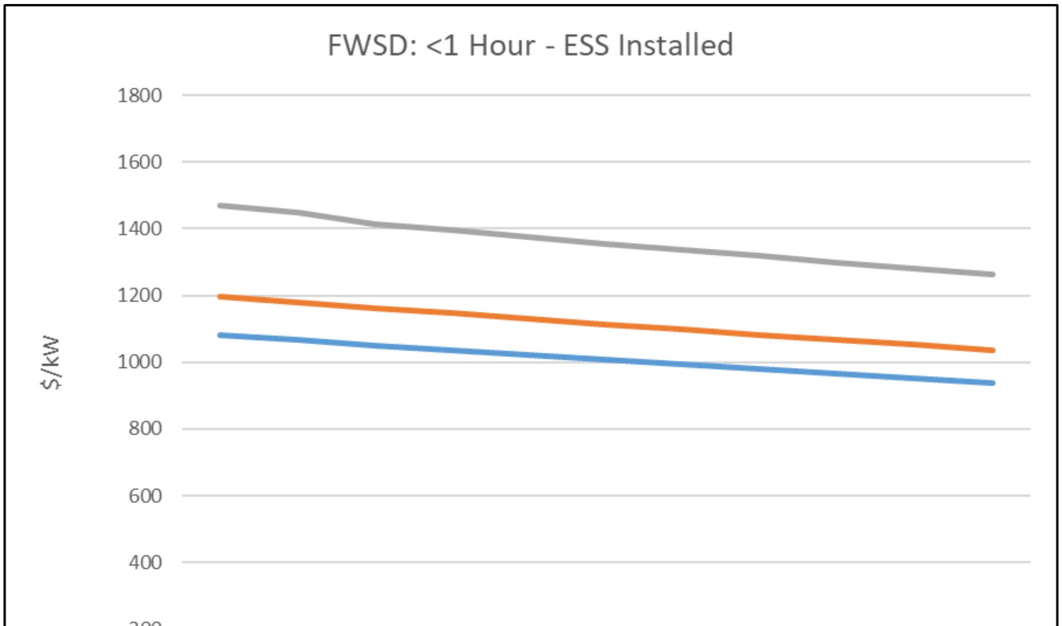
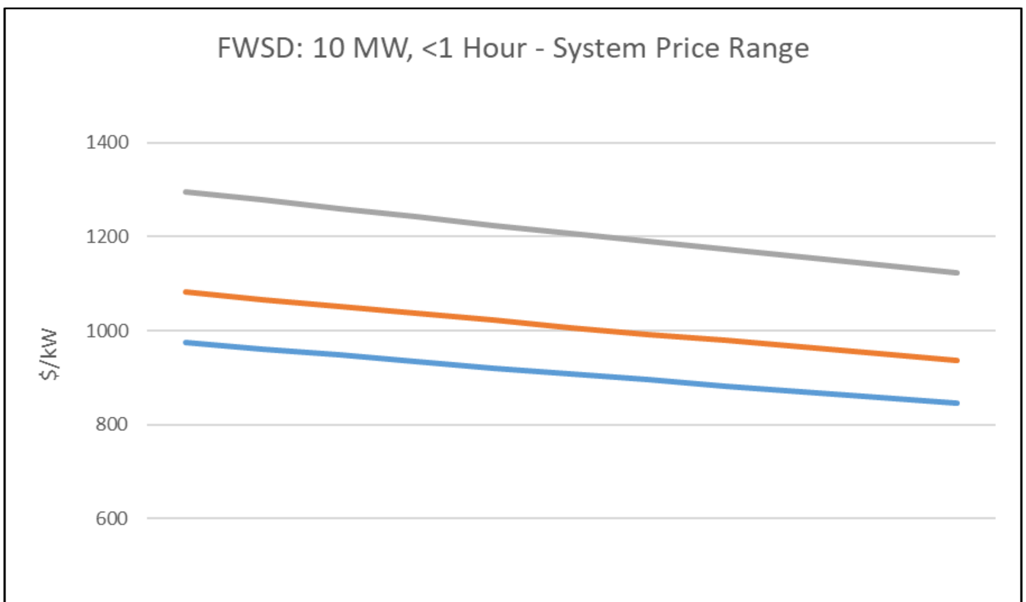


Figure 5-37. Flywheel: Short Duration (FWSD) 2020 Installed System Costs



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
10 MW	1,081.	1,066.	1,051.	1,036.	1,021.	1,007.	992.8	978.6	964.7	950.9	937.3
1 MW	1,196.	1,179.	1,163.	1,146.	1,130.	1,114.	1,098.	1,082.	1,067.	1,052.	1,037.
0.1 MW	1,470.	1,449.	1,414.	1,394.	1,375.	1,355.	1,336.	1,317.	1,298.	1,280.	1,262.

Figure 5-38. Flywheel: Short Duration (FWSD) System Price Forecast



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low	975.0	961.2	947.6	934.2	921.0	907.9	895.0	882.3	869.7	857.3	845.0
Med	1081.5	1066.2	1051.1	1036.3	1021.6	1007.1	992.8	978.6	964.7	950.9	937.3
Hi	1296.0	1277.7	1259.6	1241.8	1224.2	1206.8	1189.7	1172.7	1156.0	1139.5	1123.2

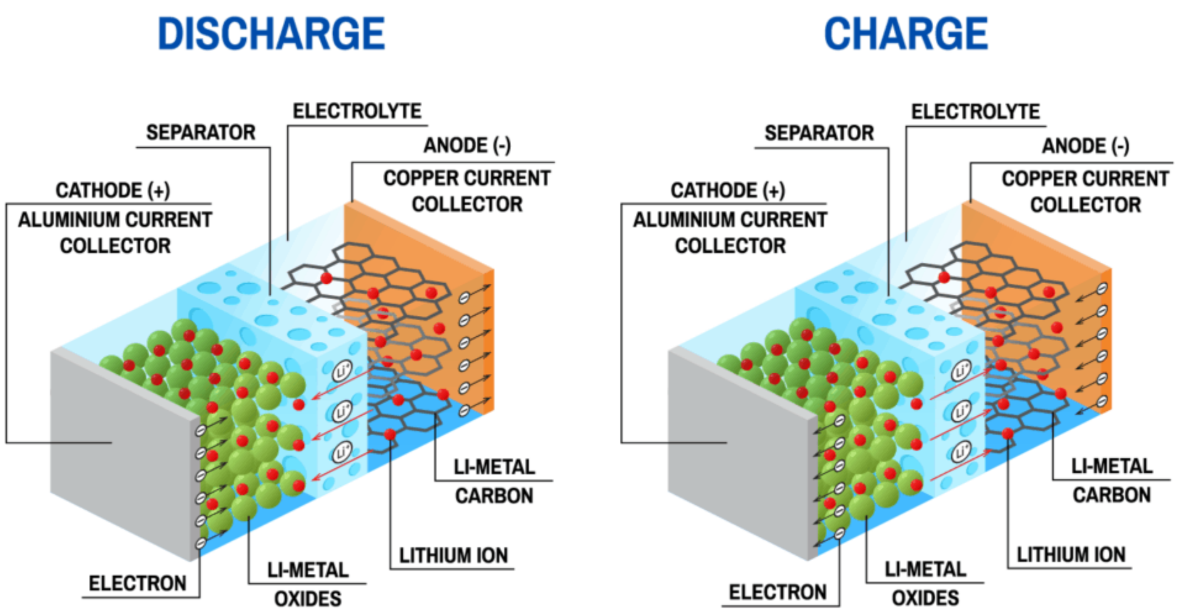
Figure 5-39. Flywheel: Short Duration (FWSD) System Price Range

5.12. Lithium Ion: NMC (LiNMC)

Capital costs for lithium -ion Nickel Manganese Cobalt (LiNMC) energy storage systems are provided in $/kWh for the energy storage pricing survey as the value of the technology is predominately tied to the amount of energy the system is able to store and discharge.

5.12.1. Technology Description & System Design

LiNMC batteries are cell-based energy storage systems. The individual cells are arrayed in modules that fit withing standard rack-systems which are installed stand-alone enclosures, or standard containers of up to 40'. As a cell-based system, the power and energy of each lithium battery is fixed. Typically, LiNMC system for energy applications can range from 10 kW's to over 100 MWs, with the energy capacity ranging anywhere from 2 to 8 hours, with durations approaching 4 hours becoming the norm in many utility RFPs. For LiNMC systems, the improving energy storage capacity of emerging chemistries utilizing less or even no precious metals is coupled with some continued improvement in manufacturing improvements point to continuing lower overall capital costs.



Source: EnergyLink, LLC.

Figure 5-40. Lithium Ion: NMC (LiNMC) System Design

5.12.2. Deployment Options

LiNMC battery systems can be deployed in either indoor or outdoor deployments. Outdoor deployments require increased environmental conditioning as elevated temperatures will degrade the batteries, sometimes significantly. Increasing safety concerns is impacting the containment strategy, and the amount and scale of fire suppression systems included.

5.12.3. Operating Characteristics

The round-trip efficiency of Li-NMC systems is determined primarily by the modules, the power electronics, and the cooling load. The power electronics have improved over time and now range between 97% to 99%, depending on the usage. The cooling load will vary due to usage patterns and environmental conditions. Overall, the round-trip efficiency of Li-NMC systems is estimated to be between 80% and 85% in real world operation.

LiNMC systems experience energy capacity degradation through both calendar and cycle aging. Calendar aging occurs through the slow chemical change in the cell and can accelerate at higher temperature. Cycle aging is predominately driven by the number of cycles, but rate of charging/discharging, depth of discharge, and environmental conditions all impact the cycle life of the unit.

The conditions under which the cell operates (temperature), and the rate at which the cell operates (charge / discharge or C-Rate). Cycle life also is dependent upon a variety of issues, such as depth of discharge, the set-point around which the cycling occurs, and rate of charge-/ discharge.

Table 5-18. Li-NMC System Performance Characteristics

Li-NMC Energy Performance Characteristics	
Lifespan:	10-20 Yrs.
Round-Trip Efficiency (AC):	80-85%
Operating Range (Depth of Discharge %):	80-100%
Capacity at End of Life (% of Original):	70%
Operation & Maintenance (O&M):	2-3%

5.12.4. Applications

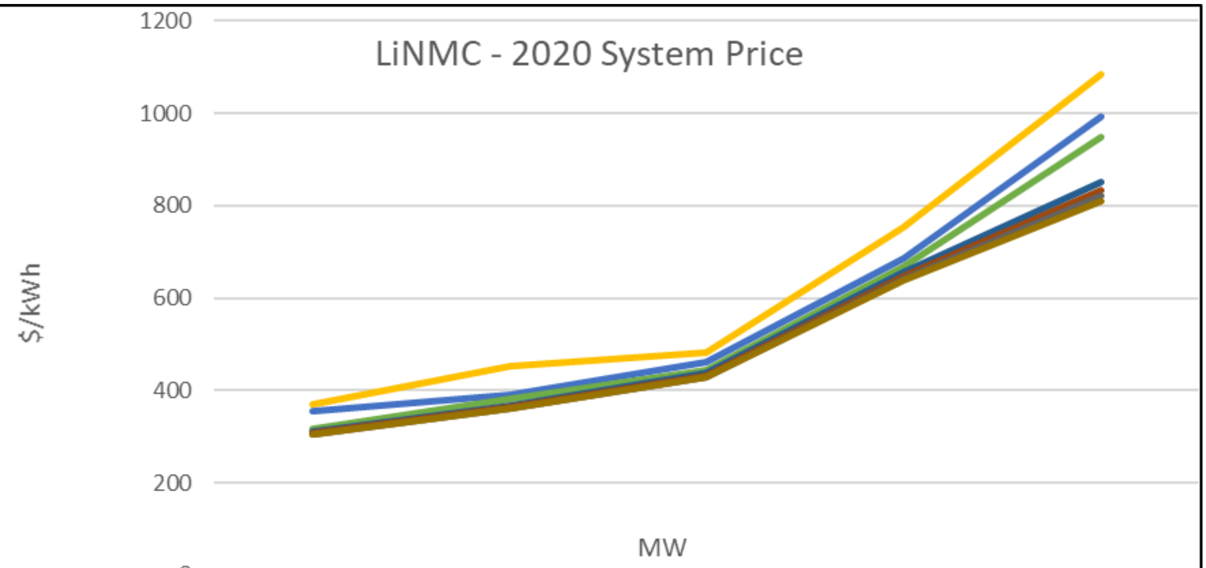
LiNMC systems are capable of supporting a variety of market applications due the ability to structure systems across a variety of power and energy ratings. As these designs can reach up to eight hours of duration, Li-NMC systems are easily geared toward energy applications, they are designed for a wide range of market operation. Improving chemistry designs are improving their performance, but they still suffer lifespan and efficiency declines under harsh environmental and operational experience. Li-NMC systems are designed for operation across the entire market value chain, ranging from residential, commercial, and wholesale power applications.

5.12.5. System Capital Costs

Key drivers for LiNMC system costs are the improving chemistry of the individual cells, which allow lower cost manufacturing and lower cost material selection.

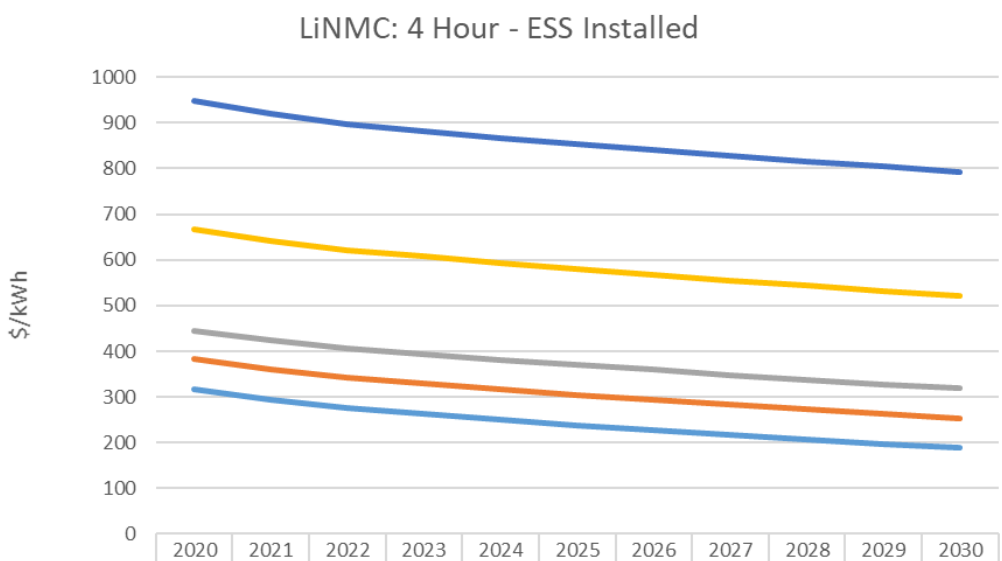
The equipment cost for LiNMC systems is expected to sustain continued cost reductions over the forecast.

Potential significant improvements in future capital cost reductions for LiNMC systems are expected through improved chemistry and manufacturing design such as a move to solid state batteries.



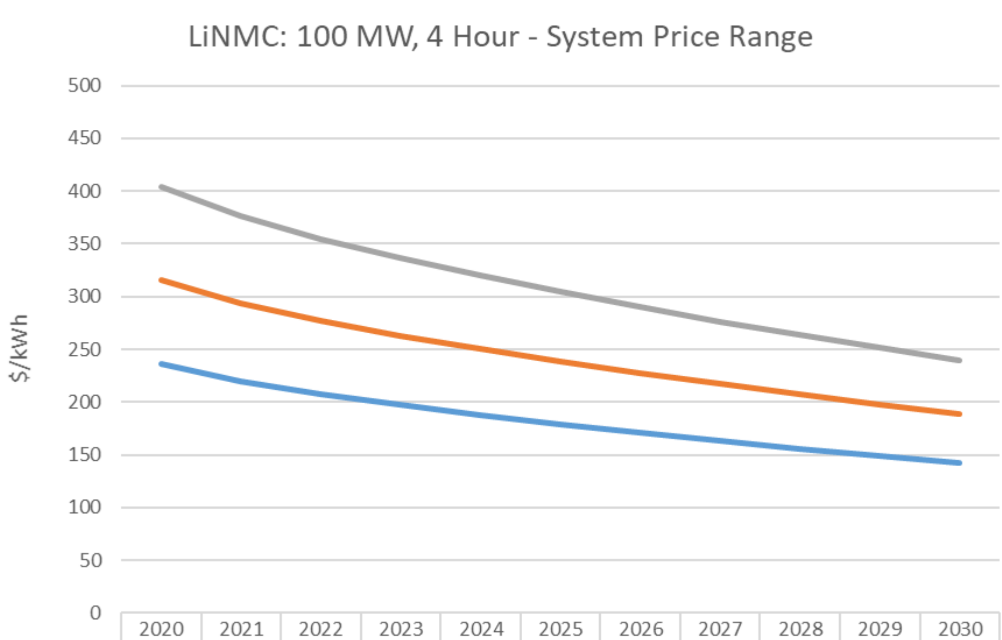
	100	10	1	0.1	0.01
LiNMC: 2-Hr	370.6	452.9	482.1	753.7	1083.4
LiNMC: 3-Hr	355.5	390.4	460.9	687.3	992.8
LiNMC: 4-Hr	315.6	382.3	444.9	667.8	947.5
LiNMC: 5-Hr	311.1	368.1	437.1	656.1	851.6
LiNMC: 6-Hr	308.1	364.9	432.9	648.3	833.4
LiNMC: 7-Hr	305.9	362.6	429.9	642.7	820.5
LiNMC: 8-Hr	304.3	360.8	427.6	638.6	810.8

Figure 5-41. Lithium Ion: NMC (LiNMC) 2020 Installed System Costs



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
100 MW	315.6	294.1	276.9	263.2	250.6	238.7	227.5	216.9	206.9	197.5	188.6
10 MW	382.3	360.3	343.1	329.9	317.2	305.3	293.8	282.8	272.5	262.6	253.1
1 MW	444.9	423.4	406.9	394.2	381.9	370.4	359.1	348.3	338.0	328.1	318.5
.1 MW	667.8	641.8	622.2	607.8	593.8	580.6	567.7	555.0	543.2	531.5	520.2
.01 MW	947.5	918.8	897.2	882.1	867.3	854.0	840.8	827.9	816.3	804.8	793.4

Figure 5-42. Lithium Ion: NMC (LiNMC) System Price Forecast



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low	235.8	220.0	207.3	197.2	187.9	179.2	171.0	163.1	155.9	149.0	142.4
Med	315.6	294.1	276.9	263.2	250.6	238.7	227.5	216.9	206.9	197.5	188.6
Hi	404.3	376.5	354.1	336.4	319.9	304.6	290.0	276.2	263.3	251.1	239.5

Figure 5-43. Lithium Ion: NMC (LiNMC) System Price Range

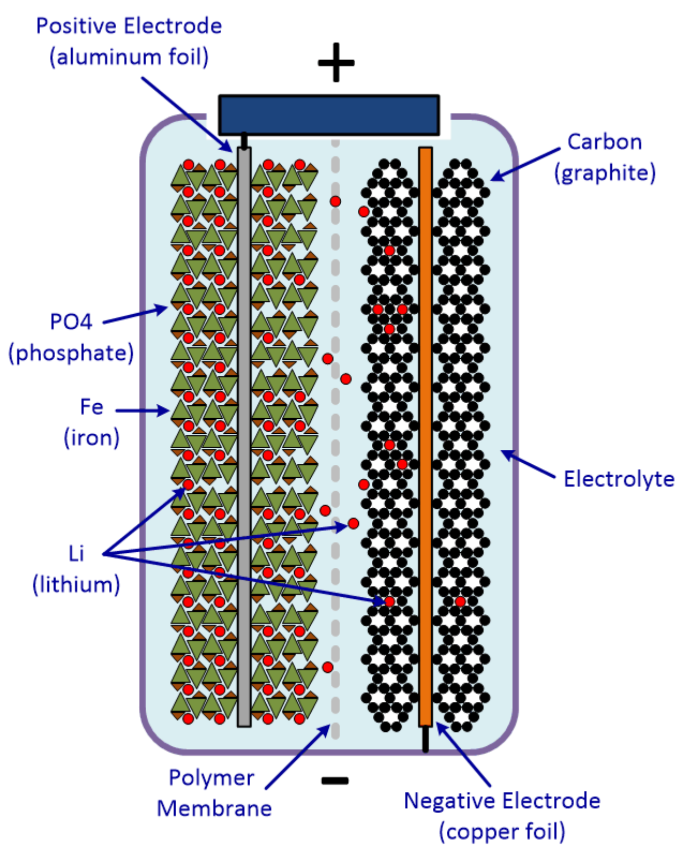
5.13. Lithium Ion: LFP (LiLFP)

Capital costs for Lithium Iron Phosphate (LiLFP) energy storage systems are provided in $/kWh for the energy storage pricing survey as the value of the technology is tied to the amount of energy the system is able to store and discharge.

5.13.1. Technology Description & System Design

LiLFP systems are cell-based energy storage systems. The individual cells are arrayed in modules that fit withing standard rack-systems which are installed stand-alone enclosures, or standard containers of up to 40', although many power centric systems are found built around the 20' container. As a cell-based system, the power and energy of each lithium battery is fixed. Typically, LiLFP system for energy applications can range from 10 kW's to over 100 MWs, with the energy capacity ranging anywhere from 2 to 8 hours.

Power centric system can utilize standard energy cells, but increasingly are comprised of power-oriented cells and module designs that are optimize for the greater current flow and heat generation. For LiLFP systems, the improving performance of emerging chemistries utilizing less or even no precious metals is coupled with some continued improvement in manufacturing improvements point to continuing lower overall capital costs.



Source: SolarCity, Inc.

Figure 5-44. Flow Battery: Lithium Ion LFP (LiLFP) System Design

5.13.2. Deployment Options

LiLFP systems can be deployed in either indoor or outdoor deployments. Outdoor deployments require increased environmental conditioning as elevated temperatures will degrade the batteries, sometimes significantly. Increasing safety concerns is impacting the containment strategy, and the amount and scale of fire suppression systems included.

5.13.3. Operation

The round-trip efficiency of LiLFP systems is determined primarily by the modules, the power electronics, and the cooling load. The power electronics have improved over time and now range between 97% to 99%, depending on the usage. The cooling load will vary due to usage patterns and environmental conditions. Overall, the round-trip efficiency of LiLFP systems is estimated to be between 80% and 85% in real world operation.

LiLFP systems experience energy capacity degradation through both calendar and cycle aging. Calendar aging occurs through the slow chemical change in the cell and can accelerate at higher temperature. Cycle aging is predominately driven by the number of cycles, but rate of charging/discharging, depth of discharge, and environmental conditions all impact the cycle life of the unit. LiLFP cells typically have a longer lifespan than LiNMC cells and are able to tolerate higher charging / discharging rates and a wider temperatures range. For these reasons, LiLFP based systems are becoming very prevalent in the grid energy storage market.

The conditions under which the cell operates (temperature), and the rate at which the cell operates (charge / discharge or C-Rate). Cycle life also is dependent upon a variety of issues, such as depth of discharge, the set-point around which the cycling occurs, and rate of charge-/ discharge. Because of the more aggressive usage profile, power centric lithium-ion systems will have a lower round trip efficiency than energy cells.

Table 5-19. Lithium Ion: Power (LiLFP) System Performance Characteristics

Lithium-ion: Power Performance Characteristics	
Lifespan:	10 Yrs.
Round-Trip Efficiency (AC):	80-85%
Operating Range (Depth of Discharge %):	100%
Capacity at End of Life (% of Original):	70%
Operation & Maintenance (O&M):	2-3%

5.13.4. Applications

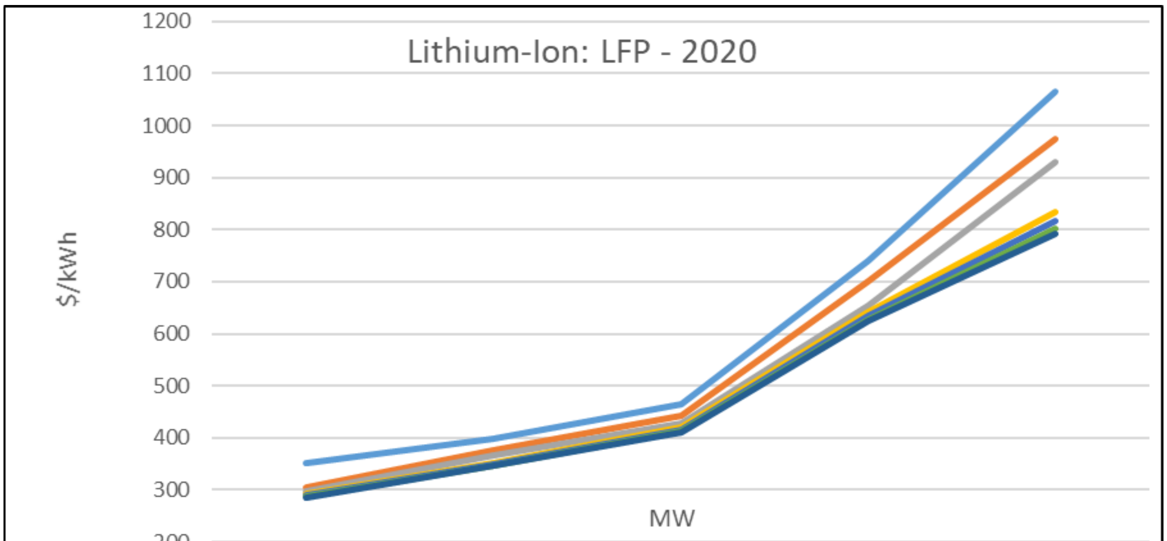
LiLFP systems are capable of supporting a variety of market applications due the ability to structure systems across a variety of power and energy ratings. As these designs can reach up to eight hours of duration, LiLFP systems are easily geared toward energy and power applications, and they are designed for a wide range of market operation. Improving chemistry designs are improving their performance, but they still suffer lifespan and efficiency declines under harsh environmental and operational experience. LiLFP systems are designed for operation across the entire market value chain, ranging from residential, commercial, and wholesale power applications.

5.13.5. System Capital Costs

Key drivers for LiLFP cell costs are the improving chemistry of the individual cells, which allow lower cost manufacturing and lower cost material selection.

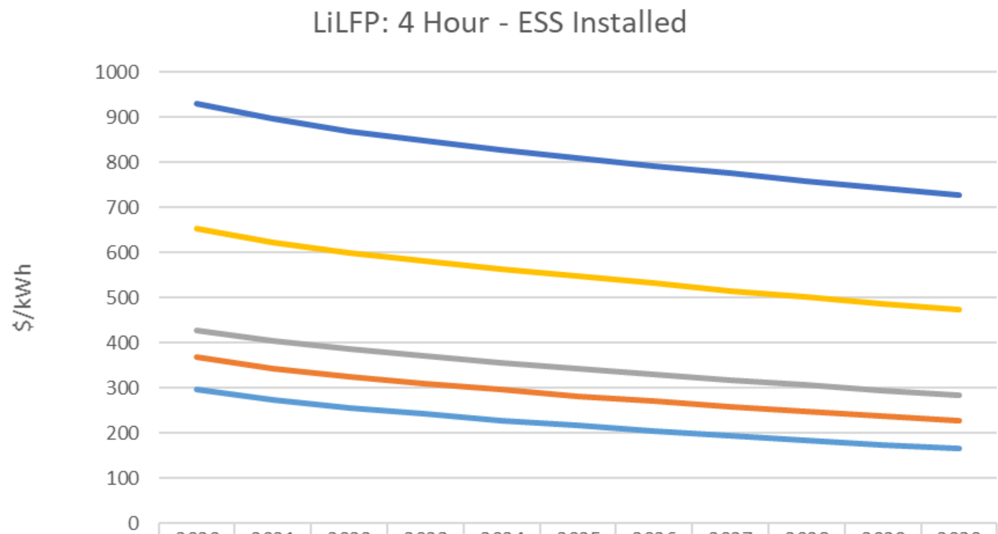
The equipment cost for lithium-ion battery is expected to sustain continued cost reductions over the forecast.

Potential significant improvements in future capital cost reductions for LiLFP systems are expected through improved chemistry and manufacturing design such as a move to solid state batteries.



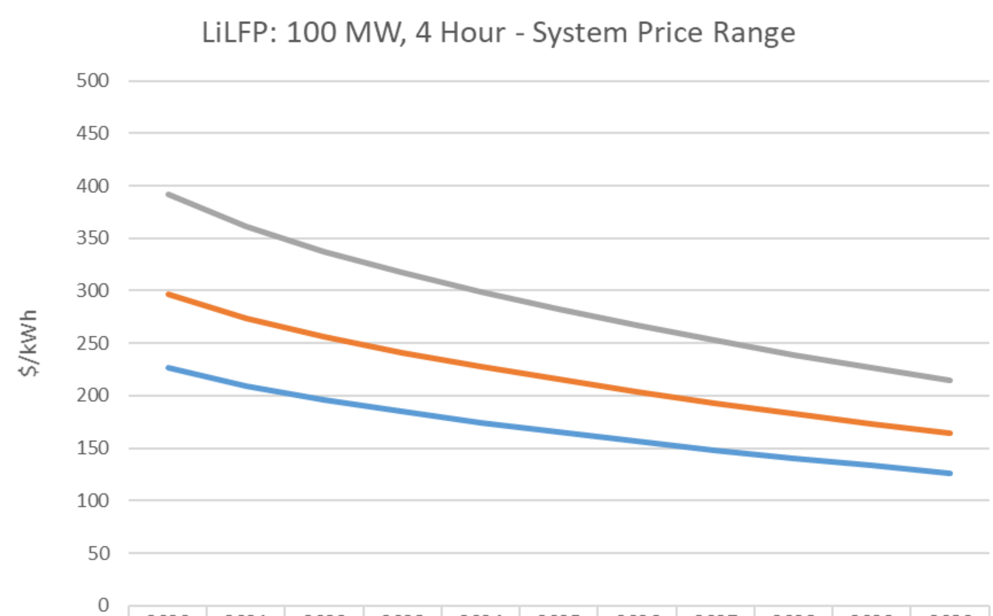
	100	10	1	0.1	0.01
LiLFP: 2-Hr	351.6	397.9	465.0	739.1	1065.6
LiLFP: 3-Hr	304.2	375.0	443.8	700.2	975.0
LiLFP: 4-Hr	296.6	366.8	427.7	653.2	929.7
LiLFP: 5-Hr	292.1	352.7	420.0	641.5	833.8
LiLFP: 6-Hr	289.1	349.5	415.8	633.7	815.6
LiLFP: 7-Hr	286.9	347.1	412.7	628.2	802.7
LiLFP: 8-Hr	285.3	345.4	410.5	624.0	793.0

Figure 5-45. Lithium Ion: LFP (LiLFP) 2020 Installed System Costs



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
100 MW	296.6	274.2	256.0	241.4	228.0	215.6	204.0	193.0	182.9	173.4	164.5
10 MW	366.8	343.1	324.1	309.3	295.3	282.1	269.6	257.7	246.7	236.2	226.2
1 MW	427.7	403.8	385.1	370.2	355.9	342.6	329.7	317.4	305.9	294.8	284.1
.1 MW	653.2	623.1	599.5	581.3	563.7	547.1	531.1	515.5	500.9	486.7	473.0
.01 MW	929.7	895.4	868.5	848.1	828.1	809.9	792.1	774.6	758.6	743.0	727.7

Figure 5-46. Lithium Ion: LFP (LiLFP)System Price Forecast



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low	226.7	209.7	195.9	184.8	174.7	165.3	156.5	148.2	140.5	133.4	126.6
Med	296.6	274.2	256.0	241.4	228.0	215.6	204.0	193.0	182.9	173.4	164.5
Hi	391.3	361.2	336.8	317.3	299.4	282.7	267.1	252.5	238.9	226.2	214.2

Figure 5-47. Lithium Ion: LFP (LiLFP) System Price Range

5.14. Zinc (Zn)

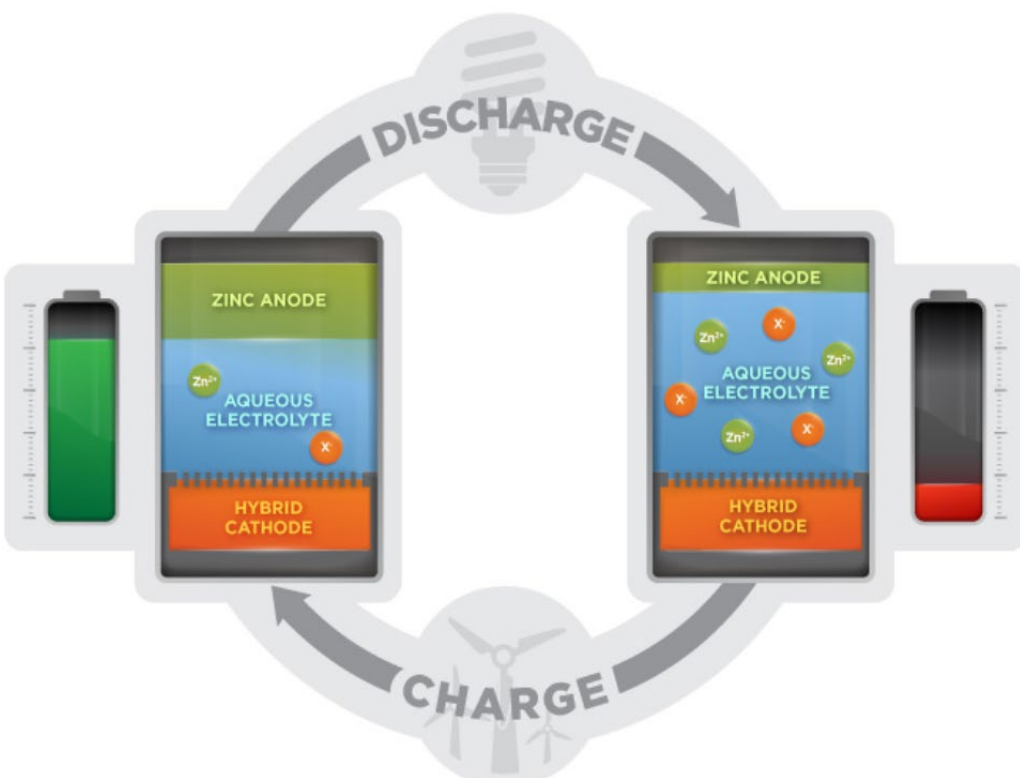
Capital costs for zinc (Zn) energy storage systems are provided in $/kWh for the energy storage pricing survey as the value of the technology is tied to the amount of energy the system is able to store and discharge. In addition, the majority of the active ingredients in the cell chemistry are designed to maximize the storage of energy.

5.14.1. Technology Description & System Design

A number of zinc-based energy storage technologies exist, including Aqueous Zinc, Zinc Air, and Nickel Zinc. Because Nickel Zinc technology is primarily focused on the UPS market, it is not covered in the 2020 Energy Storage Pricing Survey.

Aqueous Zinc battery systems are designed in both the cell and integrated system. Both variants have the energy and power fixed for each basic unit, allowing larger scale systems to be designed by scaling the same DC building block. Zinc air systems can take a variety of forms based on the manufacturer.

For all zinc systems, the material selection and manufacturing process have the largest impact on the capital equipment costs. Zinc battery systems are designed for indoor and outdoor deployment.



Source: EOS Energy Storage

Figure 5-48. Zinc Battery (Zn) System Design

5.14.2. Deployment Options

Zinc based energy storage systems can support either indoor or outdoor deployment. Depending on the technology, the systems can be incorporated into cabinets able to protect the cells / system from extremes in temperatures.

5.14.3. Operation

The round-trip efficiency of Zinc systems is determined by efficiency of the reversible chemical reaction. This will depend on the specific sub-class of technology.

Zinc aqueous based energy storage systems experience energy capacity degradation through both calendar and cycle aging. Calendar aging occurs through the slow chemical change in the cell and can accelerate at higher temperature. Cycle aging is predominately driven by the number of cycles, but rate of charging/discharging, depth of discharge, and environmental conditions all impact the cycle life of the unit.

For the integrated system designs, improved combination of the different steps could also lead to efficiency improvements. These systems can tolerate a wider environmental range than many other technologies and support a long operating lifespan.

Table 5-20. Zinc (Zn) System Performance Characteristics

Zinc (Zn) Performance Characteristics	
Lifespan:	15 Yrs.
Round-Trip Efficiency (AC):	70%
Operating Range (Depth of Discharge %):	80-100%
Capacity at End of Life (% of Original):	80%
Operation & Maintenance (O&M):	2-3%

5.14.4. Applications

Zinc based energy storage systems are geared toward longer discharge applications, and thus energy centric applications have been the central focus of deployment opportunities for these systems.

5.14.5. System Capital Costs

Key drivers for zinc-based energy storage technology costs are the improving chemistry of the system design, which allow lower cost manufacturing and lower cost material selection.

The equipment cost for zinc-based battery technology has the opportunity for modest and sustained cost reductions over the forecast.

Potential significant improvements in future capital cost reductions for zinc batteries are possible but are not factored into the forecast until additional details about the proposed technological improvements are provided.

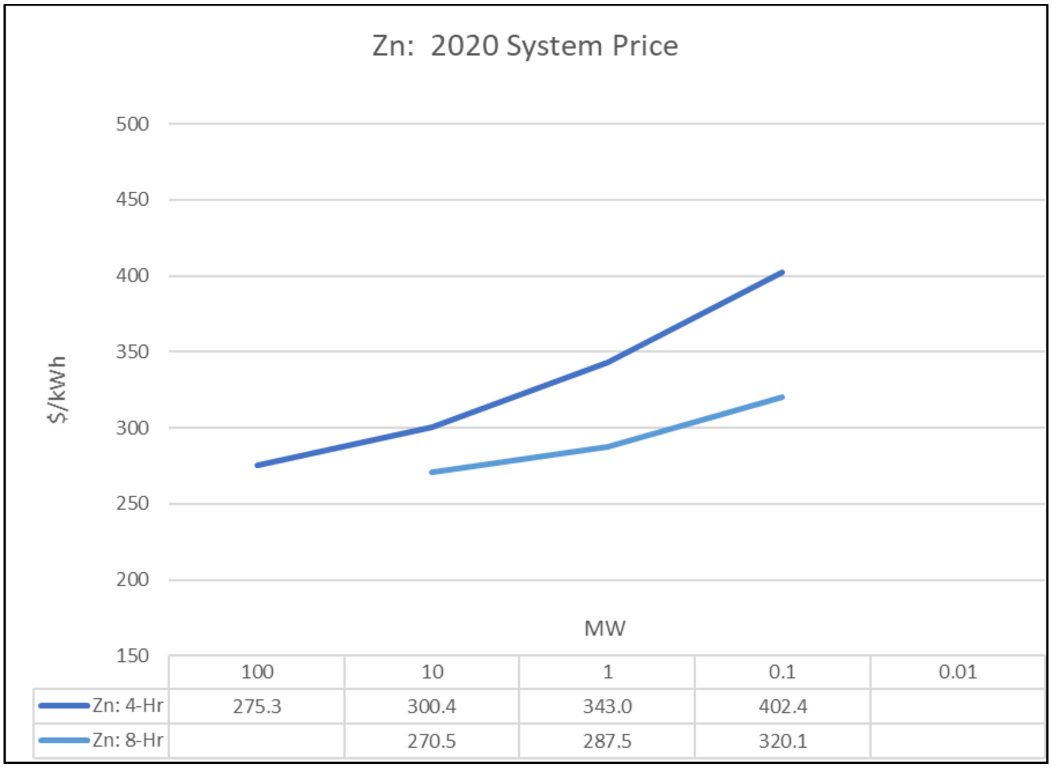


Figure 5-49. Zinc (Zn) 2020 Installed System Costs

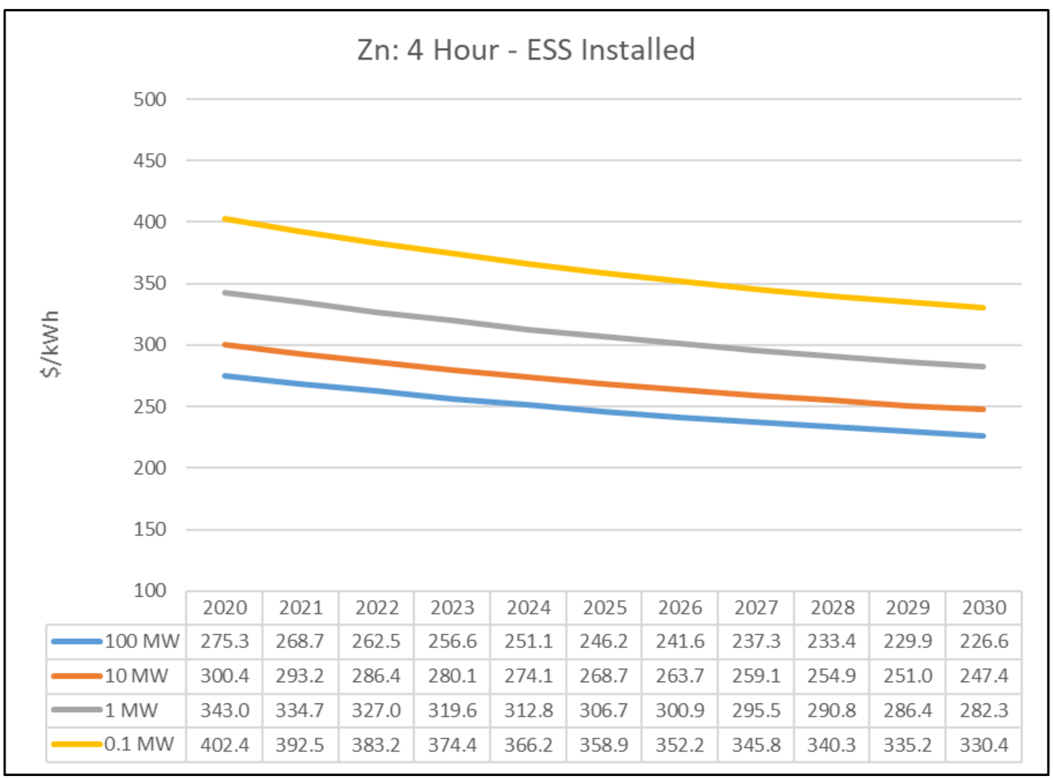
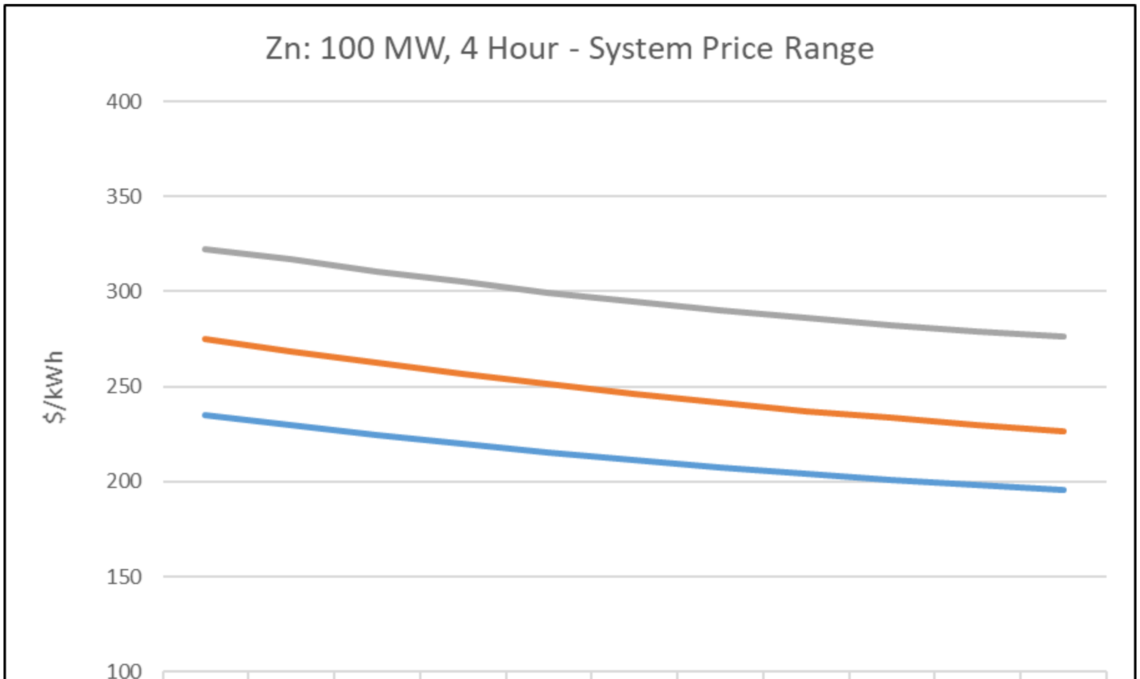


Figure 5-50. Zinc (Zn) System Price Forecast



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low	235.1	229.7	224.6	219.9	215.4	211.4	207.7	204.2	201.1	198.3	195.7
Med	275.3	268.7	262.5	256.6	251.1	246.2	241.6	237.3	233.4	229.9	226.6
Hi	322.1	316.8	310.7	304.9	299.5	294.7	290.2	286.0	282.4	279.1	276.0

Figure 5-51. Zinc (Zn) System Price Range

5.15. Lead (Pb)

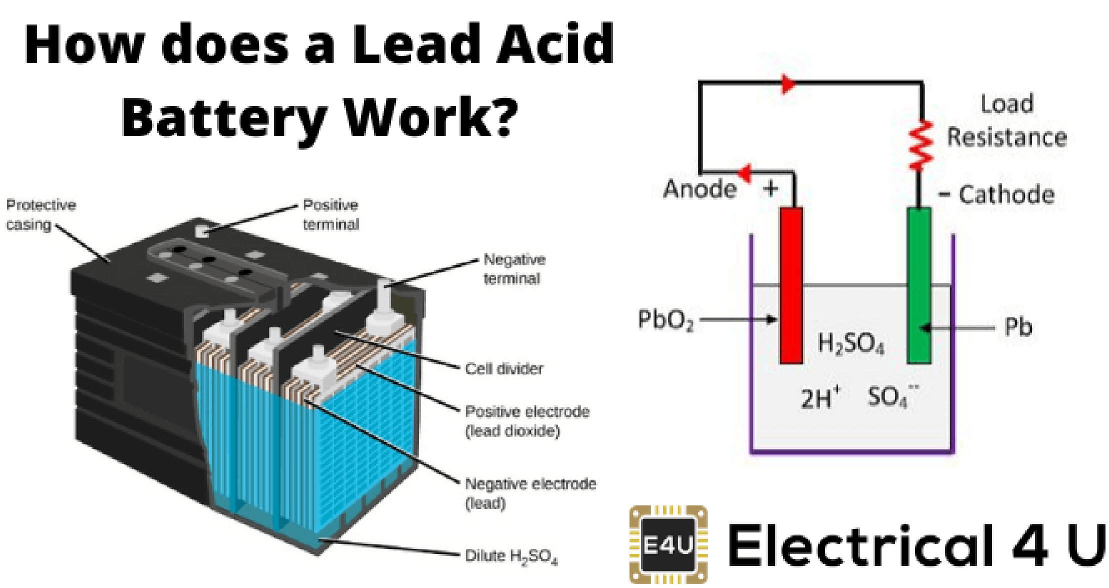
Capital costs for lead (Pb) energy storage systems are provided in $/kWh for the energy storage pricing survey as the value of the technology is tied to the amount of energy the system is able to store and discharge. In addition, the majority of the active ingredients in the cell chemistry are designed to maximize the storage of energy.

5.15.1. Technology Description & System Design

Lead battery system are cell-based energy storage systems, typically a number of these individual cells are designed into one sealed module to act as a building block. As a cell-based system, the power and energy of each lead battery is fixed.

Three designs dominate lead acid batteries: flooded, absorbed glass matt (AGM), and Gel. In the traditional flooded design, the electrodes in lead acid batteries are used for part of the chemical reaction and for storing the results of the chemical reactions on their surfaces. Therefore, both the energy storage capacity and the power rating are based on the size and geometry of the electrodes. A higher power rating requires a larger surface area for each electrode, often leading to more and thinner plates in a battery. However, the energy storage capability is based on the mass of the plate, leading to fewer and thicker plates. Recent advances in lead-based batteries have incorporated carbon into the anode (and sometimes cathode), increasing the system's dynamic operating capabilities.

Lead-based energy storage systems are used in a variety of market roles, including UPS/standby power, starting power for vehicles, industrial applications, and renewable energy. Many of the technology designs are used extensively in some applications, and far less frequently in others. For that reason, the pricing of lead-based systems will be representative of those products most closely aligned with other energy storage technologies that support multi-hour discharge: for example, systems used for integration of renewable power systems.



Source: Electrical4U

Figure 5-52. Lead Battery (Pb) System Design

For Pb systems, the material selection and manufacturing process have the largest impact on the capital equipment costs. Lead battery systems can be deployed in either indoor or outdoor deployments. Outdoor deployments require increased environmental conditioning as elevated temperatures will degrade the batteries. Stationary deployment options for lead-based systems typically include backup power systems or off-grid power applications. For non-UPS uses, steady charge and discharges is preferred to improve the economics of the applications.

5.15.2. Deployment Options

Lead-based battery systems can be deployed in either indoor or outdoor deployments. Due to the impact on performance by environmental conditions on the system's performance, however, any installation typically requires some degree of environmental controls if the system is to last an appreciable amount of time. Safety concerns for lead system are centered around leaking electrolyte, but that is typically a primary problem with flooded systems instead of AGM or Gel based systems.

5.15.3. Operation

The round-trip efficiency of lead acid batteries is relatively low and suffers significantly from high rates of charging and discharging. For this reason, lead acid batteries are typically designed for intermittent and moderate duty cycles as these batteries also degrade significantly under harsh environmental and operational experience. The round-trip efficiency of lead carbon batteries is somewhat higher than for lead batteries, but the range can vary. For this reason, and because of their wider performance operating range, lead carbon batteries typically are deployed in more challenging applications than traditional lead-based batteries.

Lead based energy storage systems experience energy capacity degradation through both calendar and cycle aging. Calendar aging occurs through the slow chemical change in the cell and can accelerate at higher temperature. Cycle aging is predominately driven by the number of cycles, but rate of charging/discharging, depth of discharge, and environmental conditions all impact the cycle life of the unit.

Table 5-21. Lead (Pb) System Performance Characteristics

Lead (Pb) Performance Characteristics	
Lifespan:	5+ Yrs.
Round-Trip Efficiency (AC):	60-75%
Operating Range (Depth of Discharge %):	50-70%
Capacity at End of Life (% of Original):	80%
Operation & Maintenance (O&M):	2-3%

A number of factors can negatively affect the cycle-life a lead acid battery, including temperature, depth of discharge, and the charge/discharge rate. The operating temperature may be one of the most important aspects affecting the cycle life; for instance, the typical operating temperature roughly 80°F, but operating the battery 40 or more degrees above this point can cut the life of the battery by 50%. Deep discharges also impact the battery's life. Typically, lead-based batteries designed for UPS and other stationary applications are designed for steady, prolonged discharges to 50% to 80% of capacity—with the understanding that deeper discharges decrease the lifespan significantly. The length of time used for charging and discharging also impacts the cells life. Generally, longer cycle life is achieved with a significantly longer charge cycle than the discharge cycle.

5.15.4. Applications

Lead-based energy storage systems are used in a variety of market roles, including UPS/standby power, starting power for vehicles, industrial applications, and renewable energy. For stationary applications, the Energy Storage Pricing Survey will concentrate on those applications with a 2-4-hour discharge in order to provide a comparable usage pattern with other energy storage technologies. Energy storage technologies targeted at UPS systems are not currently covered by the Energy Storage Pricing Survey.

5.15.5. System Capital Costs

Key drivers for lead-based battery cell costs are the improving chemistry of the individual cells, which allow lower cost manufacturing and lower cost material selection.

Potential significant improvements in future capital cost reductions for lead-based batteries are expected to continue to improve, especially driven by the development of further lead-carbon based cell technology.

The equipment cost for lead-based battery technology is not expected to change dramatically over the forecast.

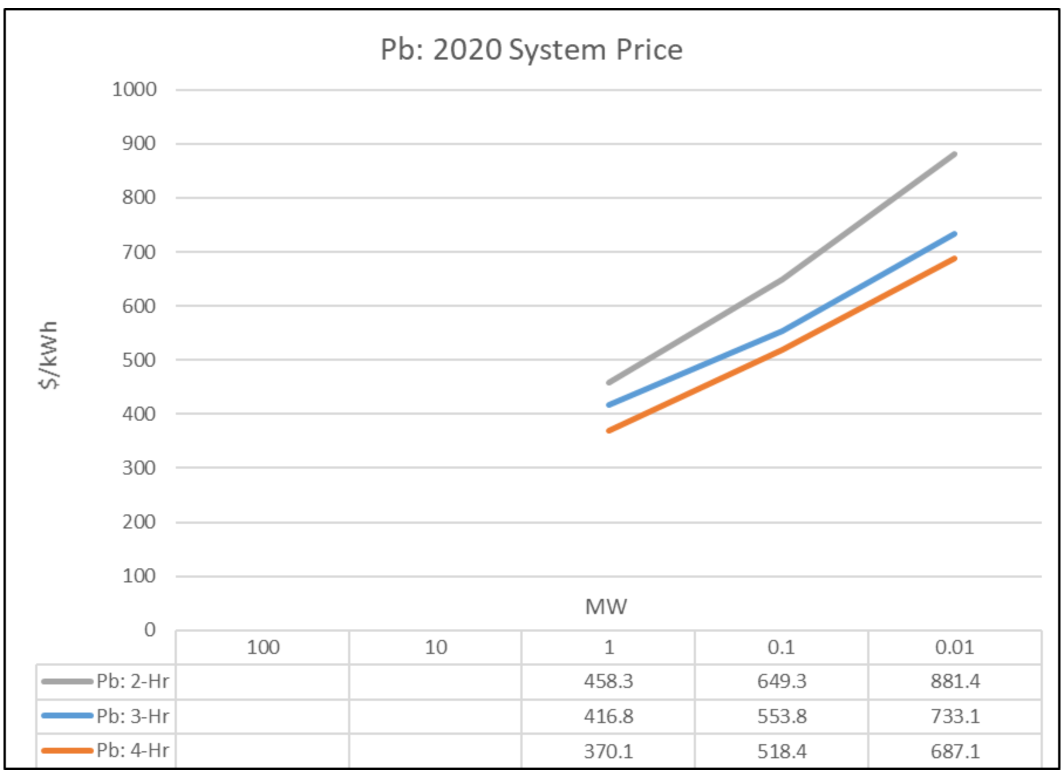
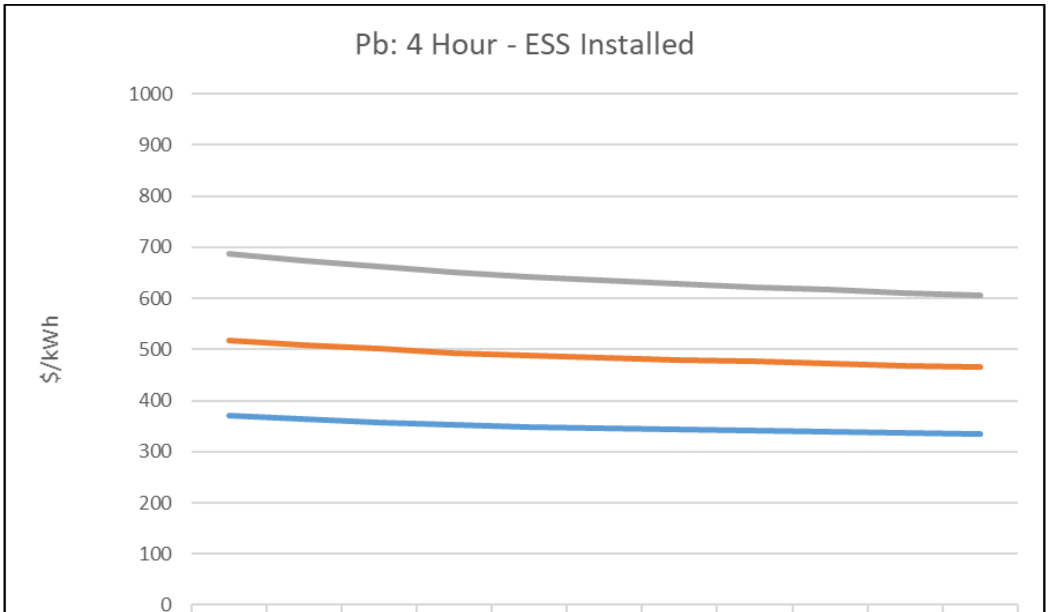
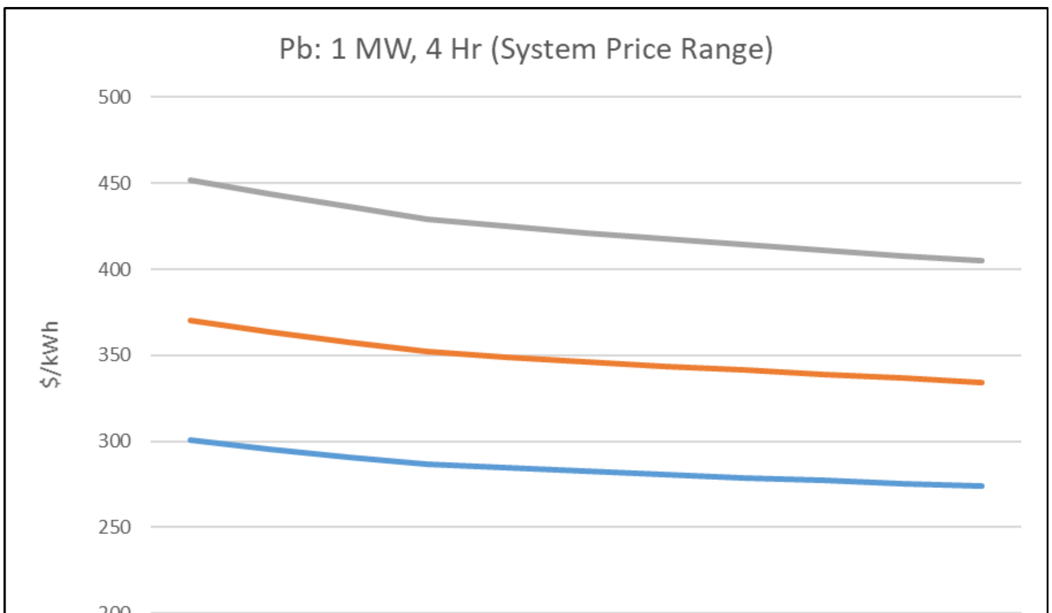


Figure 5-53. Lead (Pb) 2020 Installed System Costs



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
1 MW	370.1	363.6	357.8	352.0	349.0	346.4	343.8	341.2	338.9	336.6	334.3
0.1 MW	518.4	509.3	501.0	492.8	488.1	484.0	479.9	475.9	472.4	468.9	465.5
0.01 MW	687.1	674.5	662.2	650.2	642.0	635.2	628.5	622.0	616.7	611.4	606.2

Figure 5-54. Lead (Pb) System Price Forecast



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low	300.4	295.3	290.9	286.5	284.3	282.4	280.5	278.6	277.0	275.4	273.8
Med	370.1	363.6	357.8	352.0	349.0	346.4	343.8	341.2	338.9	336.6	334.3
Hi	451.9	443.6	436.1	428.8	424.8	421.2	417.7	414.2	411.0	407.8	404.7

Figure 5-55. Lead (Pb) System Price Range

6. COMPARING TECHNOLOGIES IN OPERATION

As the focus in the industry moves toward project economics from capital costs, better comparative methodologies must be developed for comparing the project operating costs of projects. To ensure that the comparisons provide an evenhanded comparison, it is critical that the comparisons be on as similar basis as possible.

6.1. Assumptions

Extend the core energy storage pricing survey capital costs model to support the development of metrics that can be used to provide a realistic expectation for project operating costs requires a clear understanding of the assumptions used to ensure transparency for comparative purposes.

6.1.1. Equipment Costs

Equipment costs must be compared at the same power and energy rating. The energy storage pricing survey will utilize the nameplate rating for the different technologies instead of maintaining an effectively equal discharge capability. Although the later could be useful, system nameplate ratings are used for consistency with power industry standards.

6.1.2. Use Cases

Specific standardized use cases are critical to comparing the cost of different technologies in support of a specific market application. Typical attributes include:

- Power Rating (kW)
- Energy Rating (kWh)
- Lifespan: Typically denominated in years of operation.
- Usage Profile (Cycles / Year): The periodic usage profile of the system.
- Charge / Discharge Rate: The rate at which energy is injected or withdrawn into the facility.
- Throughput: The amount of energy cycled through the facility in a given time period.

6.1.3. Economic Drivers

A number of economic drivers are used in the analysis of determining the project operating costs. Typical components include:

- Cost of Electricity – The cost of electricity cycled through the unit, used to calculate the charging losses.
- Debt / Equity split. The ratio of debt to equity used to fund the project.
- Discount rate. Used to bring forward future costs to present day terms. Weighted average of the debt and equity costs.

6.1.4. Operating Costs

A number of operating costs are used in the analysis of determining the project operating costs. Typical components include:

- Operation & Maintenance Costs: The cost to ensure the system is maintained in good working order.
- Round Trip Efficiency: A critical driver to determine the cost of efficiency loss from operation.
- Refreshment Cost. The cost to maintain the nameplate energy capacity (kWh) of the system throughout the life of the unit.

6.1.5. Project Costs

A number of operating costs are used in the analysis of determining the project operating costs. Typical components include:

- Warranty: Required by insurance and capital providers to ensure that there is recourse available from the OEM in the event that the system does not operate according to the original specifications of the system.
- Insurance: Covers a variety of potential events that would impact the continuing operation or damage to the system so the project can be brought back online for commercial operation.

6.2. Comparative Project Cost Metrics

In an attempt to move the comparison of energy storage technologies from a product cost comparison to a project cost comparison, a section on comparative metrics was added to the Energy Storage Pricing Survey. The first comparative matric is a lifetime throughput metric base on the initial capital cost of the system, and the total amount of energy cycled through the system over the life of the unit; lower results indicate a lower capital cost per lifetime energy throughput.

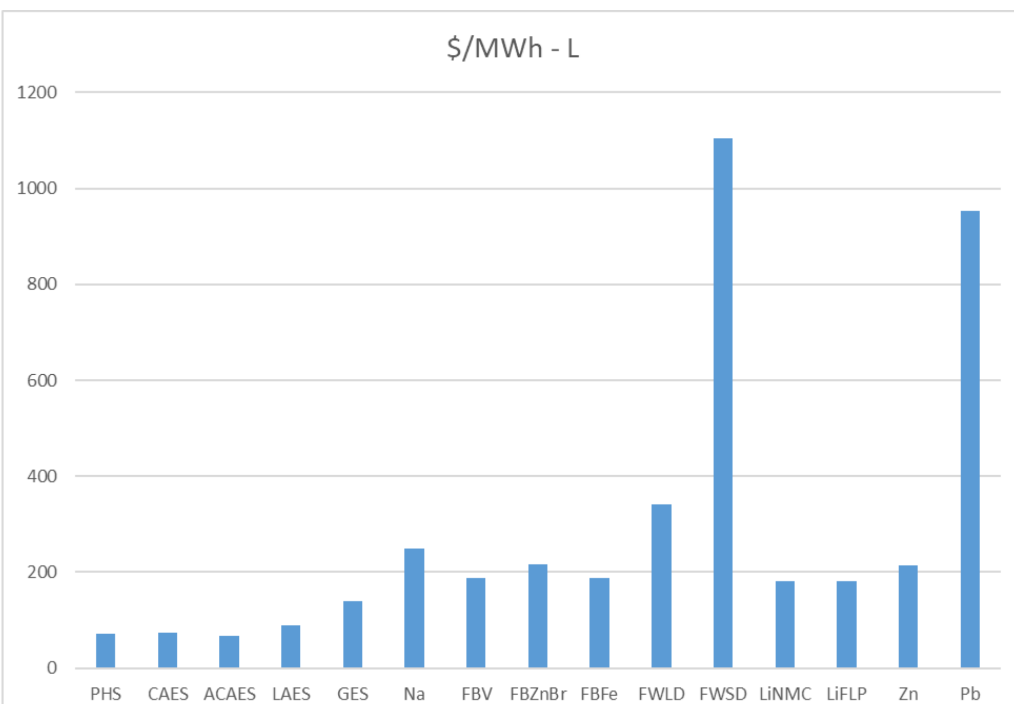


Figure 6-1. Energy Storage Lifetime Throughput Cost Metric

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