SANDIA REPORT
SAND2021-0831
Printed January 2021

Sandia National Laboratories

2019 Energy Storage Pricing Survey

Richard Baxter
Mustang Prairie Energy

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico
87185 and Livermore,
California 94550

Issued by Sandia National Laboratories, operated for the United States Department of Energy by National Technology & Engineering Solutions of Sandia, LLC.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-Mail: reports@osti.gov
Online ordering: http://www.osti.gov/scitech

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Rd
Alexandria, VA 22312

Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-Mail: orders@ntis.gov
Online order: https://classic.ntis.gov/help/order-methods/

ABSTRACT

Since grid energy storage is still evolving rapidly, it is often difficult to obtain project specific capital costs for various energy storage technologies. This information is necessary to evaluate the profitability of the facility, as well as comparing different energy storage technology options. The goal of this report is to summarize energy storage capital costs that were obtained from industry pricing surveys. The 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 synthetic 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.

ACKNOWLEDGEMENTS

The author would like to acknowledge the support and guidance of Dr. Imre Gyuk, Director of the U.S. Department of Energy's Office of Electricity Delivery and Energy Reliability's Energy Storage Program, and Dr. Babu Chalamala and Dr. Ray Byrne of the Energy Storage Systems Program of Sandia National Laboratories.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. This research was supported by the U.S. Department of Energy Office of Electricity Energy Storage program under the guidance of Dr. Imre Gyuk.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

This page left blank

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
AC	Alternating current
BESS	Battery energy storage system
BOM	Bill of materials
BOS	Balance of system
DC	Direct current
DMS	Data management system
EMS	Energy management system
EPC	Engineering, procurement and construction
ESS	Energy storage system
HVAC	Heating, ventilation and air conditioning
kW	Kilowatt
kWh	Kilowatt hour
MW	Megawatt
MWh	Megawatt hour
NRE	Non-recurring engineering
O&M	Operation and maintenance
OEM	Original equipment manufacturer
PCS	Power conversion system
RTE	Round trip efficiency
SCADA	Supervisory control and data acquisition
SM	Storage module

This page left blank

1. THE ENERGY STORAGE PRICING SURVEY

1.1. Purpose

The Energy Storage Pricing Survey is designed to provide a reference system price to customers for various energy storage technologies at different power and energy sizes. 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.

The goal of this series of reports 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.

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 pricing. The Energy Storage Pricing Survey accomplishes this by developing the pricing structure and forecast at the component level.

This approach benefits the results in a number of ways. First, all technologies are broken down into the most basic component possible, allowing the different technologies to have a similar frame of evaluation where 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. 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.

1.2. Coverage

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

Table 1-1. Energy Storage Technologies

Energy Storage Technologies		
Pumped Hydro Storage	Flow Battery: Vanadium	Lithium Ion: Energy
Compressed Air Energy Storage	Flow Battery: Zinc Bromide	Lithium Ion: Power
Liquid Air Energy Storage	Flow Battery: Iron	Zinc
Gravity Energy Storage	Flywheel: Long Duration	Lead
Sodium	Flywheel: Short Duration	Lead Carbon

The list of technologies covered is assumed to be flexible going forward in future editions of the Energy Storage Pricing Survey. This flexibility is to account for new technologies emerging with sufficient representation to justify a separate category. This flexibility can 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 1-2. System Ratings

Energy Storage Technologies	
Power (kW) Rating	Standardizes Power ratings from 10 kW to 100 MW. Note not all technologies are viable at all scale
Energy (kWh) Rating	Standardized Energy ratings from less than 1 hour to 8 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 2.

1.3. Survey Outreach

The 2019 Energy Storage Pricing Survey is centered on obtaining relevant pricing information about energy storage system and components to provide an internally consistent range of prices for energy storage systems according to the power and energy ratings. Overall, 72 interviews were conducted that yielded over 234 unique energy storage component prices. This information was used to develop the 114 final prices provided in Chapter 4.

Table 1-3. Survey Outreach Components

Energy Storage Price Survey	
Total Interviews	72
Unique Component Price Quotes	234
Final Synthetic Price Quotes	114

1.4. Survey Results

The Energy Storage Pricing Survey developed a range of unique system price quotes for the year 2019, and a 10-year forecast. Table 1-4 provides a snapshot of the pricing in 2019. The full compliment of 2019 survey results and resulting forecasts can be found in Chapter 4.

Table 1-4. 2019 Energy Storage Pricing Snapshot

2019 Energy Storage Pricing					
	Size (MW)				
	100	10	1	0.1	0.01
$/kW					
PHS	1676.9				
CAES	1506.2				
FW SD		984.0	1190.0	1500.0	
$/kW (1 Hr)					
Li (Power)	504.2	545.6	629.1		
$/kW (4 Hr)					
LAES	451.0	511.5			
GES	903.0				
FW LD		677.8	766.0	855.3	975.0
Li (Energy)	392.0	430.6	493.4	623.0	850.3
Zn	271.4	289.7	336.8	398.7	
Pb			352.0	425.5	588.4
PbC			557.2	620.0	768.2
$/kW (6 Hr)					
Na	376.3	389.6	428.7		
FB ZnBr	450.9	464.9	478.8	510.6	
$/kW (8 Hr)					
FB V	309.7	372.2	439.0	620.2	
FB Fe	362.7	381.7	404.7	438.4	

2. METHODOLOGY

In order to provide the energy storage industry with a standardized reference 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 consistent reference prices to customers for the different energy storage technologies. The price is the expected installed capital cost of an energy storage system for 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. The key takeaway is that the Energy Storage Pricing Survey is designed to provide a consistent estimation for customers for what they should expect a particular energy storage technology should be priced; depending on market conditions, the actual price offered to a particular customer will vary from customer to customer. In this way, the goal of the Energy Storage Pricing Survey is accuracy for all customers, over precision for one customer.

To bolster the accuracy of the results of the Energy Storage Pricing Survey, the analysis is based first on the 72 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. 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 as the available data comes in a variety of types and qualities. If complete AC system prices were provided, these were used fully. The vast majority of price quotes typically collected were for system components. These component data points were averaged together to arrive at component price which was then added to other component pricing to arrive a full system price.

2.1. System Price

The Energy Storage Pricing Survey is designed to provide an expected system cost for customers of energy storage systems. 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 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, unfortunately for them. They are presented with an all-in total that will include equipment, services, and overhead charges needed to keep the various firms in operation.

Pricing issues above equipment costs specific to 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.

2.1.1. Synthetic 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 pricing structure to produce "synthetic price quotes" for the modeled installed system price. Many of the direct data points received from the survey are either only for system components or are prices for specific power/energy designs.

In order to produce the pricing of different energy storage systems at all potential power and energy ratings, all of the 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 accuracy obtained from a particular data point, it more than makes up by ensuring consistency across all of the different power and energy system ratings.

Critically, this approach ensures that proprietary pricing from a particular vendor is not disclosed directly, and that all potential survey participants know that all data provided 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 support s the goal of the Energy Storage Pricing Survey to focus on the accuracy of the overall forecast over the precision of 1 particular system estimate.

2.1.2. Overnight Construction Cost

The 2019 energy storage pricing survey utilizes an overnight construction cost pricing structure for the energy storage prices developed for the survey and forecast. 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 2019.

Overnight capital cost or overnight construction cost are terms used in the power generation is a term used in the power generation industry to describe the cost of building a power plant overnight. This framework is used when 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, the benefit is that is an accepted means of comparing the different technology costs of power facilities.

When utilizing this approach for energy storage system pricing, the drawback exists that systems quoted for 2019 are not built in 2019, not simply because of the construction time, but also because of the backlog stemming from a lack of battery system. 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, t2his 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, utilizing the overnight construction costs framework allows the energy storage pricing survey to include pricing quoted in that year in a systematic comparative framework. Since comparing the technologies on as an even-handed process as possible, this approach is utilized to normalize all quoted prices to the current year. In that way, if a system is quoted in a particular year, that is the year that the pricing data will represent.

2.1.3. Forecast

The 2019 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.

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 take into account the different price trends for the different components. The different components include (to be discussed in the next chapter):

Table 2-1. Energy Storage System Components

Energy Storage System Components	
Storage Module	SM
Balance of System	BOS
Power Conversion System	PCS
Energy Management System	EMS
Engineering, Procurement, and Construction	EPC

2.2. 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. To accomplish this goal, the Energy Storage Pricing Survey utilizes both Primary and Secondary data sources in order to obtain as much data as possible.

2.2.1. Primary Data Sources

The core component and system pricing data for the Energy Storage Pricing Survey is derived from data sourced directly from firms active in the energy storage industry. This is primarily the different energy storage OEMs—primarily energy storage technology manufacturers, but also balance of system and other component manufacturers. In addition to these groups, others with direct knowledge of the most up to date pricing including system integrators, project developers, EPC firms, and capital providers.

Participating Groups	19 ESPS
Energy Storage OEM	29
Gov. / NGO / Academia	4
System Integrator	9
Power Electronics	2
Project Developer	7
Financial Industry	11
Consultants	6
Balance of System	1
EPC	1
Electrical Construction Industry	1
Utility	1
Total Interviews	**72**
Published Data Sources	7
Total All Data Sources	**77**

Figure 2-1. 2019 Energy Storage Pricing Survey

In total, data from 72 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.

2.2.2. 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.

2.2.3. 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. Two primary metric 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.

2.2.4. 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 2-2. Energy Storage Technology List

Energy Storage Price Survey	
Unique Component Price Quotes	234
Final Synthetic Price Quotes	114

2.3. Technologies: List and Description

There are a number of energy storage technologies

2.3.1. Technology Types

A total of 15 energy storage technology types are included in the 2019 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 2019 Energy Storage Pricing Survey are:

Table 2-3. Energy Storage Technology List

	Technology	Abbreviation
1	Pumped Hydro Storage	PHS
2	Compressed Air Energy Storage	CAES
3	Liquid Air Energy Storage	LAES
4	Gravity Energy Storage	GES
5	Sodium	Na
6	Flow Battery: Vanadium	FB V
7	Flow Battery: Zinc Bromide	FB ZnBr
8	Flow Battery: Iron	FB Fe
9	Flywheel: Long Duration	FW LD
10	Flywheel: Short Duration	FW SD
11	Lithium Ion: Energy	Li
12	Lithium Ion: Power	Li
13	Zinc	Zn
14	Lead	Pb
15	Lead Carbon	PbC

2.3.2. System Scaling: Power

Energy Storage technologies are used at all levels of the electric power system. In order to provide an indicative pricing guide for potential customers across this spectrum in a systematic manner, energy storage systems were designed according to 5 different power ratings to provide a relevant system price-point close to their desired needs. This approach provides the benefit that many existing and future uses already correspond to these general pricing levels. Some of these current applications cover deployments in wholesale (Size 1), utility (Size 2), distribution/microgrid (Size 3), commercial & industrial (Size 4), and residential markets (Size 5).

These examples should not be taken as limiting the "Size" category to these specific applications but are for illustrative 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.

Table 2-4. System Power Rating Sizing

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

Different energy storage technologies are typically available at different scales typically based on either engineering or economics reasons. 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 much past 1 MW.

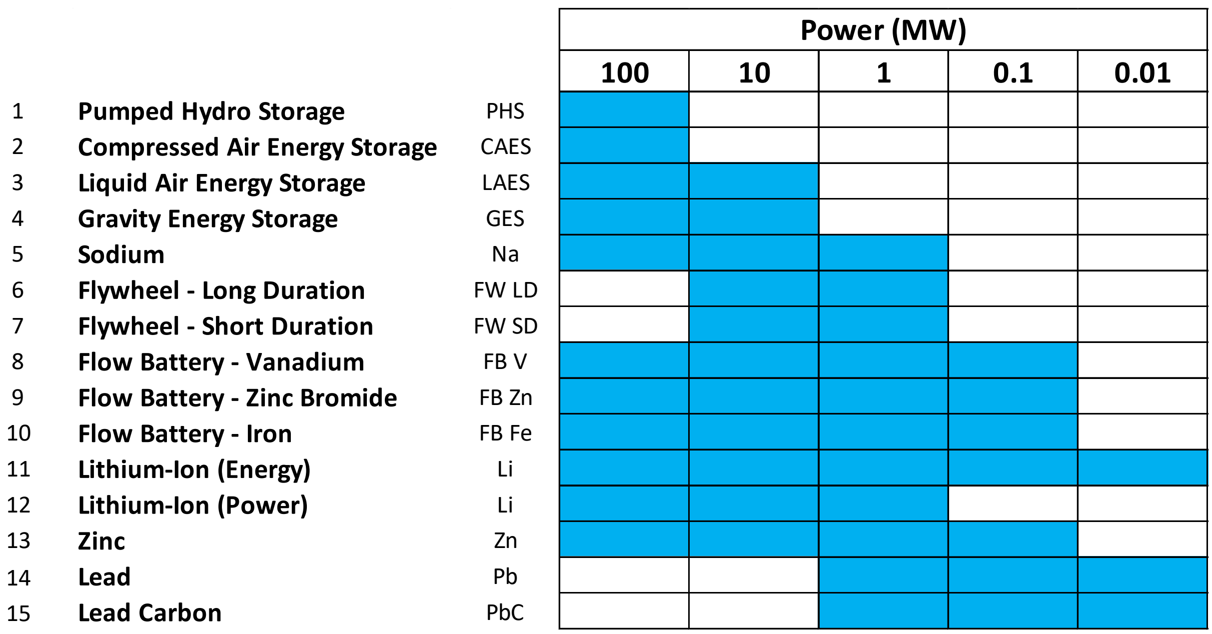


Figure 2-2. Power Rating System Range

2.3.3. *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. For instance, most flow batteries are not available for short duration (less than 3 hours). This table displays the general availability of energy storage technologies on an energy scaling capability.

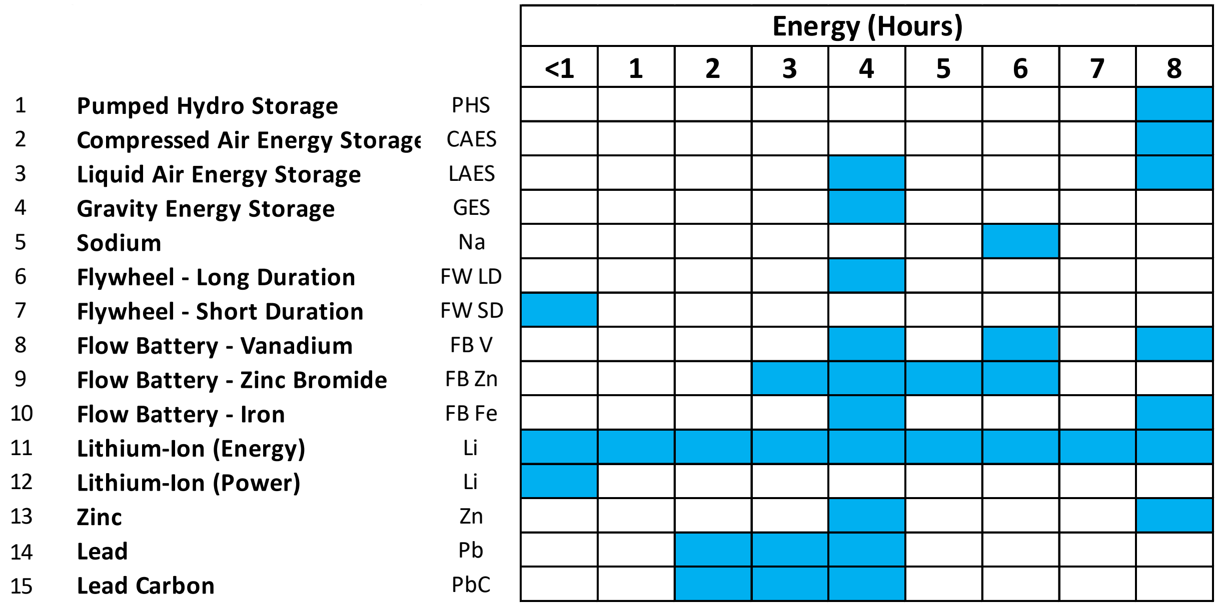
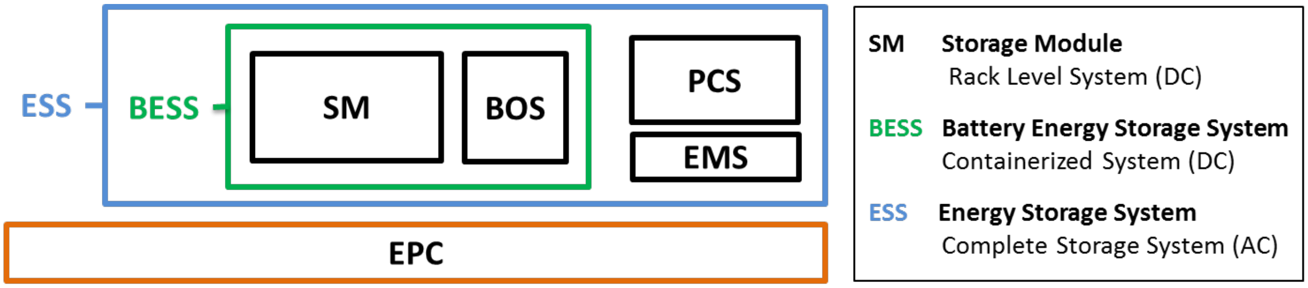


Figure 2-3. Energy Rating System Range

2.4. System Cost Structure

The Energy Storage Pricing Survey utilized a systematic component 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. Where applicable, the specific values for the same components may differ based on survey data (cost of Storage module, etc.), but the structure remains similar.



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 2-4. Energy Storage System Structure

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**

Figure 2-5. Energy Storage System Component Relationships

2.4.1. System Cost Structure Components

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

- **Storage Module (SM)**: The storage module is the most basic component, typically an assembly of energy storage medium components (battery) 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.
- **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.
- **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. For many energy storage systems, these other electrical systems would be an inverter to provide AC power, but 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.
- **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.
- **Energy Management Software (EMS):** The Energy Management System is the software 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 only providing 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.
- **Energy Storage System (ESS):** The Energy Storage System is the complete equipment list 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.

- **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.

2.4.2. 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.

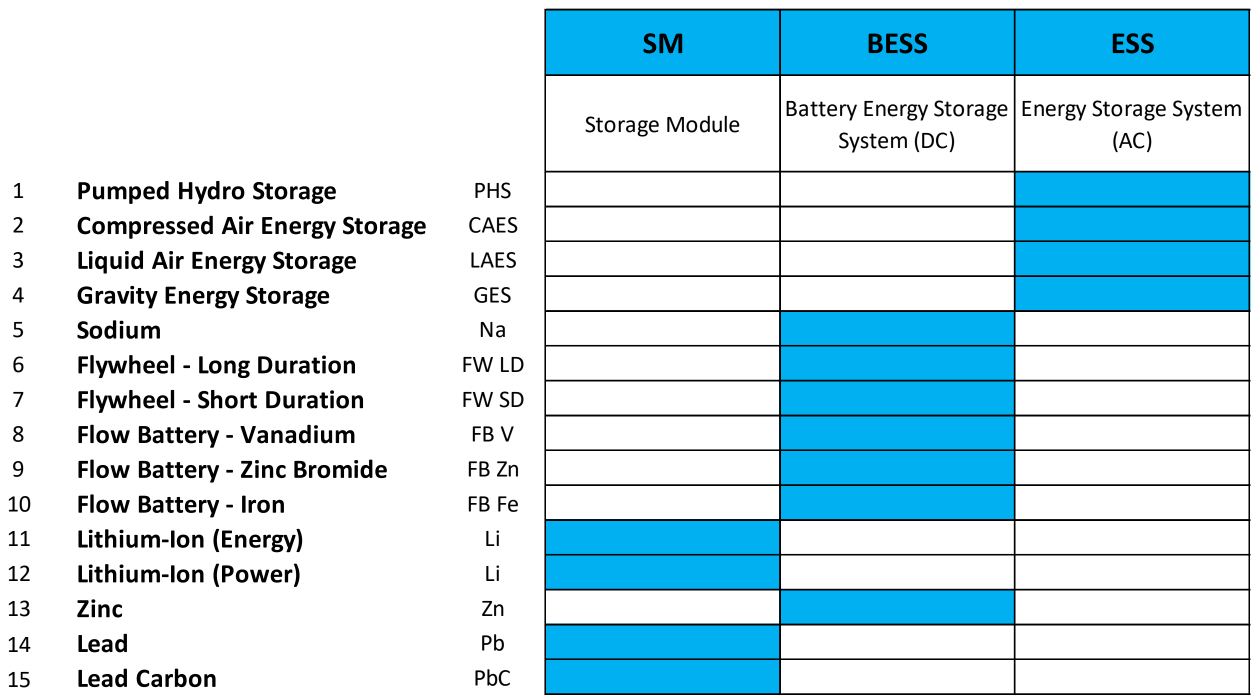


Figure 2-6. Pricing Data Available by Technology

2.5. Engineering, Procurement & Construction (EPC)

EPC costs have proven to be the most variable component of energy storage project installation costs. 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.

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. Experience, partner continuity, and improved designs are expected to provide the basis for cost reductions for the near future. As the name indicates, EPC costs are derived from three areas, engineering, procurement, and construction.

- 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.

The 2019 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.

Table 2-5. Energy Storage EPC Cost Estimates

System Size	EPC Cost Estimate
1	20.0%
2	20.0%
3	22.5%
4	25.0%
5	30.0%

These 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 in EPC costs exists, and is expected to continue with a large variance until significant experience is reached across the industry. 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 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.

2.6. 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 for energy storage assets include charging/operating losses, operating and maintenance costs, and warranty costs.

2.6.1. Charging/Operating Losses

Efficiency loss represents an important 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 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 taken into account). Because the HVAC 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.

2.6.2. Operation & Maintenance

As energy storage systems become more widely deployed, Operation and Maintenance (O&M) costs are becoming of greater concern in order 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 a moving parts that require more frequent maintenance. On average, higher usage of the system will require a larger degree of 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 have been expressed as the annual maintenance contract that is sold by OEMs. These 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.

With the growing number of units deployed, the ability of developing O&M costs that incorporate a fixed and variable component is emerging. Currently some anecdotal information for a few applications have become available, and the expectation is that additional information from a wider set of vendors covering a wider set of applications will allow for a reliable and systematic breakout of O&M costs for all energy storage technologies that would cover all operating modes. This would allow for a clearer costs structure differentiating passive and active operating modes. In addition, environmental conditions should also be taken into account as energy storage systems in some extreme environments are expected to have a higher O&M cost structure that those in a more temperate climate.

2.6.3. Warranty

Warranty coverage is typically focused on two areas; manufacturing defect, and performance. The limited warranty covering manufacturing defect guarantees the battery 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 is not extended to any design issues of the product, and does not reimburse for economic loss resulting from downtime.

The warranty period can vary depending upon the market and/or usage profile under which the battery is intended to operate. Typically, manufacturing warranties and performance warranties are provided with differing coverage periods. Generally, the manufactures warranty can be 15+ years, while performance warranty is provided for a much shorter period of time, and requires the operator to keep the operation of the system between certain parameters (temperature, Depth of Discharge, C-Rate, etc.)

Warranty periods are also dependent upon the usage profile expected for the facility. For instance, in the commercial and residential market with a simplistic usage assumption, the warranty period would be listed in years, with 10 years being typical now, which is simply capitalized into purchase. Increasingly, this time period is being supplemented by a throughput level not to be exceeded. For larger utility scale systems that will define coverage in more detail depending on the usage, typical original equipment warranty coverage is 1-3 years, with the ability for the customer to buy an extended warranty on a year by year basis.

The performance warranty is a growing area of focus for developers and lenders. The performance warranty will cover the technical rating of the unit, with respect to such issues as: power, energy, efficiency, duration, and availability. Performance warranties vary by OEM provider, but are generally centered on energy storage capacity (kWh) or energy throughput (kWh) provisions over the life of the unit. Using storage capacity as a framework, the performance warranty is typically described as a specified schedule of guaranteed energy capacity (kWh) of at least X% of the rated energy capacity for a specific number of years (or cycles) after the date of the initial installation. The rated capacity under the warranty is typically either step down every few years, or be a straight-line annual reduction. Using energy throughput as a framework, the performance warranty is typically described as a certain amount of energy throughput over the life, generally according to a specific table per annual usage while the system is operated under normal conditions and can include such issues as temperature, charging/discharging rates, state of charge operating range.

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.

3. CHANGES IN THE ENERGY STORAGE PRICING SURVEY

The Energy Storage Pricing Survey is designed to provide an accurate benchmark system price for a variety of energy storage technologies at a range of different power and energy ratings.

3.1. Changes from the Previous Edition

There are a number of both minor and major changes between the 2018 and 2019 edition of the Energy Storage Pricing Survey.

3.1.1. Technologies

The area of change is the alteration of the energy storage covered in the Survey, resulting in the number of technologies covered moving from 14 to 15 energy storage technology categories.

The energy storage technologies added were:

- Liquid Air Energy Storage (LAES)
- Gravity Energy Storage (GES)

Changes in Definitions

- Compressed Air Energy Storage (CAES). LAES prices were included in CAES pricing in the 2018 survey and are now their own technology category.

The energy storage technologies removed were:

- Nickel (Ni)

3.1.2. Forecast

The 2019 Energy Storage Pricing Survey add a 10-year forecast to the single-year survey results. The forecast is for each data point calculated for the current year, for a total of ___ individual system cost forecasts.

These system price forecasts are developed by developing a pricing forecast for each of the different components of the energy storage systems, and then adding these individual price components together. The core energy storage technology prices are obviously different, and the remaining components – balance of system, power conversion system, EPC work will vary by the power and/or energy rating of the facility. As more data becomes available, these component prices are being tailored to the different energy technology categories.

3.1.3. Structure

Significant work was undertaken between the 2018 and 2019 Energy Storage Pricing Survey to strengthen the core pricing structure to align the Survey with typical practices in the industry, and to allow for future developments of the Survey.

The calculations for the final system prices are done from a system integrator's point of view, since the goal is to provide potential customers with the most accurate price estimate for a particular energy storage technology a specific power & energy rating, This was chosen as the most all-inclusive pricing total that a potential customer would receive. Incumbent in this decision is the inclusion of component mark-ups and profit margin into the final price. Since the forecasts are done by estimating all of the components individually, simply totaling them together would provide the reader with an estimate of the costs of a system, but only at the component costs, and not at a price that is required for the long-term financial viability of the system integrators. Recent experience with a hyper-competitive market has provided customers with a possibly incorrect expectation for pricing based on large purchasers who receive best in class pricing due to their large purchases.

The core modeling structure of the Survey allows for a variety of additional work to continue at multiple points in the framework. For instance, improved views into the component pricing at different levels / volume purchases will provide a better insight into the pricing differentials of the same equipment to different customer classes. More layers of analysis can be added, such as a deeper view into usage profiles by adding specific augmentation and operational costs, which will support the development o the complete cost structure for a particular usage profile of energy storage system.

3.2. Future Edition Enhancements

There are a number of improvements planned for the future editions of the Energy Storage Pricing Survey to support improved accuracy of the system price estimation, and usefulness to the readers.

3.2.1. OEM Input

As the industry evolves, additional energy storage OEMs emerge to provide new energy storage technologies. In order to have a comprehensive reach into all potential vendors, the Energy Storage Pricing Survey should maintain contact with as many OEMs as possible.to best represent the energy storage technologies of greatest interest. Over the last few years a number of different flow battery chemistries were active and had pricing estimations included in the database. However, some of the OEMs that were the major, or even single champion of the technology folded, leaving the technology without a near term production option, and hence warranted removal from the pricing survey effort.

On the other hand, emerging technologies, once established with actual deployments such as the liquid air energy storage (LAES) technology option, warrants individual effort. In addition, if different variants within one technology family continue to provide significant different in performance, than the single technology category can be split.

3.2.2. Capital Costs

Constant effort will need to be made to improve the core effort of the Energy Storage Pricing Survey – the deeper and comprehensive review of capital costs. The first effort will be to improve storage module pricing through expanding the network of OEMS and developers to obtain a clearer pricing structure for the different energy storage technologies at different deployment scale.

Another effort will be to improve Balance of System and power conversion system cost estimates through more detailed pricing analysis. There are a number of different components required for improving safety and environmental conditioning requirements. Improving the component specification for different operating environments would improve deployment specific cost requirements.

3.2.3. Operating & Maintenance Costs

With the growing interest in the operating cost for energy storage systems, the effort to improve collection of fixed and variable O&M costs is gaining prominence. Breaking out these costs from a simple, single metric is beginning to become available as more projects have been deployed and experience gained.

This effort will be useful to characterize the operating cost for different operating modes and applications. This will be important if this effort moves towards presenting total operating costs for energy storage systems for specific usage profiles.

3.2.4. Warranty Costs

As possible insurance coverage gains greater scrutiny for cost recovery in the event of a system failure, improving the structuring of warranty costs to be better representative of both their coverage and cost during operation. As operating experience has been gained, warranty coverage and costs are becoming more specific to usage profile. Future pricing analysis that will take into account usage profiles will need to have a better understating of usage profiles and their effect on operating lifespan. Warranty analysis can be used as a proxy for operating lifespan.

3.2.5. Insurance

Insurance costs are becoming more important to the financial viability of an energy storage system. Coupled with the requirement for standard insurance coverage, having an understanding of these costs will be important for customers to frame the full operating costs for an energy storage project.

3.2.6. EPC Costs

Engineering, procurement, and construction (EPC) costs are a significant component of the overall cost of a delivered energy storage system, and that due to the lack of widespread experience with these technologies, there is a very wide range of costs that can be incurred. Additional experience by firms active in the market are expected to drive down EPC costs over time. However, additional variation can be traced to deployment in different deployment environments or building types.

The goal of a future refinement of the energy storage pricing survey's analytical framework would be to develop a US regional and deployment specific (urban, suburban, & rural) EPC cost structure.

There will be three areas of effort towards improving the EPC cost estimate in future pricing surveys.

- First, as non-lithium systems gain experience in deployments, better costs estimates will be derived for the differing energy storage technologies.
- Second, the survey will attempt to improve its cost estimates for site-specific costs driven by variabilities, even for the same size system. For instance, the EPCs costs for the same size (power and energy) system will vary depending on if it is deployed inside a commercial building, exterior to a customer's building, or in a greenfield location.
- Finally, the survey will attempt to develop a better price estimate for EPC costs for different regions of the country.

3.2.7. End of Life

End of life costs for energy storage assets have been given scant if any coverage in system costs. As the focus of energy storage projects move from not just initial capital costs to total cost of ownership, potential customers should have a framework for understanding what the End of Life costs for these systems will be, as they will vary from storage technology to storage technology.

4. ENERGY STORAGE TECHNOLOGY DETAIL

The technology detail chapter will include more detailed information on both the technologies, and the results of the pricing survey.

- System pricing will be provided at the DC System, AC System, and AC fully installed levels.

Where available, a standard list of details is provided for each of the 15 different technologies. These include:

The first table is the 2019 Installed System Costs.

- Relevant energy ratings at different power levels.
- Shows structure of technology at different scales
- To highlight both the power and energy aspect of the technologies, different energy durations will be provided with a similar power rating to give readers the ability to understand the cost impact of additional energy storage capacity at similar power levels.
- Buying power

Performance Characteristics (Table).

- Relevant operating information
- Useful when trying to determine the annual and lifetime cost of ownership.

2019 Installed Costs (graph)

- Forecasted prices.
- Focused only 4-hour systems (where possible) for comparisons across different power ratings

4.1. Pumped Hydro Storage (PHS)

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

A typical PHS facility consists of two large reservoirs, with the upper one 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. Generally, pumped hydro storage facilities can be sized anywhere from the 10s to 100's of MWs (although above 100Mw is typical due to the high fixed costs of the power train and storage facility). The discharge duration can also range from a few to more than 10 hours, depending on need. For PHS systems, the size and the elevation difference of the reservoirs are aspect of the system that most impacts the storage costs of the facility.

Location of these facilities is dictated by geography. Although the upper reservoir is typically constructed (and 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 the lake level is controlled.

Table 4-1. Pumped Hydro Storage (PHS) 2019 Installed System Costs

Pumped Hydro (PHS) - 2019					
$/kW	Size (MW)				
	100	10	1	0.1	0.01
PHS	1676.9				

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 pipeline 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 75%-80% (AC:AC).

Table 4-2. Pumped Hydro Storage (PHS) System Performance Characteristics

Pumped Hydro Storage (PHS) Performance Characteristics	
Lifespan:	40-60 Yrs.
Round-Trip Efficiency (AC):	75-80%
Operating Range (Depth of Discharge %):	100%
Capacity at End of Life (% of Original):	100%
Operation & Maintenance (O&M):	1%
Extended Warranty:	0%

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. 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.

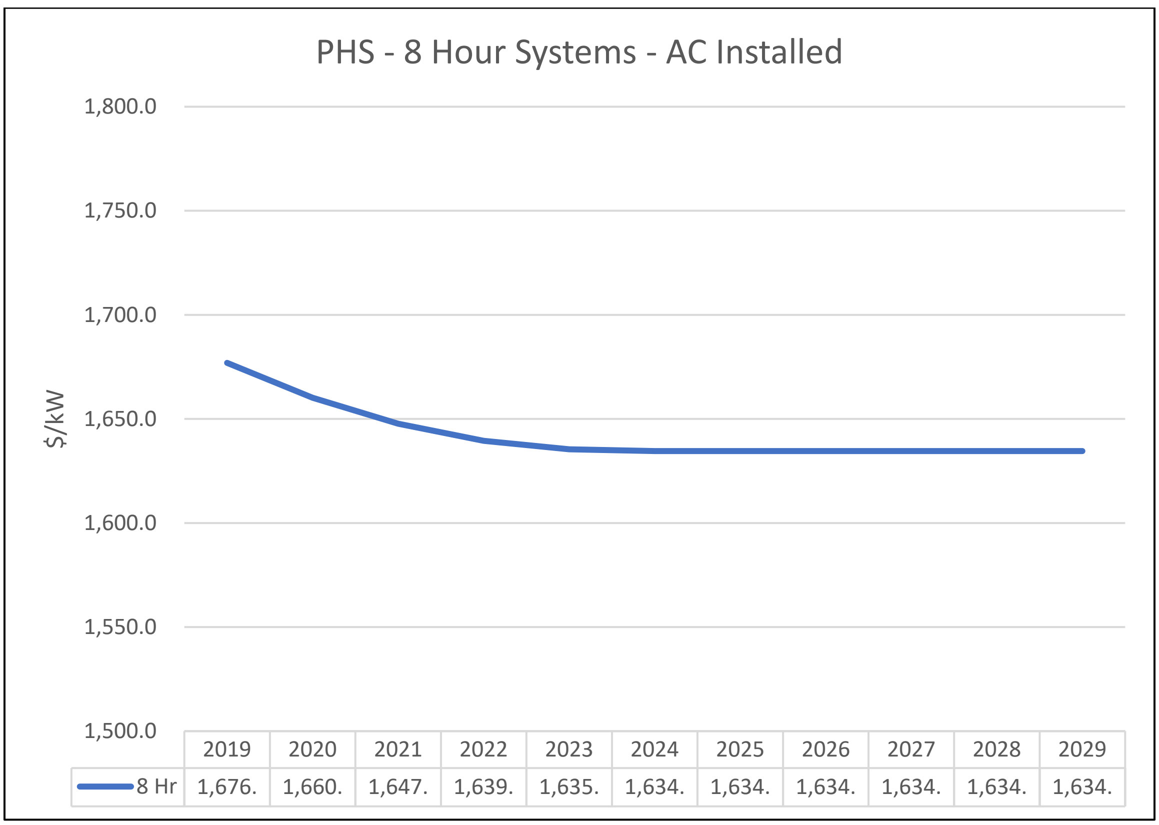


Figure 4-1. Pumped Hydro Storage (PHS) System Price Forecast

The equipment cost for pumped hydro storage systems is not expected to change dramatically over the forecast due to the more mature nature of the technology. Key drivers for PHS equipment costs are the amount of land required, and the scale of construction and cement required to build the two holding reservoirs. The powerhouse equipment can also be substantial, increasing the relative costs of smaller facilities.

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 with regard to improvement in power train technology.

4.2. 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 aspect of the technology. Depending on the market use of the facility, a set of small or large air reservoirs could be used for the same powerhouse equipment, skewing the more common $/kWh pricing metric for energy storage technologies.

Traditional CAES facilities are essentially 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. Modern variants utilize only the compressor stage with an electric motor generator, eliminating the need for natural gas. Potentially, compressed air energy storage facilities could be sized anywhere from the 10s to 100's of MWs, depending on the technology used. The discharge duration can also range from a few to more than 10 hours, depending on need.

CAES system deployment is regulated on the location of the available storage option. Many traditional CAES facilities utilize natural geological features like aquifers, hard rock mines, salt caverns, or conversely, man-made surface tank storage. Due to their physical size, compressed air energy storage facilities are active primarily in the wholesale power market, providing both energy and ancillary services.

Table 4-3. Compressed Air Energy Storage (CAES) 2019 Installed System Costs

Compressed Air Energy Storage (CAES) - 2019					
$/kWh	Size (MW)				
	100	10	1	0.1	0.01
CAES	1506.2				

The round-trip efficiency of compressed air energy storage facilities is determined by the efficiency of the pump/generator, and friction losses stemming from driving the air into the typically underground cavern. The average round-trip efficiency for existing diabatic CAES facilities ranges between 75% and 80%; with newer designs claim upward of 85%. 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,

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.

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

Compressed Air Energy Storage (CAES) System Performance Characteristics	
Lifespan:	40 Yrs.
Round-Trip Efficiency (AC):	55-80%
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%

The equipment cost for compressed air energy storage systems is not expected to change dramatically over the forecast for more traditional designs due to the mature nature of the technology but has the opportunity to decrease somewhat with newer designs.

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. Potential significant improvements in future capital cost reductions of traditional compressed air energy storage systems are limited due to the level of maturity of the technology. Continued improvements in newer variants are expected to be more pronounced.

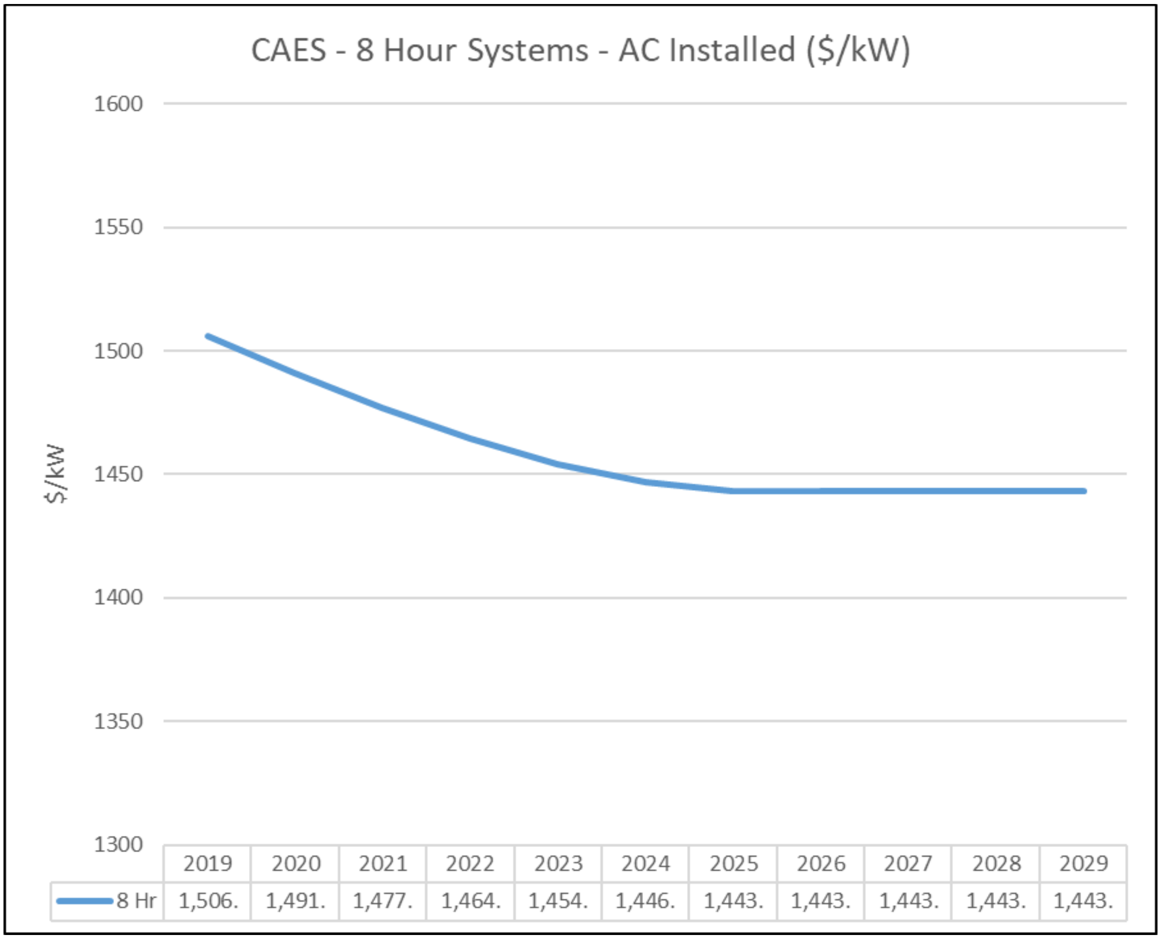


Figure 4-2. Compressed Air Energy Storage (CAES) System Price Forecast

4.3. 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 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. The energy storage capital equipment of this technology has a more pronounced c

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 10s 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 are aspect of the system that most impacts the storage costs of the facility.

LAES system can be deployed at the developer's discretion as the storage medium is hosed 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.

Table 4-5. Liquid Air Energy Storage (LAES) 2019 Installed System Costs

Liquid Air Energy Storage (LAES) - 2019					
$/kWh	Size (MW)				
	100	10	1	0.1	0.01
LAES: 4-Hr	451.0	511.5			
LAES: 8-Hr	305.3	353.4			

The round-trip efficiency of liquid air energy storage facilities is determined by the efficiency of the charging/discharging equipment. 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 4-6. Liquid Air Energy Storage (LAES) System Performance Characteristics

Liquid Air Energy Storage Performance Characteristics	
Lifespan:	40+ Yrs.
Round-Trip Efficiency (AC):	55-80%
Operating Range (Depth of Discharge %):	100%
Capacity at End of Life (% of Original):	100%
Operation & Maintenance (O&M):	1%

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. Key drivers for LAES equipment costs are the integrated storage facility and cryogenic storage technology. Most designs have a relatively fixed conversion system, so storage capacity can lower energy storage costs through additional tankage deployment. 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.

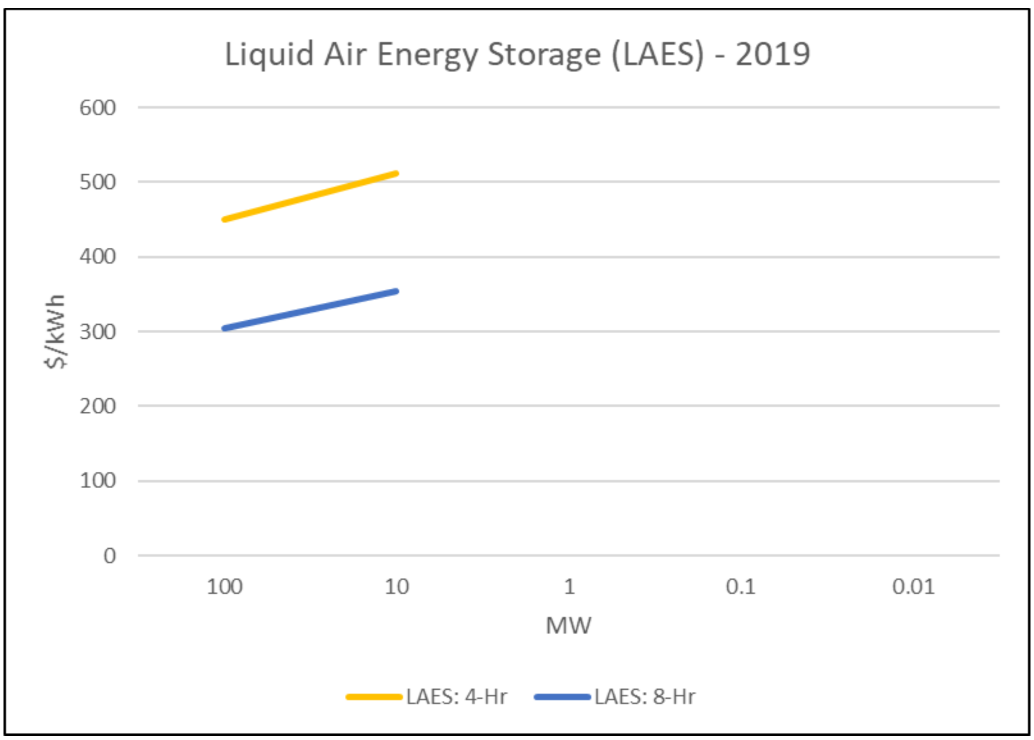
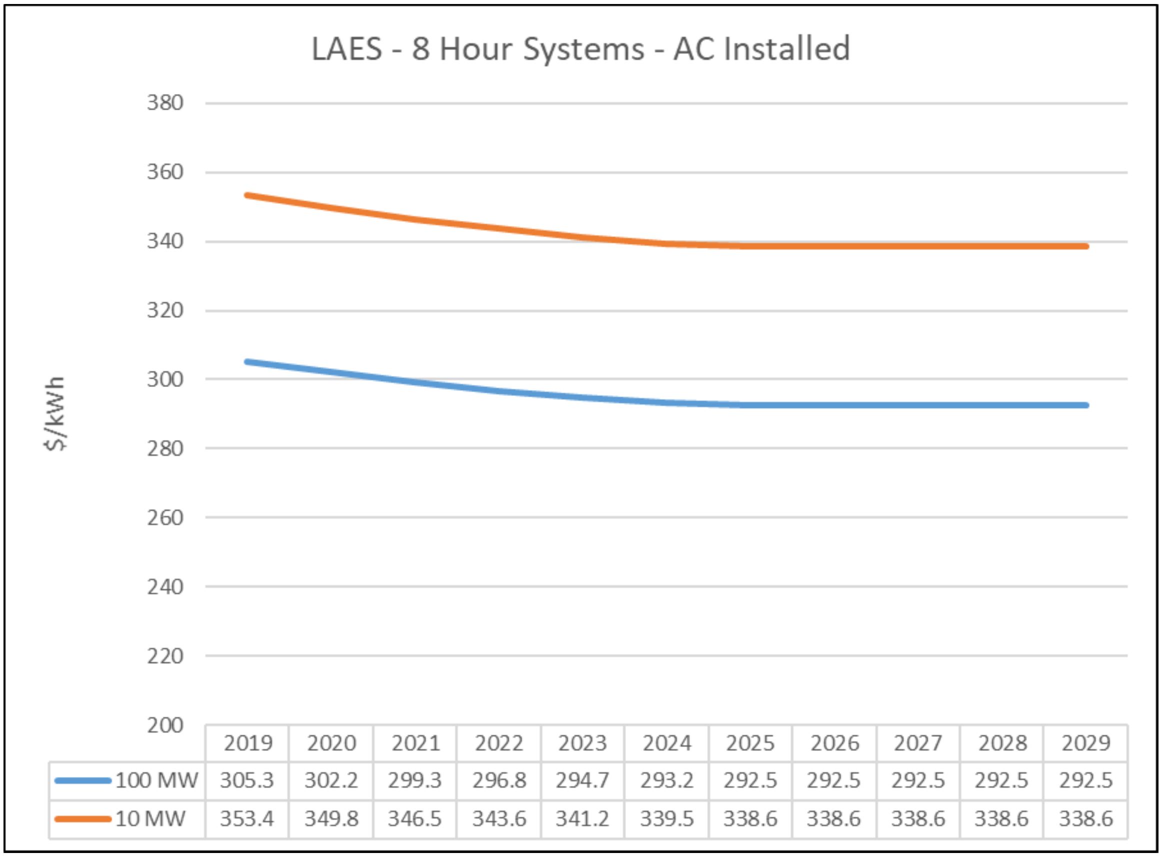


Figure 4-3. Liquid Air Energy Storage (LAES) 2019 Installed System Costs



	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
100 MW	305.3	302.2	299.3	296.8	294.7	293.2	292.5	292.5	292.5	292.5	292.5
10 MW	353.4	349.8	346.5	343.6	341.2	339.5	338.6	338.6	338.6	338.6	338.6

Figure 4-4. Liquid Air Energy Storage (LAES) System Price Forecast

4.4. Gravity Energy Storage (GES)

Capital costs for gravity energy storage (GES) systems are provided in $/kW for the energy storage pricing survey because the majority of the costs are associated with the power aspect of the technology. Depending on the market use of the facility, a set of small or large energy cycling capacity could be used for the same powerhouse equipment, skewing the more common $/kWh pricing metric for energy storage technologies.

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 10s 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.

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 needed. 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.

Table 4-7. Gravity Energy Storage (GES) 2019 Installed System Costs

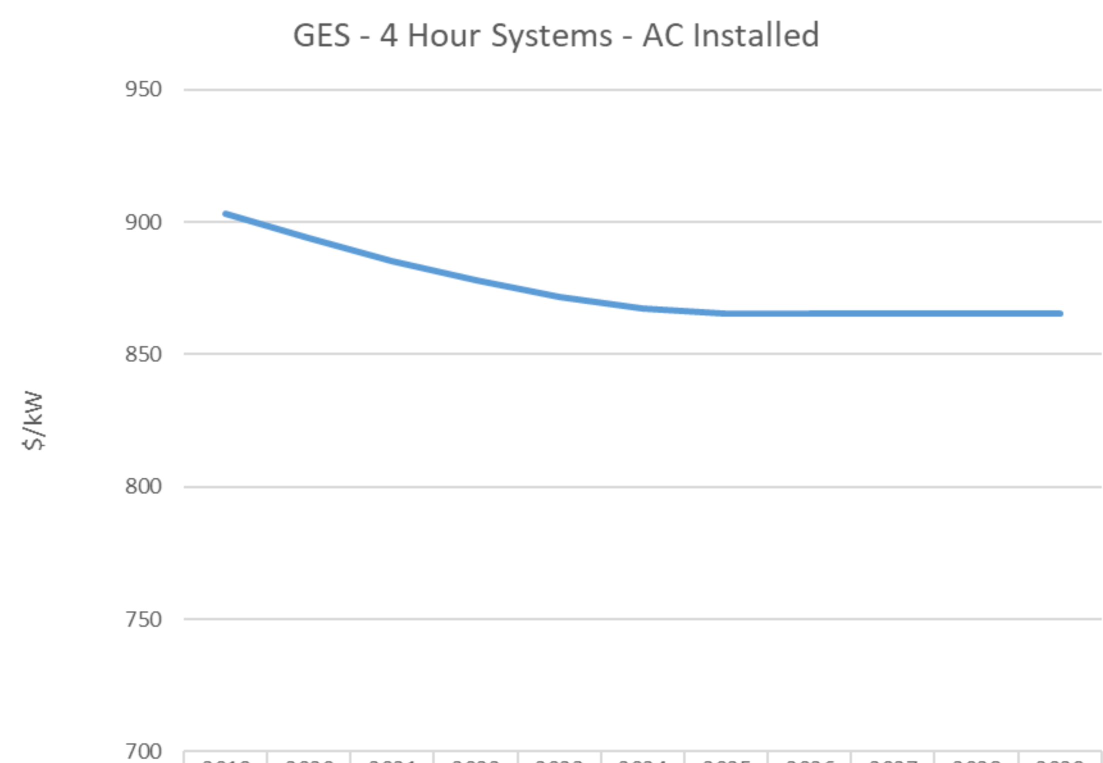
Gravity Energy Storage (GES) - 2019					
$/kWh	Size (MW)				
	100	10	1	0.1	0.01
GES: 4-Hr	903.0				

The round-trip efficiency of sodium (Na) 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 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.

Table 4-8. Gravity Energy Storage (GES) System Performance Characteristics

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

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. 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. 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.



	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
100 MW	903.0	894.0	885.5	878.0	871.8	867.4	865.3	865.3	865.3	865.3	865.3

Figure 4-5. Gravity Energy Storage (GES) System Price Forecast

4.5. 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. In addition, the majority of the active ingredients in the cell chemistry are designed to maximize the storage of energy.

The 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.

For sodium systems, the material selection and manufacturing process have the largest impact on the capital equipment costs. 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. Sodium 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.

Table 4-9. Sodium (Na) 2019 Installed System Costs

Sodium (Na) - 2019					
$/kWh	Size (MW)				
	100	10	1	0.1	0.01
NA: 6-Hr	376.3	389.6	428.7		

With minimal cell degradation, the cycle life is also far higher than many other chemical batteries, generally using 15 years as an average estimation. 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. 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.

Table 4-10. Sodium (Na) System Performance Characteristics

Sodium (Na) Performance Characteristics	
Lifespan:	15 Yrs.
Round-Trip Efficiency (AC):	75%
Operating Range (Depth of Discharge %):	80%
Capacity at End of Life (% of Original):	80%
Operation & Maintenance (O&M):	1-2%

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

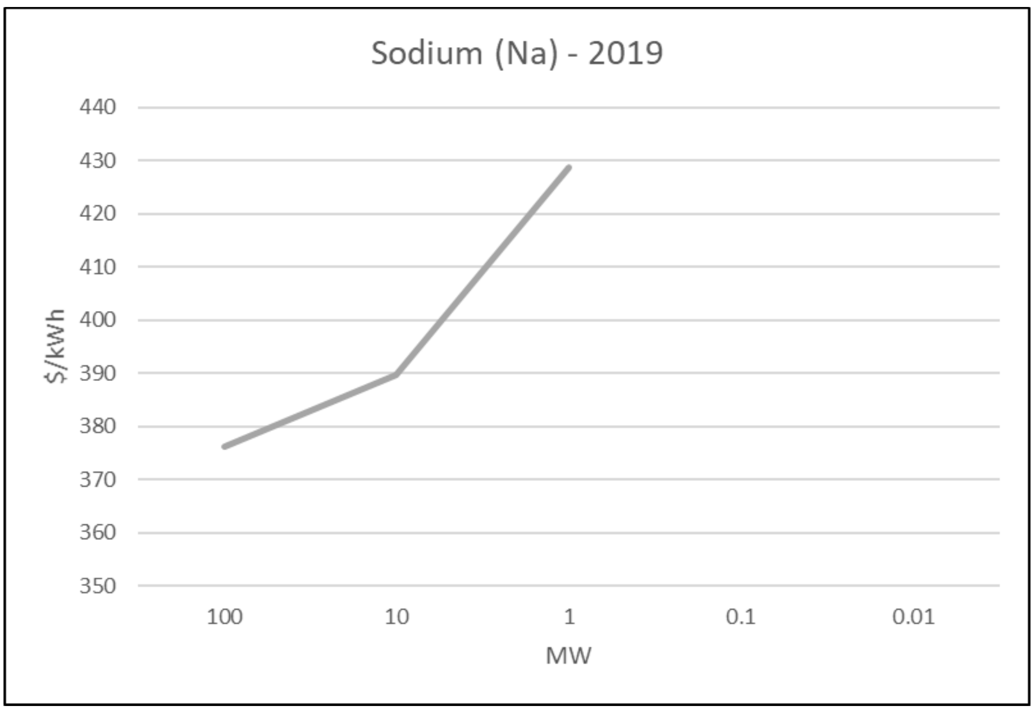
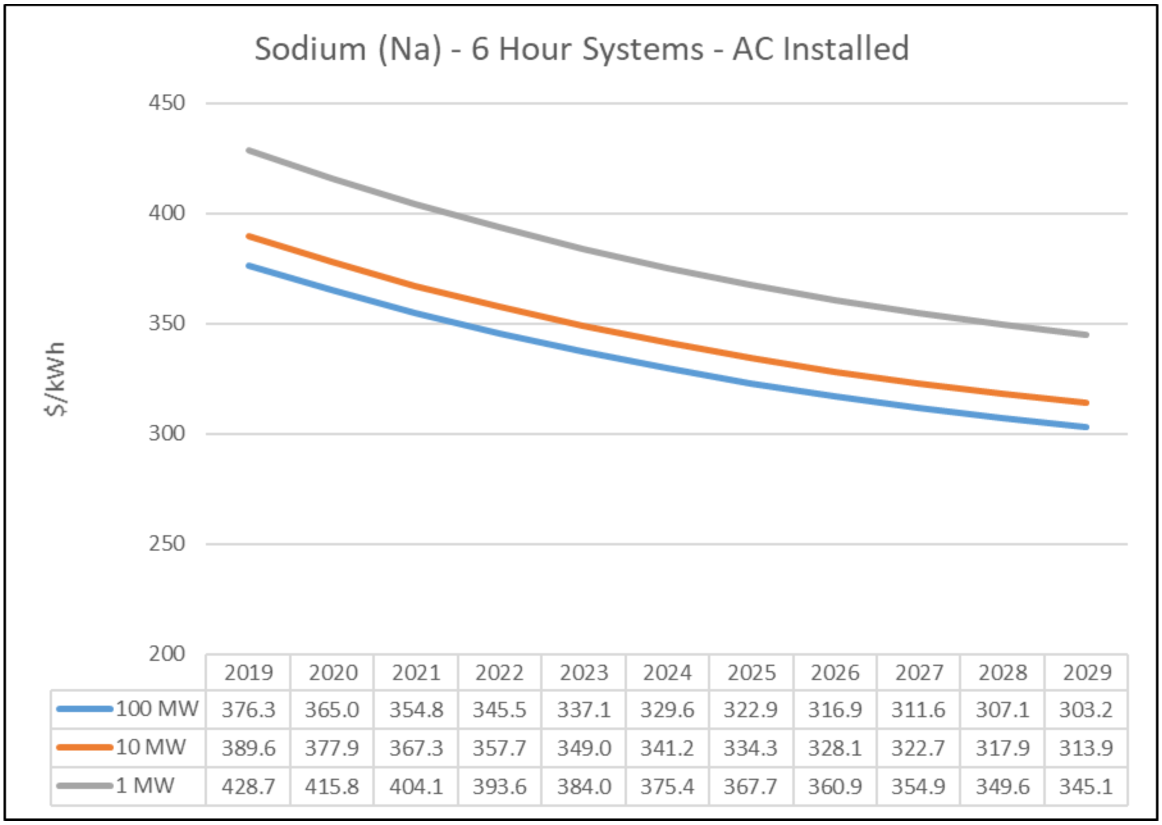


Figure 4-6. Sodium (Na) 2019 Installed System Costs



	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
100 MW	376.3	365.0	354.8	345.5	337.1	329.6	322.9	316.9	311.6	307.1	303.2
10 MW	389.6	377.9	367.3	357.7	349.0	341.2	334.3	328.1	322.7	317.9	313.9
1 MW	428.7	415.8	404.1	393.6	384.0	375.4	367.7	360.9	354.9	349.6	345.1

Figure 4-7. Sodium (Na) System Price Forecast

4.6. Flow Battery: Vanadium (FB V)

Capital costs for vanadium flow battery (FB V) 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.

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 ions. 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.

Vanadium flow batteries are designed for outdoor deployment. 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.

Table 4-11. Flow Battery: Vanadium (FB V) 2019 Installed System Costs

Flow Battery - Vanadium - 2019					
$/kWh	Size (MW)				
	100	10	1	0.1	0.01
FB V: 4-Hr	417.0	489.9	568.4	863.0	
FB V: 6-Hr	376.5	448.6	506.7	764.5	
FB V: 8-Hr	309.7	372.2	439.0	620.2	

The round-trip efficiency of vanadium flow battery facilities is determined by the efficiency of the charging/discharging equipment. The technology can have a wide operating efficiency range, depending on the amount of operation. 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.

Table 4-12. Flow Battery: Vanadium (FB V) System Performance Characteristics

Flow Battery: Vanadium 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):	2-3%

The equipment cost for vanadium flow battery technology has the potential for modest cost reductions over the forecast period. Key drivers for vanadium flow battery equipment costs is 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. Potential significant improvements in future capital cost reductions for vanadium flow batteries are possible through improved chemistry.

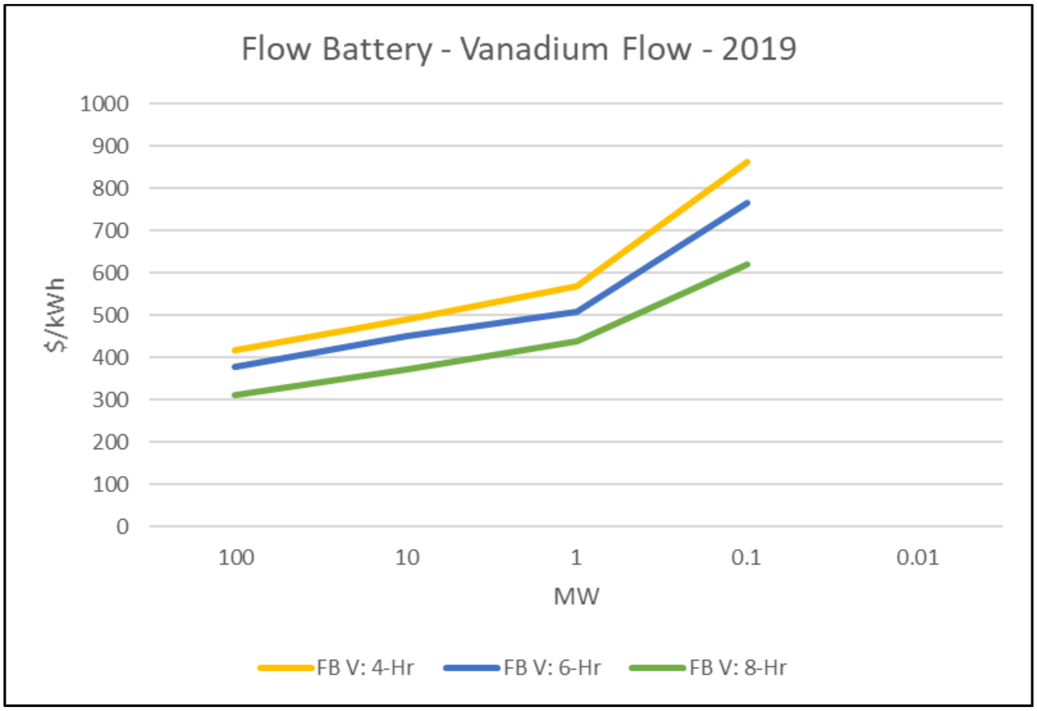
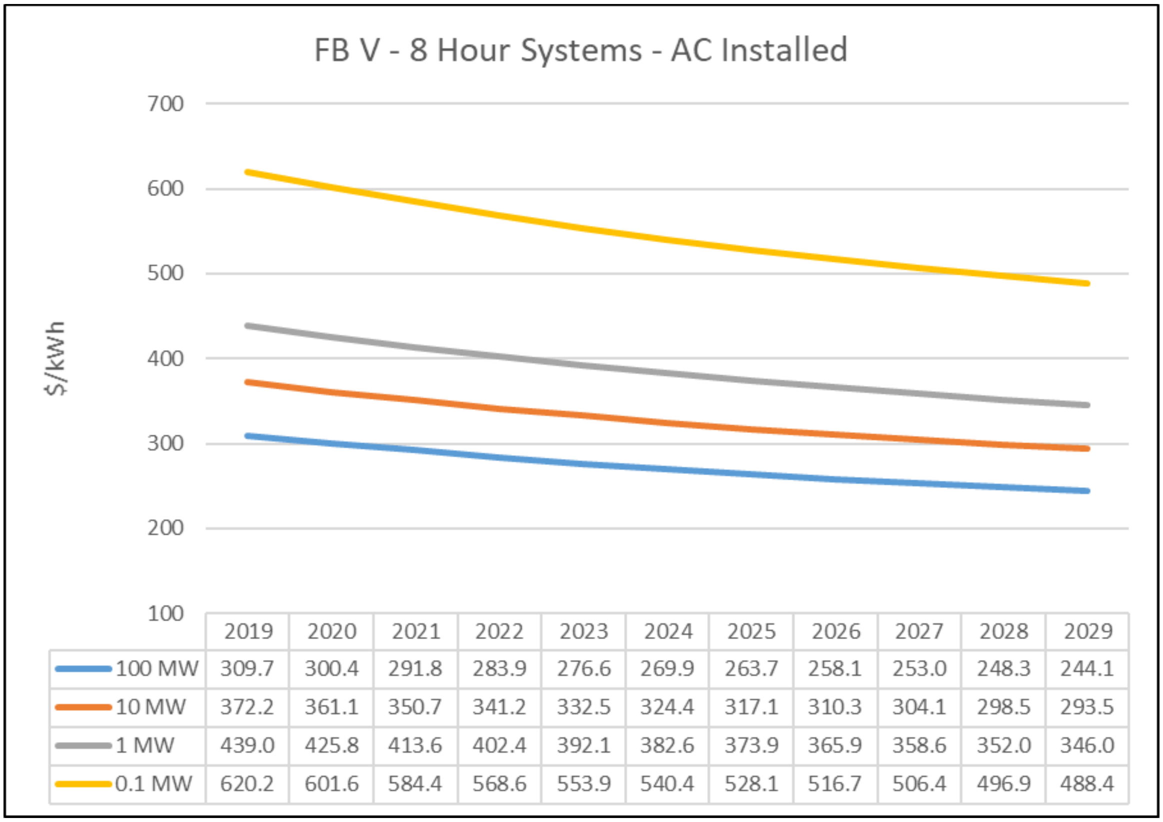


Figure 4-8. Flow Battery: Vanadium (FB V) 2019 Installed System Prices



	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
100 MW	309.7	300.4	291.8	283.9	276.6	269.9	263.7	258.1	253.0	248.3	244.1
10 MW	372.2	361.1	350.7	341.2	332.5	324.4	317.1	310.3	304.1	298.5	293.5
1 MW	439.0	425.8	413.6	402.4	392.1	382.6	373.9	365.9	358.6	352.0	346.0
0.1 MW	620.2	601.6	584.4	568.6	553.9	540.4	528.1	516.7	506.4	496.9	488.4

Figure 4-9. Flow Battery: Vanadium (FB V) System Price Forecast

4.7. Flow Battery: Zinc Bromide (FB ZnBr)

Capital costs for zinc bromide (FB ZnBr) 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.

Zinc Bromide flow batteries store energy through the plating of Zinc onto electrodes. The zinc is held in solution and pumped through a reaction chamber. Because of 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.

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.

Table 4-13. Flow Battery: Zinc Bromide (FB ZnBr) 2019 Installed System Costs

Flow Battery - Zinc Bromide - 2019					
$/kWh	Size (MW)				
	100	10	1	0.1	0.01
FB ZnBr: 3-Hr					
FB ZnBr: 4-Hr	513.5	551.4	592.1	650.9	
FB ZnBr: 5-Hr	475.9	490.7	506.0	542.0	
FB ZnBr: 6-Hr	450.9	464.9	478.8	510.6	

The round-trip efficiency of zinc bromide flow battery facilities is determined by the efficiency of the charging/discharging equipment. 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 4-14. Flow Battery: Zinc Bromide (FB ZnBr) 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%

The equipment cost for zinc bromide flow battery technology has the potential for modest cost reductions over the forecast period. Key drivers for zinc bromide flow battery equipment costs are the cost of the stacks, and plumbing/piping for the electrolyte. Overall manufacturing cost reduction, scale, and material sourcing advances are the key avenues for continued cost reductions. Potential significant improvements in future capital cost reductions for zinc bromide flow batteries are possible through improved chemistry.

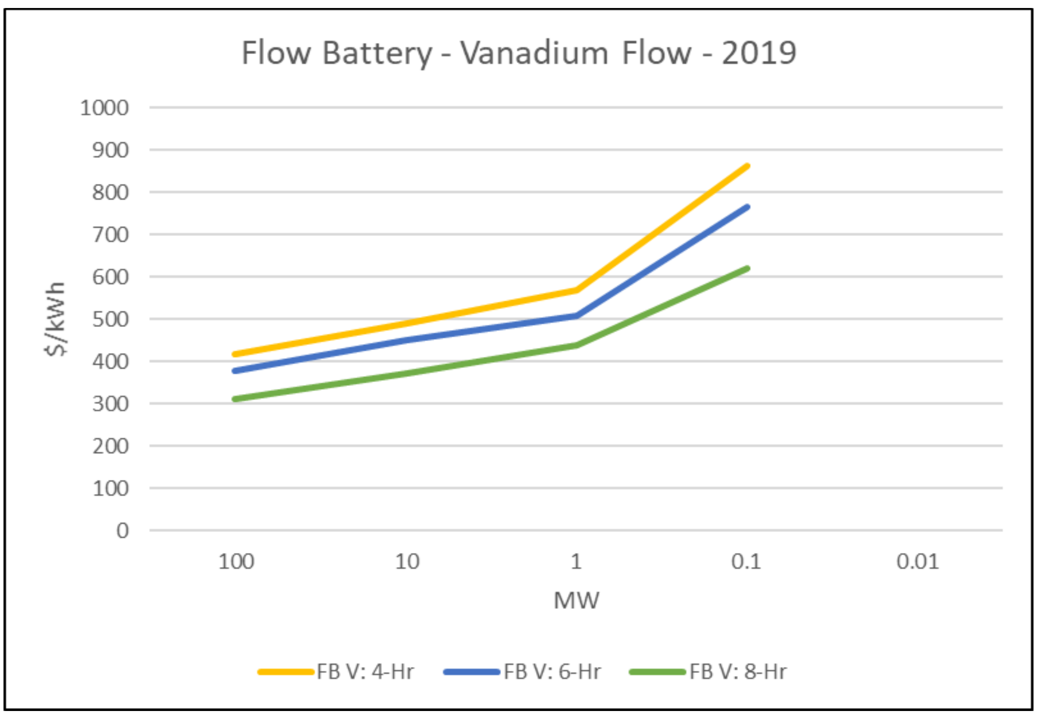
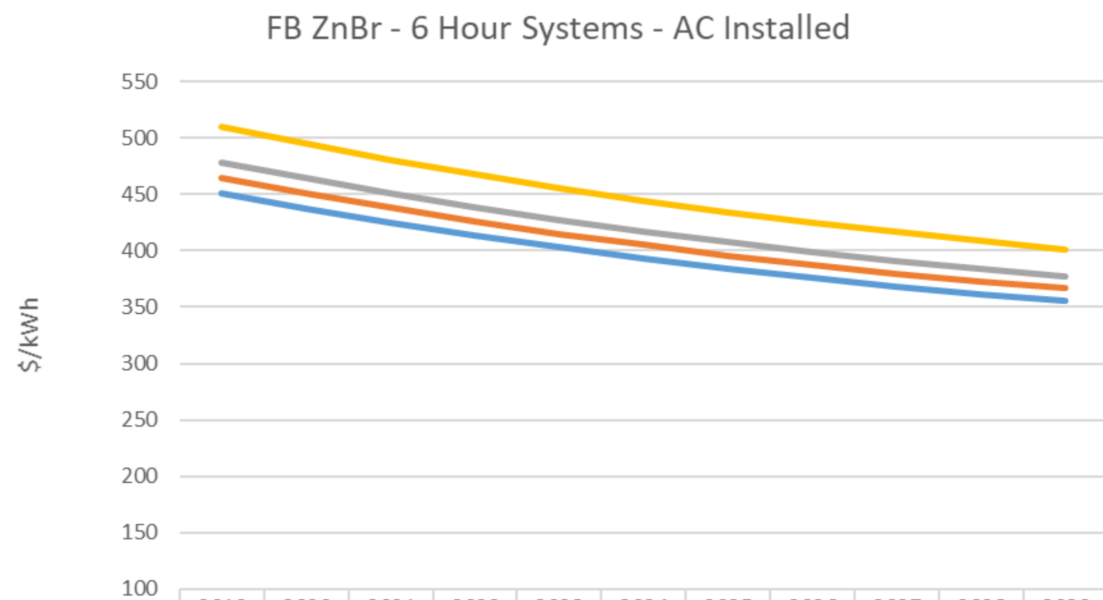


Figure 4-10. Flow Battery: Zinc Bromide (FB ZnBr) 2019 System Price Forecast



	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
100 MW	450.9	437.4	424.9	413.4	402.8	393.0	384.1	375.9	368.4	361.6	355.5
10 MW	464.9	450.9	438.0	426.2	415.2	405.2	395.9	387.5	379.8	372.8	366.5
1 MW	478.8	464.4	451.2	438.9	427.6	417.3	407.7	399.0	391.0	383.8	377.2
100 kW	510.6	495.2	481.1	468.0	455.9	444.7	434.5	425.0	416.4	408.5	401.4

Figure 4-11. Flow Battery: Zinc Bromide (FB ZnBr) System Price Forecast

4.8. Flow Battery: Iron (FB Fe)

Capital costs for iron flow battery (FB Fe) 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.

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.

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.

Table 4-15. Flow Battery: Iron (FB Fe) 2019 Installed System Costs

Flow Battery - Iron - 2019					
$/kWh	Size (MW)				
	100	10	1	0.1	0.01
FB Fe: 4Hr	413.9	435.5	464.3	529.5	
FB Fe: 8Hr	362.7	381.7	404.7	438.4	

The round-trip efficiency of iron flow battery facilities is determined by the efficiency of the charging/discharging equipment. The technology can have a wide operating efficiency range, depending on the amount of operation. 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.

Table 4-16. Flow Battery: Iron (FB Fe) 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%

The equipment cost for iron flow battery technology has the potential for modest cost reductions over the forecast period. 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. Potential significant improvements in future capital cost reductions for iron flow batteries are possible through improved chemistry.

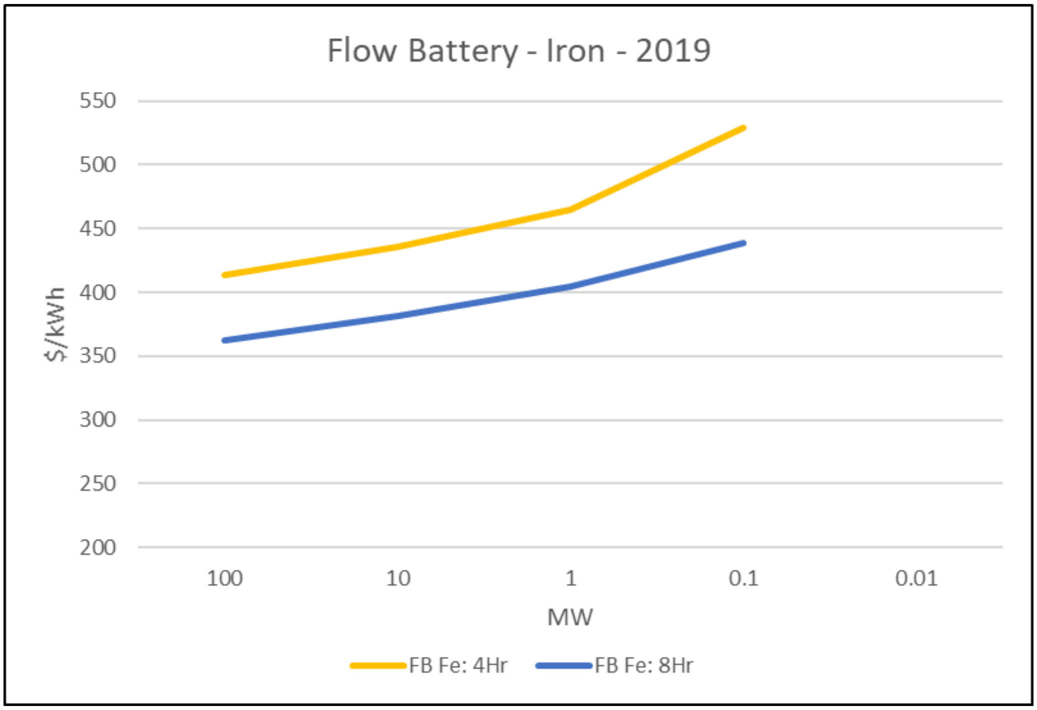
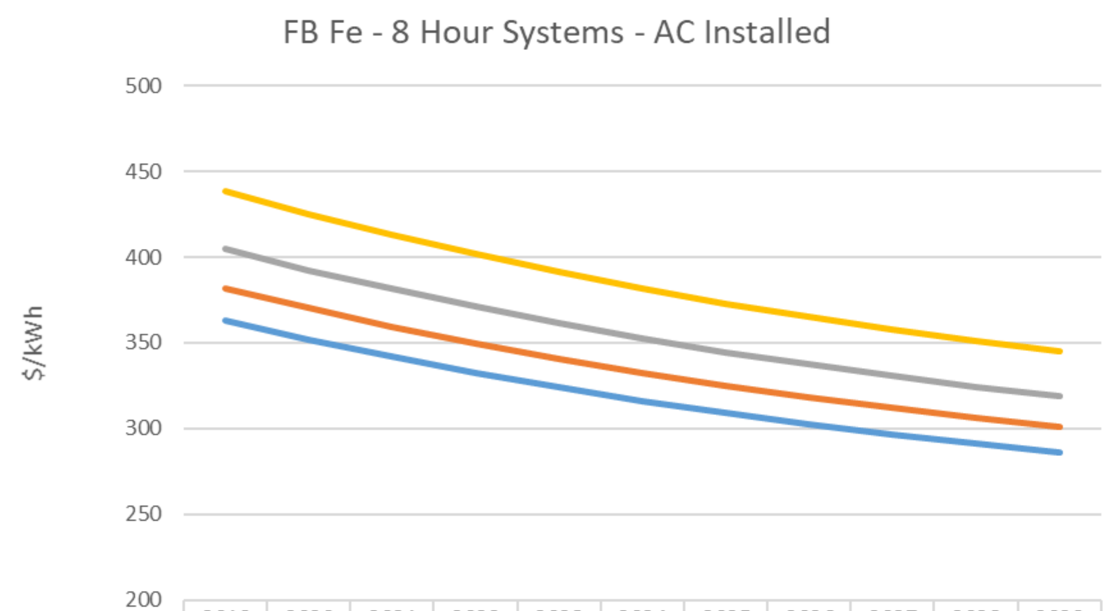


Figure 4-12. Flow Battery: Iron (FB Fe) 2019 System Price Forecast



	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
100 MW	362.7	351.8	341.7	332.5	323.9	316.1	308.9	302.3	296.3	290.9	286.0
10 MW	381.7	370.2	359.6	349.9	340.9	332.7	325.1	318.2	311.9	306.1	301.0
1 MW	404.7	392.6	381.3	371.0	361.5	352.7	344.7	337.3	330.6	324.5	319.0
100 kW	438.4	425.2	413.0	401.8	391.4	381.9	373.1	365.0	357.7	351.0	344.9

Figure 4-13. Flow Battery: Iron (FB Fe) System Price Forecast

4.9. Flywheel: Long Duration (FW LD)

Capital costs for long duration flywheel (FW LD) 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.

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.

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

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

Table 4-17. Flywheel: Long Duration (FW LD) 2019 Installed System Costs

Flywheel - Long Duration - 2019					
$/kWh	Size (MW)				
	100	10	1	0.1	0.01
FW LD: 4-Hr		677.8	766.0	855.3	975.0

The round-trip efficiency of long duration flywheel systems is predominately determined by the efficiency of the motor/generator. 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.

These systems are also able to tolerate operation in temperature ranges far higher than is acceptable for typical chemical battery systems. 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. Roundtrip efficiencies of many current production models are in the 70% to 80% range, with some newer designs even higher. Flywheel energy storage systems are designed to maintain their performance under harsh environmental and operational experience.

Table 4-18. Flywheel: Long Duration (FW LD) System Performance Characteristics

Flywheel: Long Duration Performance Characteristics	
Lifespan:	20 Yrs.
Round-Trip Efficiency (AC):	95%
Operating Range (Depth of Discharge %):	100%
Capacity at End of Life (% of Original):	100%
Operation & Maintenance (O&M):	1-2%

The equipment cost for existing long duration flywheel technology has the potential for some cost reductions over the forecast period. 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. Potential significant improvements in future capital cost reductions in flywheels are possible through improved motor/generator design or use of different materials.

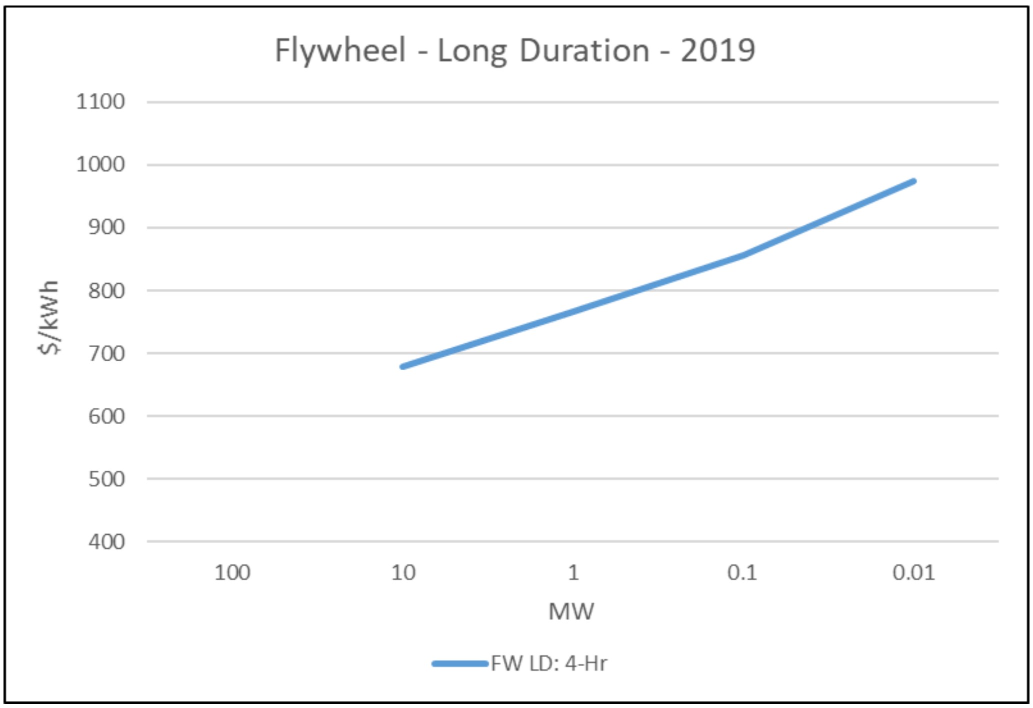
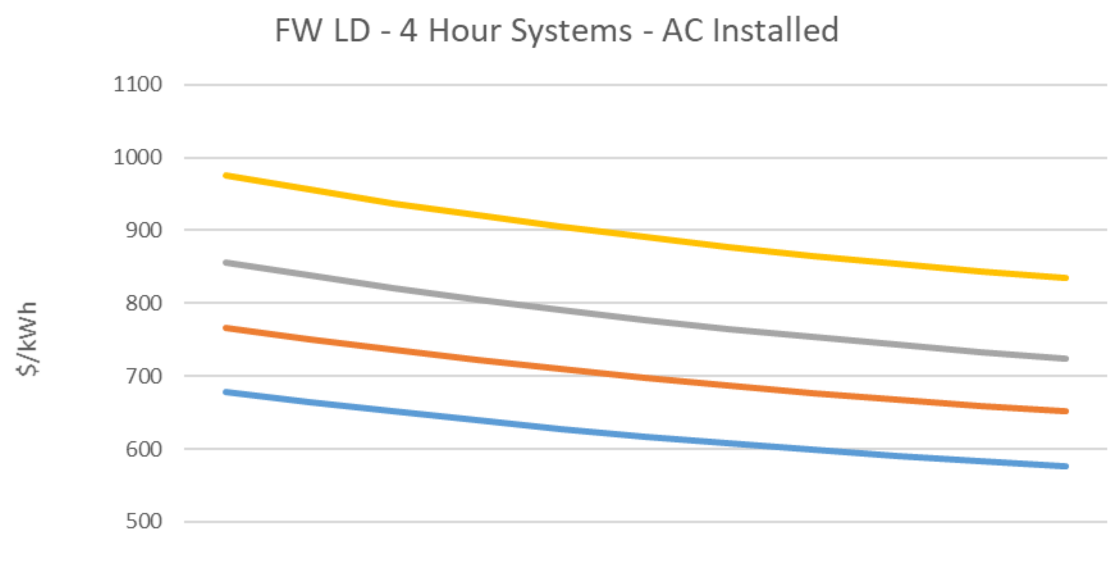


Figure 4-14. Flywheel: Long Duration (FW LD) 2019 Installed System Costs



	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
10 MW	677.8	664.0	651.1	639.1	627.9	617.5	607.9	599.1	590.9	583.5	576.7
1 MW	766.0	750.4	735.7	722.1	709.4	697.6	686.7	676.6	667.3	658.8	651.1
0.1 MW	855.3	837.5	820.9	805.4	791.0	777.5	765.0	753.4	742.8	732.9	723.9
0.01 MW	975.0	955.5	937.3	920.5	904.8	890.3	877.0	864.7	853.5	843.2	834.0

Figure 4-15. Flywheel: Long Duration (FW LD) System Price Forecast

4.10. Flywheel: Short Duration (FW SD)

Capital costs for short duration flywheel (SD FW) 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, non-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.

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.

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. 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. 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 2019 Energy Storage Pricing Survey is not explicitly covering that application.

Table 4-19. Flywheel: Short Duration (FW SD) 2019 Installed System Costs

Flywheel - Short Duration - 2019					
$/kW	Size (MW)				
	100	10	1	0.1	0.01
FW SD		984.0	1190.0	1500.0	

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

These systems are also able to tolerate operation in temperature ranges far higher than is acceptable for typical chemical battery systems. In addition, most short duration flywheel system designs focused on non-UPS markets are able to cycle tens of thousands of times, in support of the frequency regulation application usage requirements. Flywheels are capable of reacting very quickly—as one would assume given the widespread use of this technology in the UPS role.

Roundtrip efficiencies of many current production models are in the 70% to 80% range, with some newer designs even higher. Typically, these will fall lower than the energy centric flywheels as the short duration ones are designed to produce higher power output. Flywheel energy storage systems are designed to maintain their performance under harsh environmental and operational experience.

Table 4-20. Flywheel: Short Duration (FWSD) System Performance Characteristics

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

The equipment cost for existing short duration flywheel technology has the potential for some cost reductions over the forecast period. 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. Potential significant improvements in future capital cost reductions in flywheels are possible through improved motor/generator design or use of different materials.

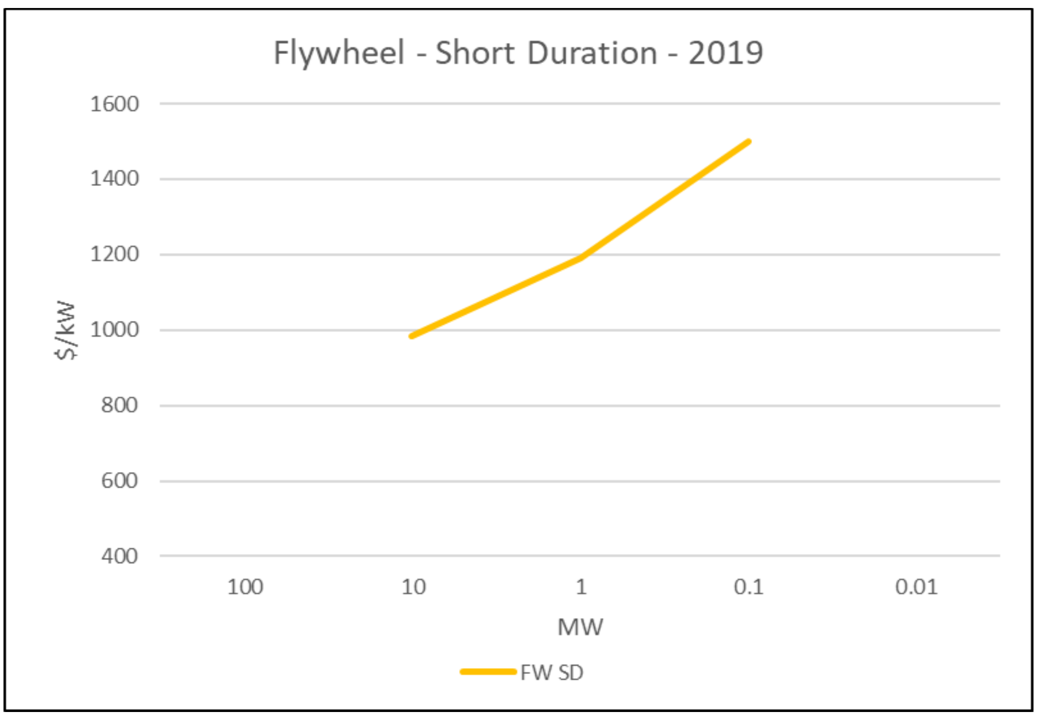
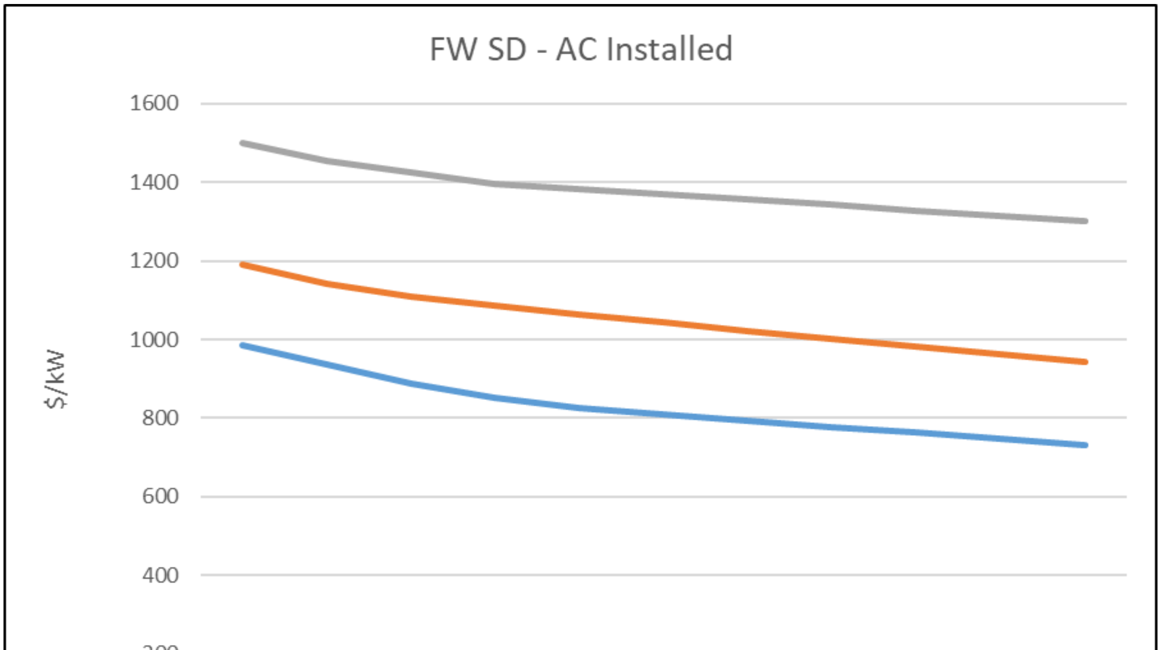


Figure 4-16. Flywheel: Short Duration (FW SD) 2019 Installed System Costs



	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
10 MW	984.0	934.8	888.1	852.5	827.0	810.4	794.2	778.3	762.8	747.5	732.6
1 MW	1,190.	1,142.	1,108.	1,086.	1,064.	1,043.	1,022.	1,001.	981.6	962.0	942.8
0.1 MW	1,500.	1,455.	1,425.	1,397.	1,383.	1,369.	1,355.	1,342.	1,328.	1,315.	1,302.

Figure 4-17. Flywheel: Short Duration (FW SD) System Price Forecast

4.11. Lithium Ion: Energy (Li)

Capital costs for lithium ion (Li) 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.

Lithium ion 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, lithium system for energy applications can range from 10 kWs 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 RFPs. For Lithium ion 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.

Lithium ion 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. Lithium ion systems in energy applications are designed for operation across the entire grid storage market, ranging from residential to wholesale power can operate across a number of market uses, ranging from large commercial, to utility, and wholesale applications.

Table 4-21. Lithium Ion: Energy (Li) 2019 Installed System Costs

Lithium-Ion (Energy) - 2019					
$/kWh	Size (MW)				
	100	10	1	0.1	0.01
Li: 2-Hr	425.1	460.2	527.0	683.6	1004.8
Li: 3-Hr	408.4	439.3	504.6	643.2	901.8
Li: 4-Hr	392.0	430.6	493.4	623.0	850.3
Li: 5-Hr	384.7	425.4	486.7	610.8	819.4
Li: 6-Hr	381.4	421.9	482.2	602.8	798.8
Li: 7-Hr	379.0	419.4	479.0	597.0	784.1
Li: 8-Hr	377.2	417.5	476.6	592.7	773.1

The round-trip efficiency of lithium ion facilities is determined by the efficiency of the ion exchange in the individual cell. 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 4-22. Lithium Ion: Energy (Li) System Performance Characteristics

Lithium-Ion: Energy Performance Characteristics	
Lifespan:	10-15 Yrs.
Round-Trip Efficiency (AC):	80-85%
Operating Range (Depth of Discharge %):	80-100%
Capacity at End of Life (% of Original):	70-80%
Operation & Maintenance (O&M):	1-2%

Lithium ion systems are capable of supporting a variety of market applications due the ability to be structured across a variety of power and energy ratings. As these designs can reach up to eight hours of duration, Lithium systems are easily geared toward energy applications. Lithium ion batteries are designed for a wide range of operation. Improving chemistry designs are improving their performance, but they still suffer lifespan and efficiency declines under harsh environmental and operational experience.

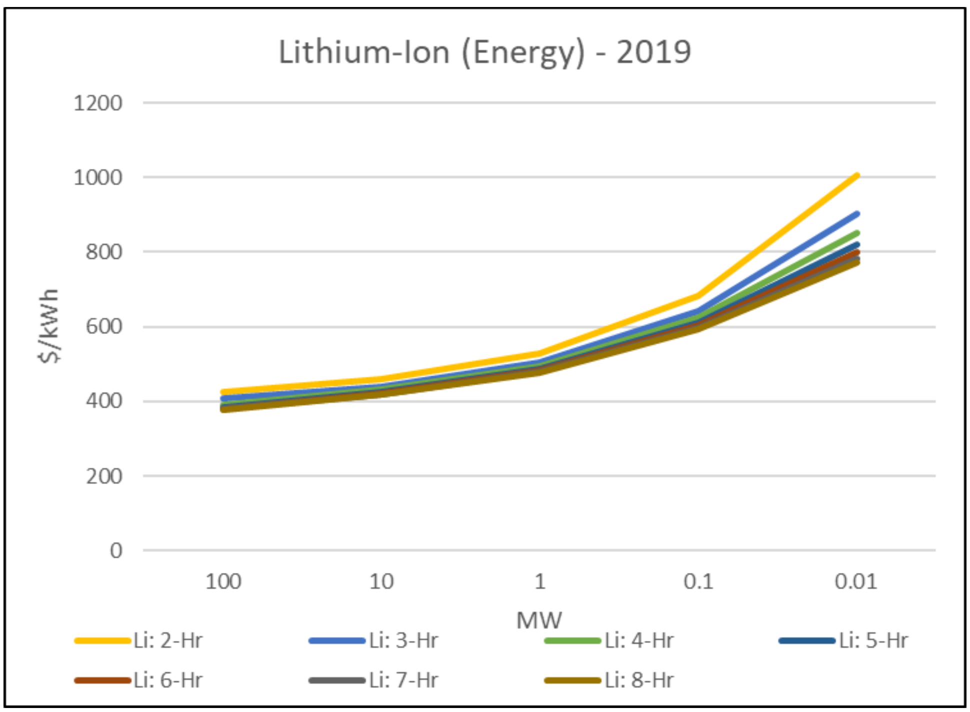
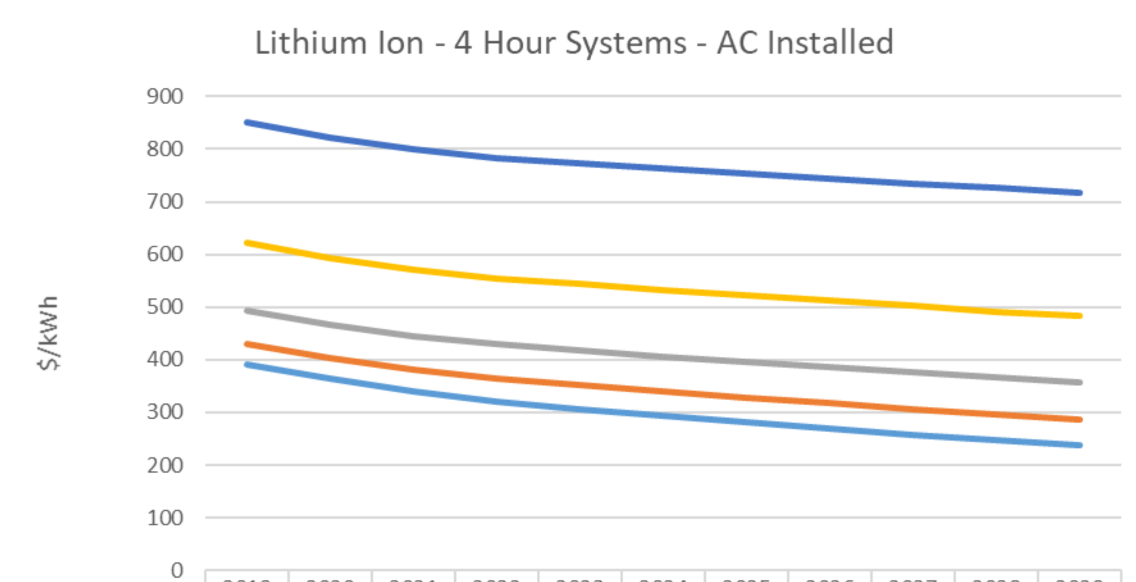


Figure 4-18. Lithium Ion: Energy (Li) 2019 Installed System Costs

The equipment cost for lithium ion battery is expected to sustain continued cost reductions over the forecast. Key drivers for lithium battery cells 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 lithium ion batteries are expected through improved chemistry and manufacturing design such as a move to solid state batteries.



	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
100 MW	392.0	363.1	339.8	321.2	306.7	293.2	280.7	268.8	257.5	246.8	236.6
10 MW	430.6	403.2	381.5	364.5	351.7	339.4	328.1	317.3	306.8	296.8	287.2
1 MW	493.4	466.6	445.7	429.9	418.2	406.7	396.2	386.0	376.1	366.5	357.2
0.1 MW	623.0	594.0	571.7	555.2	543.9	532.8	522.2	511.9	501.8	491.9	482.3
0.01 MW	850.3	822.0	800.0	783.9	773.3	762.8	752.5	743.7	735.1	726.6	718.3

Figure 4-19. Lithium Ion: Energy (Li) System Price Forecast

4.12. Lithium Ion: Power (Li)

Capital costs for lithium ion (Li) power 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, even if used for power applications.

Lithium ion 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', 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, lithium system for energy applications can range from 10 kWs 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 Lithium ion 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.

Lithium ion 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. For power centric systems that produce more heat from operation, Lithium ion systems in energy applications are designed for operation across the entire grid storage market, ranging from residential to wholesale power can operate across a number of market uses, ranging from large commercial, to utility, and wholesale applications.

Lithium ion systems in power applications are designed for markets primarily where the rapid charging or discharging of batteries are at a premium. Typically, this will be in specialized commercial or industrial markets, or ancillary services market in the wholesale power market.

Table 4-23. Lithium Ion: Power (Li) 2019 Installed System Costs

Lithium-ion (Power) - 2019					
$/kWh	Size (MW)				
	100	10	1	0.1	0.01
Li: 0.5-Hr	650.7	699.6	819.2		
Li: 1-Hr	504.2	545.6	629.1		

The round-trip efficiency of lithium ion facilities is determined by the efficiency of the ion exchange in the individual cell. 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 4-24. Lithium Ion: Power (Li) System Performance Characteristics

Lithium-ion: Power Performance Characteristics	
Lifespan:	10 Yrs.
Round-Trip Efficiency (AC):	80-85%
Operating Range (Depth of Discharge %):	80-100%
Capacity at End of Life (% of Original):	70-80%
Operation & Maintenance (O&M):	1-2%

The equipment cost for lithium ion battery is expected to sustain continued cost reductions over the forecast. Key drivers for lithium battery cells 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 lithium ion batteries are expected through improved chemistry and manufacturing design such as a move to solid state batteries.

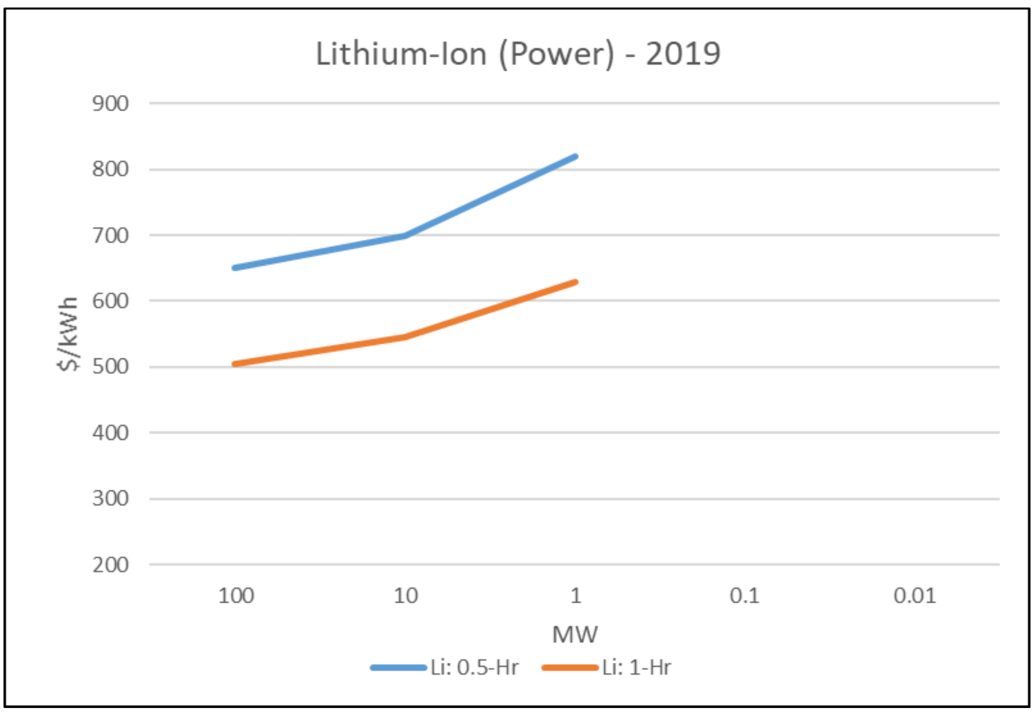
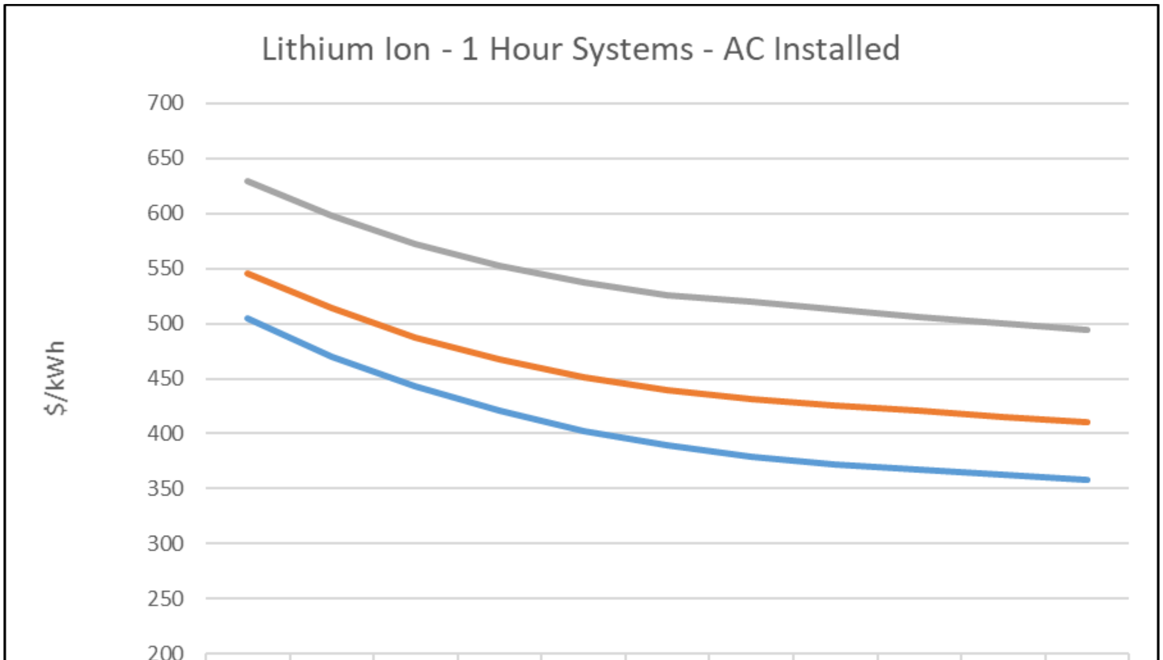


Figure 4-20. Lithium Ion: Power (Li) 2019 Installed System Costs



	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
100 MW	504.2	470.4	442.8	420.5	402.8	389.0	378.9	371.5	366.8	362.2	357.6
10 MW	545.6	513.5	487.7	467.3	451.5	439.3	431.0	425.7	420.5	415.5	410.5
1 MW	629.1	597.4	572.1	552.5	537.3	526.2	519.4	512.8	506.4	500.0	493.8

Figure 4-21. Lithium Ion: Power (Li) System Price Forecast

4.13. 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.

Zinc battery systems highlighted in the 2019 Energy Storage Pricing Survey are based on the Zinc-Air technology family. There are a number of other zinc-based technologies such as Nickel Zinc etc., but the majority of their deployment opportunities is targeted at the UPS market. This deployment profile will be undertaken in future Surveys. The Zinc-Air system is more geared toward longer discharge applications, and thus of a higher priority to potential customers of longer-duration energy storage systems.

Zinc Air 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.

For 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.

Table 4-25. Zinc (Zn) 2019 Installed System Costs

Zinc (Zn) - 2019					
$/kWh	Size (MW)				
	100	10	1	0.1	0.01
Zn: 4-Hr	271.4	289.7	336.8	398.7	
Zn: 8-Hr		271.2	294.4	328.3	

The round-trip efficiency of Zinc systems is determined by efficiency of the reversible chemical reaction. 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 4-26. Zinc (Zn) System Performance Characteristics

Zinc (Zn) Performance Characteristics	
Lifespan:	15 Yrs.
Round-Trip Efficiency (DC):	75%
Operating Range (Depth of Discharge %):	80%
Capacity at End of Life (% of Original):	80%
Operation & Maintenance (O&M):	2%

The equipment cost for zinc-based battery technology has the opportunity for modest and sustained cost reductions over the forecast. Key drivers for zinc-air energy storage technology are the improving chemistry of the system design, which allow lower cost manufacturing and lower cost material selection. 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.

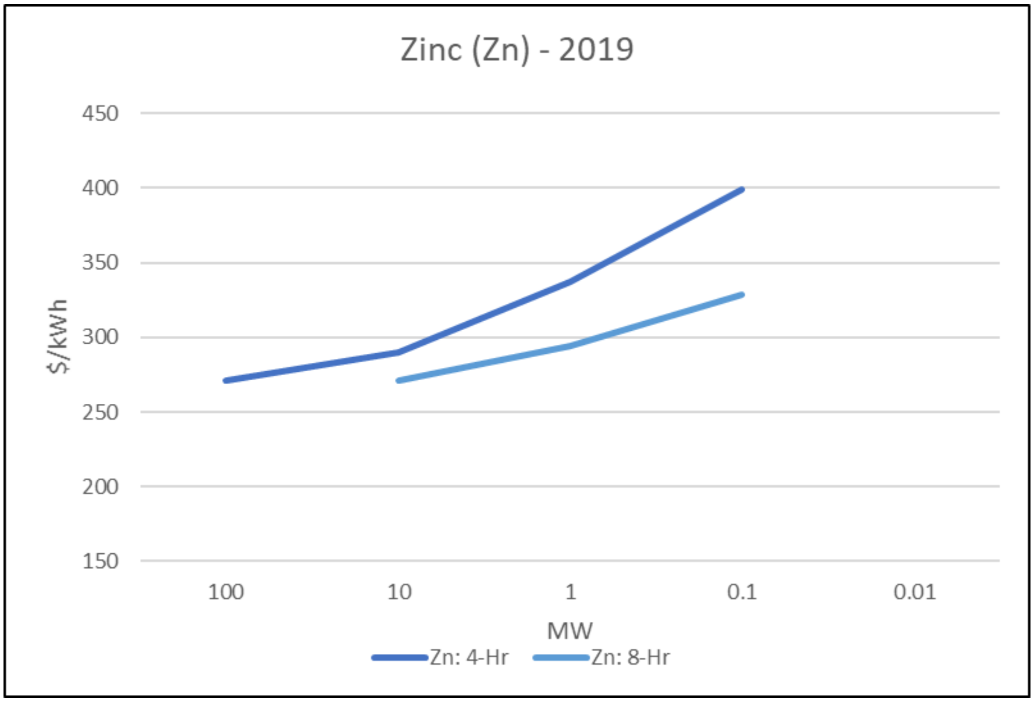
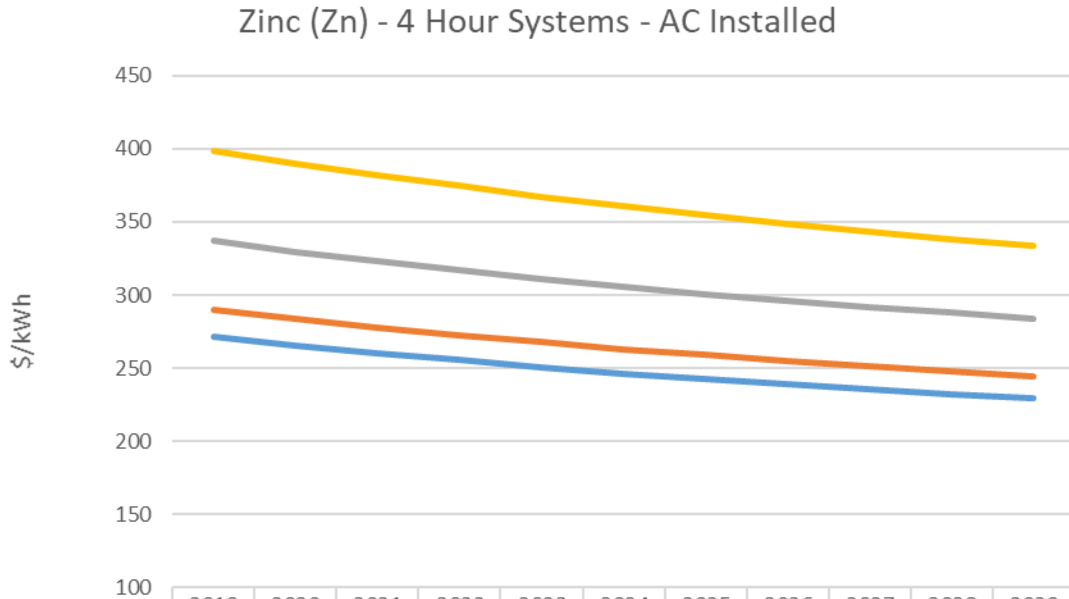


Figure 4-22. Zinc (Zn) 2019 Installed System Costs



	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
100 MW	271.4	265.7	260.4	255.4	250.8	246.5	242.5	238.8	235.3	232.1	229.2
10 MW	289.7	283.6	278.0	272.7	267.7	263.1	258.9	254.9	251.2	247.8	244.7
1 MW	336.8	329.7	323.1	316.9	311.1	305.7	300.7	296.0	291.7	287.8	284.1
0.1 MW	398.7	390.1	382.1	374.5	367.4	360.7	354.5	348.7	343.4	338.4	333.7

Figure 4-23. Zinc (Zn) System Price Forecast

4.14. Lead (Pb)

Capital costs for lead carbon (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.

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.

Table 4-27. Lead (Pb) 2019 Installed System Costs

Lead (Pb) - 2019					
$/kWh	Size (MW)				
	100	10	1	0.1	0.01
Pb: 2-Hr			433.5	529.6	808.5
Pb: 3-Hr			391.8	461.2	647.9
Pb: 4-Hr			352.0	425.5	588.4

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.

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 acid batteries designed for UPS and other stationary applications are designed for steady, prolonged discharges to 80% of capacity—deeper than this decreases the lifespan significantly. The length of time used for charging and discharging also impacts the cells life. Typically, longer cycle life is achieved with a significantly longer charge cycle than the discharge cycle.

Table 4-28. Lead (Pb) System Performance Characteristics

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

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. Lead based systems are typically utilized in 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.

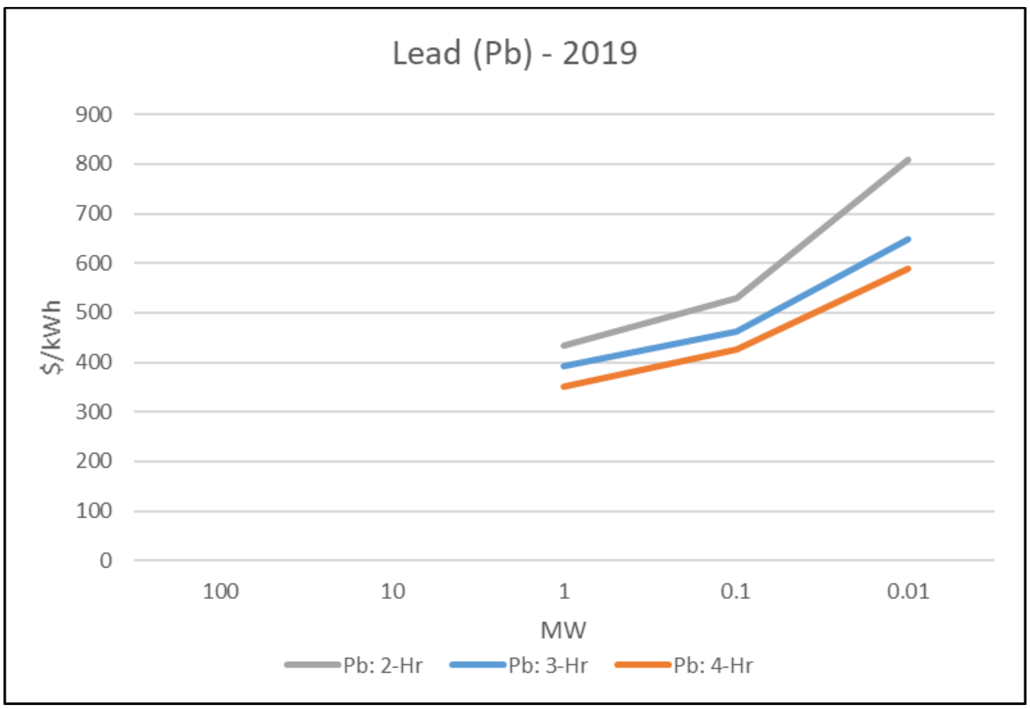
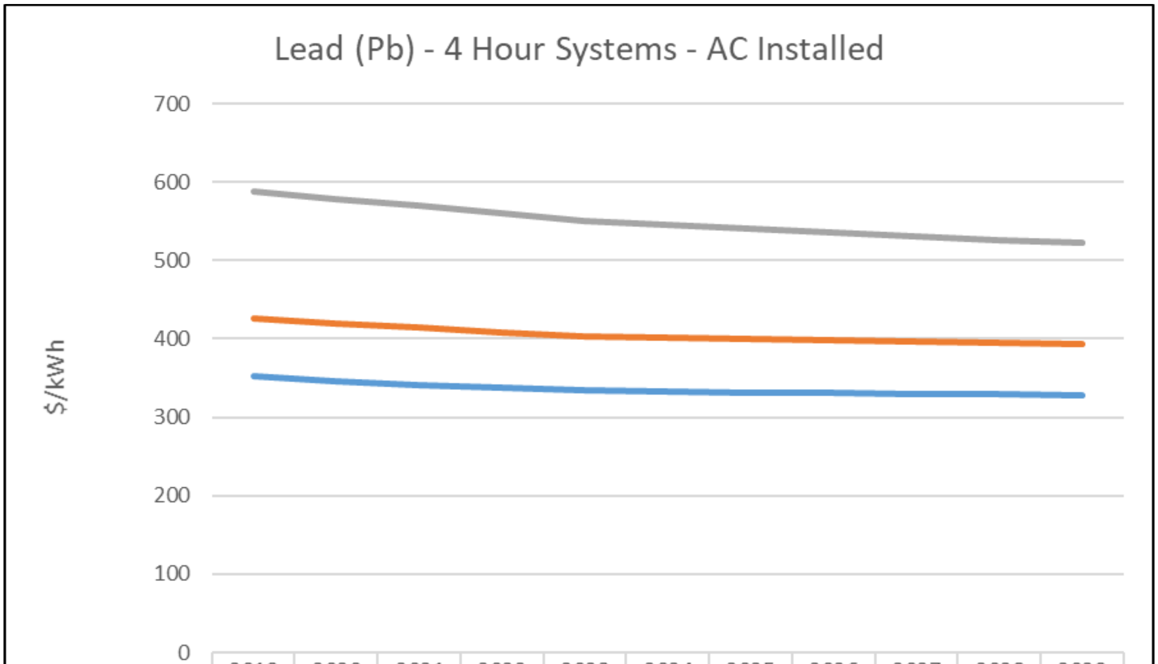


Figure 4-24. Lead (Pb) 2019 Installed System Costs

The equipment cost for lead based battery technology is not expected to change dramatically over the forecast. Key drivers for lead battery cells 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 batteries are possible, but not expected.



	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
1 MW	352.0	346.5	341.8	337.7	333.7	332.2	331.4	330.5	329.7	328.8	328.1
0.1 MW	425.5	419.6	414.1	408.8	403.5	401.6	400.0	398.4	396.9	395.4	394.0
0.01 MW	588.4	578.8	569.3	560.1	551.1	545.4	539.9	535.2	530.7	526.3	522.0

Figure 4-25. Lead (Pb) System Price Forecast

4.15. Lead Carbon (PbC)

Capital costs for lead carbon (PbC) 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.

Lead carbon batteries differ from their traditional counterparts by the inclusion of carbon into the electrodes. This comes by incorporating carbon into the anode and/or cathodes. The carbon greatly enhances the operating capabilities of the battery. The carbon allows for a much faster charge/discharge rate and allows for extended partial state of charge (PSoC) operation.

Similar to lead batteries, the power and energy of each lead carbon battery is fixed. Generally, lead carbon systems are design for higher power applications, and especially higher cycling applications. This performance capability lends itself for a wider range of industrial and renewable energy applications than available to simple lead battery systems.

For PbC systems, the material selection and manufacturing process have the largest impact on the capital equipment costs of the battery. Because of the evolving nature of the technology and the importance for fine carbon particle design and size control, incorporating the carbon additives has is a critical, and has been at times a costly process—albeit one that is advancing rapidly.

Lead carbon battery systems can be deployed in either indoor or outdoor deployments. Outdoor deployments require increased environmental conditioning as elevated temperatures will degrade the batteries, although not as significantly generally as lead batteries. Lead carbon systems are typically utilized in backup power systems or off-grid power applications, with lead carbon having a wider and more dynamic operating range than traditional lead acid batteries.

Table 4-29. Lead Carbon (PbC) 2019 Installed System Costs

Lead Carbon (PbC) - 2019					
$/kWh	Size (MW)				
	100	10	1	0.1	0.01
PbC: 2-Hr			693.2	811.0	1121.6
PbC: 3-Hr			625.5	698.4	912.3
PbC: 4-Hr			557.2	620.0	768.2

The round-trip efficiency of lead carbon batteries is somewhat higher than for lead batteries, but the range can vary. For this reason, lead carbon batteries typically are deployed in more challenging applications than lead batteries.

A number of factors can negatively affect the cycle-life a lead carbon battery, including temperature, depth of discharge, and the charge/discharge rate—similar to those affecting lead acid batteries, but generally not to the same extent. As with lead acid batteries, lead carbon batteries are designed for UPS and other stationary applications are designed for steady, prolonged discharges to 80% of capacity—deeper than this decreases the lifespan significantly. The length of time used for charging and discharging also impacts the cells life. Typically, longer cycle life is achieved with a significantly longer charge cycle than the discharge cycle.

Table 4-30. Lead Carbon (PbC) System Performance Characteristics

Lead Carbon (PbC) Performance Characteristics	
Lifespan:	5+ Yrs.
Round-Trip Efficiency (AC):	65-75%
Operating Range (Depth of Discharge %):	70%
Capacity at End of Life (% of Original):	80%
Operation & Maintenance (O&M):	2-3%

Key drivers for lead carbon battery 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 of lead carbon batteries are expected to only be modest, focused of improved chemistry of the cell.

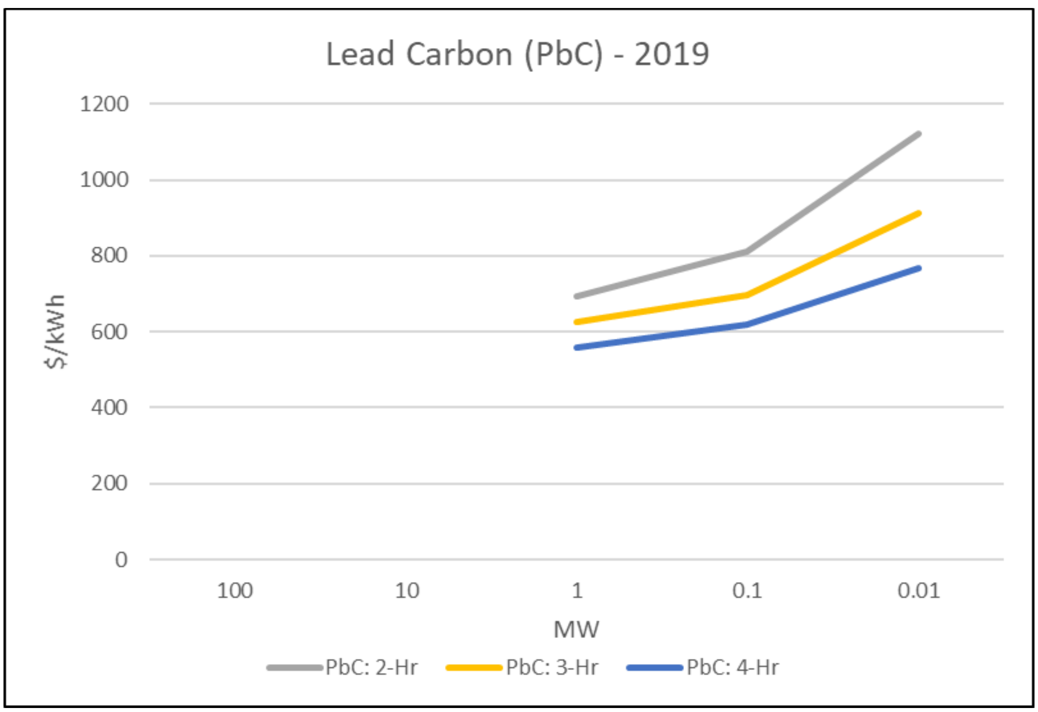
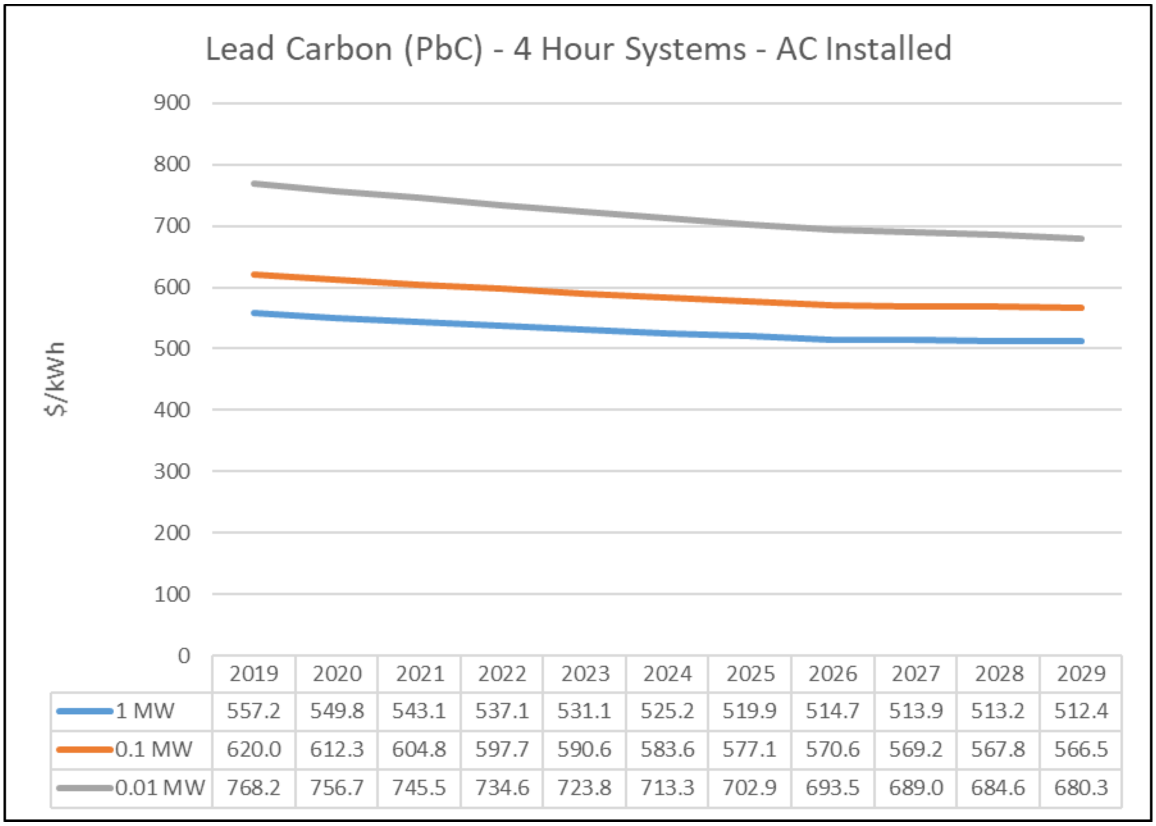


Figure 4-26. Lead Carbon (PbC) 2019 Installed System Costs



	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
1 MW	557.2	549.8	543.1	537.1	531.1	525.2	519.9	514.7	513.9	513.2	512.4
0.1 MW	620.0	612.3	604.8	597.7	590.6	583.6	577.1	570.6	569.2	567.8	566.5
0.01 MW	768.2	756.7	745.5	734.6	723.8	713.3	702.9	693.5	689.0	684.6	680.3

Figure 4-27. Lead Carbon (PbC) System Price Forecast

This page left blank

DISTRIBUTION

Email—Internal

Name	Org.	Sandia Email Address
Babu Chalamala	08811	bchalam@sandia.gov
Joseph McNamara	08811	jwmcnam@sandia.gov
Howard Passell	08811	hdpasse@sandia.gov
Tu Nguyen	08811	tunguy@sandia.gov
Raymond Byrne	08813	rhbyrne@sandia.gov
Technical Library	01177	libref@sandia.gov

Email—External (encrypt for OUO)

Name	Company Email Address	Company Name
Dr. Imre Gyuk	imre.gyuk@hq.doe.gov	US DOE
Richard Baxter	rbaxter@mustangprairie.com	Mustang Prairie Energy

This page left blank

Sandia National Laboratories

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.