SANDIA REPORT
SAND2019-14896
Printed December 2019

Sandia National Laboratories

2018 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 a nascent industry, it is often difficult to obtain capital costs for various energy storage technologies. This type of information is required to perform an initial cost-benefit analysis related to a potential energy storage deployment, as well as to compare 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 categories: the storage module; the balance of system; the power conversion system; the energy management system; and the engineering, procurement, and construction costs. Pricing data is presented for the following technologies: pumped hydro storage; compressed air energy storage; sodium battery storage; zinc battery storage; long duration flywheels; short duration flywheels; vanadium flow batteries; zinc bromide flow batteries; iron flow batteries; nickel batteries; lithium ion energy batteries; lithium ion power batteries; lead acid batteries; and advanced lead carbon batteries.

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

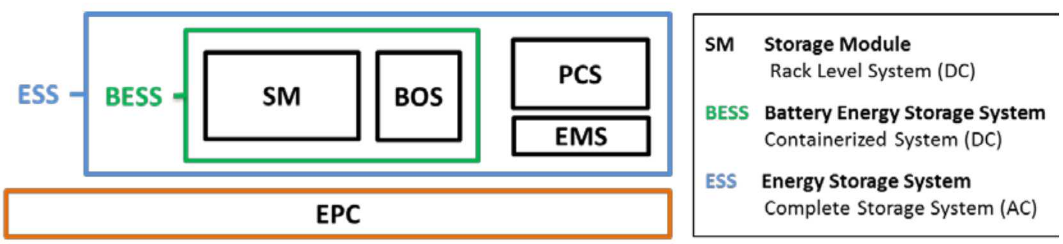
LIST OF TABLES

EXECUTIVE SUMMARY

The 2018 Energy Storage Pricing Survey is designed to provide a reference price to customers for the different energy storage technologies. The price is the expected installed capital cost 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.

Participating Company Type	2018 ESPS
Energy Storage OEM	30
Government / Academia	3
System Integrator	6
Power Electronics	9
Project Developer	6
Financial Industry	4
Consultants	7
Balance of System	1
EPC	4
Total Interviews	**70**
Published Data Sources	**3**
Total All Data Sources	**73**
Individual System Price Quotes	**197**

Figure ES-1. Pricing Survey Participants



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 ES-2. Energy Storage System Diagram

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
AC	Alternating current
BESS	Battery energy storage system
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
NRE	Non-recurring engineering
OEM	Original equipment manufacturer
O&M	Operation and maintenance
PCS	Power conversion system
RTE	Round trip efficiency
SCADA	Supervisory control and data acquisition
SM	Storage module

1. SURVEY METHODOLOGY

The 2018 Energy Storage Pricing Survey is designed to provide a reference price to customers for the different energy storage technologies. The price is the expected installed capital cost 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 pricing survey for the 2018 Energy Storage Pricing Survey is based primarily on 70 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. If complete AC system prices were provided, these were used fully; for the vast majority of price quotes that consisted of components; these were averaged together to arrive at component price which was then added to other component pricing to arrive a full system price.

1.1. Data Acquisition

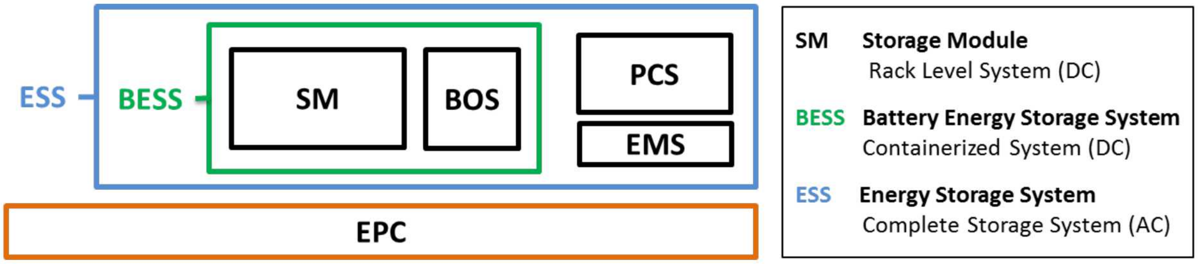
The interviews to obtain the data were derived from companies from across the energy storage industry.

Participating Company Type	2018 ESPS
Energy Storage OEM	30
Government / Academia	3
System Integrator	6
Power Electronics	9
Project Developer	6
Financial Industry	4
Consultants	7
Balance of System	1
EPC	4
Total Interviews	**70**
Published Data Sources	**3**
Total All Data Sources	**73**
Individual System Price Quotes	**197**

Figure 1-1. Pricing Survey Participants

1.2. Equipment Costs

In order to discuss the capital equipment costs between different energy storage technologies, we need a common system architecture framework to describe structurally the different components of an energy storage system. Different system architectures exist, but we will describe here a structure that follows an emerging general consensus.



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 1-2. Energy Storage System Diagram

- **Storage Module (SM)**: The storage module is 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 need 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. 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, this also 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.

1.3. System Scale Availability by Technology

Energy Storage technologies are used at all levels of the power system. In order to provide a more precise prices estimate for potential customers, systems were priced according to 5 different power ratings to provide a relevant system comparison. The scale of an energy storage system impacts pricing, with larger systems are typically lower cost (on a $/kWh basis) than smaller ones.

This page left blank

2. PRICING SURVEY RESULTS

Each of the following sections contains results for the 2018 pricing survey.

2.1. Pumped Hydro Storage (PHS)

Table 2-1. Pumped Hydro Storage (PHS) Installed System Costs

Pumped Hydro Storage Costs					
$/kW	Size (MW)				
	100	10	1	0.1	0.01
PHS	1633.2				

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

Pumped Hydro Storage Performance Characteristics	
Lifespan:	40 Yrs.
Round-Trip Efficiency (AC):	82%
Operating Range (Depth of Discharge %):	100%
Capacity at End of Life (% of Original):	100%
Operation & Maintenance (O&M):	1%
Extended Warranty:	0%

2.2 Compressed Air Energy Storage (CAES)

Table 2-3. Compressed Air Energy Storage (CAES) Installed System Costs

Compressed Air Storage Costs					
$/kW	Size (MW)				
	100	10	1	0.1	0.01
CAES	1614.3				

Table 2-4. Compressed Air Energy Storage (CAES) Performance Characteristics

Compressed Air 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%
Heat Rate (DT/MWh):	4.1%

2.3 Sodium (Na)

Table 2-5. Sodium (Na) Installed System Costs

Sodium (Na) Costs					
$/kWh	Size (MW)				
	100	10	1	0.1	0.01
NA: 6-Hr	378.5	400.7	439.9		

Table 2-6. Sodium (Na) Performance Characteristics

Sodium (Na) 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):	2%

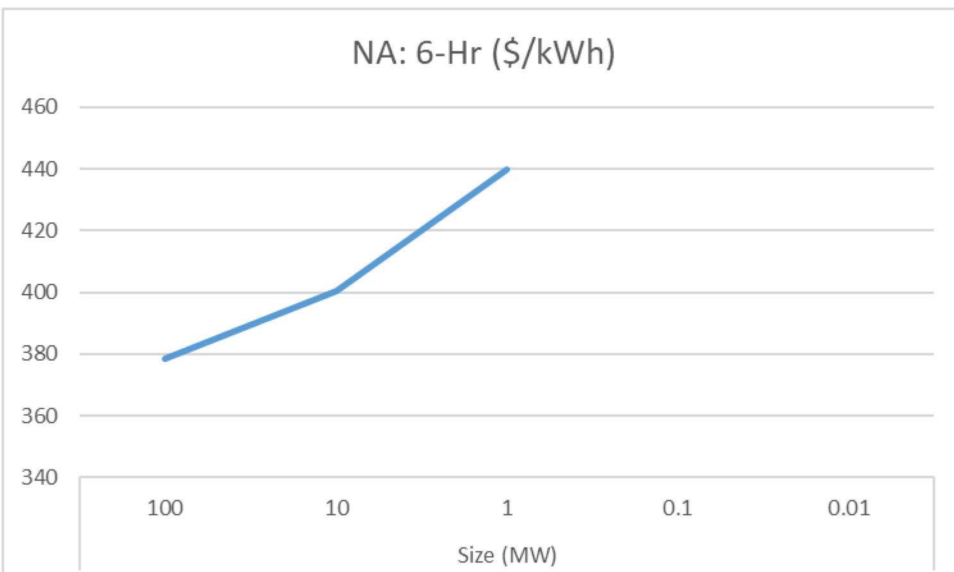


Figure 2-1. Sodium (Na) Installed System Costs

Zinc (Zn)

Table 2-7. Zinc (Zn) Installed System Costs

Zinc (Zn) Costs					
$/kWh	Size (MW)				
	100	10	1	0.1	0.01
Zn: 4-Hr	252.1	268.0	310.7	366.1	

Table 2-8. Zinc (Zn) Performance Characteristics

Zinc (Zn) Characteristics	
Lifespan:	10 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%

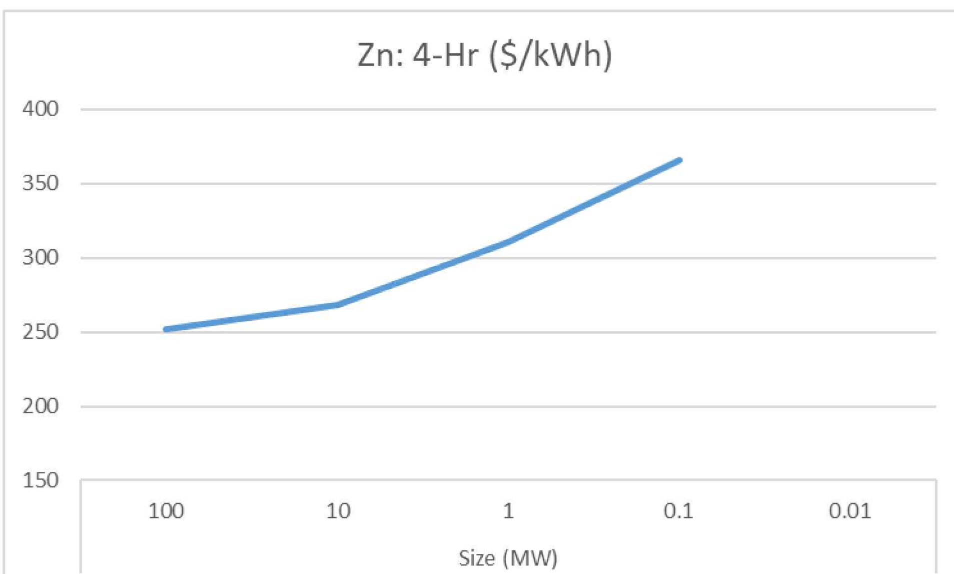


Figure 2-2. Zinc (Zn) Installed System Costs

2.2. Flywheel: Long Duration (FWLD)

Table 2-9. Flywheel: Long Duration (FWLD) Installed System Costs

Flywheel: Long Duration Costs					
$/kWh	Size (MW)				
	100	10	1	0.1	0.01
FWLD: 4-Hr		676.0	753.3		

Table 2-10. Flywheel: Long Duration (FWLD) Performance Characteristics

Flywheel: Long Duration Characteristics					
$/kWh	Size (MW)				
	100	10	1	0.01	0.001
FWLD: 4-Hr		676.0	753.3		

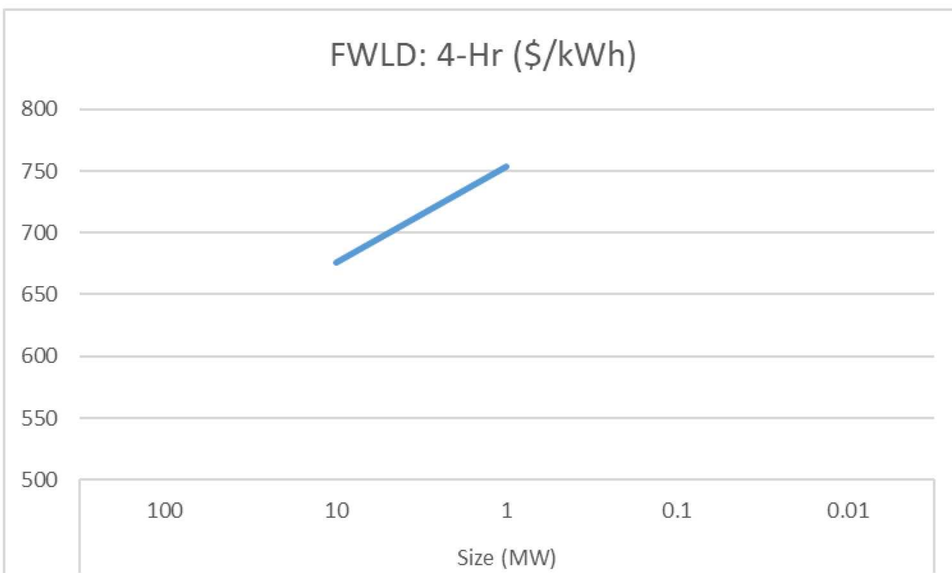


Figure 2-3. Flywheel: Long Duration (FWLD) Installed System Costs

2.3. Flywheel: Short Duration (FWSD)

Table 2-11. Flywheel: Short Duration (FWSD) Installed System Costs

Flywheel: Short Duration Costs					
$/kW	Size (MW)				
	100	10	1	0.1	0.01
FWSD		880.0	1146.5	1250.0	

Table 2-12. Flywheel: Short Duration (FWSD) Performance Characteristics

Flywheel: Short Duration 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):	2%

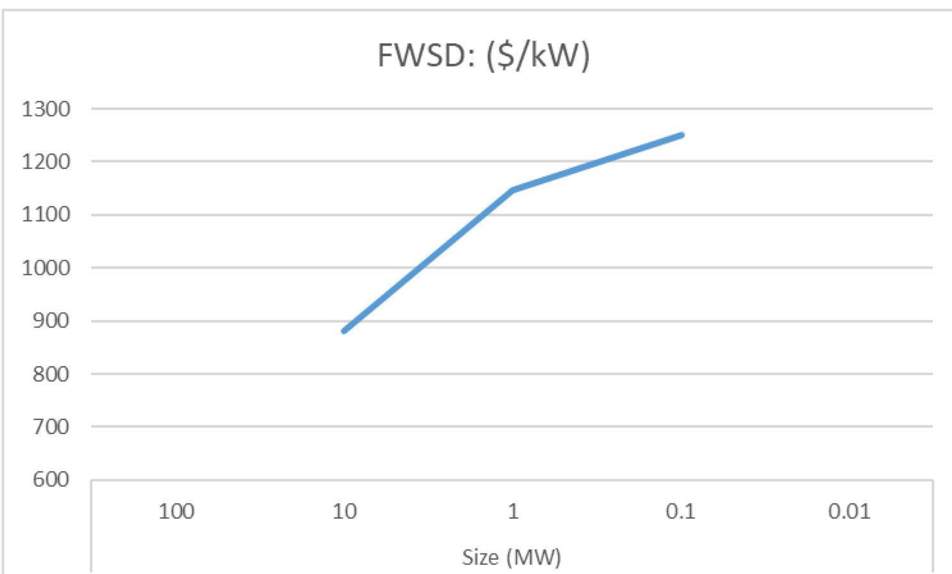


Figure 2-4. Flywheel: Short Duration (FWSD) Installed System Costs

2.4. Flow Battery: Vanadium (FB V)

Table 2-13. Flow Battery: Vanadium (FB V) Installed System Costs

Flow Battery: Vanadium Costs					
$/kWh	Size (MW)				
	100	10	1	0.1	0.01
FB V: 4-Hr	409.9	424.2	520.1	617.3	
FB V: 6-Hr	345.5	379.1	432.1	522.5	
FB V: 8-Hr	304.6	343.1	402.4	487.2	

Table 2-14. Flow Battery: Vanadium (FB V) Performance Characteristics

Flow Battery: Vanadium 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):	3%

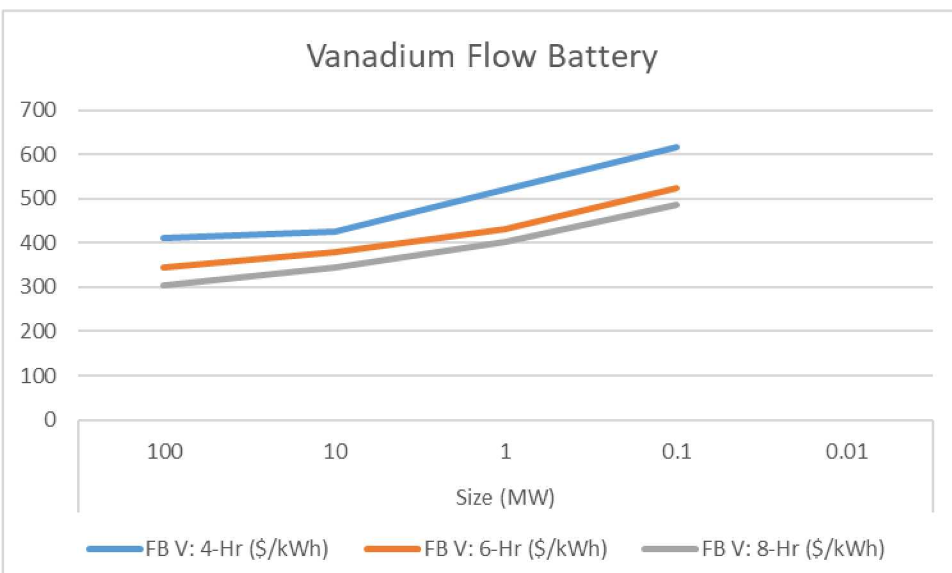


Figure 2-5. Flow Battery: Vanadium (FB V) Installed System Costs

2.5. Flow Battery: Zinc Bromide (FB ZnBr)

Table 2-15. Flow Battery: Zinc Bromide (FB ZnBr) Installed System Costs

Flow Battery: Zinc Bromide Costs					
$/kWh	Size (MW)				
	100	10	1	0.1	0.01
FB ZnBr: 3-Hr				746.5	
FB ZnBr: 4-Hr	472.2	506.0	555.3	630.3	
FB ZnBr: 5-Hr	417.2	429.5	452.0	493.9	
FB ZnBr: 6-Hr	413.5	425.7	447.3	485.9	

Table 2-16. Flow Battery: Zinc Bromide (FB ZnBr) System Costs

Flow Battery: Zinc Bromide 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):	3%

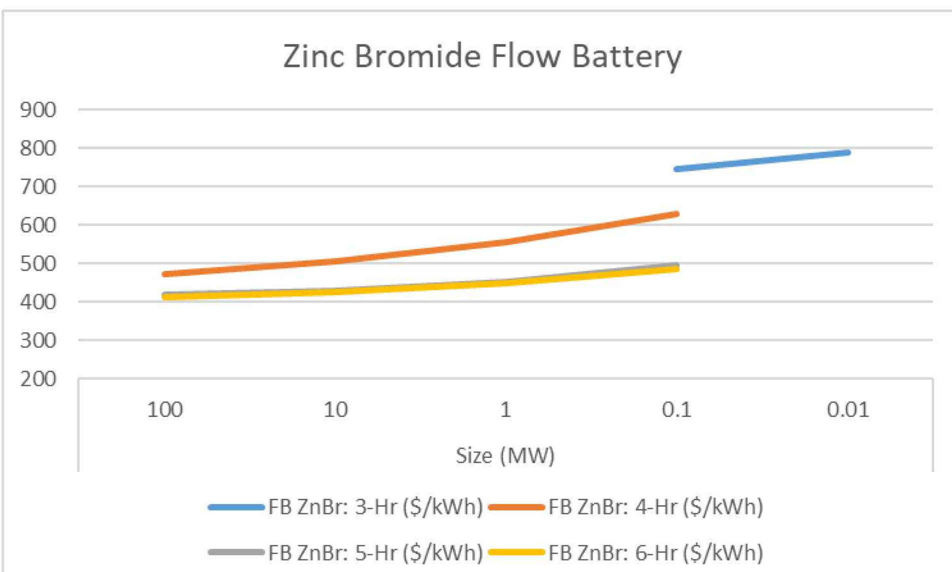


Figure 2-6. Flow Battery: Zinc Bromide (FB ZnBr) Installed System Costs

2.6. Flow Battery: Iron (FB Fe)

Table 2-17. Flow Battery: Iron (FB Fe) Installed System Costs

Flow Battery: Iron Costs					
$/kWh	**Size (MW)**				
	100	**10**	**1**	**0.1**	**0.01**
FB Fe: 4Hr	404.5	416.4	443.8	505.1	

Table 2-18. Flow Battery: Iron (FB Fe) System Costs

Flow Battery: Iron 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):	3%

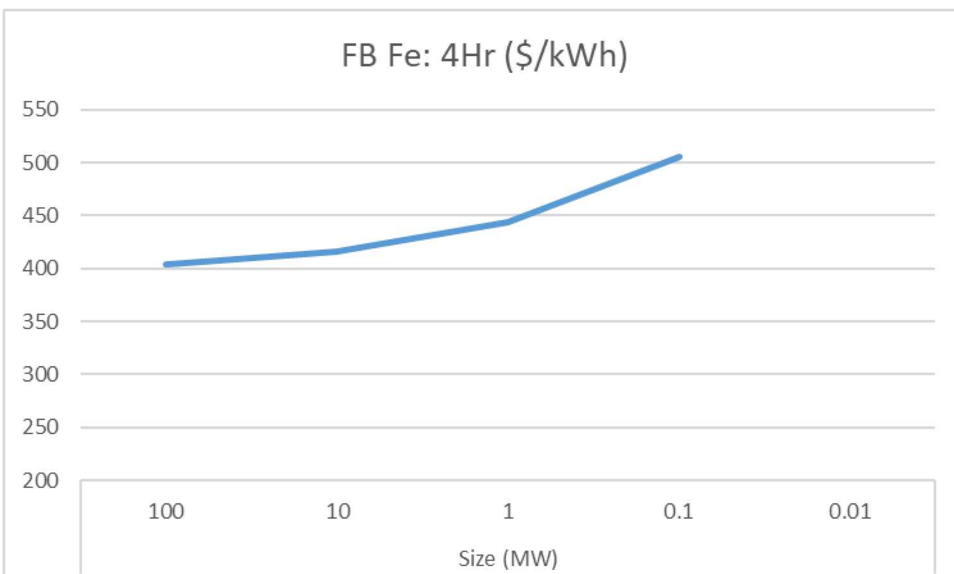


Figure 2-7. Flow Battery: Iron (FB Fe) Installed System Costs

2.7. Nickel (Ni)

Table 2-19. Nickel (Ni) Installed System Costs

Nickel (Ni) Costs					
$/kWh	Size (MW)				
	100	10	1	0.1	0.01
Ni: 2-Hr			339.6	466.4	835.2
Ni: 3-Hr			320.5	434.4	741.6
Ni: 4-Hr			311.0	418.5	694.8

Table 2-20. Nickel (Ni) Performance Characteristics

Nickel (Ni) Characteristics	
Lifespan:	10 Yr.
Round-Trip Efficiency (AC):	75%
Operating Range (Depth of Discharge %):	80%
Capacity at End of Life (% of Original):	80%
Operation & Maintenance (O&M):	2%

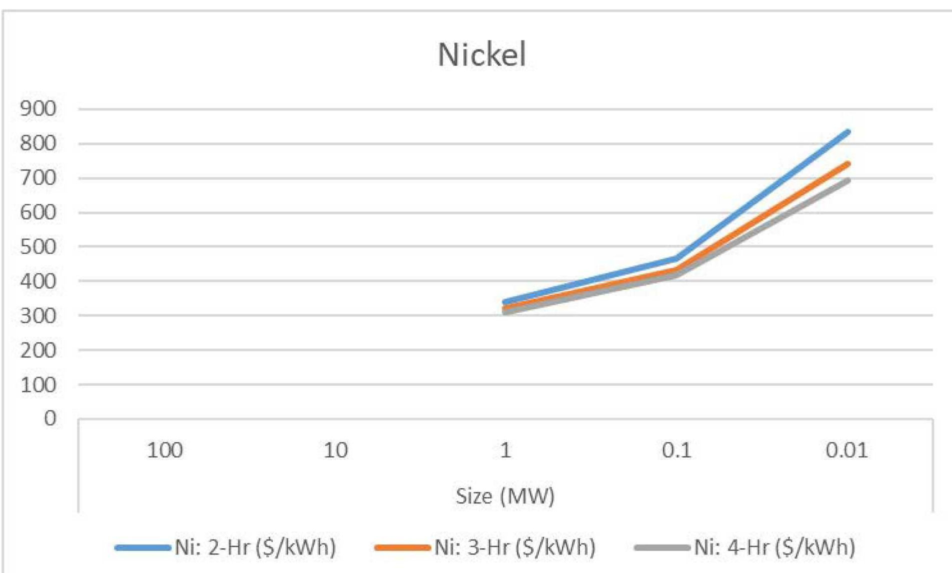


Figure 2-8. Nickel (Ni) Installed System Costs

2.8. Lithium-Ion: Energy (Li)

Table 2-21. Lithium Ion: Energy (Li) Installed System Costs

Lithium-Ion: Energy Costs					
$/kWh	Size (MW)				
	100	**10**	**1**	**0.1**	**0.01**
Li: 2-Hr	451.8	474.6	558.9	719.4	1057.8
Li: 3-Hr	429.3	449.9	535.5	679.5	930.9
Li: 4-Hr	420.1	440.6	523.8	659.6	867.4
Li: 5-Hr	410.5	435.0	516.8	647.6	829.3
Li: 6-Hr	406.8	431.2	512.1	639.6	803.9
Li: 7-Hr	404.2	428.6	508.8	633.9	785.8
Li: 8-Hr	402.2	426.6	506.3	629.6	772.2

Table 2-22. Lithium Ion: Energy (Li) Performance Characteristics

Lithium-Ion: Energy Characteristics	
Lifespan:	10 Yrs.
Round-Trip Efficiency (AC):	85%-90%
Operating Range (Depth of Discharge %):	80%-100%
Capacity at End of Life (% of Original):	70%-80%
Operation & Maintenance (O&M):	2%

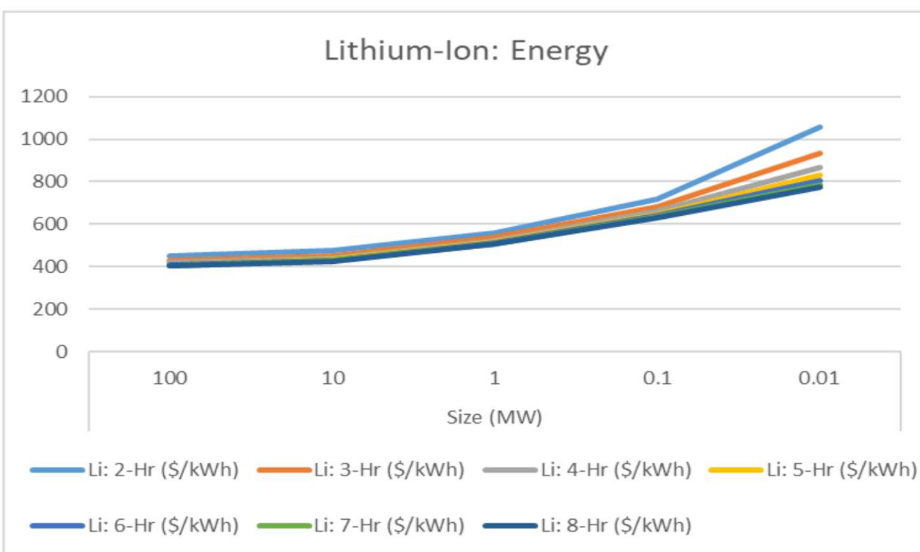


Figure 2-9 Lithium Ion: Energy (Li) Installed System Costs

2.9. Lithium-Ion: Power (Li)

Table 2-23. Lithium-Ion: Power (Li) Installed System Costs

Lithium-ion: Power Costs					
$/kWh	Size (MW)				
	100	10	1	0.1	0.01
Li: 0.5-Hr	808.5	849.8	1007.3	1398.9	
Li: 1-Hr	466.3	485.5	592.3	755.2	

Table 2-24. Lithium Ion: Power (Li) Performance Characteristics

Lithium-ion: Power 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):	2%

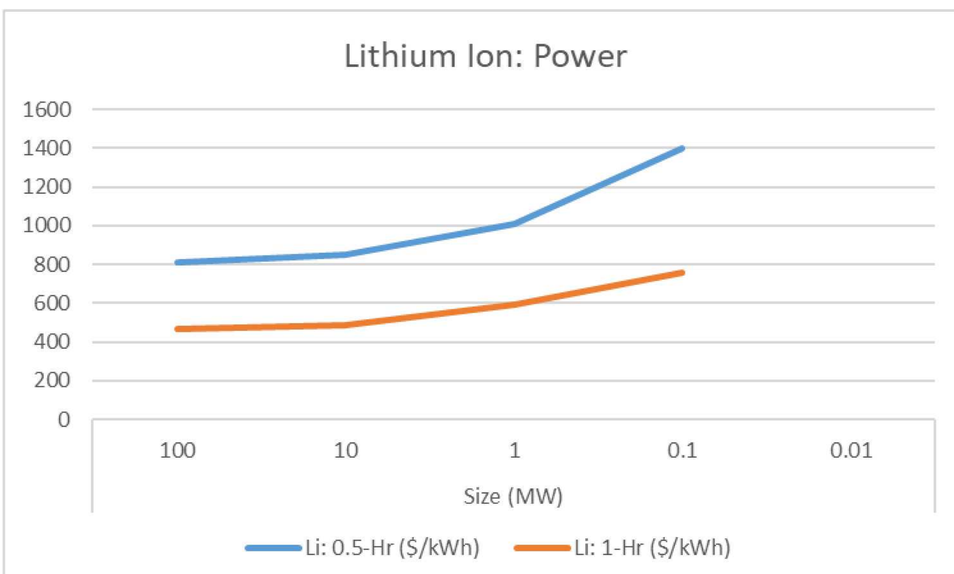


Figure 2-10. Lithium-Ion: Power (Li) Installed System Costs

2.10. Lead (Pb)

Table 2-25. Lead (Pb) Installed System Costs

Lead (Pb) Costs					
$/kWh	Size (MW)				
	100	10	1	0.1	0.01
Pb: 2-Hr			445.8	550.4	810.6
Pb: 2-Hr			375.5	461.8	633.2
Pb: 2-Hr			338.4	415.4	542.3

Table 2-26. Lead (Pb) Performance Characteristics

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

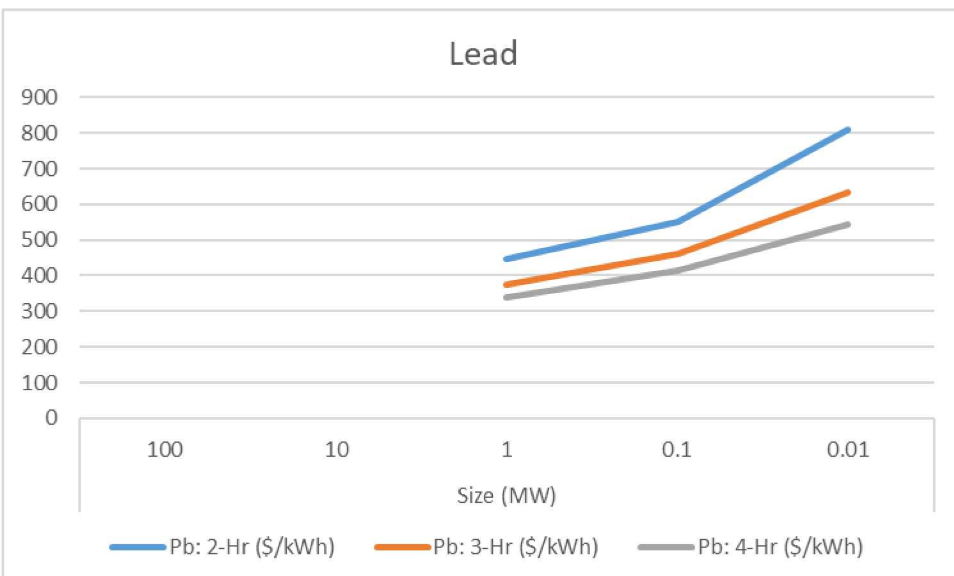


Figure 2-11. Lead (Pb) Installed System Costs

2.11. Lead Carbon (PbC)

Table 2-27. Lead Carbon (PbC) Installed System Costs

Lead Carbon (PbC) Costs					
$/kWh	Size (MW)				
	100	**10**	**1**	**0.1**	**0.01**
PbC: 2-Hr			720.9	877.8	1201.6
PbC: 3-Hr			598.1	738.4	973.8
PbC: 4-Hr			547.5	664.4	855.0

Table 2-28. Lead Carbon (PbC) Performance Characteristics

Lead Carbon (PbC) Characteristics	
Lifespan:	5-10 Yrs.
Round-Trip Efficiency (AC):	80%
Operating Range (Depth of Discharge %):	70%
Capacity at End of Life (% of Original):	80%
Operation & Maintenance (O&M):	3%

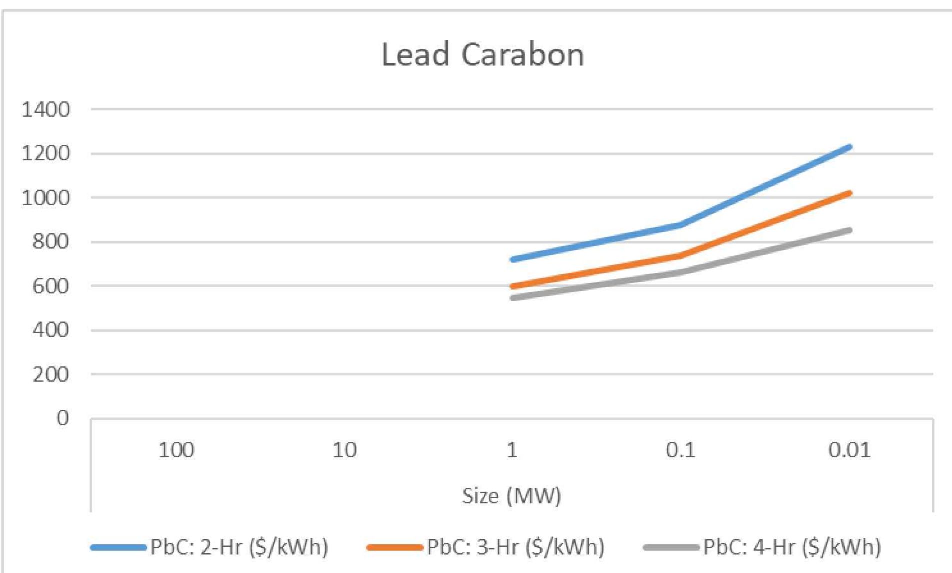


Figure 2-12. Lead Carbon (PbC) Installed System Costs

DISTRIBUTION

Email—Internal

Name	Org.	Sandia Email Address
Charles J. Hanley	08810	cjhanle@sandia.gov
Daniel Borneo	08811	drborne@sandia.gov
Babu Chalamala	08811	bchalam@sandia.gov
Alexander Headley	08811	aheadle@sandia.gov
Joseph W. McNamara	08811	jwmcnam@sandia.gov
Tu A. Nguyen	08811	tunguy@sandia.gov
Howard D. Passell	08811	hdpasse@sandia.gov
Benjamin Schenkman	08811	blschen@sandia.gov
Raymond H. Byrne	08813	rhbyrne@sandia.gov
Ricky J. Concepcion	08813	rconcep@sandia.gov
Felipe Wilches-Bernal	08813	fwilche@sandia.gov
Technical Library	01177	libref@sandia.gov

Hardcopy—External

Number of Copies	Name	Company Name and Company Mailing Address
1	Dr. Imre Gyuk	U. S. Department of Energy 1000 Independence Avenue, SW Washington, DC 20585
1	Richard Baxter	14 Westminster Street Somerville, MA 02144

This page left blank

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.