ELECTRIC POWER
RESEARCH INSTITUTE

Energy Storage Technology and Cost Assessment: Executive Summary

3002013958

Project Manager
Erin Minear

December 2018

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THE ELECTRIC POWER RESEARCH INSTITUTE (EPRI) PREPARED THIS REPORT.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

Acknowledgments

This report was prepared by

Electric Power Research Institute
3420 Hillview Avenue
Palo Alto, California 94304

Principal Investigators
E. Minear
P. Ip
B. Westlake
M. Alexander
M. Evans
M. Pellow
H. Kamath

The following organizations, under contract to the Electric Power Research Institute (EPRI), contributed to the preparation of this report:

Bear Peak Energy Consulting, LLC
1195 Albion Road
Boulder, CO 80305

Principal Investigator
N. Lenssen

Independent Contractor
D. Becker

EPRI would like to acknowledge the following individuals and organizations who contributed to this research: EPRI (J. Bistline, M. Smith, E. Giarta, C. Lyons), Avalon, BYD, Dynapower, Enel X, Energport, Engie, EnSync, ESS, Inc., Fractal, Greentech Media Research, Lockheed Martin Energy, Mustang Prairie Energy, NEC, Northern Reliability, Pacific Northwest National Laboratory, Primus, Sinexel, Trimark Associates, VRB Energy

This report describes research sponsored by the Electric Power Research Institute (EPRI)

Abstract

Rapid change is underway in the energy storage sector. Prices for energy storage systems remain on a downward trajectory. The deployment of energy storage systems (ESSs) -- measured by capacity or energy -- continue to grow in the U.S., with a widening array of stationary power applications being successfully targeted. This is an executive summary of a study that evaluates the current state of technology, market applications, and costs for the stationary energy storage sector. The study emphasizes the importance of understanding the full lifecycle cost of an energy storage project, and provides estimates for turnkey installed costs, maintenance costs, and battery decommissioning costs. This executive summary also provides a view of how costs will evolve in the future. Focus is placed on lithium ion and flow battery technologies; the former being the current market leader, the latter in the early stages of market adoption. Results of this analysis support the continued evaluation and potential deployment of energy storage as a grid asset.

Keywords

Energy storage costs
Resource planning
Lithium ion
Flow battery
Operations and maintenance (O&M)
Recycling

ELECTRIC POWER RESEARCH INSTITUTE

Contents

This report that was prepared as a utility resource for planners and other stakeholders who are tasked with evaluating energy storage. The executive summary includes key findings organized in the following contents:

Storage Parameters for Modeling

Energy storage technologies have unique attributes compared to other generation resources. Understanding these parameters can assist in making comparisons among different options, particularly in determining which storage technology best meets a particular grid service. The table below provides definitions for key performance characteristics and their potential impact on lifecycle project costs.

Characteristics	Definition	Potential Impact
Auxiliary power	Also known as "housekeeping power", the load that is required to maintain the system during normal operations; can include thermal management, communications, and monitoring system.	Auxiliary power requirements result in energy losses and decreased system efficiency.
Calendar life (for lithium ion)	The number of years until the energy storage system reaches its end-of-life (EOL), independent of cycling degradation.	Storage systems with longer calendar life can serve long-term needs. Similar to cycle life (below), systems requiring more frequent replacement increases maintenance costs.
Charge power	The maximum steady state active power at which the ESS can continuously absorb at the AC terminals of the Power Conversion System (PCS).	Limitations in charge power or rate may impact the storage systems ability to perform dynamic responses such as frequency regulation, and its ability to perform multiple cycles per day.
Cycle life (for lithium ion)	The number of cycles (typically given at specified depths of discharge) that the energy storage system can perform until EOL; is independent of calendar life degradation.	Systems with longer cycle life can undergo more charge/discharge cycles and be more suitable for use cases with daily cycling. Systems with shorter cycle life may require more frequent augmentation or component replacement, increasing maintenance expenses. Depending on duty cycle, cycle life may not be a concern as the system may reach the end of its calendar life ahead of end of cycle life.
Energy density	The amount of energy stored per unit mass occupied by the system, (kWh/kg); can be expressed per volume basis for other energy sources, (kWh/L).	If space is a concern, systems that have higher energy density may be more desirable because they could have a smaller footprint. However, based on the packaging, two systems of the same technology may have different system footprints (e.g., ISO containers vs. dedicated building).
Power density	The amount of power delivered on demand per unit mass (kW/kg).	High power density chemistries are lighter for high power usage; can be important for transportation, less so for stationary applications.
Roundtrip efficiency (RTE)	Total AC roundtrip efficiency of the facility is defined as the ratio of the delivered discharge energy to the delivered charge energy, including facility parasitic loads. Note: RTE varies at different charge/discharge rates.	More energy can be extracted per charge/discharge cycle for systems with higher RTE. RTE has a larger impact on applications that are more frequently cycled and have higher energy throughput as RTE will impact cost of charging. RTE assumptions are also important in calculating the emissions implications of energy storage.
Self-discharge rate	Rate at which the ESS will lose state of charge (SOC) while being held at a given SOC, not including auxiliary load energy (%/hour).	Systems with high self-discharge rate are less effective when idling for long duration, making it less suitable for infrequent operations and seasonal storage than systems with a lower self-discharge rate.
Time between overhaul (for flow battery)	The number of run hours or calendar time before a mechanical part or other component requires overhaul (often used in aviation.)	Flow batteries require equipment overhauls, such as pump or stack replacement. More frequent overhauls increase operating and maintenance costs.

Cost Assessment Scope and Data Collection Methodology

Technology Focus

Cost assessment focus is on lithium ion and flow battery technologies. Lithium ion currently dominates battery storage deployments with more than 97% of the capacity of stationary ESS installations in the United States in 2017. [1] Given current and projected costs, lithium ion is likely to remain in the leading position for most stationary applications for at least the next five to ten years, and probably beyond.

Flow battery projects are primarily in the demonstration phase, especially within the U.S., with initial commercial deployments starting to come on-line or be announced. If flow battery technology costs decrease sufficiently, it has the potential to be competitive in longer duration applications, including resource adequacy or variable renewable energy integration (via energy time shift).

Scope

The lifecycle cost of an ESS are divided into four main categories: Upfront Owners Costs; Turnkey Installation Costs (energy storage system, grid integration equipment, and EPC); Operations and Maintenance Costs; and Decommissioning Costs [2]. The table here further segments costs into subcategories and shows items included in this study.

Data Collection Methodology

The data for this analysis came from several sources, including EPRI projects, utility members, publicly-available and fee-based analyses, and EPRI surveys of vendors and integrators. EPRI combined data from EPRI and utility projects with publicly available and paid cost and technology reports to develop initial performance assumptions and cost ranges. EPRI also conducted interviews with other cost analysts to understand underlying assumptions in order to ensure that the data used in this study were consistent. The initial findings from EPRI's analysis were shared with vendors and integrators to obtain their feedback and recommendations.

Cost Line Item	Scope of Cost Assessment
Upfront Owners Costs	
Project Development	Excluded
Program Development	Excluded
Energy Storage System	
Battery/Storage Medium	**Included**
Power Conversion System (PCS)	**Included**
ESS Balance of Plant (BOP)	**Included**
Control	**Included (site level)**
Grid Integration Equipment	
Grid Integration Equipment	**Included (up to the high side of the transformer)**
Engineering, Procurement, and Construction (EPC)	
ESS Installation	**Included**
Site Installation	**Included**
Project Management	**Included**
Engineering	**Included**
ESS Shipping	**Included**
Grid Integration Installation	**Included**
Commissioning and Acceptance	**Included**
Operations & Maintenance	
Annual Software Licensing Fees	Excluded
Fixed Maintenance	**Included**
Energy Costs (Charge/Discharge Losses, Housekeeping Power, Self-Discharge)	Excluded
Other On-going Owners Costs, e.g., insurance, scheduler fees, project administration, etc.	Excluded
Variable Maintenance	**Included**
ESS Extended Warranty	**Included**
Performance Guarantees	**Included**
Augmentation or Overhaul	**Included**
Decommissioning	
ESS Decommissioning	**Included**
Grid Related Decommissioning	Excluded

Energy Storage Installed Cost Summary for 2019 Commercial Operating Date

Application	Technology	Capacity (MW)	Duration (hours)	2019 Cost Range ($/kW)	2019 Cost Range ($/kWh)
Bulk Services	Lithium ion	50-100	4	$1300 - $2100	$325 - $525
	Flow battery	50-100	4	$2000 - $3400	$500 - $850
	Lithium ion	50-100	1	$500 - $900	$500 - $900
	Lithium ion	30-50	8	$2350 - $3800	$295 - $475
	Flow battery	30-50	8	$3500 - $5800	$440 - $725
	Lithium ion	30-50	6	$1800 - $2900	$300 - $485
	Flow battery	30-50	6	$2700 - $4500	$450 - $750
Frequency Regulation	Lithium ion	10-20	0.5	$450 - $1000	$900 - $2000
T&D Grid Support	Lithium ion	10-20	4	$1350 - $2400	$340 - $600
	Flow battery	10-20	4	$2200 - $3600	$550 - $900
	Lithium ion	1-5	2	$1000 - $2000	$500 - $1000
Commercial Use	Lithium ion	0.25	4	$1900 - $3000	$475 - $750
	Flow battery	0.25	4	$3000 - $5000	$750 - $1250
	Lithium ion	0.25	2	$1150 - $1950	$575 - $975

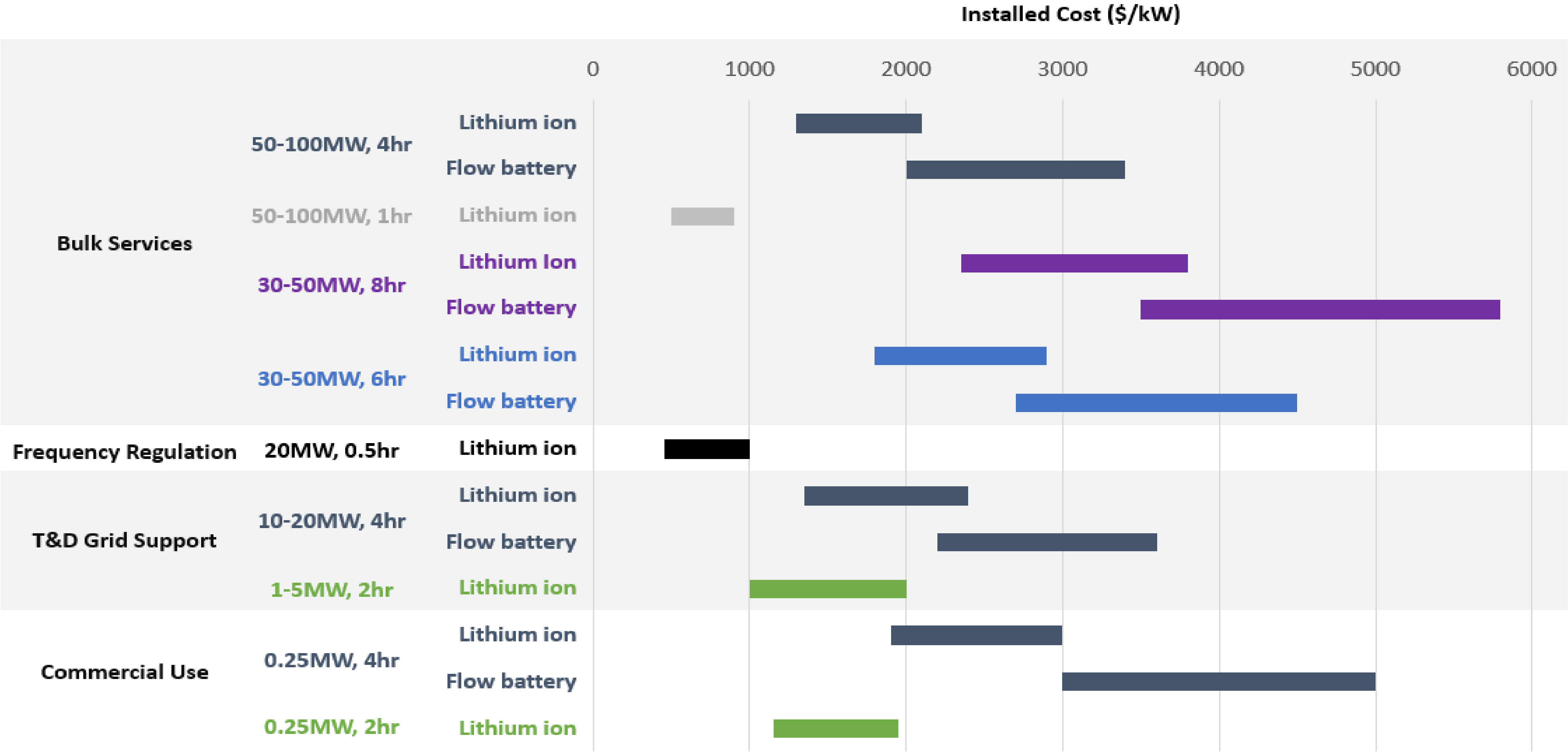
A summary overview of EPRI's projected turnkey installed EPC costs for 2019 is shown in the table and on the next two pages. The power and energy durations for the ESSs presented in these summaries represent example applications (or use cases). These cost values are provided over a range as installed costs can vary based on location, site conditions, project specific requirements, supply constraints or excess manufacturing, among other factors.

Costs are presented in $/kW per the convention used for expressing generator costs and also in $/kWh due to energy storage being an energy limited device. Caution should be used in evaluating installed costs simply through $/kW or $/kWh values, as scale and energy duration characteristics impact a specific project's overall economics. For example, installed cost in $/kW for an ESS with a high power-to-energy ratio would have a value far lower than an ESS with the a higher energy-to-power ratio.

Lithium ion battery systems are projected to remain the lowest cost battery energy storage option in 2019 for a given site and utility use case. The costs of lithium ion batteries have decreased by roughly 80% since 2010 due to a number of factors. Furthermore, the storage industry as a whole has been able to benefit from cost reductions of PCSs and other BOP components.

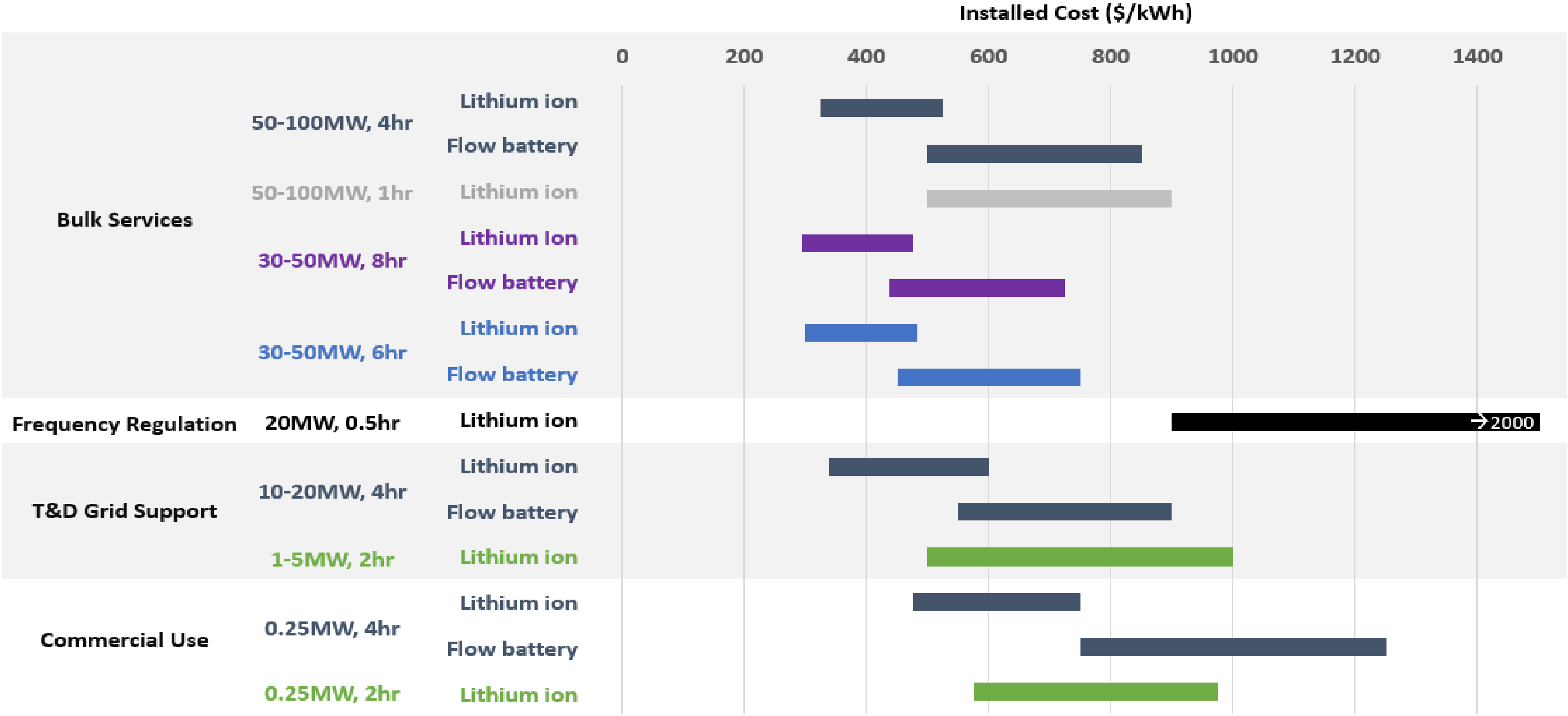
The range of flow battery installed costs is wider than the lithium ion range (within a given application). Most flow battery vendors have yet to successfully move beyond demonstration or small commercial projects, and each manufacturer is at a different stage of design maturity; some larger flow battery systems installed to date are one-off designs, while others are systems based on small modular designs. Finally, most of the systems installed are demonstration projects. Demonstration projects typically incur additional soft costs on top of what suppliers and integrators can provide for commercial projects.

Energy Storage Installed Cost Summary per Unit Rated Power Capacity for 2019 Commercial Operation Date



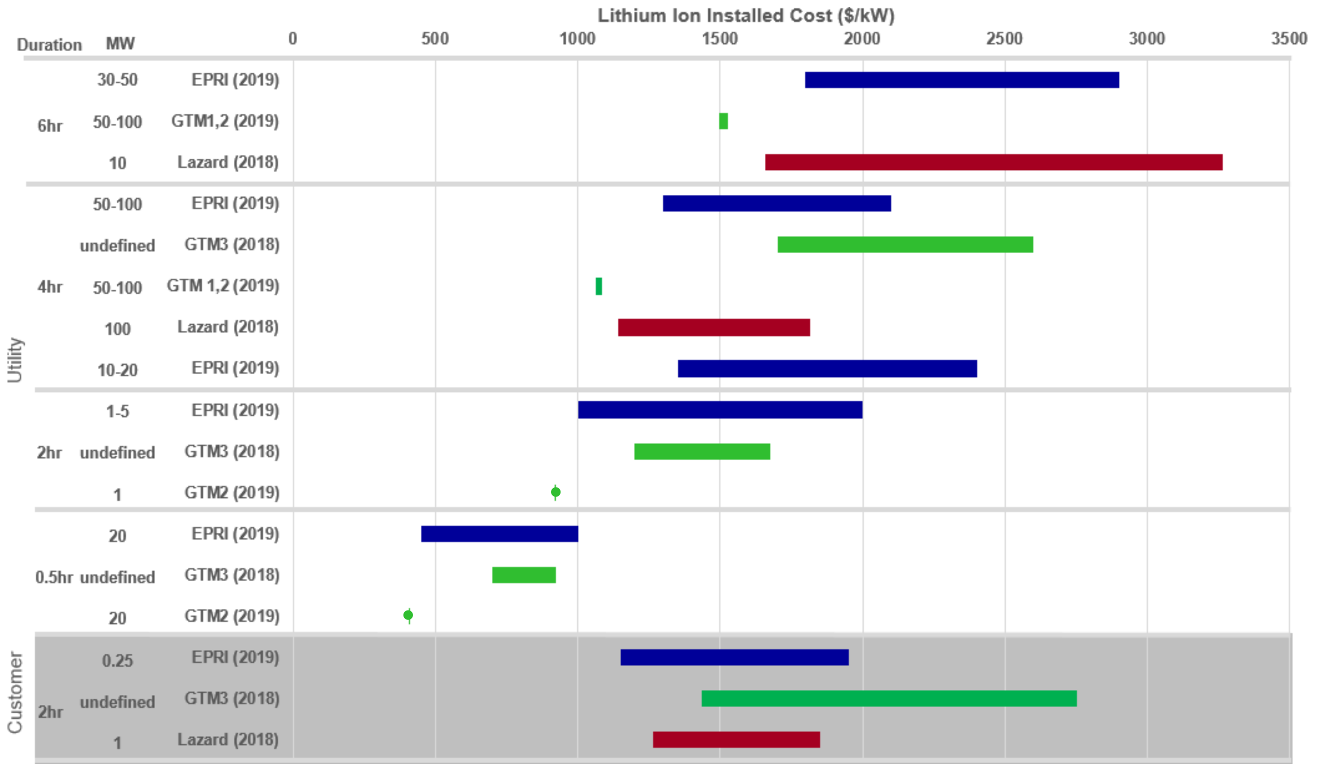
EPRI ELECTRIC POWER RESEARCH INSTITUTE

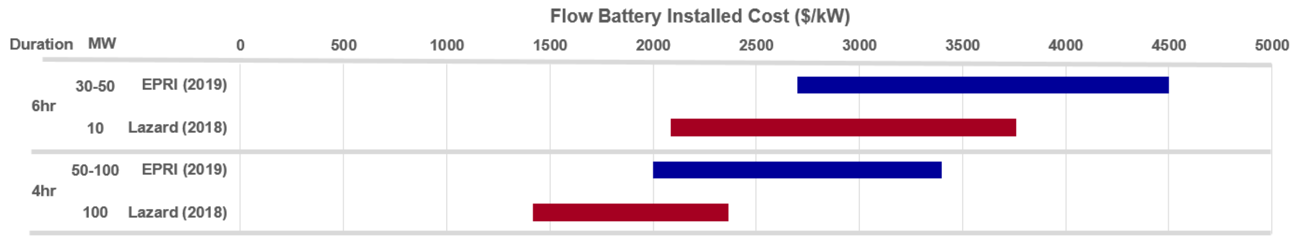
Energy Storage Installed Cost Summary per Unit Rated Energy for 2019 Commercial Operation Date



EPRI ELECTRIC POWER RESEARCH INSTITUTE

Comparison of Installed Cost Estimates from Various Resources



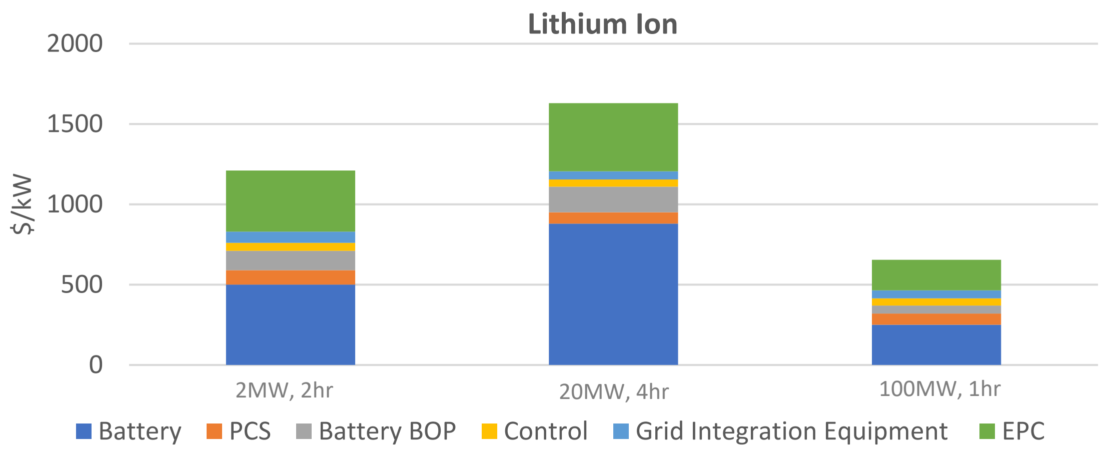


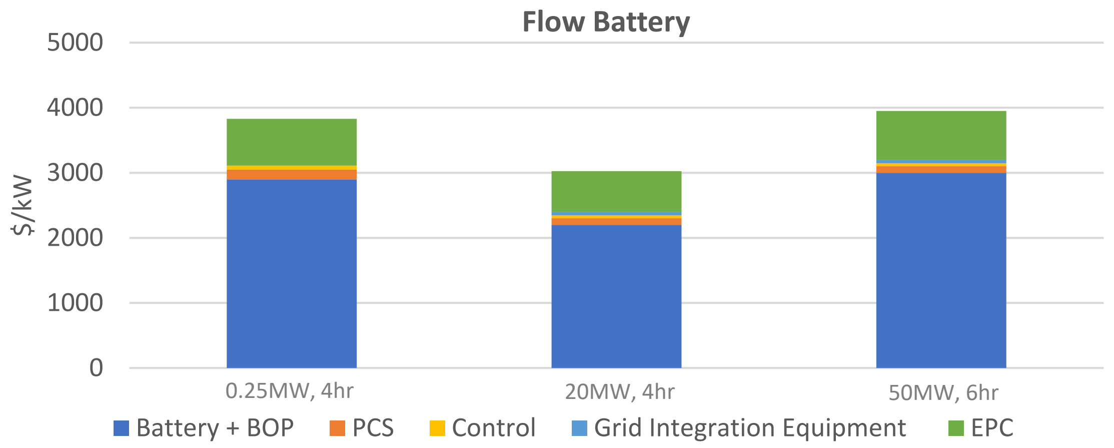
When looking at cost studies, it is important to consider the scope of the installation, scale of the system, and the year the costs are estimated for, as these assumptions can vary among studies. The cost comparison plots compare this study's 2019 projected costs for lithium ion and flow batteries, with those from other studies' cost estimate and projections.

Data Sources:

- EPRI (2019) is the projected 2019 cost range from this report
- GTM1 (2019) is the projected 2019 cost range from GTM Research, *Energy Storage For Peaker Plant Replacement* [3]
- GTM2 (2019) is a projected 2019 cost data point from GTM Research, *U.S. Front-of-the-Meter Energy Storage System Prices*, *2018-2022* [4]
- GTM3 (2018) is the Q3 2018 cost range from GTM Research and ESA, U.S. Energy Storage Monitor Q3 2018 [1]
- Lazard (2018) is the estimated 2018 cost range from Lazard, *Levelized Cost of Storage version 4.0.* [5] Note: Flow battery costs are for vanadium flow batteries.

Example Installed Cost Breakdown for 2019 Commercial Operation Date





The figures above include example breakdown costs for example lithium ion and flow battery systems, representing different applications and system sizing.

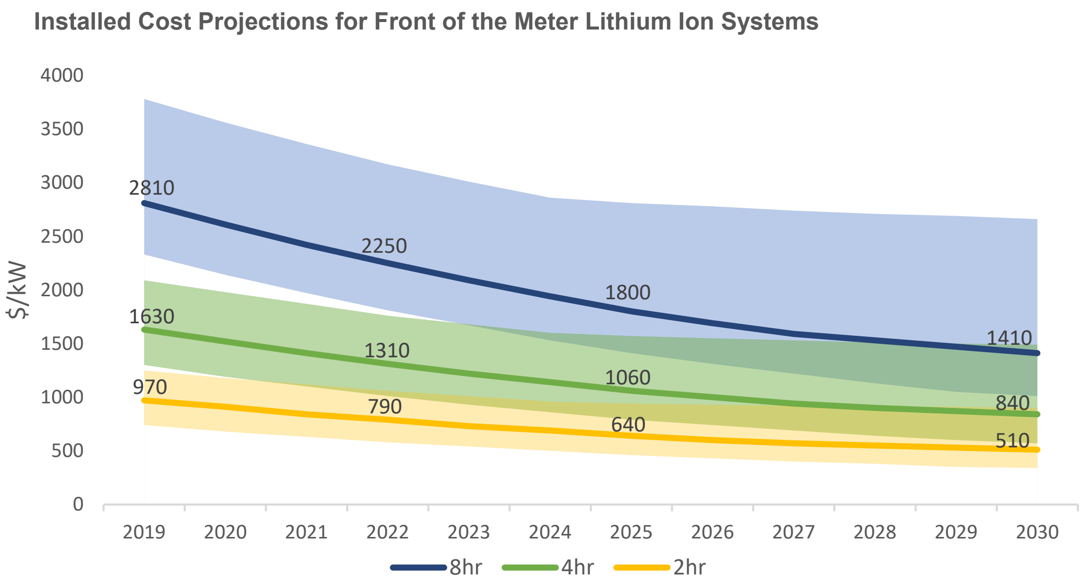
In 2019, lithium ion battery rack costs are anticipated to remain relatively unchanged from 2018, but may decrease if there is a balance in supply/demand or even excess production capacity. Lithium ion BOP costs will vary based on design (thermal management, enclosures, UPS, fire detection and suppression, etc.). The battery cost line item for a flow battery includes the battery and its BOP, which are delivered as a packaged unit. Flow battery costs vary markedly due to the different levels of commercialization by various manufacturers and the different durations provided in their standard offerings.

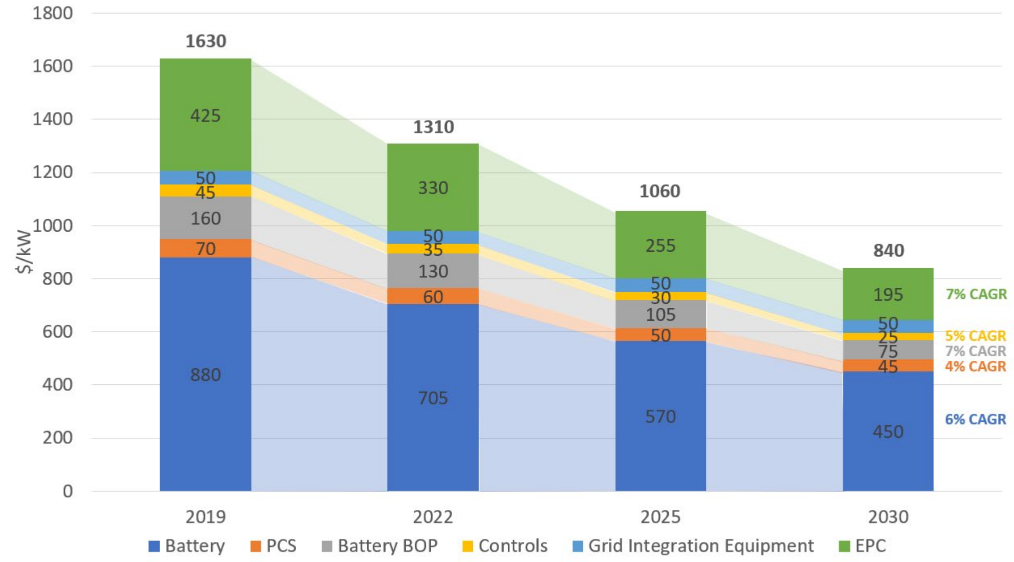
PCS costs vary from discounts due to project economies of scale, differences in standard warranty offerings, functional requirements (e.g., advanced inverters, UL 1741SA), and differences between manufacturers. PCS costs may be higher for flow batteries due to their lower operating voltage and potential need for specialized equipment (e.g., two-stage inverter).

Grid integration equipment includes transformers, switchgear, protection, and other equipment to support the integration of the ESS to the utility grid. Grid integration costs will vary based on the interconnection voltage, availability and use of existing infrastructure, and design requirements.

EPC encompass the remaining costs for a turnkey project. The main cost segments are installation, project management, engineering, shipping, and commissioning. Variations in EPC costs may arise from specific site conditions or project requirements. For flow batteries, most installations have been demonstration projects and it remains unclear whether there will be additional costs for commercial flow battery installations beyond those required for lithium ion installations. However, given flow batteries' lower energy density than an equivalently rated lithium ion system, a flow battery installation would probably have a larger project footprint and be heavier, and thus incur additional site preparation and installation labor costs.

Lithium Ion Installed Cost Projections





Lithium ion installed costs are projected to continue to decrease through 2030 and potentially beyond. The top figure illustrates projected installed cost for front of the meter systems with upper and lower bounds based on the potential differences in costs due to the specific project requirements, scale, and uncertainty in future costs reductions. Cost reductions will likely be accomplished across all major cost categories. The bottom figure illustrates an example breakdown of installed cost for a 20MW, 4hr system through 2030.

Battery cost declines will be a function of continued manufacturing improvements, such as economies of scale and new manufacturing techniques; cell chemistry improvements, such as reduction in expensive raw materials (e.g., transitions to lower cobalt blends); engineering and design improvements; and efficiencies gained in supply chain management.

Energy storage PCSs currently have a cost premium compared to solar PV inverters, but they are expected to achieve parity with solar PV inverter costs within five to ten years. The reductions will driven by standardization of products, which enables increased manufacturing volume and system design improvements.

BOP costs are anticipated to decline due to increased standardization of design and packages, as well as incorporating lessons learned from past integration experience. However, newly established and emerging codes and standards may dictate added requirements and cost for fire protection, space for clearance requirements, and monitoring, potentially limiting the otherwise expected BOP cost reductions.

Grid integration equipment was assumed to stay flat in the base case analysis.

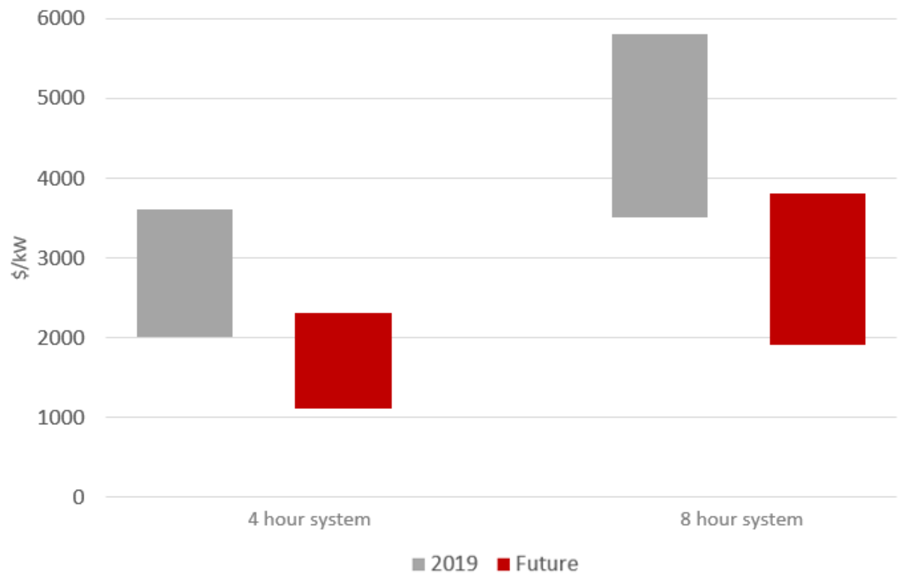
EPC cost declines are anticipated from several sources, including improvements in energy density, which could decrease site and electrical installation, and soft costs which may be reduced with project experience.

Flow Battery Installed Cost Projections

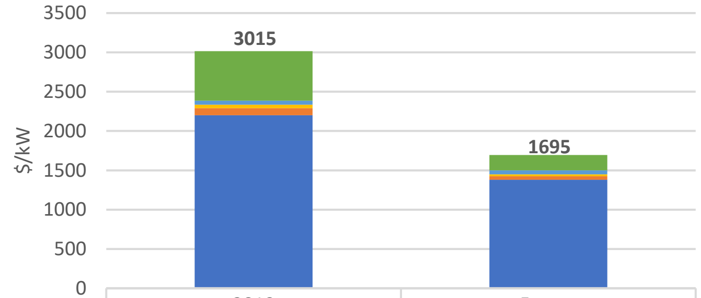
The figures to the right show flow battery cost projections, illustrating the potential range in costs and an example breakdown. The battery cost estimates are largely based on the then future costs estimated in a 2007 EPRI study of vanadium redox flow batteries [5], while the grid integration, PCS, controls, and EPC costs are assumed to be the same as the lithium ion 2030 projections from this study. Cost projections were not performed for other flow battery chemistries as further research is needed to better understand the various components and cost drivers. Costs presented are not tied to a specific year, but characterized simply as future.

The uncertainty over future costs for flow batteries comes from a number of areas. For example, there is uncertainty in future raw material costs for flow batteries. As the electrolyte makes up approximately one-third of the technology cost, the viability of all vanadium flow batteries largely depends on vanadium costs. In the EPRI 2007 study and this analysis, future electrolyte costs were based on an assumption of $4-$5/lb. for vanadium pentoxide. In October 2018, however, the vanadium pentoxide price exceeded $20/lb., so the future scenario would require a large raw material price reduction.

Installed Cost Projections for Front of the Meter Flow Battery Systems



Installed Cost Projections for a 4 hour Flow Battery System



	2019	Future
EPC	630	195
Grid Integration Equipment	50	50
Controls	45	25
PCS	90	45
Battery + BOP	2200	1380

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Operations and Maintenance (O&M) Costs

This study focuses on gathering and evaluating data on maintenance, warranty, and performance guarantee costs. The table below summarizes recommended O&M inputs for cost-benefit modeling. There may exist additional owners costs incurred during operations, such as dispatch monitoring, scheduler fees, reporting, or other on-going project costs, which have been excluded from the scope of this analysis as they are highly specific to an owner or application.

Maintenance – The fixed maintenance cost data collected in this study varied greatly. For lithium ion systems, costs are presented as a percentage of CapEx per year as it scales with both power and energy similar to installed costs. For flow battery systems, costs scale more closely with $/kW-year, as most of the maintenance costs are related to the power components, such as the stack and pumps. Generally, results from this report show that variable O&M cost, which is proportional to the storage throughput, was negligible for lithium ion systems. Flow battery system maintenance contracts were not based on cycling and therefore are not considered in modeling.

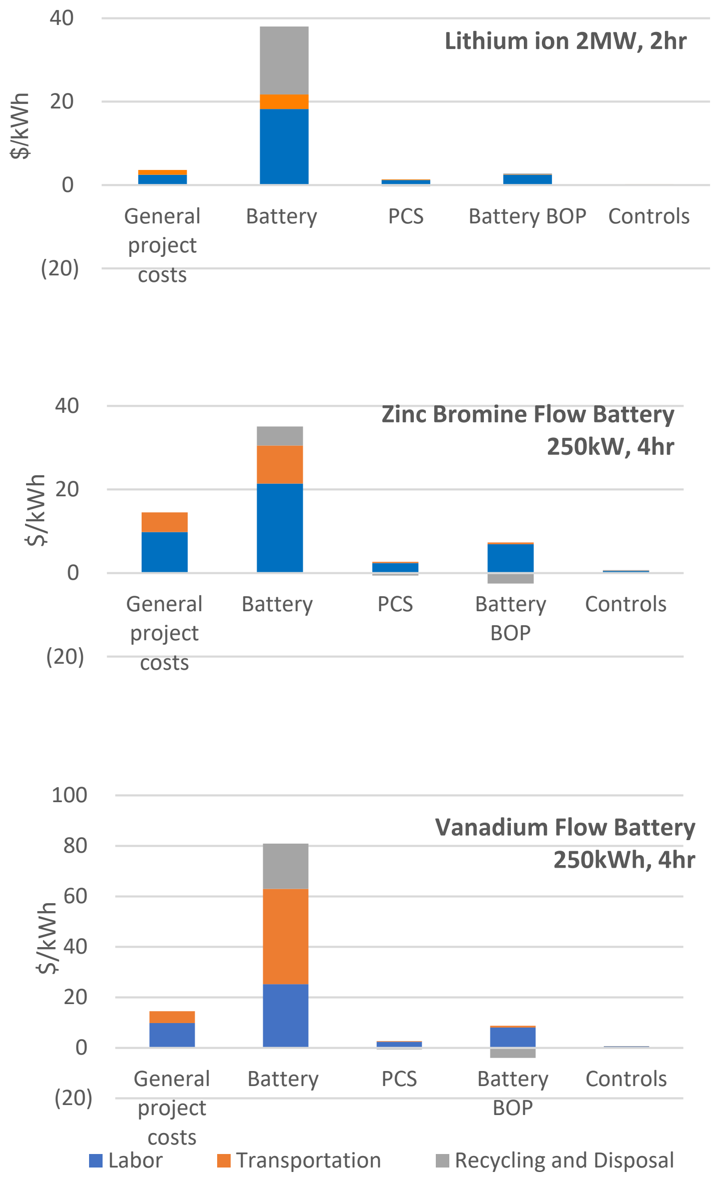
Warranty – As of 2018, warranty packages across suppliers are not consistent. A standard warranty is assumed to be included in the upfront purchase of the system, while an extended warranty is an additional cost per year after the standard warranty. The main differences between standard warranty packages are length of warranty terms (varied from 1 to 10 years) and coverage (e.g., guaranteed energy based on cycling and calendar life or workmanship only).

Performance Guarantee – In addition to standard or extended warranty coverage, suppliers may provide performance guarantees, such as an energy capacity guarantee and an uptime (or availability) guarantee, for an added cost. There was not sufficient data to report on performance guarantee costs.

Replacement – Lithium ion systems may require battery replacement or augmentation depending on the use case. Replacement costs estimates are listed in the table and includes the battery modules, BOP upgrades, shipping, labor, and equipment (assuming augmentation occurs after 2020). Flow batteries may require stack and pump replacements during the system life.

	Lithium Ion	**Flow Battery**
Fixed Maintenance	1.5% of CapEx per year	$80/kW-year (commercial systems) $40/kW-year (utility scale systems)
Warranty	1% of CapEx per year after 3 years	1.5% of CapEx per year after 2 years
Replacement	$200-$300/kWh	Stack at 5 years: $1000/kW (commercial system); $750/kW (utility scale system)

Decommissioning and End of Life Costs



Assumptions for Cost and Value Inputs	
Labor rate (2030 $/hr)	$175
Transport cost ($/ton) at 100 miles	$70
Transport cost for batteries, electrolyte, and stacks ($/ton) at 1,500 miles	$340
Construction & demolition waste disposal fee ($/ton)	$60
Lithium ion battery disposal fee (commercial) ($/ton)	$2000
Hazardous material disposal fee (commercial) ($/ton)	$160
Steel scrap salvage value for PCS, racks, HVAC enclosure ($/ton)	$135
Container resale value ($/unit)	$1500

The methodology and assumptions used for calculating the disposal costs for the lithium ion and flow battery systems is based on a 2017 EPRI battery storage disposal and recycling report [7] and a 2018 EPRI solar decommissioning report [8]. The scope includes decommissioning and disposal of the battery system, though excludes grid integration equipment and site restoration.

Results	Lithium ion (NMC)			Zinc Bromine Flow Battery	Vanadium Flow Battery
System Size	4MW, 1hr	2MW, 2hr	1MW, 4hr	250kW, 4hr	250kW, 4hr
Disposal cost ($/kWh)	$54	$45	$39	$58	$104

Lithium Ion – The study assessed the disposal costs for high power (4MW, 1hr), medium power (2MW, 2hr), and energy (1MW, 4hr) applications. The disposal cost for the power application is more expensive on a per-kWh basis than the energy application. The power system cost is penalized by a lower system energy density and a higher PCS rating. Lower energy density translates to more racks, resulting in more labor for disassembly and a higher system weight, which adds to transportation and disposal costs. Also, there are more PCS units (in 1MW increments) required that further contributes to additional relative cost to power applications. Overall, the highest fraction of cost is attributed to handling, transporting, and recycling of the battery components, approximately 80% in all three modeled systems.

Flow Battery – Similar to lithium ion, higher disposal costs are associated with lower energy density. Vanadium flow batteries have a lower energy density than zinc-bromine flow batteries, and therefore has more labor costs associated with the disassembly of the additional enclosures, tanks, and pumps, and added transportation costs for the electrolyte.

References

[1] *U.S. Energy Storage Monitor*, GTM Research and ESA, Q3, 2018.

[2] *ESIC Energy Storage Cost Template and Tool (ESIC Cost Tool) v2.0.*, EPRI, Palo Alto, CA: 2018. 3002006072.

[3] *Energy Storage for Peaker Plant Replacement: Economics and Opportunity in the U.S.* GTM Research. March 2018.

[4] *U.S. Front-of-the-Meter Energy Storage System Prices, 2018-2022.* GTM Research May 9, 2018.

[5] *Lazard's Levelized Cost of Storage – Version 4.0*. Lazard. November 2018.

[6] *Vanadium Redox Flow Batteries: An In-Depth Analysis.* EPRI. Palo Alto, CA: 2007. 1014836.

[7] *Recycling and Disposal of Battery-Based Grid Energy Storage Systems: A Preliminary Investigation.* EPRI, Palo Alto, CA: 2017. 3002006911.

[8] *PV Plant Decommissioning Salvage Value Conceptual Cost Estimate.* EPRI Palo Alto, CA: 2018. 3002013116.

Full Report

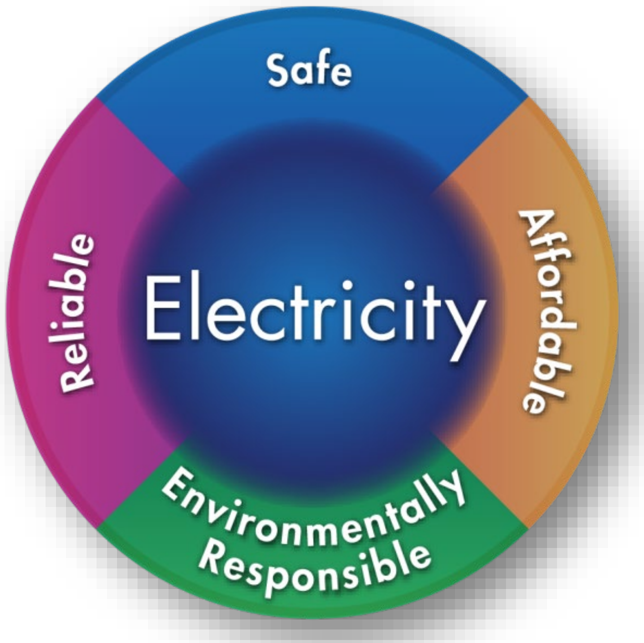
Energy Storage Technology and Cost Assessment. EPRI, Palo Alto, CA: 2018. 3002013957.

For more information visit www.epri.com

ELECTRIC POWER RESEARCH INSTITUTE

Together…Shaping the Future of Electricity

The Electric Power Research Institute, Inc. (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI members represent of the electric utility revenue in the United States with international participation in 35 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.



The Electric Power Research Institute, Inc. (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI members represent 90% of the electric utility revenue in the United States with international participation in 35 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lennox, Mass.

Together…Shaping the Future of Electricity

3002013958