2020 Grid Energy Storage Technology Cost and Performance Assessment

Kendall Mongird, Vilayanur Viswanathan, Jan Alam, Charlie Vartanian, Vincent Sprenkle*, Pacific Northwest National Laboratory.

Richard Baxter, Mustang Prairie Energy

* vincent.sprenkle@pnnl.gov

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Disclaimer

Acronyms

AC	alternating current
Ah	ampere-hour
BESS	battery energy storage system
BLS	U.S. Bureau of Labor Statistics
BMS	battery management system
BOP	balance of plant
BOS	balance of system
C&C	controls & communication
C&I	civil and infrastructure
CAES	compressed-air energy storage
DC	direct current
DOD	depth of discharge
DOE	U.S. Department of Energy
E/P	energy to power
EPC	engineering, procurement, and construction
EPRI	Electric Power Research Institute
ESGC	Energy Storage Grand Challenge
ESS	energy storage system
EV	electric vehicle
GW	gigawatts
HESS	hydrogen energy storage system
hr	hour
HVAC	heating, ventilation, and air conditioning
kW	kilowatt
kWe	kilowatt-electric
kWh	kilowatt-hour
LCOE	levelized cost of energy
LFP	lithium-ion iron phosphate
MW	megawatt
MWh	megawatt-hour
NHA	National Hydropower Association
NMC	nickel manganese cobalt
NRE	non-recurring engineering
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
PCS	power conversion system
PEM	polymer electrolyte membrane
PNNL	Pacific Northwest National Laboratory
PSH	pumped storage hydro
PV	photovoltaic
R&D	research & development
RFB	redox flow battery
RTE	round-trip efficiency

SB	storage block
SBOS	storage balance of system
SCADA	sensors, supervisory control, and data acquisition
SM	storage module
SOC	state of charge
USD	U.S. dollars
V	volt
Wh	watt-hour

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Lead-Acid Batteries

Capital Cost

While lead-acid battery technology is considered mature, recent industry R&D has focused on improving the performance required for grid-scale applications. Lead-acid battery life is highly dependent on DOD where typically the battery is cycled between 50% and 80%. The reason the battery must operate within this stated range is that the Ah and Wh capacity for most lead-acid batteries are rated at the 50- to 100-hour rate, hence cycling them at 100% DOD would require a discharge duration of 50 to 100 hours. However, only about 50% of the energy capacity is available at the 1-hour rate and 80% of the energy capacity is available at the 10-hour rate.

Lead-acid batteries also do not typically operate at low SOC, and the SOC is generally prevented from going below 20% when an extended battery life is desired. Table 1 shows the energy capacity in Wh and the corresponding DOD obtained from a 12 V, 200 Ah (2,400 Wh) battery at various discharge durations (C&D Technologies Inc., Undated). A separate calculation to find the adjusted DOD limitations accounting for battery degradation of 5% is provided as a separate column in Table 1. The number of cycles at each adjusted DOD is obtained from Figure 1 using information provided from conversation with a lead-acid battery expert (Raiford, 2020a). Note that since single-cell cycle life was much higher than for assembled modules or packs, this study uses cycle life data obtained from modules.

Table 1. Energy Capacity by Duration of Lead-Acid Batteries

Duration (hrs)	Watts/cell	Wh	DOD	Degradation	# Cycles
1	206	1,236	51.5%	48.9%	1,030
2	122	1,464	61.0%	58.0%	862
3	89.4	1,609	67.1%	63.7%	781
4	70.6	1,694	70.6%	67.1%	739
5	59.2	1,776	74.0%	70.3%	704
6	51.3	1,847	77.0%	73.1%	675
8	40.8	1,958	81.6%	77.5%	635
10[(a)]		2,070	86.3%	81.9%	599

(a) Watts/cell was not provided for a 10-hour system

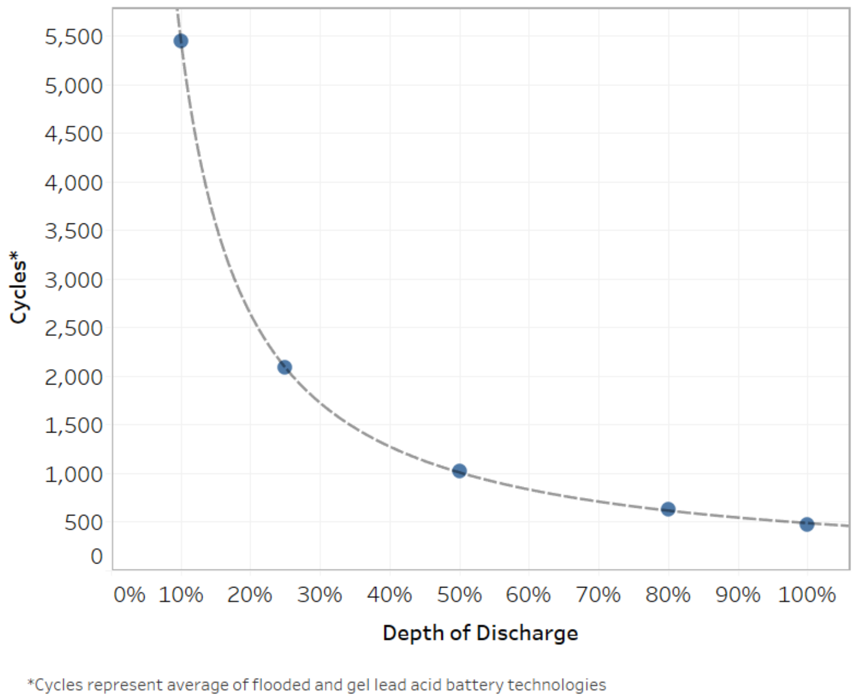

Figure 1. Cycles by DOD for 12 V Lead-Acid Battery Modules

In the literature, lead-acid battery prices are reported as low as $200-220/kWh (Aquino, Zuelch, & Koss, 2017; G. J. May, Davidson, & Monahov, 2018; PowerTech Systems, 2015). Cost information was provided for a 10 MW, 50 MWh system for a utility-scale BESS installed in Europe and is shown in Table 2 (Raiford, 2020a). The SB cost based on rated energy was $236/kWh. Note that the power component of lead-acid batteries in Table 5 includes converters, rectifiers, internal cabling, and piping. The SBOS costs are estimated by subtracting DC-DC converter and PCS costs from the power component costs and was 23% of SB cost. No attempt was made to differentiate the cost between valve-regulated and flooded lead-acid batteries.

Table 2. Costs by Category for a 10 MW, 50 MWh Lead-Acid Battery

Category	Value
DC battery ($/kWh)	236
Power component ($/kW) [(a)]	675
Fixed O&M ($/kW-year)	8.0
Variable O&M ($/MWh)	1.0
RTE (%)	84
Cycles at 50% DOD	5,500
Cycles at 100% DOD	3,000
Shelf life (years)	12

(a) Includes converters, rectifiers, internal cabling, and piping

Table 3 summarizes the capital cost and performance metrics for a 1, 10, and 100 MW, 5-hour lead-acid battery system. The 10 MW system cost was provided by vendors directly and estimates for the 1 MW and 100 MW system were calculated using a cost decrease for 10x increase in MW capacity, where 10

MW is used as the baseline (Raiford, 2020b). Conversely, cost increases for a 10x decrease in MW was also employed for this study. Additional capital costs provided by another energy storage expert have also been included for lead-acid and lead-carbon batteries at a 1 MW power capacity (Baxter, 2020d) and shows a wide range of data depending on the different battery designs being considered. Cost associated with system integration, EPC, and project development were determined using the same approach used for lithium-ion batteries described previously in this report, but with a reduction of markup and profit changed to 15% instead of 20%. The primary reason for the lower markup and profit is that there are generally fewer safety-related issues associated with lead-acid batteries. The SBOS for the Raiford (2020a) system has been estimated by removing PCS (assumed equivalent to PCS cost for lithium-ion) and DC-DC converter prices (Wood Mackenzie, 2020b) from the total power component cost as stated earlier. Note that the SBOS per the European example (Raiford, 2020a) was 23% of SB cost; slightly higher than other studies referenced in this report. For this study, the SBOS was set at 20% of SB cost, in line with lithium-ion BOS.

Table 3. Capital Costs and Performance Metrics for Lead-Acid Systems Across Various Capacities

	Raiford (2020a)	Raiford (2020a)		Baxter (2020d)	
Power capacity (MW)	10	1	100	1	1[a]
Energy capacity (MWh)	50	5	500	4	4
DC SB ($/kWh)	471	495	447	183	349
DC-DC converter ($/kW)	60	70	52		
PCS ($/kW)	73	85	63	24	24
SBOS ($/kWh)	108	114	103	44	44
Energy management system ($/kW)	8	40	2		
System integration ($/kWh)	83	88	78	38	42
EPC ($/kWh)	93	99	88	58	92
Project development ($/kWh)	118	125	111		
Grid integration ($/kW)	25	31	20		
Total ESS installed costs ($/kWh)	**906**	**965**	**855**	**347**	**551**

[a] Lead-carbon system

Note that the capital cost information provided from Raiford (2020a) corresponds to $/kWh of available energy at 50% DOD for lead-acid BESS comprised of single cells, which are more expensive but have a higher cycle life. To be consistent with other BESS, the SB capital cost is represented as $/kWh of rated energy in this study and is $236/kWh for BESS comprised of single cells, with rack cost estimated at $70/kWh (30% of SB cost). The 12 V battery module costs are estimated at $100/kWh (Raiford, 2020c), resulting in SB cost of $170/kWh regardless of DOD. The DOD corresponding to each duration is determined from Table 1, while the cycle life corresponding to DOD is determined from Figure 1. Table 4 provides a detailed category cost breakdown for a 10 MW, 40 MWh, lead-acid BESS with a comprehensive reference list for each category.

Table 4. Price Breakdown for Various Categories for a 10 MW, 40 MWh, Lead-Acid Battery

Cost Category	Nominal. Size	2020 Price	Content	Additional Notes	Source(s)
SB	40 MWh	$171/kWh	$/kWh cost for SB	Lead-acid battery module price of $100/kWh (Raiford, 2020a) used along with $70/kWh for racking the modules	Baxter (2020a); Frith (2020a); Frith (2020b); Goldie-Scot (2019); Aquino et al. (2017); G. J. May et al. (2018); PowerTech Systems (2015); Raiford (2020a)
BOS	40 MWh	$47/kWh	$/kWh cost for BOS	Obtained by subtracting DC-DC converter and PCS price from power component price of Aquino et al. (2017), works out to be 20% of SB cost based on single-cell strings	Raiford (2020a)
DC-DC converter	10,000 kW	$60/kW	DC-DC converter cost		Wood Mackenzie (2020b)
PCS	10 MW	$73/kW	PCS cost	Includes cost for additional equipment such as safety disconnects that are site-specific, cost aligns with numbers provided by PCS vendor for utility scale	Austin (2020); Baxter (2020a); Goldie-Scot (2019); Vartanian (2020); Wood Mackenzie (2020a)
C&C	10 MW	$7.8/kW		Source provides estimate for C&C, PNNL approach for scaling across various power levels	Baxter (2020c)
System integration	N/A	7.5% markup on hardware and 7.5% profit on sum of above rows		Lowered from 10% markup and 10% profit for lithium-ion due to lower safety concerns	Baxter (2020b)
EPC	N/A	15% markup + profit on sum of above rows		Lowered from 15% markup and 5% profit for lithium-ion due to lower safety concerns	
Project development	N/A	15% markup + profit on sum of above rows		Lowered from 5% markup and 15% profit for lithium-ion due to lower safety concerns	
Grid integration	10 MW	$24.9/kW		Source provided estimate for C&C, PNNL approach for scaling across various power levels	
O&M			Fixed O&M		Aquino et al. (2017); Raiford (2020a)
Performance metrics			DOD at various discharge durations		C&D Technologies Inc. (Undated)
Performance metrics			Cycles as a function of DOD		Anuphappharadorn, Sukchai, Sirisamphanwong, and Ketjoy (2014); BAE Batteries (2016); DiOrio, Dobos, and Janzou (2015); Raiford (2020a)
Performance metrics			Calendar life		C&D Technologies Inc. (2015); G. J. May et al. (2018)
Performance metrics			RTE		Anuphappharadorn et al. (2014); G. May (2020); Raiford (2020a)

The price range for 2020 was 0.9 to 1.1 times the nominal values for each category. For the 2030 price, the learning rate for the SB was set at 1.5%, with the low and high end of the price range having learning rates of 2.5% and 0.5% respectively. The learning rates for other categories are the same as for the lithium-ion system and are shown in Table 5.

Table 5. Learning Rates Used to Establish 2030 Lead-Acid Capital Cost and Fixed O&M Ranges

Component	Low Price	Nominal Price	High Price
DC SB ($/kWh)	2.50%	1.50%	0.50%
DC SBOS ($/kWh)	10%	7%	4%
DC-DC converter ($/kW)	7%	3%	2%
PCS ($/kW)	7%	3%	2%
C&C ($/kW)	10%	7%	4%
System integration ($/kWh)	6%	4%	2%
EPC ($/kWh)	6%	4%	2%
Project development ($/kWh)	6%	4%	2%
Grid integration ($/kW)	6%	4%	2%
O&M ($/kW-year)	6%	4%	2%

O&M Costs

There are not many examples in the literature of O&M costs specific to lead-acid systems. Aquino et al. (2017) estimated that the fixed O&M cost for an advanced lead-acid battery combined with an asymmetric supercapacitor to be in the range of $7-15/kW-year, and that the variable cost for the same system is estimated to be $0.0003/kWh ($0.3/MWh). Raiford (2020a) places fixed O&M costs closer to the low end of the range at $8/kW-year, which corresponds to 0.86% of the direct capital cost for a 4-hour duration. As described in the lithium-ion section, fixed costs were assumed to be 0.43% of SM capital cost for all BESS. The fixed O&M range for the year 2020 was 0.9 to 1.1 times the nominal values for each category. The fixed O&M learning rate was in the 2 to 6% range.

For basic variable O&M, there is inconsistent nomenclature regarding what this category consists of. Due to the lack of detailed justification regarding what comprises basic variable O&M for each technology, this work sets the basic variable O&M to be $0.5125/MWh and is derived here based on the average across various technologies (Table 6). Depending on duty cycle, the energy throughput will vary, thus affecting total basic variable O&M costs.

Table 6. Variable O&M Estimate Calculation for Energy Storage Systems

Reference(s)	Technology	Value ($/MWh)
Raiford (2020a)	Lead Acid	1
Hunter et al. (In Press)	Hydrogen	0.5
Aquino et al. (2017); Wright (2012); Black & Veatch (2012)	CAES	0.25
Mongird et al. (2019)	Non-specific	0.30
	Average	**0.5125**

Performance Metrics

Lead-acid batteries typically have a shorter cycle life compared to lithium-ion systems and are primarily used for resource adequacy and capacity applications (Aquino et al., 2017). The lead-acid battery cycle life depends highly on DOD, hence its operating life depends on the number of cycles needed per year at the desired DOD along with cycle life at the desired DOD (Anuphappharadorn et al., 2014; BAE Batteries, 2016; DiOrio et al., 2015). Therefore, operating life can be limited to 1-5 years depending on chosen DOD. Other sources estimate lead-acid systems to be capable of a much longer calendar life (15-20 years), which, as defined earlier, is the maximum life of a battery under specified ambient temperature, regardless of operating conditions (C&D Technologies Inc., 2015; G. J. May et al., 2018). Raiford (2020a) is consistent with the lower end of the cycle range specified in the literature with an estimate of 675 cycles and a calendar life of 12 years. The calendar life is assumed to be consistent with that of Raiford (2020a) in this analysis along with a varying cycle life based on assumed number of cycles per day and DOD corresponding to the values in Table 1.

The RTE of lead-acid systems is typically estimated to fall between 75-84% but is dependent on the chosen operation of the system where operating at a higher duration corresponds with a higher RTE (Anuphappharadorn et al., 2014; G. J. May et al., 2018; Raiford, 2020a). Taking the average of the values provided in the literature gives an RTE of 82% and is the value assumed in this analysis for 6-hour duration, with 77% RTE for 2-hour duration and 85% RTE for 10-hour duration.

Response time estimation for lead-acid systems follows the same methodology as that of lithium-ion. That is, the time to go from rest to rated power is determined by the inverter selection and the overall system design. A specific PCS or DC stack design can be chosen so that the system can respond at the desired rate for the chosen application. Here, response time is assumed to be between 1-4 seconds for lead-acid systems.

Losses due to RTE were estimated based on an assumed electricity cost of $0.03/kWh and the RTE corresponding to each duration. For example, for a 6-hour duration with RTE of 82%, the cost due to RTE losses is $0.007/kWh for the lead-acid system.

R&D Trends in Lead-Acid Batteries

Lead-acid batteries are quite complex and come in two main categories: flooded and valve-regulated. Flooded lead-acid batteries have different charge procedures compared to valve-regulated lead acid batteries. Flooded lead-acid batteries use Pb-Sb grids to improve cyclability. Sb improves castability of grids and reduces resistance of the positive grid corrosion layer while also improving positive active material cycle life by promoting interparticle contact (Pavlov, 2017c). However, Sb results in increased oxygen generation at the positive and especially increased hydrogen generation at the negative, requiring frequent topping off of water. This results in very low shelf life for flooded batteries with Pb-Sb alloy grids. To avoid a high self-discharge rate, battery manufacturers use Pb-Ca grids, which increase the shelf life and reduce or eliminate the need for topping off with water. However, absence of Sb led to premature capacity loss related to formation of high resistance layer of PbO between positive grid and active material and high resistance between positive active material particles, in addition to poor castability. Alloying Pb-Ca with Sn mitigated this premature capacity. Some manufactures use low Sb alloy grid for the positive and Pb-Ca-Sn alloy for the negative to take advantage of the positive effects of Sb on positive active material cyclability. However, this results in Sb ion transport to the negative, where it promotes self-discharge via hydrogen evolution (Pavlov, 2017c).

The modes and causes of degradation for lead-acid batteries are:

- Positive grid corrosion to high resistance oxide – mitigated by Sb or Sn alloy (Pavlov, 2017c).
- Premature capacity loss for the positive – mitigated by Sb or Sn alloy (Pavlov, 2017c).
- Passivation of negative electrode with continuous film of lead-sulfate crystals.
  - Mitigated by addition of expanders such as carbon black, activated carbon, barium sulfate, and lignocellulose (Pavlov, 2017a).
  - Carbon has two purposes: to increase conductivity and provide suitable pore structure (Pavlov, 2017a).
    - Carbon black has high surface area but low pore size – pores too small for Pb^{+2} and HSO_4- ion transport.
    - Activated carbon has lower surface area, but sufficiently large pores for transport of Pb^{+2} and HSO4- ions.
  - $BaSO_4$ promotes nucleation of $PbSO_4$, avoiding crustal growth and passivation of active material (Boden, 1998).
  - Lignocellulose provides the desired pore structure to form $PbSO_4$ crystals during discharge of the right size such that they dissolve and reprecipitate on the electrode, in equilibrium with dissolved $PbSO_4$ near the electrode. Upon charge the dissolved lead sulfate gets reduced to Pb. As $PbSO_4$ gets consumed more $PbSO_4$ dissolved near the electrode is reduced (Pavlov, 2017a).
  - The correct choice of expander depends on application; therefore, it is anticipated that there will be a focus on mapping the available expanders to batteries developed for various grid services.
- Improper balance between electrolyte and negative and positive active material utilization – balance between initial capacity and cycle life (Pavlov, 2017b).
- High temperature during formation that leads to macrocracks between grid and active material resulting in poor contact and high resistance (Pavlov, 2017d).
- Excessively high sulfuric acid concentration during formation that leads to a higher amount of undesired α-PbO_2 (Pavlov, 2017b).
- Electrolyte stratification resulting in sulfation at the bottom which can result in permanent capacity loss (Pavlov, 2017b). This is not a factor for valve-regulated lead-acid batteries, especially if the battery is placed horizontally.
- High temperature during operation that promotes water decomposition and cell dry out, positive grid oxidation from evolved oxygen, expander degradation resulting in negative electrode passivation with lead sulfate (Pavlov, 2017a).
- Improper choice of grid for the application (Pavlov, 2017c):
  - Deep cycle application would require more Sb or Sn at the positive and suitable expander composition.

- Valve-regulated batteries for deep cycling would be a challenge since Sb used to increase cycle life promotes gassing and water loss.

The utilization of electrolyte is typically designed as the limiting factor, with excess positive and negative active material. This results in low DOD for the positive and negative electrode at the rated capacity (Pavlov, 2017b). Increasing the DOD without adversely affecting cycle life would be a substantial achievement for lead-acid batteries. Module cycle life typically is 2x lower than single-cell cycle life as reported earlier (Raiford, 2020a). However, it would be reasonable to assume that, in addition to poorer cell-to-cell temperature and voltage uniformity for modules, the above factors may also play a role. Modules are typically lower value products used in starting, lighting and ignition, and other commodity applications. Whereas, single cells connected in series/parallel are used in stationary applications in substations and have a robust design, which may take the above factors into account in greater detail.

Based on the above information, to narrow the wide range of cycle life observed in battery cells and modules, the trends in lead-acid battery energy storage R&D are expected to be:

- Improving cycle life for valve-regulated cells/modules at high DOD
- Identification of grid alloy that promotes further oxidation of highly resistive PbO without increasing self-discharge
- Further understanding the mechanism of role of expander on negative active material performance
- Increasing DOD such that rated capacity is based on higher DOD than the current ~ 50% DOD
- Designing cells to fit the grid service by proper choice of electrolyte, positive and negative utilization, and grid composition
- Replacing negative grid with copper for improved performance
- Having a standardized formation procedure conducive to intended grid service
- Addressing electrolyte stratification with nonintrusive ways to circulate the electrolyte
  - Baffles
  - Reverse pulses
  - Micropumps
- Finding a suitable substitute for Sb at the positive grid to avoid highly resistive PbO layer and promoting interparticle conductive among PbO_2 active material particles
- Improving stability of expanders at higher temperature to mitigate degradation at high temperature
- Understanding the mechanism of additives to electrolytes for increasing battery life.

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