2020 Grid Energy Storage Technology Cost and Performance Assessment

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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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Vanadium Redox Flow Batteries

Capital Cost

A redox flow battery (RFB) is a unique type of rechargeable battery architecture in which the electrochemical energy is stored in one or more soluble redox couples contained in external electrolyte tanks (Yang et al., 2011). Liquid electrolytes are pumped from the storage tanks through electrodes where the chemical energy in the electrolyte is converted to electrical energy (discharge) or vice versa (charge). The electrolytes flowing through the cathode and anode are often different and referred to as catholyte and anolyte, respectively. Between the anode and cathode compartments is a membrane (or separator) that selectively allows cross-transport of a charge-carrying species (e.g., H+, Cl-) to maintain electrical neutrality and electrolyte balance. In traditional battery designs like lithium-ion, the stored energy is directly related to the amount of electrode material and increasing the power capacity of these systems also increases the energy capacity as more cells are added. In RFB systems the power and energy capacity can be designed separately. The power (kW) of the system is determined by the size of the electrodes and the number of cells in a stack, whereas the energy storage capacity (kWh) is determined by the concentration and volume of the electrolyte. Both energy and power can be easily adjusted for storage from a few hours to days, depending on the application. This flexibility makes RFBs an attractive technology for grid-scale applications where both high-power and high-energy services are being provided by the same storage system. Sufficient data are not currently available to estimate the life of RFB stack components, such as membranes and electrodes, with a proposed lifetime of 10 years.

There is not a substantial amount of capital cost data available for redox flow systems. Price information was primarily provided by discussions with an energy storage expert, an RFB manufacturer, and from past research conducted by PNNL. Estimates for a 1 MW and 10 MW redox flow system from Baxter (2020d) are shown in Table 1. Both estimates are for 4-hour systems.

Table 1. Cost Estimates for 1 MW and 10 MW Redox Flow Battery Systems

	1 MW/4 MWh System		10 MW/40 MWh System	
Estimate Year	2020	2030	2020	2030
DC system (with SB and container costs) ($/kWh)	$367	$299	$341	$278
PCS ($/kWh)	$22	$17	$17	$13
PCS markup ($/kW)	$2.2	$1.7	$2	$1
ESS equipment total ($/kWh)	**$391**	**$318**	**$360**	**$292**
Integrator margin ($/kWh)	$58	$48	$36	$29
Complete ESS equipment total ($/kWh)	**$449**	**$365**	**$396**	**$321**
EPC ($/kWh)	$101	$82	$79	$64
AC Installed Cost ($/kWh)	**$551**	**$447**	**$475**	**$386**

Estimates from past PNNL research of RFBs provided additional cost information and were adjusted based on an objective function that lowered total capital cost for systems of various E/P ratios (A. Crawford et al., 2015; V. Viswanathan et al., 2014). It is assumed that stacks for flow batteries would be run at various power densities depending on E/P ratio. That means for a high E/P ratio, since electrolyte costs dominate, the power density would be adjusted lower to improved efficiency and thus reduce electrolyte cost. This results in a lower $/kWh for the energy component (electrolyte) and a higher $/kW for the power component (stacks). For this work, the $/kW for stacks and $/kWh for electrolyte and tanks were averaged across the durations studied (1, 4, and 10 hours). It is also assumed the numbers calculated correspond to a 10 MW system. The optimization approach also lends itself to a greater DOD for higher E/P ratio to save on electrolyte cost. The optimized DOD at 1-, 4- and 10-hour durations was found to be 78%, 85%, and 85%, respectively. In other words, no change in DOD was observed between 4 and 10 hours, while the 1-hour DOD was 78%. With the assumption that the 2-hour DOD would be a third of the way between the 1- and 4-hour DODs, the DOD for a 2-hour system was estimated to be 80.3%. The average DOD for 2-, 4-, and 10-hour systems was found to be 83.4%.

Conversation with an RFB manufacturer indicated that oversizing the electrolyte in the tank can achieve an effective DOD of 75% (Cipriano, 2020b). The BMS adjusts the SOC such that, at 75% DOD, the SOC registers 0% (and at full charge, SOC registers 100%). The DOD for this study was set as the average of the PNNL estimate described previously (83.4%) and the 75% value provided by the redox flow manufacturer (Cipriano, 2020b) to get 79.2% DOD. After these adjustments, the unit power cost of the DC SB was estimated to be $351.5/kW, while the energy-related cost for the SB was $177.7/kWh.

The SBOS for the RFB system is assumed to be in line with lithium-ion and lead-acid BESS at 20% of SB cost. While flow battery SBOS is expected to be slightly greater than lead-acid due to lower specific energy and energy density, some of the SBOS elements such as pumps are already included in the SB capital cost. Table 2 shows results for various durations at 10 MW from the previous PNNL analysis (A. Crawford et al., 2015; V. Viswanathan et al., 2014) as well as the total DC system cost for the 10 MW, 4-hour system provided by Baxter (2020d) for comparison.

Table 2. Cost Estimates for Various Durations for RFBs

E/P	DCSB Cost ($/kWh)	SBOS Cost ($/kWh)	Total DC System Cost ($/kWh) [(a)]	Total DC System Cost ($/kWh) [(b)]
2	353	71	424	
4	266	53	319	341
6	236	47	283	
8	222	44	266	
10	213	43	255	

[(a)] A. Crawford et al. (2015); V. Viswanathan et al. (2014)

[(b)] Baxter (2020d)

Comparing the total DC system cost from A. Crawford et al. (2015); V. Viswanathan et al. (2014), and Baxter (2020d) finds them to be similar for the 4-hour duration. Taking the average of the total cost across both estimates gives $330/kWh, which is 1.035 times the PNNL number. To obtain estimates for the remaining durations, the PNNL numbers for the 2-, 6-, 8-, and 10-hour systems were multiplied by this ratio with results shown in Table 3.

Table 3. Cost Estimates for a 10 MW RFB Across Various Durations

E/P	DC SB Cost ($/kWh)	SBOS Cost ($/kWh)	Total DC System Cost ($/kWh)
2	366	73	439
4	275	55	330
6	245	49	293
8	229	46	275
10	220	44	264

To obtain cost estimates for various power capacities, a 5% premium was added for a 1 MW system and a 5% discount was included for a 100 MW system, also including PCS, C&C, and grid integration cost estimates obtained from the lithium-ion reference literature. The system integration, EPC, and project development costs as a percentage of previous line items were kept at 15%, the same as for lead-acid, due to higher capital costs compared to the lithium-ion system and lower safety-related issues. Table 4 provides a detailed category cost breakdown for a 10 MW, 100 MWh vanadium redox flow BESS, with a comprehensive reference list for each category. Note that the SB has power and energy cost components. The power cost is associated with stack, pumps, and piping, while energy costs are associated with electrolyte and tank costs.

Table 4. Price Breakdown for Various Categories for a 10 MW, 100 MWh Vanadium RFB

Cost Category	Nominal Size	2020 Price	Content	Additional Notes	Source(s)
SB	100 MWh	$352/kW for power $178/kWh for energy			Baxter (2020d); Cipriano (2020a); A. Crawford et al. (2015); V. Viswanathan et al. (2014)
BOS		$44/kWh		Used same 20% of SM cost as for lead-acid	Raiford (2020)
DC-DC converter	10 MW	$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	C&C cost	PNNL approach for scaling across various power levels	Baxter (2020c)
System integration	N/A	7.5% markup on hardware + 7.5% profit on sum of above rows	System integration cost	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	EPC cost	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	Project development cost	Lowered from 5% markup and 15% profit for lithium-ion due to lower safety concerns	
Grid Integration	10 MW	$24.9/kW	Grid integration cost	PNNL approach for scaling across various power levels	
O&M			O&M fixed costs		Aquino, Zuelch, and Koss (2017); DNV GL (2016)
Performance metrics			Calendar life		Aquino et al. (2017); EASE (2016); May, Davidson, and Monahov (2018)
Performance metrics			Cycle life		Aquino et al. (2017); Greenspon (2017); EASE (2016); May et al. (2018)
Performance metrics			RTE		Aquino et al. (2017); EASE (2016); May et al. (2018); Uhrig, Koenig, Suriyah, and Leibfried (2016)

The price range for 2020 was 0.9 to 1.1 times the nominal values for each category. For the year 2030, the learning rate for SB was set at 4.5%, with the low and high end of the price range having learning rates of 9% and 2% respectively. The learning rates for other categories are set to be the same as for the lithium-ion system and are shown in Table 5.

Table 5. Learning Rates Used to Establish 2030 Redox Flow Capital Cost and Fixed O&M Ranges

Component	Low Price	Low Price	Nominal Price	High Price
DC SB ($/kWh)	14%	9%	4.50%	2%
DC SBOS ($/kWh)	10%	10%	7%	4%
DC-DC converter ($/kW)	7%	7%	3%	2%
PCS ($/kW)	7%	7%	3%	2%
C&C ($/kW)	10%	10%	7%	4%
System Integration ($/kWh)	6%	6%	4%	2%
EPC ($/kWh)	6%	6%	4%	2%
Project Development ($/kWh)	6%	6%	4%	2%
Grid Integration ($/kW)	6%	6%	4%	2%
O&M ($/kW-year)	6%	6%	4%	2%

O&M Costs

Fixed O&M costs for battery systems appear in the range of $6–$20/kW-year within the literature, with most in the $7-16/kW-year range (Aquino et al., 2017; DNV GL, 2016). As with lithium-ion and lead-acid, there are not many examples in the literature of O&M costs that provide substantial clarity for RFB systems. For this study, the fixed O&M is set to 0.43% of direct capital cost, as described in the lithium-ion section. The actual value specific to each technology will depend on the capital cost. 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- 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 (2020)	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

Compared to other electrochemical battery systems, RFBs typically have longer lifespans due to being insensitive to temperature and avoiding the stress experienced by other battery systems during cycling. The typical calendar life of these systems typically falls between 10 and 20 years, though most estimates place it in the middle of those two values (Aquino et al., 2017; EASE, 2016; May et al., 2018). It should be noted that the electrolyte essentially does not degrade, while stack components such as membranes and electrodes may need replacement every 10 years (V. Viswanathan et al., 2014) and pumps may need replacement every 15 to 20 years (Elsey, 2016; ITT Industries, Undated). With regards to cycle life, the literature provided a small range of estimates, but with almost all estimating its capability at 10,000 cycles and above (EASE, 2016; Greenspon, 2017; May et al., 2018). Only one estimate placed its capability as low as 5,000 cycles for an unknown DOD for a vanadium system (Aquino et al., 2017). While RFB systems use non-degradable electrolyte under proper usage, as the system is used the stack may need replacement. Assuming a calendar life of 15 years and one cycle per day, with 5% of that time allocated to downtime, this corresponds to a total cycle life of 5,201 cycles.

The literature places the RTE for RFB systems between 65% and 80% (Aquino et al., 2017; EASE, 2016; May et al., 2018; Uhrig et al., 2016). PNNL testing in the past has shown that 4-hour systems typically reflect the lower end of this range at closer to 65% RTE. Past analysis also found that there exists an optimum operational regime that changes depending on design of stacks, the E/P (h) ratio, and the SOC (A. J. Crawford, Viswanathan, Vartanian, Alam, et al., 2019; A. J. Crawford, Viswanathan, Vartanian, Mongird, et al., 2019; V. V. Viswanathan et al., 2018). For this analysis, a 67.5% RTE is assumed for 2020 and expected to rise to 70% by 2030 due to innovations in the technology.

Losses from RTE were estimated based on an assumed electricity cost of $0.03/kWh and an RTE of 68% for 2020 and 70% for 2030. Following these two items, it can be determined that the cost is $0.014/kWh for 2020 and $0.013/kWh for 2030 for the RFB system.

R&D Trends in Redox Flow Batteries

Typical flow batteries are composed of two tanks of electrolyte solution, one for the cathode and the other for the anode. The technology is still in the early phases of commercialization compared to more mature battery systems such as lithium-ion and lead-acid. However, scalability due to modularity, ability to change energy and power independently, and long electrolyte cycle and calendar life are attractive features of this technology. The basic RFB design is also flexible in the chemistries and architectures it can accommodate. Any multivalent element that can be dissolved in a solution can potentially be used in RFB designs and several hybrid designs may eliminate/augment one flowing electrolyte in favor of metal anode in which the electrochemical species is plated during charge.

To date, vanadium-based and hybrid zinc-bromine flow batteries have achieved the most commercial success, with other technologies based on iron-chrome and polysulfide-bromine having been demonstrated but falling short of commercialization. Vanadium flow batteries use the ability of vanadium to exist in four distinct electrically charged species to serve as both the anolyte and catholyte, limiting the impact of species crossover on battery performance. The technology was first demonstrated in the 1980s by Maria Skyllas-Kazacos at the University of New South Wales, with various generations of the technology having attempted field demonstrations and commercialization. In the past decade, the technology has re-emerged as a candidate for grid-scale storage applications due to its long cycle life and effective use of available SOC range. Replacing the flowing anolyte with a metal electrode (e.g., zinc in Zn-Br2 and iron in Fe/Fe2+ technologies) increases the number of chemistries available for use, but also couples power and energy which reduces operational flexibility. Zinc-based hybrid flow batteries are one of the more promising systems for medium- to large-scale energy storage applications, with advantages in safety, cost, cell voltage, and energy density. Zinc-hybrid systems have the highest energy content due to the high solubility of zinc ions (> 10 M) and the solid negative electrode (Li et al., 2015).

While vanadium flow batteries have achieved initial commercial deployment, further R&D efforts are needed to push the technology to lower cost. Efforts supported by DOE are focused on increasing performance and reducing the cost of advanced systems by replacing vanadium with lower cost raw materials to approach the $100/kWh targets required for wider scale deployment of energy storage. One pathway is to replace vanadium with lower cost, easy to synthesize, redox active-organic molecules. A critical design aspect is ensuring these organic redox systems use existing RFB manufacturing capabilities necessitating that new technologies are water soluble with similar concentrations, viscosities, and performance to today's RFBs. Designing these new organic systems to be soluble in water—called aqueous soluble organics—not only ensures these systems are compatible with existing RFB infrastructure but also provide inherent fire safety. Additional efforts to use Earth-abundant zinc and iron electrodes for the anode in hybrid flow battery designs also offer a pathway to lower cost systems.

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