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WHITE PAPER / **REDOX FLOW BATTERY TECHNOLOGY**

FLOW BATTERIES OFFER UTILITIES ANOTHER ENERGY STORAGE OPTION

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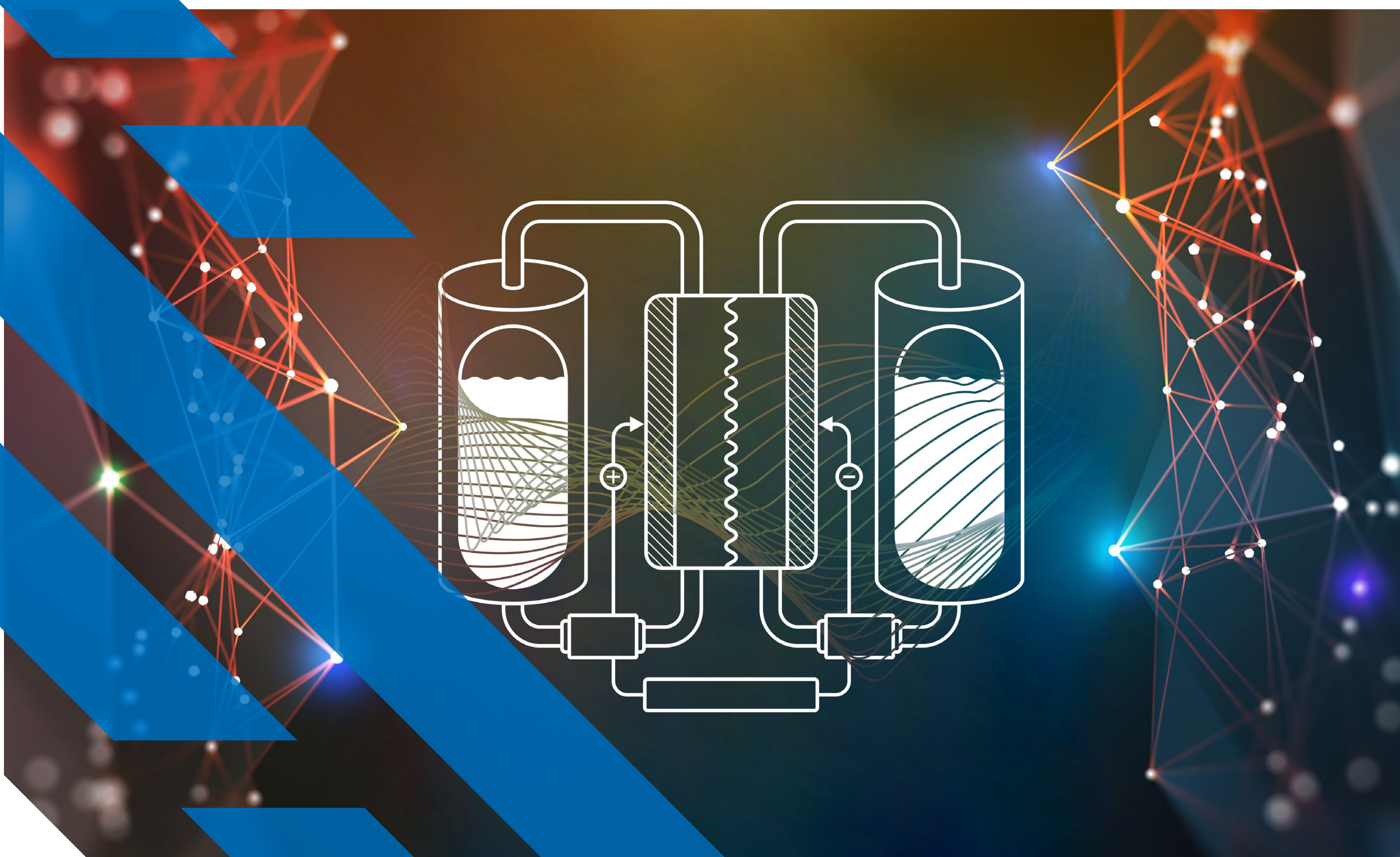
Lithium-ion technology dominates the market for battery energy storage systems, but redox flow battery technology is gaining traction as an energy storage alternative that can make economic sense under several scenarios for utility-scale applications.



As renewable energy resources continue to gain market share, it is increasingly apparent that battery energy storage systems must become a greater part of the conversation. Among other use cases, the economics of new solar and wind installations can generally be improved when paired with storage.

Lithium-ion batteries have emerged as the leading battery storage technology. But now, flow batteries are entering the discussion as another alternative that may make economic sense in certain scenarios.

COST IS KING

If flow batteries are to gain market share, they must compete head-to-head with lithium-ion, a technology that is now in a dominant market position. Demand is surging for these battery types due to widespread use in electric vehicles, consumer electronics and utility-scale storage systems. As a result, costs are being driven down sharply.

In 2010, lithium-ion battery prices were averaging around $1,160 per kilowatt-hour (kWh). Today, prices have dropped to around $170 per kWh for utility-scale storage systems and could continue dropping, going as low as $100/kWh by 2024 and even to $60/kWh by 2030. Costs are generally tracking the pricing curve of photovoltaic (PV) solar technology, which is nearly five times cheaper than installed costs of PV approximately 10 years ago.

Flow battery costs have similarly dropped from around $1,600/kWh to less than $800/kWh, but the pace of future decline is difficult to predict, primarily because flow batteries are still in testing and piloting phases, making the rate of future commercial development a large unknown.

There are several good business cases for flow battery technologies where many megawatts of output are needed over durations of more than 6 hours. As more utility-scale flow battery installations are tested and piloted, battery chemistries are expected to improve, leading to wider acceptance. With greater production, manufacturers will improve processes and gain supply chain efficiencies. Further, as flow battery systems are installed in the field, additional cost savings are likely to be realized as engineer-procure-construct (EPC) contractors gain field experience with actual system installations.

POTENTIAL FOR FLOW BATTERIES

The chemistry behind flow batteries has long been proven in the power industry and most analysts agree that such batteries are ideal for long-duration energy output with very low degradation of components within larger, utility-scale deployments.

With life spans reaching up to 30 years, depending on the electrolyte chemistry, flow batteries provide unrivalled cost certainty versus other storage technologies emerging on the market. Though flow batteries currently represent a higher upfront capital investment than a similar-sized lithium-ion configuration, they become more competitive when evaluated on a total cost of ownership basis over a 20-to-30-year life cycle.

In the utility space, flow batteries often are appropriate for longer discharge durations (6+ hours) in megawatt-scale power increments. Certain use cases argue in favor of flow batteries over other storage types. For applications where multiple charge/discharge cycles are required over each day, for example, flow batteries can offer many advantages. These include response times that are comparable to lithium-ion systems. Flow batteries of every chemistry type can respond to load demand within milliseconds if pumps are running.

Following discharge, flow batteries can quickly recharge from a variety of available power sources. In fact, depending on tank configurations, flow batteries can discharge and recharge simultaneously, providing power capacity or voltage support almost indefinitely.

Attributes for flow batteries include:

- Demonstrated 10,000-plus battery cycles with little or no loss of storage capacity.
- Ramp rates of milliseconds for discharge if pumps are running.
- Recharge rates for flow batteries also are reasonably fast.

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- Wide temperature ranges for operation and standby modes compared to lithium-ion batteries.
- Little or no fire hazard.
- Chemistries that pose limited human health risk due to exposures.
- Easy scale-up of capacity by adding electrolyte volume (may involve more tanks and piping).

HOW THE FLOW SYSTEMS WORK

Though there are dozens of different types of flow batteries, only about 10-12 specific chemistries appear ready for commercial applications. All operate on the same basic principle of incorporating liquid electrolyte to function as a source of direct current (DC) electricity that runs through an inverter for conversion to alternative current (AC) power.

In a reduction oxidation (redox) flow battery, positive and negative electrolyte solutions are stored in separate tanks. When power is needed, pumps are used to circulate the fluids into a stack with electrodes separated by a thin membrane. This membrane permits ion exchange between the anolyte and catholyte to produce electricity. The power produced is dependent on the surface area of the electrodes, while the storage duration is a function of the electrolyte volume. For some technologies, the power and energy can be scaled independently, allowing for an easily customizable battery.

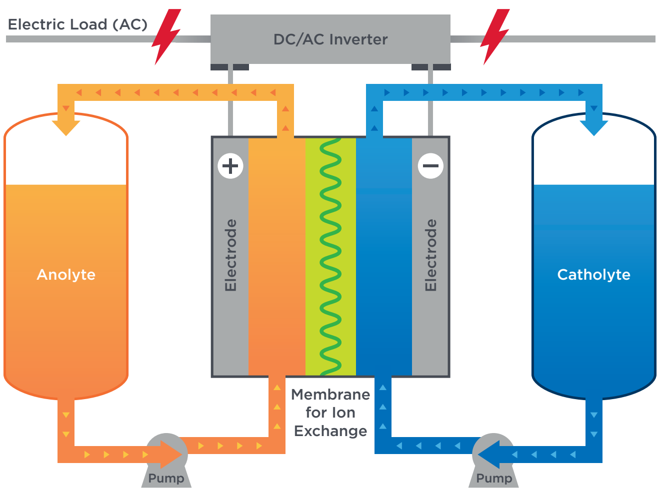

FIGURE 1: *FIGURE 1: Diagram of flow battery process. Source: Summary of 2017 NASA Workshop on Assessment of Advanced Battery Technologies for Aerospace Applications.*

In a hybrid flow battery, electroactive material is deposited on the surface of the electrode during the charge cycle and then dissolved back into the electrolyte solution during discharge. For hybrid technologies, the storage duration is a function of both the electrolyte volume and the electrode surface area. While most hybrid technologies can achieve durations of 6-12 hours, power and energy are not fully decoupled.

Flow batteries can be configured as a single tank — usually for smaller applications — or as a dual tank, usually on a larger footprint. The single-tank systems typically feature zinc or other metal batteries, while dual-tank systems are usually used for electrolyte composed of salt water, iron, vanadium or other minerals.

Flow battery system designs change depending on the application and project size. Behind-the-meter commercial systems are commonly kilowatt-scale packaged units that can fit into a typical utility room. For distribution applications in the 1-MW to 5-MW range, containerized and/or modular solutions exist with varying levels of scalability depending on the storage duration requirements. Utility-scale designs in development may have millions of gallons of electrolyte storage, so the industry is trending toward large quantities of stack modules headered together and piped to large, field-erected tanks.

Power stacks and balance of system components — like piping, pumps, seals, cooling systems and control instrumentation — require more routine maintenance than lithium-Ion configurations. However, if routine maintenance guidelines are followed, flow battery performance should not degrade within the project lifetime. When the O&M costs are compared to lithium-ion capacity augmentation costs required to offset performance degradation, flow battery annual costs are less expensive.

REDOX FLOW CHEMISTRIES

Of all the various flow battery technologies currently being developed, systems incorporating vanadium-based electrolyte are particularly promising. Electrolytes in other systems under development include chemistries incorporating zinc bromine, iron-chromium, iron/salt water and metal-ligand coordination chemistries.

Vanadium chemistry configurations represent the highest energy density application. Round-trip efficiencies may be greater than 70%, depending on the AC losses in a given system.

The primary drawback to vanadium-based systems is volatility of pricing for the vanadium itself. With the costs of vanadium comprising approximately half of the entire system, the economics of systems based on this chemistry can fluctuate widely depending upon raw material pricing, making the economics of installed costs a potential barrier to market development.

Pricing volatility for vanadium is driving the market to identify additional sources. Vanadium is a metallic mineral that is present in the fly ash produced from combustion of certain coal types. Millions of tons of fly ash have been deposited in landfills, and research is underway on whether vanadium could be economically recovered as a beneficial byproduct.

Costs of minerals in other types of electrolytes are not as volatile but those have a range of other potential drawbacks.

For example, zinc bromine is an inexpensive and abundant chemical that can act as a caustic in a single-tank configuration. In dual-tank configurations, two different electrolytes flow past carbon-plastic composite electrodes in two compartments, separated by a micro-porous membrane. Zinc-bromine systems have relatively high energy densities but face some obstacles, including buildup of zinc plating on electrodes that limits scaling to no longer than 6-8 hours, and may require more frequent rebalancing cycles than other technologies.

Other chemistries employed in electrolyte solutions — such as iron chromium, iron/salt water and metal ligand coordination chemistries have similar advantages and disadvantages, including varying energy densities.

USE CASES

Though specific power markets and load factors will vary widely throughout the world, flow batteries can perform several use cases. More importantly, a flow battery may have greater use case flexibility than lithium-ion systems designed for a specific application.

Storage Chemistry	AC Roundtrip Efficiency (%)	Storage Duration (Hours)	Capital Cost Range ($/kWh)	Life Span (Years)	System Architecture Notes
Vanadium Redox	70-80	4-12+	500-1,100	20+	Containerized, modular, and custom solution; two-tank system
Zinc Bromide	65-70	4-6	450-900	20+	Containerized; plating electrode; one-tank system
Iron-Salt	65-70	4-10	600-1,200	20+	Containerized. modular, and custom solutions; plating electrode; two-tank system
Lithium-ion Comparison	80-90	1-4	300-1,000	5-20	Containerized, modular, and custom solutions; consider degradation/ augmentation

FIGURE 2: *Four leading flow battery chemistries provide a range of cost and performance characteristics.*

Lithium-ion systems designed for deep discharge will exhibit greater performance degradation (with potential warranty implications) if they are cycled multiple times per day or used for different applications, such as frequency response. Because flow battery performance doesn't degrade, there are fewer limitations on use cases once the system is installed.

More importantly, a flow battery can potentially perform multiple use cases, depending on market signals and energy management system capabilities. With the uncertainty surrounding pricing, operating parameters and standards set by respective ISO/RTO authorities, combined with the dynamically evolving resource mix on the grid, storage market development is still somewhat uncertain. For a flow battery asset to remain relevant in the market for its 20-to-30 year expected life span, owners are looking for clear use cases that can result in a reasonable return on investment.

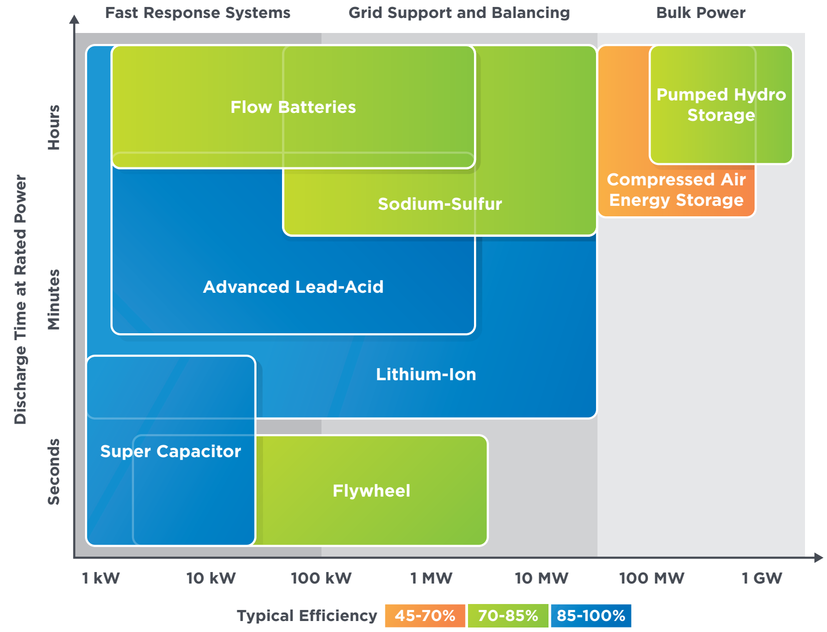

FIGURE 3: *Efficiencies and durations for flow battery chemstries.*

The California Energy Commission (CEC) has recognized this problem and recently added flow batteries to the mix of candidates to be eligible for funding for energy storage resources. The CEC noted its goal is to add resource diversity and introduce technologies that will provide longer-duration storage as the state moves toward its goal of achieving 100% clean energy by 2045.

A few potential flow battery use cases include:

1. **Arbitrage**
   Depending on your power market, arbitrage might be the best use case for flow battery capacity. Particularly during high-peak seasons, wholesale power markets have demonstrated rapid pricing swings and as power costs begin to spike, capacity available from large-scale flow battery configurations can become economical. By syncing flow battery capacity to be available quickly and with durations of 6-8+ hours while prices per kilowatt are at a peak, significant revenue can be realized.

2. **Behind the Meter**
   Commercial-scale units are being deployed behind the meter in manufacturing facilities, hospitals, campuses and even residential locations as a means to shave power demand when premium rates are charged. Depending on rate tariffs and demand response energy curtailment programs available from local utilities, flow batteries can be an economical option to reduce energy costs simply by discharging batteries during periods of voluntary curtailment or when local rates are high.

3. **Volt/VAR Support**
   Inverter-based generation, like flow and lithium-ion batteries, can perform similarly to synchronous condensers on feeder circuits due to its ability to provide quick-acting voltage support. With the ability to generate or absorb reactive power as needed to adjust grid voltage, flow batteries connected to smart inverters can provide a distribution grid support function, particularly as systems are designed for emerging peak recharging demand from electric vehicles.

4. **Renewables Pairing**
   Both flow batteries and lithium-ion batteries are emerging as attractive options to extend the availability of renewable solar and wind resources across more hours of the day to counter well-known intermittency issues. With flow batteries capable of providing power over longer duration, and with the ability to ramp up or down with no degradation, developers and utilities are actively evaluating these technologies.
5. **Black Start Capacity**
   Normally, when a power plant is shut down, it will draw power from the grid in order to provide the initial power needed to restart the large generators and return the plant to full service. However, during a widespread outage when backfeed power is not available, generator startup may require an on-site black start unit. Conventional black start generators are fueled by diesel or natural gas, but black start power also can be provided by batteries scaled up to provide the necessary power to return the plant to service.
6. **Resource Diversity**
   Many utilities have long opted for resource planning strategies that make use of a variety of energy sources, ranging from conventional fossil and nuclear generation to renewables and energy storage. By blending the favorable characteristics of both lithium-ion and flow batteries, utilities can reduce risk across their entire portfolio of energy storage options.

BARRIERS FLOW BATTERY TECHNOLOGY MUST OVERCOME

As renewable energy market penetration increases, more owners are looking at longer duration storage assets. Costs are declining for all storage technologies and it is difficult to predict where and when the prices will settle.

With today's technology, lithium-ion unit costs ($/kWh) generally flatten out beyond 4-hour storage durations because of the essential addition of higher quantities of the same batteries. However, flow battery unit costs continue to decline as the storage duration increases to 8-12 hours. The power modules for a 4-hour system are the same as for a 12-hour system, so the incremental cost of adding duration/energy storage to a flow battery is tied to the addition of electrolyte to the system.

Figure 4 shows the results of a life cycle cost analysis comparing 20-MW, 8-hour (160-MWh) lithium-ion and flow battery systems. The model includes capital, O&M and charging costs for a 20-year project life. The net present value (NPV) totals are calculated and compared. The analysis is based on the following key assumptions:

- Single contract, full wrap EPC methodology.
- Owner's costs, decommissioning costs, insurance, taxes and revenues are excluded.
- Costs are based on Burns & McDonnell experience and vendor information for technology projected to be available in 2021 and are not representative of any particular technology or OEM. Cost projections are based on experience and averages and may not reflect localized factors or conditions that could cause variations.

NPV Results: 20 MW/160 MWh (Net at POI)		
Description	**Li-Ion**	**Flow**
Capital Cost		
Project Capital	$48,770,000	$95,930,000
Owner	Excluded	Excluded
Total Installed	**$48,770,000**	**$95,930,000**
O&M and Other Annual Costs, NPV		
Battery Charging	$39,070,000	$43,380,000
O&M	$12,580,000	$4,640,000
Total O&M/ Charging	**$51,650,000**	**$48,020,000**
Life Cycle, NPV	**$100,420,000**	**$143,950,000**

FIGURE 4: *Cost analysis comparing lithium-ion and flow batteries.*

- Routine maintenance for 20 years is included. Augmentation is included for lithium-ion based on minimal initial overbuild.
- Year 1 round trip efficiency values of 70% for the flow system and 84% for the lithium-ion system are included.
- Discount rate is 8.5%. Escalation rate for O&M and energy costs is 2.5%.

With today's technology, flow battery capital costs are nearly double those of a similarly sized lithium-ion system. With longer storage durations and longer life spans, the economics improve but are not expected to achieve parity with lithium-ion at today's pricing. Decommissioning and recycling costs may favor flow batteries because the electrolyte is more easily recyclable or disposable (depending on technology type), but these costs are not well developed. As flow OEMs improve manufacturing scale and supply chain efficiencies, and as EPC contractors gain field experience, costs will continue to plummet. Still, flow batteries are chasing a moving target as costs for lithium-ion fall.

The primary barrier to full market penetration of flow battery technologies today is simply current lack of commercialization compared to the heavy installation base of competing lithium-ion technology. In the near term it is likely that more relatively small flow battery facilities will be installed until a widespread commercial track record is established and use cases, costs and returns on investment are proven.

BIOGRAPHIES

TISHA SCROGGIN-WICKER, PE, is the flow battery business manager for Burns & McDonnell and is leading some of the nation's most complex and innovative solutions in the industry. Throughout her 17 years of experience, she's worked extensively on a variety of power generation projects including coal, gas, reciprocating engines and now energy storage. She proposed on over 100 MWh of flow battery projects in 2019 with a pipeline of over a gigawatt-hour of opportunities in the next few years.

KIERAN McINERNEY, PE, CEM, is a senior engineer focused on energy storage project and market development at Burns & McDonnell. His experience includes economic evaluations, conceptual designs, development consulting, and EPC proposals for over 4 GWh of energy storage projects, including both lithium-ion and flow technologies.

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