Flow Batteries: Has Really Large Scale Battery Storage Come of Age?

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ABSTRACT

The market for electrical energy storage (ES) solutions has been mostly limited to relatively small applications of battery uninterruptible power supply systems (UPS's) and very large site-specific systems such as pumped hydro storage, two completely different types of ES with separate markets. Flow batteries (FBs) are promising to change that by providing a technology that can potentially span this entire range of applications. Flow batteries have demonstrated providing ES from sub-second local power reliability to hours-long load shaping and price arbitrage functions at the large commercial end-user-scale (500 kW, 520 kWh). Several pilot plants have been built at this scale and early results are positive. In addition, pilot utility-scale systems (12 megawatt, 120 megawatt-hour) are being constructed. The scale and variety of these pilots reflects high confidence in this technology by developers. This paper details technical principles of 2 competing flow battery technologies available in the immediate future, compares their market-readiness, and analyzes economics and market potential for this technology to compete with UPSs as well as play into new commercial load management markets.

Introduction

Electricity storage has long been identified as an element that adds great value to electrical energy resources. When its application is feasible, such storage allows load leveling and peak rate dispatch, contributes to power reliability and quality and enables distributed generation assets to time-shift their output for the most economical use. Such applications are seen at the utility scale on a limited basis, using pumped hydro storage and compressed air energy storage (CAES). Electrochemical energy storage, (lead-acid battery banks) in uninterruptible power supplies (UPS), is widely used to support critical end-uses for short periods in commercial facilities. Unfortunately these batteries have relatively low energy densities, high lifecycle costs and utilize toxic materials. The generators that provide longer-term outage support to these facilities have severely limited applicability because of emissions.

New electrochemical technologies are now being commercialized that represent an unprecedented breakthrough in large-scale energy storage. Drawing on both battery and fuel cell design elements, these systems are based on reversible chemical reactions with separate extensible electrolyte energy storage. Charging and discharging does not significantly degrade either the cells or the electrolytes, resulting in greatly increased in battery life relative to current technologies. These systems are simple, durable, and relatively efficient; offer flexible output modes that optimize either power or energy as desired, and are only limited in their storage capacity by the size of their tanks.

Two primary approaches that have been developed are closely comparable, distinguished primarily by their differing electrolyte solutions. The Regenesys system, developed by Innogy in the UK, uses sodium bromide and sodium polysulfide electrolytes. Another type under development by a number of companies uses two vanadium-salt solutions at different valence states. Extensive field-testing of full-scale demonstrations of both battery types has been completed at numerous locations worldwide, and commercialization is proceeding apace.

This paper comparatively reviews these technologies, markets and market readiness and the economics of these new devices for applications in large commercial facilities, as substitutes for the dominant UPS technologies employed at this time: lead–acid batteries for short term interruptions supported by diesel generators for longer term outages. These new flow battery solutions potentially offers all the services of currently available UPS systems, while expanding the value proposition by allowing peak load shaving functions and even time-of-day rate energy price arbitrage on the part of their operators.

Flow Battery Technologies

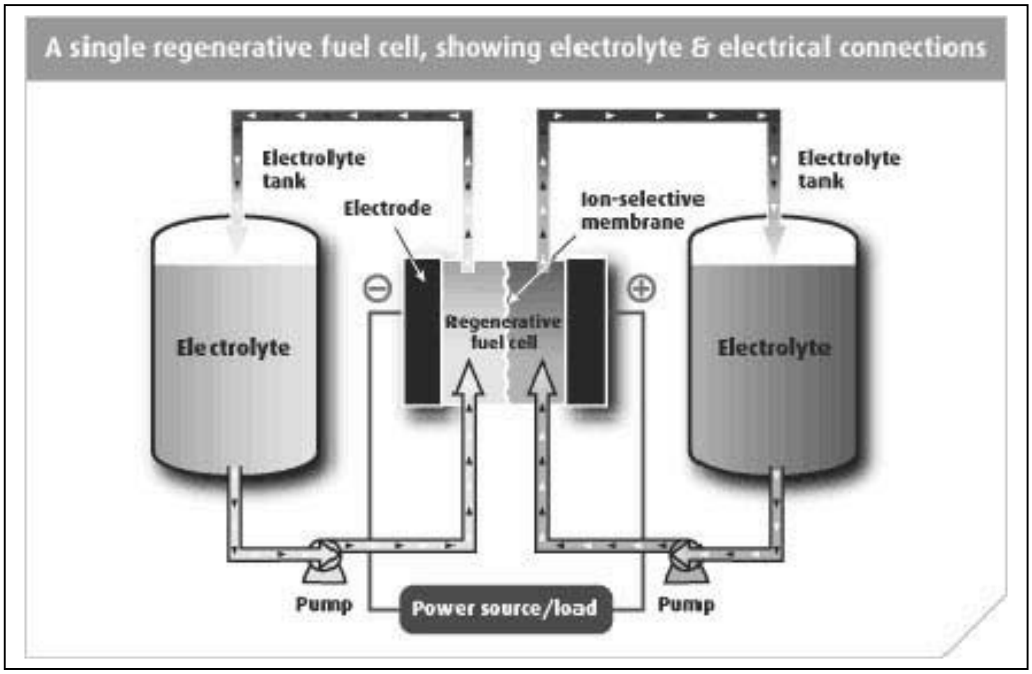
How Flow Batteries Work

Flow batteries combine some the best features of fuel cells and batteries, yet avoid many of battery technologies' most significant problems. FBs use two salt solution electrolytes, which store or release electricity by means of reversible electrochemical reactions. The electrolytes are stored in independent reservoirs, and are pumped through separate manifolds into and out of half-cell compartments that are physically separated by an ion-selective membrane. The two electrolytes are transformed electrochemically inside each cell, without direct mixing, as shown in figure 1. (In actuality, some cross-contamination of electrolytes across the membrane may occur in some designs). Transfer of ions occur between the electrolytes and result in free electrons that are collected on the electrodes, generating electricity. The most significant difference between traditional batteries and flow batteries is that the electrodes are not directly involved in the electrochemical reactions, and thus do not degrade. Also, charged flow batteries do not suffer from leakage currents because the electrolytes are kept physically separated until a reaction is desired.

Regenesys Flow Battery Technology

One of the leading flow battery technologies is the Regenesys model, developed and manufactured by the British firm Regenesys Technologies Limited, which is owned by Innogy, formed by demerger of National Power in Oct 2000.

Figure 1. A Representative Flow Battery



Source: www.regensys.com

The Regenesys technology is based on a reversible electrochemical reaction between two salt solution electrolytes: sodium bromide and sodium polysulfide (in their uncharged state). Each electrolyte flows through a half-cell on either side of a (positive) cation-selective DuPont (ENDS 2000) polymer membrane, sodium bromide on the positive side and sodium polysulfide on the negative. The membrane prevents the sulfur anions from reacting directly with the bromine. During charging, sodium ions are transferred from the sodium bromide to the sodium polysulfide across the membrane. When fully charged, the bromide ions from the sodium bromide are oxidized to bromine and complexed as tribromide ions in sodium tribromide ($NaBr_3$). The zero-valent sulfur in the polysulfide anion is converted to sulfide. During discharge, the sulfide ion becomes the reducing agent and the tribromide ion becomes the oxidizing agent. Some heat is generated in the process, which is removed by a plate cooler situated in the polysulfide circulation network. Regenesys operates ideally in a temperature range of 20–40°C, but will tolerate a 0–40°C range (Price 2000). Approximately 16 m^3 (21 yd^3) of each electrolyte is needed for each megawatt-hour of storage. A small quantity of sodium-sulfate byproduct is produced and removed during operation. The system also produces small amounts of hydrogen gas, which is managed in a venting system to mitigate fire risks, similar to lead-acid batteries. Although not quite a closed-loop system, Regenesys emits very little gaseous, liquid, or solid waste.

The electrochemical reaction produces about 1.5 V across the membrane in each cell. Linking cells electrically in series create higher voltage output in bipolar modules, with the cathode of one cell becoming the anode of the next cell. The cells are connected hydraulically in parallel by a network of distribution manifolds on a pumping loop running to the electrolyte storage tanks. This approach enables both manufacturing and power and energy capacity economies of scale. The more cells and the faster the flow of electrolyte solutions, the higher the power rating. The more electrolyte storage capacity, the greater the energy rating. A commercial 100 kW module comprising a stack of 200 cells puts out about 300 VDC (Bush 2000).

Regenesys' net efficiency (AC-AC, or "kWh in to kWh out") ranges from as low as approximately 55% to about 75% depending on its operational mode, including power conversion and energy losses due to auxiliary equipment such as pumps. The Regenesys system outputs AC power via a power-conditioning system (PCS). The system can make a "cold" start up in less than 10 minutes, but if held in standby mode with charged electrolyte in the stacks it can respond in fraction of a second to supply more 83% of rated power (Davidson et al. 2000). Reportedly, the system can respond and go from charging to discharging to the grid within 20 milliseconds (0.02 seconds), allowing it to provide both load shaping and voltage shifting. The PCS can provide real and reactive power from 90 degrees leading to 90 degrees lagging (Bush 2000).

Vanadium Flow Battery Technology

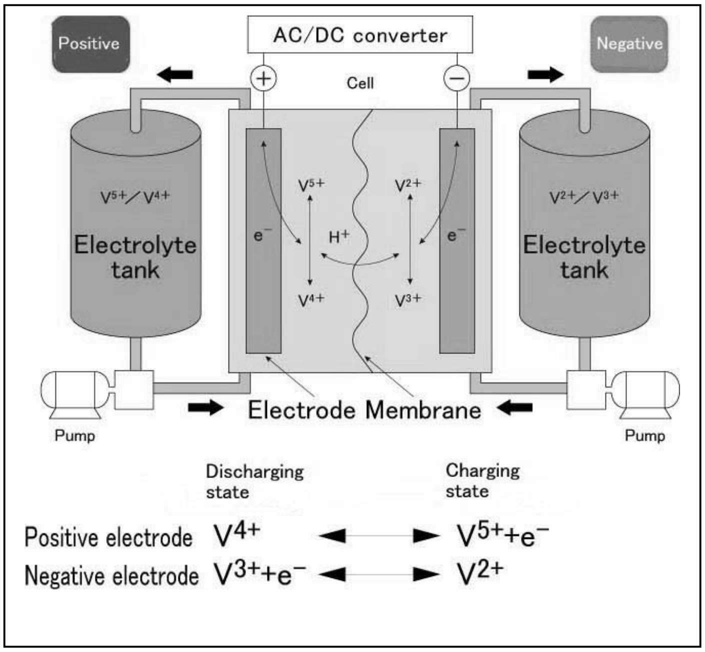
A second major flow battery technology under development is based on vanadium-salt electrolytes. The vanadium redox battery (VRB) was pioneered at the University of New South Wales (UNSW) in Sydney, Australia and the Japanese Electro-Technical Laboratory (ETL) in the 1980's. Developers and suppliers include Vanteck Technology Corp, Sumitomo Electric Industries, Ltd. (SEI); Kashima-Kita power company and Mitsubishi Chemicals, and Cellennium Company Limited.

Vanadium batteries share many characteristics with Regenesys. They use two electrolyte solutions stored in separate tanks that are pumped via manifolds through half-cells separated by an ion-selective membrane, as shown in Figure 2. The electrolytes interact across the membrane, and concentration of each ionic form changes as the battery cycles. The electrochemical reaction is reversible, allowing deep cycling and very rapid recharging and discharging. Power and energy ratings are independent, and are a function of cell area (power), electrolyte storage (energy) and electrolyte flow rate (both power and energy). Cycling rate is a function of electrolyte flow and volume, as well as control system capabilities. Cells are connected electrically in series and hydraulically in parallel. All cells in a stack are readily maintained at the same state of charge hydraulically, and with minimal standby losses.

VRBs are more durable than conventional secondary batteries (*e.g.*, lead-acid) because they have no liquid-solid phase changes to degrade the electrodes. Fluctuating loads and charging voltages do not damage the battery, nor does overcharging. (Indeed, with the proper controls, inputs, and cellular capacity, the system can be charged and discharged simultaneously). The electrolyte solutions are not consumed in cycling, are stable, and have an indefinite life. The battery operates at room temperature.

VRB cells produce from 1.2–1.6 V across the membrane, depending upon the electrolyte solution, temperature, and state of charge (Skyllas-Kazacos, 2000). VRBs are scalable over a wide capacity range, from watts to kilowatts (demonstrated) or megawatts (studied).

Figure 2. Vanadium Battery Function



Source: Sumitomo. (www.sei.co.jp/sn/0105/p1.html.)

Cells last at least 10,000 cycles, and lab tests have exceeded 16,000 cycles. Stack service life is determined by the longevity of the membrane, and to a lesser degree the life of pumps and other auxiliary components. SEI recommends that the stack be replaced be replaced every 10 yrs, reflecting an expected membrane life of 8–10 yrs (there are no units that have yet been in service long enough to know for sure). VRBs are designed for easily replacement of primary components, and recycling or reuse of as many of the parts as possible. SEI VRBs are largely built from recyclable plastics. The electrolytes have an indefinite life, and can be reprocessed for reuse in new VRBs.

Several VRB characteristics distinguish them from the Regenesys technology. VRB electrolytes contain different ionic species of vanadium solutions in sulphuric acid, with a similar pH as that found in a lead-acid battery. Ions are transferred between these species across a proton-exchange membrane (PEM). The concentration of each ionic form of the vanadium electrolyte changes as the battery is charged and discharged. Electrolytes are typically used at 1.6–1.8M, reportedly a stable concentration that is well suited to automated, low-maintenance VRB systems. Higher concentrations are possible and could reduce electrolyte storage requirements and increase energy density, but are not yet economic or stable.

VRBs have demonstrated they can respond and switch from charging and discharging within 1/1000 second, and sustain high-power output (more than twice standard output) for up to several minutes, allowing them to counteract voltage sags. They can also supply nominal power for hours, depending on the amount of electrolyte storage. These characteristics enable them to compete directly with traditional UPS systems, employing both batteries and generators (SEI 2001).

Flow Battery Advantages

Flow battery design avoids many of the life-limiting factors affecting conventional batteries. Unlike most rechargeable batteries, FBs do not directly engage electrodes in the electron transfer process nor involve them in solid-state reactions. Thus the electrodes do not steadily degrade, and neither energy storage nor power capacity is dependent on their dimensions for the Regenesys or VRB. The inventor of the vanadium redox flow battery notes, “The use of solutions to store the energy overcomes many of the life limiting problems associated with conventional batteries. FBs can thus be fully discharged without harm, they can be stored indefinitely at any state-of-charge with only negligible self-discharge or irreversible capacity loss, and there are no problems associated with shedding of active material, nor short circuiting of the electrodes due to metal penetration of the separator” (Skyllas-Kazacos, 2000).

Environmental Advantages

Many conventional battery systems contain hazardous or toxic materials. Heavy metals, including toxic elements such as lead and cadmium, are commonly found in battery ES systems, along with hazardous electrolyte solutions, such as sulfuric acid. Although most conventional batteries are recyclable, many are simply disposed of and can introduce toxic materials into the environment when they are managed improperly. Large-scale ES systems tend to foster more careful management than consumer-scale batteries, but their life-cycle O&M costs reflect the need to manage these materials.

FB electrolytes are long-lived and essentially are components of the capital asset rather than consumable fuels. In general they present few hazards and risks during handling, storage, and use, and are often stored in relatively large quantities. FB electrolytes are non-flammable, but some can present health and safety risks in the event of large-volume catastrophic releases. Regenesys systems include safety and emission-control equipment to mitigate the risk of releasing hazardous bromine or hydrogen sulfide gases, but the concentrations generated are too low to be much cause for concern during normal operations. In their charged state, a few of the electrolyte solutions can be corrosive.

FBs produce minimal or no emissions during operation. To the extent they improve power plant efficiency—or replace generation capacity—they reduce emissions associated with electricity production. FB reactive power supply reduces the need for additional generation during peak periods. FBs are well suited to complement renewable electricity resources, making them more effective and economical. Large-scale ES systems can also enable more efficient utilization of electric generating capacity, which helps reduce emissions both by bolstering “sweet spot” operating levels and optimal fuel conversion efficiencies.

Flow Battery Markets And Market Readiness

Flow batteries are being commercialized now, and as the technology matures they are likely to play a major and growing role in the ES sector. Vanadium batteries, in particular, appear very well positioned for the large UPS market. FBs versatility allows them to provide multiple services and compete against a range of technologies in a broad spectrum of applications.

Part of the challenge facing FB developers is that they operate in a market sector that does not yet exist in mature form—an integrated, large-scale energy storage industry. In a sense, the ES industry already exists but in fragmented form, and some of the participants do not yet realize they are in it. The emerging ES industry spans a number of discrete market niches and applications that are not often viewed as being directly related: integrated power service and grid planning; transmission and distribution (T&D) capacity and O&M costs; generation capacity investment deferral; power quality; power reliability; generator black-start capability; momentary and extended outage ride-through (UPS); time-shifting dispatch of intermittent generation; output stabilization of renewable power sources; grid integration of distributed generation; and island supply.

A mix of backup and peak generators, large-scale ES systems, mid- and smaller-scale battery arrays, UPS systems, capacitors, and both end-user and utility-directed energy efficiency and load-management strategies currently serves these markets. No single technology or approach has before offered practical solutions in all of these areas—until now. FBs are the first technology to provide a suite of services matched to this spectrum, all provided by the same system or installation. Their decoupled power and energy capacities on such a significant scale is unique among ES technologies, enabling new energy management options and strategies.

Dr. Joe Hoagland, Senior Manager for Clean and Advanced Energy at the Tennessee Valley Authority (TVA), indicates the primary sources of value of ES systems for TVA are in ancillary services—*e.g.*, power quality and T&D deferral, rather than time-shifting generation for arbitrage. TVA is following developments in a range of large-scale ES technologies, and encouraging them where possible with demonstration projects such as the 12 MW Regenesys plant it is building in Mississippi. "If we can make storage work as is hoped, it will fundamentally transform the way TVA runs the grid," he predicts.

Potential Energy Storage Markets

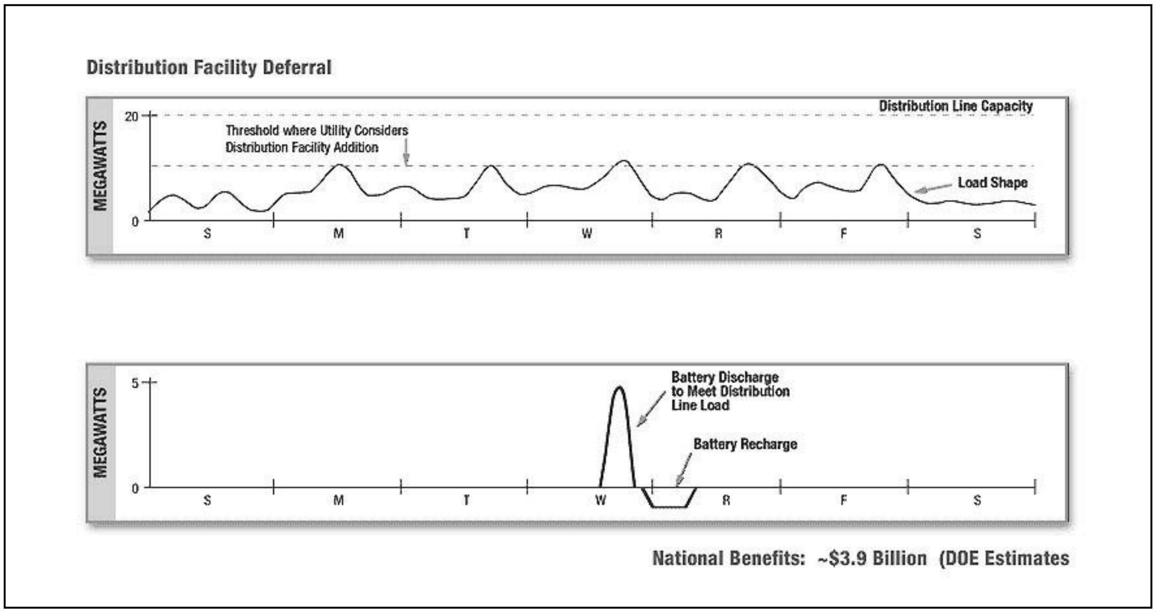
Distinguishing and quantifying these potential ES markets is very challenging. Research methods and calculations are not standardized and often opaque. Available data tends to be inconsistent, duplicative, and misleading, in aggregate. Many FB developers and ES analysts heavily discount such numbers and studies. Although a thorough ES market analysis is beyond the scope of this paper, we will provide sample data to help sketch out a rough indication of the scale and scope of some of these opportunities.

Distribution System Support And Capacity Deferral Market

ES can help reduce T&D costs related to power quality, capacity expansion, and O&M costs. Locating ES close to local loads can also defer investment in additional distribution network capacity. The Department of Energy estimates the total potential economic benefit of this application as being $3.9 billion. The concept is shown in figure 3. ES systems may often be installed in larger customer facilities, where value of storage accrues to both the utility and the customer.

One example of a potential application of large-scale ES for transmission support is the New England ISO's 2,000 MW high-voltage DC line bringing power from Quebec. Line failure could cause voltage collapse as far away as New York and New Jersey, but only 1,200 MW of spinning reserve capacity are available, so the line is under utilized by 800 MW. A large ES system could provide cheaper reserve capacity than building new generating plant—and idling it (Gyuk, I. 2001).

Figure 3. Estimated Distribution System Cost Deferral



Source: Powercell, Inc. (www.powercell.com).

Distribution System Support Case Study (Commercial Installation)

In 2000, an alliance between several leaders in vanadium battery technology (Vanteck, TSI and Highveld) installed a 250 kW, 520 kWh VRB demonstration installation on a 400 VAC line at the University of Stellenbosch in the Western Cape region, near Cape Town, South Africa. This is the largest vanadium redox battery (VRB) installation outside of Japan to date. Six 42 kW, 100-cell stacks were supplied by Sumitomo Electric Inc. (SEI). The two-level structure stands 4.5 m high with a 5 m X 8 m site footprint, as shown in Figure 4. Vanteck anticipates future installations of equivalent capacity could be reduced in volume by up to 30%. The automated system provided power quality and reliability (UPS) services for a critical load at the University, including voltage sag support and two hour outage ride-through supply (Hawkins, & Robbins 2001).

The developers report that the trial has been running successfully since August 2001. The stacks' overall DC energy efficiency has been in the 82–85% range. Reportedly Eskom (the local South African utility, and a sponsor) has been impressed with the versatility and wide range of services provided by the single installation. Vanteck believes that this success will speed VRB entry into the U.S. and other markets. No financial data was available for this installation

In January 2002 Vanteck announced that it would supply the U.S. utility PacifiCorp with a 250 kW, 2000 kWh (8 hour) VRB system. The modular, relocatable unit will provide peak power capacity, and provide end-of-line voltage support (with up to 250 kVAR of reactive power) in a remote area in southeastern Utah, deferring the need for a new substation. Installation and commissioning is to be completed by July 2002. This is the first commercial vanadium energy storage system (VESS) application in North America.

Figure 4. Vanteck Capetown Installation

VRB-VESS 5m x 8m by 4.5m high housing structure (cell stacks upper deck/electrolyte storage balance of system lower deck).

Source: Vanteck Inc. (www.vrbpower.com)

Power Quality And Reliability Markets

Roughly 80% of the power quality (PQ) incidents that trouble industries are voltage sags lasting from milliseconds to a few seconds at most, but it typically takes backup generation 10–45 seconds to come on line (Krepchin & Howe 1999). Rapid-reaction ES systems, most notably the vanadium FB, are well placed to serve this market. These FBs combine millisecond response, charging and discharging flexibility and surge peak capability substantially in excess of design continuous power capacity with the capability to support large loads for hours. This suite of services potentially spans the full range of UPS needs.

Facility-Scale Critical Application PQ And Reliability Management Case Study

In April 2001 an SEI VRB system began operation at the Tottori SANYO Electric Co., Ltd liquid crystal factory in Tottori prefecture, Japan. This system normally operates as a 1.5 MW, 1.5 MWh peak-shaving device. It also provides power quality support, and can deliver an instantaneous maximum power overload discharge of 3 MW for 1.5 seconds to prevent production line stoppages caused by a momentary voltage drop, typically caused by lightning. Since the start of its operation until the end of August 2001, Tottori Sanyo experienced 21 sags yet no interference with LCD production. (SEI 2000). This installation is shown in Figure 5. SEI did not provide financial data.

Figure 5. Tottori SANYO Factory VRB Installation

Source: Sumitomo, Inc. (www.sei.co.jp/sn/0106/p1.html)

Mr. Yasushi Santo of Green Energy Inc. reported that one aspect of Sanyo's interest was due to the VRB's lack of emissions, which avoided the need to go through environmental assessment processes required by local governments for installing conventional power plants such as back-up generators. He added that that SEI anticipated that Sanyo's positive experience would produce more orders from Japanese high-tech manufacturers for sag protection, but the recent business decline in Japanese information technologies industries has delayed purchases. Still, SEI believes the sag protection market will be a promising one after Japanese economy returns to normal (Santo 2002).

Comparative Commercialization Factors For FBs

These two FB systems now being commercialized have relative attributes and marketing strategies that help define particular markets where each might compete more or less effectively. Some commercialization factor comparisons are in Table 2:

Regenesys systems are considerably larger in scale of the two. It has a minimum capacity of 5 MW, excluding it from smaller applications where vanadium FBs compete. It was developed by a utility, primarily for large-scale applications. Each installation is built as an integrated, turnkey system, rather than a modular scalable approach (save with regard to additional electrolyte storage capacity). This approach might be seen as focusing on optimal facility scale economies of re-generation and storage of electrons.

Most VRB FB developers are concentrating on modular, scalable systems, which to date have not exceeded 500 kW of power capacity. Their approach might be seen as optimizing mass production economies of scale of components for power and energy capacity and balance of system auxiliaries such as power electronics. Many are clearly planning to develop much larger installations, and point out that multi-MW facilities—even hundreds of MWs in scale—are feasible and are attracting customer interest. The companies that are primarily targeting utilities and network operators are more likely to directly compete with Regenesys and each other for large customers.

Table 2. Product Comparison of 2 Leading Flow Battery Developers

BATTERY	REPRESENTATIVE SYSTEMS	PROJECTED CAPACITIES	PRIMARY DEVELOPERS
Regenesys	12–15 MW, 120 MWh	5–50 MW, 100–250+ MWh; 500 MW feasible	Regenesys (www.Regenesys.com, www.innogy.com)
Vanadium	250 kW, 520 kWh; 1.5 MW, 1.5 MWh	50 kW, 500 kWh to 5 MW, 20 MWh; 50–100 MW upper range; 500 MW feasible	Sumitomo Electric Industries (www.sei.com) Vanteck (www.vrbpower.com)

Comparative Costs

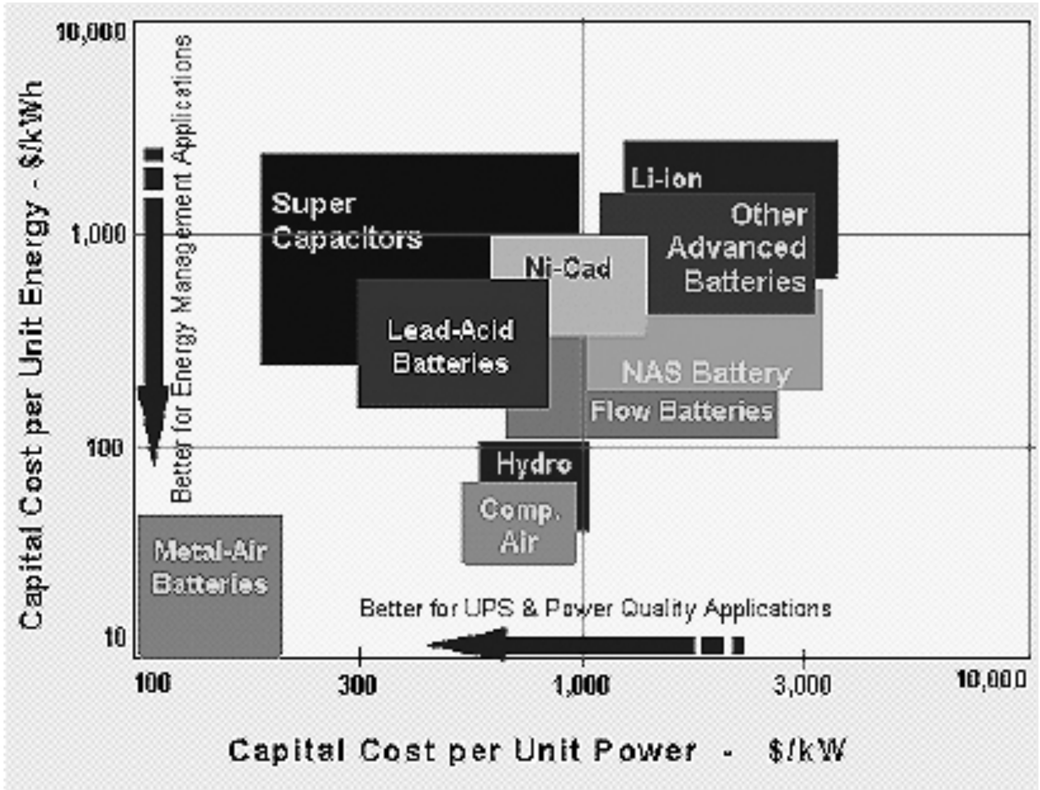
FB technologies remain relatively new, and the systems and commercialization strategies are still evolving even as they enter the marketplace. Manufacturing capacity is new and relatively limited, orders are few, and producers have yet to realize scale economies of production. Different companies are at different stages of development of production capacity. So current first costs are high, and comparisons between firms and technologies are not direct. Cost information is hard to acquire from competing commercialization-oriented companies. Nonetheless some information is available for consideration. Rough comparative numbers are offered below in Table 3. Cost comparisons to other energy storage technologies are attractive, as shown in Figure 6., and these are expected to drop substantially when FBs are mass-produced:

Table 3. Comparative Economic Characteristics of 2 Leading Flow Batteries

BATTERY	POWER COST	ENERGY COST	O&M COST	SYSTEM COST
Regenesys	~$1,500/kW Projected: ~$750/kW	Electrolyte: $10–20/kWh System: n/d ($160–185/kWh)	n/d	$20–25 million for 10–15 MW, 100–150+ MWh
Vanadium	$1,500–5,500/kW Projected: $1,000/kW	Electrolyte: $30–50/kWh System: $300–1,000/kWh	~$50,000/y for 2.5 MW, 10 MWh system	~$11 million for 2.5 MW, 10 MWh system

Note: n/d = not determined

Figure 6. Cost Comparisons Between Various Battery Storage Types



Source: Energy Storage Assoc. (www.esa.org)

Total Cost Of Ownership

In 2000, a Tennessee Valley Authority/EPRI study assessed overall system costs of ownership for a large (roughly 10 MW, 100+ MWh) FB. The study evaluated VRBs, Regenesys and Zinc-Bromide batteries (Zn-Br, another FB technology not considered here). A TVA summary of the proprietary study reported that the purpose was to evaluate which technology currently in the process of being commercialized would most likely provide the lowest cost of operation of a life-cycle-cost basis for multi-hour utility energy storage, while providing other energy storage services that have economic value to electric utilities. Regenesys met all the requirements according to TVA. Zinc-bromide was the second choice, The study also concluded that VRBs and Zn-Br batteries had lower power and energy ratings and higher capital costs than Regenesys, and that Zn-Br electrolytes that are twice the cost per kilowatt of those used for the Regenesys technology.

Total (or lifecycle) cost of ownership is the most important economic indicator in the final analysis. Any prospective buyer will need to compare different technologies on the same power, energy storage, construction and O&M cost basis. This should be practical through a detailed comparison process, as TVA has demonstrated. For the near term, the most difficult to estimate will be O&M costs, since these systems do not have a long history of operation.

Conclusions/Future Prospects

The uniquely flexible capabilities offered by FBs appear compelling as outlined in this paper. Their technical practicality is being demonstrated at large scale relatively quickly, as compared to other new energy technologies such as fuel cells and microturbines. Also, the batteries produce virtually no emissions Based on these indicators, the authors conclude it is likely that as both FB technologies and their markets mature, these systems will move steadily into the mainstream of larger-scale ES applications.

At present it is impossible to predict what share of the various proposed markets for FBs they may succeed in, and if so when this may occur. Clearly some price reductions will occur as FBs are mass manufactured, but it is still too early to determine how much of the predicted price reductions will be realized, what the O&M costs for these devices will be and how long they will last. All these parameters are elements of their lifecycle costs that will ultimately be the basis for decisions on whether FBs are chosen over other alternatives.

If the lifecycle costs of FBs become competitive, they will be an alternative tool for achieving reliability, power systems management and energy trading, thus providing energy and asset utilization benefits at all levels of the market. Electricity will increasingly become storable and therefore commodified, and the power and energy markets will behave more like other commodity markets that feature with significant capital asset investments in production, storage and distribution.

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