Going with the Flow: Flow Batteries Offer Benefits and Challenges for Grid-Level Storage

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The world market is seeing a surging demand for energy storage, as well as heightened interest in how to make energy storage affordable, both for utilities and other private sectors dependent on energy consumption. Driving this demand from the utility side is the need to capture additional energy from renewable sources, and the need for back-up energy and load balancing for more effective grid management. For other sectors, energy storage is key for energy savings and for meeting reduced carbon emissions goals.

Developing an electrochemical energy storage solution that is safe, efficient and long-lasting is a complex task, and products cannot be rushed to market. Not every battery or energy storage application will meet every need, and the U.S. Department of Energy has actually called for the development of a portfolio of energy storage technologies to assist industry players in meeting various energy challenges. At the same time, says the Joint Center for Energy Storage and Research, the risk is high but the rewards are great for organizations who can develop a next-generation battery that meets multiple needs. In a December 2013 report entitled Grid Energy Storage, the DOE specified that energy storage solutions must address several key challenges, including cost, validated performance and safety, an equitable regulatory environment, and last but not least, acceptability to industry.

On top of this, in January 2015 the International Renewable Energy Agency identified a host of purchase criteria that add to the challenge, including maintenance requirements, power component availability and cost, company warranties and performance guarantees, operating condition parameters, installation infrastructure, footprint and energy density, and more.

Precisely because energy storage is critical technology that will play a major role in supporting our grid and many related uses, the industry needs to ensure its ability to design, model and test battery solutions in order to provide the most reliable data is reliable and so that all trade-offs are known. While most recently the spotlight has been on lithium-ion (Li-ion) battery technologies, these batteries are not well suited to utility use, as the grid requires more safety, flexibility and reliability. Because they discharge at a high voltage compared to standard lead acid batteries, Li-ion batteries pose a risk of overheating causing a chemical fire in the event of a short circuit. Li-ion for energy storage in buildings is actually banned in New York City, where officials have concerns about volatility.

In response to the long 20-year development period for Li-ion batteries, the U.S. Department of Energy began to fast-track government-funded research efforts to develop additional forms of energy storage. The results of these projects have pushed flow batteries to the foreground, where they are gaining significant momentum with industry. Some utilities have made initial purchases and are testing the batteries at a number of installations. As the industry expands its knowledge of flow batteries and begins to deploy them, we thought it might be interesting to take a closer look at the benefits and challenges of the technology.

Flow Batteries

Currently the industry is seeing commercialization of flow batteries using a number of different battery chemistries, and each R&D team claims certain unique benefits. Unlike conventional lead acid batteries and Li-Ion batteries, flow batteries are more like rechargeable fuel cells. They contain two separate external chambers, each containing electrolyte solutions with a different dissolved electrochemical element. The electrolyte solutions are pumped into a reactor cell where the liquids flow adjacent to each other separated by a permeable membrane. When the ions pass back and forth through the membrane a charge is created.

"Redox" flow batteries (RFBs) refer to a reduction-oxidation of the electrochemically active species in the solution. RFBs are practical because the electrolyte tanks act as a heat sink to prevent overheating, and the physical separation of the tanks from the reactor cell reduces the potential for thermal runaway found in Li-ion batteries. Operation can be stopped at any time by turning off pumping of electrolyte solution. Also, since there is no insertion and removal of ions from a solid electrode area, RFBs offer a longer cycle life by preserving the structural integrity of the stacks and cells.

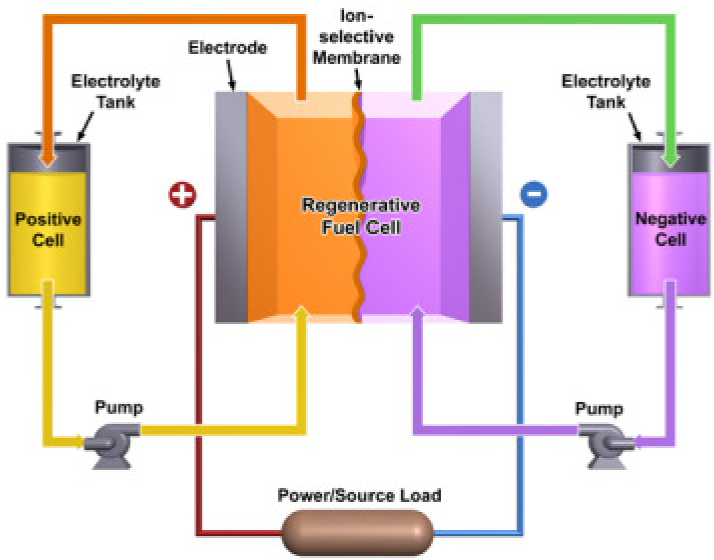


Diagram: a Redox Flow Battery

Vanadium redox flow batteries have recently received a good deal of publicity, with new results from research by the U.S. DOE's Pacific Northwest National Laboratories and licensing of the technology by a number of companies seeking a foothold in the energy storage market. UniEnergy Technologies (UET) is one of the first to market with a 1MW pilot installation in Pullman, Washington for Avista Utilities. Imergy has also shipped product for various installations and signed a 5MW contract with SunEdison. However, other flow batteries are also gaining traction. New batteries under development and targeting for commercialization include types that use all iron, iron and chromium, zinc and bromine, and zinc and iron.

Vanadium Redox Flow Batteries

Vanadium RFBs are now in their second generation form following the incorporation of advances from PNNL that increase reliability and double energy density. Their large capacities make them appropriate for utility use and their limited self-discharge capability allows them to sit in a ready state over long periods of time. They offer a rapid response time to changing power loads and large overload capacity. Rather than relying on two separate elements to create a reaction, the batteries combine vanadium in 4 different oxidized states to bring about the electrical charge. The advances also improve operating temperature tolerance, and tolerance to impurities in the electrolytes due to chemical changes. Vanadium is a relatively abundant material found in about 65% of minerals and fossil fuel deposits, and one company is seeking to reduce material cost even further through the use of recycled vanadium. Disadvantages include the expense of the ion exchange membrane, which until recently constituted 40% of the battery cost. The latest generation of vanadium RFB utilizes a lower cost electrolyte that can significantly offset overall system cost.

Iron Chromium Flow Batteries

Iron Chromium flow batteries (ICRBs) are also true flow batteries. Earlier efforts encountered some problem areas, including irreversible capacity loss and membrane fouling, but new iron chromium electrolytes have mitigated the phenomenon and enabled use of lower cost membrane materials that are not subject to fouling. A recent study* found that ICRBs have similar energy efficiencies at high current densities, but that the ICRB has a higher capacity decay rate. At the same time the ICRB is less expensive in capital costs when operating at high power densities or large capacities. Commercialized units must be designed in such a way as to minimize parasitic side reactions and to mitigate capacity loss.

All-Iron Flow Batteries

New all-iron flow batteries recently appeared on the market but there are no installations of yet. With a recyclable iron-based electrolyte and no toxic materials, the batteries apparently may exceed the performance of vanadium flow batteries while coming in at 70% below the cost of other electrochemical batteries due to the simplicity and recyclability of the materials.

Zinc Bromine Hybrid Flow Batteries

Zinc bromine batteries are now under commercial development for applications such as telecommunications back-up systems. These batteries are considered hybrid flow batteries because one of the electrochemically active components remains in the reactor when charging. In this case, the zinc ions attach to and "plate" the negative electrode surface as zinc metal. The benefits include a lower cost of materials and the ability to discharge the battery completely without degrading the performance. The drawbacks are that the battery must be fully discharged every few days in order to mitigate the zinc dendrites that can puncture the separator when allowed to grow. Any zinc bromide system requires a "strip cycle" to remove excess zinc, a procedure that can take between 30 minutes to 2 hours depending on conditions.

Zinc-Iron Redox Flow Battery

The zinc-iron redox battery offers the cost-effectiveness of readily available materials, an alkaline base for environmental safety, and an expectation of a 20-year lifetime. The commercial products are just now making their way into the market, with commissioning of the installations scheduled for this year.

Meeting the Challenge for Effective Flow Batteries

The need for energy storage is critical, but does not justify rushing solutions to market. In a September 2015 talk at the University of Washington/PNNL Energy Storage Symposium, George Crabtree, director of the Joint Center for Energy Storage Research, said that many teams and entrepreneurs have developed simple, elegant concepts for electrochemical storage, but that an immense number of variables will create complex interfering side effects so that most ideas ultimately will not work.

Mining Public/Private Research

Battery technology companies must do their homework, but the past several years of government-funded research offer development teams an enormous amount of data to leverage. A number of currently commercialized solutions have come from licensing government research. Combing the results of work executed at PNNL, Argonne, and affiliated universities can help research teams weed out unsuccessful technology approaches or determine whether a particular approach could be harnessed with more attention to a particular challenge.

Using the Best Design Tools for Characterization and Modeling

Taking a battery product or solution to market requires intensive testing and extensive data before grid and automotive partners will even consider evaluation of the technology. One of the serious sticking points for large customers is degradation, which battery manufacturers and integrators tends to skim over or not emphasize during the customers' due diligence process. Flow batteries can store and cycle large amounts of energy, but reactors will naturally suffer oxidative damage during battery cycling. This oxidation can negatively impact the lifespan of the reactor as well as limit the battery's operating efficiency.

"Carbon materials serve as cost-effective reaction surfaces for charging and discharging the electrolyte, a process by which electrical energy is converted to chemical potential and vice versa," says Alex Bistrika, president and chief engineer at eChemion, a Corvallis, Ore., company that analyzes and enhances the performance characteristics of carbon materials. "Unfortunately, carbon materials begin to degrade in these environments immediately upon cycling, leading to lower operating current over time and eventually resulting in complete failure of the electrode stack."

Degradation can have serious technological and financial implications that will be discussed in a subsequent article. New characterization and modeling tools for materials and electrochemical side effects are being developed and used in university and commercial environments that can better predict performance over time and potential problem areas.

Leveraging New Enhancement Technologies

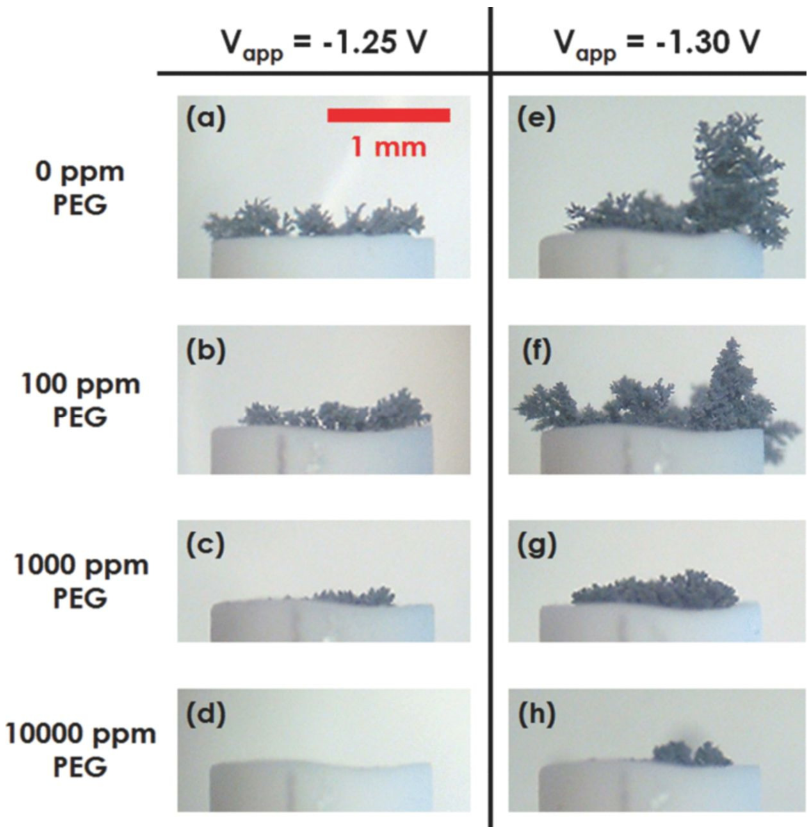
Using materials and techniques that enhance battery performance can make a large difference in predicting and preventing side effects. In order not to fall captive to the 20-year development cycle of the Li-ion battery, battery developers must emulate the "fail fast" and "fix fast" mantra of the software industry. eChemion specializes in optimizing the graphite materials (felt, paper or foil) used in the battery's reactor core, while companies such as EasyXAFs in Seattle provide an accessible way for industry and other battery developers to use X-rays to monitor degradation and condition of new battery materials in real time under a variety of conditions.

Testing

While many tests can be conducted in the lab, such variables as battery life can be very difficult to predict based on a variety of operating conditions, from temperature to humidity. Lifetime test can be costly as large numbers of batteries must be tested to destruction. Additionally, the period required to extensively and reliably test batteries can exceed the commercialization window, prompting developers to bring products to market that are not proven, and worse, potentially dangerous.

At the same time, using the option of accelerated lifetime testing may generate misleading data, as discharge times for high capacity batteries are long, and battery life depends on rate and depth of discharge. Artificially imposed test conditions to accelerate the occurrence of failure are likely to introduce new and unrepresentative failure modes.

In planning for testing for utility and grid-related use, the ability to prototype and test at scale is critical, since such products are immensely capital-intensive to launch. The Clean Energy Institute and a network of national labs are working to develop test beds that will enable corporate and public sector researchers to fabricate and rigorously test batteries that store renewable energy or run electric vehicles, using test hardware and software operating systems that can be deployed at utility scale.



Formation of these needle-like zinc dendrites from repeat electrodeposition can cause a problem with zinc flow batteries, requiring periodic stripping. Such electrochemical side effects happen frequently with complex battery chemistries, but may be predicted and mitigated through careful research, modeling and design. Photo Credit: Stephen J. Banik and Rohan Akolkarz, Department of Chemical Engineering, Case Western Reserve University.

Assuring Continued Advances through Front-End Research

Flow batteries seem to be the best solution to fill the short-term energy storage gap at grid scale, but despite a prodigious amount of development, the industry as a whole still lacks the in-depth understanding and the full data sets required to effectively make reliable decisions about deployment.

This lack of knowledge poses a barrier to faster adoption of flow battery-based energy storage solutions. Lack of information on degradation, performance testing, and expected short- and long-term chemical side effects -- such data holes are causing hesitation among potential adopters. In the case of early adopters with testbeds or working operational installations, incomplete data may jeopardize a large investment. While this is by no means saying that currently deployed solutions are ineffective or risky, utility and grid-related evaluation and purchasing staff are not chemical engineers. Despite having a long checklist of IRENA-style requirements that any vendor must meet, these staff may not always be aware of what questions to ask from the chemistry side to effectively evaluate a new product.

Part of the solution to speeding this promising technology to market is to conduct as much research and analysis early on. This is important for several reasons. First, it's important for the industry to have an initial group of products that are known and stable. This goal requires good design tools, modeling, optimization and significant testing – at each interval of the development process. Reliable in-depth data will enable developers, manufacturers and integrators to provide proven products upon which to build and improve performance.

Second, battery development itself is only part of the equation. Control software and other software/hardware interfaces also play a key role in time-to-market. Performance analysis is key for the chemical engineering community to look at now, during development, so that control software can be developed in parallel or quickly afterwards.

Finally, in addition to stimulating even more demand for renewable energy, the practice of better testing and characterization can also assist in fostering new business opportunities through the development of new tools, best design practices, standards evolution, and related equipment.

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