Vanadium-Bromine Redox Flow Battery

Flow Batterie Kolloquium in Karlsruhe am 27. September 2017

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Devens, Massachusetts USA
In the past few years the demand for large-scale energy storage has increased for several applications:

- **Renewables integration**
- Ancillary services
- Arbitrage
- Grid asset optimization
- T&D deferral
- Telecommunications – substitute for diesel
Renewables Integration

Wind & Solar Variability Problem

Wind Output

Solar Output

Oregon Wind Farm
10 - 100% in 1 hour

Arizona Solar Farm
10 - 80% in 5 min
Why Redox Flow Batteries?

- Separation of POWER and ENERGY
- More POWER = larger stack
- More ENERGY = larger tank
- Competitive energy efficiency

- Highly durable: 10,000+ cycles
- Safe, non-flammable liquid
- Lowest CapEx & OpEx
- Large application space

WattJoule

AICL Industrial Products

Where needs take us
Product Development Approach

- Start with a proven chemistry to lower risk: vanadium redox
- Engineer a next-gen OEM platform: quantum improvement
- Identify key barriers preventing full commercialization
- Utilize open innovation approach to secure best IP
- Leverage the best expertise wherever it is
- Develop a multi-generational pipeline of product improvements
## Building a Superior Product

<table>
<thead>
<tr>
<th>CURRENT PROBLEM SET</th>
<th>WATTJOULE IMPROVEMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrochemical stacks are large and use expensive materials</td>
<td>New breakthroughs now allow major reductions in stack size</td>
</tr>
<tr>
<td>Electrolyte energy density is low and requires large tanks</td>
<td>We have technology that increases the energy we can store in every liter</td>
</tr>
<tr>
<td>System needs refrigerated cooling thereby increasing costs and lowering efficiency</td>
<td>We can now eliminate AC and chiller equipment with our platform</td>
</tr>
<tr>
<td>Lifetime system efficiency needs improvement</td>
<td>We now add major efficiency improvements with no added cost</td>
</tr>
<tr>
<td>Need for costly, high purity active materials like vanadium</td>
<td>We have a pathway to utilizing less and then no vanadium over time</td>
</tr>
<tr>
<td>Relatively high cost vs. attractive economics</td>
<td>All of the above improvements translate to significantly lower cost</td>
</tr>
</tbody>
</table>
# Quantum Improvement Factors

Pathway to Better VRB Metrics

<table>
<thead>
<tr>
<th>Key Metric</th>
<th>SOA¹</th>
<th>Gen 1</th>
<th>Gen 2 V-Br</th>
<th>Core Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Converter Stack Power Density</td>
<td>1X</td>
<td>6X</td>
<td>7X</td>
<td>Lower material cost</td>
</tr>
<tr>
<td>Electrolyte Energy Density</td>
<td>1X</td>
<td>2X</td>
<td>3X</td>
<td>Less liquid required</td>
</tr>
<tr>
<td>Electrolyte Temperature Range</td>
<td>1X</td>
<td>3X</td>
<td>3.2X</td>
<td>No active cooling needed</td>
</tr>
<tr>
<td>Roundtrip Efficiency</td>
<td>1X</td>
<td>1.1X</td>
<td>1.2X</td>
<td>Lower life cycle cost</td>
</tr>
<tr>
<td>Vanadium Cost Reduction</td>
<td>1X</td>
<td>1.4X</td>
<td>2.2X</td>
<td>Lower vanadium cost</td>
</tr>
<tr>
<td>DC System Capital Cost ($/kWh)</td>
<td>600</td>
<td>200</td>
<td>150</td>
<td>Significantly lower CapEx</td>
</tr>
</tbody>
</table>

¹ State-of-the-Art Redox Flow Battery
ElectriStor™ ES10 Test System

2kW, 10kWh Engineering Prototype II, DC Only

1,000-fold increase in power and energy from 2014-2016
So...What’s Next?

- We believe that the improvements made in the chemistry, materials and design of our Gen 1 all-vanadium redox flow battery have pushed this system nearly to its maximum performance and minimum cost limits.
- Further improvements in our RFB platform will require a change in the basic system chemistry.
- With financial and technical support from ICL, we have chosen the vanadium-bromine redox flow battery for further development.
V-Br Redox Flow Battery

Performance
• Electrolyte energy density of ≥ 50 Wh/kg
• Operating electrode current density of ≥ 200 mA/cm²
• Maximum power density of ≥ 1000 mW/cm²
• Standard operating temperature of 45°C
• Round-trip DC electrical efficiency of 80%

Cost
• $150/kWh for DC energy storage system
V-Br Redox Flow Battery

Electrode reactions for charge:

Negative electrode reaction:

$$2V^{3+} + 2e^- \rightarrow 2V^{2+}$$

Positive electrode reaction:

$$2Br^- + QB_{r_n} \rightarrow QB_{r_{n+2}} + 2e^-$$

Insoluble bromine oil falls to the bottom of the catholyte tank
V-Br Redox Flow Battery Advantages Over All-Vanadium

- Decrease amount of Vanadium by nearly 50%
- Increased electrolyte energy density
- Technology demonstrated in lab-scale hardware
- Utilizes Gen 1 high-power density cell technology
- Proprietary complexing agent provides multiple system benefits
- Strong WattJoule IP position
## V-Br Redox Flow Battery
### Advantages Over Other Chemistries

<table>
<thead>
<tr>
<th>ALTERNATIVE FLOW CHEMISTRIES</th>
<th>VANADIUM BROMINE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen bromine requires large high pressure tanks to store flammable and explosive gaseous hydrogen, and needs expensive catalyst that degrades over time</td>
<td>Requires no catalyst and all the energy is safely stored in liquid form. Electrolyte contains over 60% water and cannot burn or explode.</td>
</tr>
<tr>
<td>Zinc bromine has dendrite problems on electrodes that require stripping and have durability issues. Power and energy coupled since hybrid flow. Low power density.</td>
<td>True redox flow battery that requires no plating and therefore has no dendrite problems. Power and energy capability completely uncoupled.</td>
</tr>
<tr>
<td>Iron chromium has a significant hydrogen and chlorine gassing problem under normal operation and has low energy density.</td>
<td>Virtually no gassing potential due to electrochemical operating mode. Much higher energy density can be achieved.</td>
</tr>
<tr>
<td>Vanadium-vanadium requires large stacks and tanks and the higher cost of vanadium, also has a limited temperature range.</td>
<td>Much higher power and energy density can be achieved while cutting vanadium use by 50%. Temperature range not an issue.</td>
</tr>
</tbody>
</table>
V-Br Test Results

Initial Results of Polarization Test on Gen 2
At 45°C in 25-cm² Cell

\[ y = -0.0415x + 1.3373 \]
V-Br Test Results

Gen 2 Power Capability in 25-cm\(^2\) cell at 45°C
Vanadium Concentration 2.0 Mol/L

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<tr>
<th>Membrane</th>
<th>P(_{\text{max}}), mW/cm(^2)</th>
<th>Specific Resistance, Ωcm(^2)</th>
</tr>
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<tr>
<td>Fluorinated Ion-Exchange</td>
<td>431</td>
<td>1.0375</td>
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**Power Performance Similar to Gen 1 in First Experiments**
V-Br Test Results

Typical UNSW Cycling with Bromine Complexation
Current Density only 10 mA/cm$^2$

Figure H.23 Charge / discharge cycles of 2 M V$^{3.7+}$, 0.19 M MEM, 0.56 M MEP, 6.1 M HBr, 1.2 M HCl using ChiNafion membrane at 25°C (CY060929.cel; 50ml electrolytes; (+ve) 27°C (-ve) 26°C)
WattJoule Cycling Results at 200 mA/cm²
2M V at 45°C

V-Br Test Results
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WattJoule expresses its sincere thanks to ICL for its financial and technical assistance in carrying out the work on the V-Br redox flow battery system.